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Software Testing and Quality Assurance

Theory and Practice

Chapter 5

Data Flow Testing

Outline of the Chapter

- The General Idea
- Data Flow Anomaly
- Overview of Dynamic Data Flow Testing
- Data Flow Graph
- Data Flow Terms
- Data Flow Testing Criteria
- Comparison of Data Flow Testing Criteria
- Feasible Paths and Test Selection Criteria
- Comparison of Testing Techniques
- Summary

The General Idea

- A program unit accepts inputs, performs computations, assigns new values to variables, and returns results.
- One can visualize of "flow" of data values from one statement to another.
- A data value produced in one statement is expected to be used later.
  - Example
    - Obtain a file pointer ……. use it later.
  - If the later use is never verified, we do not know if the earlier assignment is acceptable.
- Two motivations of data flow testing
    - The memory location for a variable is accessed in a "desirable" way.
    - Verify the correctness of data values "defined" (i.e. generated) – observe that all the "uses" of the value produce the desired results.
- Idea: A programmer can perform a number of tests on data values.
  - These tests are collectively known as data flow testing.

The General Idea

- Data flow testing can be performed at two conceptual levels.
  - Static data flow testing
  - Dynamic data flow testing
- Static data flow testing
  - Identify potential defects, commonly known as **data flow anomaly.**
  - Analyze source code.
  - Do not execute code.
- Dynamic data flow testing
  - Involves actual program execution.
  - Bears similarity with control flow testing.
    - Identify paths to execute them.
    - Paths are identified based on **data flow testing criteria**.

Data Flow Anomaly

- Anomaly: It is an abnormal way of doing something.
  - Example 1: The second definition of x overrides the first.

```
x = f1(y);
x = f2(z);
```

- Three types of abnormal situations with using variable.
  - Type 1: Defined and then defined again
  - Type 2: Undefined but referenced
  - Type 3: Defined but not referenced

