EDITH COWAN UNIVERSITY

CSI3105: Software Testing

Module 6a: Data Flow Testing Introduction

Creative thinkers made here.

Lecture Summary

The learning goals for this week are:

- To learn about the coverage associated with Structural testing
- To employ data flow techniques for test case generation

This module relates to Chapter 7 of the textbook (but all the relevant information is here)

Outline of the Chapter

Lecture Summary

- Video 6b
    - Data flow anomalies
- Video 6c
    - Data flow graphs
- Video 6d
    - Data flow terminology
- Video 6e
    - Testing criteria
- Video 6f
    - Generating tests

CSI3105: Software Testing

Module 6b: Data Flow Anomalies

Creative thinkers made here.

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

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

Example 1

EDITH COWAN UNIVERSITY

Type 1: Defined and then defined again

- 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 another value

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

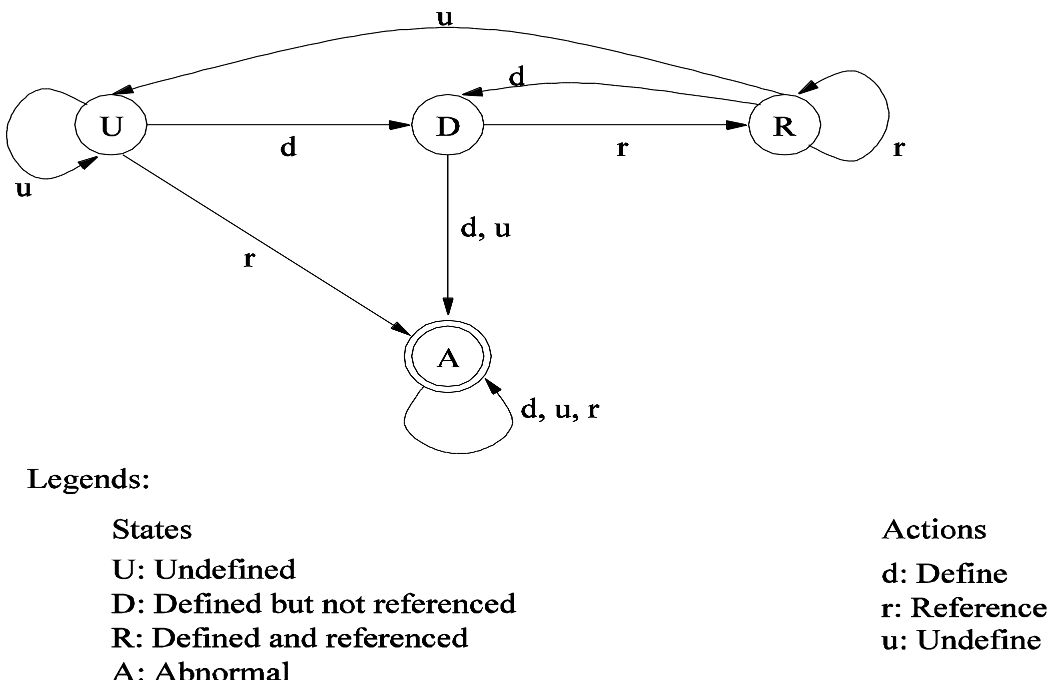


Figure 5.2: State transition diagram of a program variable [10] (©[1979] IEEE).

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

How do we interact with data?

A programmer manipulates/uses variables in several ways.

- Initialization, assignment, using in a computation, using in a condition

Overview of Dynamic Data Flow Testing

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 (Last weeks lecture.)
- Solve the path predicate expressions to derive test inputs (Last weeks lecture

CSI3105: Software Testing

Module 6c: Data Flow Graphs

Creative thinkers made here.

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.
  - iptr = i + x; // assign a value to the pointer
  - iptr = malloc(sizeof(int)); // unreferenced that value
- 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.

