SENG3320/6320:
Software Verification and Validation

Data Flow Coverage

Motivation

```
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)
9         z=z/x;
10      else z=z*x;
11      output(z):
12 end
```

Any bug in this program?

Motivation

```
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)  //should be y!=0 and x!=0
9         z=z/x;
10      else z=z*x;
11      output(z):
12 end
```

Test case	x	y	z
t1	0	0	0.0
t2	1	1	1.0

- 100% statement and decision coverage
- Still cannot discover the bug at line 8

Motivation

```
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)  //should be y!=0 and x!=0
9       z=z/x;
10    else z=z*x;
11    output(z):
12 end
```

Test Case	x	y	z
t1	0	0	0.0
t2	1	1	1.0
t3	0	1	NaN
t4	1	0	1.0

Dataflow coverage

- Considers how data gets accessed and modified in the system and how it can get corrupted
- Common access-related bugs
  - Using an undefined or uninitialized variable
  - Deallocating or reinitializing a variable before it is constructed, initialized, or used
  - Deleting a collection object leaving its members unaccessible

Variable definition

- A program variable is DEFINED whenever its value is modified:
  - on the *left* hand side of an assignment statement
    - *e.g.,* **y** = 17
  - in an input statement
    - *e.g.,* read(**y**)
  - as an call-by-reference parameter in a subroutine call
    - *e.g.,* update(x, &**y**);

Variable use

- A program variable is USED whenever its value is read:
  - on the right hand side of an assignment statement
    - *e.g.,* y = **x**+17
  - as an call-by-value parameter in a subroutine or function call
    - *e.g.,* y = sqrt(**x**)
  - in the predicate of a branch statement
    - *e.g.,* if (**x** > 0) { … }

Variable use: p-use and c-use

- Use in the predicate of a branch statement is a predicate-use or "p-use"
- Any other use is a computation-use or "c-use"
- For example, in the program fragment:

```
if ( x > 0 ) {
        print(y);
}
```

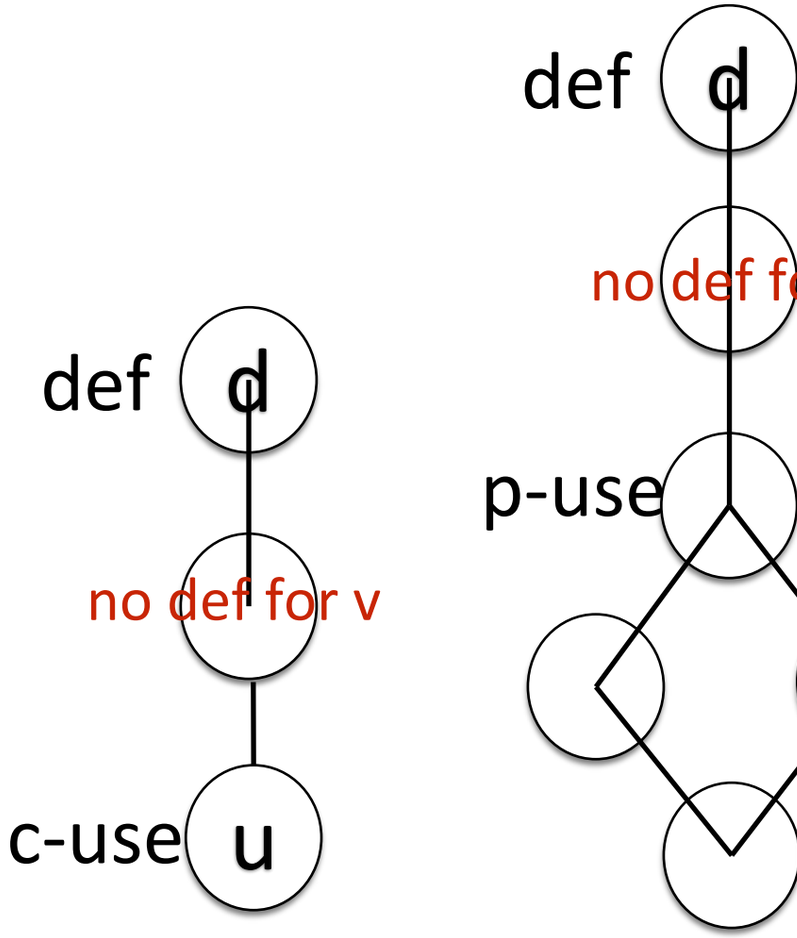
There is a p-use of x and a c-use of y

Variable use

- A variable can also be used and then re-defined in a single statement when it appears:
  - on both sides of an assignment statement
    - *e.g.,* **y** = **y** + x
  - as an call-by-reference parameter in a subroutine call
    - *e.g.,* increment(&**y**)

Definition-use pair (du-pair)

