CAS 741, CES 741 (Development of Scientific Computing Software)

Fall 2017

09 Verification and Validation

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Verification and Validation

- Administrative details
- Questions?
- 741 workflow
- Testing from SE perspective
- Testing from SC perspective
- V&V template
- V&V examples
    - SWHS
    - Mesh Gen
    - Rogue Reborn

Administrative Details

- SRS Presentation grades on Avenue
- GitHub issues for colleagues
  - Assigned 1 colleague (see `Repos.xlsx` in repo)
  - Provide at least 5 issues on their SRS
  - Grading
    - Not enough issues, or poor issues 0/2
    - Enough issues, but shallow 1/2
    - Enough issues and deep (not surface) 2/2
  - Due by Tuesday, Oct 10, 11:59 pm
- Reading week next week, no 741 classes

Administrative Details: Deadlines

SRS	Week 05	Oct 4
SRS Issues	Reading week	Oct 10
V&V Present	Week 06	Week of Oct 16
V&V Plan	Week 07	Oct 25
MG Present	Week 08	Week of Oct 30
MG	Week 09	Nov 8
MIS Present	Week 10	Week of Nov 13
MIS	Week 11	Nov 22
Impl. Present	Week 12	Week of Nov 27
Final Documentation	Week 13	Dec 6

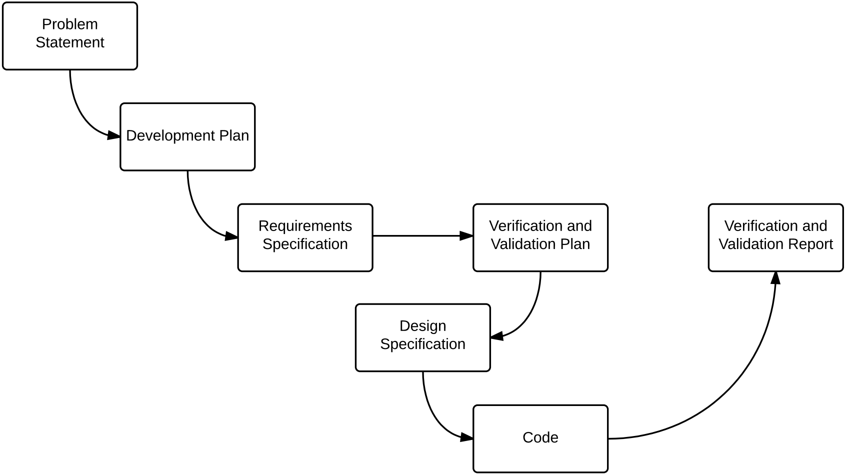
Administrative Details: Presentation Schedule

- V&V Present
  - **Tuesday: Steven, Alexandre P., Alexander S.**
  - **Friday: Geneva, Jason, Yuzhi**
- MG Present
  - Tuesday: Xiaoye, Shusheng, Devi, Keshav, Alex P, Paul
  - Friday: Yuzhi, Jason, Geneva, Alex S, Isobel, Steven
- MIS Present
  - Tuesday: Isobel, Keshav, Paul
  - Friday: Shusheng, Xiaoye, Devi
- Impl. Present
  - Tuesday: Alexander S., Steven, Alexandre P.
  - Friday: Jason, Geneva, Yuzhi

Questions?

- Questions about SRS?

“Faked” Rational Design Process



Outline of Verification Topics

- What are the goals of verification?
- What are the main approaches to verification?
  - What kind of assurance do we get through testing?
  - Can testing prove correctness?
  - How can testing be done systematically?
  - How can we remove defects (debugging)?
- What are the main approaches to software analysis?
- Informal versus formal analysis

Incorrect Version of Delete

Using `s = new T[MAX_SIZE]`, for some type `T`

```
public static void del(int i)
{
  int j;

  for (j = i; j <= (length - 1); j++)
  {
    s[j] = s[j+1];
  }

  length = length - 1;
}
```

- What is the error?
- What test case would highlight the error?

