White-box testing techniques

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White-box Testing

- Designing white-box test cases:
  - Requires knowledge about the internal structure of software.
  - White-box testing is also called structural testing.
  - In this unit we will study white-box testing.

White-Box Testing Methodologies

- There exist several popular white-box testing methodologies:
  - Statement coverage
  - Branch coverage
  - Condition coverage
  - MC/DC coverage
  - Path coverage
  - Data flow-based testing
  - Mutation testing

Statement Coverage

- Statement coverage methodology:
  - Design test cases so that every statement in the program is executed at least once.

Statement Coverage

- The principal idea:
  - Unless a statement is executed,
  - We have no way of knowing if an error exists in that statement.

Statement Coverage Criterion

- Observing that a statement behaves properly for one input value:
  - No guarantee that it will behave correctly for all input values.

Statement Testing

- Coverage measurement:

  # executed statements

  # statements

- Rationale: a fault in a statement can only be revealed by executing the faulty statement

Example

```
int f1(int x, int y){
while (x != y){
   if (x>y) then
        x=x-y;
   else y=y-x;
}
return x;       }
```

Euclid's GCD Algorithm

Euclid's GCD Algorithm

- By choosing the test set {(x=3,y=3),(x=4,y=3), (x=3,y=4)}
  - All statements are executed at least once.

Branch Coverage

- Test cases are designed such that:
  - different branch conditions
    - given true and false values in turn.

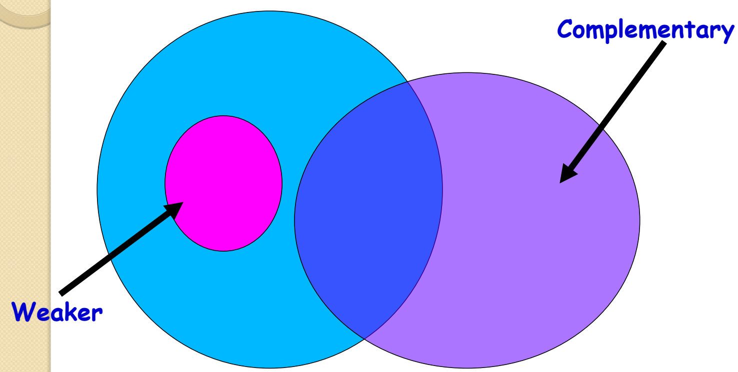
Branch Coverage

- Branch testing guarantees statement coverage:
  - A stronger testing compared to the statement coverage-based testing.

Stronger Testing

- Test cases are a superset of a weaker testing:
  - A stronger testing covers at least all the elements covered by a weaker testing.

Stronger, Weaker, and Complementary Testing



Example

```
int f1(int x,int y){
while (x != y){
   if (x>y) then
          x=x-y;
   else y=y-x;
}
return x;        }
```


Example

- Test cases for branch coverage can be:
- {(x=3,y=3),(x=3,y=2), (x=4,y=3), (x=3,y=4)}

Branch Testing

- Adequacy criterion: Each branch (edge in the CFG) must be executed at least once
- Coverage:

$$\frac{\#\ \text{executed branches}}{\#\ \text{branches}}$$

Statements vs Branch Testing

- Traversing all edges of a graph causes all nodes to be visited
  - So test suites that satisfy the branch adequacy criterion for a program P also satisfy the statement adequacy criterion for the same program
- The converse is not true
  - A statement-adequate (or node-adequate) test suite may not be branch-adequate (edge-adequate)

Condition Coverage

- Test cases are designed such that:
  - Each component of a composite conditional expression
    - Given both true and false values.

Branch vs Condition testing

- Condition testing:
  - Stronger testing than branch testing.
- Branch testing:
  - Stronger than statement coverage testing.

Branch vs Condition testing

- Branch testing is the simplest condition testing strategy:
  - Compound conditions appearing in different branch statements
    - are given true and false values.

