SOFTWARE TESTING

Tester's Job:

- Find as *many* faults of different *kinds* as he can.
- Certify some kind of quality measure for the software based on the test results, meaning he must
  - carefully select test cases, and
  - evaluate the test results.

Software testing does not show that there are no faults, even when every test-case gives the correct output.

Basic Assumption in Software Testing:

- Errors are not intentional by the programmer, i.e., they are not specially crafted.
- All Testing methods depend on this assumption.

Test Coverage Measures:

- They are based on program's structure or more abstract forms like finite-state model or data-flow model.

Mapping Test Results to Error Discovery: ???

INPUT-OUTPUT SPECIFICATIONS, PROGRAM-BEHAVIOR, AND TEST-CASES

Program-Behavior:

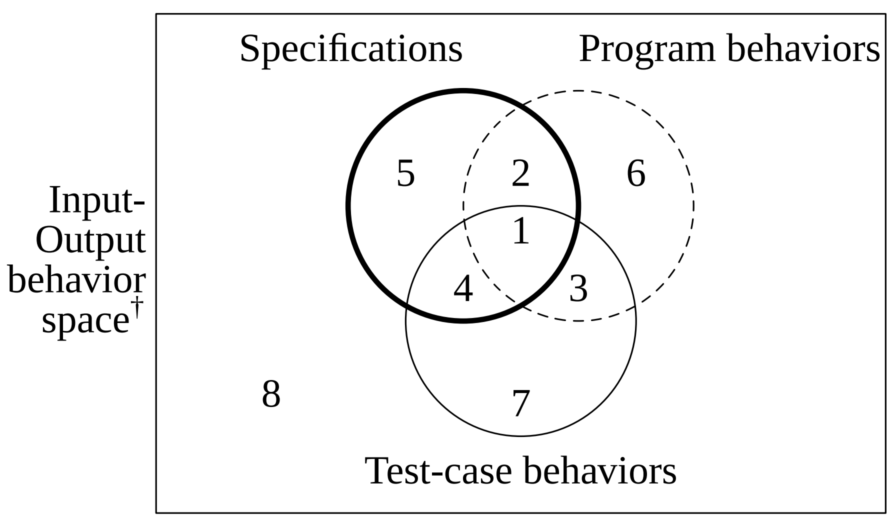
- *Actual* observable input-output behavior of the program; it may be different from the *expected* (based on requirements) behavior.
  - We typically do not have a complete knowledge of the program-behavior even if we have the code

Test-Case Behaviors:

- The input-output behavior that we want to *test/observe*.

Example. *Requirement:* compute n^2 for $-20 \le n \le 20$.

- Program computes n^2 for $0 \le n \le 10$ and n^3 for $10 < n \le 100$.



(1) Areas 1+2 = $\{(n, n^2): 0 \le n \le 10\}$ and
Areas 4+5 = $\{(n, n^2): -20 \le n < 0 \text{ or } 10 < n \le 20\}$

(2) $(-3, 10) \in$ Area#7 $\cup$ Area#8.

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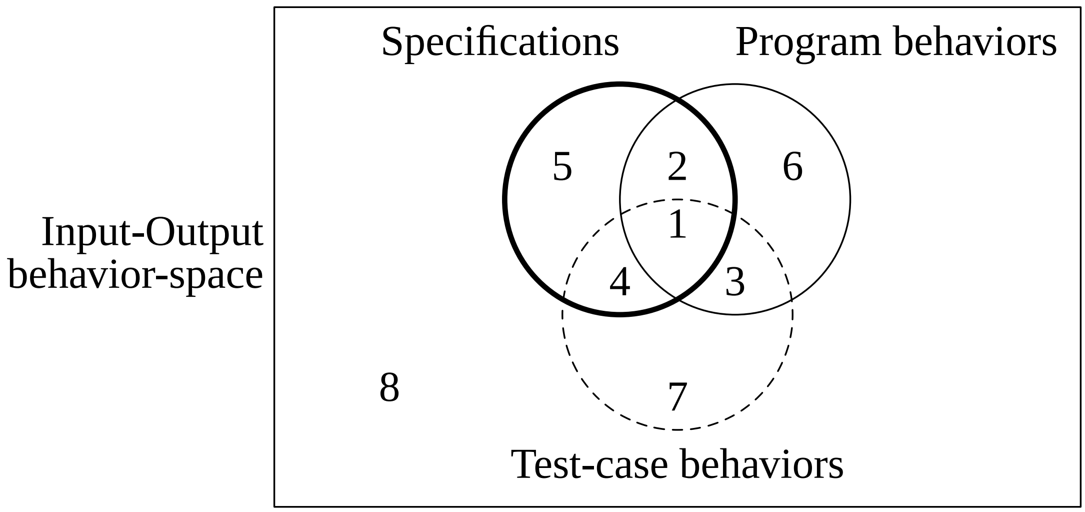
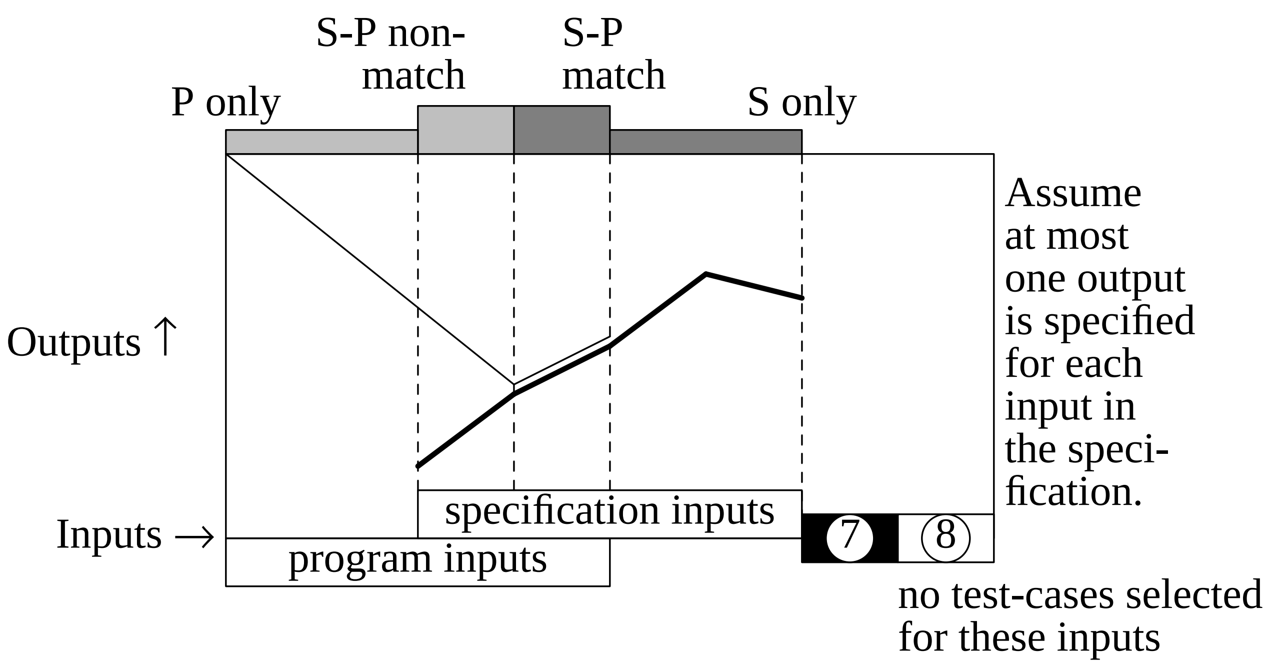
† Fig. 1.4 in "Software Testing" (3rd ed.) by P.C. Jorgensen.

