Testing, debugging and verification

Notes based on lectures for DIT084 (Testing, debugging and verification) at Gothenburg University, Autumn 2023

Sebastian Pålsson

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1. Introduction

How do we judge failure in software development? In general, we need a measure to judge failure. This is given by means of satisfaction of a specification. A specification is a set of requirements that a system must satisfy. A specification can be given in many forms, such as a formal mathematical description, a set of examples, or a set of requirements in natural language. The specification is the basis for testing, debugging and verification.

In simple terms:

$$\text{Spec} = \text{Require} + \text{Ensure} \qquad [1]$$

where **Require** is the set of requirements the program must satisfy in order to behave correctly, and **Ensure** is the set of guarantees that the program must satisfy.

Example

Imagine a programs that sorts an array of integers. The program must satisfy the following specification:
- **Require:** Accept only input as an array of integers.
- **Ensure:** Return a sorted array of integers.

1.1. The contract methaphor

Same priciple as a **legal contract**, between supplier and client.
- **Supplier:** aka implementer, here a *class or method* in Java.
- **Client:** mostly *caller object or human user* calling main-method.
- **Contract:** One or more *pairs of ensures-requires clauses*, defining *mutual obligations* between supplier and client.

*"If the caller (the client) of the method **m** (the supplier) gives inputs which fulfils the required **precondition**, then the method **m** ensures that the **postcondition** holds after **m** finishes execution."*

1.2. Specification, failure, correctness

A failure/correctness is relative to a specification.
- A method **fails** when called in a *state fulfilling the required precondition* of its contract and it *does not terminate in a state fulfulling the postcondition* to be ensured.
- A method is **correct** whenever it is started in a *state fulfilling the required precondition*, then it *terminates in a state fulfilling the postcondition to be ensured.*
- **Correctness:** Proving absence of failures.

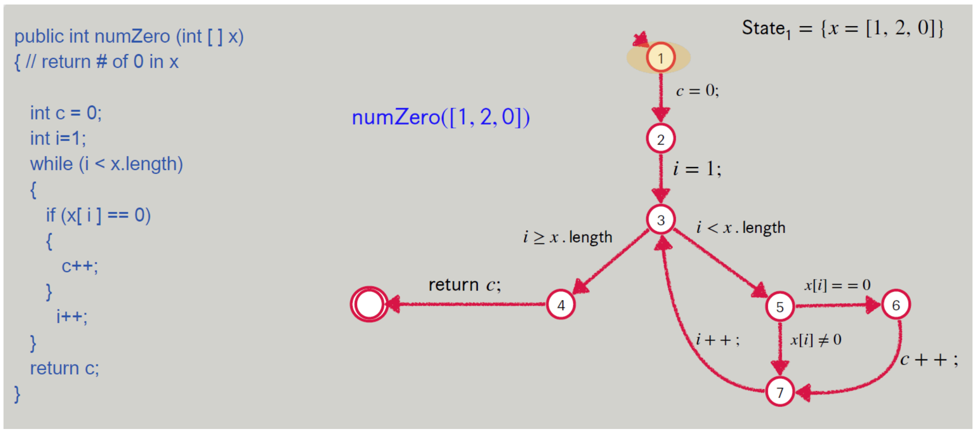
2. Testing

Some terminology regarding faults, errors & failures:
- **Fault:** a static defect in the software.
- **Error:** an incorrect internal state that is the manifestation of some fault.
- **Failure:** external, incorrect behaviour with respect to expected behaviour.

2.1. The State of a program

A program can be seen as a function that maps a state to a state. The state of a program is the values of all variables at a given point in time.

Inputs in the program in Figure 1 does not always trigger failures. This is the case for most programs!



```
public int numZero (int [ ] x)
{ // return # of 0 in x

  int c = 0;
  int i=1;
  while (i < x.length)
  {
    if (x[ i ] == 0)
    {
      c++;
    }
     i++;
  }
  return c;
}
```

Figure 1: A graph showing the states of a program

2.1.1. Program to graph

How does one convert a program to a state graph?