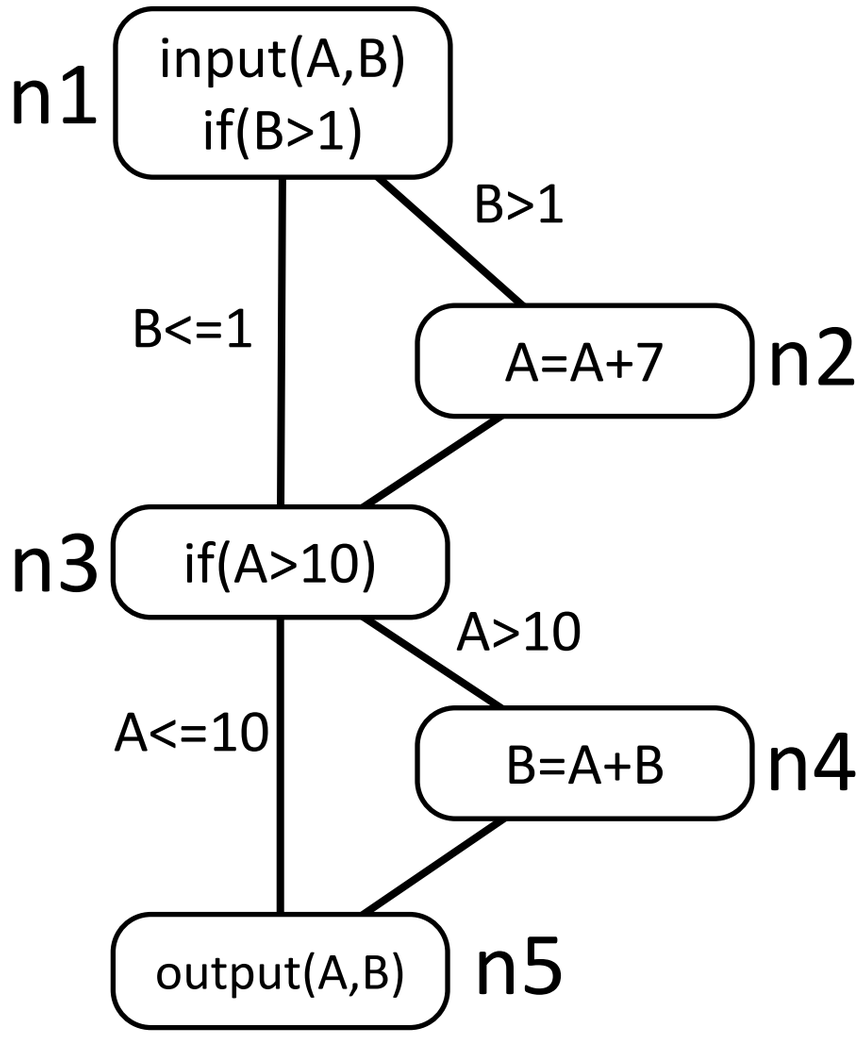
- A **definition-use pair** (“du-pair”) with respect to a variable **v** is a pair (**d**,**u**) such that
  - **d** is a node defining **v**
  - **u** is a node or edge using **v**
    - when it is a p-use of **v**, **u** is an outgoing edge of the predicate statement
  - there is a def-clear path with respect to **v** from **d** to **u**
  - A path is **definition clear** (“def-clear”) with respect to a variable **v** if it has no variable re-definition of **v** on the path



c-use example p-use example

Du-pair: example 1

```
1. input(A,B)
    if (B>1) {
2.      A = A+7
    }
3. if (A>10) {
4.      B = A+B
    }
5. output(A,B)
```

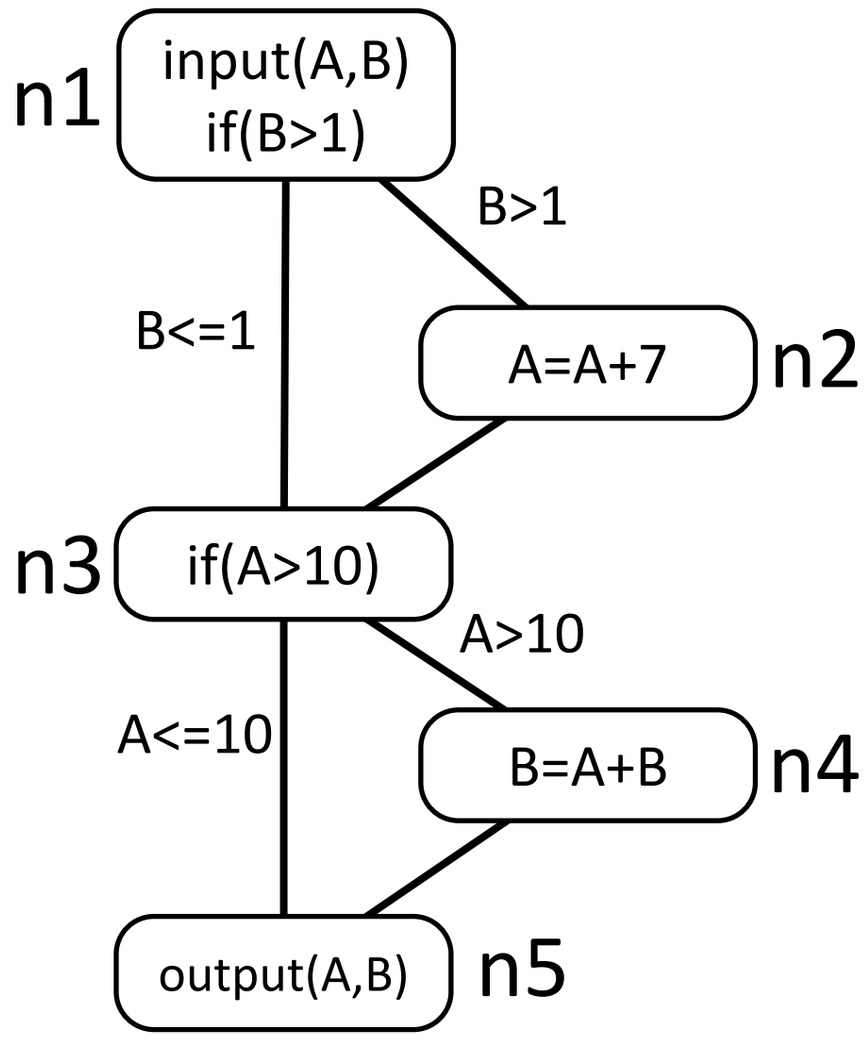


Statements or blocks?