Multiple Condition Coverage

- Multiple condition coverage reports whether every possible combination of Boolean sub-expressions occurs.
- The test cases required for full multiple condition coverage of a condition are essentially given by the logical operator truth table for the condition.

Multiple Condition Coverage cont …

- Test cases are designed such that:
  - each component of a composite conditional expression
    - given both true and false values.

Example

- Consider the conditional expression
  - ((c1.and.c2).or.c3):
- Each of c1, c2, and c3 are exercised at least once,
  - i.e. given true and false values.

Multiple Condition Coverage Examples

```
if(A && B)   // condition 1
    F1();
  else
    F2();
if(C || D)     // condition 2
    F3()
  else
    F4();
```

Test Cases for MCC:

For condition 1	For condition 2
A=T, B=T	C=T, D=T
A=T, B=F	C=T, D=F
A=F, B=T	C=F, D=T
A=F, B=F	C=F, D=F

MCC Testing Adequacy Criterion

- Adequacy criterion: Each basic condition must be executed at least once
- Coverage:

$$\frac{\text{\# truth values taken by all basic conditions}}{2 * \text{\# basic conditions}}$$

Branch Testing vs MCC Testing

- Multiple Condition Coverage testing:
  - Stronger testing than branch testing.
- Branch testing:
  - Stronger than statement coverage testing.

Need of a Feasible Testing Technique

- Consider a boolean expression having **n** components:
  - For condition coverage we require 2^n test cases. (example in next slide)
- Condition coverage-based testing technique:
  - Practical only if **n** (the number of component conditions) is small.

Consider: **if (a || b && c) then …**

Test	a	b	c
(1)	T	T	T
(2)	T	T	F
(3)	T	F	T
(4)	T	F	F
(5)	F	T	T
(6)	T	T	F
(7)	F	F	T
(8)	F	F	F

MCC

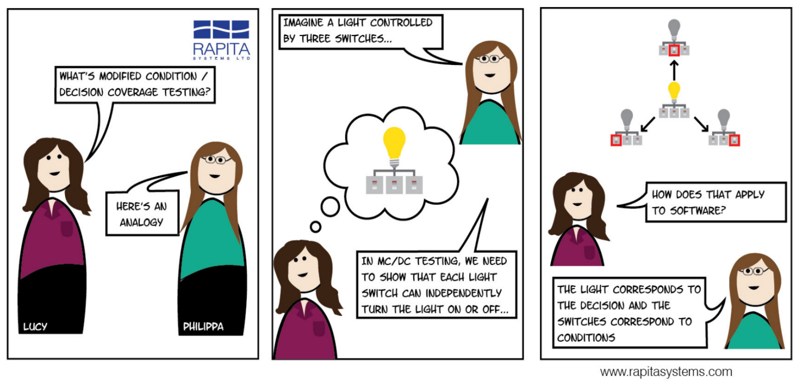
Exponential in the number of basic conditions

Modified condition/decision (MC/DC)

- Motivation: Effectively test important combinations of conditions, without exponential blowup in test suite size
  - "Important" combinations means: Each basic condition shown to independently affect the outcome of each decision
- Requires:
  - For each basic condition C, two test cases,
  - values of all *evaluated* conditions except C are the same
  - compound condition as a whole evaluates to *true* for one and *false* for the other

What is MC/DC?

- MC/DC stands for **M**odified **C**ondition / **D**ecision **C**overage
- A kind of Predicate Coverage technique
  - Condition: Leaf level Boolean expression.
  - Decision: Controls the program flow.
- Main idea: Each condition must be shown to independently affect the outcome of a decision, i.e. the outcome of a decision changes as a result of changing a single condition.



Condition Coverage

- Every condition in the decision has taken all possible outcomes at least once.
- If ((a) && (b) || (c)) then…
  - (a): true / false
  - (b): true / false
  - (c): true / false

MC/DC Coverage

- Every condition in the decision independently affects the decision's outcome.