A labelled graph G is of the form

$$G = (N, E, L) \qquad [2]$$

where N is a set of nodes, E is a set of edges and L is a set of labels. $E \subseteq N \times L \times N$

A program P is a set of statements

$$P = \{s_1, s_2, ..., s_n\} \qquad [3]$$

The following function is used to transform the program to a graph:

$$[\cdot]^{0,f} : S \to 2^E \qquad [4]$$

The function takes an initial state 0 and a final state f and a **statement** and **return a set of edges**. We use the special state $\bot$ to mean an exit state (for return statements).

The transformation rule are as follows:

$$[s_1; s_2]^{0,f} = [s_1]^{0,1} \cup [s_2]^{1,f} \qquad [5]$$

where 1 is a fresh state.

Example

Some examples of transformations:

- $[x = a;]^{0,f} = \{(0, f = a, f)\}$
- $[\text{return } a;]^{0,f} = \{(0, \text{return } a, \bot)\}$
- $[\text{if}(b)\{s_1\}]^{0,f} = \{(0, b, 1), (0, !b, f)\} \cup \{s_1\}^{1,f}$
- $[\text{while}(b)\{s_2\}]^{0,f} = \{(0, b, 1), (0, !b, f)\} \cup \{s_2\}^{1,0}$

2.2. Complexity of testing (and why we need models)

No other engineering field builds products as complicated as software. The term correctness has no meaning. Like other engineers, we must use abstraction to cope with complexity. We use **discrete mathematics** to raise our level of abstraction.

Abstraction is the purpose of *Model-Driven Test Design* (MDTD). The "model" is an abstract structure.

2.2.1. Software testing foundations

Testing can only show the presence of failures, not their absence.

- **Testing:** Evaluate software by observing its execution.
- **Test Failure:** Execution of a test that results in a software failure.
- **Debugging:** The process of finding a fault given a failure.

Not all inputs will "trigger" a fault into causing a failure

2.2.2. RIPR model (or fault and failure model)

Four conditions necessary for a failure to be observed:
- **Reachability:** The location or locations in the program that contain the fault must be reached.
- **Infection:** The state of the program must be incorrect.
- **Propagation:** The infected state must cause some output/final state to be incorrect.
- **Reveal:** The tester must observe part of the incorrect state.

The RIPR model is a framework for understanding and categorizing software bugs. It stands for Reach, Infection, Propagation, and Reveal. Reach refers to the execution reaching the defect, Infection is when the defect causes an incorrect program state, Propagation is when this incorrect state leads to incorrect behavior or output, and Reveal is when this incorrect behavior is observed.

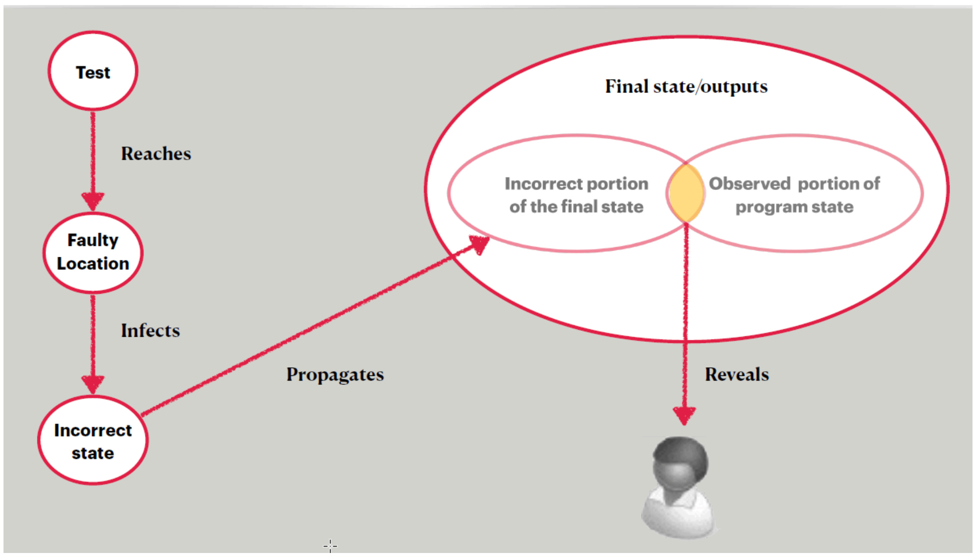


Figure 2: The RIPR model

2.2.3. The V model

The V-model emphasizes a parallel relationship between development and testing stages. Each development stage has a corresponding testing phase, ensuring that issues are identified and fixed early. *It's called the V-model due to its V-like structure, representing the sequence of execution of processes.*