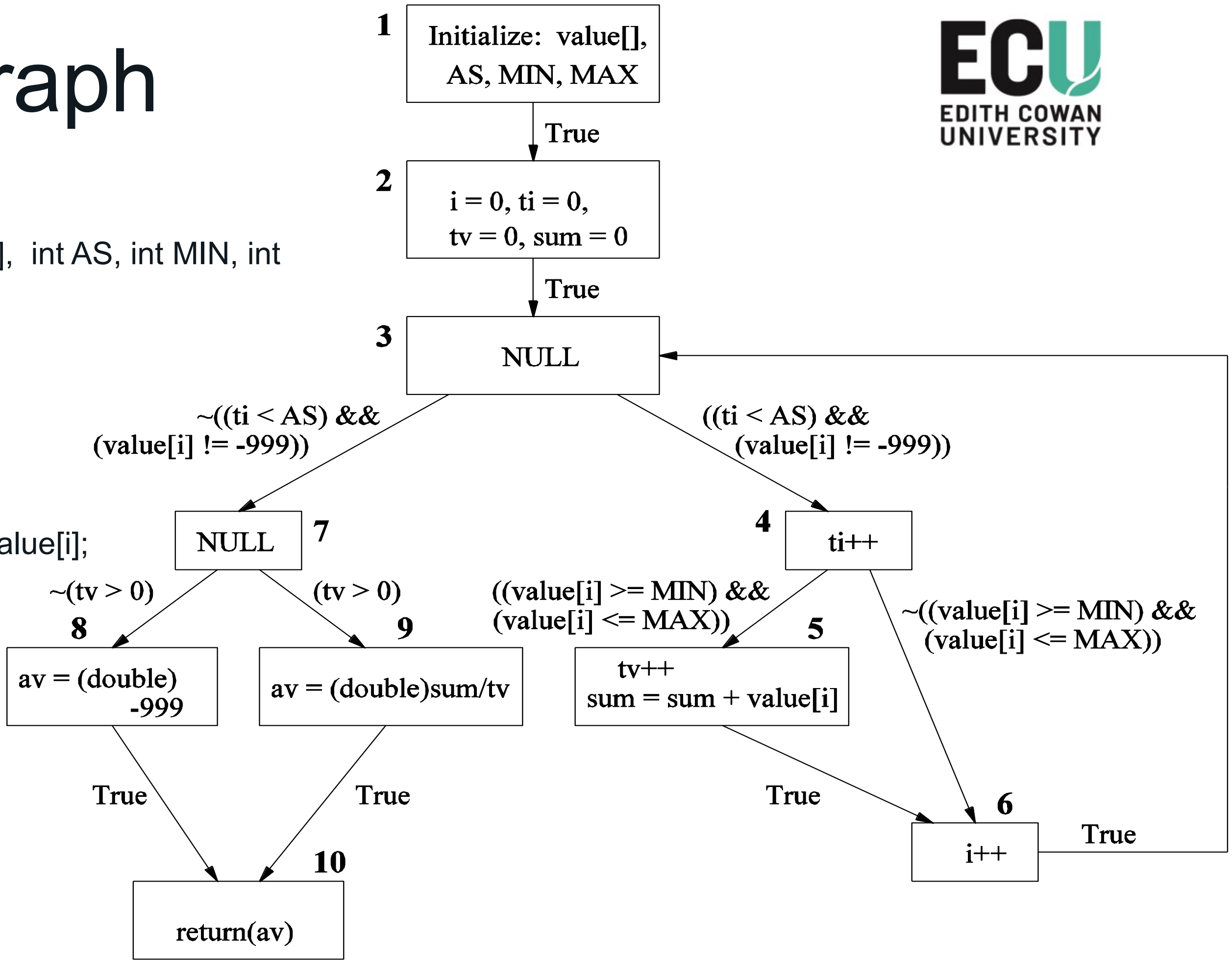

```
public static double ReturnAverage(int value[],  int AS,
int MIN, int MAX){

        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);
}
```

Data Flow Graph

```
public static double ReturnAverage(int value[],  int AS, int MIN, int MAX){

        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);
}
```



EDITH COWAN UNIVERSITY

CSI3105: Software Testing

Module 6d: Data Flow Testing Terms

Creative thinkers made here.

