Software Validation and Testing
Verification vs. Validation

- **Verification**: using logical techniques and tools to assess correctness of the product with respect to specifications.

- **Validation**: establishing that the software developed correctly capture the user’s needs and intent.
Validation vs. Verification vs. Testing

- **Client perceived needs**
- **Requirements specification**
  - Formal specification of software (if one exists)
  - Actual software
- **Test**
  - **Formal specification**
  - **Verification**
  - **Testing**
- **Client Satisfaction**
Sometimes heard...

- **Verification**: Are we building the product right?

- **Validation**: Are we building the right product?

- Apparently due to Barry Boehm (the spiral model guy).
Validation may involve Testing

- **Testing**: trying to find errors in the product

- **Verification**: using specifications, logical techniques and tools to assess correctness of the product.

- The two can be mutually supportive, in ways to be discussed.
Testing is Necessary, but not really sufficient
Recall Famous Dijkstra Quote:

• “Testing can show the presence of errors, but never their absence.”

• Rare exception: When the set of all inputs is finite and of a reasonable size, exhaustive testing can be used.

• Exhaustive testing is only feasible for small systems, typically hardware units, that are finite-state machines.
Exhaustive Testing

- Suppose we wanted to test a 32-bit multiply routine exhaustively. How long would it take?

- $2^{32} \times 2^{32} = 2^{64}$ input combinations at, say, 1 combination per nanosecond

- about 585 years, according to Unicalc
Verification alone is not sufficient either

- Creating a formal specification is hard, sometimes as hard as developing the software, or harder.

- A formal specification seldom captures all needs and intent.

- It is difficult to ascertain that all needs are covered until the system is built.

- Therefore, validation may not be complete without testing in addition to verification.
The terminology is not standardized.

Some people use “verification” to mean one of:

- validation
- testing
Standard Testing Terminology

- **Unit testing** tests self-contained units: classes, methods, functions, procedures.

- **Integration testing** tests combinations of units, such as packages, that have already been unit-tested, by having them mutually form an environment similar to actual use.

- **System testing** is top-level integration testing.

- **Acceptance testing** tests the final product according to pre-agreed criteria of the customer.
Regression Testing

- **Regression testing**: when changes are made, re-test previous test cases to ascertain that no new errors were introduced in the changes.

- **“Smoke test”**: A coarse form of regression test to determine that the product doesn’t simply crash as a result of recent changes. [Apply to “daily build” to see if there is any “smoke” (sign of new errors).]
Mutation Testing

- A scheme for testing tests, by gauging their effectiveness of a given test.

- Assume that we have a test T which the code passes.

- The code is subjected to “mutation”. If the mutated code also passes test T, then T is less-likely to be regarded as a good test.
"V" model: A possible incorporation of testing in the software life-cycle.
“Fault” vs. “Failure” Terminology

- **A fault** is an error in the code.

- **A failure** is the manifestation of a fault at runtime.

- The mapping from failures to faults is many-to-one.

- *(A flaw is an error in the design.)*
Typical Fault Profile
(faults/KLOC)

vs.

Development phase

Thousands of lines of source code

Faults per thousand lines of source code

Requirements analysis
High-level design
Low-level design
Coding
Unit test
Integration test
System test
Beta ship

Thousands of lines of source code
Relative **Cost** of Fixing Errors vs. Phase (typical)
The “Y2k Problem” probably would have cost 1/1000 (ignoring inflation) as much to fix at design/coding time as it actually took to fix in the field.

(Then there is the cost of “fixing the fixes”.)
Testing Approaches

- Test your own code
- Test code of other people in your group
- One person dedicated to testing
- Outside testing group
- Independent testing company
- Cleanroom approach
“Cleanroom” Approach

- Programmers do not test, or otherwise execute, their code.

- Instead, programmers establish correctness by formal reasoning methods and construction techniques.

- The actual testing takes place in the integration phase, which is done by a different team from the programmers.
Approach testing as an *intellectual challenge* in its own right

- Think as if testing *someone else’s* program, not your own.

- The objective is to find as many *distinct* problems as possible.

- Remember that you are testing the *program* and not the *person*.
Things Testing Can’t/Shouldn’t Do

- Don’t expect testing in itself to improve a poor design.