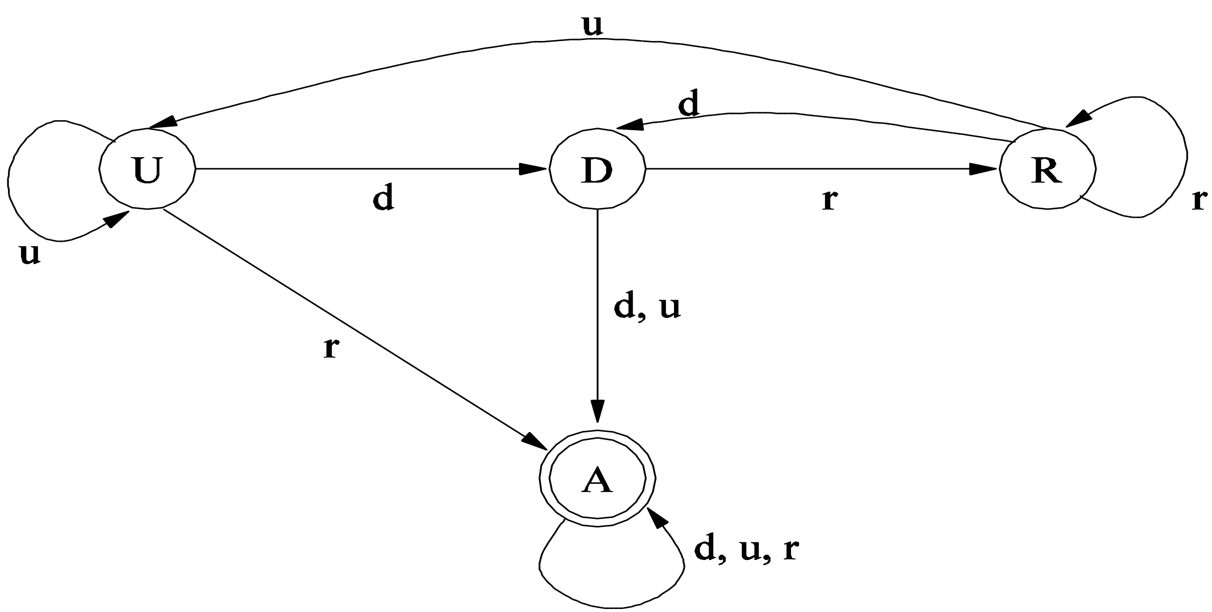
Data Flow Anomaly

- Type 1: Defined and then defined again (Example 1 above)
  - Four interpretations of Example 1
    - The first statement is redundant.
    - The first statement has a fault -- the intended one might be: w = f1(y).
    - The second statement has a fault – the intended one might be: v = f2(z).
    - There is a missing statement in between the two: v = f3(x).
  - Note: It is for the programmer to make the desired interpretation.
- Type 2: Undefined but referenced
  - Example: x = x – y – w; /* w has not been defined by the programmer. */
  - Two interpretations
    - The programmer made a mistake in using w.
    - The programmer wants to use the compiler assigned value of w.
- Type 3: Defined but not referenced
  - Example: Consider x = f(x, y). If x is not used subsequently, we have a Type 3 anomaly.

Data Flow Anomaly

- The concept of **a state-transition diagram** is used to **model a program variable** to identify data flow anomaly.
- Components of the state-transition diagrams
  - The states
    - U: Undefined
    - D: Defined but not referenced
    - R: Defined and referenced
    - A: Abnormal
  - The actions
    - *d*: define the variable
    - *r*: reference (or, read) the variable
    - *u*: undefine the variable

Data Flow Anomaly



Legends:

States

U: Undefined
D: Defined but not referenced
R: Defined and referenced
A: Abnormal

Actions

d: Define
r: Reference
u: Undefine

Figure 5.2: State transition diagram of a program variable [10] (©[1979] IEEE).

Data Flow Anomaly

- Obvious question: What is the relationship between the **Type 1, Type 2,** and **Type 3** anomalies and Figure 5.2?
- The three types of anomalies (Type 1, Type 2, and Type 3) are found in the diagram in the form of **action sequences**:
  - Type 1: *dd*
  - Type 2: *ur*
  - Type 3: *du*
- Detection of data flow anomaly via program instrumentation
  - Program instrumentation: Insert new code to monitor the states of variables.
  - If the state sequence contains *dd*, *ur*, or *du* sequence, a data flow anomaly is said to occur.
- Bottom line: What to do after detecting a data flow anomaly?
  - Investigate the cause of the anomaly.
  - To fix an anomaly, write new code or modify the existing code.

Overview of Dynamic Data Flow Testing

- A programmer manipulates/uses variables in several ways.
  - Initialization, assignment, using in a computation, using in a condition
- Motivation for data flow testing?
  - One should not feel confident that a variable has been **assigned the correct value**, if no test causes the execution of a **path** from the point of assignment to a point where the value is **used**.
  - Note
    - Assignment of correct value means whether or not a value has been correctly generated.
    - Use of a variable means
      - If new values of the same variable or other variables are generated.
      - If the variable is used in a conditional statement to alter the flow of control.
- The above motivation indicates that **certain kinds of paths** are executed in data flow testing.

Overview of Dynamic Data Flow Testing

- Data flow testing is outlined as follows:
  - Draw a data flow graph from a program.
  - Select one or more data flow testing criteria.
  - Identify paths in the data flow graph satisfying the selection criteria.
  - Derive path predicate expressions from the selected paths (See **Chapter 4**.)
  - Solve the path predicate expressions to derive test inputs (See **Chapter 4**.)

Data Flow Graph

- Occurrences of variables
  - Definition: A variable gets a new value.
    - i = x; /* The variable i gets a new value. */
  - Undefinition or kill: This occurs if the value and the location become unbound.
  - Use: This occurs when the value is fetched from the memory location of the variable. There are **two forms** of uses of a variable.
    - Computation use (c-use)
      - Example: x = 2*y; /* y has been used to compute a value of x. */
    - Predicate use (p-use)
      - Example: if (y > 100) { …} /* y has been used in a condition. */

Data Flow Graph

- A data flow graph is a directed graph constructed as follows.
  - A sequence of **definitions** and **c-uses** is associated with each **node** of the graph.
  - A set of **p-uses** is associated with each **edge** of the graph.
  - The entry node has a definition of each edge parameter and each nonlocal variable used in the program.
  - The exit node has an undefinition of each local variable.

