Dynamic Test

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- ☐ Structural testing
  - Control flow testing
  - Data flow testing
- ☐ Functional test
- ☐ Diversified test

Properties and Goals

- ☐ Properties of the dynamic test
  - Executable program is provided with concrete input values and is executed
  - Program may be tested in the real environment
  - Never complete
  - Correctness of the tested program cannot be proven
- ☐ Characteristics of the application of dynamic test methods in practice
  - Widely-used
  - Often very unsystematically applied
  - Tests often not reproduceable
  - Diffuse activity (Management problems)

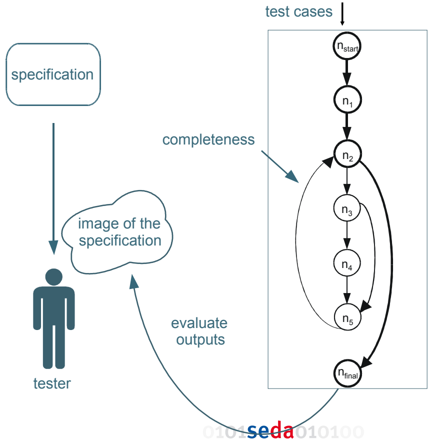
Properties and Goals

- ☐ The goal of dynamic testing is the generation of test cases that are
  - Representative
  - Fault sensitive
  - Distinct from each other (minimal redundancy)
  - Economic

Structural Testing

- ☐ Evaluation of the adequacy and completeness of the test cases on the basis of the software structure. Determination of the correctness of the outputs based on the specification
  - Benefit: Code structure is considered (instructions, branches, data accesses, etc.)
  - Disadvantage: Forgotten (not implemented), but specified functions cannot be detected
- ☐ Two approaches
  - Control flow testing
  - Data flow testing

Structural Testing



test cases

specification

completeness

image of the specification

evaluate outputs

tester

Control Flow Testing

- ☐ Statement coverage test
- ☐ Branch coverage test
- ☐ Condition coverage test
  - simple
  - minimal multiple
  - multiple
- ☐ LCSAJ-based test
- ☐ Boundary interior-path test
- ☐ Structured path test
- ☐ Path test

Control flow testing is based on the control structure respectively on the control flow. The basis is the control flow graph

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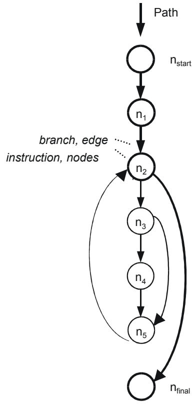
Control Flow Testing

Example

```
void CountChars(int &VowelNumber, int &TotalNumber)
// Precondition: VowelNumber <= TotalNumber
{  char ch;
   cin>>ch;
   while ((ch >= 'A')&&(ch <= 'Z')&&
                 (TotalNumber < INT_MAX))
   { TotalNumber = TotalNumber+1;
        if((ch == 'A')||(ch == 'E')||(ch == 'I')||
                (ch == 'O')||(ch == 'U'))
        {            VowelNumber = VowelNumber + 1;
        }
        cin>>ch;
   } //end while
}
```

Control Flow Testing
Control Flow Diagram for the Operation CountChars



```
void CountChars (int &VowelNumber
      int & TotalNumber)
{
  char ch;
  cin >> ch ;

  while ((ch >=‘A‘) && (ch <= ‘Z‘)
          && (TotalNumber < INT_MAX))
  {
    TotalNumber = TotalNumber + 1;
    if ((ch == ‘A‘) || (ch == ‘E‘) ||
       (ch == ‘I‘) || (ch == ‘O‘) ||
       (ch == ‘U‘))
    {
         VowelNumber= VowelNumber + 1;

    }

  cin >> ch

  }
}
```

Control Flow Testing
Statement Coverage

☐ The statement coverage is the simplest control flow test technique. It is also referred to as C_0-test

☐ The goal of the statement coverage is to execute each statement at least once, i.e., the execution of all nodes of the control flow graph

☐ The statement coverage rate is the relation of the executed instructions to the total number of the instructions

$$C_{instruction} = \frac{number\ of\ executed\ instructions}{number\ of\ instructions}$$

☐ Then all instructions of the module to be tested are executed at least once a complete statement coverage test is achieved

➔ No untested code !?

Control Flow Testing
Statement Coverage

☐ Statement coverage test demands the execution of all nodes of the control flow graph, i.e., the corresponding program paths must contain all nodes of the control flow graph

☐ Test case

call of *CountChars* with:	totalnumber = 0
input chars:	’A’, ’1’
path:	(n_{start}, n1, n2, n3, n4, n5, n2, n_{final})

☐ Observation

- The test path contains all nodes
- **but it does not contain all edges** of the control flow graph. The edge (n3,n5) is not contained

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Control Flow Testing
Statement Coverage

☐ Statement coverage is considered to be a weak criterion. It has a limited practical importance

☐ The standard RTCA DO-178B for software applications in aviation demands to apply statement coverage to level-C-software. In case of a software failure such a software can cause a major failure condition

Control Flow Testing
Branch Coverage

- ☐ Branch coverage aims at executing all branches of the program to be tested. This requires the execution of all edges of the control flow graph. It is also referred to as C_1-test
- ☐ Branch coverage is a stricter test technique than statement coverage. Statement coverage is fully contained in branch coverage. Branch coverage **subsumes** statement coverage
- ☐ Branch coverage is generally considered as a minimal criterion in software unit testing
- ☐ The standard RTCA DO-178B requires branch coverage testing for level-B-software

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Control Flow Testing
Branch Coverage

- ☐ Example

  Branch coverage demands the execution of all edges of the control flow graph. This is achieved if every decision of the unit under test had at least once the logical value *false* and *true*
- ☐ Test case

call of CountChars with:	totalnumber = 0
input chars:	„A“, „B“, „1“
flow path:	$(n_{start}, n_1, n_2, n_3, n_4, n_5, n_2, n_3, n_5, n_2, n_{final})$

- ☐ The test path contains all edges. In particular it contains the edge (n_3,n_5) which is not necessarily executed by statement coverage. Branch coverage subsumes statement coverage

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Control Flow Testing
Branch Coverage