- As a developer, don’t rely on testing by others as the prime method for identifying your own mistakes.
A reputable programmer has produced a binary search method for searching an array:

```c
int search(float* a, int M, int N, float sought);
```

The method is supposed to determine whether the value sought occurs in the array `a` in the range of indices `M` to `N-1`. If the value occurs, its index is returned. If not, -1 is returned. (If `M > N`, the range is considered to be empty.)

It is to be assumed that the elements of the array are sorted in that range of indices.
Another reputable programmer has produced a complete program “triangle” that reads triples of numbers at a time and classifies them as to whether they are the lengths of the sides of some triangle, and if so, what kind.

Negative side-length counts as a side with the length as absolute value.

The sides are in a specified range between 1E-150 and 1E150. Negative sides are converted to the corresponding positive value.
Testing Example (2)

- The possible outputs are:
  - “not a triangle”
  - “equilateral triangle”
  - “isosceles triangle”
  - “scalene triangle”
  - Any of the last three above preceded by “right”.
  - Or none of the above, with an indication that one or more of the inputs is out of range.

- “All classifications are based on native machine arithmetic”.
Your team’s tasks

- Determine how you would test each method or program.

- What essential differences are there between the two testing approaches?

- If you intend to use test cases, what are they or how would they be created?
Testing Terminology

- **Black-box** (or opaque box) testing tests software against the operating environment, without using knowledge of internal structure.
  Also called: **Functional Testing**

- **White-box** (or clear-box) testing uses *knowledge of internal structure* to test specific pieces.
  Also called: **Structural Testing**
Testing Terminology

- **Gray-box**: Functional Testing assisted by structural knowledge to reduce unnecessary blind testing.
Testing Continuum

<table>
<thead>
<tr>
<th>Pure white-box (structural)</th>
<th>Gray-box (some structural)</th>
<th>Pure black-box (behavioral)</th>
<th>Live tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development activity</td>
<td>Testing activity</td>
<td>Technical support, beta testing</td>
<td></td>
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</tbody>
</table>
Black- vs. White Box

- **Black-box** focuses on the specification: What is in the spec that the program doesn’t do?

- **White-box** focuses on the program: What does the program do that is not in the spec?

- Normally don’t rely on one or the other exclusively. “Mow the grass in two directions” for better cutting.
Basic Testing Tools

- **Plan & Checklists**: tests to perform
  - With each test, pre-condition, post-condition
- **Test matrix/spreadsheet**: listing tests against use cases and potential error areas
- **Logging capability**
  - Note pad
  - Keystroke recorder (for playback)
  - Event logger
  - Screen recorder
  - Video camera
- **Tracking Database**
## Testing Matrix

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<tr>
<th>Tested by</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
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<td>Use Case 3</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
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</tbody>
</table>
Test Result Categorization

- Area of defect
- Severity level of defect
- Follow up:
  - Responsibility
  - Time to fix
  - Lines of code affected
10 Sample Severity Levels, with examples (Boris Beizer)

- **Mild**: misspellings in output
- **Moderate**: misleading or redundant behavior
- **Annoying**: truncated names, etc.
- **Disturbing**: some transactions not processed
- **Serious**: lost transaction
- **Very serious**: incorrect output
- **Extreme**: frequent “very serious” errors
- **Intolerable**: data corrupted
- **Catastrophic**: shutdown
- **Infectious**: shutdown spreading to others
4 Possible Reaction Levels to failed tests

- **Defer**: fix as time permits
- **Schedule**: fix by some future date
- **Required**: fix before acceptance
- **Immediate**: fix before testing is continued
Testing Forms and Tracking

- Discrepancy report form
- Error investigation form
- Error reporting/tracking system/database
DISCREPANCY REPORT FORM

DRF Number:__________________________________________  Tester name:__________________________________________
Date: ___________________________________  Time: ______________________________
Test Number: ______________________________
Script step executed when failure occurred: __________________________________________________________
Description of failure: ________________________________________________________________________
_______________________________________________________________________________________
_______________________________________________________________________________________
_______________________________________________________________________________________
Activities before occurrence of failure:
_______________________________________________________________________________________
_______________________________________________________________________________________
Expected results:
_______________________________________________________________________________________
_______________________________________________________________________________________
Requirements affected:
_______________________________________________________________________________________
_______________________________________________________________________________________
Effect of failure on test:
_______________________________________________________________________________________
_______________________________________________________________________________________
Effect of failure on system:
_______________________________________________________________________________________
_______________________________________________________________________________________
Severity level:
(LOW) 1 2 3 4 5 (HIGH)
## FAULT REPORT

**ORIGINATOR:** Joe Bloggs

**BRIEF TITLE:** Exception 1 in dps_c.c line 620 raised by NAS

**FULL DESCRIPTION:** Started NAS endurance and allowed it to run for a few minutes. Disabled the active NAS link (emulator switched to standby link), then re-enabled the disabled link and CDIS exceptioned as above. (I think the re-enabling is a red herring.)