- Nodes in a control flow graph often represent basic blocks of multiple statements
  - Some standards refer to *basic block* coverage or *node coverage*
    - Difference in granularity, not in concept
- No essential difference
  - 100% node coverage <-> 100% statement coverage
  - A test case that improves one will improve the other

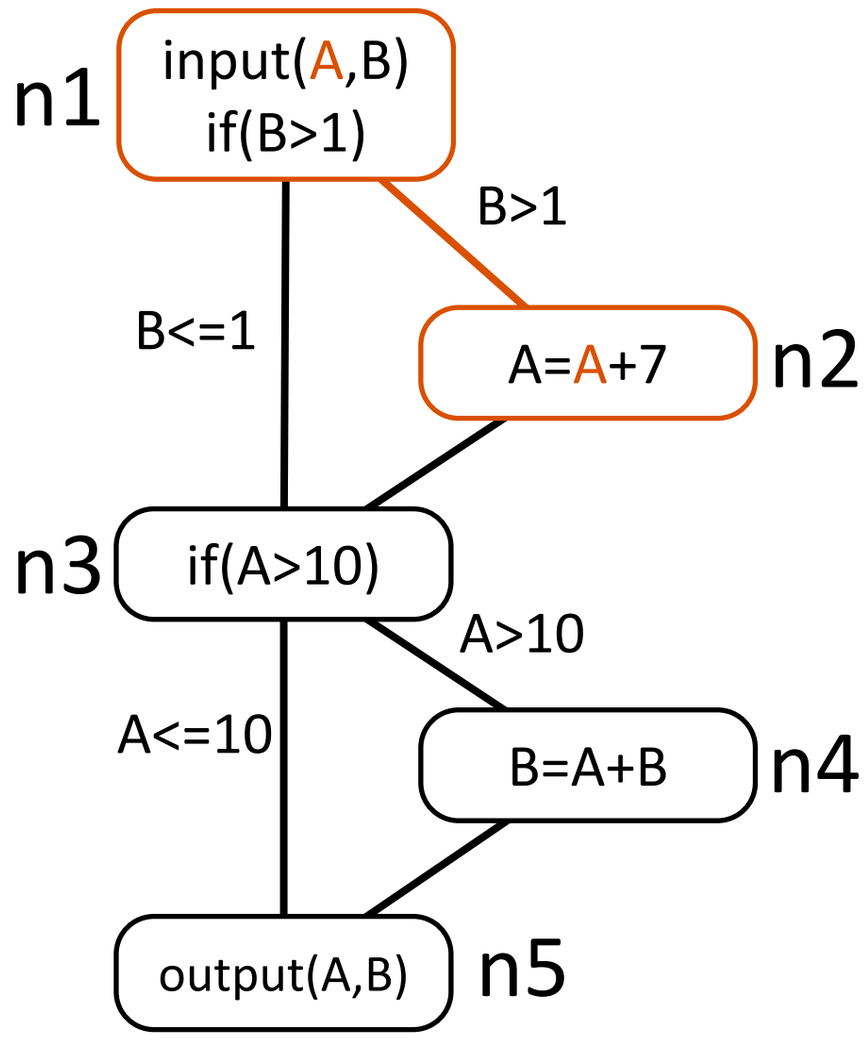
Identifying du-pairs – variable **A**