- ☐ **Question:** Is branch coverage adequate for testing of complicated, composite decisions?
- ☐ Examples
  - Simple decision: if (x > 5)...;
    - The decision (x > 5) can be regarded as sufficiently tested if both logical values occurred within the test. The decision subdivides the possible test data into two classes and demands that at least one test date is selected from every class
  - Complex decision: if (((u == 0) || (x > 5)) && ((y < 6) || (z == 0))) ...
    - A test of the decision (((u == 0) || (x > 5)) && ((y < 6) || (z == 0))) against both logical values cannot be regarded as sufficient, as the structure of the decision is not considered appropriately
    - A complete branch coverage test can be achieved e.g. with the following test cases

      Test case 1: u = 1, x = 4, y = 5, z = 0
      Test case 2: u = 0, x = 6, y = 5, z = 0

Control Flow Testing
Condition Coverage

- ☐ Assumption: Composite decisions are tested from left to right. The evaluation of decisions stops when its logical value is known. This is referred to as incomplete evaluation of decisions
- ☐ Test case 1 leads to the following situation
  - Value 1 of the variable u for the first condition of the OR-connection gives the logical value false. Therefore the second condition of the OR-connection defines the logical value of the OR-connection. The choice of the value 4 for the variable x inserted into the second condition (x > 5) also gives the logical value false. Thus the connection of the first two decisions also has the logical value false. Due to the subsequent AND-connection it is already known at this time that the overall decision has the logical value false. This result is independent from the logical values of the 3rd and 4th condition. This test case thus does not test these parts of the decision
  - In many cases the logical values of some conditions are not tested. Independently of the fact if they are tested the logical value false for the first condition in an AND-connection masks the logical values of all further conditions. Such a test case thus is "blind" with regard to faults in the remaining conditions

Control Flow Testing
Condition Coverage

- ☐ Test case 2 causes the following situation
  - The choice of the value 0 for the variable u has the effect that the first condition (u == 0) has the logical value true. Due to the OR-connection of the first two conditions it is ensured that the result of the first OR-connection is true. The second condition has not to be tested. The testing can be directly continued with the first condition of the second OR-connection. The value 5 of the variable y causes the logical value true for the condition (Y < 6). Due to the OR-operator it is ensured at that time that the overall result will be true, independently of the logical value of the fourth condition. Thus this test case is "blind" with regard to the faults in the 2nd and 4th condition
- ☐ The test cases 1 and 2 cause a complete branch coverage. None of the two test cases tests the fourth partial decision. Then decisions are evaluated from left to right the conditions at the right hand site may remain untested

➔ branch coverage is usually inadequate for testing compound decisions

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Control Flow Testing
Condition Coverage

- ☐ The decision (((u ==0) || (x > 5)) && ((y < 6) || (z ==0))) is abbreviated to ((A || B) && ((C || D). We assume that between the values of the variables u, x, y, and z no dependences exist. Then the partial decisions A, B, C, and D can be *true (T)* or *false (F)* independently of each other. Concerning a complete evaluation of decisions 16 combinations of logical values are possible

	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
1	F	F	F	F	F	F	F
2	F	F	F	T	F	T	F
3	F	F	T	F	F	T	F
4	F	F	T	T	F	T	F
5	F	T	F	F	T	F	F
6	F	T	F	T	T	T	T
7	F	T	T	F	T	T	T
8	F	T	T	T	T	T	T
9	T	F	F	F	T	F	F
10	T	F	F	T	T	T	T
11	T	F	T	F	T	T	T
12	T	F	T	T	T	T	T
13	T	T	F	F	T	F	F
14	T	T	F	T	T	T	T
15	T	T	T	F	T	T	T
16	T	T	T	T	T	T	T

Control Flow Testing
Simple Condition Coverage

- ☐ The simple condition coverage demands the test of all simple conditions concerning *true* and *false*
- ☐ Benefits: simple, low test costs
- ☐ Disadvantages
  - Limited performance
  - In general (concerning the complete evaluation of decisions) it cannot be guaranteed that the simple condition coverage subsumes the branch coverage

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Control Flow Testing
Simple Condition Coverage

- ☐ A simple condition coverage can be achieved, e.g., with the two test cases 6 and 11. The four simple conditions A, B, C, D are tested each against *true* and *false*
- ☐ The conditions (A || B) and (C || D) and the decision ((A || B) && (C || D)) are *true* in both cases
- ☐ These test cases do **not** achieve a complete branch coverage

	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
1	F	F	F	F			
2	F	F	F	T			
3	F	F	T	F			
4	F	F	T	T			
5	F	T	F	F			
6	F	T	F	T	T	T	T
7	F	T	T	F			
8	F	T	T	T			
9	T	F	F	F			
10	T	F	F	T			
11	T	F	T	F	T	T	T
12	T	F	T	T			
13	T	T	F	F			
14	T	T	F	T			
15	T	T	T	F			
16	T	T	T	T			

Control Flow Testing
Simple Condition Coverage

- ☐ If the test cases 1 and 16 were chosen a complete branch coverage would have been achieved
- ☐ As the example shows there are test cases which fulfill the simple condition coverage without ensuring a branch coverage
- ☐ The simple condition coverage does **not** ensure the branch coverage

	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
1	F	F	F	F	F	F	F
2	F	F	F	T			
3	F	F	T	F			
4	F	F	T	T			
5	F	T	F	F			
6	F	T	F	T			
7	F	T	T	F			
8	F	T	T	T			
9	T	F	F	F			
10	T	F	F	T			
11	T	F	T	F			
12	T	F	T	T			
13	T	T	F	F			
14	T	T	F	T			
15	T	T	T	F			
16	T	T	T	T	T	T	T

Control Flow Testing
Simple Condition Coverage

- ☐ If decisions are evaluated incomplete from left to right only 7 combination of truth-values exist (instead of 16)
- ☐ The test cases 6 and 11 which produce a simple condition coverage if decisions are evaluated completely are mapped to test cases III and VII
- ☐ In contrast to the incomplete evaluation of decisions the two test cases cause no complete simple condition coverage

	Test cases	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
I	1, 2, 3, 4	F	F	-	-	F	-	F
II	5	F	T	F	F	T	F	F
III	6	F	T	F	T	T	T	T
IV	7, 8	F	T	T	-	T	T	T
V	9, 13	T	-	F	F	T	F	F
VI	10, 14	T	-	F	T	T	T	T
VII	11, 12, 15, 16	T	-	T	-	T	T	T

Control Flow Testing
Simple Condition Coverage

- ☐ Partial decision B can be tested against *false* only by selecting test case I
- ☐ To test D against *false* either test case II or V has to be executed
- ☐ A simple condition coverage is possible, e.g., with the test cases I, II, III and VII
- ☐ In addition these test cases ensure a complete branch coverage
- ☐ This rules is valid in every situation: **If decisions are evaluated incompletely the simple condition coverage subsumes branch coverage**

