Combinatorial Testing

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Combinatorial Testing: Motivation

- The behavior of a program may be affected by many factors:
  - **Input parameters,**
  - **Environment configurations (global variables),**
  - **State variables. ..**
- Equivalence partitioning of an input variable:
  - Identify the possible types of input values requiring different processing.
- If the factors are many:
  - It is impractical to test all possible combinations of values of all factors.

Combinatorial: Relating to, or involving combinations

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Combinatorial Testing: Motivation

- Many times, the specific action to be performed depends on the value of a set of Boolean variable:
  - Controller applications
  - User interfaces

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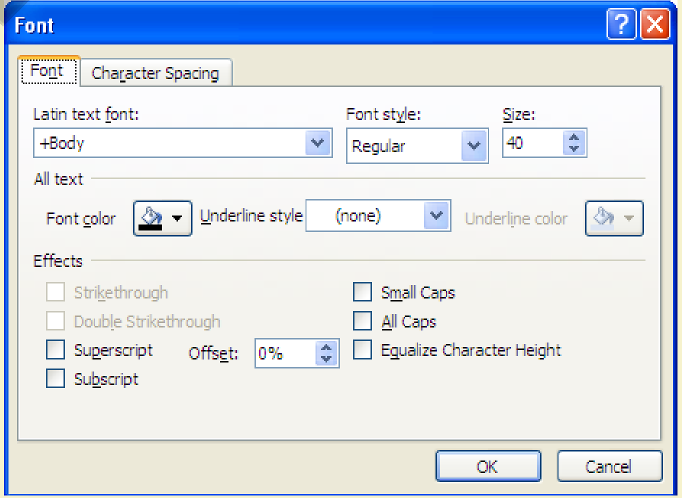
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Combinatorial Testing

- Several combinatorial testing strategies exist:
  - Decision table-based testing
  - Cause-effect graphing
  - Pair-wise testing (reduced number of test cases)

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- Applicable to requirements involving conditional actions.
- This is represented as a decision table:
  - Conditions = inputs
  - Actions = outputs
  - Rules =test cases
- Assume independence of inputs
- Example
  - If c1 AND c2 OR c3 then A1

Decision table-based Testing (DTT)

	Rule1	Rule2	Rule3	Rule4
Condition1	Yes	Yes	No	No
Condition2	Yes	X	No	X
Condition3	No	Yes	No	X
Condition4	No	Yes	No	Yes
Action1	Yes	Yes	No	No
Action2	No	No	Yes	No
Action3	No	No	No	Yes

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Combinations

	Rule1	Rule2	Rule3	Rule4
Condition1	Yes	Yes	No	No
Condition2	Yes	X	No	X
Condition3	No	Yes	No	X
Condition4	No	Yes	No	Yes
Action1	Yes	Yes	No	No
Action2	No	No	Yes	No
Action3	No	No	No	Yes

Conditions

Actions

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- A decision table consists of a number of columns (rules) that comprise all test situations
- Example: the triangle problem
  - C1: a, b,c form a triangle
  - C2: a=b
  - C3: a= c
  - C4: b= c
  - A1: Not a triangle
  - A2:scalene
  - A3: Isosceles
  - A4:equilateral
  - A5: Right angled

Sample Decision table

	r1	r2	...				rn
C1	0	1					0
c2	-	1					0
C3	-	1					1
C4	-	1					0
a1	1	0					0
a2	0	0					1
a3	0	0					0
a4	0	1					0
a5	0	0					

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Test cases from Decision Tables

Test Case ID	a	b	c	Expected output
TC1	4	1	2	Not a Triangle
TC2	2888	2888	2888	Equilateral
TC3	?	|	)	Impossible
TC4				
…				
TC11				

C1: a, b,c form a triangle

C2: a=b

C3: a= c

C4: b= c

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More Complete Decision Table for the Triangle Problem

Conditions											
C1: a < b+c?	F	T	T	T	T	T	T	T	T	T	T
C2: b < a+c?	-	F	T	T	T	T	T	T	T	T	T
C3: c < a+b?	-	-	F	T	T	T	T	T	T	T	T
C4: a=b?	-	-	-	T	T	T	T	F	F	F	F
C5: a=c?	-	-	-	T	T	F	F	T	T	F	F
C6: b-c?	-	-	-	T	F	T	F	T	F	T	F
Actions											
A1: Not a Triangle	X	X	X								
A2: Scalene											X
A3: Isosceles							X		X	X	
A4: Equilateral				X							
A5: Impossible					X	X		X			

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Test Cases for the Triangle Problem

Case ID	a	b	c	Expected Output
DT1	4	1	2	Not a Triangle
DT2	1	4	2	Not a Triangle
DT3	1	2	4	Not a Triangle
DT4	5	5	5	Equilateral
DT5	?	?	?	Impossible
DT6	?	?	?	Impossible
DT7	2	2	3	Isosceles
DT8	?	?	?	Impossible
DT9	2	3	2	Isosceles
DT10	3	2	2	Isosceles
DT11	3	4	5	Scalene

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Decision Table – Example 2

Printer Troubleshooting

Conditions	Printer does not print	Y	Y	Y	Y	N	N	N	N
	A red light is flashing	Y	Y	N	N	Y	Y	N	N
	Printer is unrecognized	Y	N	Y	N	Y	N	Y	N
Actions	Check the power cable			X					
	Check the printer-computer cable	X		X					
	Ensure printer software is installed	X		X		X		X	
	Check/replace ink	X	X			X	X		
	Check for paper jam		X		X				

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Quiz: Develop BB Test Cases

- Policy for charging customers for certain in-flight services:

If the flight is more than half-full and ticket cost is more than Rs. 3000, free meals are served unless it is a domestic flight. Otherwise, no meals are served. Meals are charged on all domestic flights.

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Fill all combinations in the table.

