

CAS 741 (Development of Scientific Computing Software)

Winter 2025

10 Verification and Validation Continued

Dr. Spencer Smith

Faculty of Engineering, McMaster University

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Verification and Validation Continued

- Administrative details
- Questions?
- Nonfunctional software testing
- Theoretical foundations of testing
- Complete coverage principle
- White box testing
- Oracle problem
- SCS Specific Ideas
- Overview of [template](#)

Administrative Details: Report Deadlines

System VnV Plan	Week 06	Feb 24
MG + MIS	Week 09	Mar 14
Final Documentation	Week 13	Apr 11

- The written deliverables will be graded based on the repo contents as of 11:59 pm of the due date
- If you need an extension for a **written** doc, please ask
- When ready, assign issues to your primary and secondary reviewers
- GitHub issues due two days after assignment deadlines
- From Drasil Code onward, Drasil projects no longer need to maintain traditional SRS

Administrative Details: Presentations

Syst. VnV	Week 06
POC Demo	Week 07
MG + MIS	Week 09
Drasil	Week 11
Unit VnV/Implement	Week 12

- Specific schedule depends on final class registration
- Informal presentations with the goal of improving everyone's written deliverables
- Time for presentation includes time for questions
- We will have to be strict with the schedule
- Presentations WILL be interrupted with questions/criticism; please do not take it personally
- Any concerns, let the instructor know

Presentation Schedule

- Syst V&V Plan Present (L11, L12) (20 min)
 - ▶ **Feb 14: Qianlin, Junwei, Joe, Volunteer?**
 - ▶ **Feb 25: Yinying, Bo, Hussein, Volunteer?**
- Proof of Concept Demonstrations (L14) (20 min)
 - ▶ **Mar 4: Christopher, Uriel, Volunteer?, Volunteer?**
- MG+MIS Present (L17, L18) (20 minutes)
 - ▶ Mar 11: Ziyang, Aliyah, Yuanqi, Alaap
 - ▶ Mar 14: Phillip, Baptiste, Kiran, Volunteer?

Presentation Sched Cont'd

- Implementation Present (L22 – L25) (20 min each)
 - ▶ Mar 28: Aliyah, Uriel, Ziyang, Yuanqi
 - ▶ Apr 1: Christopher, Bo, Joe, Junwei
 - ▶ Apr 4: Hussein, Kiran, Alaap, Qianlin
 - ▶ Apr 8: Yinying, Baptiste, Phillip

Presentation Schedule

- 3 presentations each
 - ▶ SRS everyone
 - ▶ VnV and POC subset of class
 - ▶ Design subset of class
 - ▶ Implementation or testing results everyone
- If you will miss a presentation, please trade with someone
- Implementation presentation could be used to run a code review, or code walkthrough

Administrative Details: Drasil Resources

- [Learn you a Haskell for Great Good](#)
- [Drasil on GitHub](#)
- [Design Language for Code Variabilities in Chapter 6 of Brook's thesis](#)
- [Drasil Generated Examples](#)
- [Drasil Haddock Documentation](#)
- [Package Dependency Graph \(at the bottom of the page\)](#)
- [Creating your project in Drasil](#)
- [Drasil Wiki](#)

Administrative Details Continued

- Some Domain Expert assignments have changed
- Yasmin dropped the course, so Bo will need to find another project to evaluate

Questions?

- Questions about V&V?
- Questions about PoC?
- Other questions?

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 15 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

Description Rather Than Specification

- Test cases are often phrased as Expected = Calculated
- In scientific software you generally should not test for equality
 - ▶ Absolute error within tolerance
 - ▶ Relative error within tolerance
 - ▶ If comparing matrices or vectors, consider using norms of residual
- Even a specific tolerance often doesn't make sense in a scientific context
- Often your plan should be to **describe** the error rather than **prescribe**
 - ▶ Plot of error versus problem size, or condition number, or ...
 - ▶ Consider summarizing multiple tests with the infinity norm of the relative error (or similar)
- Your description plan is part of your V&V plan!

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 (including [rubber duck debugging](#))
 - ▶ 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

- Building and testing software on every push (see [Fowler](#))
- Information available on [Wikipedia](#)
- Developers frequently integrate code into a shared repo
- 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
- Jenkins
- Travis
- Shared Team's Video on Continuous Integration with extra material
- 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

Sample Functional System Testing

- Parallel: Determines the results of the new application are consistent with the processing of the previous application or version of the application

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 an ideal T leads to several **undecidable 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.