Data Flow Terms

We are interested in finding *paths* that include pairs of **definition and use of variables**

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) is a def-clear paths w.r.t. variable tv from node 2 to 5 ain Fig. 5.4.

Data Flow Graph

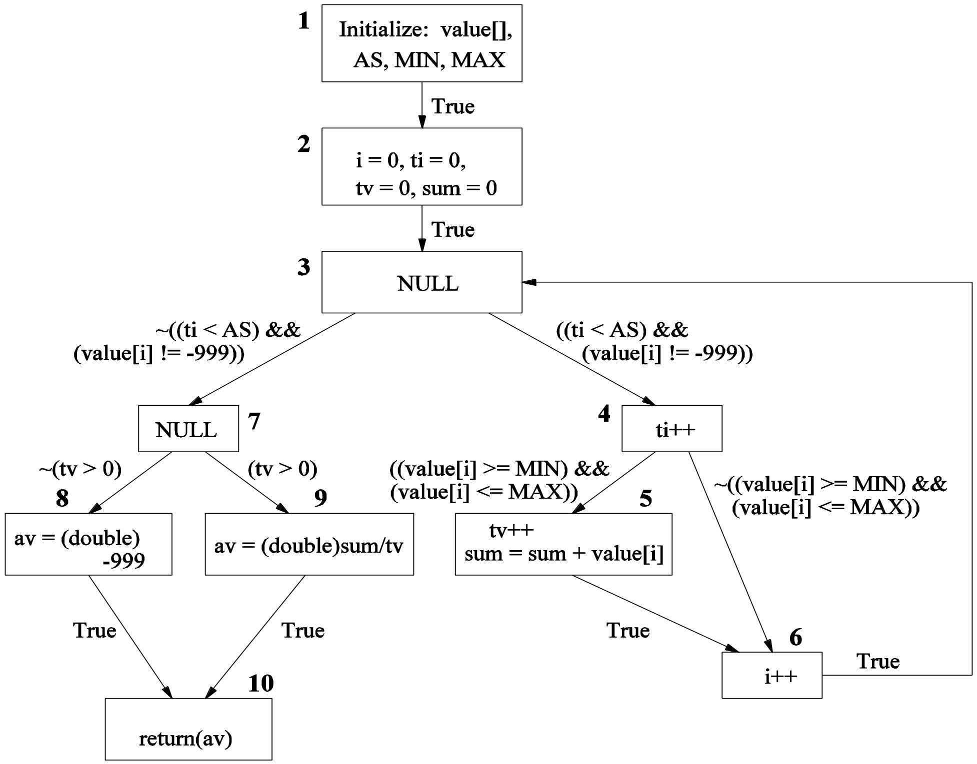


Figure 5.4: A data flow graph of ReturnAverage() example.

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) is a def-clear paths w.r.t. variable tv from node 2 to 5 ain 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

. Tv – global def in 2, global c use in 9 (2, 3, 7, 9)

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 Graph

An example of a global definition is, variable tv is **defined in node 2** and then **used globally in node 9**. If there is a def-clear path between these points—like (2 → 3 → 7 → 9)—so node 2 holds a **global definition** of tv. This ensures that the variable's value remains valid and unchanged along the way.