**ASSIGNED FOR EVALUATION TO:**

**DATE:**

**CATEGORY:** 0 2 3 Design Spec Docn

**SEND COPIES FOR INFORMATION TO:**

**DATE:** 8/7/92

**EVALUATOR:**

**CONFIGURATION ID**

<table>
<thead>
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<th>CONFIGURATION ID</th>
<th>ASSIGNED TO</th>
<th>PART</th>
</tr>
</thead>
<tbody>
<tr>
<td>dpo_s.c</td>
<td></td>
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</table>

**COMMENTS:** dpo_s.c appears to try to use an invalid CID, instead of rejecting the message. AWJ

### ITEMS CHANGED

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<tr>
<th>CONFIGURATION ID</th>
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<th>REVIEWER/DATE</th>
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<td>MAR 8/7/92</td>
<td>6.120</td>
<td>RA 8-7-92</td>
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**COMMENTS:**

CLOSED

**FAULT CONTROLLER:**

**DATE:** 9/7/92
### Testing Issue Spreadsheet

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</table>
Open/Closed Bug Tracking
General Testing Approach

- Create lists of potential problems and categorize them by area.

- Design repeatable tests, for proof of problems and problem resolutions.
Broad Categories for Errors

- Errors in interpreting requirements
- Errors in translating requirements into design, i.e. in programming
- Errors in implementing design
- Errors in the testing process itself
Program Behavior Views
(sets of behaviors taken over all inputs)

Specified (desired) behaviors

Observable behaviors (produced by program)
The Ideal

Specified (desired) behaviors

Observable behaviors
The ideal might not be fully realizable because

- Some aspects of a specification may be left arbitrary, unspecified.
- Either:
  - The specification is to be regarded as incomplete, or
  - Any behavior **consistent with** the specification will be accepted.
Testing asks questions:
Does a behavior occur?

Specified (desired) behaviors

Observable behaviors

Tested Behaviors
(i.e. behaviors tested for)
Testing

Specified (desired) behaviors

Observable behaviors

Specified, but not tested

Not specified, but tested

Tested Behaviors
Which regions of the diagram indicate errors?

Specified (desired) behaviors

Observable behaviors

Tested Behaviors
Which regions of the diagram indicate errors?

Specified (desired) behaviors

Observable behaviors

Specified and tested, but not observed

Tested Behaviors

Not specified but tested and observed
Black- vs. White Box (recap)

- **Black-box** focuses on the **specification**: What is in the spec that the program doesn’t do?

- **White-box** focuses on the **program**: What does the program do that is not in the spec?

- Normally don’t rely on one or the other exclusively. “Mow the grass in two directions” for better cutting.
Black-Box Testing
Good Black-Box Test Plan

Specified (desired) behaviors

Observable behaviors

Tested, Specified Behaviors
(as large as is feasible)
Recall that “black box” means we do not get to see the code; we only have access to an installation of the product.

Also called “functional testing” (vs. “structural testing”, which would be “white box”)

Driven by requirements, use cases
Black-Box Techniques

- **Equivalence Partitioning:**
  - Use a small number of test *equivalence classes*, rather than a large number of individual test data points.

  - The actual tests are representatives of the equivalence classes.

  - Partitioning based on their relative likelihood of exposing logic errors in the code.

- Example: Partition a number space into:
  - less than 0
  - equal to 0
  - greater than 0, less than 100
  - greater than or equal to 100
Black-Box Techniques

- Equivalence Partitioning Examples (cont’d):
  - Partition a two-dimensional number space into \((x, y)\) where:
    - \(x < y\)
    - \(x == y\)
    - \(x > y\)
  - Partition a String space into
    - \(\text{length} = 0\)
    - \(\text{length} = 1\)
    - \(\text{length} = 2\)
    - \(\text{length} > 2\)
    - \(\text{length} \text{ extremely large}\)
Black-Box Techniques

- How would you equivalence-partition the triangle program input space?
A “declarative” means to categorize input

- Partitions input space (triples of numbers) into equivalence classes.
- All inputs in a cell should have the same anticipated equivalence class.