		POSSIBLE COMBINATIONS							
CONDITONS	*more than half-full*	N	N	N	N	Y	Y	Y	Y
	more than Rs.3000 per seat	N	N	Y	Y	N	N	Y	Y
	domestic flight	N	Y	N	Y	N	Y	N	Y
ACTIONS									

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Analyze column by column to determine which actions are appropriate for each combination

		POSSIBLE COMBINATIONS							
CONDITONS	*more than half-full*	N	N	N	N	Y	Y	Y	Y
	more than Rs. 3000 per seat	N	N	Y	Y	N	N	Y	Y
	domestic flight	N	Y	N	Y	N	Y	N	Y
ACTIONS	*serve meals*					Y	Y	Y	Y
	free							Y	

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Reduce the table by eliminating redundant columns.

		POSSIBLE COMBINATIONS							
CONDITONS	more than half-full	N	N	N	N	Y	Y	Y	Y
	more than Rs. 3000 per seat	N	N	Y	Y	N	N	Y	Y
	domestic flight	N	Y	N	Y	N	Y	N	Y
ACTIONS	serve meals					X	X	X	X
	free							X	

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Final solution

		Combinations			
CONDITONS	more than half-full	N	Y	Y	Y
	more than 3000 per seat	-	N	Y	Y
	domestic flight	-	-	N	Y
ACTIONS	serve meals		X	X	X
	free			X	

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Assumptions regarding rules

–Rules need to be complete:

- **That is, every combination of decision table values including default combinations are present.**

–Rules need to be consistent:

- That is, there is no two different actions for the same combinations of conditions

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Guidelines and Observations

- Decision table testing is appropriate for programs:
  - There is a lot of decision making
  - Output is a logical relationship among input variables
  - Results depend on calculations involving subsets of inputs
  - There are cause and effect relationships between input and output
- Decision tables do not scale up very well

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Quiz: Design test Cases

- Customers on a e-commerce site get following discount:
  - A member gets 10% discount for purchases lower than Rs. 2000, else 15% discount
  - Purchase using SBI card fetches 5% discount
  - If the purchase amount after all discounts exceeds Rs. 2000/- then shipping is free.

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Cause-effect Graphs

- Overview:
  - Explores combinations of possible inputs
  - Specific combination of inputs (causes) results in outputs (effects)
  - Represented as nodes of a cause effect graph
  - The graph also includes constraints and a number of intermediate nodes linking causes and effects

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- If depositing less than Rs. 1 Lakh, rate of interest:
  - 6% for deposit upto 1 year
  - 7% for deposit over 1 year but less than 3 yrs
  - 8% for deposit 3 years and above
- If depositing more than Rs. 1 Lakh, rate of interest:
  - 7% for deposit upto 1 year
  - 8% for deposit over 1 year but less than 3 yrs
  - 9% for deposit 3 years and above

Cause-Effect Graph Example

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Cause-Effect Graph Example

Causes	**Effects**
C1: Deposit<1yr	e1: Rate 6%
C2: 1yr<Deposit<3yrs	e2: Rate 7%
C3: Deposit>3yrs	e3: Rate 8%
C4:Deposit <1 Lakh	e4: Rate 9%
C5: Deposit >=1Lakh	

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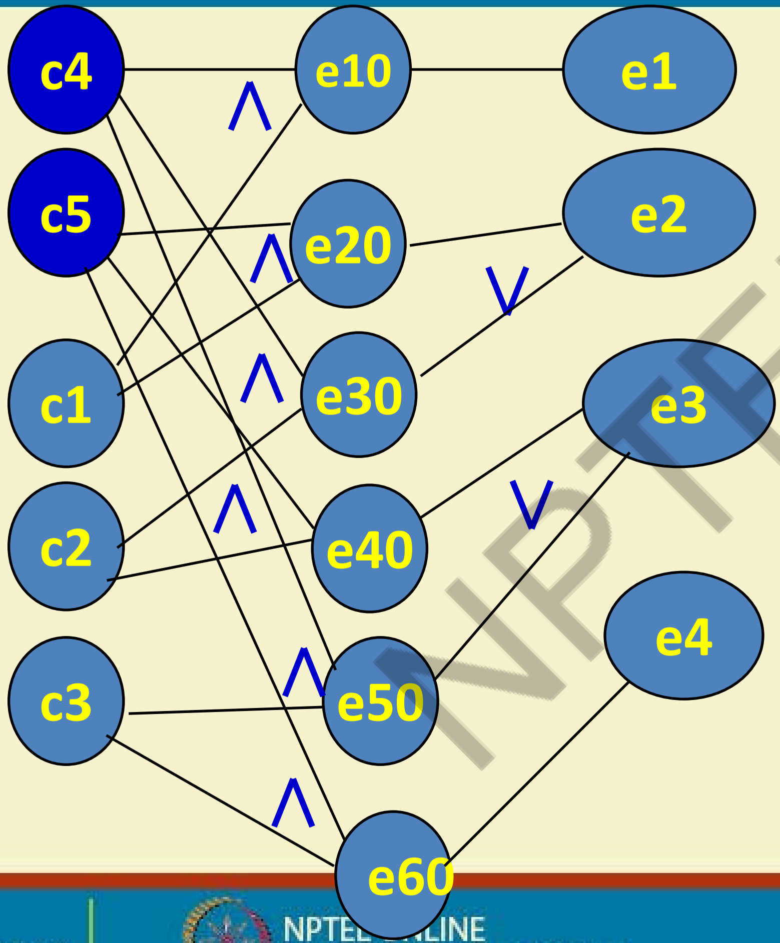

Cause-Effect Graphing

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Develop a Decision Table

C1	C2	C3	C4	C5	e1	e2	e3	e4
1	0	0	1	0	1	0	0	0
1	0	0	0	1	0	1	0	0
0	1	0	1	0	0	1	0	0
0	1	0	0	1	1	0	1	0

