Dependable Software Systems

Topics in Software Testing

Material drawn from [Beizer, Sommerville, Neumann, Mancoridis, Vokolos]
The first “bug”

Photo # NH 96566-KN First Computer "Bug", 1945

9/9

0800 Arden started
1000 stopped - Arden
1300 (033) MP - MG
033 PRO 2.130647465
code 2.130676485
Relays # 2 in 033 failed special speed test
in testing. 10,000 test.

1100 Started Cosine Tape (Sine chart)
1525 Started Multi Adder Test.

1545 Relay #70 Panel F
(moth) in relay.

First actual case of bug being found.

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The first “bug”

- Moth found trapped between points at Relay #70, Panel F, of the Mark II Aiken Relay Calculator, while it was being tested at Harvard University, September 9, 1945.

www.history.navy.mil/photos/images/h96000/h96566k.jpg
Myths About Bugs

- **Benign Bug Hypothesis:** Bugs are nice, tame, and logical.
- **Bug Locality Hypothesis:** A bug discovered within a component affects only that component’s behavior.
- **Control Bug Dominance:** Most bugs are in the control structure of programs.
- **Corrections Abide:** A corrected bug remains correct.
Myths About Bugs (Cont’d)

- **Silver Bullets**: A language, design method, environment grants immunity from bugs.
- **Sadism Suffices**: All bugs can be caught using low cunning and intuition. (Only easy bugs can be caught this way.)
Defective Software

- We develop programs that contain defects
  - How many? What kind?
- Hard to predict the future, however… it is highly likely, that the software we (including you!) will develop in the future will not be significantly better.
Sources of Problems

- **Requirements Definition:** Erroneous, incomplete, inconsistent requirements.

- **Design:** Fundamental design flaws in the software.

- **Implementation:** Mistakes in chip fabrication, wiring, programming faults, malicious code.

- **Support Systems:** Poor programming languages, faulty compilers and debuggers, misleading development tools.
Sources of Problems (Cont’d)

- **Inadequate Testing of Software:** Incomplete testing, poor verification, mistakes in debugging.

- **Evolution:** Sloppy redevelopment or maintenance, introduction of new flaws in attempts to fix old flaws, incremental escalation to inordinate complexity.
Adverse Effects of Faulty Software

- **Communications:** Loss or corruption of communication media, non delivery of data.
- **Space Applications:** Lost lives, launch delays.
- **Defense and Warfare:** Misidentification of friend or foe.
Adverse Effects of Faulty Software (Cont’d)

- **Transportation:** Deaths, delays, sudden acceleration, inability to brake.
- **Safety-critical Applications:** Death, injuries.
- **Electric Power:** Death, injuries, power outages, long-term health hazards (radiation).
Adverse Effects of Faulty Software (Cont’d)

• **Money Management:** Fraud, violation of privacy, shutdown of stock exchanges and banks, negative interest rates.

• **Control of Elections:** Wrong results (intentional or non-intentional).

• **Control of Jails:** Technology-aided escape attempts and successes, accidental release of inmates, failures in software controlled locks.

• **Law Enforcement:** False arrests and imprisonments.
Bug in Space Code

- Project Mercury’s FORTRAN code had the following fault:
  - `DO I=1.10` instead of `DO I=1,10`
- The fault was discovered in an analysis of why the software did not seem to generate results that were sufficiently accurate.
- The erroneous `1.10` would cause the loop to be executed exactly once!
Military Aviation Problems

- An F-18 crashed because of a missing exception condition: 
  \( \text{if ... then ... without the else clause that was thought could not possibly arise.} \)

- In simulation, an F-16 program bug caused the virtual plane to flip over whenever it crossed the equator, as a result of a missing minus sign to indicate south latitude.
Year Ambiguities

• In 1992, Mary Bandar received an invitation to attend a kindergarten in Winona, Minnesota, along with others born in '88.
• Mary was 104 years old at the time.
Year Ambiguities (Cont’d)

- Mr. Blodgett’s auto insurance rate tripled when he turned 101.
- He was the computer program’s first driver over 100, and his age was interpreted as 1.
- This is a double blunder because the program’s definition of a teenager is someone under 20!
Dates, Times, and Integers

• The number $32,768 = 2^{15}$ has caused all sorts of grief from the overflowing of 16-bit words.