du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



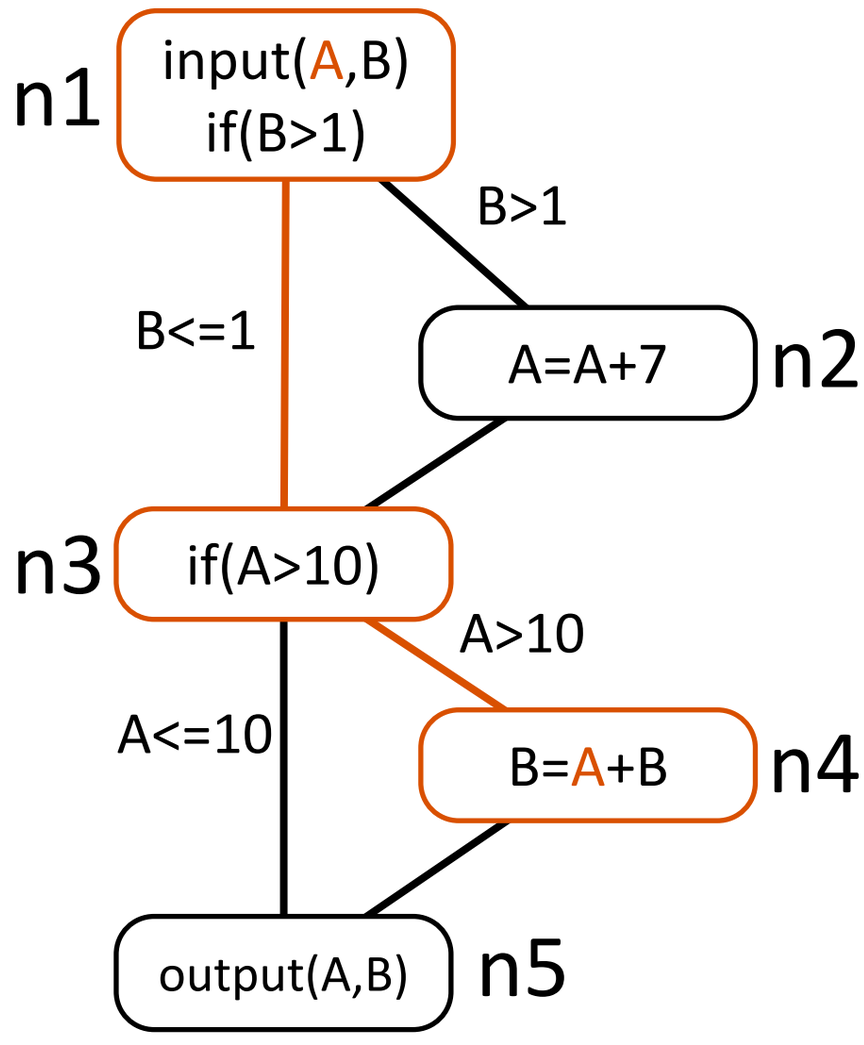
Identifying du-pairs – variable **A**

du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



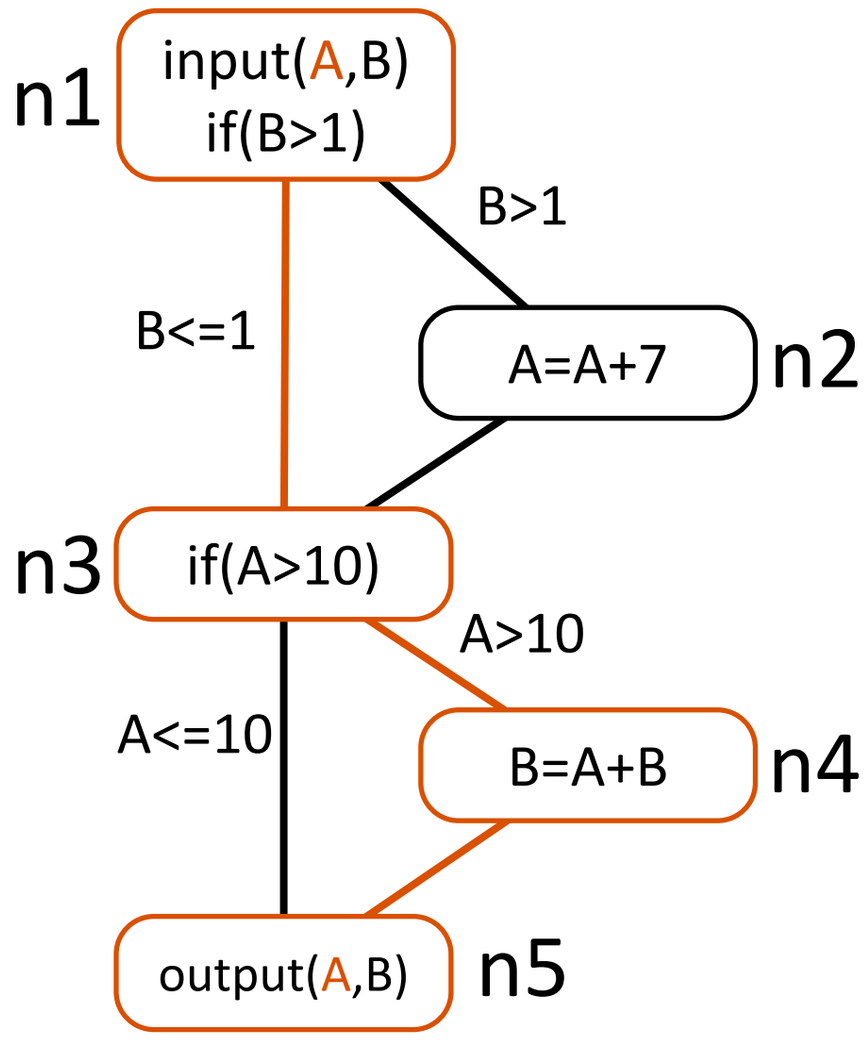
Identifying du-pairs – variable **A**

du-pair	path(s)
(1,2)	<1,2>
(1,4)	**<1,3,4>**
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