<table>
<thead>
<tr>
<th>a, b, c a triangle?</th>
<th>N</th>
<th>Y</th>
<th>Y</th>
<th>Y</th>
<th>N</th>
<th>N</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>a = b?</td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>a = c?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b = c?</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Input Categories

Output Categories

not a triangle
scalene
isosceles
equilateral
should not occur
## Decision Table Variant

- Slightly more condensed, based on logical equivalences
- Fewer or no “should not occur” entries

### Input Categories
- $a, b, c$ a triangle?
- $a = b$?
- $a = c$?
- $b = c$?

### Output Categories
- Not a triangle
- Scalene
- Isosceles
- Equilateral

<table>
<thead>
<tr>
<th>N</th>
<th>Y</th>
<th>N</th>
<th>Y</th>
<th>N</th>
<th>Y</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td></td>
<td>Y</td>
<td></td>
<td>N</td>
<td></td>
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</tr>
<tr>
<td>-</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>
Black-Box Techniques

- **Boundary-value testing**: Pick test cases near to “natural” boundaries in data space, so as to test whether the program performs the correct classification of borderline cases.
Black-Box Techniques

- **Logarithmic testing**: Repeatedly split the data space into two, testing sample points in the upper and lower halves of the split, then repeat on the lower half only.
Black-Box Techniques

- **Cause-Effect Graphing**: Examine requirements specification for *chains of conditions*; develop test cases that check whether these chains are actually observed.

  - Example: “If the clipboard is empty, then the paste menu option should *not* be selectable.”

  Therefore: Develop a test in which the clipboard should be empty, and check that the menu option is not selectable.
Black-Box Techniques

- **Cause-Effect Graphing**, possible relationships:
  - A condition *implies* an action
  - A condition *precludes* an action
  - Two actions are *mutually exclusive*
  - A combination (conjunction) of two conditions implies an action
  - etc.
Example Cause-Effect Graph

Causes

C1

C2

C 3

C 4

C 5

Effects

E3

E1

E2

(disjunction implied)

∧

∧

∧

∧

conjunctions, negations, etc.
Exercise

- Discuss cause-effect graphing for the Traffic Jam program.
Black-Box Techniques

- **Comparison Testing:**

  Test product side-by-side with a "gold standard", a program believed to be correctly operating (such as an earlier version having most, if not all, of the features)
Black-Box Techniques

- **Garbage-In Test**: See if unusual input characters, click sequences, etc. can force the system into inconsistent states.

- **Open-Book Test**

- **Data-Quantity Stress Test**: See if unusually large amounts of data cause nominal values to be exceeded, revealing untested overflow conditions, etc.
White-Box Testing
Good White-Box Test Plan

Specified (desired) behaviors

Observable behaviors

Tested Behaviors
(as large as possible)
Consider the “triangle” program

- You are now given source code for the triangle program.

- What tests would you perform?
Code Inspection and Walkthrough

- **Used for:**
  - Identifying errors
  - Identifying test cases
  - Helping yourself and others to understand how the program works.
class Conversion
{
public:
/** top of acceptable numeric range */
static const double MAX = 1e150;
/** bottom of acceptable numeric range */
static const double MIN = 1e-150;
/** Check whether argument is within range **/
inline static bool inRange(double value) {return MIN <= value && value <= MAX;}
/**
* Check whether an input string represents a valid floating point numeral
* (as opposed to some non-digit characters, etc.)
* and, if so, whether the number is in the specified range.
* @param inputString string to be checked for being a numeral, and possibly
* converted to number result.
* @param result number to which string was converted, if successful
* @return true if the input represents a valid number in the specified
* range and result is the numeric value,
* otherwise return false and 'result' is undefined.
* pre-condition: true <br>
* post-condition: If returned value is true, then result is the numeric
* representation of the argument inputString.
* If returned value is false, then 'result' is undefined.
**/
static bool convert(const string inputString, double& result)
{
    char* endptr;