	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
I	F	F	-	-	F	-	F
II	F	T	F	F	T	F	F
III	F	T	F	T	T	T	T
IV	F	T	T	-	T	T	T
V	T	-	F	F	T	F	F
VI	T	-	F	T	T	T	T
VII	T	-	T	-	T	T	T

Control Flow Testing
Condition/Decision Coverage

- ☐ The condition/decision coverage guarantees a complete branch coverage in addition to a simple condition coverage
- ☐ It demands that the branch coverage is taken into account explicitly in addition to the condition coverage
- ☐ As this is already ensured by the simple condition coverage test concerning an incomplete evaluation of decisions this method is important only for the case of the complete evaluation of decisions
- ☐ Benefits: simple, low test costs, branch coverage is ensured
- ☐ Disadvantages
  - Limited performance
  - Structure of decisions is not really considered

Control Flow Testing
Condition/Decision Coverage

- ☐ The execution of the test cases 5 and 12 results in a complete condition/decision coverage, as the partial decisions A, B, C, and D **and** the overall decision are each evaluated to *true* and *false*
- ☐ This is possible without testing the composite conditions (A || B) and (C || D) against both logical values
- ☐ The condition/decision coverage tests simple conditions and decisions
- ☐ **It widely ignores the decomposition of compound decisions into conditions on several levels**

	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
1	F	F	F	F			
2	F	F	F	T			
3	F	F	T	F			
4	F	F	T	T			
5	F	T	F	F	T	F	F
6	F	T	F	T			
7	F	T	T	F			
8	F	T	T	T			
9	T	F	F	F			
10	T	F	F	T			
11	T	F	T	F			
12	T	F	T	T	T	T	T
13	T	T	F	F			
14	T	T	F	T			
15	T	T	T	F			
16	T	T	T	T			

Control Flow Testing
Minimal Multiple Condition Coverage

- ☐ The minimal multiple condition coverage test demands that besides the simple conditions and the decision also all composite conditions are tested against *true* and *false*
- ☐ As decisions can be hierarchically structured it is useful to consider this structure during testing
- ☐ This condition coverage technique takes into account the structure of decisions in a better way than the methods presented above, as all nesting levels of a compound decision are equally considered

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Control Flow Testing
Minimal Multiple Condition Coverage

- ☐ Concerning a complete evaluation of decisions the execution of the test cases 1 and 16 results in a complete minimal multiple condition coverage (all conditions A, B, C, D, (A || B) and (C || D) and the decision ((A || B) && (C || D)) are tested against both logical values)
- ☐ Upon closer examination it can be recognized that these two test cases do not test the logic structure of the decision in a really useful way: If the decision incorrectly was ((A && B) || (C && D)), none of the two test cases would have detected this, although all operators would be faulty. For all conditions and the overall decision identical logical values would have appeared. The test cases are “blind“ towards this fault

	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
1	F	F	F	F	F	F	F
2	F	F	F	T			
3	F	F	T	F			
4	F	F	T	T			
5	F	T	F	F			
6	F	T	F	T			
7	F	T	T	F			
8	F	T	T	T			
9	T	F	F	F			
10	T	F	F	T			
11	T	F	T	F			
12	T	F	T	T			
13	T	T	F	F			
14	T	T	F	T			
15	T	T	T	F			
16	T	T	T	T	T	T	T

Control Flow Testing
Minimal Multiple Condition Coverage

- ☐ Concerning an incomplete evaluation of decisions, e.g., the four test cases I, II, VI, and VII are required
  - higher test costs
  - better results
- ☐ If the decision incorrectly was ((A && B) || (C && D)), e.g., test case I would have proceeded differently. The conditions A, C, (A && B) and (C && D) would have been evaluated to *false*. The conditions B and D would not have been evaluated. The overall decision is *false*. The same result is obtained, but in a different way. The evaluation of the decision is broken off at other points which is a chance for the detection of faults

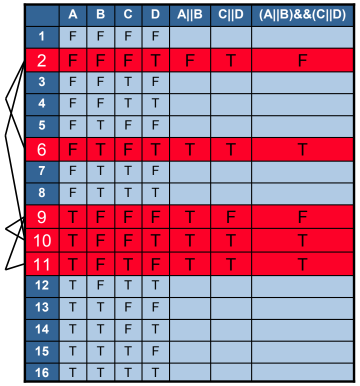
	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
I	F	F	-	-	F	-	F
II	F	T	F	F	T	F	F
III	F	T	F	T	T	T	T
IV	F	T	T	-	T	T	T
V	T	-	F	F	T	F	F
VI	T	-	F	T	T	T	T
VII	T	-	T	-	T	T	T

Control Flow Testing
Modified condition/decision coverage

- ☐ The modified condition/decision coverage requires test cases which demonstrate that every condition can influence the logical value of the overall decision independently of the other conditions
- ☐ The application of this method is required by the standard RTCA DO-178 B for flight critical software (level A)
- ☐ Basically the method aims at a test as extensive as possible with justifiable test costs
  - The relation between the number of conditions and the required test cases is linear
  - For the test of a decision with *n* conditions at least *n+1* test cases are required. The maximum number of test cases is *2n*

Control Flow Testing
Modified Condition/Decision Coverage

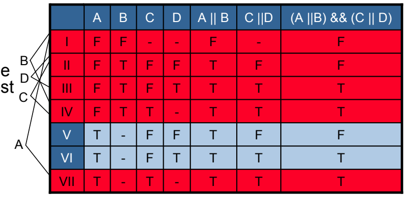
- ☐ Test of the condition B with the test cases 2 and 6
  - Show **identical** logical values for the conditions A, C, and D
  - **Differ** in the logical values of the condition B. In test case 2 condition B has the logical value *false*. In test case 6 condition B is *true*
  - **Differ** in the overall result (test case 2 gives the overall result *false*, while in test case 6 the decision has the value *true*)
- ☐ Thus it is proven that the simple condition B can **independently** influence the logical value of the overall decision
- ☐ A corresponding situation is given for the test cases 2 and 10 concerning A, 9 and 10 concerning D, and 9 and 11 concerning C