- Convert each row to a test case

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Pair-wise Testing

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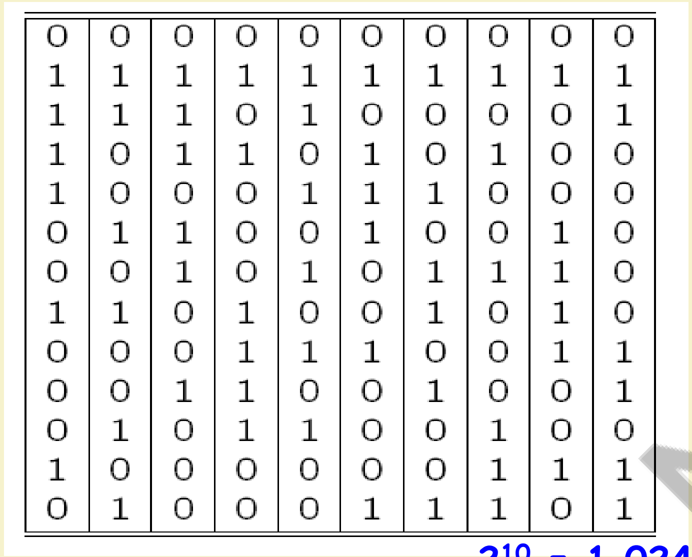
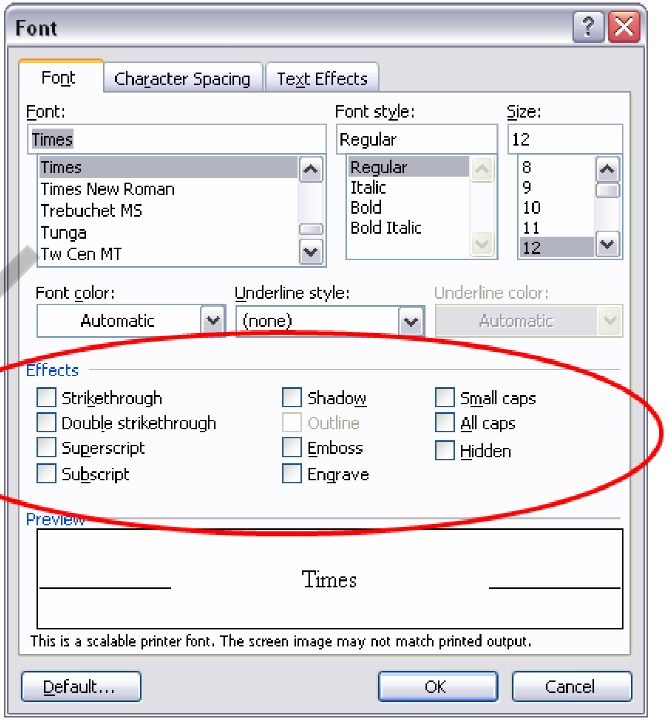
Combinatorial Testing of User Interface



0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1
1	1	1	0	1	0	0	0	0	1
1	0	1	1	0	1	0	1	0	0
1	0	0	0	1	1	1	0	0	0
0	1	1	0	0	1	0	0	1	0
0	0	1	0	1	0	1	1	1	0
1	1	0	1	0	0	1	0	1	0
0	0	0	1	1	1	0	0	1	1
0	0	1	1	0	0	1	0	0	1
0	1	0	1	1	0	0	1	0	0
1	0	0	0	0	0	0	1	1	1
0	1	0	0	0	1	1	1	0	1

0 = effect off
1 = effect on



Font

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Font: Times
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Size: 12

Times, Times New Roman, Trebuchet MS, Tunga, Tw Cen MT
Regular, Italic, Bold, Bold Italic
8, 9, 10, 11, 12

Font color: Automatic
Underline style: (none)
Underline color: Automatic

Effects

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- [ ] Small caps
- [ ] All caps
- [ ] Hidden

Preview

Times

This is a scalable printer font. The screen image may not match printed output.

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2^{10} = 1,024 tests for all combinations

* 10 ^{3} = 1024 * 1000 …. Just too many to tests

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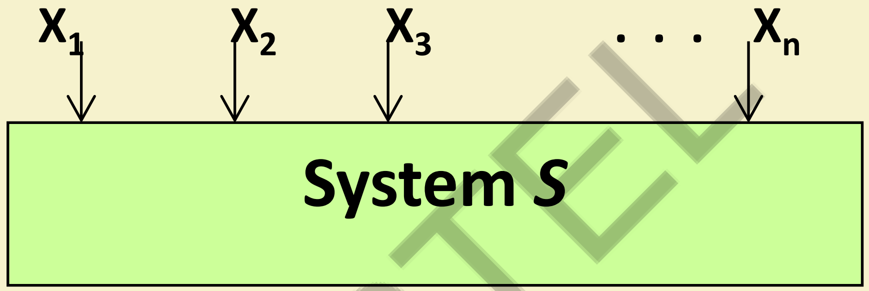
Combinatorial Testing Problem



•Combinatorial testing problems generally follow a simple input-process-output model;

•The “state” of the system is not the focus of combinatorial testing.

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t-way Testing

- Instead of testing all possible combinations:
  - A subset of combinations is generated.
- Key observation:
  - **It is often the case that a fault is caused by interactions among a few factors.**
- t-way testing can dramatically reduce the number of test cases:
  - but remains effective in terms of fault detection.

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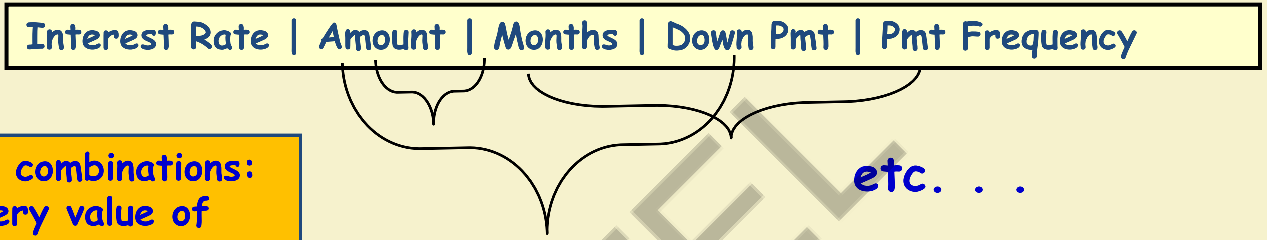
t-way Interaction Testing