Data Flow Graph

- **Example code: ReturnAverage() from Chapter 4**

```
public static double ReturnAverage(int value[],  int AS, int MIN, int MAX){
  /* Function: ReturnAverage  Computes the  average of all  those  numbers in the  input array  in
     the  positive  range  [MIN, MAX]. The  maximum size  of the array is AS.  But, the  array size
     could be smaller than AS in which case the end of input is represented by -999. */

      int i, ti, tv, sum;
      double av;
      i = 0; ti = 0; tv = 0; sum = 0;
      while (ti < AS && value[i] != -999) {
         ti++;
         if (value[i] >= MIN && value[i] <= MAX) {
            tv++;
            sum = sum + value[i];
         }
         i++;
      }
      if (tv > 0)
         av = (double)sum/tv;
      else
         av = (double) -999;
      return (av);
  }
```

Figure 4.6: A function to compute the average of selected integers in an array.

Data Flow Graph

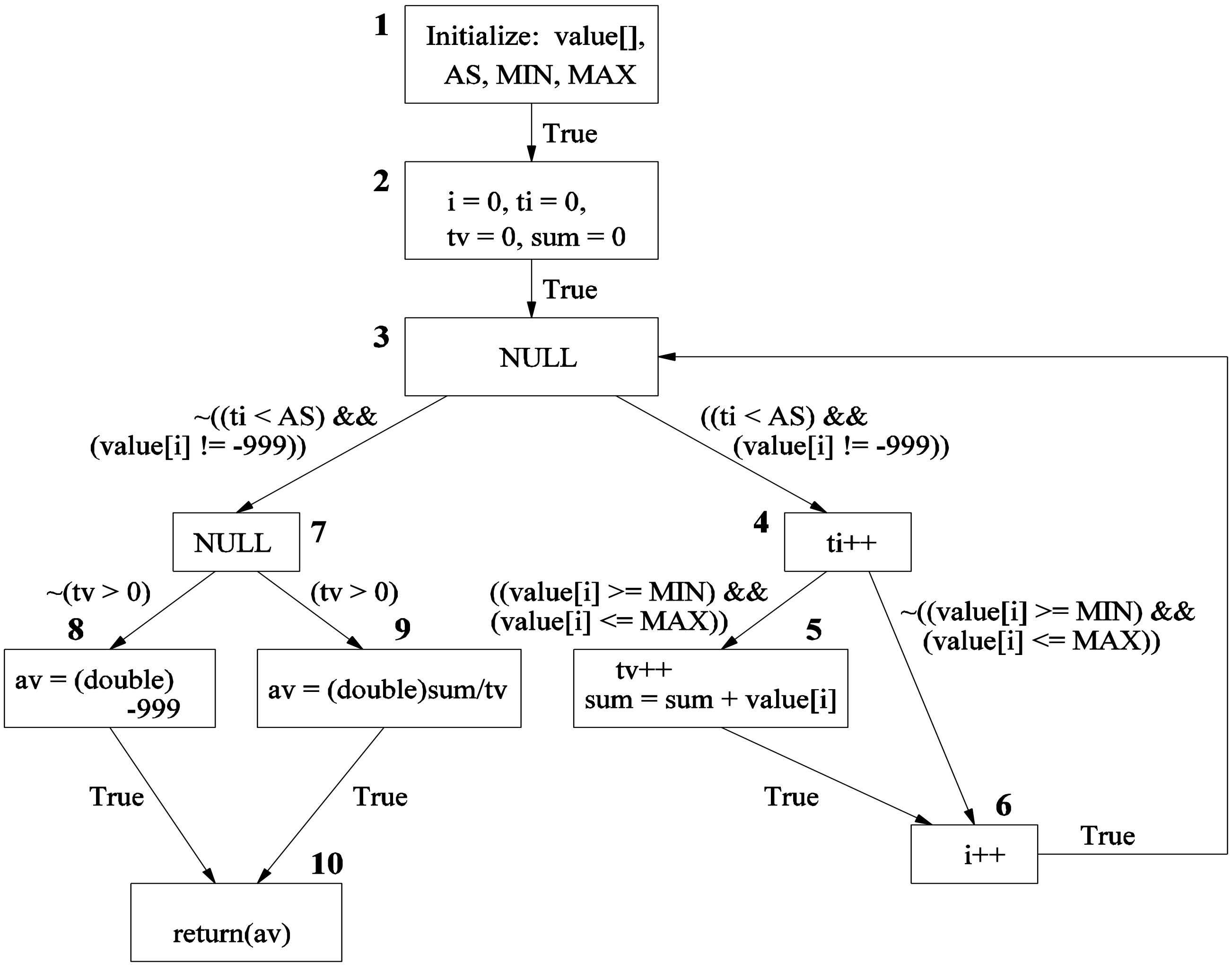


Figure 5.4: A data flow graph of ReturnAverage() example.

