Dataflow-based Coverage Criteria

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Speaker Biographical Sketch

- Professor & Director of International Outreach
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Basic Concepts

- We will now examine some test adequacy criteria based on the flow of "data" in a program. This is in contrast to criteria based on the flow of "control" that we have examined so far.
- Test adequacy criteria based on the flow of data are useful in improving tests that are adequate with respect to controlflow-based criteria.
- Let us look at an example.

Example: Test Enhancement using Dataflow **(1)**

```
begin
  int x, y; float z;
  input (x, y);
  z=0;
  if (x== 0)
    z=z+y;
  else z=z-y;
  if (y! =0)
    z=z/x;
  else z=z*x;
  output(z);
end
```

Question: Does the following test set reveal the bug?

Test	x	y	z
t_1	0	0	0.0
t_2	1	1	1.0

Example: Test Enhancement using Dataflow (2)

- Neither of the two test cases forces the use of *z* defined on line 6, at line 9. To do so one requires a test that causes conditions at lines 5 and 8 to be true (i.e., need to satisfy *x* = = 0 and *y* != 0)

- The test which we have does not force the execution of this path and hence the *divide by zero* error is not revealed.

```
1    begin
2      int x, y; float z;
3      input (x, y);
4      z=0;
5      if (x==0)
6        z=z+y;
7      else z=z-y;
8      if (y! =0) ← This condition should be (y! =0 and x! =0)
9        z=z/x;
10     else z=z*x;
11     output(z);
12   end
```

define *z* here (line 6)

use *z* here (line 9)

Example: Test Enhancement using Dataflow (3)

- Verify that the following test set covers all def-use pairs of *z* and reveals the bug.

Test	x	y	z	*def-use pairs covered	
t_1	0	0	0.0	(4,6), (6,10), (10, 11)	4, 5, 6, 8, 10
t_2	1	1	−1.0	(4,7), (7,9), (9, 11)	4, 5, 7, 8, 9
t_3	0	1	---	(4,6), (6,9)	4, 5, 6, 8, 9 (reveal the bug)
t_4	1	0	0.0	(4,7), (7,10), (10, 11)	4, 5, 7, 8, 10

*In the pair (l_1, l_2), z is defined in l_1 and used in line l_2.

def-use pairs with respect to the variable *z*

Definitions and Uses (1)

- A program written in a procedural language, such as C and Java, contains variables.
- Variables are defined by assigning values to them and are used in expressions.
  - Statement $x = y + z$ defines variable x and uses variables y and z
  - Statement scanf ("%d %d", &*x*, &*y*) defines variables *x* and *y*
  - Statement printf ("Output: %d \n", *x* + *y*) uses variables *x* and *y*

Definitions and Uses (2)

- A parameter *x* passed as *call-by-value* to a function, is considered as *a use* of (or a reference to) *x*
- A parameter *x* passed as *call-by-reference*, can serve as *a definition* and *use* of *x*

Definitions and Uses: Pointers

- Consider the following sequence of statements that use pointers.

```
z=&x;
y=z+1;
*z=25;
y=*z+1;
```

  - The first defines a pointer variable *z*
  - the second defines *y* and uses *z*
  - the third defines *x* through the pointer variable *z*, and
  - the last defines *y* and uses *x* accessed through the pointer variable *z*

Variable *z* is a pointer pointing to variable *x* and contains the memory address of variable *x*.
**z* retrieves the value at the memory address pointed by variable *z*. Consequently, **z* = 25 is to assign 25 to the memory address pointed by variable *z*. That is, to assign 25 to variable *x*.

y = **z* + 1 is to define *y* as the sum of 1 and the value at the memory address pointed by variable *z*, i.e., the value of *x*

Definitions and Uses: Arrays

- Arrays are also tricky. Consider the following declaration and two statements in C:

```
int A[10];
A[i]=x+y;
```

- The first statement defines variable A.
  The second statement defines A and uses *i*, *x*, and *y*.