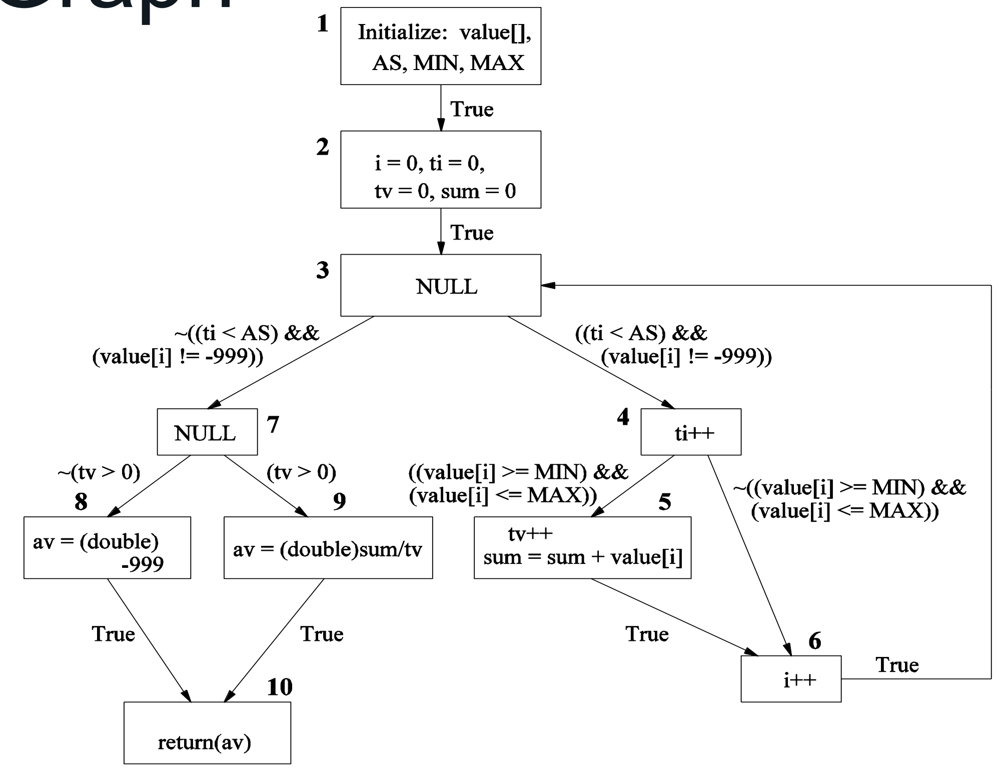


Figure 5.4: A data flow graph of ReturnAverage() example.

Data Flow Terms

Du-path: A path ($n_1 – n_2 – … – n_j – n_k$) is a du-path path w.r.t. variable x if node n_1 has a global definition of x and either

- node n_k has a global c-use of x and ($n_1 – n_2 – … – n_j – n_k$) is a def-clear simple path w.r.t. x, or
- Edge (n_j, n_k) has a p-use of x and ($n_1 – n_2 – … – n_j – n_k$) 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.

CSI3105: Software Testing

Module 6e: Data Flow Testing Criteria

Creative thinkers made here.

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

First step

- Build a Def-use table

```
1  double power(int x,int y){
2      int exp;
3      double res;
4      if (y>0)
5        exp = y;
6      else
7        exp = -y;
8      res=1;
9      while (exp!=0){
10       res *= x;
11       exp -= 1;
12     }
13     if (y<=0)
14       if(x==0)
15         abort;
16       else
17         return 1.0/res;
18     return res;
19 }
```