AN ALTERNATE VIEW





Question:

•? Mark all parts of the input-space (horizontal axis) corresponding to the other areas in the top-diagram. (It may not be meaningful to do the same for output-space – why?)

•? Which points in the second diagram belong to the input-output behavior space in the top diagram?

•? Show a modified version of the "alternative" view if the specification allows multiple different acceptable outputs for some inputs.

BLACK-BOX TESTING

- Based on requirements; uses an executable code only.

Example Requirements (for an WordCharCounts-function):

(1) Words in the input text file are at most 20 characters long. (This is not same as saying that longer words are to be ignored.)

(2) Blanks, tabs, and new-lines are considered word-separators.

(3) Comma, semicolon, and colon are not part of a word; hyphens as in "son-in-law" are part of a word.

Example Test-case (input file is shown as a string):

- The test-case below ([t] for a tab) can verify requirement (1) and parts of (2), making it of category 1 or 4 (see page 3).

```
"This    text [t] [t] has five words  "
```

- This would not verify requirement (3), i.e., the required behavior; requirement (3) falls in category 2 or 5 w.r.t this test case.

Question: Which of the requirements in (1)-(3) are of category 2 w.r.t the above test case and the source-code below? Give a requirement of category 5 w.r.t this test case.

```
#define WORDLEN 20
void WordCharCounts(FILE *inFile)
{ int i;
  char word[WORDLEN+1];
  wordCount = charCount = 0;
  while (fscanf(inFile, "%s", word) > 0) {
        wordCount++;
        for (i=0; i<=WORDLEN; i++)
            if ('\0' == word[i]) break;
            else charCount++;
  }
}
```

EXERCISE

1. Read the manual page for `strcpy`-function in **C** (Unix; type "man strcpy" to see the manual-page); why do you think the source-string pointer is not to be changed by `strcpy`-function? Make sure that you understand what would go wrong with `strcpy`-function for the situation below; here, the destination and source strings are next to each other but they do not overlap. Things would also go wrong if we let destination = source + 2, i.e., the destination-string starts at two places after the start of source-string.

destination ↓				source ↓					
a	b	c	\0	d	e	f	g	h	\0

   Then, write a "good" set of requirements for a function, whose profile is given below, and explain what should the new `safeStrcpy`-function do in each of the above cases. Indicate what should be the return-values in each of the cases.

   int safeStrcpy(char * destination, char *source)

   A programmer should be able to find out if a successful copy action has been properly carried out while using `safeStrcpy`-function or the nature of the problem that would have happened, so that he can take appropriate alternate action (which could be to use the old `strcpy`-function). Finally, give an implementation (or a pseudocode) that meets the requirements you formulated.

2. The next-page gives several incorrect versions of `safeStrcpy`-function; comments are added by me. Find out what is the problem in each case.

INCORRECT safeStrcpy-FUNCTIONS

Comments are added by me.