  Alternate: *second statement defines* A[*i*] *and not the entire array* A. The choice of whether to consider the entire array A as defined or the specific element *depends upon how stringent the requirement for coverage analysis is.*

C-Use

- Uses of a variable that occurs within an expression as part of an *assignment statement*, in an *output statement*, as a *parameter within a function call*, and in *subscript expressions*, are classified as c-use, where the "c" in c-use stands for computational.
- How many c-uses of *x* can you find in the following statements?

```
z=x+1;
A[x-1]= B[2];
foo(x*x)
output(x);
```

- Answer = ?

P-Use

- The occurrence of a variable in an expression used as a *condition in a branch statement* such as an *if* and a *while*, is considered as a p-use. The “p” in p-use stands for predicate.

- How many p-uses of *z* and *x* can you find in the following statements?

```
if(z>0){output (x)};
while(z>x){...};
```

- Answer = ?

P-Use: Possible Confusion

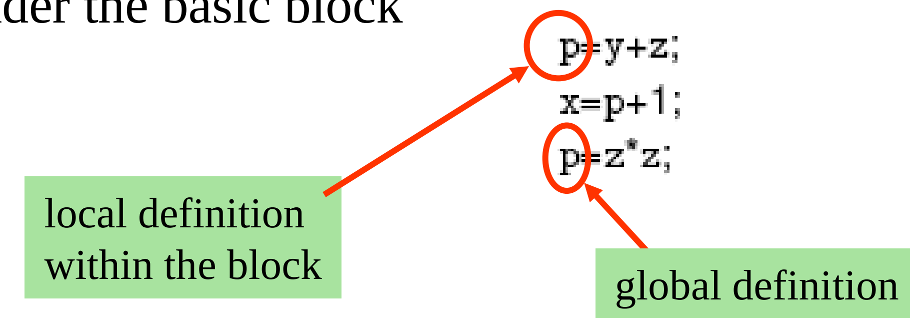
- Consider the statement:

```
if(A[x+1]>0){output (x)};
```

- The use of A is clearly a p-use.
- Is the use of *x* in the subscript a c-use or a p-use?

C-Uses Within a Basic Block

- Consider the basic block



- While there are two definitions of *p* in this block, *only the second definition will propagate to the next block.* The first definition of *p* is considered local to the block while the second definition is global. *We are only concerned with global definitions and uses.*
- Note that *y* and *z* are global uses; their definitions flow into this block from some other block.