    // After strtok, endptr will point to end of converted string.
    // Conversion is successful iff *endptr is the null character (0).
    result = strtok(inputString.c_str(), &endptr);
    if(*endptr == 0)
    {
        result = fabs(result);
        return inRange(result);
    }

    return false;
}
}; // Conversion
/**
 * TriangleTester deals analyze three sides as a triangle and reading
 * sets of three sides from an input stream.
 **/

class TriangleTester
{
public:
static const int SIDES = 3; // This is about triangles.

static enum{ NOT_A_TRIANGLE,
              EQUILATERAL_TRIANGLE,
              SCALENE_TRIANGLE,
              RIGHTSCALENE_TRIANGLE,
              ISOSCELES_TRIANGLE,
              RIGHTISOSCELES_TRIANGLE} Classification;

/**
 * Return the type of triangle, if any, that is formed by three sides.
 * @param a first side
 * @param b second side
 * @param c third side
 *
 * pre-condition: all sides are positive and in-range <br>
 *
 * post-condition: the correct classification is returned
 **/

static int analyze(double a, double b, double c)
{
    // Arrange the three sides to simplify subsequent analysis.
    order(a, b);
    order(b, c);
    order(a, c);

    // assert( a <= b && b <= c );

    if( a + b <= c ) // The only test needed for triangle-ness, due to ordering.
    {
        return NOT_A_TRIANGLE;
    }

    if( a == b && b == c )
    {
        return EQUILATERAL_TRIANGLE;
    }

    bool right = isRight(a, b, c);

    if( a == b || b == c )
    {
        return right ? RIGHTISOSCELES_TRIANGLE : ISOSCELES_TRIANGLE;
    }

    return right ? RIGHTSCALENE_TRIANGLE : SCALENE_TRIANGLE;
}
/**
 * Return 1 if the triangle is a right triangle, otherwise return 0.
 * @param a length of the first side
 * @param b length of the second side
 * @param c length of the third side
 * @return 1 if the triangle is a right triangle, otherwise return 0.
 *
 * pre-condition: a <= b && b <= c <br>
 *
 * post-condition: return value indicates right triangle
 **/

static inline int isRight(double a, double b, double c)
{
    return a*a + b*b == c*c ? 1 : 0;
}

/**
 * Order numbers a and b so that a <= b.
 * @param a one of the two numbers to be ordered
 * @param b the other of the two numbers to be ordered
 *
 * pre-condition: true <br>
 *
 * post-condition: a <= b
 **/

static inline void order(double& a, double& b)
{
    if( a > b )
    {
        double temp = a;
        a = b;
        b = temp;
    }
    // assert( a <= b );
}
/**
 * Until end-of-file, read groups of three numbers and classify whether they
 * are all in range and could be the sides of a triangle, and if so,
 * what kind:
 * [right] {equilateral, isosceles, scalene}
 *
 * @param in istream containing groups of three sides
 * @param out ostream on which results are shown
 **/

static void test(istream& in, ostream& out)
{
    string inputSide[SIDES];
    double side[SIDES];

    // read numbers as strings, exit loop if end-of-file
    {
        for( int i = 0; i < SIDES; i++ ) // echo sides
            out << inputSide[i] << " ";

        // convert inputs to numeric and show any bad ones
        bool inputOk = true;
        for( int i = 0; i < SIDES; i++ )
            if( !Conversion::convert(inputSide[i], side[i]) )
                inputOk = false;
        out << \nbad input: " << inputSide[i];
    }

    if( inputOk )
    {
        switch( analyze(side[0], side[1], side[2]) )
        {
            case NOT_A_TRIANGLE: out << "not a triangle."; break;
            case SCALENE_TRIANGLE: out << "scalene triangle."; break;
            case RIGHTSCALENE_TRIANGLE: out << "right scalene triangle."; break;
            case ISOSCELES_TRIANGLE: out << "isosceles triangle."; break;
            case RIGHTISOSCELES_TRIANGLE: out << "right isosceles triangle."; break;
            case EQUILATERAL_TRIANGLE: out << "equilateral triangle."; break;
        }
    }
    out << endl;
}
} // TriangleTester
White-Box in Conjunction with Verification Techniques

- Verification is based on techniques for reasoning about programs.

- These techniques can also be used to simplify the number of white-box test cases.
Using Live Assertions

- order(a, b);
  order(b, c);
  order(a, c);

  assert( a <= b && b <= c );

- The program will now tell us when the assumption is wrong.
- It will provide an indication of what has to be rethought.
Verification + W.B. Testing

- Could use verification to help fix the problem.