1.
```
int safeStrcpy(char *destination, char *source)
{ int *ptr = malloc(strlen(source));
  strcpy(ptr, source);
  strcpy(destination, ptr);
  source = ptr;
  return destination;
}
```

2.
```
int safeStrcpy(char *destination, char *source)
{ int length = strlen(source);
  char array[length]; //does not work - use malloc
  strcpy(temp, source); //what is temp?
  strcpy(destination, temp);
  return 1;
}
```

3.
```
int safeStrcpy(char *destination, char *source)
{ int length = strlen(source);
  char *temp[length];
  strcpy(temp, source);
  strcpy(destination, temp);
  return 1;
}
```

4.
```
int safeStrcpy(char *destination, char *source)
{ int n = LENGTH; //what is the relevance of LENGTH?
  if (n != 0) {
     char *d = dst;
     const char *s = src;
     while (--n != 0) {
           if ((*d++ = *s++) == 0) { //you meant ’\0’
              while (--n != 0) *d++ = 0; // ’\0’ ?
              break;
           }
     }
  }
  return(&des);
}
```

5. Pseudocode for `safeStrcpy(char *destination, char *source)`
```
int length = getLength of string; //which string?
int arrayLength = getLength of array; //what array?
if (length < arrayLength)
   strcpy(destination, course)
else strncpy(destination, source, arrayLength)
```

WHITE-BOX TESTING

- Uses the source-code, in addition to the requirements.
- Can focus on the way an output variable is affected by inputs (static code analysis) and relationship among output variables.
- Allows more detailed testing, taking advantage of *automated* code instrumentation. (Automated instrumentation prevents erroneous code modification.)
- Helps to identify sources of error.
- Better assess the quality of testing in terms of test-coverage measures.

Example. Static-analysis can show that we will always have "charCount ≥ wordCount", which is obviously true (if we do not exclude single character words).

```
#define WORDLEN 20
void WordCharCounts(FILE *inFile)
{ int i;
  char word[WORDLEN+1];
  wordCount = charCount = 0;
  while (fscanf(inFile, "%s", word) > 0) {
        wordCount++;
        for (i=0; i<=WORDLEN; i++)
            if ('\0' == word[i]) break;
            else charCount++;
  }
}
```

Question: Give another property (relationship) among the outputs or between inputs and outputs that can be obtained by examining the code.

PATH-EQUIVALENCE OF INPUTS

Path-Equivalence of Inputs:

- Two inputs I_1 and I_2 are *path-equivalent*, denoted by $I_1 \approx I_2$, if they have the same execution paths $\pi(I_1) = \pi(I_2)$.
  - $\pi(I_1)$ and $\pi(I_2)$ follow the same true/false branch at each decision-node for each execution of them, executing same sequence of actions.

Characteristics of An Equivalence Relation:

- Reflexive: $x \approx x$.
- Symmetric: If $x \approx y$, then $y \approx x$.
- Transitive: If $x \approx y$ and $y \approx z$, then $x \approx z$.

Equivalence Class: $[x]_{\approx} = \{y: y \approx x\}$.

Example: Considering the input file as a string of characters and I_1 = "`abc de`", I_2 = "` abc ed `", and I_3 = "`ab cde`", we only have $I_1 \approx I_2$, i.e., $[I_1] = [I_2] \neq [I_3]$. Why?

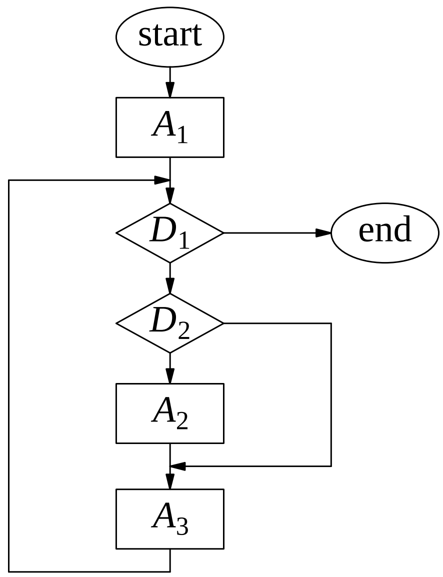
```
#define WORDLEN 20
void WordCharCounts(FILE *inFile)
{ int i;
  char word[WORDLEN+1];
  wordCount = charCount = 0;
  while (fscanf(inFile, "%s", word) > 0) {
        wordCount++;
        for (i=0; i<=WORDLEN; i++)
            if ('\0' == word[i]) break;
            else charCount++;
  }
}
```

Question: Which of I_1, I_2, and I_3 are path-equivalent if we replace the for-loop by "charCount += length(word)"?

REACHABILITY RELATION IS NOT AN EQUIVALENCE RELATION

Reachability Relation in a Flowchart (any directed graph):

- xRy, meaning y can be reached from x.



Here,
A_1RA_2 but not A_2RA_1
although
D_1RA_2 and A_2RD_1.

Question:

•? Which of the three equivalence-relation properties are violated for the reachability relation?

Output-Equivalence of Inputs:

- I_1 and I_2 are *output-equivalent* if $P(I_1) = P(I_2)$.

Question:

•? Which of I_1, I_2, and I_3 in the previous page are output-equivalent? How about for the modified program with the for-loop replaced by "charCount += length(word)"?

•? Does $P(I_1) = P(I_2)$ imply that $I_1 \approx I_2$? How about the converse?

•? For a function P, what else should be considered as the output $P(I)$ other than the value returned by P?