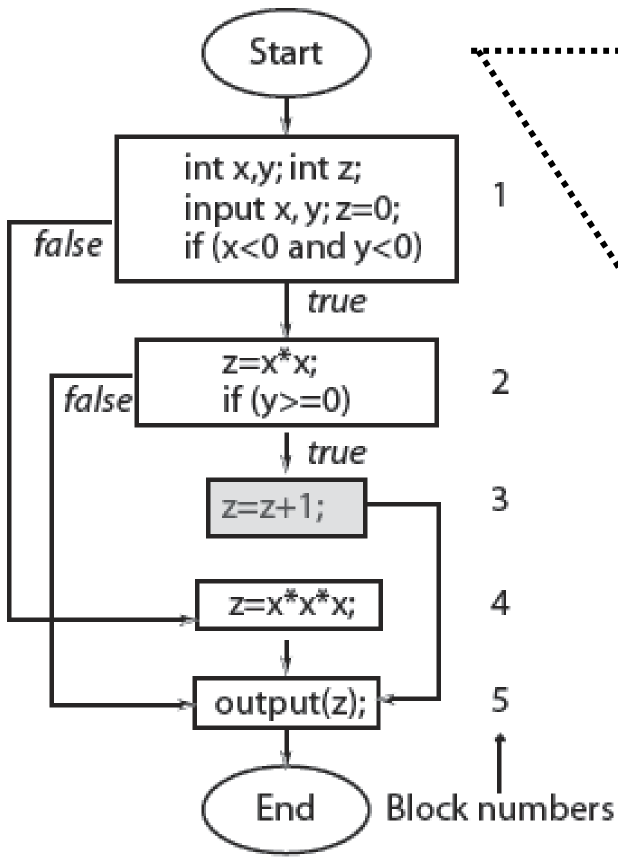
Dataflow Graph

- *A dataflow graph of a program*, also known as *def-use graph*, captures the flow of definitions (also known as defs) and uses across basic blocks in a program.
- *It is similar to a control flow graph* of a program in that the nodes, edges, and all paths in the control flow graph are preserved in the data flow graph. An example follows.

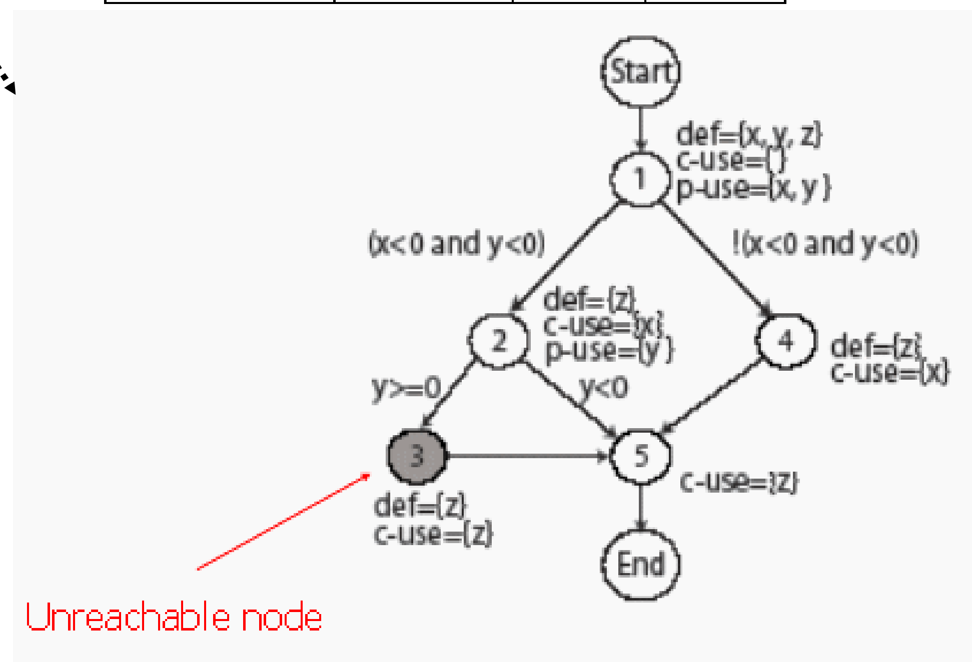
Dataflow Graph: Example **(1)**

- Given a program, find its basic blocks, compute defs, c-uses and p-uses in each block. *Each block becomes a* node *in the def-use graph (this is similar to the control flow graph).*
- *Attach defs, c-use and p-use to each node in the graph.*
  Label each edge with the condition which when true causes the edge to be taken.
- We use $d_i(x)$ to refer to the definition of variable x at node i. Similarly, $u_i(x)$ refers to the use of variable x at node i.