- Having verified the assertion
  
  ```
  assert( a <= b && b <= c );
  
  will testing be simplified?
  ```

- How?
Some Ideas for
More Effective Testability
Ideas for More Effective Testability

- **Instrument** your code as you build it; this could help with unit tests
  - Code-in traces, explanations, indications, ...
  - Being able to turn instrumentation on or off can help understand whether subsystems are working correctly.
Example: C++ Instrumentation

class Trace
{
    static int currentLevel;

    static void trace(string message, int level)
    {
        if( level >= currentLevel )
            cerr << message << endl;
    }

    static void setLevel(int level)
    {
        currentLevel = level;
    }
};
Ideas for More Effective Testability

- Build **testing interfaces** into the code. These are interfaces that can be seen by the developer but not the user.

- These interfaces allow greater automation in the testing process, since they can be driven by a testing program more readily than one requiring a user interface (such as a GUI or CLI).
Testing Interface

<table>
<thead>
<tr>
<th>User Interface</th>
<th>Testing Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Model” aspect of the product</td>
<td></td>
</tr>
</tbody>
</table>
Build Self-Test Routines into the Code

- **Self-tests** can employ data generators that will stress test the code.
Classifying Programming Errors
Categories of Programming Errors

- Logic errors
- Pointer errors
- Numeric accuracy/precision/roundoff errors
- Input/output representation errors
- Data structure usage errors
- Memory errors
- User-interface errors (windows, etc.)
- Environment errors, such as misuse of file-system, devices, etc.
- Timing errors, such as in a real-time system
Exercise

- Each team take one category of error.
- List as many specific sub-types of this error as you can.
- **Example:** Logic Errors:
Logic Error Categories (1)

- Numeric and character boundary
  - Off-by-1
- Array-out-of-bound
  - Insufficient space allocated
  - Input or output buffer overflow
- Inequality comparison (used > instead of >= or <)
- Used ++ instead of --.
- Used pre-incrementation rather than post.
Logic Error Categories (2)

- Negation error
- Loop continuation criterion
  - Infinite loops
- Flag not cleared when used
- Flag, count, or sum not initialized
- Routine not reinitialized before subsequent use
- Dynamic type-casting exception
Theoretical Aspects of Whitebox Testing
White-Box Coverage

**“Coverage” notion:**
- View the program as a directed graph (flowchart or data-flow diagram)
- Develop (external or internal) tests that "cover", i.e. exercise program to various degrees.

Specified (desired) behaviors

Observable behaviors

Tested Behaviors (= amount of “coverage”)
Minimal Coverage

- Tests should exercise, at least once, every:
  - variable
  - assignment box
  - decision box
  - simple path through flow chart
Testing Based on Paths

Example of a single path to be covered by test (in red).

Insufficient to simply identify path; need to have data set that will exercise it.
Infeasible to test *all* paths, etc.

Instead, identify a “*basis*” from which all paths can be constructed.

Make sure every element of basis is covered by some test

**Example**: Basis could be set of all edges; Compute a set of tests that covers all.
Estimate the number of elements in a basis set of paths that will cover all edges.
D-D Path Nomenclature
(Ed Miller 1977)

- D-D = “Decision to Decision”

- Path between two decisions, that contains no decision itself

- Dependence among D-D paths, e.g. a variable defined in one path is referenced in another.
Classification of Structural Test Coverage

- $C_0$: Every statement tested
- $C_1$: Every D-D path tested
- $C_{1p}$: Every predicate & outcome tested
- $C_d$: $C_1 +$ every inter-dependent pair of D-D paths tested
- $C_{i^k}$: Every path that contains up to $k$ repetitions of a loop (e.g. $k = 2$) tested
- $C_\infty$: Every path tested
“Baseline”-based method for constructing a basis

- Pick a single linear path through the program, the “baseline”.
- Pick the next path by taking decisions alternate to the baseline.
- Repeat picking other alternates to the alternates, etc.
- Eventually a basis number of tests will be reached.
Baseline Testing Method
(in McCabe's Cyclomatic Tool)

Test Path 1 (baseline): 0 1 2 3 4 5 2 3 6 7 10 11 14 16 17
11(1): string[index]=='A' ==> TRUE
13(3): string[index]=='B' ==> TRUE
13(3): string[index]=='B' ==> FALSE
18(7): string[index]=='C' ==> FALSE
25(11): string[index]!="\0" ==> FALSE