All combinations: every value of every parameters

All pairs: every value of each pair of parameters

etc. . . .

t-way interactions: every value of every t-way combination of parameters

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Pairwise Testing

Pressure	Temperature	Velocity	Acceleration	Air Density
A	T1	1	10	1.1
B	T2	2	0	2.1
	T3	3	20	3.1
		4	0	
		5		
		6		

Pressure	Temperature
A	T1
A	T2
A	T3
B	T1
B	T2
B	T3

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Pairwise Reductions

Number of inputs	Number of selected test data values	Number of combinations	Size of pair wise test set
7	2	128	8
13	3	1.6×10^{6}	15
40	3	1.2×10^{19}	21

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Fault-Model

- **A t-way interaction fault:**
  - Triggered by a certain combination of t input values.
  - A simple fault is a 1-way fault
  - Pairwise fault is a t-way fault where t = 2.
- **In practice, a majority of software faults consist of simple and pairwise faults.**

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Single-mode Bugs

- The simplest bugs are single-mode faults:
  - **Occur when one option causes a problem regardless of the other settings**
  - **Example:** A printout is always gets smeared when you choose the duplex option in the print dialog box
    - Regardless of the printer or the other selected options

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Double-mode Faults

- **Double-mode faults**
  - Occurs when two options are combined
  - **Example:** The printout is smeared only when duplex is selected and the printer selected is model 394

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Multi-mode Faults

- **Multi-mode faults**
  - Occur when three or more settings produce the bug
  - This is the type of problems that make complete coverage necessary

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Example of Pairwise Fault

```
• begin
  – int x, y, z;
  – input (x, y, z);
  – if (x == x1 and y == y2)
      • output (f(x, y, z));
  – else if (x == x2 and y == y1)
      • output (g(x, y));
  – Else          // Missing (x == x2 and y == y1) f(x, y, z) – g(x, y);
      • output (f(x, y, z) + g(x, y))
• end
```

- **Expected**: x = x1 and y = y1 => f(x, y, z) – g(x, y);

  x = x2, y = y2 => f(x, y, z) + g(x, y)

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Example: Android smart phone testing

• Apps should work on all combinations of platform options, but there are 3 x 3 x 4 x 3 x 5 x 4 x 4 x 5 x 4 = 172,800 configurations

HARDKEYBOARDHIDDEN_NO
HARDKEYBOARDHIDDEN_UNDEFINED
HARDKEYBOARDHIDDEN_YES

KEYBOARDHIDDEN_NO
KEYBOARDHIDDEN_UNDEFINED
KEYBOARDHIDDEN_YES

KEYBOARD_12KEY
KEYBOARD_NOKEYS
KEYBOARD_QWERTY
KEYBOARD_UNDEFINED

NAVIGATIONHIDDEN_NO
NAVIGATIONHIDDEN_UNDEFINED

NAVIGATIONHIDDEN_YES

NAVIGATION_DPAD
NAVIGATION_NONAV
NAVIGATION_TRACKBALL
NAVIGATION_UNDEFINED
NAVIGATION_WHEEL

ORIENTATION_LANDSCAPE
ORIENTATION_PORTRAIT
ORIENTATION_SQUARE
ORIENTATION_UNDEFINED

SCREENLAYOUT_LONG_MASK
SCREENLAYOUT_LONG_NO
SCREENLAYOUT_LONG_UNDEFINED

SCREENLAYOUT_LONG_YES

SCREENLAYOUT_SIZE_LARGE
SCREENLAYOUT_SIZE_MASK
SCREENLAYOUT_SIZE_NORMAL

SCREENLAYOUT_SIZE_SMALL
SCREENLAYOUT_SIZE_UNDEFINED

TOUCHSCREEN_FINGER
TOUCHSCREEN_NOTOUCH
TOUCHSCREEN_STYLUS
TOUCHSCREEN_UNDEFINED

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White-Box Testing

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What is White-box Testing?

- White-box test cases designed based on:
  - Code structure of program.
  - White-box testing is also called structural testing.

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White-Box Testing Strategies

- **Coverage-based:**
  - Design test cases to cover certain program elements.
- **Fault-based:**
  - Design test cases to expose some category of faults

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- Several white-box testing strategies have become very popular :
  - Statement coverage
  - Branch coverage
  - Path coverage
  - Condition coverage
  - MC/DC coverage
  - Mutation testing
  - Data flow-based testing

White-Box Testing

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Why Both BB and WB Testing?

Black-box	White-box
• Impossible to write a test case for every possible set of inputs and outputs • Some code parts may not be reachable • **Does not tell if extra functionality has been implemented.**	• Does not address the question of whether a program matches the specification • Does not tell if all functionalities have been implemented • **Does not uncover any missing program logic**

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Coverage-Based Testing Versus Fault-Based Testing

- Idea behind coverage-based testing:
  - Design test cases so that certain program elements are executed (or covered).
  - Example: statement coverage, path coverage, etc.
- Idea behind fault-based testing:
  - Design test cases that focus on discovering certain types of faults.
  - Example: Mutation testing.

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- **Statement:** each statement executed at least once
- **Branch:** each branch traversed (and every entry point taken) at least once
- **Condition:** each condition True at least once and False at least once
- **Multiple Condition:** All combination of Condition covered
- **Path**:
- **Dependency:**