• A Washington D.C. hospital computer system collapsed on September 19, 1989, $2^{15}$ days after January 1, 1900, forcing a lengthy period of manual operation.
Dates, Times, and Integers (Cont’d)

- COBOL uses a two-character date field …
- The Linux **term** program, which allows simultaneous multiple sessions over a single modem dialup connection, died word wide on October 26, 1993.
- The cause was the overflow of an **int** variable that should have been defined as an **unsigned int**.
In the US, five nuclear power plants were shut down in 1979 because of a program fault in a simulation program used to design nuclear reactor to withstand earthquakes.

This program fault was, unfortunately, discovered after the power plants were built!
Shaky Math (Cont’d)

- Apparently, the arithmetic sum of a set of numbers was taken, instead of the sum of the absolute values.
- The five reactors would probably not have survived an earthquake that was as strong as the strongest earthquake ever recorded in the area.
**Therac-25 Radiation “Therapy”**

- In Texas, 1986, a man received between 16,500-25,000 rads in less than 1 sec, over an area of about 1 cm.
- He lost his left arm, and died of complications 5 months later.
- In Texas, 1986, a man received at least 4,000 rads in the right temporal lobe of his brain.
- The patient eventually died as a result of the overdose.
Therac-25 Radiation “Therapy” (Cont’d)

- In Washington, 1987, a patient received 8,000-10,000 rads instead of the prescribed 86 rads.
- The patient died of complications of the radiation overdose.
AT&T Bug: Hello? ... Hello?

- In mid-December 1989, AT&T installed new software in 114 electronic switching systems.
- On January 15, 1990, 5 million calls were blocked during a 9 hour period nationwide.
The bug was traced to a C program that contained a break statement within an switch clause nested within a loop.

The switch clause was part of a loop. Initially, the loop contained only if clauses with break statements to exit the loop.

When the control logic became complicated, a switch clause was added to improve the readability of the code...
Bank Generosity

• A Norwegian bank ATM consistently dispersed 10 times the amount required.
• Many people joyously joined the queues as the word spread.
Bank Generosity (Cont’d)

- A software flaw caused a UK bank to duplicate every transfer payment request for half an hour. The bank lost 2 billion British pounds!
- The bank eventually recovered the funds but lost half a million pounds in potential interest.
Making Rupee!

- An Australian man purchased $104,500 worth of Sri Lankan Rupees.
- The next day he sold the Rupees to another bank for $440,258.
- The first bank’s software had displayed a bogus exchange rate in the Rupee position!
- A judge ruled that the man had acted without intended fraud and could keep the extra $335,758!
Bug in BoNY Software

• The Bank of New York (BoNY) had a $32 billion overdraft as the result of a 16-bit integer counter that went unchecked.

• BoNY was unable to process the incoming credits from security transfers, while the NY Federal Reserve automatically debited BoNY’s cash account.
Bug in BoNY Software (Cont’d)

• BoNY had to borrow $24 billion to cover itself for 1 day until the software was fixed.
• The bug cost BoNY $5 million in interest payments.
Programs and their Environment

• A program’s environment is the hardware and systems software required to make it run.

• Programmers should learn early in their careers that it is not smart to blame the environment for bugs.

• Bugs in the environment are rare because most bugs have been found over a long period of usage by a large number of users.
SE Community Response

- Improved environments for software development.
- Better processes to ensure that we are building the right thing.
- Technology to help us ensure that we built the thing right.
Arsenal for Dependable Software

- Automated development aids
- Static source code and design analysis
- Formal methods
  - Requirements specification, Program Verification
- Inspections
- Peer reviews
- Testing
Software Testing

• Software testing is a critical element of software quality assurance and represents the ultimate review of:
  – specification
  – design
  – coding

• Software life-cycle models (e.g., waterfall) frequently include software testing as a separate phase that follows implementation!
Software Testing (Cont’d)