	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
1	F	F	F	F			
2	F	F	F	T	F	T	F
3	F	F	T	F			
4	F	F	T	T			
5	F	T	F	F			
6	F	T	F	T	T	T	T
7	F	T	T	F			
8	F	T	T	T			
9	T	F	F	F	T	F	F
10	T	F	F	T	T	T	T
11	T	F	T	F	T	T	T
12	T	F	T	T			
13	T	T	F	F			
14	T	T	F	T			
15	T	T	T	F			
16	T	T	T	T			

Control Flow Testing
Modified Condition/Decision Coverage

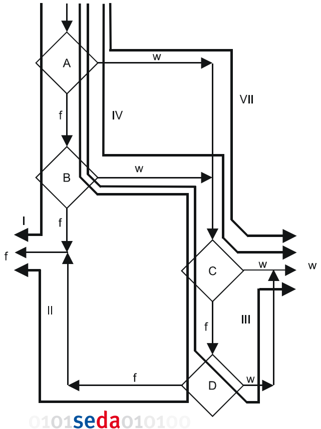
- ☐ Concerning an incomplete evaluation of decisions it is necessary to modify the requirement, to retain the logical values of the respectively not tested conditions, while the logical values of the condition under test and the overall decision change
- ☐ Now, for every simple condition the existence of a test case pair is required which
  - Covers both logical values concerning this condition
  - Covers both logical values concerning the overall decision
  - Has identical logical values for all other simple conditions or was not evaluated at this point
- ☐ Example: Test cases I and VII are testing the condition A. They give different logical values for the condition A and the overall decision and concerning the remaining conditions only have logical values if these were not evaluated in the respectively other test case



	A	B	C	D	A || B	C ||D	(A ||B) && (C || D)
I	F	F	-	-	F	-	F
II	F	T	F	F	T	F	F
III	F	T	F	T	T	T	T
IV	F	T	T	-	T	T	T
V	T	-	F	F	T	F	F
VI	T	-	F	T	T	T	T
VII	T	-	T	-	T	T	T

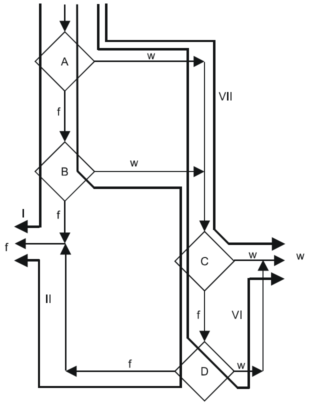
Control Flow Testing
Modified Condition/Decision Coverage

- ☐ A complete modified condition/decision coverage causes a branch coverage on the object code level



Control Flow Testing
Modified Condition/Decision Coverage

☐ But: Not every branch coverage test on the object code level causes a complete modified condition/decision coverage



Control Flow Testing
Multiple Condition Coverage

☐ The multiple condition coverage requires the test of all value combinations of the conditions

☐ Benefits

- Very extensive test
- Subsumes the branch coverage test and all other condition coverage test techniques

☐ Disadvantages

- High test costs (2^n test cases for a decision which is contains *n* simple conditions)
- Sometimes there exists no test data for certain combinations (e.g., because of incomplete evaluation of decisions or dependences between conditions)

	A	B	C	D	A||B	C||D	(A||B)&&(C||D)
1	F	F	F	F	F	F	F
2	F	F	F	T	F	T	F
3	F	F	T	F	F	T	F
4	F	F	T	T	F	T	F
5	F	T	F	F	T	F	F
6	F	T	F	T	T	T	T
7	F	T	T	F	T	T	T
8	F	T	T	T	T	T	T
9	T	F	F	F	T	F	F
10	T	F	F	T	T	T	T
11	T	F	T	F	T	T	T
12	T	F	T	T	T	T	T
13	T	T	F	F	T	F	F
14	T	T	F	T	T	T	T
15	T	T	T	F	T	T	T
16	T	T	T	T	T	T	T

Control Flow Testing
Path Coverage

☐ A program execution causes the execution of a program path which usually contains several branches and instructions

☐ Question: How can this be taken into account by a test technique?

Control Flow Testing
Path Coverage

☐ A complete path coverage requires the execution of all different paths of the program to be tested

- A path p is a sequence of nodes (i, n_1,.., n_m, j) in the control flow graph with the start node i and the end node j

☐ Disadvantages

- The path coverage test normally is not executable for real programs, as they can have an infinite number of paths. Assuming that the maximum value of an Integer-variable is 32767, we get 2^{32768}-1 test paths for the operation *CountChars*. This is roughly 1,41 · 10^{9864} paths. The required test time for a test that runs non-stop and executes 1000 paths per second would be 4,5 · 10^{9853} years. For comparison: The age of the earth is estimated to roughly 4,5 · 10^9 years. Therefore, a complete path coverage test of the operation *CountChars* is absolutely impossible
- Often a fraction of the paths is not executable

☐ Question: How can the path coverage test be modified so that it is feasible?

Control Flow Testing
Structured Path Test and Boundary Interior Path Test

☐ The Structured path test distinguishes only paths that execute a loop not more than k times. This avoids the explosion of the number of paths caused by loops

☐ The structured path test with k=2 is called boundary interior coverage

☐ The boundary interior coverage differentiates the three cases *no loop execution, one loop execution* and *at least two loop executions*. This is especially useful due to the possible interactions between variables before, in and after the loop

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Control Flow Testing
Boundary Interior Test

☐ **Example**

The following test cases are necessary for a boundary interior test of the operation *CountChars*

- 1. Test case for the path outside of the loop
  The execution with *totalnumber = INT_MAX* results in the non-execution of the loop body

  test path: n_{start}, n_1, n_2, n_{final}

Control Flow Testing
Boundary Interior Test

- 2. Boundary test cases
  a. The execution with *totalnumber = 0* and the input of the character string *A1* causes the entering of the loop body, the execution of the *true*-branch of the selection, and subsequently the termination of the loop
  test path: n_{start}, n_1, n_2, n_3, n_4, n_5, n_2, n_{final}
  b. The execution with *totalnumber = 0* and the input of the character string *B1* causes the entering of the loop body, the execution of the *false*-branch of the selection and subsequently the termination of the loop
  test path: n_{start}, n_1, n_2, n_3, n_5 ,n_2, n_{final}