Correct Version of Delete

```
public static void del(int i)
{
  int j;

  for (j = i; j < (length - 1); j++)
  {
    s[j] = s[j+1];
  }

  length = length - 1;
}
```

Avoids potential ArrayIndexOutOfBoundsException Exception

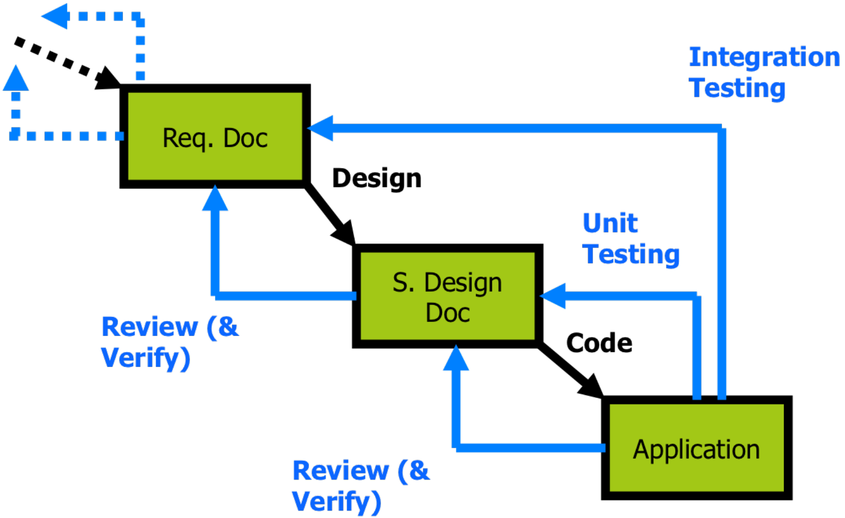
Verification Versus Validation

- What is the difference between verification and validation?

Verification Versus Validation

- Verification - Are we building the product right? Are we implementing the requirements correctly (internal)
- Validation - Are we building the right product? Are we getting the right requirements (external)
- According to Capability Maturity Model (CMM)
  - Software Verification: The process of evaluating software to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase. [IEEE-STD-610]
  - Software Validation: The process of evaluating software during or at the end of the development process to determine whether it satisfies specified requirements. [IEEE-STD-610]
- We will focus on verification

Verification Activities



Need for Verification

- Designers are fallible even if they are skilled and follow sound principles
- We need to build confidence in the software
- Everything must be verified, every required functionality, every required quality, every process, every product, every document
- For every work product covered in this class we have discussed its verification
- Even verification itself must be verified

Properties of Verification

From [1]

- May not be binary (OK, not OK)
  - Severity of defect is important
  - Some defects may be tolerated
  - Our goal is typically acceptable reliability, not correctness
- May be subjective or objective - for instance, usability, generic level of maintainability or portability
  - How might we make usability objective?
- Even implicit qualities should be verified
  - Because requirements are often incomplete
  - For instance robustness, maintainability
- What is better than implicitly specified qualities?

Approaches to Verification

- What are some approaches to verification?
- How can we categorize these approaches?

Approaches to Verification

- Experiment with behaviour of product
  - Sample behaviours via testing
  - Goal is to find "counter examples"
  - Dynamic technique
  - Examples: unit testing, integration testing, acceptance testing, white box testing, stress testing, etc.
- Analyze product to deduce its adequacy
  - Analytic study of properties
  - Static technique
  - Examples: Code walk-throughs, code inspections, correctness proof, etc.

Does our Engineering Analogy Fail?

- If a bridge can hold 512 kN, can it hold 499 kN?
- If our software works for the input 512, will it work for 499?