• Contrary to life-cycle models, testing is an activity that must be carried out throughout the life-cycle.
• It is not enough to test the end product of each phase. Ideally, testing occurs during each phase.
**Terminology**

- **Error**: A measure of the difference between the actual and the ideal.
- **Fault**: A condition that causes a system to fail in performing its required function.
- **Failure**: The inability of a system or component to perform a required function according to its specifications.
- **Debugging**: The activity by which faults are identified and rectified.
Terminology

- **Test case**: Inputs to test the program and the predicted outcomes (according to the specification). Test cases are formal procedures:
  - inputs are prepared
  - outcomes are predicted
  - tests are documented
  - commands are executed
  - results are observed and evaluated

Note: all of these steps are subject to mistakes.

- When does a test “succeed”? “fail”? 
Terminology

- **Test suite**: A collection of test cases

- **Testing oracle**: A mechanism (a program, process, or body of data) which helps us determine whether the program produced the correct outcome.
  - Oracles are often defined as a set of input/expected outcome pairs.
**Terminology: Sources of Testing Oracles**

- **Regression Test Suites:** Test software using the test suites developed for previous versions of the same software.

- **Purchased Test Suites:** Highly standardized software (compilers, mathematical routines) often have commercially available test suites.

- **Existing Program:** A working, trusted, program that is being re-hosted to a new language or O/S.
**Terminology**

- **Outcome**: What we expect to happen as a result of the test. In practice, *outcome* and *output* may not be the same.
  - For example, the fact that the screen did not change as a result of a test is a tangible *outcome* although there is not *output*.

In testing we are concerned with outcomes, not just outputs.

- If the predicted and actual outcome match, can we say that the test has passed?
**Terminology**

- **Strictly speaking -- NO!**

- **Coincidental correctness**: A program is said to be coincidentally correct if the test results in the expected outcome, even though the program performs the incorrect computation.

Example: A program is to calculate $y = x^2$. It is incorrectly programmed as $y = 2x$, and it is tested with the input value $x = 2$.
Expected Outcome

- Some times, specifying the expected outcome for a given test case can be tricky business!
  - For some applications we might not know what the outcome should be.
  - For other applications the developer might have a misconception
  - Finally, the program may produced too much output to be able to analyze it in a reasonable amount of time.
  - In general, this is a fragile part of the testing activity, and can be very time consuming.
  - In practice, this is an area with a lot of hand-waving.
  - When possible, automation should be considered as a way of specifying the expected outcome, and comparing it to the actual outcome.
Software Testing Myths

• If we were really good at programming, there would be no bugs to catch.
• There are bugs because we are bad at what we do.
• Testing implies an admission of failure.
• Tedium of testing is a punishment for our mistakes.
Software Testing Myths (Cont’d)

• All we need to do is:
  – concentrate
  – use structured programming
  – use OO methods
  – use a good programming language
  – ...

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Software Testing Reality

- Human beings make mistakes, especially when asked to create complex artifacts such as software systems.
- Studies show that even good programs have 1-3 bugs per 100 lines of code.
- People who claim that they write bug-free software probably haven’t programmed much.
Goals of Testing

• Discover and prevent bugs.
• The act of designing tests is one of the best bug preventers known.
  – Test, then code philosophy
• The thinking that must be done to create a useful test can discover and eliminate bugs in all stages of software development.
• However, bugs will always slip by, as even our test designs will sometimes be buggy.
The Significance of Testing

- Most widely-used activity for ensuring that software systems satisfy the specified requirements.
- Consumes substantial project resources. Some estimates: ~50% of development costs
- NIST Study: The annual national cost of inadequate testing can be as much as $59B.