Control Flow Testing
Boundary Interior Test

- 3. Interior test cases
  a. The execution with *totalnumber = 0* and the input of the character string *EIN1* causes three executions of the loop body. At the first two executions the *true*-branch of the selection is passed through. The third loop execution is irrelevant for the test

  test path: n_{start}, n_1, n_2, n_3, n_4, n_5, n_2, n_3, n_4, n_5, n_2, n_3, n_5, n_2, n_{final}

  b. The execution with *totalnumber = 0* and the input of the character string *AH!* causes two executions of the loop body. At the first execution the *true*-branch of the selection is passed through. At the second execution the *false*-branch is passed. The exclamation mark terminates the execution of the loop which is allowed for the interior test after the second execution of the loop body

  test path: n_{start}, n_1, n_2, n_3, n_4 ,n_5 , n_2, n_3, n_5, n_2, n_{final}

Control Flow Testing
Boundary Interior Test

c. The execution with *totalnumber = 0* and the input of the character string *HH!* causes two executions of the loop body. At both executions the *false*-branch of the selection is passed through. The exclamation mark terminates the loop execution

   test path: n_{start}, n_1, n_2, n_3, n_5, n_2, n_3, n_5, n_2, n_{final}

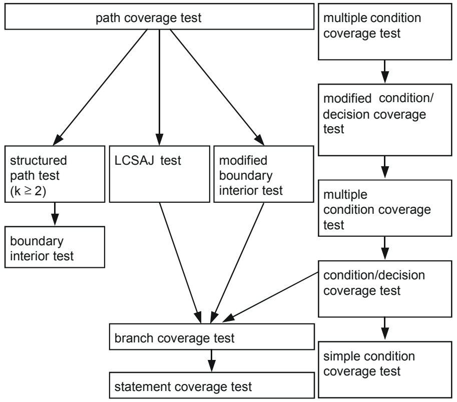
d. The execution with *totalnumber = 0* and the input of the character string *HA!* causes two executions of the loop body. At the first execution the *false*-branch of the selection is passed through. At the second execution the *true*-branch of the selection is passed through. The exclamation mark terminates the loop execution

   test path: n_{start}, n_1, n_2, n_3, n_5, n_2, n_3, n_4, n_5, n_2, n_{final}

- ☐ The seven test cases are sufficient for the complete test of the loop according to the boundary interior criterion

---

Control Flow Testing
Relations of the Control Flow Tests (Subsumes Hierarchy)



path coverage test

structured path test (k ≥ 2)

LCSAJ test

modified boundary interior test

boundary interior test

branch coverage test

statement coverage test

multiple condition coverage test

modified condition/ decision coverage test

multiple condition coverage test

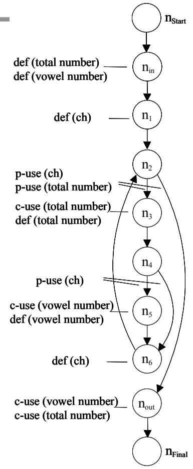
condition/decision coverage test

simple condition coverage test

Data Flow Testing

- ☐ Data flow testing is based on the data flow. The basis is the control flow graph enhanced by data flow attributes
- ☐ Accesses to variables are assigned to one of the classes
  - write: definition *(def)*
  - read: computational use *(c-use)*
  - read: predicate use *(p-use)*

Data Flow Testing
Control Flow Graph with Data Flow Attributes for CountChars



```
void CountChars ( int &vowel number,
     int &total number)
{
    cin >> ch ;


     while ((ch >= 'A') && (ch <= 'Z')
            && (total number < INT_MAX))
     {

          total number = total number + 1;


          if ((ch == 'A') || (ch == 'E') ||
              (ch == 'I') ||  (ch == 'O') ||
              (ch == 'U'))
          {
               vowel number = vowel number + 1;
           }

      cin >> ch
      }

}
```

Data Flow Testing

☐ Example

- The instruction y = x+1; contains a c-use of the variable x, followed by a definition (def) of the variable y
- The instruction IF (x=0) THEN... contains a p-use of the variable x

☐ The all defs-criterion demands

- That every definition (all defs) of a variable is used at least once in a computation or a predicate. The objective of an assignment to a variable is that this value is used somewhere once again. The tests have to be chosen in such a way that this is tested at least once for every assignment to every variable

---

Data Flow Testing

☐ All p-uses-test

- The all p-uses-test requires that every p-use that exists w.r.t. each definition is taken into account during testing

☐ All c-uses-test

- The all c-uses-test requires that every c-use that exists w.r.t. each definition is taken into account during testing

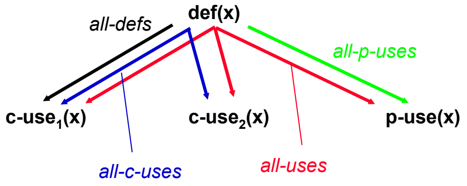
☐ All c-uses / some p-uses-test resp. all p-uses / some c-uses-test

- If no c-uses resp. p-uses exist for some variable definitions, it is required that at least one p-use resp. c-use is tested

☐ All uses-test

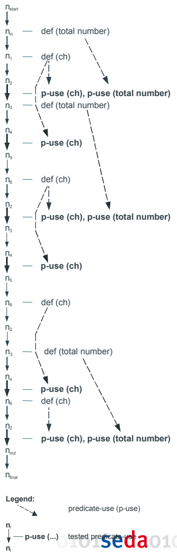
- All c-uses-test + All p-uses-test

Data Flow Testing

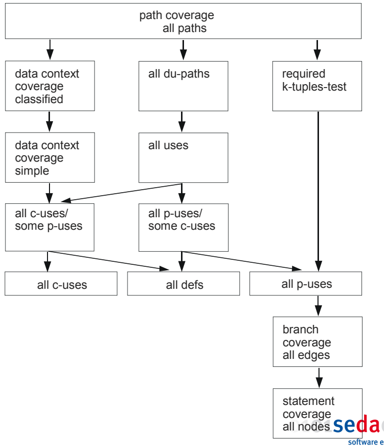

all-defs
def(x)
all-p-uses
c-use$_1$(x)
c-use$_2$(x)
p-use(x)
all-c-uses
all-uses

Data Flow Testing

☐ Test path for the all p-uses-test


n_{start}
n_{in}
def (total number)
n_1
def (ch)
n_2
p-use (ch), p-use (total number)
n_3
def (total number)
n_4
p-use (ch)
n_5
n_6
def (ch)
n_2
p-use (ch), p-use (total number)
n_3
n_4
p-use (ch)
n_5
n_6
def (ch)
n_2
n_3
def (total number)
n_4
p-use (ch)
n_6
def (ch)
n_2
p-use (ch), p-use (total number)
n_{out}
n_{final}
Legend:
predicate-use (p-use)
n_i
p-use (...)
tested predicate-use
n_j