IMPORTANCE OF PATH-EQUIVALENCE RELATION

An Elementary Form of Error:

- An error in an action A which does not affect any branch-test condition (hence the execution path $\pi(I)$ for any I).
- If P' be an erroneous version of program P due to an elementary error in the action A in P, then for each input I
  - Path $\pi(I)$ in P equals $\pi'(I)$ in P', with each occurrence of A in $\pi(I)$ replaced by A' in $\pi'(I)$.

Question: Give examples of elementary and non-elementary errors in WordCharCounts-program below.

```
#define WORDLEN 20
void WordCharCounts(FILE *inFile)
{int i;
 char word[WORDLEN+1];
 wordCount = charCount = 0;
 while (fscanf(inFile, "%s", word) > 0) {
       wordCount++;
       for (i=0; i<=WORDLEN; i++)
           if ('\0' == word[i]) break;
           else charCount++;
 }
}
```

Assumption in Program Testing for an Elementary Error:

- Each test-case I for which $\pi(I)$ goes through the erroneous action will show an error in the output.
- If I shows the error and $I' \approx I$, then I' will also show the error.

TESTING STRATEGY FOR ELEMENTARY ERRORS

Single Elementary Error:

- If we select one test-case I_j from each path-equivalence class of inputs such that

  (a) the execution paths $\pi(I_j)$ together cover all actions, and

  (b) each I_j produces correct output,

  then the program is error free.

Assumption for Multiple Elementary Errors:

- No two errors cancel each other's effect.
- Thus, a test case I_j whose execution path $\pi(I_j)$ goes through one or more errors will result in an error in the output.

Same testing strategy applies for multiple elementary errors.

Simplest Test Coverage Measure:

- C_0 = The percentage of actions covered by the test-cases.
- We want C_0 = 100% for any acceptable level of testing.
- If C_0 < 100%, then there is some action A such that $A \notin \pi(I_j)$ for any of the test cases I_j and we can replace A by an *arbitrary* A' without any impact on the test-outputs $P(I_j)$.

Question: How can we always introduce an elementary error in a program P to create a new program P' with the property that the error shows up in the output?

MEASURING ACTION-COVERAGE

Code Instrumentation:

- At the start of each non-trivial action-block introduce a suitable print-operation to indicate that this block is entered:

Example. An instrumentation of WordCharCounts-function.

```
#define WORDLEN 20
void WordCharCounts(FILE *inFile)
{int i;
 char word[WORDLEN+1];
 printf(testCovFile, "entered block A1\n");
 wordCount = charCount = 0;
 while (fscanf(inFile, "%s", word) > 0) {
       printf(testCovFile, "entered block A2\n");
       wordCount++;
       for (i=0; i<=WORDLEN; i++)
           if ('\0' == word[i]) break;
           else {printf(testCovFile, "entered block A3\n");
                 charCount++;
                }
 }
}
```

Output in testCovFile for I **= "abc de"** (without indentations):

```
entered block A1
     entered block A2
          entered block A3
          entered block A3
          entered block A3
     entered block A2
          entered block A3
          entered block A3
```

$$C_0\textbf{-coverage: } \frac{\sum_{A_i \text{ covered in all test cases}} (\#actions\ in\ A_i)}{\sum_{A_j \text{ in the program}} (\#actions\ in\ all\ A_j)} = 100\% \text{ for this } I.$$

Question: Give an I with the smallest C_0-coverage and give that value of C_0.

IT CAN BE DIFFICULT TO ACHIEVE C_0 = 100%

Difficulties:

- Unreachable code; no execution ever goes through some action-blocks. Cannot achieve C_0 = 100%.
- Difficulty in finding test-input I for which $\pi(I)$ contains a specific action-block.
- Both can happen when there are many interdependent if-statements.

Problems with Code Instrumentation:

- Although code instrumentation can be done via automated tools, it can increase the program size significantly.
- It can slow down the execution significantly.
- The instrumentation output file can be too large.

Approximate Methods:

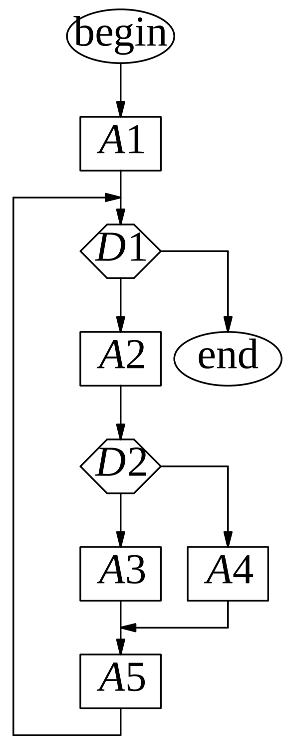
- The runtime machine code execution is sampled.
- Each executed machine code is mapped to the program source-code.
- Reduces program overhead in terms of program-memory, execution time, and measurement-output file.

Question:

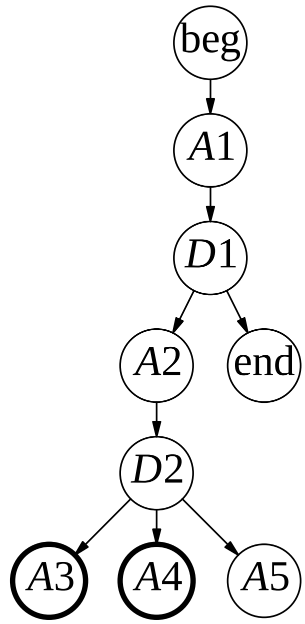
•? How can we instrument a code more intelligently to minimize the instrumentation-output and still have enough information to compute C_0? Show the instrumented form for WordCharCounts-function and the instrumentation output for I = "abc de".