[ IEEE Software Nov/Dec 2002 ]
**Limitations of Testing**

- Testing cannot occur until after the code is written.
- The problem is big!
- Perhaps the least understood major SE activity.
- *Exhaustive testing* is not practical even for the simplest programs. WHY?
- Even if we “exhaustively” test all execution paths of a program, we cannot guarantee its correctness.
  - The best we can do is *increase our confidence*!
- “*Testing can show the presence of bug, not their absence.*” EWD
Limitations of Testing

- Testers do not have immunity to bugs.
- Even the slightest modifications – after a program has been tested – invalidate (some or even all of) our previous testing efforts.
- Automation is critically important.
- Unfortunately, there are only a few good tools, and in general, effective use of these good tools is very limited.
Phases in a Testers Mental Life

• Testing is debugging.
• The purpose of testing is to show that the software works.
• The purpose of testing is to show that the software doesn’t work.
• The purpose of testing is to reduce the risk of failure to an acceptable level.
Testing Isn’t Everything

- Other methods for improving software reliability are:
  - **Inspection methods:** Walkthroughs, formal inspections, code reading.
  - **Design style:** Criteria used by programmers to define what they mean by a “good program”.
  - **Static analysis:** Compilers take over mundane tasks such as type checking.
  - **Good Programming Languages and Tools:** Can help reduce certain kinds of bugs *(e.g., Lint).*
Testing Versus Debugging

- The **purpose of testing** is to show that a program has bugs.
- The **purpose of debugging** is to find the faults that led to the program’s failure and to design and implement the program changes that correct the faults.
- Testing is a demonstration of failure or apparent correctness.
- Debugging is a deductive process.
Testing Versus Debugging (Cont’d)

- Testing proves a programmer’s failure.
- Debugging is a programmer’s vindication.
- Testing can be automated to a large extent.
- Automatic debugging is still a dream.
- Much of testing can be done without design knowledge (by an outsider).
- Debugging is impossible without detailed design knowledge (by an insider).
Designer Versus Tester (Cont’d)

- The more the tester knows about the design, the more likely he will eliminate useless tests (functional differences handled by the same code).
- Testers that have design knowledge may have the same misconceptions as the designer.
Designer Versus Tester (Cont’d)

• Lack of design knowledge may help the tester to develop test cases that a designer would never have thought of.

• Lack of design knowledge may result in inefficient testing and blindness to missing functions and strange cases.
Program Testing

• A successful test is a test which discovers one or more faults.
• Only validation technique for non-functional requirements.
• Should be used in conjunction with static verification.
Defect Testing

• The objective of defect testing is to discover defects in programs.

• A successful defect test is a test which causes a program to behave in an anomalous way.

• Tests show the presence not the absence of defects.
Testing Priorities

• Only exhaustive testing can show a program is free from defects. However, exhaustive testing is impossible.
• Tests should exercise a system’s capabilities rather than its components.
• Testing old capabilities is more important than testing new capabilities.
• Testing typical situations is more important than boundary value cases.
Test Data and Test Cases

- **Test data:** Inputs which have been devised to test the system.

- **Test cases:** Inputs to test the system and the predicted outputs from these inputs if the system operates according to its specification.
Testing Effectiveness

• In an experiment, black-box testing was found to be more effective than structural testing in discovering defects.
White- and Black-box Testing

• **White-box (Glass-box or Structural) testing**: Testing techniques that use the source code as the point of reference for test selection and adequacy.
  – a.k.a. program-based testing, structural testing

• **Black-box (or functional) testing**: Testing techniques that use the specification as the point of reference for test selection and adequacy.
  – a.k.a specification-based testing, functional testing

Which approach is superior?
Black-box Testing

- Characteristics of Black-box testing:
  - Program is treated as a black box.
  - Implementation details do not matter.
  - Requires an end-user perspective.
  - Criteria are not precise.
  - Test planning can begin early.
Black-box Testing
Equivalence Partitioning
procedure Search (Key : INTEGER ; T: array 1..N of INTEGER;
    Found : BOOLEAN; L: 1..N) ;

Pre-condition
    -- the array has at least one element
    1 <= N

Post-condition
    -- the element is found and is referenced by L
    ( Found and T (L) = Key)
    or
    -- the element is not in the array
    ( not Found and
    not (exists i, 1 <= i <= N, T (i) = Key ))
Search Routine - Input Partitions

- Inputs which conform to the pre-conditions.
- Inputs where a pre-condition does not hold.
- Inputs where the key element is a member of the array.
- Inputs where the key element is not a member of the array.
## Search Routine - Input Partitions