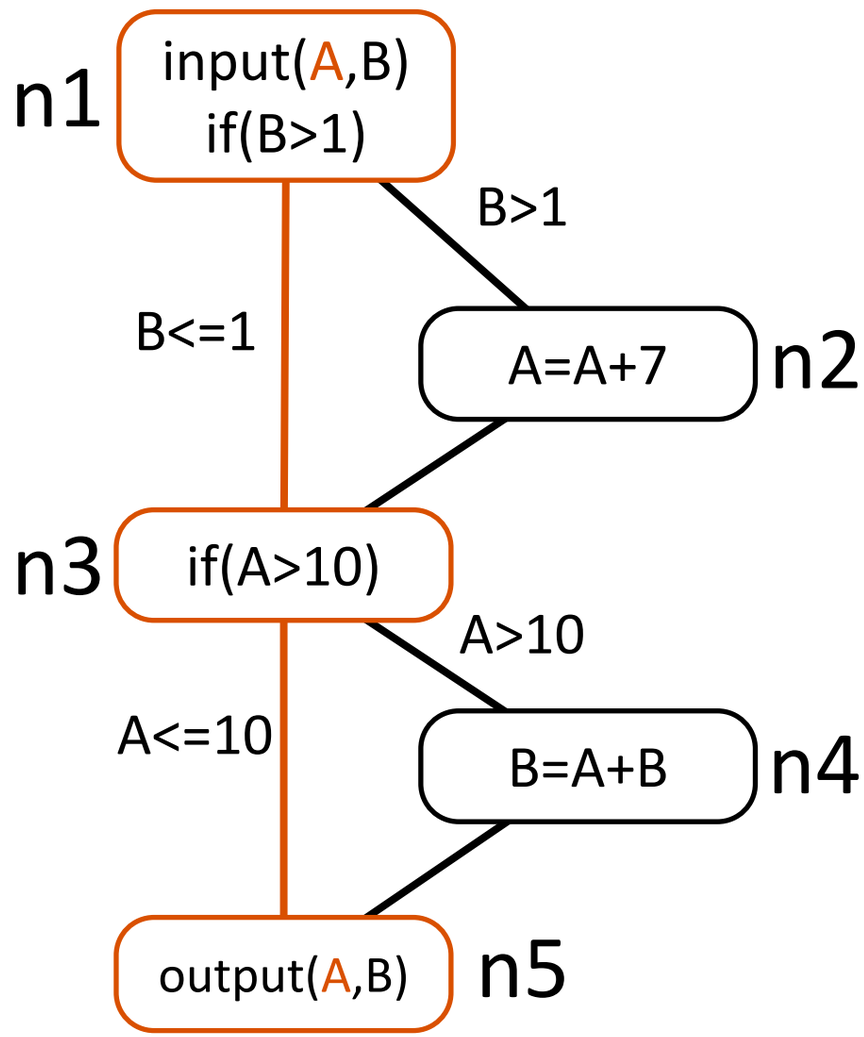
Identifying du-pairs – variable **A**

du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	**<1,3,4,5>**
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



Identifying du-pairs – variable **A**

du-pair	**path(s)**
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



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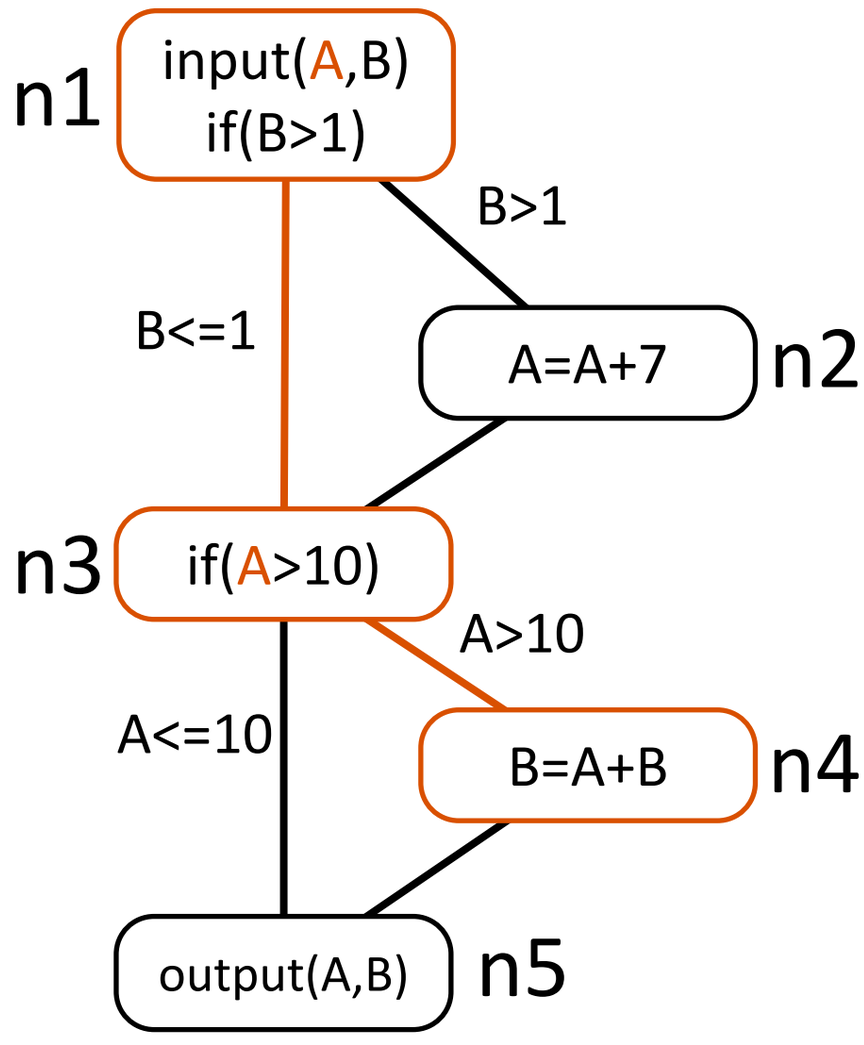
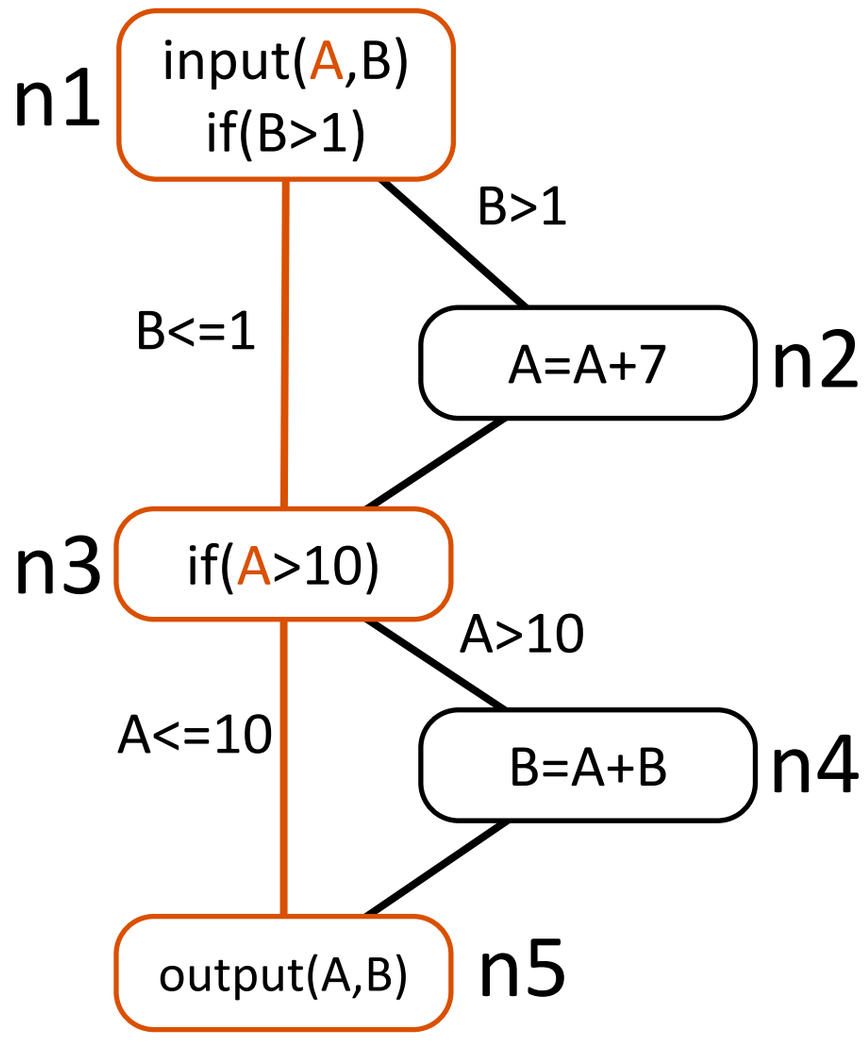
du-pair	**path(s)**
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	**<1,3,4>**
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