Dataflow Graph: Example **(2)**

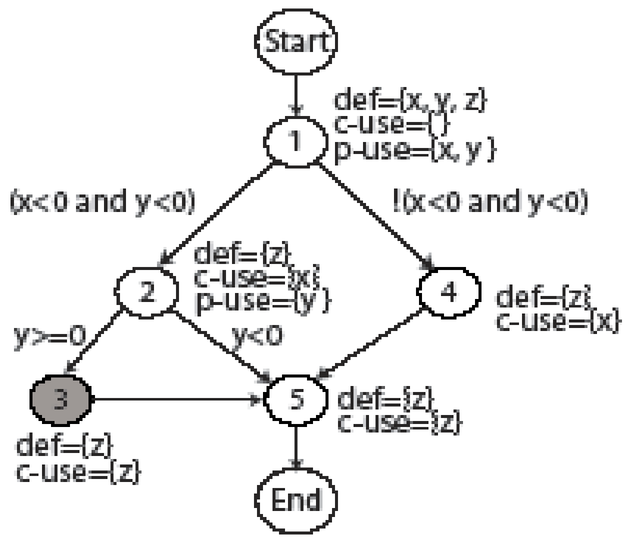


Node (or Block)	def	c-use	p-use
1	{x, y, z}	{ }	{x, y}
2	{z}	{x}	{y}
3	{z}	{z}	{ }
4	{z}	{x}	{ }
5	{ }	{z}	{ }



Def-Clear Path

- Any path starting from a node at which variable *x* is defined and ending at a node at which *x* is used, *without redefining x anywhere else along the path*, is a def-clear path for *x*
- Path 2-5 is def-clear for variable *z* defined at node 2 and used at node 5.
- Path 1-2-5 is *NOT def-clear for variable z* defined at node 1 and used at node 5.
- Thus definition of z at node 2 is live at node 5 while that at node 1 is not live at node 5.



(a)

Def-Use Pairs

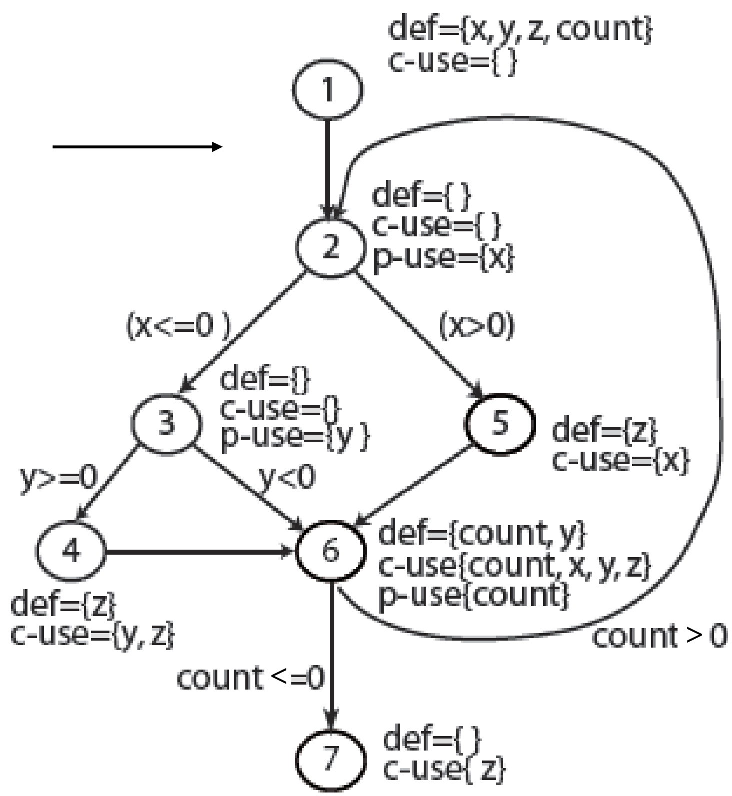
- Definition of a variable at line l_1 and its use at line l_2 constitute *a def-use pair*. l_1 and l_2 can be the same.
  - dcu($d_i(x)$) denotes the set of all nodes where $d_i(x)$ is live and c-used.
  - dpu($d_i(x)$) denotes the set of all edges (k, l) such that there is a def-clear path from node i to edge (k, l) and x is p-used at node k.

- We say that a def-use pair ($d_i(x)$, $u_j(x)$) is covered when a *def-clear path* that includes nodes i to node j is executed.

- If $u_j(x)$ is a p-use then all edges of the kind (j, k) must also be taken during some executions.