Each testing phase uses a different type of testing level:

- **Acceptance testing:**: Assess software with respect to user requirements
- **System Testing:**: Assess software with respect to system-level specification.
- **Integration Testing:** Assess software with respect to high-level design
- **Unit Testing:** Assess software with respect to low-level unit design

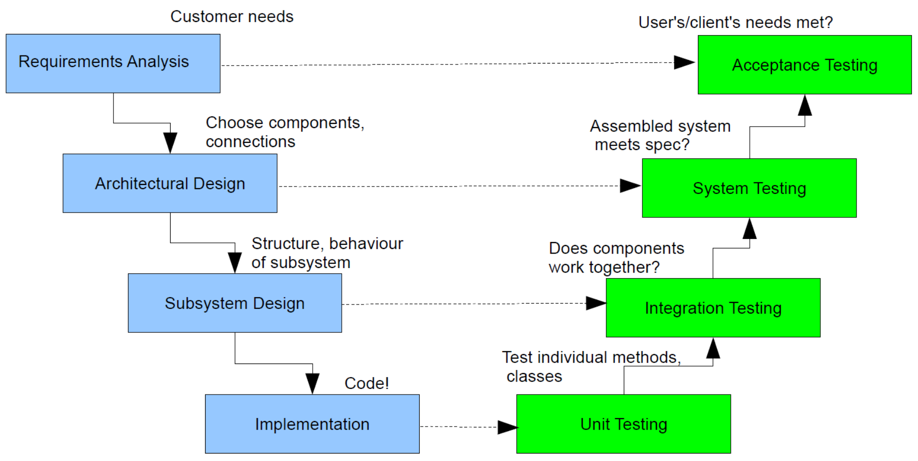

Customer needs
Requirements Analysis
User's/client's needs met?
Acceptance Testing
Choose components, connections
Architectural Design
Assembled system meets spec?
System Testing
Structure, behaviour of subsystem
Subsystem Design
Does components work together?
Integration Testing
Code!
Implementation
Test individual methods, classes
Unit Testing

Figure 3: The V model

2.3. Test automation

The use of software to control *the execution* of tests, the *comparison* of actual outcomes to predicted outcomes, the *setting up* of test preconditions, and other test *control* and test reporting functions.

- Reduces cost
- Reduces human error
- Reduces variance in test quality from different individuals
- Reduces cost of **regression testing**

2.4. Regression testing

Regression testing is a type of software testing that seeks to uncover new software bugs, or regressions, in existing functional and non-functional areas of a system after changes such as enhancements, patches or configuration changes, have been made to them.

- Orthogonal to other mentioned tests
- Testing that is done **after changes** in the software (updates)
- Standard part of maintenance phase of software development

The purpose of regression testing is to gain confidence that changes did not cause new failures.

2.5. Software testability

The degree to which a system or component facilitates the establishment of test criteria and the performance of tests to determine whether those criteria have been met. *In simple terms: how hard is it to finds faults?*

Testability is a condition of two factors:
- How to provide the test values to the software?
- How to observe the results of test execution?

2.6. Observability

How easy it is to observe the behaviour of a program in terms of its outputs, effects on the environment and other hardware and software components.

Software that affects hardware devices, databases, or remote files have low observability!

2.7. Controllability

How easy it is to provide a program with the needed inputs, in terms of values, operations, and behaviours.

- Easy to control software with inputs from keyboards
- Inputs from hardware sensors or distributed software is harder

2.8. Test suit construction

A test suite is a collection of test cases that are intended to be used to test a software program to show that it has some specified set of behaviours.

- Most central actitivy of testing
- Determines if we have enough test cases (stopping criteria)
- Determines if we have the right test cases (represenative test cases)

The quality of test suites defines the quality of the overall testing effort. When presenting test suites, we show only relevant parts of test cases.

2.8.1. Black box testing

Deriving test suites from external descriptions of the software, e.g.
- Specifications
- Requirements / Design
- Input space knowledge

2.8.2. White box testing

Deriving test suites from the source code, e.g.