Types of program element Coverage

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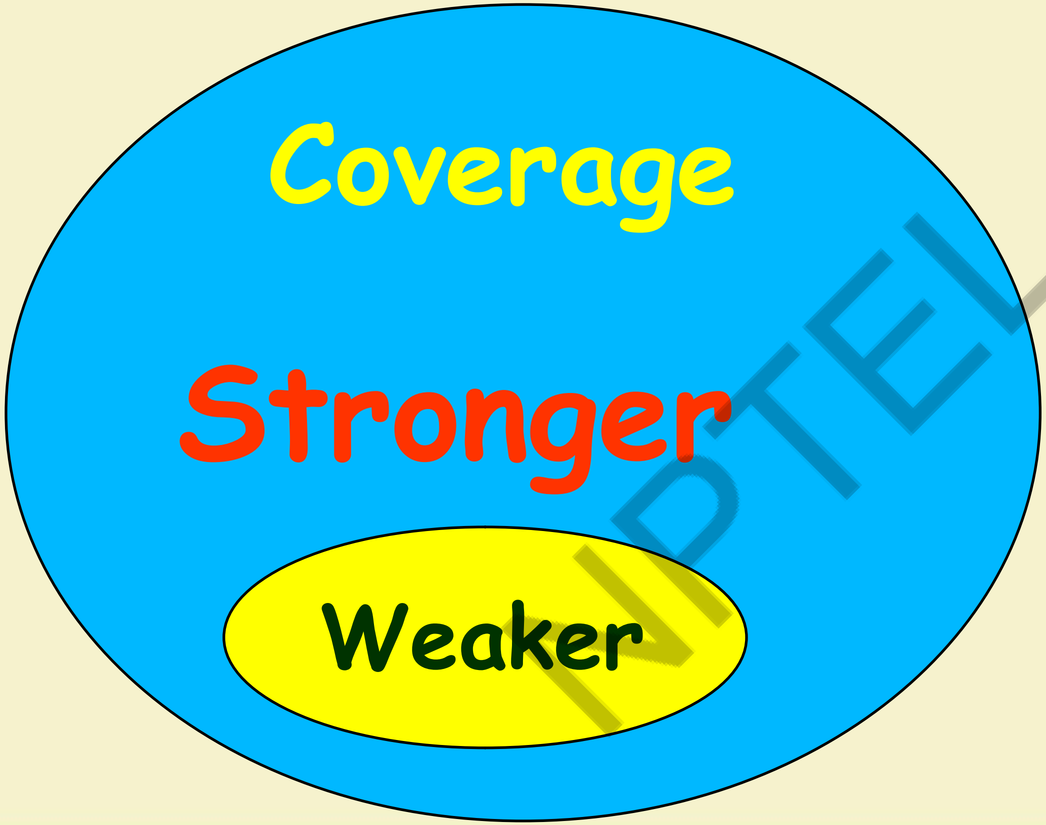
Stronger and Weaker Testing



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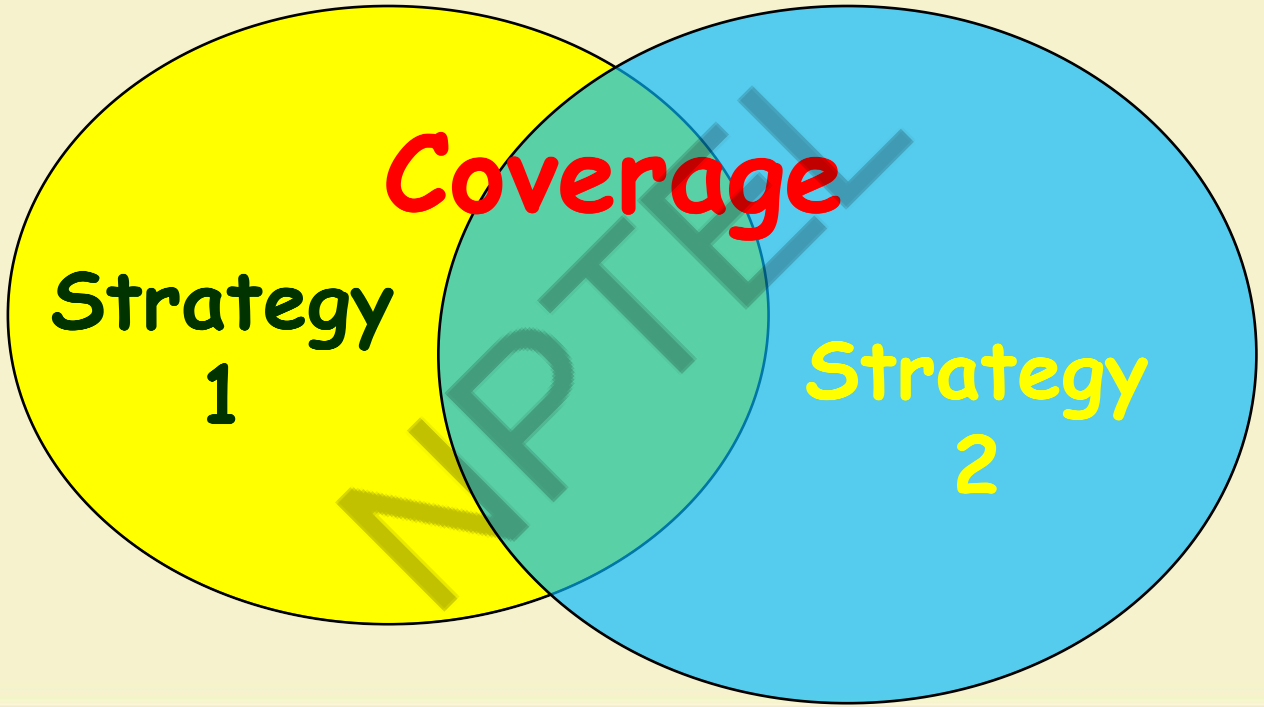
Complementary Testing