A REFINEMENT OF C_0-MEASURE

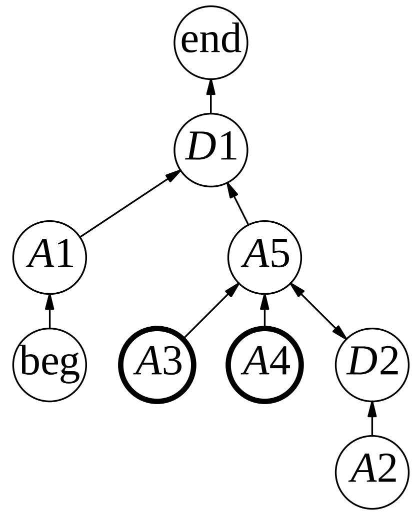
- Not all action-blocks A_i are of equal relevance in execution paths.



(i) A flowchart.



(ii) The domination tree.



(iii) The reverse domination tree.

- If a set of begin-end paths cover the terminal nodes $\{A3, A4, A5\}$ in the domination-tree, then it covers all flowchart nodes.
- Similarly, for the terminal nodes of the reverse-domination tree.

> For 100% C_0-coverage, we only need to cover the common terminal nodes in domination and reverse-domination trees.

Question:

•? State the definition of the new C_0-coverage measure based on the common terminal nodes of the two domination trees.

•? Give the new measure for I = empty-text-file for the WordChar-Count function (with bounded word-length).

BRANCH-COVERAGE MEASURE

$$C_1\textbf{-coverage:}\quad \frac{\sum_{D_i \text{ covered in all test runs}} (\#T/F \text{ branches covered at } D_i)}{2\times(\#\text{branch nodes in program})}$$

= 100% for I = "abc de".

Additional Instrumentation (for empty then/else blocks):

```
#define WORDLEN 20
 void WordCharCounts(FILE *inFile)
 {int i;
  char word[WORDLEN+1];
  printf(testCovFile, "entered block A1\n");
  wordCount = charCount = 0;
  while (fscanf(inFile, "%s", word) > 0) {
        printf(testCovFile, "entered block A2\n");
        wordCount++;
        for (i=0; i<=WORDLEN; i++)
            if ('\0' == word[i]) {
               printf(testCovFile, entered block A4\n");
               break;
               }
            else {printf(testCovFile, "entered block A3\n");
                  charCount++;
                 }
  }
 }
```

Output in testCovFile for I **= "ab cde"** (without indentations):

```
entered block A1
     entered block A2
          entered block A3
          entered block A3
          entered block A3
          entered block A4
     entered block A2
          entered block A3
          entered block A3
          entered block A4
```

Question: Should we instrument the exits from loops (for, while-do, etc.)? What is the minimum C_1-coverage for an I here?

BOUNDARY TESTING

- This may involve both valid test-cases that are "within specification limits" and also invalid test-cases that are outside the limits (testing for graceful-failing vs. "abort").

Requirement based:

- Many requirements represent constraints on inputs and outputs, and they can give rise to the respective boundary values.
  - Boundary testing can apply to inputs and to the outputs (trying to push respectively the input and/or the output to the boundary limits).
- The boundary values can be related to both entities and relationships in the data-model.

Example.

- For WordCharCounts-program,
  - Input text files with words of size 1 and of max length WORDLEN = 20 represent a form of boundary case.
  - Empty input file itself is also a boundary case.
  - An input file with words longer than WORDLEN = 20 represent a test-case for testing graceful-degradation.
- For TriangleClassification-function
  - An input file containing triplets for each category of triangles (equilateral, isosceles, and scalar) and also non-triangular triplets is a regular test-case.
  - An input to test graceful-failing would be an *abc*-triplets where the input-condition "$a \leq b \leq c$" is violated, which can happen in more than one way.

NOTION OF PROGRAM SLICE

Program Slice:

- Given an output variable *x*, it is part of the program involving only those (parts of) statements that may affect *x*.
- Includes relevant branch-statements, variables *y* that affect those branches, and the statements that affect those *y* in turn.
- The slice may be a small fragment of the original program and hence easier to test or debug.

Example. The bold lines below show the parts deleted to obtain the slices of WordCharCounts-function for the output variable wordCount and for charCount.

```
#define WORDLEN 20 //slice for wordCount
void WordCharCounts(FILE *inFile)
{ int i;
  char word[WORDLEN+1];
  wordCount = charCount = 0;
  while (fscanf(inFile, "%s", word) > 0) {
        wordCount++;
        for (i=0; i<=WORDLEN; i++)
            if ('\0' == word[i]) break;
            else charCount++;
  }
}
```

```
#define WORDLEN 20 //slice for charCount
void WordCharCounts(FILE *inFile)
{ int i;
  char word[WORDLEN+1];
  wordCount = charCount = 0;
  while (fscanf(inFile, "%s", word) > 0) {
        wordCount++;
        for (i=0; i<=WORDLEN; i++)
            if ('\0' == word[i]) break;
            else charCount++;
  }
}
```

DEFINITION-USE RELATIONSHIP

Definition of a Variable: *def*(x, s)

- A statement s is a *definition* of x if an execution of s assigns a value to x.
- s can be a input-statement from a file, an assignment statement, or a function-call statement.