- Conditions
- Branches in execution
- Statements

Modern techniques are a hybrid of both black- and white box

2.8.3. Coverage criteria

3. Debugging

- How to systematicly find source of failer
- Test-case to reproduce errors
- Finidng a small failing input (if possible)
- Observing exceution: Debbuggers and Logging
- Program dependencies: data- and control

3.1. Motivation

- Debuging needs to be systematic
- Debuging may involve large inputs
- Programs may have have thousands of memory locations
- Program may pass through milions of states before failure occurs

3.2. The Steps Of Debugging

1. Reproduce the error and try to understand the cause.
2. Isolate and minimise the diffrent factors. (**Simplification**)
3. Eyeball the code, where could it be? (**Reason backwards**)
4. Devise experiments to test your hypothesis. (**Test hypothesis**)
5. Repeat step 3 and 4 until the cause of the bug is determined
6. Fix the bug and verify the fix
7. Create a regression test (See below)

Regression testing is a type of software testing that checks if recent code changes have negatively impacted existing features. It involves re-running previously created test cases after code modifications to catch any unintended side effects and ensure the ongoing stability of the software.

3.3. Problem Simplification

As described in the diffrent steps of debugging, simplification is a way to determine the bug. The idea behing simplification is to minimize the failing input, so that it will be easier to understand what inputs causes the bug.

Simplification can be reached by **Divide-and-Conquer**, where you ->

1. Cut away one half of the test input
2. Check if any of the halves still exhibit failure.
3. Repeat, until minimal input has been found.

Although this works in some scenarios, this method has the following problems ->

- Tedious to re-run test manually
- Boring, cut and paste, re-run …
- What, if none of the halves exhibits a failure?

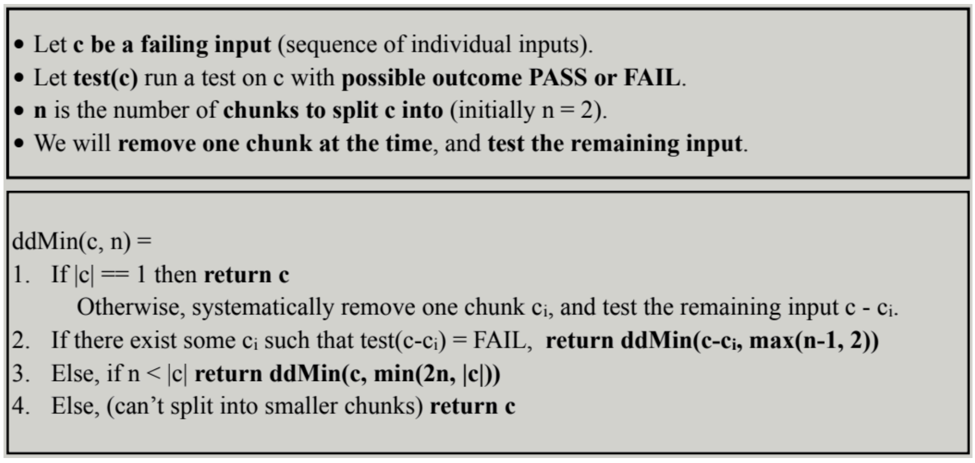
Because of the problems with **Divide-and-Conquer**, in most cases automation of input simplificartion is more favourable.

3.3.1. AUTOMATION OF INPUT SIMPLIFICATION

Automation of input simplification in debugging involves using tools or algorithm to automatically reduce the complexity of input data. This helps identify and isolate bugs more efficiently, especially in large or complex software systems.

One exampel of such a algorrithm is **Delta Debugging**. Delta debugging is a software debugging technique that aims to isolate and identify the cause of a failure in a program by systematically narrowing down the input that triggers the failure. The term “delta” refers to the minimal change needed to reproduce the failure.

The algorithm **Delta debugging** or **DD-Min** as it is also called, works as seen in figure 4 below.