`If ((a) && (b) || (c)) then…`

(a): *true* / *false*; ((b) || (c)): *true* / *false*

Change the value of each condition individually while keeping all other conditions constant.

MC/DC: linear complexity

- N+1 test cases for N basic conditions

(((a || b) && c) || d) && e

Test Case	a	b	c	d	e	outcome
(1)	true	--	true	--	true	true
(2)	false	true	true	--	true	true
(3)	true	--	false	true	true	true
(6)	true	--	true	--	false	false
(11)	true	--	false	false	--	false
(13)	false	false	--	false	--	false

- Underlined values independently affect the output of the decision
- Required by the RTCA/DO-178B standard

Comments on MC/DC

- MC/DC is
  - basic condition coverage (C)
  - branch coverage (DC)
  - plus one additional condition (M): every condition must *independently affect* the decision's output
- It is subsumed by compound conditions and subsumes all other criteria discussed so far
  - stronger than statement and branch coverage
- A good balance of thoroughness and test size (and therefore widely used)

Example

If (A && B) then…

(1) create truth table for conditions.

(2) Extend truth table so that it indicated which test cases can be used to show the independence of each condition.

A B	Result
T T	T
T F	F
F T	F
F F	F

Number	A	B	Result	A	B
1	T	T	T	3	2
2	T	F	F		1
3	F	T	F	1	
4	F	F	F		

Example cont …

Number	A B	Result	A	B
1	T T	T	3	2
2	T F	F		1
3	F T	F	1	
4	F F	F		

- Show independence of **A**:
  - Take 1 + 3
- Show independence of **B**:
  - Take 1 + 2
- Resulting test cases are
  - 1 + 2 + 3
  - (T , T) + (T , F) + (F , T)

More advanced example

```
If (A && (B || C)) then…
```

Number	A B C	Result	A	B	C
1	T T T	T	5		
2	T T F	T	6	4	
3	T F T	T	7		4
4	T F F	F		2	3
5	F T T	F	1		
6	F T F	F	2		
7	F F T	F	3		
8	F F F	F			

More advanced example contd..

Note: We want to determine the MINIMAL set of test cases

Here:

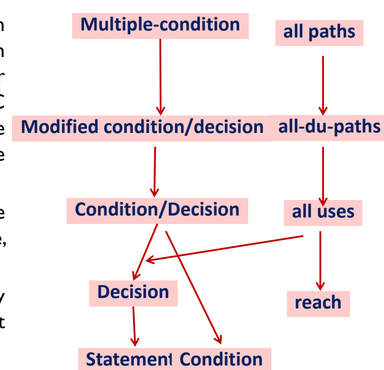
- {2,3,4,6}
- {2,3,4,7}

Non-minimal set is:

- {1,2,3,4,5}

Where does it fit in?

- The MC/DC criterion is much stronger than the condition/decision coverage criterion, but the number of test cases to achieve the MC/DC criterions still varies linearly with the number of conditions **n** in the decisions.
  - Much more complete coverage than condition/decision coverage, but
  - at the same time it is not terribly costly in terms of number of test cases.



Comparison of different coverage based Testing Strategies

Coverage Criteria	Statement Coverage	Decision Coverage	Condition Coverage	Condition/ Decision Coverage	MC/DC	Multiple Condition Coverage
Every point of entry and exit in the program has been invoked at least once		•	•	•	•	•
Every statement in the program has been invoked at least once	•					
Every decision in the program has taken all possible outcomes at least once		•		•	•	•
Every condition in a decision in the program has taken all possible outcomes at least once			•	•	•	•
Every condition in a decision has been shown to independently affect that decision's outcome					•	•[8]
Every combination of condition outcomes within a decision has been invoked at least once						•

weakest strongest

Summary

- Discussed white-box test case design using:
  - Statement coverage technique
  - Branch coverage technique
  - Condition coverage technique
  - MC/DC technique

References

1. Rajib Mall, Fundamentals of Software Engineering, (Chapter – 10), Fifth Edition, PHI Learning Pvt. Ltd., 2018.
2. Naresh Chauhan, Software Testing: Principles and Practices, (Chapter – 5), Second Edition, Oxford University Press, 2016.