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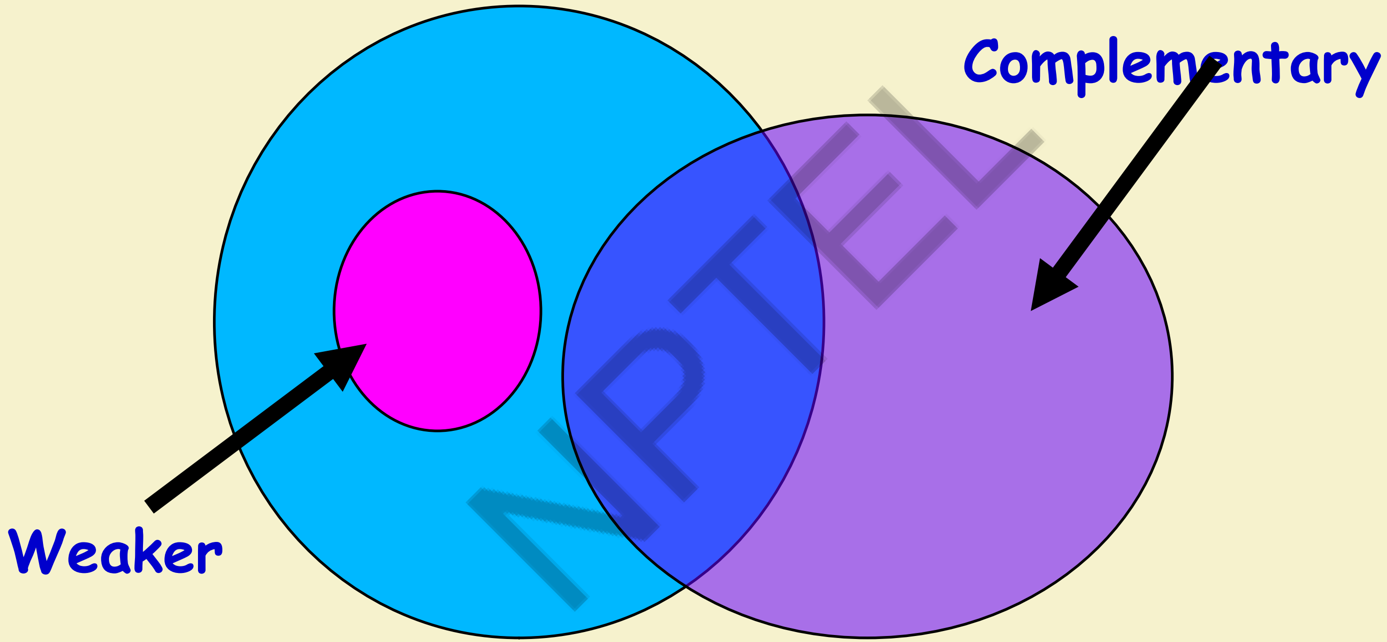
Stronger, Weaker, and Complementary Testing



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Statement Coverage

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

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Statement Coverage

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

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Statement Coverage Criterion

- However, observing that a statement behaves properly for one input value:
  - **No guarantee that it will behave correctly for all input values!**

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Statement Coverage

- Coverage measurement:

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

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

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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; }

Euclid's GCD Algorithm

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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;        }
```

Euclid's GCD Algorithm

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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.

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Branch Coverage

- **Also called decision coverage.**
- Test cases are designed such that:
  - Each branch condition
    - Assumes true as well as false value.

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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;       }
```

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Example

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

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Branch Testing

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

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

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Quiz 1: Branch and Statement Coverage: Which is Stronger?

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

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Stronger Testing

- Stronger testing:
  - –Superset of weaker testing
  - –A stronger testing covers all the elements covered by a weaker testing.
  - –Covers some additional elements not covered by weaker testing

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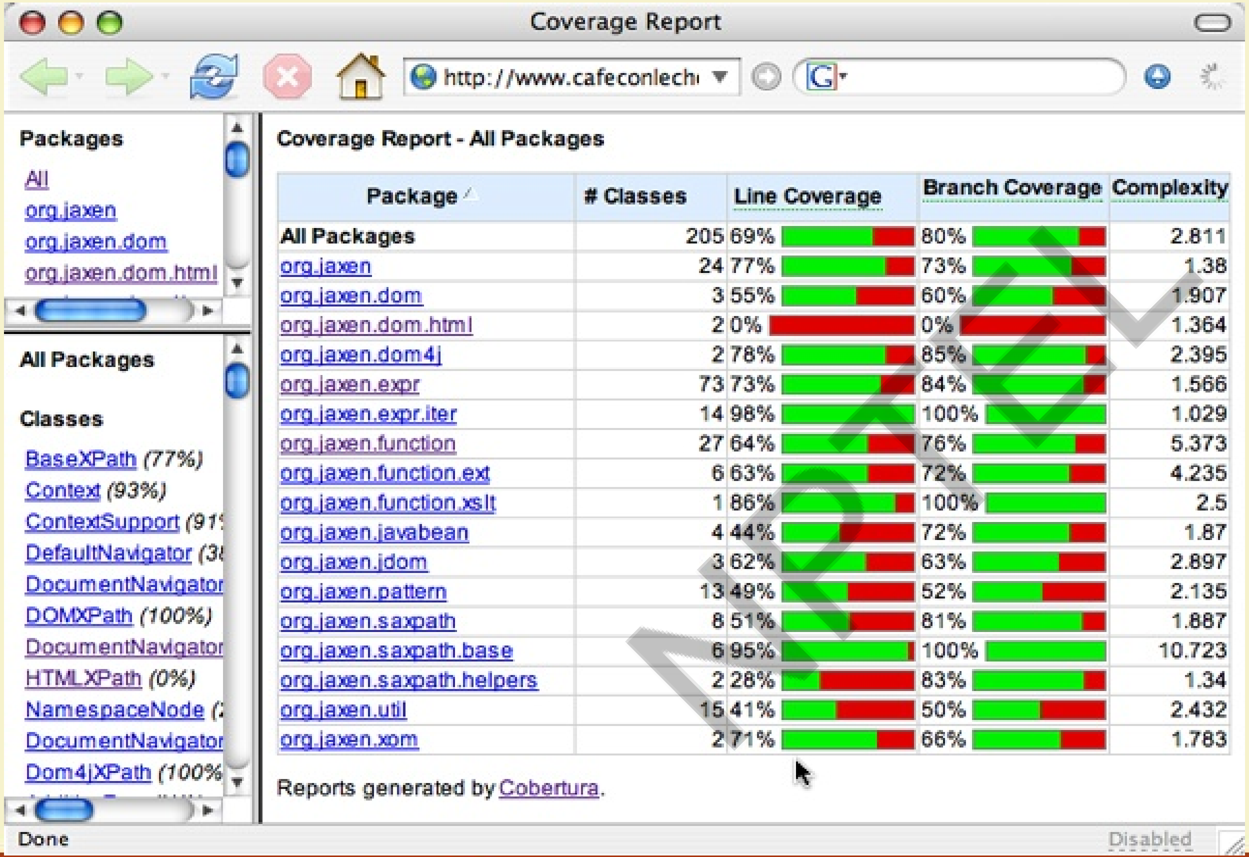
Sample Coverage Report