Use of a Variable: *use*(x, s)

- A statement s is an *use* of a variable x if an execution of s requires a value of x.

Example:

- The statement

  ```
  fscanf(fp, "%s", word);
  ```

  is a definition of `word`, assuming that `fp` ≠ NULL. It assigns a value to `word` only if reading a non-empty string succeeds and otherwise the old value (if any) is retained.

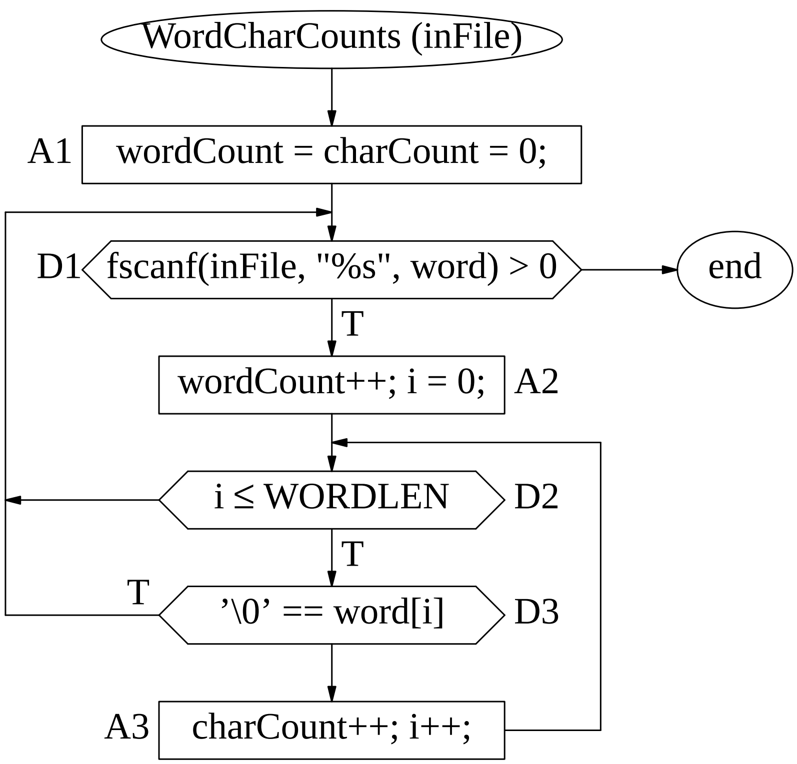
  It is also a definition `fp`, as it may update `fp`.
- The above statement is not an use of `word`; it uses the address of `word`. It also uses the file-pointer `fp`.
- The statement

  ```
  fscanf(fp, "%s %d", word, &i);
  ```

  may define `i` and in that case it is also an use of word!
- The statement "`i++;`" is both a definition and an use of `i`.

AN EXAMPLE

```
 1. void WordCharCounts(FILE *inFile)
 2. { int i;
 3.   char word[WORDLEN+1];
 4.   wordCount = charCount = 0;
 5.   while (fscanf(inFile, "%s", word) > 0) {
 6.         wordCount++;
 7.         for (i=0; i<=WORDLEN; i++)
 8.             if ('\0' == word[i]) break;
 9.             else charCount++;
10.   }
11. }
```



Variables	Definitions	Uses
inFile	1, 5	5
charCount	4, 9	4, 9
i	7	7, 8
word (addr of word)	5 (3)	8 (5, 8)
wordCount	4, 6	6

DEF-USE RELATIONSHIP

Def-Use relationship:

- We say *def*(x, s) is related to *use*(x, s'), where s may equal s', if there is an ss'-path of length ≥ 0 such that there is no other definition of x on that path in between s and s'.

Example of Def-Use Relationship.

```
 1. void WordCharCounts(FILE *inFile)
 2. { int i;
 3.   char word[WORDLEN+1];
 4.   wordCount = charCount = 0;
 5.   while (fscanf(inFile, "%s", word) > 0) {
 6.         wordCount++;
 7.         for (i=0; i<=WORDLEN; i++)
 8.             if ('\0' == word[i]) break;
 9.             else charCount++;
10.   }
11. }
```

Variable	Definitions	Uses of each definition
inFile	1	5
	5	5
charCount	4	4, 9
	9	9
i	7 (twice)	7 (twice), 8
word	5	8
wordCount	4	6
	6	6

- A definition with no uses is a potential flaw (e.g., a missing use).
- Even if a definition has an use, this may not be a "true" use because the def-use path is not executable.

Question: Is there any non-realizable (non-executable) def-use relationship above?

EXERCISE

1. Show the def-use relationships for the code below. Show a test-data that covers all the def-use relationships, but does not give 100% C_1-coverage; give the C_1-coverage measure for this test data and indicate the branch(es) not covered. Give another test-data to cover some of those uncovered branch(es). If we insert a suitable print-statement in the beginning of the body of the outer while-loop, then which def-use relationship-pairs will it track, and what happens if we put the print-statement just before line 4? (Draw the flowchart to see things more clearly.)

```
01. void WordCharCounts(FILE *inFile)
02. {char ch;
03.  wordCount = charCount = 0;
04.  while (fscanf(inFile, "%c", &ch) > 0)
05.        if ((ch != ’ ’) && (ch != ’\n’)) {
06.           charCount++; wordCount++;
07.           while (fscanf(inFile, "%c", &ch) > 0)
08.                 if ((ch != ’ ’) && (ch != ’\n’))
09.                    charCount++;
10.                 else break;
11.        }
12. }
```

2. How do you define a coverage measure based on the def-use relationship? Explain with an example.

A GLOBAL VIEW OF TESTING

Test Strategy: White-box or Black-box testing.