Identifying du-pairs – variable **A**

du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	**<1,3,5>**
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



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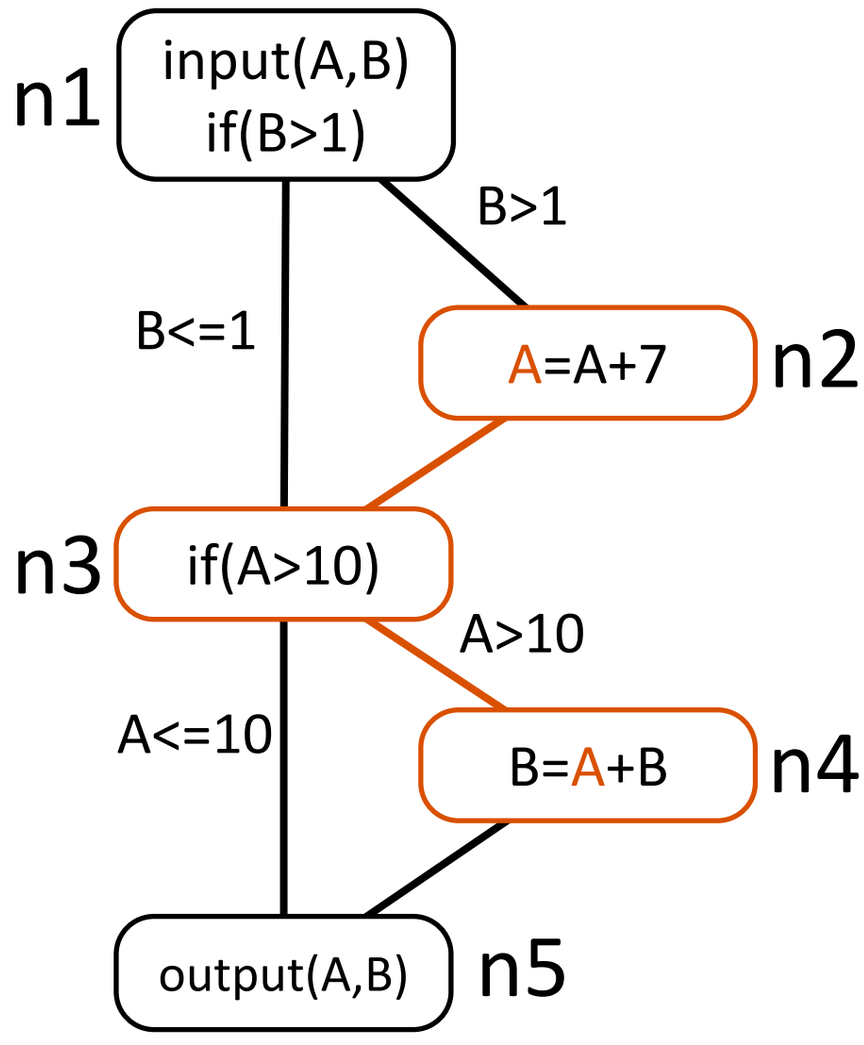
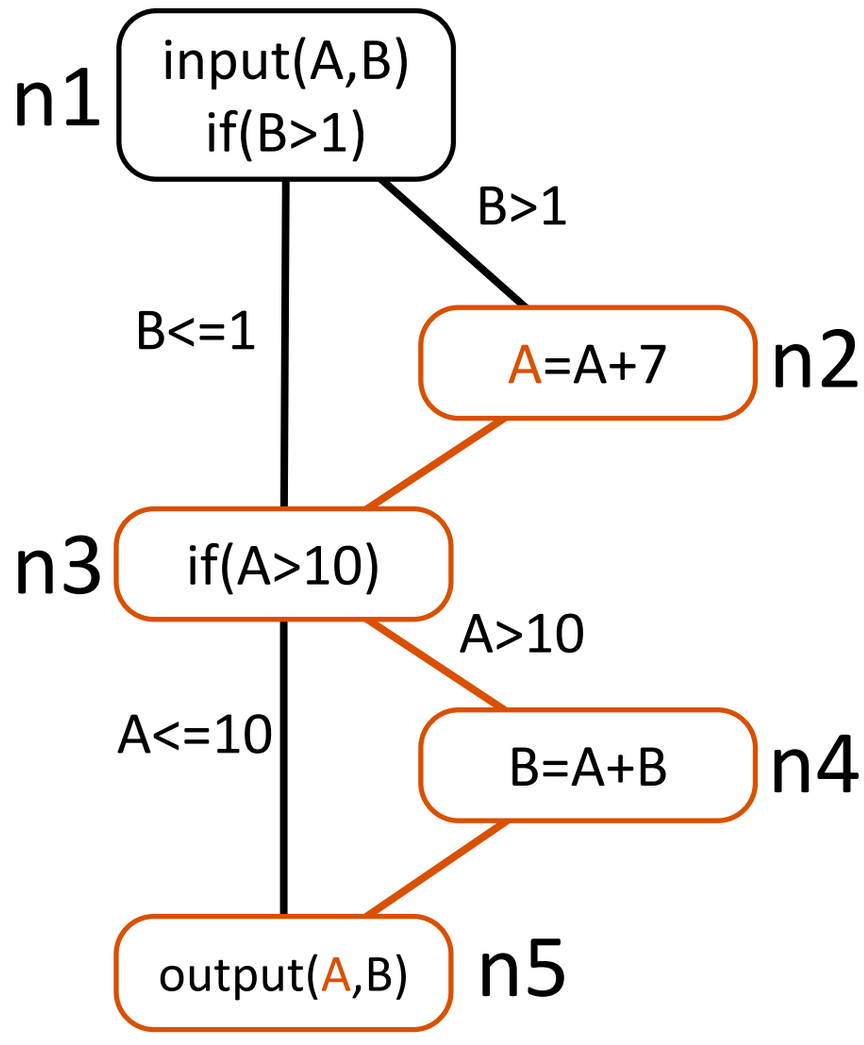
du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	**<2,3,4>**
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