Def-Clear Path (Another Example) (1)

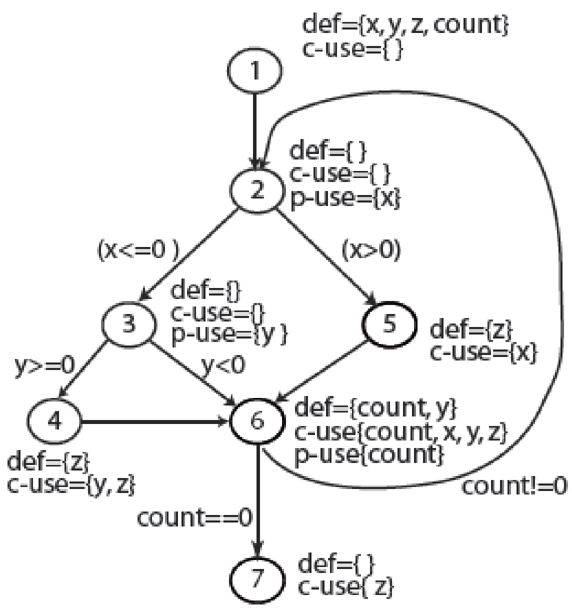
```
1   begin
2     float x, y, z=0.0;
3     int count;
4     input (x, y, count);
5     do {
6       if (x≤0) {
7         if (y≥0) {
8           z=y*z+1;
9         }
10      }
11      else{
12        z=1/x;
13      }
14      y=x*y+z
15      count=count-1
16    while (count>0)
17    output (z);
18  end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



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

Find def-clear paths for defs and uses of *x* and *z*.
Which definitions are live at node 4?

Def-Clear Path (Another Example) **(2)**



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) }

Infeasible! Why?

Def-Use Pairs: Minimal Set (1)

- Def-use pairs are items to be covered during testing. However, in some cases, coverage of a def-use pair implies coverage of another def-use pair. Analysis of the data flow graph can reveal a minimal set of def-use pairs whose coverage implies coverage of all def-use pairs.

- Exercise: Analyze the def-use graph shown on slide 20 to determine
  - Which def-uses are infeasible?
  - A minimal set of def-uses to be covered
    - corresponding to "set covering"
    - in theory, this is NP-complete
    - χSuds/ATAC provides a good "approximate" solution (will be further explained when we discuss "Regression Testing")

Def-Use Pairs: Minimal Set (2)

- What will be also covered if we have a test case which covers ($d_1(z)$, $u_4(z)$)?
- How about ($d_4(z)$, $u_4(z)$)?

C-Use Coverage