Data Flow Graph

- A data flow graph is a directed graph constructed as follows.
  - A sequence of **definitions** and **c-uses** is associated with each **node** of the graph.
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  - The exit node has an undefinition of each local variable.

Data Flow Terms

- **Global c-use**: A c-use of a variable x in node i is said to be a global c-use if x has been defined before in a node other than node i.
  - Example: The c-use of variable tv in node 9 (Figure 5.4) is a global c-use.

- **Definition clear path**: A path (i – n_1 – … n_m – j), m ≥ 0, is called a definition clear path (def-clear path) with respect to variable x

  from node i to node j, and

  from node i to edge (n_m, j),

  if x has been neither defined nor undefined in nodes n_1 – … n_m.
  - Example: (2 – 3 – 4 – 6 – 3 – 4 – 6 – 3 – 4 – 5) is a def-clear path w.r.t. tv in Fig. 5.4.
  - Example: (2 – 3 – 4 – 5) and (2 – 3 – 4 – 6) are def-clear paths w.r.t. variable tv from node 2 to 5 and from node 2 to 6, respectively, in Fig. 5.4.

Data Flow Terms

- **Global definition**: A node i has a global definition of variable x if node i has a definition of x and there is a def-clear path w.r.t. x from node i to some

    node containing a global c-use, or

    edge containing a p-use of

  variable x.

- **Simple path**: A simple path is a path in which all nodes, except possibly the first and the last, are distinct.
  - Example: Paths (2 – 3 – 4 – 5) and (3 – 4 – 6 – 3) are simple paths.
- **Loop-free paths**: A loop-free path is a path in which all nodes are distinct.
- **Complete path**: A complete path is a path from the entry node to the exit node.

Data Flow Terms

- **Du-path**: A path ($n_1 - n_2 - \ldots - n_j - n_k$) is a du-path path w.r.t. variable x if node n_1 has a global definition of x and <u>either</u>
  - node n_k has a global c-use of x and ($n_1 - n_2 - \ldots - n_j - n_k$) is a def-clear simple path w.r.t. x, <u>or</u>
  - Edge (n_j, n_k) has a p-use of x and ($n_1 - n_2 - \ldots - n_j - n_k$) is a def-clear, loop-free path w.r.t. x.

  – Example: Considering the global definition and global c-use of variable tv in nodes 2 and 5, respectively, (2 – 3 – 4 – 5) is a du-path.

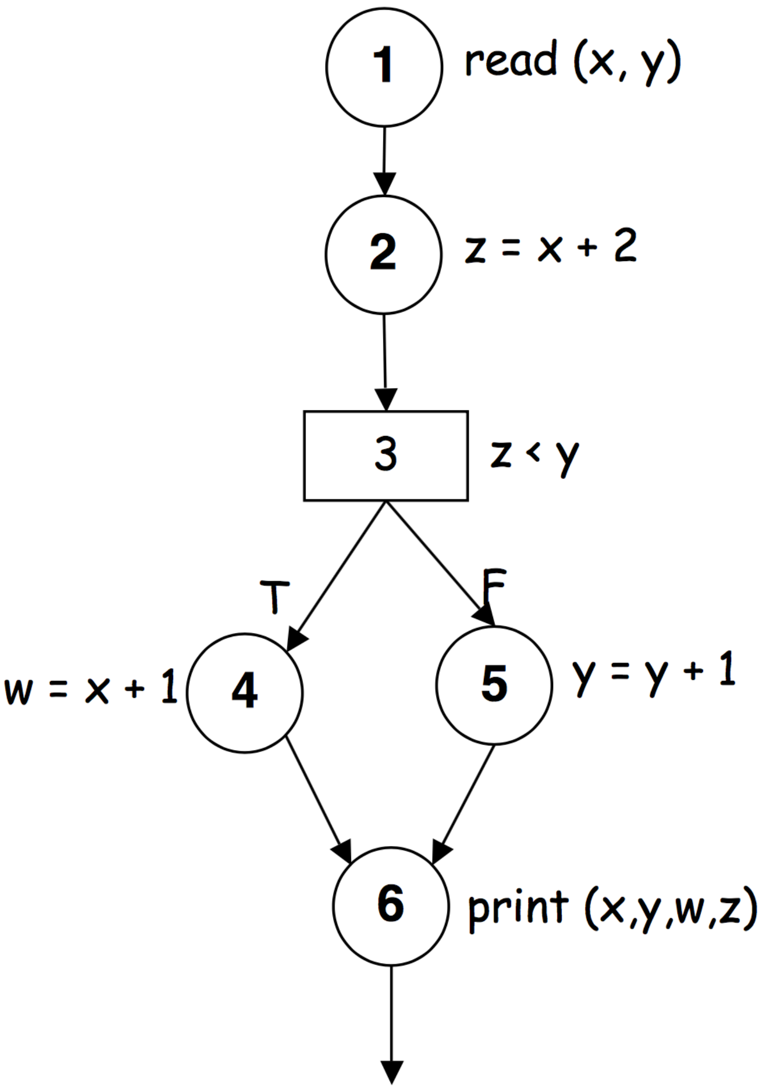
  – Example: Considering the global definition and p-use of variable tv in nodes 2 and on edge (7, 9), respectively, (2 – 3 – 7 – 9) is a du-path.