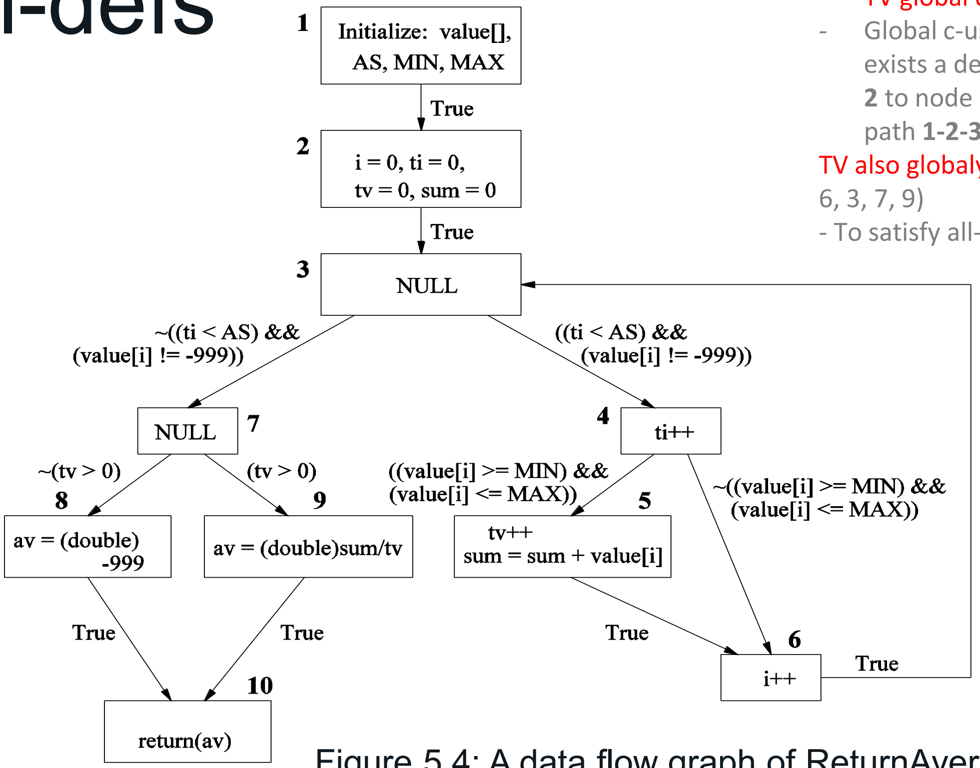
Var (v)	Defined in line (n)	C-use in line	P-use in line
X	1	10	14
Y	1	5,7	4,13
Exp	5	11	9
Exp	7	11	9
Exp	11	Etc..	
res	8	10,17,18	
res	10	10,17,18	

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.

All-defs



- TV global definition in node **2**.
- Global c-use of tv in node **5**, and there exists a def-clear path **2-3-4-5** from node **2** to node **5**. We choose a complete path **1-2-3-4-5-6-3-7-9-10**

TV also globaly defined in node 5, c use 9. (5, 6, 3, 7, 9)

- To satisfy all-defs do for values

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

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.)

Data Flow Testing Criteria

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 – 2 – 3 – 7 – 8 – 10) and (1 – 2 – 3 – 7 – 9 – 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 – <u>2 – 3 – 4 – 5 – 6</u> – 7 – 9 – 10).

Data Flow Testing Criteria

EDITH COWAN UNIVERSITY

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).

Data Flow Testing Criteria

EDITH COWAN UNIVERSITY

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 (CAN BE MULTIPLE PATHS FROM A DEF to A USE)** 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

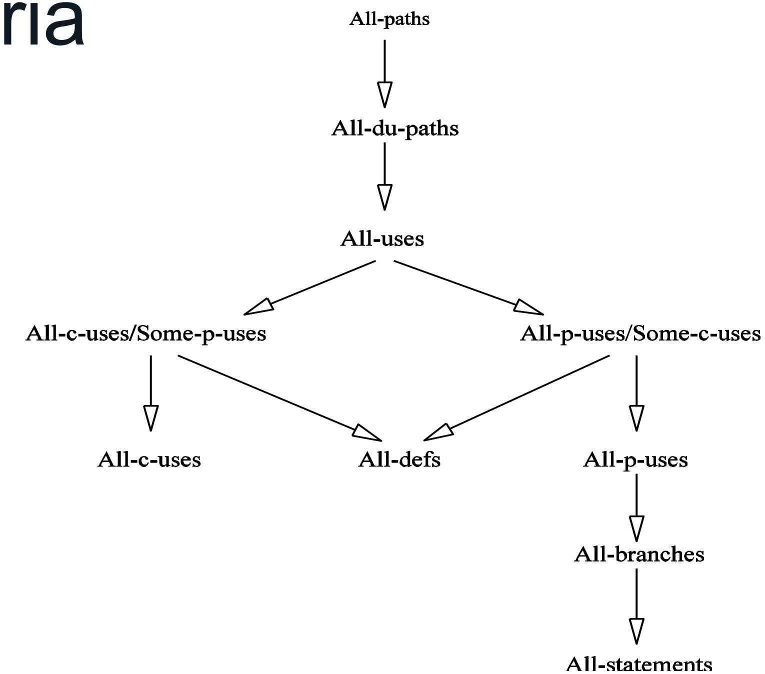


Figure 5.5: The relationship among DF (data flow) testing criteria [6] (©[1988] IEEE).