Data Flow Testing
Relations of the Control Flow Tests (Subsumes Hierarchy)



path coverage
all paths

data context
coverage
classified

all du-paths

required
k-tuples-test

data context
coverage
simple

all uses

all c-uses/
some p-uses

all p-uses/
some c-uses

all c-uses

all defs

all p-uses

branch
coverage
all edges

statement
coverage
all nodes

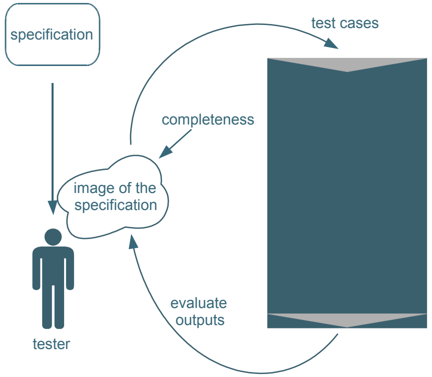
Functional Test (Specification-based Test)

☐ Determination of the adequacy and the completeness of the test cases as well as derivation of the test data and evaluation of the outputs based on the specification

- Benefits: Completeness w.r.t. the specification is checked. The test cases are systematically drawn from the specification
- Disadvantage: Information represented by the code is discarded

---

Functional Test (Specification-based Test)



specification

test cases

completeness

image of the specification

evaluate outputs

tester

Functional Test (Specification-based Test)
Equivalence Partitioning

☐ Identification of equivalence classes based on the specification (Divide & Conquer)

☐ All Values from an equivalence class

- Shall cause an identical behavior and
- Shall belong to the same specified program function

☐ All specified program functions are tested with values from the equivalence class assigned to them

☐ Equivalence classes are also generated from the outputs

Functional Test (Specification-based Test)
Equivalence Partitioning - Invalid and valid Equivalence Classes

- ☐ If a value range is specified as the valid input domain for a particular input variable, this range represents a valid equivalence class which is enframed by invalid equivalence classes at its lower and upper boundary
- ☐ Example
  - Input range: $1 \le x \le 99$
  - One valid equivalence class: $1 \le x \le 99$
  - Two invalid equivalence classes
    - $x < 1$
    - $x > 99$

Functional Test (Specification-based Test)
Equivalence Partitioning - Invalid and valid Equivalence Classes

- ☐ The equivalence classes are to be numbered. For the generation of test cases from the equivalence classes two rules have to be applied
  - The test cases for valid equivalence classes are generated by the selection of test data from as many valid equivalence classes as possible
  - The test cases for invalid equivalence classes are generated by the choice of a test date from an invalid equivalence class. It is combined with values which are extracted exclusively from valid equivalence classes
- ☐ Selection of the concrete test data from an equivalence class according to different criteria
- ☐ Often used: test of the equivalence class boundaries **(boundary value analysis)**

Functional Test (Specification-based Test)
Equivalence Partitioning

- ☐ A program for the inventory management of a shop is capable to register deliveries of wooden boards
  - If wooden boards are delivered, the sort of the wood is entered
  - The program knows the wood sorts Oak, Beech, and Pine
  - Furthermore, the length is given in centimeters which is always between 100 and 500
  - As delivered number a value between 1 and 9999 can be given
  - In addition, the delivery gets an order number
  - Every order number for wood deliveries begins with the letter H

Functional Test (Specification-based Test)
Equivalence Partitioning

Equivalence classes

Input	Valid Equivalence Class	Invalid Equivalence Class
Sort	1) Oak 2) Beech 3) Pine	4) All others, e.g. steel
Length	5) 100 <= Length <= 500	6) Length < 100 7) 500 < Length
Number	8) 1<= Number <= 9999	9) Number < 1 10) 9999 < Number
Order number	11) First character is H	12) First character is not H

Functional Test (Specification-based Test)
Equivalence Partitioning

Test cases according to equivalence partitioning combined with boundary value analysis

Test case	1	2	3	4	5	6	7	8	9
Testes Equivalence Classes	1, 5L, 8L, 11	2, 5U, 8U	3	4	6U	7L	9U	10L	12
Sort	**Oak**	**Beech**	**Pine**	**Steel**	Oak	Oak	Oak	Oak	Oak
Length	**100**	**500**	200	200	**99**	**501**	200	200	200
Number	**1**	**9999**	100	100	100	100	**0**	**10000**	100
Order number	**H1**	H2r	H54	H54	H54	H54	H54	H54	**J1**

Functional Test (Specification-based Test)
Equivalence Partitioning

Exercise

☐ The class "triangle" contains the lengths of the triangle sides side1, side2 and side3 as integer-attributes. The operation "type ()" determines the type of the triangle on the basis of these side lengths. The following cases are differentiated

- No triangle: data error of the side lengths
- Equilateral
- Right-angled
- Isosceles
- Scalene

☐ The type right-angled is output with priority, i.e., if for example a scalene triangle is right-angled, not scalene but right-angled is output

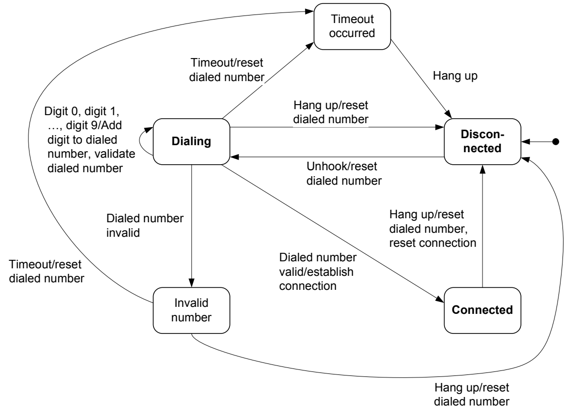
---

Functional Test (Specification-based Test)
State-based Testing

☐ Example: section of a specification

- Parameters
  - PORT_A: calling phone
  - PORT_B: called phone
- PORT_A identifies the connection from which a call is to be set up. The actual state of the call setup is globally available. Depending on this a new state arises after the evaluation of the transferred action. The delivered state is CUT, if the call setup was terminated, it is PENDING, if the call setup is in progress but not completed yet. It is READY, if the call setup was successfully completed. In this case PORT_B delivers the connection of the selected subscriber, otherwise the data content of PORT_B is undefined. A call setup requires the sequence OFFHOOK (DIGIT_N)* and the digit sequence must represent a valid number. ONHOOK always leads to the complete termination of the call. If TIMEOUT occurs, ONHOOK brings the software back into the initial state (CUT)

Functional Test (Specification-based Test)
State-based Testing


Timeout occurred
Timeout/reset dialed number
Hang up
Digit 0, digit 1, …, digit 9/Add digit to dialed number, validate dialed number
Dialing
Hang up/reset dialed number
Discon-nected
Unhook/reset dialed number
Dialed number invalid
Hang up/reset dialed number, reset connection
Timeout/reset dialed number
Dialed number valid/establish connection
Invalid number
Connected
Hang up/reset dialed number

Functional Test (Specification-based Test)
State-based Testing

☐ The minimal test strategy is to cover each state at least once.