Du Example


```
1.   read (x, y);
2.   z = x + 2;
3.   if (z < y)
4         w = x + 1;
     else
5.        y = y + 1;
6.   print (x, y, w, z);
```

Def	C-use	P-use
x, y		
z	x	
		z, y
w	x	
y	y	
	x, y, w, z	

Du Associations



Some Def-Use Associations:

(x, 1, 2), (x, 1, 4), …

(y, 1, (3,t)), (y, 1, (3,f)), (y, 1, 5), …

(z, 2, (3,t)),...

Du Associations - More examples


```
read (z)
x = 0
y = 0
if (z ≥ 0)
{
        x = sqrt (z)
        if (0 ≤ x && x ≤ 5)
                y = f (x)
        else
                y = h (z)
}
y = g (x, y)
print (y)
```

Du Associations - More examples

```
read (z)
x = 0
y = 0
if (z ≥ 0)
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Du Associations - More examples


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}
y = g (x, y)
print (y)
```

Data Flow Testing Criteria

- Seven data flow testing criteria
  - All-defs
  - All-c-uses
  - All-p-uses
  - All-p-uses/some-c-uses
  - All-c-uses/some-p-uses
  - All-uses
  - All-du-paths

Data Flow Testing Criteria

- **All-defs**
  - For ***each variable*** x and ***each node*** i, such that x has a global definition in node i, select a complete path which includes a def-clear path from node i to
    - node j having a global c-use of x, or
    - edge (j, k) having a p-use of x.
  - Example (**partial**): Consider tv with its global definition in node 2. Variable tv has a global c-use in node 5, and there is a def-clear path (2 – 3 – 4 – 5) from node 2 to node 5. Choose a complete path (1 – 2 – 3 – 4 – 5 – 6 – 3 – 7 – 9 – 10) that includes the def-clear path (2 – 3 – 4 – 5) to satisfy the all-defs criterion.

Data Flow Testing Criteria

- **All-c-uses**
  - For ***each variable*** x and ***each node*** i, such that x has a global definition in node i, select complete paths which include def-clear paths from node i to ***all*** nodes j such that there is a global c-use of x in j.
  - Example (**partial**): Consider variable ti, which has a global definition in 2 and a global c-use in node 4. From node 2, the def-clear path to 4 is (2 – 3 – 4). One may choose the complete path (1 – <u>2 – 3 – 4</u> – 6 – 3 – 7 – 8 – 10). (There three other complete paths.)
- All-p-uses
  - For ***each variable*** x and ***each node*** i, such that x has a global definition in node i, select complete paths which include def-clear paths from node i to ***all*** edges (j, k) such that there is a p-use of x on (j, k).
  - Example (**partial**): Consider variable tv, which has a global definition in 2 and p-uses on edges (7, 8) and (7, 9). From node 2, there are def-clear paths to (7, 8) and (7, 9), namely (2 – 3 – 7 – 8) and (2 – 3 – 7 – 9). The two complete paths are: (1 – <u>2 – 3 – 7 – 8</u> – 10) and (1 – <u>2 – 3 – 7 – 9</u> – 10).