SUMMARY

Let's go back over this stuff

Def-Use Pairs

```
double power(int x,int y){
    int exp;
    double res;
    if (y>0)
      exp = y;
    else
      exp = -y;
    res=1;
    while (exp!=0){
      res *= x;
      exp -= 1;
    }
    if (y<=0)
      if(x==0)
        abort;
      else
        return 1.0/res;
    return res;
}
```

This code represents a function that will return the power of two ints.

The function takes in two integers x and y and returns the output of x^y.

Def-Use Pairs

```
1  double power(int x,int y){
2       int exp;
3       double res;
4       if (y>0)
5         exp = y;
6       else
7         exp = -y;
8       res=1;
9       while (exp!=0){
10        res *= x;
11        exp -= 1;
12      }
13      if (y<=0)
14        if(x==0)
15          abort;
16        else
17          return 1.0/res;
18      return res;
19 }
```

- What are Def-use pairs?
- The definition of a variable and its use in the functions
  - Computational use
  - Predicate use

- Du pair = (def, use, var)
- A partial example for the variable **res**
- Du1 = (line 8,line 10, res)
- Du2 = (line 8,line 17, res)
- Du3 = (line 8,line 18, res)
- Du4 = (line 10,line 10, res)
- Du5 = (line 10,line 17, res)
- Du6 = (line 10,line 18, res)

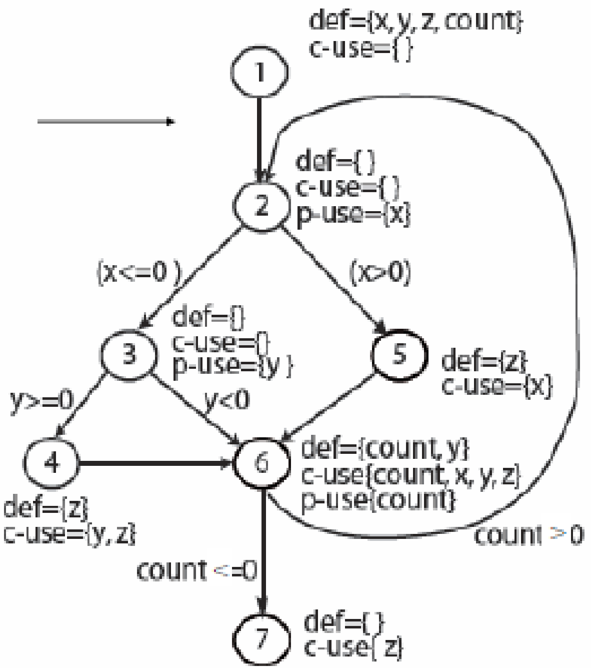
Def-Use Pairs

```
1  double power(int x,int y){
2      int exp;
3      double res;
4      if (y>0)
5        exp = y;
6      else
7        exp = -y;
8      res=1;
9      while (exp!=0){
10       res *= x;
11       exp -= 1;
12     }
13     if (y<=0)
14       if(x==0)
15         abort;
16       else
17         return 1.0/res;
18     return res;
19 }
```

Var (v)	Defined in line (n)	C-use in line	P-use in line
X	1	10	14
Y	1	5,7	4,13
Exp	5	11	9
Exp	7	11	9
Exp	11	Etc..	
res	8	10,17,18	
res	10	10,17,18	