- The c-use coverage of a test set T with respect to (P, R) is computed as

$$\frac{CU_c}{(CU - CU_f)}$$

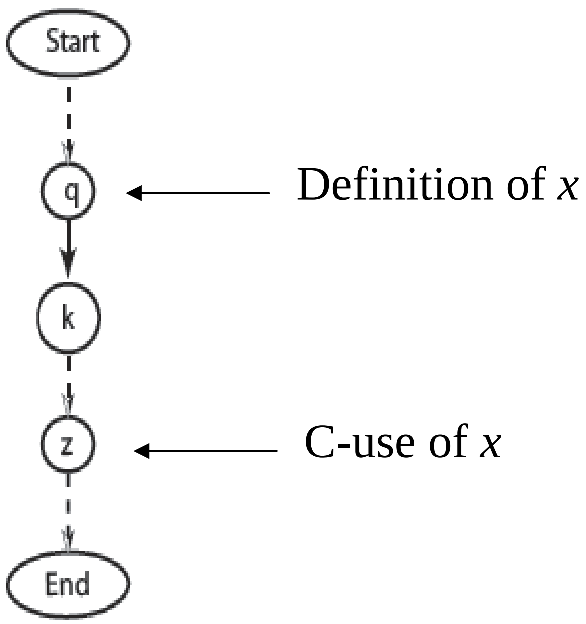
  where CU is the total number of c-uses, CU_C is the number of c-uses covered by test cases in T, and CU_f is the number of infeasible c-uses.

- T is considered adequate with respect to the c-use coverage criterion if its c-use coverage is 1.

C-Use Coverage: Path Traversed

- Path (Start, .. *q*, *k*, .., *z*, .. End) covers the c-use at node *z* of *x* defined at node *q* given that (*k* …, *z*) is def-clear with respect to *x*

- In-class Exercise: Find the c-use coverage when the code on slide 20 is executed against the test case < $x = 5$, $y = -1$, count = 1 >



P-Use Coverage

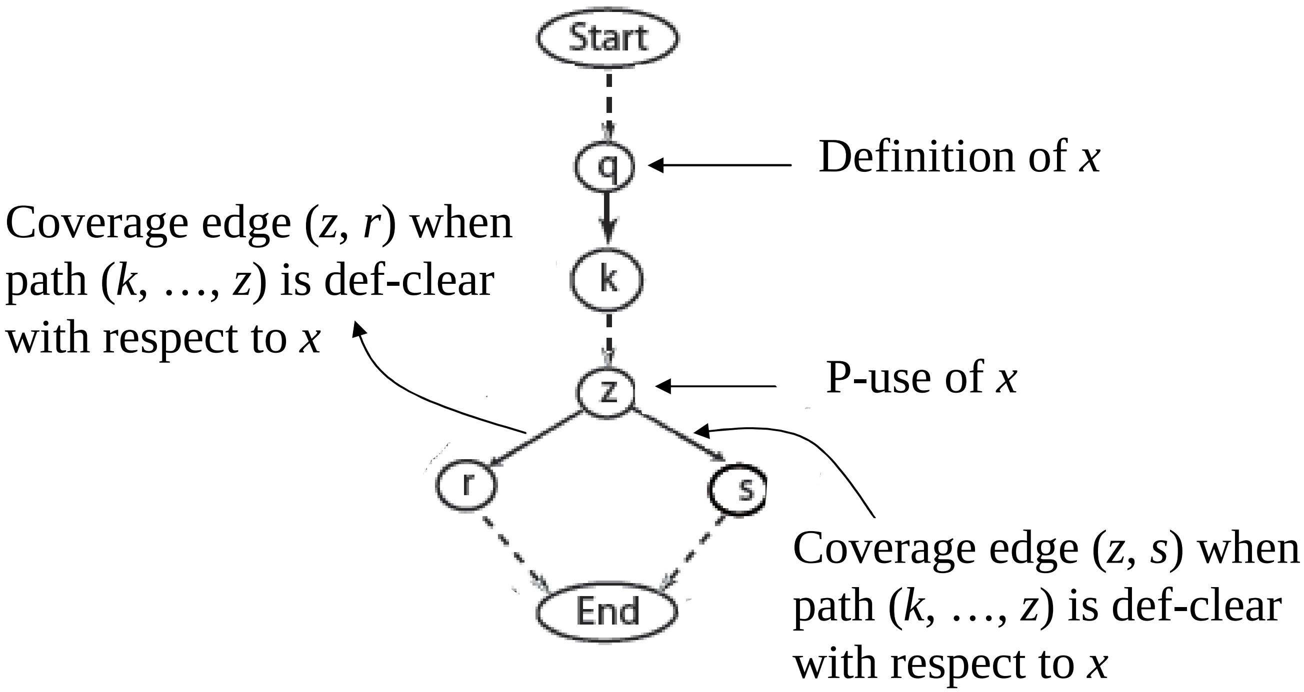
- The p-use coverage of a test set *T* with respect to (*P*, *R*) is computed as

$$\frac{PU_c}{(PU - PU_f)}$$

where *PU* is the total number of p-uses, PU_C is the number of p-uses covered by test cases in *T*, and PU_f is the number of infeasible p-uses.

- *T* is considered adequate with respect to the p-use coverage criterion if its p-use coverage is 1.

P-Use Coverage: Paths Traversed



In-class Exercise: Find the p-use coverage when the code on slide 20 is executed against the test case < $x = -2$, $y = -1$, count = 3 >

All-Uses Coverage

- The all-uses coverage of a test set T with respect to (P, R) is computed as

$$\frac{(CU_c + PU_c)}{((CU + PU) - (CU_f + PU_f))}$$

where CU, CU_C and CU_f are defined on slide 24, and PU, PU_C and PU_f are defined on slide 26.