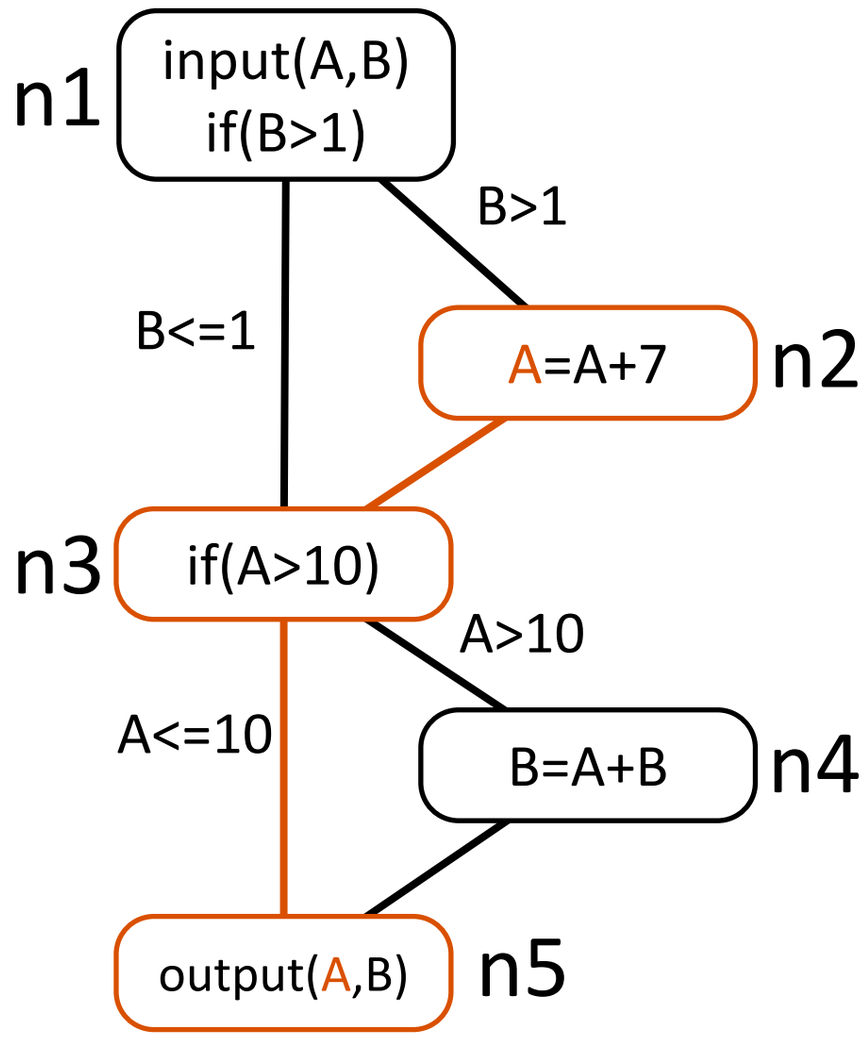
Identifying du-pairs – variable **A**

du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	**<2,3,4,5>**
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



