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

Fall 2019

10 Verification and Validation Continued

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Verification and Validation Continued

- Administrative details
- Questions?
- Finish what started last day
  - Nonfunctional software testing
  - Theoretical foundations of testing
  - Complete coverage principle
- White box testing
- Oracle problem
- SCS Specific Ideas
- Overview of template

Administrative Details

- GitHub issues for colleagues
  - Assigned 1 colleague (see `Repos.xlsx` in repo)
  - Provide at least 5 issues on their SRS
- Reading week, no 741 classes
- V&V template updated in repo

Administrative Details: Deadlines

SRS Issues	Reading week	Oct 11
Syst. VnV Present	Week 06	Week of Oct 15
System VnV Plan	Week 07	Oct 22
MG Present	Week 08	Week of Oct 29
MG	Week 09	Nov 5
MIS Present	Week 10	Week of Nov 12
MIS	Week 11	Nov 19
Unit VnV or Impl. Present	Week 12	Week of Nov 26
Unit VnV Plan	Week 13	Dec 3
Final Doc	Week 14	Dec 10

Administrative Details: Presentation Schedule

- Syst V&V Plan Present
  - Wednesday: Malavika, Robert
  - Friday: Hanane
- MG Present
  - Wednesday: Karol, Malavika, Robert, Hanane
  - Friday: Brooks, Vajiheh, Olu, Jennifer
- MIS Present
  - Wednesday: Malavika, Robert
  - Friday: Hanane, Jennifer
- Unit VnV Plan or Impl. Present
  - Wednesday: Brooks, Vajiheh
  - Friday: Olu, Karol

Questions?

- Questions about SRS?
- Questions about V&V?

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 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.

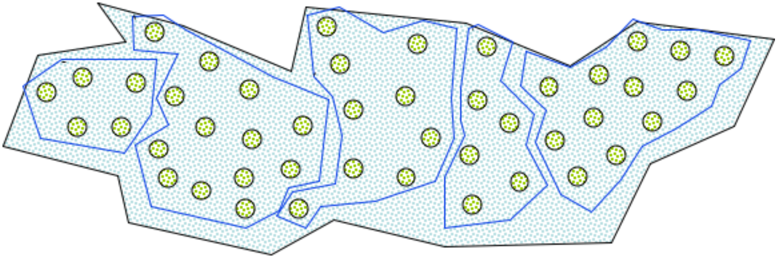
Empirical Testing

- 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
- $D = D_1 \cup D_2 \cup \ldots \cup D_n$
- 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;
```

{<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;
```

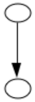
{<x=-3} covers all statements

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

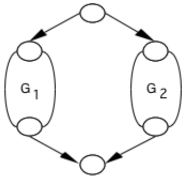
Edge-Coverage Criterion

- 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

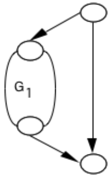
Control Graph Construction Rules



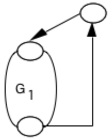
I/O, assignment, or procedure call



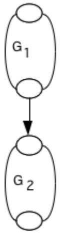
if-then-else



if-then



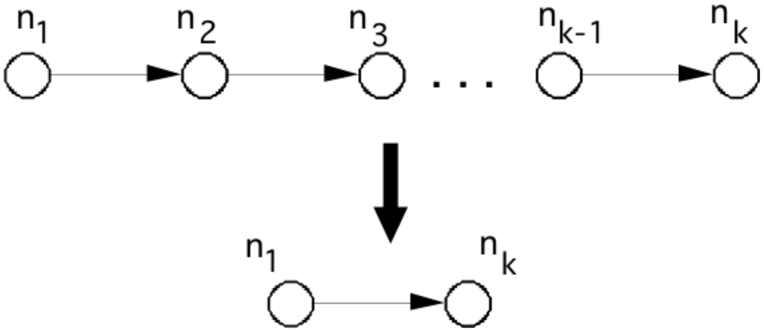
while loop



two sequential statements

Simplification

A sequence of edges can be collapsed into just one edge



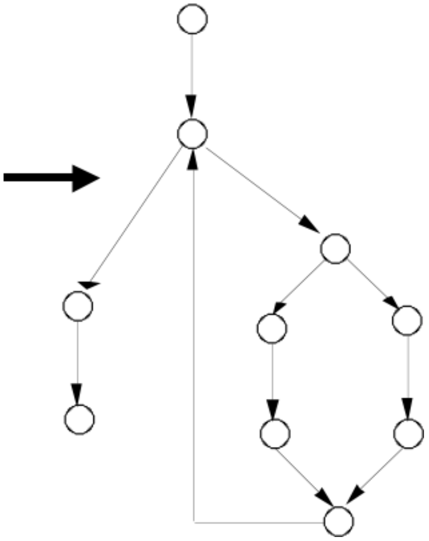
Example: Euclid's Algorithm

```
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 ≠ y loop
                if x > y then
                        x := x - y;
                else
                        y := y - x;
                end if;
        end loop;
        gcd : = x;
end;
```

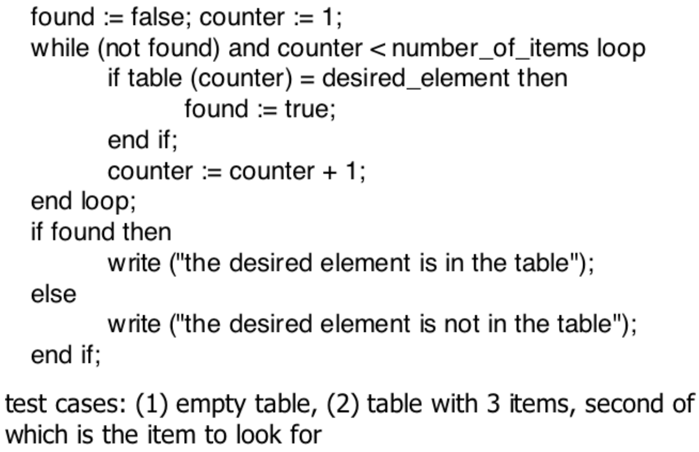


Weakness

```
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 ≠ 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
    - 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.

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]

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
  - Example

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 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

Test Plan From BlankProjectTemplate

- Add links to templates
- For Unit VnV plan mention tools
  - Linters
  - Coding standard checkers (like flake8)
  - unit testing frameworks
  - Performance testing (like Valgrind)

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