Verification in Engineering

- Example of bridge design
- One test assures infinite correct situations
- In software a small change in the input may result in significantly different behaviour
- There are also chaotic systems in nature, but products of engineering design are usually stable and well-behaved

Modified Version Works for 512, but not 499

```
procedure binary-search (key: in element;
                    table: in elementTable; found: out Boolean) is
begin
    bottom := table'first; top := table'last;
    while bottom < top loop
        if (bottom + top) rem 2 ≠ 0 then
            middle := (bottom + top - 1) / 2;
        else
            middle := (bottom + top) / 2;
        end if;
        if key ≤ table (middle) then
            top := middle;
        else
            bottom := middle + 1;
        end if;
    end loop;
    found := key = table (top);
end binary-search
```

if we omit this the routine works if the else is never hit! (i.e. if size of table is a power of 2)

Testing and Lack of "Continuity"

- Testing samples behaviours by examining "test cases"
- Impossible to extrapolate behaviour of software from a finite set of test cases
- No continuity of behaviour - it can exhibit correct behaviour in infinitely many cases, but may still be incorrect in some cases

Goals of Testing

- If our code passes all test cases, is it now guaranteed to be error free?
- Are 5000 random tests always better than 5 carefully selected tests?

Goals of Testing

- To show the presence of bugs (Dijkstra, 1972)
- If tests do not detect failures, we cannot conclude that software is defect-free
- Still, we need to do testing - driven by sound and systematic principles
  - Random testing is often not a systematic principle to use
  - Need a test plan
- Should help isolate errors - to facilitate debugging

Goals of Testing Continued

- Should be repeatable
  - Repeating the same experiment, we should get the same results
  - Repeatability may not be true because of the effect of the execution environment on testing
  - Repeatability may not occur if there are uninitialized variables
  - Repeatability may not happen when there is nondeterminism
- Should be accurate
  - Accuracy increases reliability
  - Part of the motivation for formal specification
- Is a successful test case one that passes the test, or one that shows a failure?

Test (V&V) Plan

- Given that no single verification technique can prove correctness, the practical approach is to use ALL verification techniques. Is this statement True or False?

Test (V&V) Plan

- Testing can uncover errors and build confidence in the software
- Resources of time, people, facilities are limited
- Need to plan how the software will be tested
- You know in advance that the software is unlikely to be perfect
- You need to put resources into the most important parts of the project
- A risk analysis can determine where to put your limited resources
- A risk is a condition that can result in a loss
- Risk analysis involves looking at how bad the loss can be and at the probability of the loss occurring

White Box Versus Black Box Testing

- Do you know (or can you guess) the difference between white box and black box testing?
- What if they were labelled transparent box and opaque box testing, respectively?

White Box Versus Black Box Testing

- White box testing is derived from the program's internal structure
- Black box testing is derived from a description of the program's function
- Should perform both white box and black box testing
- Black box testing
  - Uncovers errors that occur in implementing requirements or design specifications
  - Not concerned with how processing occurs, but with the results
  - Focuses on functional requirements for the system
  - Focuses on normal behaviour of the system

White Box Testing

- Uncovers errors that occur during implementation of the program
- Concerned with how processing occurs
- Evaluates whether the structure is sound
- Focuses on abnormal or extreme behaviour of the system

Dynamic Testing

- Is there a dynamic testing technique that can guarantee correctness?
- If so, what is the technique?
- Is this technique practical?

Dynamic Versus Static Testing

- Another classification of verification techniques, as previously discussed
- Use a combination of dynamic and static testing
- Dynamic analysis
  - Requires the program to be executed
  - Test cases are run and results are checked against expected behaviour
  - Exhaustive testing is the only dynamic technique that guarantees program validity
  - Exhaustive testing is usually impractical or impossible
  - Reduce number of test cases by finding criteria for choosing representative test cases

Static Testing Continued

- Static analysis
  - Does not involve program execution
  - Testing techniques simulate the dynamic environment
  - Includes syntax checking
  - Generally static testing is used in the requirements and design stage, where there is no code to execute
  - Document and code walkthroughs
  - Document and code inspections

Manual Versus Automated Testing

- What is the difference between manual and automated testing?
- What are the advantages of automated testing?
- What is regression testing?