Thank You

White-box testing techniques contd…

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Path Coverage

- Design test cases such that:
  - All linearly independent paths in the program are executed at least once.
- Defined in terms of
  - Control flow graph (CFG) of a program.

Path Coverage-Based Testing

- To understand the path coverage-based testing:
  - we need to learn how to draw control flow graph of a program.
- A control flow graph (CFG) describes:
  - The sequence in which different instructions of a program get executed.
  - The way control flows through the program.

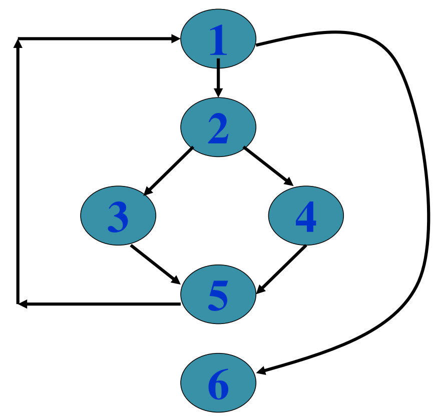
How to Draw Control Flow Graph?

- Number all statements of a program.
- Numbered statements:
  - Represent nodes of control flow graph.
- An edge from one node to another node exists:
  - If execution of the statement representing the first node
    - Can result in transfer of control to the other node.

Example

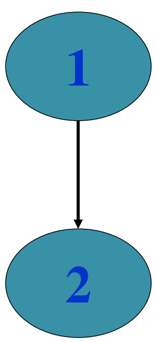
```
int f1(int x,int y){
1 while (x != y){
2   if (x>y) then
3       x=x-y;
4   else y=y-x;
5 }
6 return x;       }
```


Example Control Flow Graph



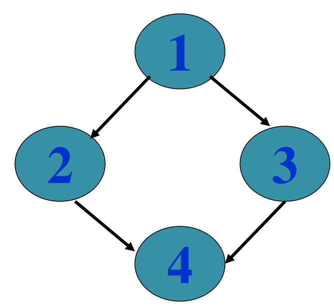
How to Draw Control flow Graph?

- **Sequence:**
  - **1 a=5;**
  - **2 b=a*b-1;**



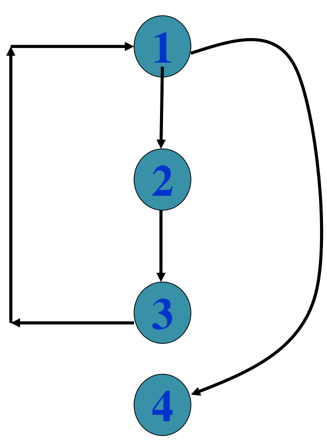
How to Draw Control Flow Graph?

- **Selection:**
  - **1 if(a>b) then**
  - **2 c=3;**
  - **3 else c=5;**
  - **4 c=c*c;**



How to Draw Control Flow Graph?

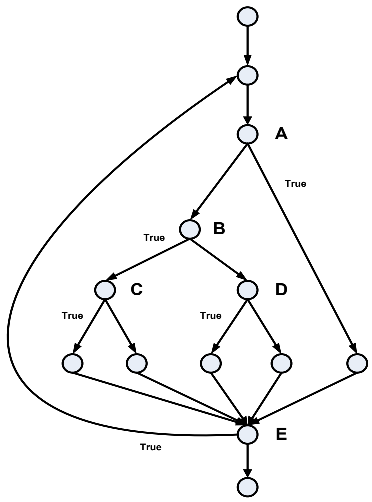
- **Iteration:**
  - **1 while(a>b){**
  - **2 b=b*a;**
  - **3 b=b-1;}**
  - **4 c=b+d;**