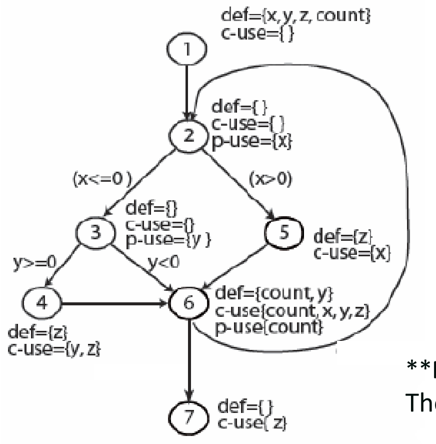
Def-Use Pairs

```
1   begin
2     float x, y, z=0.0;
3     int count;
4     input (x, y, count);
5     do {
6       if (x≤0) {
7         if (y≥0) {
8           z=y*z+1;
9         }
10      }
11      else{
12        z=1/x;
13      }
14      y=x*y+z
15      count=count-1
16    while (count>0)
17    output (z);
18  end
```



Node	Lines
1	1, 2, 3, 4
2	5, 6
3	7
4	8, 9, 10
5	11, 12, 13
6	14, 15, 16
7	17, 18

Def Use Pairs



A du-path with respect to variable v is a simple path, that is Def-clear from a definition of v to a use of v

Variable (v)	Defined in node (n)	dcu (v, n)	dpu (v, n)
x	1	{5, 6}	{(2, 3), (2, 5)}
y	1	{4, 6}	{(3, 4), (3, 6)}
y	6	{4, 6}	{(3, 4), (3, 6)}
z	1	{4, 6, 7}	{ }
z	4	{4, 6, 7 }	{ }
z	5	{4, 6, 7}	{ }
count	1	{6}	{(6, 2), (6, 7) }
count	6	{6}	{(6, 2), (6, 7) }

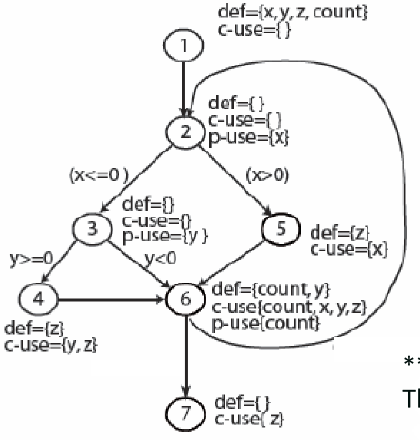
****NOTE**
The du path is underlined and bold. The du-path is sitting inside the whole path

All-defs (Each def to at least one use)
X – du (1,5,x) – path = **<u>1,2,5</u>**,6,2,3,6,7

All-c-uses (Each def reaches all c-use)
X – du (1,5,x) – path = **<u>1,2,5</u>**,6,2,3,6,7
X – du (1,6,x) – path = **<u>1,2,3,6</u>**,7

All-uses (Each def reaches all p and c use)
X – du (1,5,x) – path = **<u>1,2,5</u>**,6,2,3,6,7
X – du (1,6,x) – path = **<u>1,2,3,6</u>**,7
X – du (1,(2,3),x) – path = **<u>1,2,3</u>**, 6,7
X – du (1,(2,5),x) – path = **<u>1,2,5</u>**, 6, 7

Def Use Pairs



A du-path with respect to variable v is a simple path, that is Def-clear from a definition of v to a use of v

Variable (v)	Defined in node (n)	dcu (v, n)	dpu (v, n)
x	1	{5, 6}	{(2, 3), (2, 5)}
y	1	{4, 6}	{(3, 4), (3, 6)}
y	6	{4, 6}	{(3, 4), (3, 6)}
z	1	{4, 6, 7}	{ }
z	4	{4, 6, 7 }	{ }
z	5	{4, 6, 7}	{ }
count	1	{6}	{(6, 2), (6, 7) }
count	6	{6}	{(6, 2), (6, 7) }