Manual Versus Automated Testing

- Manual testing
  - Has to be conducted by people
  - Includes by-hand test cases, structured walkthroughs, code inspections
- Automated testing
  - The more automated the development process, the easier to automate testing
  - Less reliance on people
  - Necessary for regression testing
  - Test tools can assist, such as Junit, Cppunit, CuTest etc.
  - Can be challenging to automate GUI tests
  - Test suite for Maple has 2 000 000 test cases, run on 14 platforms, every night, automated reporting

Continuous Integration Testing

- What is continuous integration testing?

Continuous Integration Testing

- Information available on Wikipedia
- Developers integrate their code into a shared repo frequently (multiple times a day)
- Each integration is automatically accompanied by regression tests and other build tasks
- Build server
  - Unit tests
  - Integration tests
  - Static analysis
  - Profile performance
  - Extract documentation
  - Update project web-page
  - Portability tests
  - etc.
- Avoids potentially extreme problems with integration when the baseline and a developer's code greatly differ

Continuous Integration Tools

- Gitlab
  - Example at Rogue Reborn
- Jenkins
- Travis
- Docker
  - Eliminates the “it works on my machine” problem
  - Package dependencies with your apps
  - A container for lightweight virtualization
  - Not a full VM

Sample Nonfunctional System Testing

- Stress testing - Determines if the system can function when subject to large volumes
- Usability testing
- Performance measurement

Functional System Testing

- Requirements: Determines if the system can perform its function correctly and that the correctness can be sustained over a continuous period of time
- Error Handling: Determines the ability of the system to properly process incorrect transactions
- Manual Support: Determines that the manual support procedures are documented and complete, where manual support involves procedures, interfaces between people and the system, and training procedures
- Inter-systems: Determines the that interconnections between systems function correctly

Sample Functional System Testing

- Requirements: Determines if the system can perform its function correctly and that the correctness can be sustained over a continuous period of time
- Error Handling: Determines the ability of the system to properly process incorrect transactions
- Manual Support: Determines that the manual support procedures are documented and complete, where manual support involves procedures, interfaces between people and the system, and training procedures
- Parallel: Determines the results of the new application are consistent with the processing of the previous application or version of the application

Testing Phases

1. Unit testing
2. Integration testing
3. System testing
4. Acceptance testing

Theoretical Foundations Of Testing: Definitions

- P (program), D (input domain), R (output domain)
  - P: D $\rightarrow$ R (may be partial)
- Correctness defined by OR $\subseteq$ D $\times$ R
  - P(d) correct if $\langle$ d, P(d) $\rangle \in$ OR
  - P correct if all P(d) are correct
- Failure
  - P(d) is not correct
  - May be undefined (error state) or may be the wrong result
- Error (Defect)
  - Anything that may cause a failure
    - Typing mistake
    - Programmer forgot to test "x=0"
- Fault
  - Incorrect intermediate state entered by program

Definitions Questions

- A test case t is an element of D or R?
- A test set T is a finite subset of D or R?
- How would we define whether a test is successful?
- How would we define whether a test set is successful?

Definitions Continued

- Test case t: An element of D
- Test set T: A finite subset of D
- Test is successful if P(t) is correct
- Test set successful if P correct for all t in T

Theoretical Foundations of Testing

- Desire a test set T that is a finite subset of D that will uncover all errors
- Determining and ideal T leads to several undecideable problems
- No algorithm exists:
  - To state if a test set will uncover all possible errors
  - To derive a test set that would prove program correctness
  - To determine whether suitable input exists to guarantee execution of a given statement in a given program
  - etc.