Example Code Fragment

```
Do
{
  if (A) then {...};
  else {
    if (B) then {
            if (C) then {...};
            else {…}
    }
    else if (D) then {...};
          else {...};
  }
}
While (E);
```

Example Control Flow Graph



Source: The Art of Software Testing – Glenford Myers

Path

- A path through a program:
  - A node and edge sequence from the starting node to a terminal node of the control flow graph.
  - There may be several terminal nodes for program.

Linearly Independent Path

- Any path through the program:
  - Introduces at least one new edge:
    - Not included in any other independent paths.

Independent path

- It is straight forward:
  - To identify linearly independent paths of simple programs.
- For complicated programs:
  - It is not easy to determine the number of independent paths.

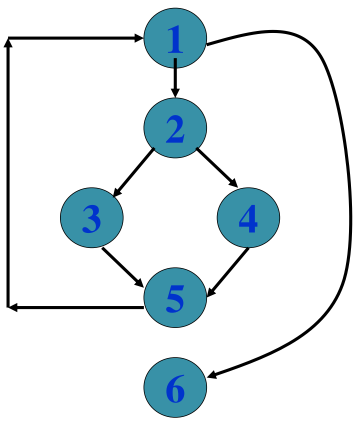
McCabe's Cyclomatic Metric

- An upper bound:
  - For the number of linearly independent paths of a program
- Provides a practical way of determining:
  - The maximum number of linearly independent paths in a program.

McCabe's Cyclomatic Metric

- Given a control flow graph G, cyclomatic complexity V(G):
  - $V(G)= E-N+2$
    - N is the number of nodes in G
    - E is the number of edges in G

Example Control Flow Graph

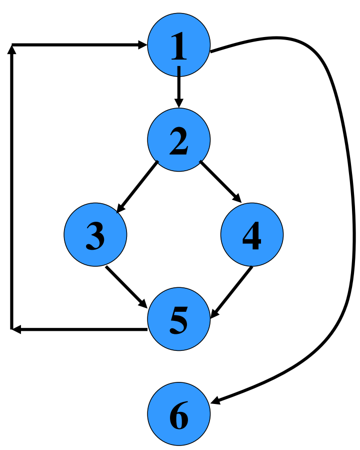


Cyclomatic complexity = 7-6+2 = 3.

Cyclomatic Complexity

- Another way of computing cyclomatic complexity:
  - inspect control flow graph
  - determine number of bounded areas in the graph
- V(G) = Total number of bounded areas + 1
  - Any region enclosed by a nodes and edge sequence.

Example Control Flow Graph



Example

- From a visual examination of the CFG:
  - Number of bounded areas is 2.
  - Cyclomatic complexity = 2+1=3.

Cyclomatic Complexity

- McCabe's metric provides:
  - A quantitative measure of testing difficulty and the ultimate reliability
- Intuitively,
  - Number of bounded areas increases with the number of decision nodes and loops.

Cyclomatic Complexity

- The first method of computing V(G) is amenable to automation:
  - You can write a program which determines the number of nodes and edges of a graph
  - Applies the formula to find V(G).

Cyclomatic Complexity

- The cyclomatic complexity of a program provides:
  - A lower bound on the number of test cases to be designed
  - To guarantee coverage of all linearly independent paths.

Cyclomatic Complexity

- A measure of the number of independent paths in a program.
- Provides a lower bound:
  - for the number of test cases for path coverage.

Cyclomatic Complexity

- Knowing the number of test cases required:
  - Does not make it any easier to derive the test cases,
  - Only gives an indication of the minimum number of test cases required.