Test Path 2: 0 1 15 16 17
11(1): string[index]=='A' ==> FALSE

Test Path 3: 0 1 2 3 6 7 10 11 14 16 17
11(1): string[index]=='A' ==> TRUE
13(3): string[index]=='B' ==> FALSE
18(7): string[index]=='C' ==> FALSE
25(11): string[index]!="\0" ==> FALSE

Test Path 4: 0 1 2 3 4 5 2 3 6 7 8 9 2 3 6 7 10 11 14 16 17
Complexity-Based Testing

- Construct the flowchart for the program.
- Calculate the graph complexity $C$.
- Find $C$ independent paths and corresponding test data for each.
- Execute program on test data.
- Check results with what is expected.
Classifying Loop Complexity (Informal)

Concatenated

Nested

Intersecting
Program Graph

Complexity Measures

- Used to determine *how much* testing required for a given sub-system

- Examples
  - McCabe Cyclomatic complexity
  - Halstead software metric
McCabe Cyclomatic complexity for a program graph

- Popular, but theoretically questionable
- \( V(G) = e - n + p \)
  - \( e \) is the number of edges (arcs), which represent data processing boxes
  - \( n \) is the number of nodes, which represent points where edges are connected
  - \( p \) is the number of separate parts (connected sub-graphs)
Example

Flowchart
Example

Flowchart

Corresponding Graph
Node Correspondence

Flowchart

Corresponding Graph
Edge Correspondence

Flowchart

Corresponding Graph

\[ \nu(G) = e - n + p = 6 - 5 + 1 = 2 \]
McCabe's measure drawn from Cyclomatic Number of a Graph

- Defined by Berge (Theory of graphs and its applications, 1962), motivated by Euler
- Originally defined for undirected graphs
- $\nu(G) = \text{edges} - \text{nodes} + \text{separate parts}$
- **Property**: Connecting two nodes increases $\nu$ value by 1 if there was a path between the two nodes; otherwise it leaves $\nu$ value the same.
Illustration of Property

Connecting two nodes increases $\nu$ value by 1 if there was a path between the two nodes; otherwise leaves $\nu$ value the same.

- $\nu = 0 - 2 + 2 = 0$
- $\nu = 1 - 2 + 1 = 0$
- $\nu = 2 - 2 + 1 = 1$
- $\nu = 3 - 2 + 1 = 2$
- $\nu = 2 - 3 + 1 = 0$
- $\nu = 3 - 3 + 1 = 1$
- $\nu = 5 - 3 + 1 = 3$
Illustration of Property

Connecting two nodes increases $\nu$ value by 1 if there was a path between the two nodes; otherwise leaves $\nu$ value the same.

\[
\nu = 6 - 4 + 2 = 4 \quad \quad \nu = 7 - 4 + 1 = 4
\]
Further Properties of the Cyclomatic Number of a Graph

- $\nu(G) = 0$ iff $G$ contains no \textit{undirected} cycles

- If $G$ is strongly connected (has only one component), then $\nu(G)$ is the maximum number of linearly-independent undirected cycles.

[This can be used to compute size of a basis.]
Think of the edges of a graph as components of a vector.

A circuit is abstracted by the number of times each edge is traversed in the (undirected) circuit.

One circuit can be constructed from others by adding (mod 2) the corresponding vectors.
Adding Circuits

\[ \nu(G) = e - n + p \]
\[ = 11 - 7 + 1 \]
\[ = 5 \]

\[ c_1 = 1-4-9-11 = (1 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 1) \]
\[ c_2 = 2-7-10-11 = (0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 1 \ 1) \]
\[ c_3 = 1-4-9-10-2-7 = (1 \ 1 \ 0 \ 1 \ 0 \ 0 \ 1 \ 0 \ 1 \ 1 \ 0) \]

\[ c_3 = c_1 + c_2 \]
\[ c_1 \text{ and } c_2 \text{ are linearly independent, etc.} \]

5 circuits form a \textbf{basis}
McCabe Complexities of Typical Program Graphs

- McCabe: If a part of a graph is not strongly connected, add a **phantom arc** from finish to start;

- Alternatively, use the *modified* formula
  \[ \mu(G) = e - n + 2p \]

- Above, 2p accounts for one *phantom arc* in each separate part.
Adding one phantom edge per separate part

\[ \mu(G) = e - n + p \] if phantom edges *counted* in e

\[ \mu(G) = e - n + 2p \] if phantom edges *not counted* in e
Complexities of Typical Program Graphs

$$\mu(G) = e - n + 2p$$

Straight-line programs have $$\mu(G) = 1.$$ Two-way branch programs have $$\mu(G) = 2.$$
Complexities of Typical Program Graphs

\[ \mu(G) = e - n + 2p \]
\[ = 6 - 5 + 2 \]
\[ = 3 \]

Three-way branch programs have \( \mu(G) = 3 \).