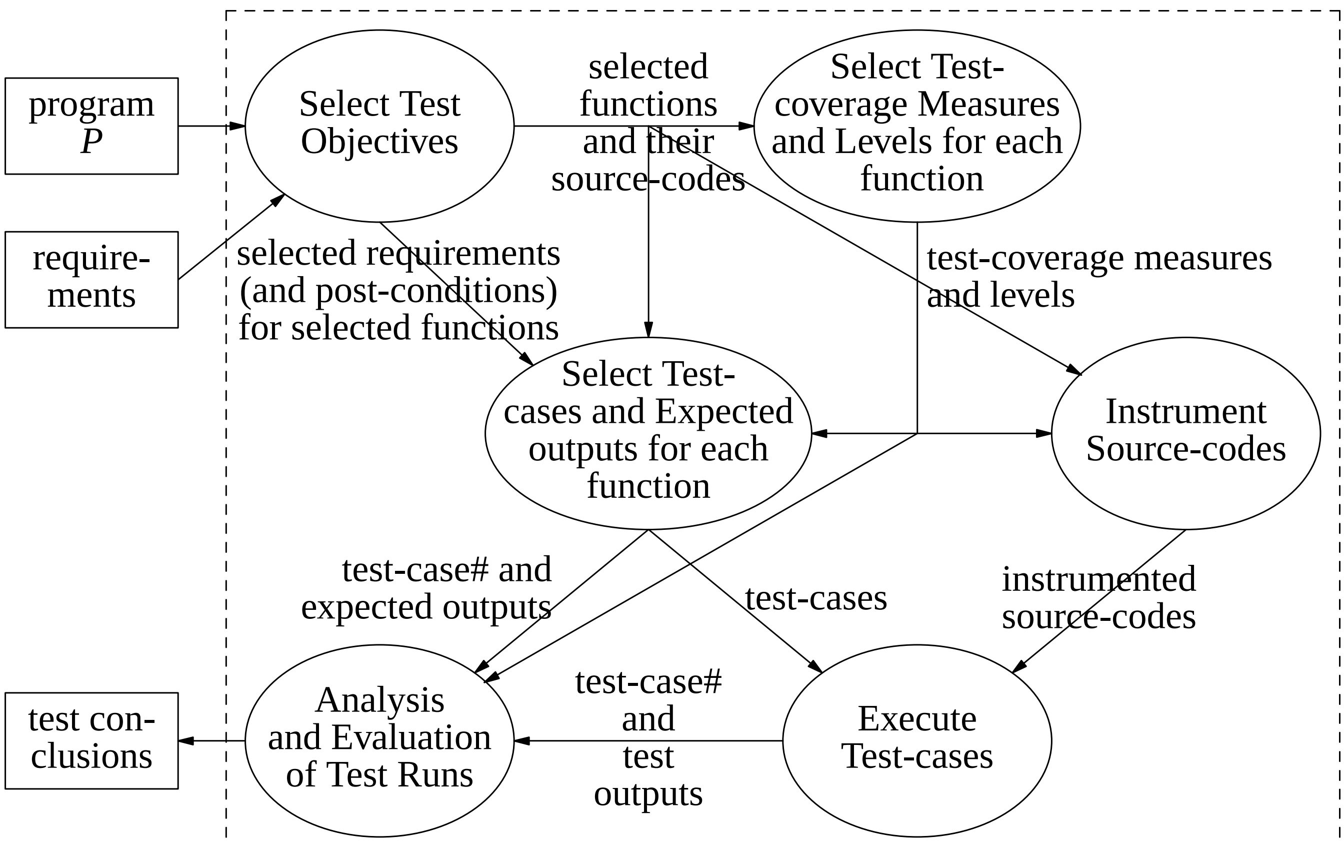
Test Goals/Objectives: Functional or performance testing.

- Select (user or design) requirements to be tested.
  - Identify functions and their input and output variables.
- Select test-coverage measures and the percentage coverage to be achieved for each measure.

Three Test Conclusions:

- More test needed, selected requirements satisfied, or not satisfied.

A Dataflow Diagram for Testing:



COMPARISON OF TEST-CASES

Basis of Comparison:

- Output point of view: how different are the outputs.
- Execution point of view: how different are the execution-paths (or the number of statements executed, etc)?
- Performance point of view: how different are the the performance parameters like execution time and memory use?

Notes:

- The first and third above falls in black-box view, and the second one in white-box view.

Question:

•? What are some other points of view for comparing test-cases, and which ones fall in black-box view and which ones fall in white-box view?

•? How would you differentiate test-cases from input point of view?

COMPARISON OF TEST-CASES VIA PROGRAM STRUCTURE

A Program Execution Path is More Than A Path:

- The nesting structure of program blocks gives a program execution-path more structure than just the linear (sequential) structure of a path in a general digraph.