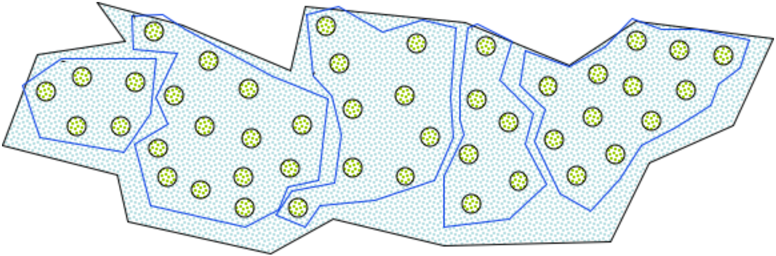
Empirical Testing

- Need to introduce empirical testing principles and heuristics as a compromise between the impossible and the inadequate
- Find a strategy to select significant test cases
- Significant means the test cases have a high potential of uncovering the presence of errors

Complete-Coverage Principle

- Try to group elements of D into subdomains D_1, D_2, ..., D_n where any element of each D_i is likely to have similar behaviour
- $D = D_1 \cup D_2 \cup ... \cup D_n$
- Select one test as a representative of the subdomain
- If $D_j \cap D_k = \emptyset$ for all $j \neq k$, (partition), any element can be chosen from each subdomain
- Otherwise choose representatives to minimize number of tests, yet fulfilling the principle

Complete-Coverage Principle



White-box Testing

- Intuitively, after running your test suites, what percentage of the lines of code in your program should be exercised?

White-box Coverage Testing

- (In)adequacy criteria - if significant parts of the program structure are not tested, testing is inadequate
- Control flow coverage criteria
  - Statement coverage
  - Edge coverage
  - Condition coverage
  - Path coverage

Statement-Coverage Criterion

- Select a test set T such that every elementary statement in P is executed at least once by some d in T
- An input datum executes many statements - try to minimize the number of test cases still preserving the desired coverage

Example

```
read (x); read (y);
if x > 0 then
        write ("1");
else
        write ("2");
end if;
if y > 0 then
        write ("3");
else
        write ("4");
end if;
```

How would you write a test case?

What is the minimum number of test cases?

Example

```
read (x); read (y);
if x > 0 then
        write ("1");
else
        write ("2");
end if;
if y > 0 then
        write ("3");
else
        write ("4");
end if;
```

{<x = 2, y = -3>, <x = - 13, y = 51>, <x = 97, y = 17>, <x = - 1, y = - 1>} covers all statements

{<x = - 13, y = 51>, <x = 2, y = - 3>} is minimal

Weakness of the Criterion

```
if x < 0 then
        x := -x;
end if;
z := x;
```

{<x=-3>} covers all statements. Why is this not enough?

Weakness of the Criterion

```
if x < 0 then
        x := -x;
end if;
z := x;
```

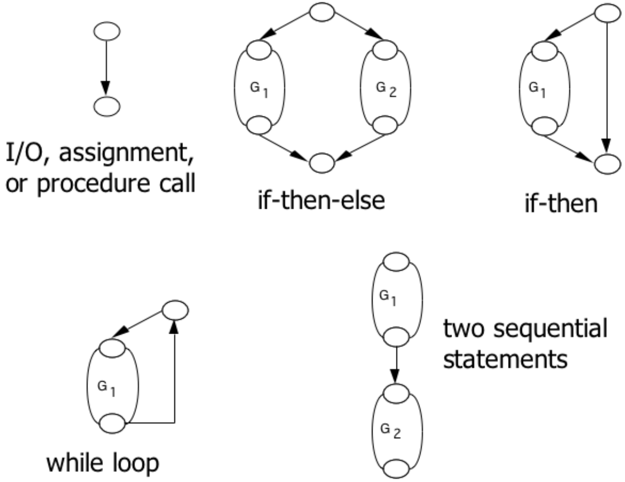
{<x=-3} covers all statements

it does not exercise the case when x is positive and the then branch is not entered