NOTE

The du path is underlined and bold. The du-path is sitting inside the whole path

All-defs (Each def to at least one use)

y – du (1,4,y) – path = **<u>1,2,3,4</u>**,6,7

y – du (6,4,y) – path = 1,2,3,**<u>6,2,3,4</u>**,6,7

All-uses (Each def reaches all p and c use)

y – du (1,4,y) – path = **<u>1,2,3,4</u>**,6,7

y – du (1,6,y) – path = **<u>1,2,3,6</u>**,7

y – du (1,(3,4),y) – path = **<u>1,2,3</u>,4**,6,7 (dup)

y – du (1,(3,6),y) – path = **<u>1,2,3,6</u>**,7 (dup)

y – du (6,4,y) – path = 1,2,3,**<u>6,2,3,4</u>**,6,7

y – du (6,6,y) – path = 1,2,5,**<u>6,2,3,6</u>**,7

y – du (6,(3,4),y) – path = **<u>a path…</u>**

y – du (6,(3,6),y) – path = **<u>a path…</u>**

All-du-paths (Each def to all possible du-paths)

y – du (1,4,y) – path = **<u>1,2,3,4</u>**,6,7

y – du (1,6,y) – path = **<u>1,2,3,6</u>**,7

y – du (1,6,y) – path = **<u>1,2,5,6</u>**,7 (extra path compared to all-uses)

y – du (1,(3,4),y) – path = **<u>1,2,3</u>,4**,6,7 (dup)

y – du (1,(3,6),y) – path = **<u>1,2,3,6</u>**,7 (dup)

y – du (6,4,y) – path = 1,2,3,**<u>6,5,2,3,4</u>**,6,7

y – du (6,6,y) – path = 1,2,5,**<u>6,5,2,3,6</u>**,7

y – du (6,6,y) – path = 1,2,5,**<u>6,5,2,3,6</u>**,7

y – du (6,(3,4),y) – path = **<u>a path…</u>**

y – du (6,(3,6),y) – path = **<u>a path…</u>**

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.

Comparison of Testing Techniques

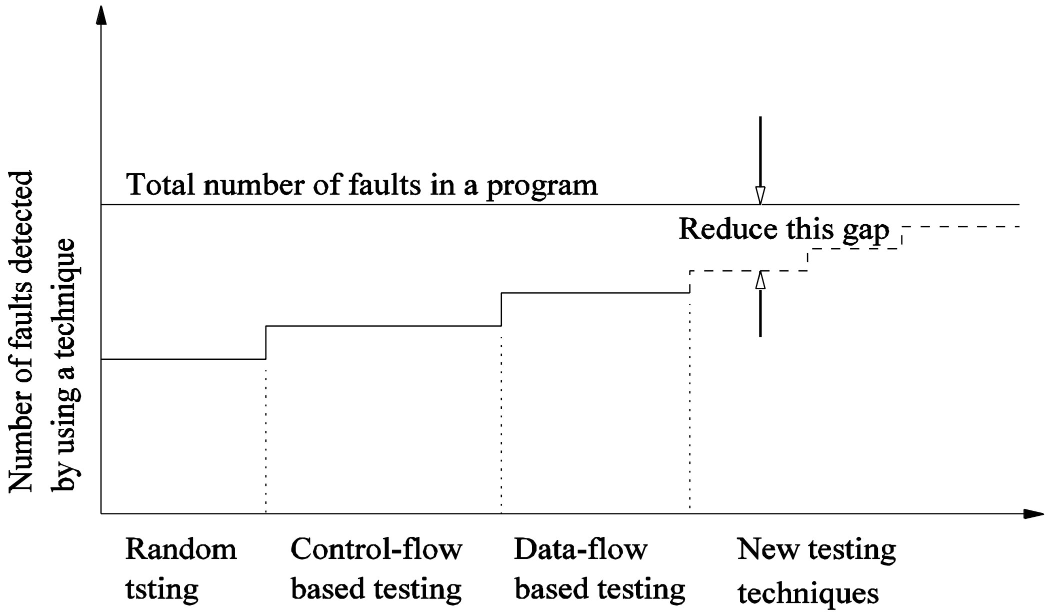


Figure 5.7: Limitations of different fault detection techniques.

CSI3105: Software Testing

Module 6f: Data Flow Testing Generation

Creative
thinkers
made here.

Generating Test Input

Having identified a path, a key question is how to make the path execute, if possible.

- Generate input data that satisfy all the conditions on the path.

Key concepts in generating test input data

- Input vector
- Predicate
- Path condition
- Predicate interpretation
- Path predicate expression
- Generating test input from path predicate expression

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.