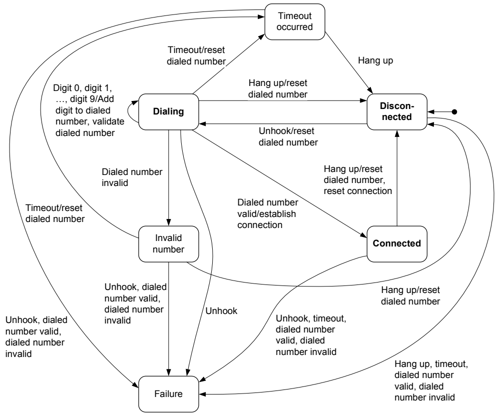
☐ A better solution is to cover each transition at least once, which leads, e.g., to the following test cases

- Cut, Offhook ➔ Pending, Onhook ➔ Cut
- Cut, Offhook ➔ Pending, Timeout ➔ Timeout occured, Onhook ➔ Cut
- Cut, Offhook ➔ Pending, Digit 0..9 ➔ Checking, Number incomplete ➔ Pending, Digit 0..9 ➔ Checking, ... , Number valid ➔ Ready, Onhook ➔ Cut
- Cut, Offhook ➔ Pending, Digit 0..9 ➔ Checking, Number incomplete ➔ Pending, Digit 0..9 ➔ Checking, ... , Number invalid ➔ Invalid number, Onhook ➔ Cut

☐ Furthermore, it is useful to test all events if transitions can be initiated by more than one events. The result is a hierarchy of test techniques
all states ⊆ all transitions ⊆ all events

☐ Important: Do not forget to test the failure treatment!

Functional Test (Specification-based Test)
State-based Testing - “Failure”-state added


Timeout occurred
Hang up
Timeout/reset dialed number
Digit 0, digit 1, …, digit 9/Add digit to dialed number, validate dialed number
Dialing
Hang up/reset dialed number
Discon-nected
Unhook/reset dialed number
Dialed number invalid
Hang up/reset dialed number, reset connection
Dialed number valid/establish connection
Timeout/reset dialed number
Invalid number
Connected
Unhook, dialed number valid, dialed number invalid
Unhook
Hang up/reset dialed number
Unhook, dialed number valid, dialed number invalid
Unhook, timeout, dialed number valid, dialed number invalid
Hang up, timeout, dialed number valid, dialed number invalid
Failure

Functional Test (Specification-based Test)
Evaluation of State-based Testing

+ State-based tests can be used in unit and system testing.

+ It has widespread use particularly in technical applications such as industry automation, avionics, or the automotive industry.

- In state charts of large systems, there tends to be an explosion in the number of states, which leads to a considerable increase in transitions.

Other Function-oriented Test Techniques
Transaction Flow Testing

☐ According to /Beizer 90/ a transaction is a processing module from the view of a system user. Transactions consist of a sequence of processing steps.

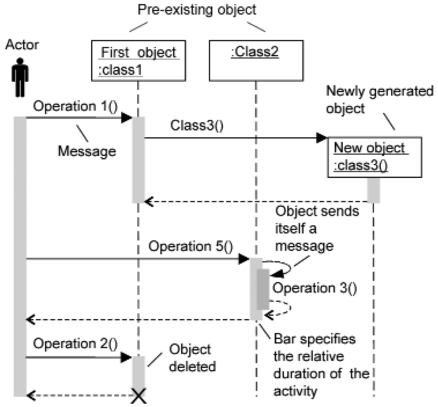
☐ Representation forms for the notation of transaction flow:

- Flow diagram /Beizer 90/
- Sequence diagrams (Message Sequence Chart (MSC) in the object oriented method UML)

+ A good basis for generating test cases. It directly specifies possible test cases.

- Sequence diagrams display only one out of many different options.

Other Function-oriented Test Techniques
Transaction Flow Testing - A message sequence diagram


Pre-existing object
Actor
First object
:class1
:Class2
Newly generated object
Operation 1()
Class3()
Message
New object
:class3()
Object sends itself a message
Operation 5()
Operation 3()
Operation 2()
Object deleted
Bar specifies the relative duration of the activity

Other Function-oriented Test Techniques
Test on the Basis of Decision Tables or Decision Trees

- ☐ Decision tables or decision trees can be used as a basis for function-oriented tests.
- + They guarantee a certain test-completeness by way of their methodical approach.
- - The size of this representation increases exponentially with the number of conditions.

Other Function-oriented Test Techniques
Test on the Basis of Decision Tables or Decision Trees

☐ Example:

The following application specifies whether an e-commerce enterprise settles orders per bill. Whether the payment of a bill is possible is determined by if the customer is a new customer, if the order amount is greater than 1000€ and if he is a private customer. The three conditions result in eight combinations.