Practical Path Testing

- The tester proposes initial set of test data :
  - Using his experience and judgment.
- A dynamic program analyzer used:
  - Measures which parts of the program have been tested
  - Result used to determine when to stop testing.

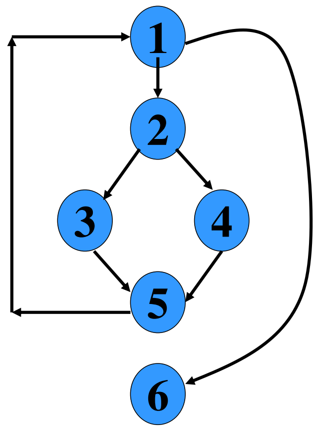
Derivation of Test Cases

- Draw control flow graph.
- Determine V(G).
- Determine the set of linearly independent paths.
- Prepare test cases:
  - to force execution along each path.

Example

```
int f1(int x,int y){
1 while (x != y){
2    if (x>y) then
3         x=x-y;
4    else y=y-x;
5 }
6 return x;        }
```

Example Control Flow Diagram



Derivation of Test Cases

- **Number of independent paths: 3**
  - **1,6** test case (x=1, y=1)
  - **1,2,3,5,1,6** test case(x=2, y=1)
  - **1,2,4,5,1,6** test case(x=1, y=2)

An Interesting Application of Cyclomatic Complexity

- Relationship exists between:
  - McCabe's metric
  - The number of errors existing in the code,
  - The time required to find and correct the errors.

Cyclomatic Complexity

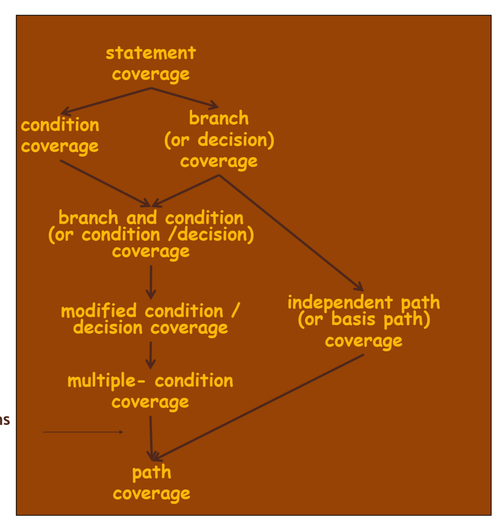
- Cyclomatic complexity of a program:
  - Also indicates the psychological complexity of a program.
  - Difficulty level of understanding the program.

Cyclomatic Complexity

- From maintenance perspective,
  - Limit cyclomatic complexity of modules
    - To some reasonable value.
  - Good software development organizations:
    - Restrict cyclomatic complexity of functions to a maximum of ten or so.

White-Box Testing : Summary

weakest



only if paths across composite conditions are distinguished

strongest

Summary

- There are two approaches to testing:
  - black-box testing and
  - white-box testing.
- Designing test cases for black box testing:
  - does not require any knowledge of how the functions have been designed and implemented.
  - Test cases can be designed by examining only SRS document.

Summary

- White box testing:
  - Requires knowledge about internals of the software.
  - Design and code is required.
- We have discussed a few white-box test strategies.
  - Statement coverage
  - Branch coverage
  - Condition coverage
  - MC/DC coverage
  - Path coverage

Summary

- A stronger testing strategy:
  - Provides more number of significant test cases than a weaker one.
  - Condition coverage is strongest among strategies we discussed.
- We discussed McCabe's Cyclomatic complexity metric:
  - Provides an upper bound for linearly independent paths
  - Correlates with understanding, testing, and debugging difficulty of a program.

References

1. Rajib Mall, Fundamentals of Software Engineering, (Chapter – 10), Fifth Edition, PHI Learning Pvt. Ltd., 2018.
2. Naresh Chauhan, Software Testing: Principles and Practices, (Chapter – 5), Second Edition, Oxford University Press, 2016.

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