Data Flow Testing Criteria

- All-p-uses/some-c-uses
  - This criterion is identical to the all-p-uses criterion **except** when a variable x has no p-use. If x has no p-use, then this criterion reduces to the some-c-uses criterion.
  - Some-c-uses: For ***each variable*** x and ***each node*** i, such that x has a global definition in node i, select complete paths which include def-clear paths from node i to ***some*** nodes j such that there is a global c-use of x in j.
  - Example (**partial**): Consider variable i, which has a global definition in 2. There is no p-use of i. Corresponding to the global definition of I in 2, there is a global c-use of I in 6. The def-clear path from node 2 to 6 is (2 – 3 – 4 – 5 – 6). A complete path that includes the above def-clear path is (1 – 2 – 3 – 4 – 5 – 6 – 7 – 9 – 10).

Data Flow Testing Criteria

- **All-c-uses/some-p-uses**
  - This criterion is identical to the all-c-uses criterion **except** when a variable x has no c-use. If x has no global c-use, then this criterion reduces to the some-p-uses criterion.
  - Some-p-uses: For ***each variable*** x and ***each node*** i, such that x has a global definition in node i, select complete paths which include def-clear paths from node i to ***some*** edges (j, k) such that there is a p-use of x on (j, k).
- **All-uses**: This criterion produces a set of paths due to the **all-p-uses** criterion **and** the **all-c-uses** criterion.

- **All-du-paths**: For each variable x and for each node i, such that x has a global definition in node i, select complete paths which include **all du-paths** from node i
  - To all nodes j such that there is a global **c-use** of x in j, and
  - To all edges (j, k) such that there is a **p-use** of x on (j, k).

Comparison of Data Flow Testing Criteria

- Comparison of two testing criteria c1 and c2
  - We need a way to compare the two.
- **Includes** relationship: Given two test selection criteria c_1 and c_2, c_1 includes c_2 if for every def/use graph, any set of complete paths of the graph that satisfies c_1 also satisfies c_2.
- **Strictly includes** relationship: Given two test selection criteria c_1 and c_2, c_1 strictly includes c_2 provided c_1 includes c_2 **and** for some def/use graph, there is a set of complete paths of the graph that satisfies c_2 but not c_1.