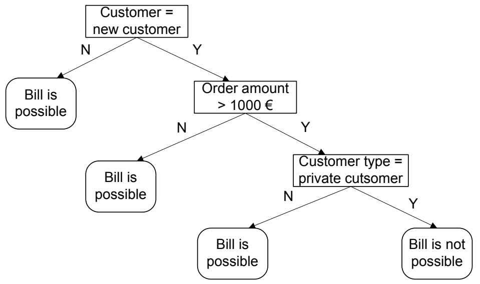
Other Function-oriented Test Techniques
Test on the Basis of Decision Tables or Decision Trees
Decision Table

Conditions	Customer = New Customer	N	N	N	N	Y	Y	Y	Y
	Order Value > 1000 €	N	N	Y	Y	N	N	Y	Y
	Customer Type = Private Customer	N	Y	N	Y	N	Y	N	Y
Action	Bill payment is possible	Y	Y	Y	Y	Y	Y	Y	N

Other Function-oriented Test Techniques
Test on the Basis of Decision Tables or Decision Trees
Optimized Decision Table

Conditions	Customer = New Customer	N	-	-	Y
	Order Value > 1000 €	-	-	N	Y
	Customer Type = Private Customer	-	N	-	Y
Action	Bill payment is possible	Y	Y	Y	N

Other Function-oriented Test Techniques
Test on the Basis of Decision Tables or Decision Trees
Decision Tree

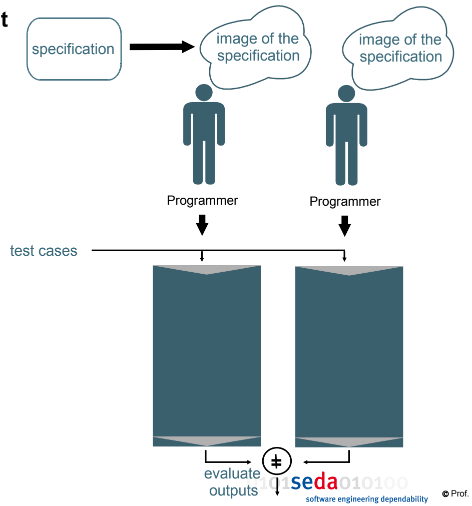

Customer = new customer
N
Y
Bill is possible
Order amount > 1000 €
N
Y
Bill is possible
Customer type = private cutsomer
N
Y
Bill is possible
Bill is not possible

Every path from the root to a leaf of the tree corresponds to a test case. Therefore, there would be four test cases.

Diversified Test

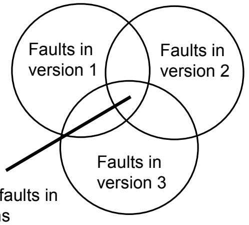
- ☐ Test of several software versions against each other
- ☐ Back to Back Test
  - Implementation of 2, 3, or even more versions by independent programmers based on the same specifications
  - Evaluation of the outputs by automated comparison
  - Benefit: test execution (incl. checking of outputs) can be done automatically (saves time and money)
  - Disadvantages: Multiple implementation is required. Faults occurring in all versions are not detected
- ☐ Mutations Test
  - In fact no test method but a possibility to evaluate the efficiency (error detection rate) of test methods. Not explained here
- ☐ Regression Test
  - Test of the present version against the previous version in order to identify undesired changes of the behavior (e.g. by faults introduced during modification and fault correction)

Diversified Test
Back to Back Test


specification
image of the specification
image of the specification
Programmer
Programmer
test cases
evaluate outputs
≠

Diversified Test
Back to Back Test

- ☐ The Back to Back Test requires the multiple realization of software modules based on identical specifications
- ☐ The Back to Back Test is economically applicable, if outstanding safety and/or reliability requirements exist or an automatic evaluation of the outputs is desired or required
- ☐ Common faults remain undetected


Faults in version 1
Faults in version 2
Faults in version 3
Common faults in all versions (will not be detected)

Some additional Dynamic Test „Techniques“

- ☐ Boundary value analysis
  - The boundary value analysis selects test data from boundaries
- ☐ Special values testing / Error guessing
  - Special values testing selects test cases based on the expertise of experienced testers => not acceptable as a single technique, but maybe ok in combination this other techniques, e.g. equivalence partitioning
- ☐ Stochastic test, also random test
  - Random test selects test data that fulfils certain statistical requirements. It is not identical with the ad hoc-procedure of unsystematic testing
  - Random testing is usually used in combination with statistical techniques, that allow to determine and predict reliability on a quantitative basis. It may also be used as the test data generation technique for Back to Back testing

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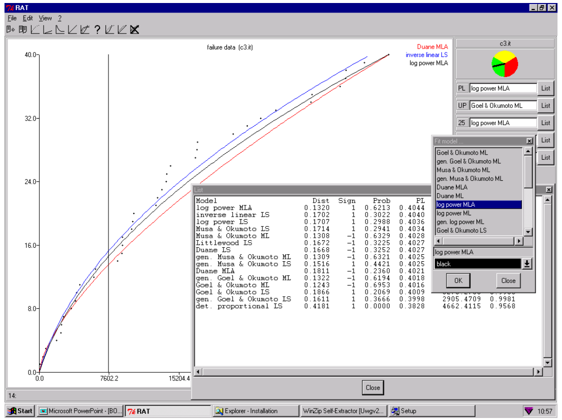
Evaluation of data from a Stochastic Test


RAT
File Edit View ?
failure data (c3.lt)
Duane MLA
inverse linear LS
log power MLA
40.0
32.0
24.0
16.0
8.0
0.0
0.0
7602.2
15204.4
14
c3.lt
PL log power MLA List
UP Goel & Okumoto ML List
25 log power MLA List
List
List
Fit model ...
Goel & Okumoto ML
gen. Goel & Okumoto ML
Musa & Okumoto ML
gen. Musa & Okumoto ML
Duane MLA
Duane ML
log power MLA
log power ML
gen. log power ML
Goel & Okumoto LS
log power MLA
black
OK
Close
List
Close
Start
Microsoft PowerPoint - [BO...
RAT
Explorer - Installation
WinZip Self-Extractor [Uwgv2...
Setup
10:57

```
Model                        Dist  Sign    Prob      PL
log power MLA              0.1320     1  0.6213  0.4044
inverse linear LS          0.1702     1  0.3022  0.4040
log power LS               0.1707     1  0.2988  0.4036
Musa & Okumoto LS          0.1714     1  0.2941  0.4034
Musa & Okumoto ML          0.1308    -1  0.6329  0.4028
Littlewood LS              0.1672    -1  0.3225  0.4027
Duane LS                   0.1668    -1  0.3252  0.4027
gen. Musa & Okumoto ML     0.1309    -1  0.6321  0.4025
gen. Musa & Okumoto LS     0.1516     1  0.4421  0.4025
Duane MLA                  0.1811    -1  0.2360  0.4021
gen. Goel & Okumoto ML     0.1322    -1  0.6194  0.4018
Goel & Okumoto ML          0.1243    -1  0.6953  0.4016
Goel & Okumoto LS          0.1866     1  0.2069  0.4009
gen. Goel & Okumoto LS     0.1611     1  0.3666  0.3998     2905.4709   0.9981
det. proportional LS       0.4181     1  0.0000  0.3828     4662.4115   0.9568
```