Edge-Coverage Criterion

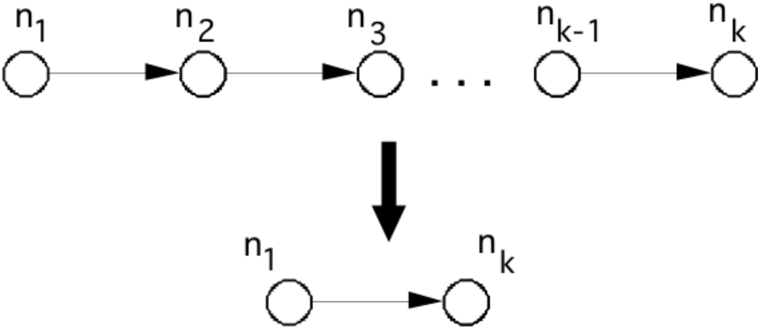
- Select a test set T such that every edge (branch) of the control flow is exercised at least once by some d in T
- This requires formalizing the concept of the control graph and how to construct it
  - Edges represent statements
  - Nodes at the ends of an edge represent entry into the statement and exit

Control Graph Construction Rules



Simplification

A sequence of edges can be collapsed into just one edge



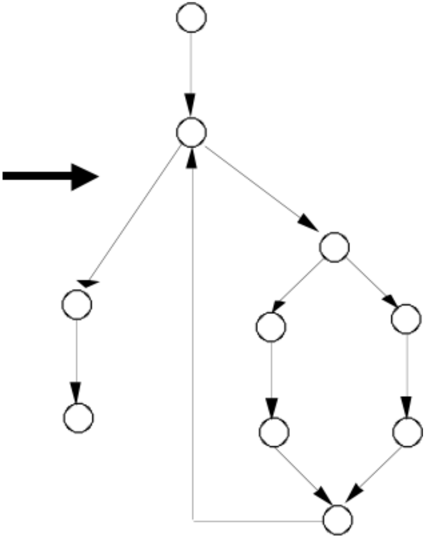
Example: Euclid's Algorithm

```
begin
        read (x); read (y);
        while x ≠ y loop
                if x > y then
                        x := x - y;
                else
                        y := y - x;
                end if;
        end loop;
        gcd : = x;
end;
```

Draw the control flow graph

Example: Euclid's Algorithm

```
begin
        read (x); read (y);
        while x ≠ y loop
                if x > y then
                        x := x - y;
                else
                        y := y - x;
                end if;
        end loop;
        gcd : = x;
end;
```



Weakness

```
found := false; counter := 1;
while (not found) and counter < number_of_items loop
        if table (counter) = desired_element then
                found := true;
        end if;
        counter := counter + 1;
end loop;
if found then
        write ("the desired element is in the table");
else
        write ("the desired element is not in the table");
end if;
```

test cases: (1) empty table, (2) table with 3 items, second of which is the item to look for

Weakness

```
found := false; counter := 1;
while (not found) and counter < number_of_items loop
        if table (counter) = desired_element then
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if found then
        write ("the desired element is in the table");
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        write ("the desired element is not in the table");
end if;
```

test cases: (1) empty table, (2) table with 3 items, second of which is the item to look for

Do not discover the error ($<$ instead of $\leq$)

```
if c1 and c2 then
   st;
else
   sf;

// equivalent to

if c1 then
   if c2 then
      st;
   else
      sf;
else
   sf;
```

Condition-Coverage Criterion

- Select a test set T such that every edge of P's control flow is traversed and all possible values of the constituents of compound conditions are exercised at least once
- This criterion is finer than edge coverage

Weakness

```
if x ≠ 0 then
        y := 5;
else
        z := z - x;
end if;
if z > 1 then
        z := z / x;
else
        z := 0;
end if;
```

{<x = 0, z = 1>, <x = 1, z = 3>} causes the execution of all edges, but fails to expose the risk of a division by zero