- Let **c be a failing input** (sequence of individual inputs).
- Let **test(c)** run a test on c with **possible outcome PASS or FAIL**.
- **n** is the number of **chunks to split c into** (initially n = 2).
- We will **remove one chunk at the time**, and **test the remaining input**.

```
ddMin(c, n) =
1. If $|c| == 1$ then return c
       Otherwise, systematically remove one chunk $c_i$, and test the remaining input $c - c_i$.
2. If there exist some $c_i$ such that $test(c-c_i) = FAIL$, return ddMin($c-c_i$, max(n-1, 2))
3. Else, if $n < |c|$ return ddMin(c, min(2n, $|c|$))
4. Else, (can't split into smaller chunks) return c
```

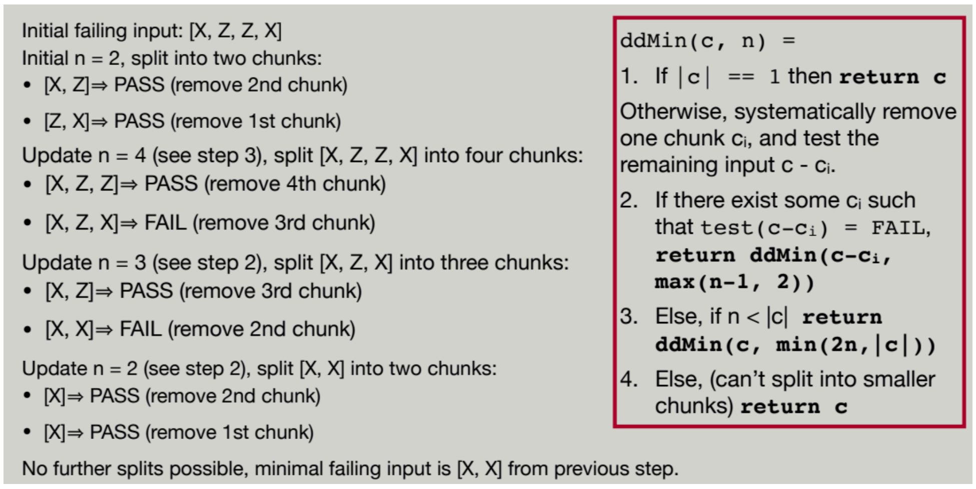
Figure 4: Delta Debugging

3.3.2. Short Quiz On Delta debugging

Question :

Suppose test(c) returns FAIL whenever ccontains two or more occurrences of the letter X. Apply the ddMin algorithm to minimise the failing input array [X, Z, Z, X] . Write down each step of the algorithm, and the values of n (number of chunks). Initially, n is 2.

Solution :



Initial failing input: [X, Z, Z, X]
Initial n = 2, split into two chunks:
- [X, Z]⇒ PASS (remove 2nd chunk)
- [Z, X]⇒ PASS (remove 1st chunk)

Update n = 4 (see step 3), split [X, Z, Z, X] into four chunks:
- [X, Z, Z]⇒ PASS (remove 4th chunk)
- [X, Z, X]⇒ FAIL (remove 3rd chunk)

Update n = 3 (see step 2), split [X, Z, X] into three chunks:
- [X, Z]⇒ PASS (remove 3rd chunk)
- [X, X]⇒ FAIL (remove 2nd chunk)

Update n = 2 (see step 2), split [X, X] into two chunks:
- [X]⇒ PASS (remove 2nd chunk)
- [X]⇒ PASS (remove 1st chunk)

No further splits possible, minimal failing input is [X, X] from previous step.

```
ddMin(c, n) =
1. If |c| == 1 then return c
Otherwise, systematically remove one chunk ci, and test the remaining input c - ci.
2. If there exist some ci such that test(c-ci) = FAIL,
   return ddMin(c-ci, max(n-1, 2))
3. Else, if n < |c| return ddMin(c, min(2n,|c|))
4. Else, (can't split into smaller chunks) return c
```

Figure 5: Delta Debugging Quiz Answer

3.4. Observing outcome, State Inspection

Mainly there are three diffrent ways to perform state inspections of a program ->

- **Simple logging :** print statements
- **Advanced loggin :** configureable what is printed based on level (e.g. OFF < FINE < INFO < WARNING < SEVERE), using e.g. Java's logging package.
- **Debugging tools :** e.g. Eclipse debugger or the Java debugger jbd (hand-in assignment 2)

3.4.1. The Quick-And-Dirty Approach : Print Logging

- **Manually add prit statements at code locations to be observed**
- System.out.println("size = "+ size);

Pros ->

- Simple and easy.
- No tools or infrastructure needed, works on any platform.