Comparison of Data Flow Testing Criteria

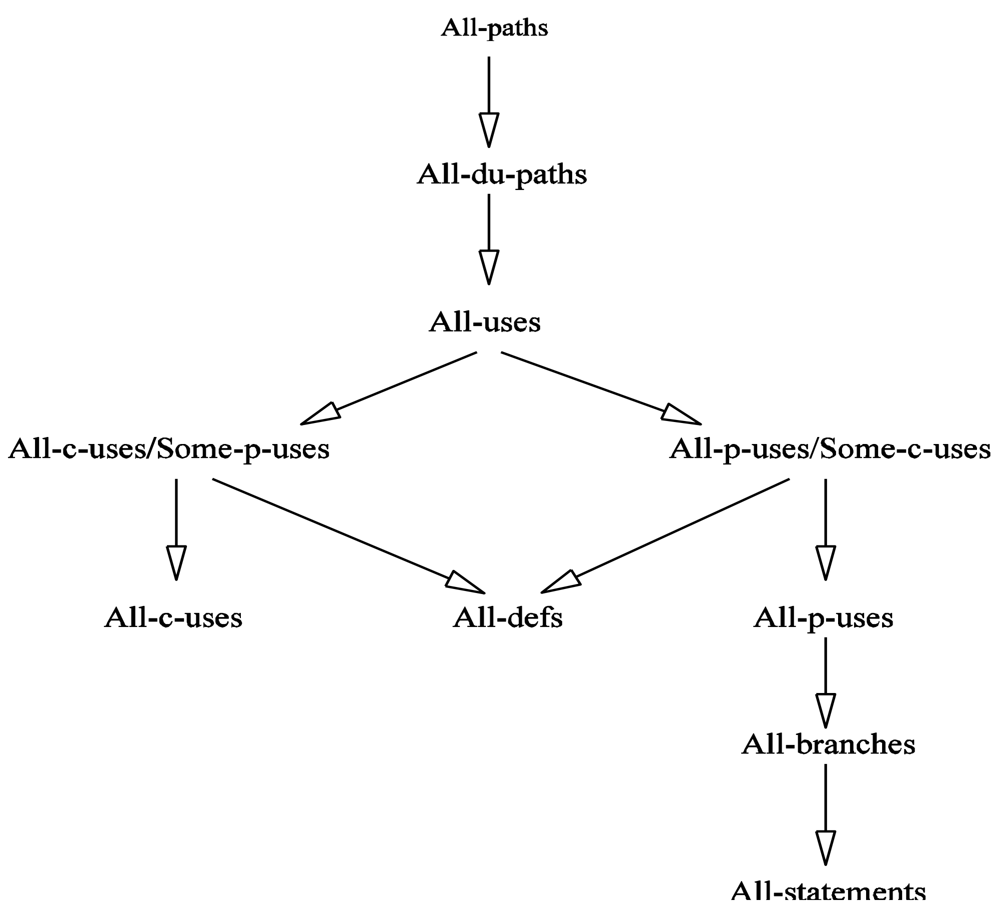

Figure 5.5: The relationship among DF (data flow) testing criteria [6] (©[1988] IEEE).

Feasible Paths and Test Selection Criteria

- Executable (feasible) path
  - A complete path is executable if there exists an assignment of values to input variables and global variables such that all the path predicates evaluate to true.

- Consideing the feasibility of paths, the "includes" relatipnships of Fig. 5.5 change to Fig. 5.6.

Comparison of Testing Techniques

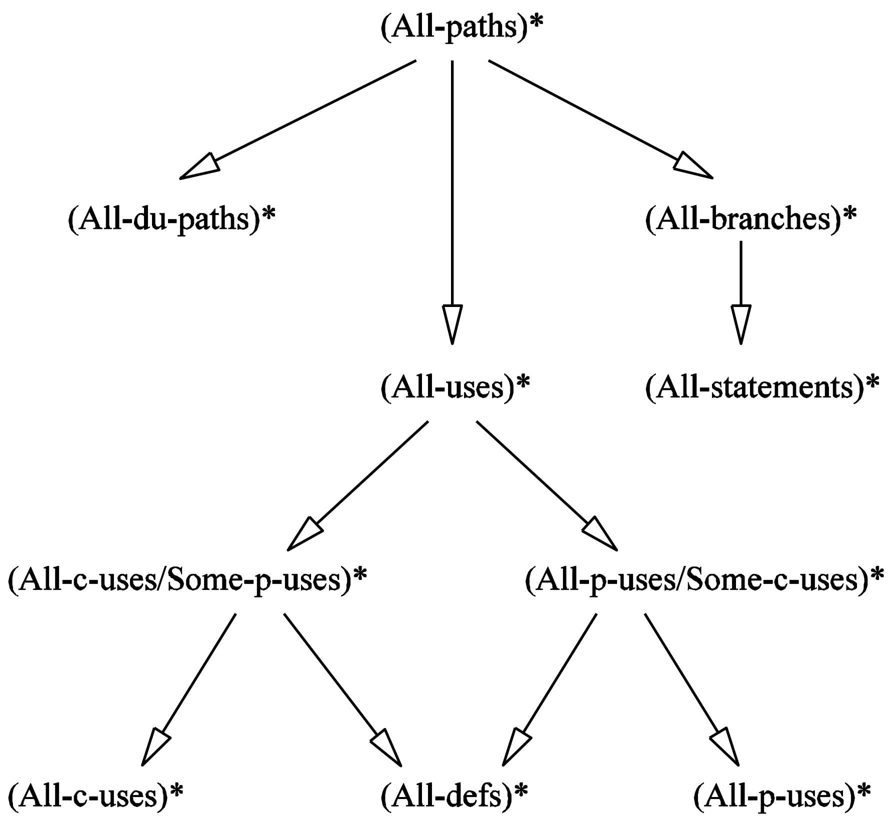

Figure 5.6: The relationship among the FDF (feasible data flow) testing criteria [6] (©[1988] IEEE).