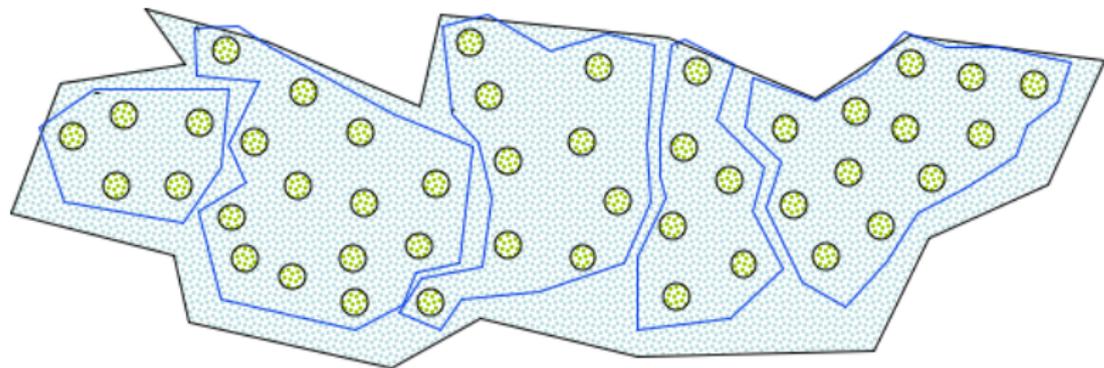
Empirical Testing

- 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, \dots, D_n where any element of each D_i is likely to have similar behaviour
- $D = D_1 \cup D_2 \cup \dots \cup D_n$
- 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

Examples that follow are from [\[1\]](#)

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;
```

**$\{\langle x = 2, y = -3 \rangle, \langle x = -13, y = 51 \rangle, \langle x = 97, y = 17 \rangle, \langle x = -1, y = -1 \rangle\}$
covers all statements**

**$\{\langle x = -13, y = 51 \rangle, \langle x = 2, y = -3 \rangle\}$
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

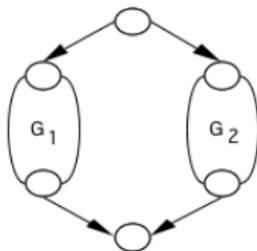
Edge-Coverage Criterion

- 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

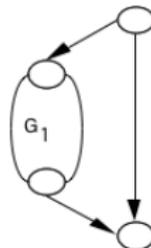
Control Graph Construction Rules



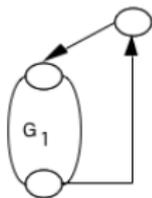
I/O, assignment,
or procedure call



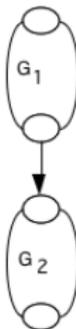
if-then-else



if-then



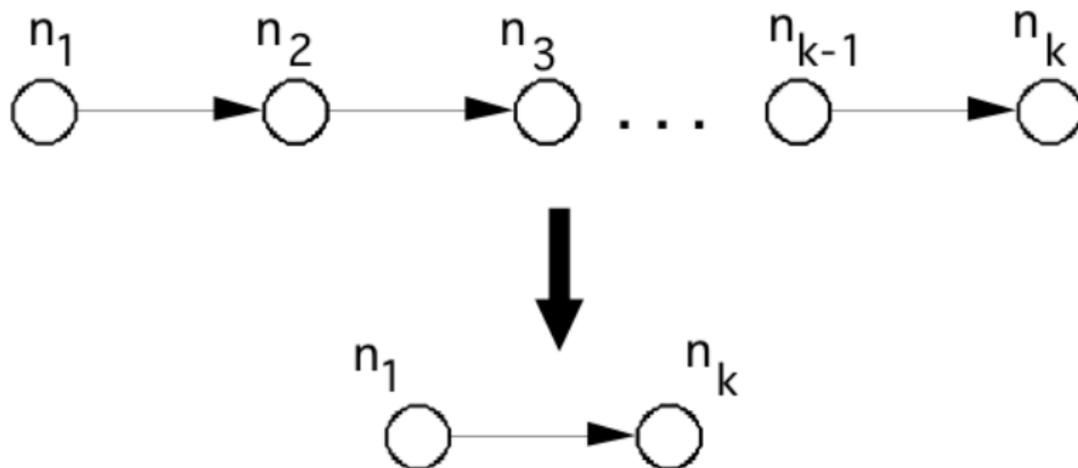
while loop



two sequential
statements

Simplification

A sequence of edges can be collapsed into just one edge



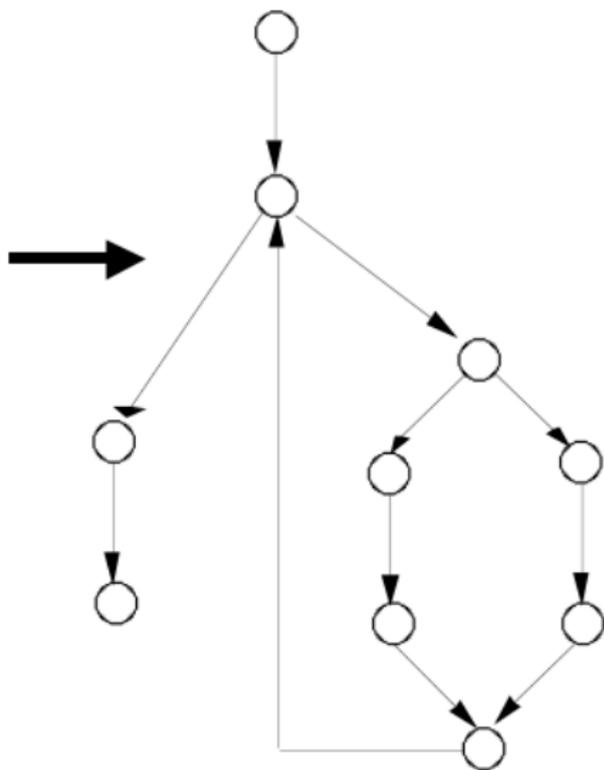
Example: Euclid's Algorithm