<table>
<thead>
<tr>
<th>Array</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single value</td>
<td>In array</td>
</tr>
<tr>
<td>Single value</td>
<td>Not in array</td>
</tr>
<tr>
<td>More than 1 value</td>
<td>First element in array</td>
</tr>
<tr>
<td>More than 1 value</td>
<td>Last element in array</td>
</tr>
<tr>
<td>More than 1 value</td>
<td>Middle element in array</td>
</tr>
<tr>
<td>More than 1 value</td>
<td>Not in array</td>
</tr>
</tbody>
</table>
# Search Routine - Test Cases

<table>
<thead>
<tr>
<th>Input array (T)</th>
<th>Key (Key)</th>
<th>Output (Found, L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>17</td>
<td>true, 1</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>false, ??</td>
</tr>
<tr>
<td>17, 29, 21, 23</td>
<td>17</td>
<td>true, 1</td>
</tr>
<tr>
<td>41, 18, 9, 31, 30, 16, 45</td>
<td>45</td>
<td>true, 6</td>
</tr>
<tr>
<td>17, 18, 21, 23, 29, 41, 38</td>
<td>23</td>
<td>true, 4</td>
</tr>
<tr>
<td>21, 23, 29, 33, 38</td>
<td>25</td>
<td>false, ??</td>
</tr>
</tbody>
</table>
White-box Testing

• Characteristics of white-box testing:
  – Looks at implementation details.
  – Aims at exercising the different control and data structures used in the program.
  – Requires the programmer’s knowledge of the source code.
  – Criteria are quite precise as they are based on program structures.
  – Assumes that the source code fully implements the specification.
White-box Testing
class BinSearch {

    // This is an encapsulation of a binary search function that takes an array of
    // ordered objects and a key and returns an object with 2 attributes namely
    // index - the value of the array index
    // found - a boolean indicating whether or not the key is in the array
    // An object is returned because it is not possible in Java to pass basic types by
    // reference to a function and so return two values
    // the key is -1 if the element is not found

    public static void search ( int key, int [] elemArray, Result r )
    {
        int bottom = 0 ;
        int top = elemArray.length - 1 ;
        int mid ;
        r.found = false ; r.index = -1 ;
        while ( bottom <= top )
        {
            mid = (top + bottom) / 2 ;
            if (elemArray [mid] == key)
            {
                r.index = mid ;
                r.found = true ;
                return ;
            } // if part
            else
            {
                if (elemArray [mid] < key)
                    bottom = mid + 1 ;
                else
                    top = mid - 1 ;
            } //else
        } //while loop
    } //search
} //BinSearch

Binary search (Java)
Binary Search - Equivalence Partitions

- Pre-conditions satisfied, key element in array.
- Pre-conditions satisfied, key element not in array.
- Pre-conditions unsatisfied, key element in array.
- Pre-conditions unsatisfied, key element not in array.
- Input array has a single value.
- Input array has an even number of values.
- Input array has an odd number of values.
Binary Search Equivalence Partitions
### Binary Search - Test Cases

<table>
<thead>
<tr>
<th>Input array (T)</th>
<th>Key (Key)</th>
<th>Output (Found, L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>17</td>
<td>true, 1</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>false, ??</td>
</tr>
<tr>
<td>17, 21, 23, 29</td>
<td>17</td>
<td>true, 1</td>
</tr>
<tr>
<td>9, 16, 18, 30, 31, 41, 45</td>
<td>45</td>
<td>true, 7</td>
</tr>
<tr>
<td>17, 18, 21, 23, 29, 38, 41</td>
<td>23</td>
<td>true, 4</td>
</tr>
<tr>
<td>17, 18, 21, 23, 29, 33, 38</td>
<td>21</td>
<td>true, 3</td>
</tr>
<tr>
<td>12, 18, 21, 23, 32</td>
<td>23</td>
<td>true, 4</td>
</tr>
<tr>
<td>21, 23, 29, 33, 38</td>
<td>25</td>
<td>false, ??</td>
</tr>
</tbody>
</table>
White-box vs. Black-box Testing

- The real difference between white-box and black-box testing is how test cases are generated and how adequacy is determined.
- In both cases, usually, the correctness of the program being tested is done via specifications.
- Neither can be exhaustive.
- Each technique has its strengths and weaknesses.
- Should use both. In what order?
Is Complete Testing Possible?