Comparison of Testing Techniques

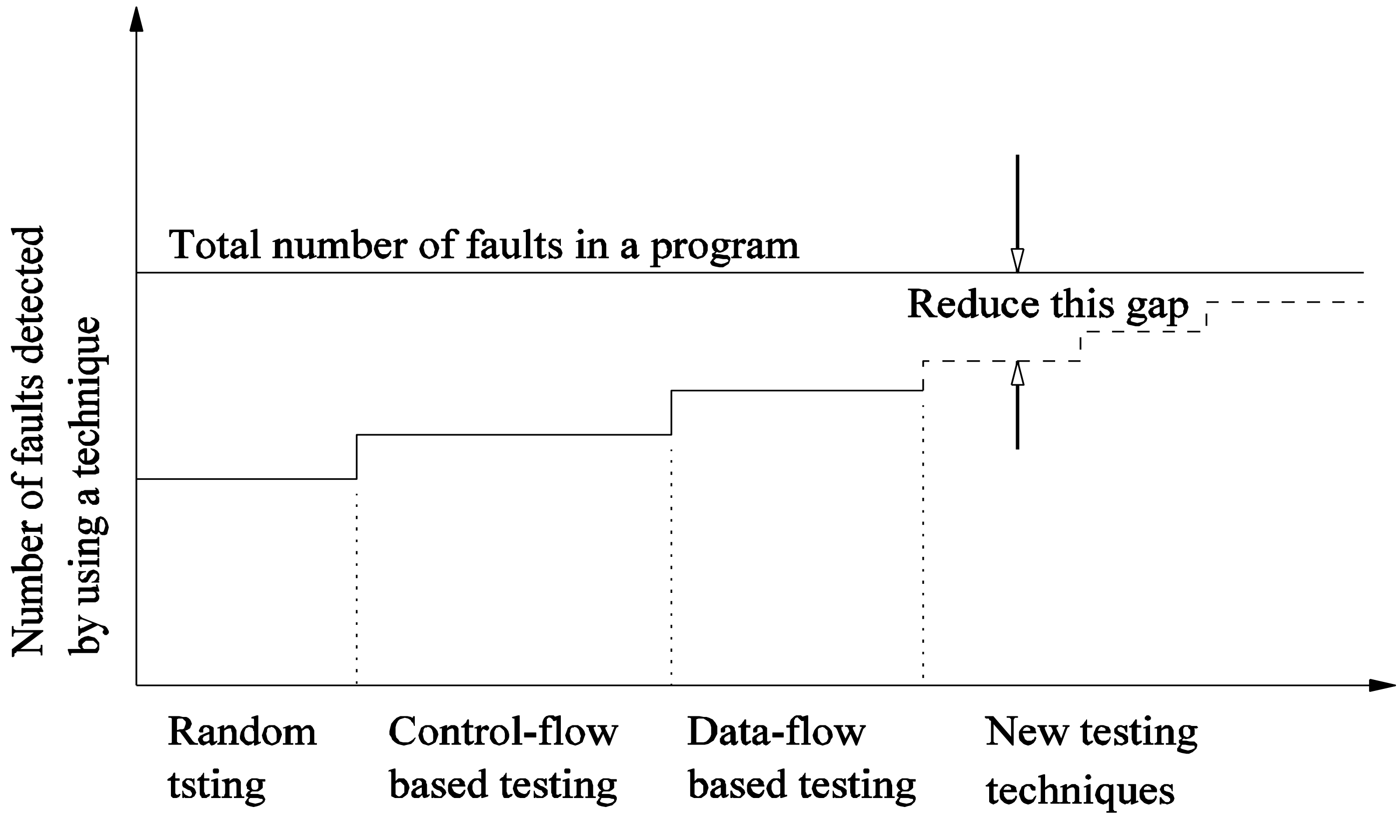

Figure 5.7: Limitations of different fault detection techniques.

Summary

- **Data flow** is a readily identifiable concept in a program unit.
- Data flow testing
  - Static
  - Dynamic
- Static data flow analysis
  - Data flow **anomaly** can occur due to programming errors.
  - **Three** types of data flow anomalies
    - (Type 1: *dd*), (Type 2: *ur*), (Type 3, *du*)
    - **Analyze** the code to **identify** and **remove** data flow anomalies.
- Dynamic data flow analysis
  - Obtain a data flow graph from a program unit.
  - Select paths based on DF criteria: *all-defs, all-c-uses, all-p-uses, all-uses, all-c-uses/some-p-uses, all-p-uses/some-c-uses, all-du-paths*.
  - The **includes** relationship is useful in comparing selection criteria.