Adding a branch increases \( e-n \) by 1, so

Simple k-way branch programs have \( \mu(G) = k \).
Complexities of Typical Program Graphs

\[ \mu(G) = e - n + 2p \]
\[ = 4 - 4 + 2 \]
\[ = 2 \]

‘while’ programs have \( \mu(G) = 2 \).

\[ \mu(G) = e - n + 2p \]
\[ = 8 - 7 + 2 \]
\[ = 3 \]

These have the same complexity. This may be undesirable.
Complexities of Typical Program Graphs

\[ \mu(G) = e - n + 2p \]

\[ = 9 - 7 + 2 \]

\[ = 4 \]

Simple k-tuply nested programs have \( \mu(G) = k+1 \).
Complexities of Typical Program Graphs

\[ \mu(G) = e - n + 2p \]
\[ = 12 - 10 + 2 \]
\[ = 4 \]

k-section “lattices” have \( \mu(G) = k+1 \).
Uses of complexity $\mu(G)$

- $\mu(G)$ can be used to indicate the minimum number of test cases required.
- Keep $\mu(G)$ small (e.g. < 10) for “understandable” programs.
- Certain constructs (e.g. switch) are exempted from the count.
Cyclomatic Tools

Module: euclid
Basis Test Paths: 3 Paths

Test Path B1: 0 1 5 6 7 11 12 13
  8(   1): n>m  ==>  FALSE
  14(   7): r!=0  ==>  FALSE

Test Path B2: 0 1 2 3 4 5 6 7 11 12 13
  8(   1): n>m  ==>  TRUE
  14(   7): r!=0  ==>  FALSE

Test Path B3: 0 1 5 6 7 8 9 10 7 11 12 13
  8(   1): n>m  ==>  FALSE
  14(   7): r!=0  ==>  TRUE
  14(   7): r!=0  ==>  FALSE


\[ \mu(G) = 3 \]
$\mu(G) = 6$
Simplified Complexity Measures

- Counting binary predicate tests only: 
  \[ \eta(G) = \text{predicates} + 1 \]

- Counting regions = \( e - n + 2p \) (Euler’s formula)
Counting Regions

regions numbered
Use of $\mu(G)$ in Integration Testing

- Composition of modules’ complexity: what is $\mu$ of overall system in terms of individual $\mu$’s?

![Diagram showing two subsystems with no connection and equations for $\mu_1$ and $\mu_2$]
Use of $\mu(G)$ in Integration Testing

- Composition of modules' complexity: what is $\mu$ of overall system in terms of individual $\mu$'s?

$\mu_1(G) = e_1 - n_1 + 2p_1 \quad \mu_2(G) = e_2 - n_2 + 2p_2$

$\mu = \mu_1 + \mu_2$

$e = e_1 + e_2$

$n = n_1 + n_2$

$p = p_1 + p_2$
Use of $\mu(G)$ in Integration Testing

- What if connected by one edge?

![Diagram showing two subsystems connected by one edge]

$\mu = \mu_1 + \mu_2 + 1 - 1$

one fewer separate part
one more edge

So $\mu = \mu_1 + \mu_2$, even if the subsystems are singly connected.
“Design-Reduction” Technique: Lumping hierarchically

Rule 0: Call

Rule 1: Sequential

Rule 2: Repetitive

Rule 3: Conditional

Rule 4: Looping

● = Call node  ○ = Non-call node
⊕ = Path of zero or more non-call nodes
□ = Any node, call or non-call
“Design-Reduction” Technique

Original graph, \( v(G) = 5 \)

Intermediate graph, after rules 3 and 4 have been applied

Reduced graph, \( v(G) = 2 \)

\( \bigcirc \) = Non-call node  \( \bullet \) = Call node
# Software Test Standards

(Order from [http://www.12207.com/test1.htm](http://www.12207.com/test1.htm))

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