Coverage Report - All Packages

Package	# Classes	Line Coverage	Branch Coverage	Complexity
All Packages	205	69%	80%	2.811
org.jaxen	24	77%	73%	1.38
org.jaxen.dom	3	55%	60%	1.907
org.jaxen.dom.html	2	0%	0%	1.364
org.jaxen.dom4j	2	78%	85%	2.395
org.jaxen.expr	73	73%	84%	1.566
org.jaxen.expr.iter	14	98%	100%	1.029
org.jaxen.function	27	64%	76%	5.373
org.jaxen.function.ext	6	63%	72%	4.235
org.jaxen.function.xslt	1	86%	100%	2.5
org.jaxen.javabean	4	44%	72%	1.87
org.jaxen.jdom	3	62%	63%	2.897
org.jaxen.pattern	13	49%	52%	2.135
org.jaxen.saxpath	8	51%	81%	1.887
org.jaxen.saxpath.base	6	95%	100%	10.723
org.jaxen.saxpath.helpers	2	28%	83%	1.34
org.jaxen.util	15	41%	50%	2.432
org.jaxen.xom	2	71%	66%	1.783

Reports generated by Cobertura.

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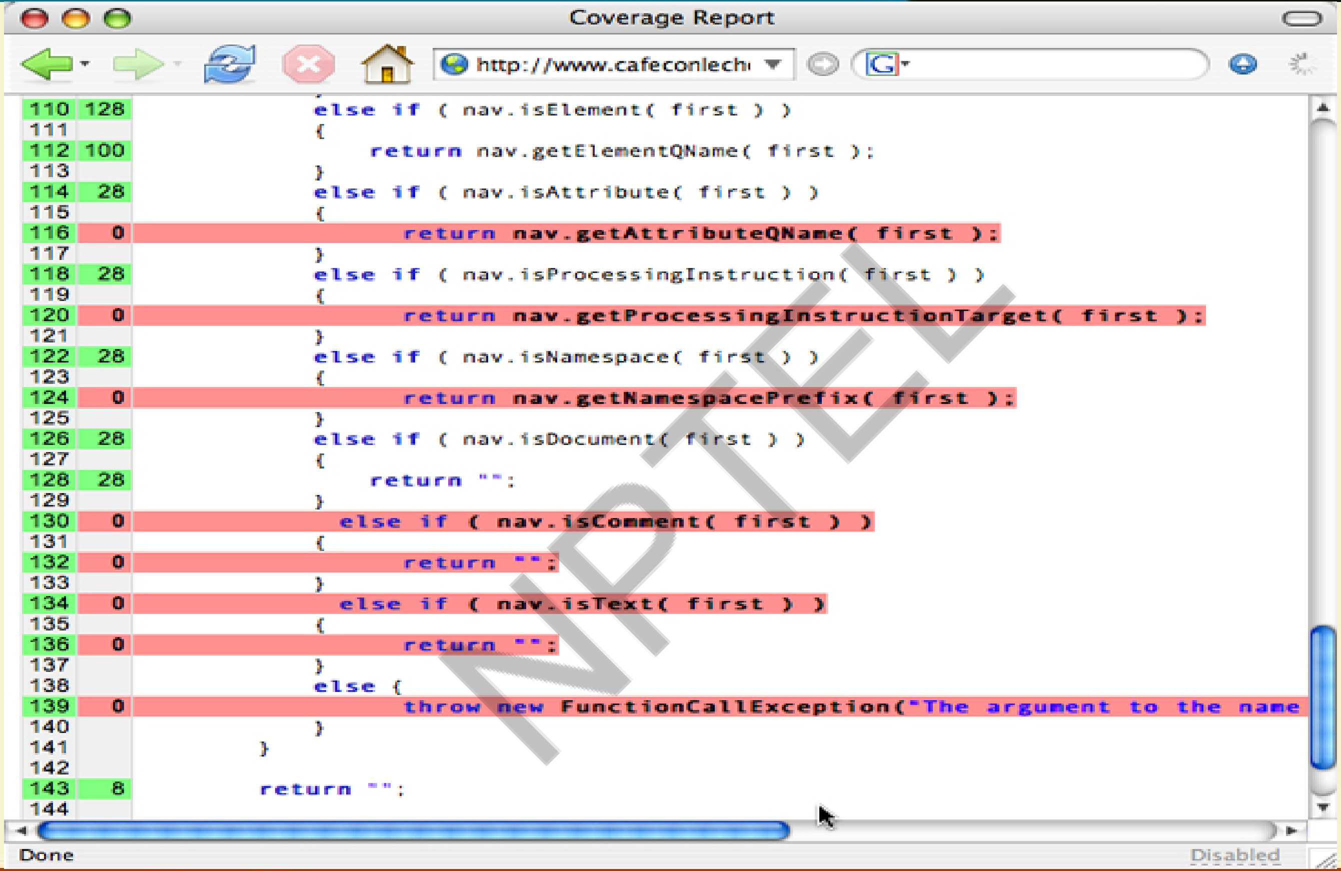

Coverage Report

http://www.cafeconlech

```
110  128            else if ( nav.isElement( first ) )
111                  {
112  100                return nav.getElementQName( first );
113                  }
114   28            else if ( nav.isAttribute( first ) )
115                  {
116    0                   return nav.getAttributeQName( first );
117                  }
118   28            else if ( nav.isProcessingInstruction( first ) )
119                  {
120    0                   return nav.getProcessingInstructionTarget( first );
121                  }
122   28            else if ( nav.isNamespace( first ) )
123                  {
124    0                   return nav.getNamespacePrefix( first );
125                  }
126   28            else if ( nav.isDocument( first ) )
127                  {
128   28                return "";
129                  }
130    0              else if ( nav.isComment( first ) )
131                  {
132    0                   return "";
133                  }
134    0              else if ( nav.isText( first ) )
135                  {
136    0                   return "";
137                  }
138                  else {
139    0                   throw new FunctionCallException("The argument to the name
140                  }
141              }
142
143    8         return "";
144
```

Done

Disabled

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Statements vs Branch Testing

- Traversing all edges of a graph causes all nodes to be visited
  - So a test suite that satisfies branch adequacy criterion also satisfies 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).