- T is considered adequate with respect to the all-uses coverage criterion if its all-uses coverage is 1.

All-Uses Coverage: Example

- In-class Exercise: Referring to the code on slide 20, is a test set T={< x = 5, y = −1, count = 1 >, < x = −2, y = −1, count = 3 >} adequate with respect to the all-uses coverage?

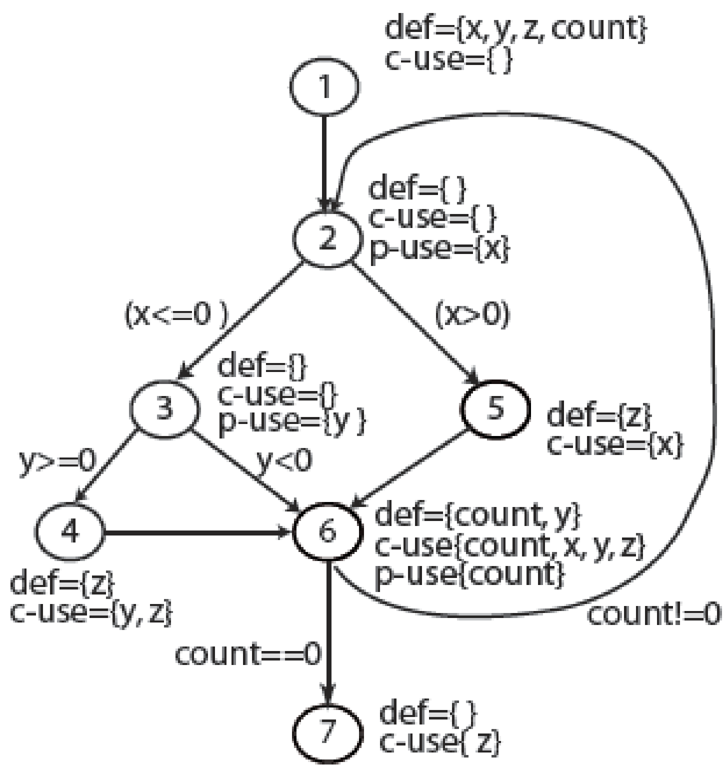
Infeasible P- and C-Uses

- Coverage of a c-use or a p-use requires a path to be traversed through the program. However, *if this path is infeasible, then some c-uses and p-uses that require this path to be traversed might also be infeasible*.

- Infeasible c-uses and p-uses are often difficult to determine.

Infeasible C-Use: Example

- Consider the c-use at node 4 of *z* defined at node 5.
- Explain why this c-use is infeasible.



Subsumes Relation

- Given a test set T that is *adequate* with respect to a criterion C_1, what can we conclude *about the adequacy* of T with respect to another criterion C_2

Effectiveness of an Adequate Test Set

- Given a test set *T* that is *adequate* with respect to a criterion *C*, what can we expect *regarding its effectiveness in revealing bugs*?

Effectiveness Relation

- Given a test set T_1 that is *adequate* with respect to a criterion C_1 and a test set T_2 that is *adequate* with respect to another criterion C_2. Assume criterion C_1 subsumes criterion C_2, what can we conclude *about the fault detection effectiveness* of T_1 with respect to the *fault detection effectiveness* of T_2?