Path-Coverage Criterion

- Select a test set T that traverses all paths from the initial to the final node of Ps control flow
- It is finer than the previous kinds of coverage
- However, number of paths may be too large, or even infinite (see while loops)
- Loops
  - Zero times (or minimum number of times)
  - Maximum times
  - Average number of times

The Infeasibility Problem

- Syntactically indicated behaviours (statements, edges, etc.) are often impossible
- Unreachable code, infeasible edges, paths, etc.
- Adequacy criteria may be impossible to satisfy
  - Manual justification for omitting each impossible test case
  - Adequacy "scores" based on coverage - example 95 % statement coverage

Further Problem

- What if the code omits the implementation of some part of the specification?
- White box test cases derived from the code will ignore that part of the specification!

Testing Boundary Conditions

- Testing criteria partition input domain in classes, assuming that behavior is "similar" for all data within a class
- Some typical programming errors, however, just happen to be at the boundary between different classes
  - Off by one errors
  - $<$ instead of $\leq$
  - equals zero

Criterion

- After partitioning the input domain D into several classes, test the program using input values not only "inside" the classes, but also at their boundaries
- This applies to both white-box and black-box techniques
- In practice, use the different testing criteria in combinations

The Oracle Problem

When might it be difficult to know the "expected" output/behaviour?

The Oracle Problem

- Given input test cases that cover the domain, what are the expected outputs?
- Oracles are required at each stage of testing to tell us what the right answer is
- Black-box criteria are better than white-box for building test oracles
- Automated test oracles are required for running large amounts of tests
- Oracles are difficult to design - no universal recipe

The Oracle Problem Continued

- Determining what the right answer should be is not always easy
  - Scientific computing
  - Machine learning
  - Artifical intelligence

The Oracle Problem Continued

What are some strategies we can use when we do not have a test oracle?

Strategies Without An Oracle

- Using an independent program to approximate the oracle (pseudo oracle)
- Method of manufactured solutions
- Properties of the expected values can be easier than stating the expected output
  - Examples?

Strategies Without An Oracle

- Using an independent program to approximate the oracle (pseudo oracle)
- Method of manufactured solutions
- Properties of the expected values can be easier than stating the expected output
  - List is sorted
  - Number of entries in file matches number of inputs
  - Conservation of energy or mass
  - Expected trends in output are observed (metamorphic testing)
  - etc.

Mutation Testing for SC

- Generate changes to the source code, called mutants, which become code faults
- Mutants include changing an operation, modifying constants, changing the order of execution, etc.
- The adequacy of a set of tests is established by running the tests on all generated mutants
- Need to account for floating point approximations
- See Hook and Kelly, 2009

Analysis of Units

- Dynamic testing of units is not the only option
- Static testing (analysis) includes the following
  - Informal inspection
  - Systematic inspection
  - Code walkthroughs, data flow analysis
  - Correctness proofs (for instance using pre and post conditions)
  - Complexity measures

Challenges Specific to Scientific Computing

- Unknown solution
- Approximation of real numbers
- Nonfunctional requirements
- Parallel computation

Validation Testing Report for PMGT

- Prepared by Wen Yu
- Do not know the correct solution, but know properties of the correct solution
- Automated correctness validation tests
  - The area of each element is greater than zero
  - The boundary of the mesh is closed
  - Vertices in a clockwise order
  - $nc + nv - ne = 1$
  - ...
- Visual correctness validation tests
  - No vertex outside the input domain
  - No vertex inside a cell
  - No dangling edges
  - All cells connected
  - The mesh is conformal

Validation Testing Report for PMGT (Continued)

- List and description of test cases
- Test cases are labelled and numbered
- Traceability to SRS requirements
- Traceability to MG
- Summary of results
- Analysis of results
  - Focus on nonfunctional requirements
  - Speed

References I

Carlo Ghezzi, Mehdi Jazayeri, and Dino Mandrioli.
Fundamentals of Software Engineering.
Prentice Hall, Upper Saddle River, NJ, USA, 2nd edition, 2003.