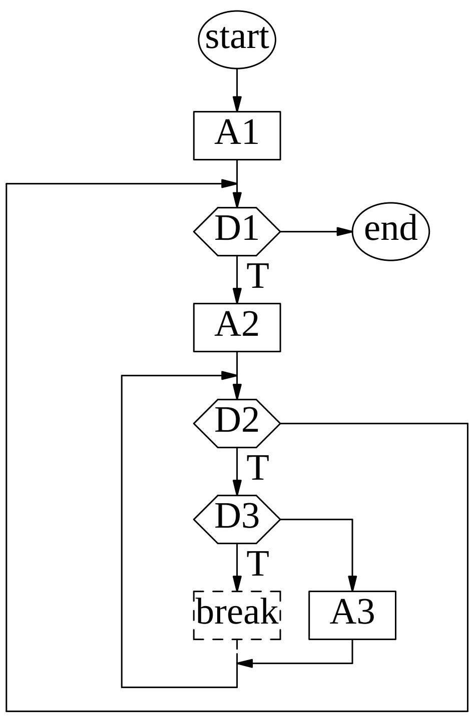
Nesting Tree of Program Blocks:

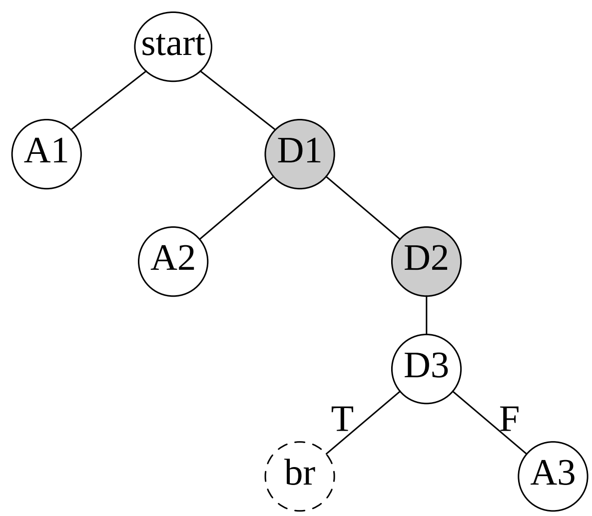
- It is a rooted ordered tree, with each node represents an one-entry-one-exit block (disregarding breaks, continues, and returns).
  - Children of a node are ordered left-to-right representing sequential order of the associated subblocks.
- If-then-else decision nodes have two children: then-part forms the left-child and else-part forms the right-child.
- The decision-nodes for for-loop and whileDo-loop are shown as filled, and those for doWhile-loops are shown as double circles.
  - The subtrees of the children of these decision nodes form the body of the loop.
- Unlike the T/F labels of the links to children of an if-then-else decision node, there are no labels of the links to the children of decision-nodes for the loops.

NESTING TREE OF PROGRAM-BLOCKS

Flowchart and Nesting Tree for wordCharCounts-function:

- We are using below the version that uses WORDLEN and does not use `strlen`-function.
- Since the then-part of D3 has no action other than transfer of abnormal (semi-structured) control via "break" (to D1) it is shown as a dashed circle.





Question: Suppose we replace the for-loop "for (i=0; i≤WORDLEN; i++) ⋯" by the following; note that the for-loop now starts with *i* = 1. Show the new action blocks, the new flowchart, and the new nesting-tree.

```
charCount++;
for (i=1; i<=WORDLEN; i++)
    if ('\0' == word[i]) break;
    else charCount++;
```

APPROX. REPRESENTATION OF AN EXECUTION-PATH USING NESTING-TREE

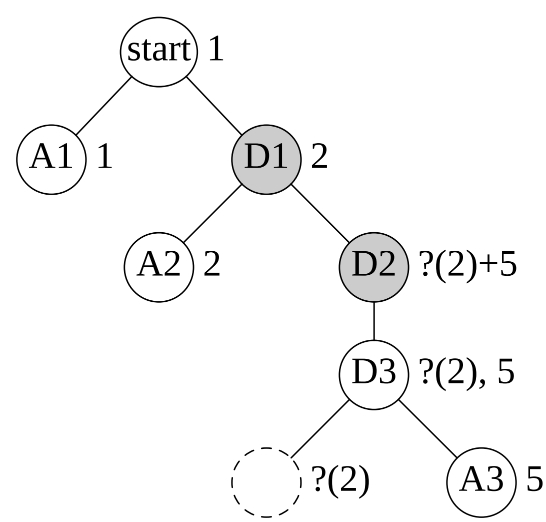
- Shows the count of each node in the nesting-tree for an execution-path $\pi(I)$ for some input I, giving an abstraction of $\pi(I)$.
  - Allows giving different weights for action-blocks at different levels and define a more refined form of C_0-measure.
  - Allows giving different weights for branches of decision-nodes at different levels and define a more refined form of C_1-measure.

Example.

- An action-block node shows its #(executions).
- A loop-decision node shows #(loop-body executions).
- An if-then-else decision node shows #(true-branch executions) and #(false-branch executions).
- The mark "?" shows an unknown value (based on the limited action-block instrumentation output); they can be derived if we know the source-code (or have the branch-instrumentation output) and they are indicated in parentheses next to '?'.

Instrumentation output for I = "abc de":

```
entered block A1
     entered block A2
          entered block A3
          entered block A3
          entered block A3
     entered block A2
          entered block A3
          entered block A3
```



EXERCISE

1. How can use the representation of test-paths to analyze a set of test-cases?