Cons ->

- Code cluttering.
- Output cluttering.
- Performance penalty, possibly changed behaviour (real time apps).
- Buffered output lost on crash
- Source code access required, recompilation necessary.

3.4.2. BASIC LOGGING IN JAVA

- Each class can have its own logger-object.
- Each logger has level:
- OFF < FINE... < INFO < WARNING < SEVERE
- Setting the level controls which messages gets written to log.
- Quick Demo: Dubbel.java

Pros ->

- Output cluttering can be mastered
- Small performance overhead
- Exceptions are loggable
- Log complete up to crash
- Etc.

Cons ->

- Code cluttering - don't try to log everything

3.4.3. Using Debuggers

Assume we have found a small failing test case and identified the faulty component.

Basic Functionality of a Debugger
- Execution Control: Stop execution at specific locations, breakpoints
- Interpretation: Step-wise execution of code
- State Inspection: Observe values of variables and stack
- State Change: Change state of stopped program
- Debugging tools: Eclipse GUI debugger or the Java debugger jbd

4. Formal Specification

4.1. Why We Need Formal Specifications:

4.1.1. The `absPositive()` Example

- Issue in Java's `Math.abs()` Function:
  - Description: The Java standard library function `Math.abs()` can return a negative number when given `Integer.MIN_VALUE`. This is counterintuitive, as the absolute value should always be non-negative.

The `absPositive()` Method
- Proposed Solution:
  - Implement a new method `absPositive()`.
- Goal:
  - Ensure that the returned value is always positive.

Formal Specification
- Necessity:
  - A formal specification is crucial to clearly define expected behavior.
- Example Specification:
  - **Precondition**: Input is any integer.
  - **Postcondition**: Output is a positive integer.
  - **Invariant**: Output is the absolute value of the input unless input is `Integer.MIN_VALUE`.
  - **Exception Handling**: For `Integer.MIN_VALUE`, output a predefined positive value.

Benefits
- Clarity and Precision:
  - Formal specifications eliminate ambiguity, ensuring that the method behaves as intended.
- Automated Verification:
  - Tools like Dafny can be used to automatically verify that `absPositive()` adheres to its specification.

4.2. Specification As Contracts

- **Concept**: Design by Contract.
  - Description: Emphasizes the mutual agreement in method calls between caller (client) and callee (implementer).
  - **Preconditions**: Requirements that the caller must fulfill.
  - **Postconditions**: Guarantees provided by the callee upon method completion.

4.3. Formal vs. Informal Specifications

- Distinction:
  - Formal Specifications: Precise, unambiguous, and enable automated analysis.
  - Informal Specifications: More readable but can be ambiguous and less precise.

Example

Informal specification:

- Very informal specification of enterPIN (pin:int)':

Enter the PIN that belongs to the currently inserted bank card into the ATM, when not yet authenticated. If a wrong PIN is entered three times in a row, the card is invalidated and confiscated. After having entered the correct PIN, the customer is regarded as authenticated.

Example

Formal specification

- Contract and Method Specification: `enterPIN` Method
- **Contract Overview**:
  - Description: Specifies the conditions and guarantees for the `enterPIN` method.
- **Method**: `enterPIN(pin:int)`
  - **Precondition**:
    - Card is inserted.
    - User not yet authenticated.
  - **Postconditions**:
    - If pin is correct:
      - User is authenticated.
    - If pin is incorrect and `wrongPINCounter` was < 2 when entering the method:
      - `wrongPINCounter` is increased by 1.
      - User is not authenticated.
    - If pin is incorrect and `wrongPINCounter` was >= 2:
      - Card is confiscated.
      - User is not authenticated.
- **Implicit Preconditions in Natural Language Specification**:
  - Assumptions:
    - Inserted card is not null.
    - The card is valid.
  - Note: These should also be formalized in the specification.

4.4. Validity

- A formula is valid if it is true in all possible states
- Valid formulas are useful to simplify other formulas.
- A formula is satisfiable if it is true at least once.