```
begin
  read (x); read (y);
  while x  $\neq$  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  $x \neq y$  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
    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

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

$\{\langle x = 0, z = 1 \rangle, \langle x = 1, z = 3 \rangle\}$
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 P 's 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
- Use testing tools for coverage metrics

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
 - ▶ Artificial 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?

- Properties of Correct Solution Section in SRS

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?
 - ▶ 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 [5, 4, 6])
 - ▶ etc.
- Properties of Correct Solution Section in SRS

Metamorphic Testing

- Used for testing when there is no test oracle
- Test program has properties known as Metamorphic Relations (MR)
- MRs specify how a change in inputs should change the output
- For instance (KanewalaEtAl2014)
 - ▶ Finding the maximum of a list should be the same no matter the permutation of the list
 - ▶ The average of a set of numbers will increase if each number added is larger than all previous numbers added
 - ▶ Etc.
- Metamorphic testing gets its name because new test cases are evolved from the old ones (ChenEtAl1998)

Challenges Specific to Scientific Computing

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

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 [3]

Model Checking

- Correctness verification, in general, is an undecidable problem
- Model checking is a recent verification technique based on the fact that most interesting system properties become decidable (algorithmically verifiable) when the system is modelled as a finite state machine

Informal Analysis Techniques: Code Walkthrough

- Code walkthroughs are a more rigorous version of [Rubber Duck Debugging](#)
- Recommended prescriptions
 - ▶ Small number of people (three to five)
 - ▶ Participants receive written documentation from the designer a few days before the meeting
 - ▶ Predefined duration of the meeting (a few hours)
 - ▶ Focus on the [discovery](#) of errors, not on fixing them
 - ▶ Participants: designer, moderator, and a secretary
 - ▶ Foster cooperation; no evaluation of people
 - ▶ Experience shows that most errors are discovered by the designer during the presentation, while trying to explain the design to other people
- Forces looking at the code from a different viewpoint
- Can be used for documentation too

Informal Analysis Techniques: Code Inspection

- A reading technique aiming at error discovery
- Based on checklists
 - ▶ Use of uninitialized variables
 - ▶ Jumps into loops
 - ▶ Nonterminating loops
 - ▶ Array indexes out of bounds

Specific SC V&V Approaches

Summary of most points below in [10]

- Compare to closed-form solutions
- Method of manufactured solutions [8]
- Interval arithmetic [2]
- Convergence studies
- Compare to other program (parallel testing)
- Can also consider using code inspection
 - ▶ [7, 9]
 - ▶ [Sample checklists](#)

Specific SC V&V NonFunctional

- Installability, consider VMs
- Portability, consider VMs, Docker, CI
- Describe (rather than specify) impact of changing inputs
 - ▶ Accuracy
 - ▶ Performance
 - ▶ Relative comparison
- Usability
 - ▶ Fairly simple standard survey

Validation Testing Report for PMGT

- Prepared by Wen Yu ([here](#))
- 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 verification 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

Other VnV Plan Examples

- SWHS
- Solar Cooker
- 3D Image Reconstruction in Medical Ultrasound
- Spectrum Image Analysis
- Chemical Speciation
- Examples folder

Test Plan From BlankProjectTemplate

- VnV template
- For Unit VnV plan mention tools
 - ▶ Linters
 - ▶ Coding standard checkers (like flake8)
 - ▶ unit testing frameworks
 - ▶ Performance testing (like Valgrind)

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