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- Statement coverage
- Branch coverage (aka decision coverage)
- Basic condition coverage
- Condition/Decision coverage
- Multiple condition coverage
- MC/DC coverage
- Path coverage
- Data flow-based testing
- Mutation testing

White-box Testing

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All Branches can still miss testing specific conditions

- Assume failure occurs when c==DIGIT

```
if((c == ALPHABET) || (c ==DIGIT))
```

- Branch adequacy criterion can be satisfied by c==alphabet and c==splchar
  - **The faulty sub-expression might not be tested!**
  - Even though we test both outcomes of the branch

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Basic Condition Coverage

- Also called condition coverage or simple condition coverage .
- Test case design: **((c = = ALPHABET) || (c= = DIGIT))**
  - –Each component of a composite conditional expression
    - Made to assume both true and false values.

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Basic Condition Testing

- **Simple or (basic) Condition Testing:**
  - Test cases make each atomic condition assume T and F values
  - Example: **if (a>10 && b<50)**
- **Following test inputs would achieve basic condition coverage**
  - **a=15, b=30**
  - **a=5, b=60**
- Does basic condition coverage subsume decision coverage?

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Example: BCC

- Consider the conditional expression
  - **((c1.and.c2).or.c3):**
- Each of c1, c2, and c3 is exercised with all possible values,
  - That is, given true and false values.

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Basic condition testing

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

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

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Is BCC Stronger than Decision Coverage?

- Consider the conditional statement:
  - **If(((a>5).and.(b<3)).or.(c==0)) a=10;**
- Two test cases can achieve basic condition coverage: (a=10, b=2, c=2) and (a=1, b=10, c=0)
- **BCC does not imply Decision coverage and vice versa**

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Condition/Decision Coverage Testing

- **Condition/decision coverage:**
  - Each atomic condition made to assume both T and F values
  - Decisions are also made to get T an F values
- **Multiple condition coverage (MCC):**
  - Atomic conditions made to assume all possible combinations of truth values

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MCC

- Test cases make Conditions to assume all possible combinations of truth values.
- 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

Exponential in the number of basic conditions

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Multiple Condition Coverage (MCC)

- Consider a Boolean expression having n components:
  - **For condition coverage we require 2^n test cases.**
- MCC testing technique:
  - Practical only if n (the number of component conditions) is small.

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MCC for Compound conditions: Exponential complexity

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

$2^5=32$

Test Case	a	b	c	d	e
(1)	T	—	T	—	T
(2)	F	T	T	—	T
(3)	T	—	F	T	T
(4)	F	T	F	T	T
(5)	F	F	—	T	T
(6)	T	—	T	—	F
(7)	F	T	T	—	F
(8)	T	—	F	T	F
(9)	F	T	F	T	F
(10)	F	F	—	T	F
(11)	T	—	F	F	—
(12)	F	T	F	F	—
(13)	F	F	—	F	—

- Short-circuit evaluation often reduces number of test cases to a more manageable number, but not always…

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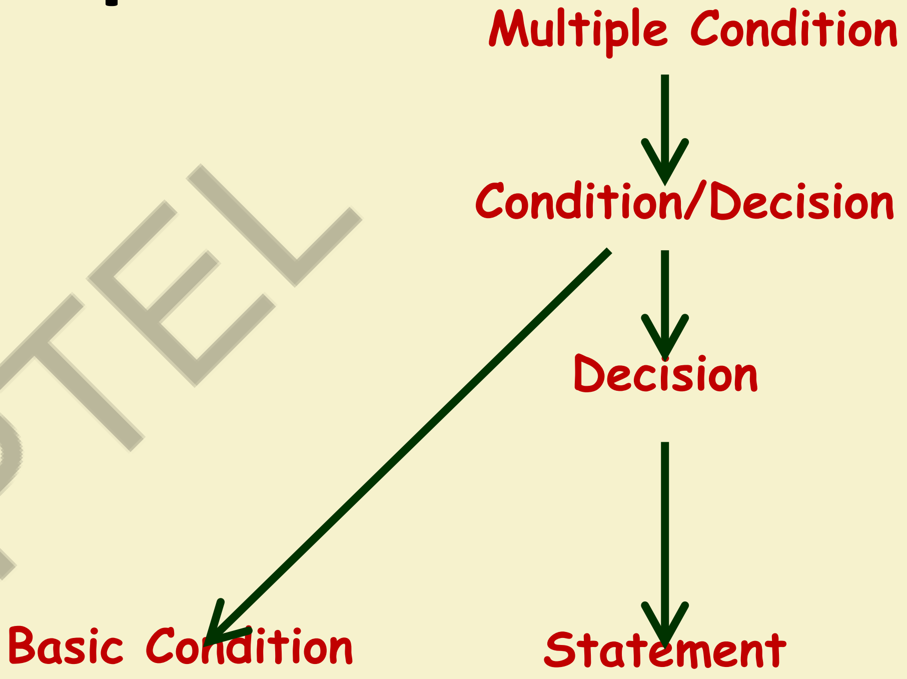
Subsumption

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



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Shortcomings of Condition Testing

- **Redundancy of test cases:** Condition evaluation could be compiler-dependent:
  - **Reason: Short circuit evaluation of conditions**
- **Coverage may be Unachievable:** Possible dependencies among variables:
  - Example: **((chr==`A´)||(chr==`E´))** can not both be true at the same time

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Short-circuit Evaluation

- **if(a>30 && b<50)…**
  - If a>30 is FALSE compiler need not evaluate (b<50)
- Similarly, **if(a>30 || b<50)…**
  - If a>30 is TRUE compiler need not evaluate (b<50)

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