• **NO.** Complete testing is both practically and theoretically impossible for non-trivial software.
Complete Functional Testing

• A complete functional test would consist of subjecting a program to all possible input streams.
• Even if the program has an input stream of 10 characters, it would require $2^{80}$ tests.
• At 1 microsecond/test, exhaustive functional testing would require more time than twice the current estimated age of the universe!
Complete Structural Testing

• One should design enough tests to ensure that every path is executed at least once.
• What if the loops never terminate?
• Even if loops terminate, the number of paths may be too large.
Small Versus Large Systems

- For small systems with one user, quality assurance may not be a major concern.
- As systems scale up in size and number of users, quality assurance becomes more of a concern.
- As systems dramatically scale up in size (e.g., millions of lines of code), our quality criteria may have to change as exhaustive testing may not be economically possible.
  - E.g., a 75% code coverage may be acceptable.
How About Correctness Proofs?

- Requirements are specified in a formal language.
- Each program statement is used in a step of an inductive proof.
- In practice, such proofs are time consuming and expensive.
- Proving the consistency and completeness of a specification is a provably unsolvable problem, in general.
- Proofs may have bugs.
Testing Strategy

- Divide-and-conquer!
- We begin by ‘testing-in-the-small’ and move toward ‘testing-in-the-large’
- For conventional software
  - The module (component) is our initial focus
  - Integration of modules follows
- For OO software
  - our focus when ‘testing in the small’ changes from an individual module (the conventional view) to an OO class that encompasses attributes and operations and implies communication and collaboration
Testing Strategy

- Understand / formulate quality objectives
- Identify the appropriate testing phases for the given release, and the types of testing the need to be performed.
- Prioritize the testing activities.
- Plan how to deal with “cycles”.

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Testing Phases

- Unit Testing
- Integration Testing
- System Testing
- Alpha Testing
- Beta Testing
- Acceptance Testing
System Testing

- Performed by a separate group within the organization.
- *Scope*: Pretend *we* are the end-users of the product.
- Focus is on functionality, but must also perform many other types of tests (e.g., recovery, performance).
- Black-box form of testing.
- Test case specification driven by use-cases.
System Testing

- The whole effort has to be planned (System Test Plan).
- Test cases have to be designed, documented, and reviewed.
- Adequacy based on requirements coverage.
  - but must think beyond stated requirements
- Support tools have to be [developed]/used for preparing data, executing the test cases, analyzing the results.
System Testing

- Group members must develop expertise on specific system features / capabilities.
- Often, need to collect and analyze project quality data.
- The burden of proof is always on the ST group.
- Often, the ST group gets the *initial blame* for “not seeing the problem before the customer did”.

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Other Testing Phases

- Depending on the system being developed, and the organization developing the system, other testing phases may be appropriate:
  - Alpha / Beta Testing
  - Acceptance Testing
Types of Testing

• Functionality
• Recovery
  – Force the software to fail in a variety of ways and verify that recovery is properly performed.
• Performance
  – Test the run-time performance of the software.
• Stress
  – Execute a system in a manner that demands resources in abnormal quantity, frequency, or volume.
Types of Testing

• Security
  – Verify that protection mechanisms built into a system will, in fact, protect it from improper penetration

• Reliability
  – Operate the system for long periods of time and estimate the likelihood that the requirements for failure rates, mean-time-between-failures, and so on, will be satisfied.

• Usability
  – Attempt to identify discrepancies between the user interfaces of a product and the human engineering requirements of its potential users.
Regression Testing

• The activity of re-testing modified software.
• It is common to introduce problems when modifying existing code to either correct an existing problem or otherwise enhance the program.
• Options:
  – Retest-none (of the test cases)
  – Retest-all
  – Selective retesting
• For some systems, regression testing can be fairly expensive.