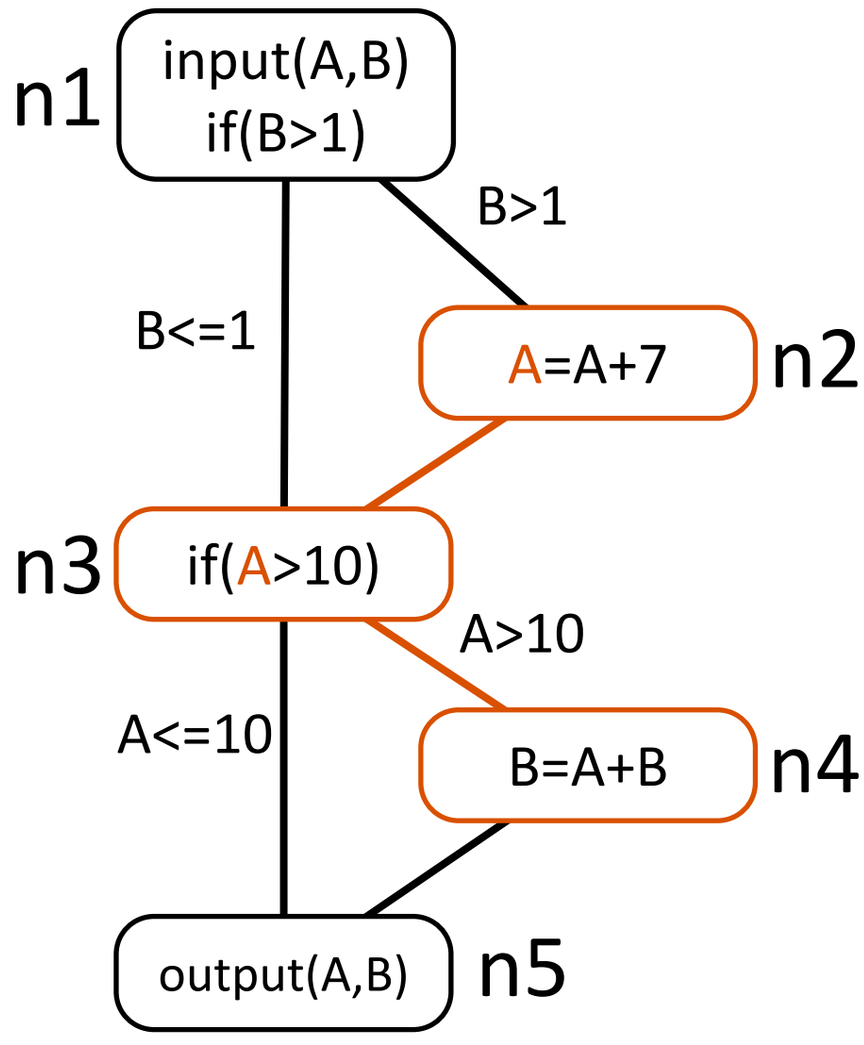
Identifying du-pairs – variable **A**

du-pair	**path(s)**
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	<2,3,5>



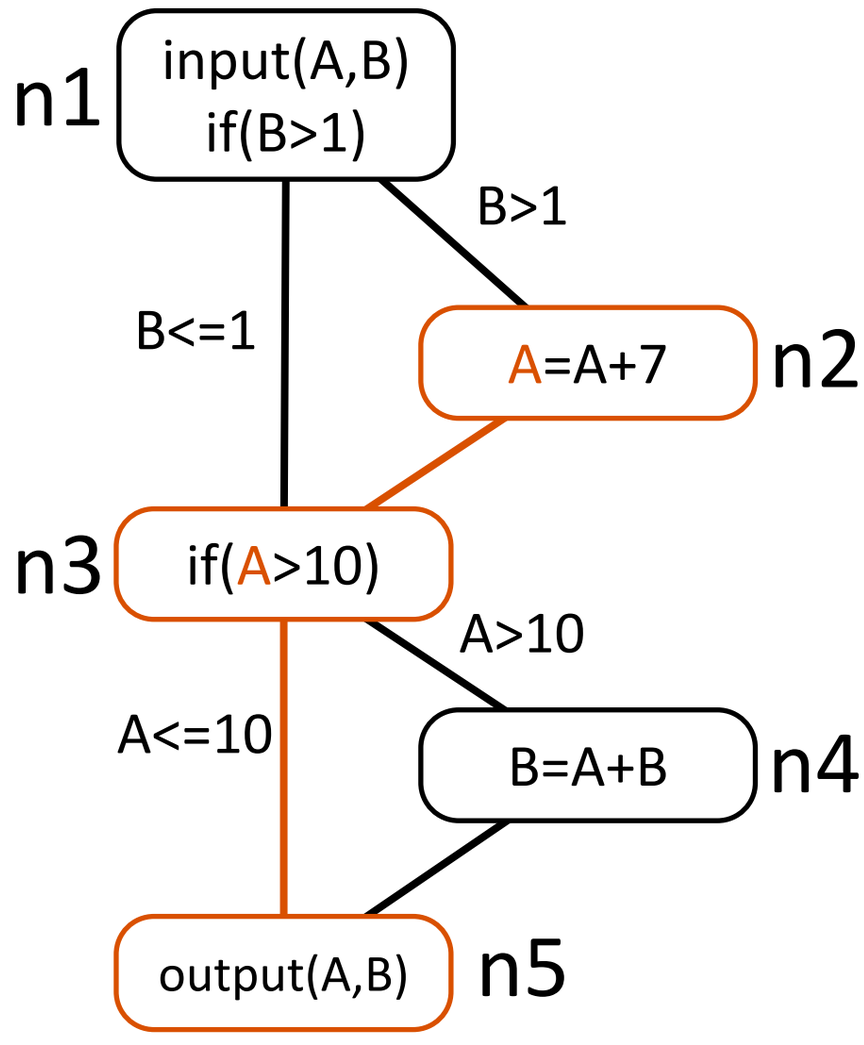
Identifying du-pairs – variable **A**

du-pair	path(s)
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	**<2,3,4>**
(2,<3,5>)	<2,3,5>



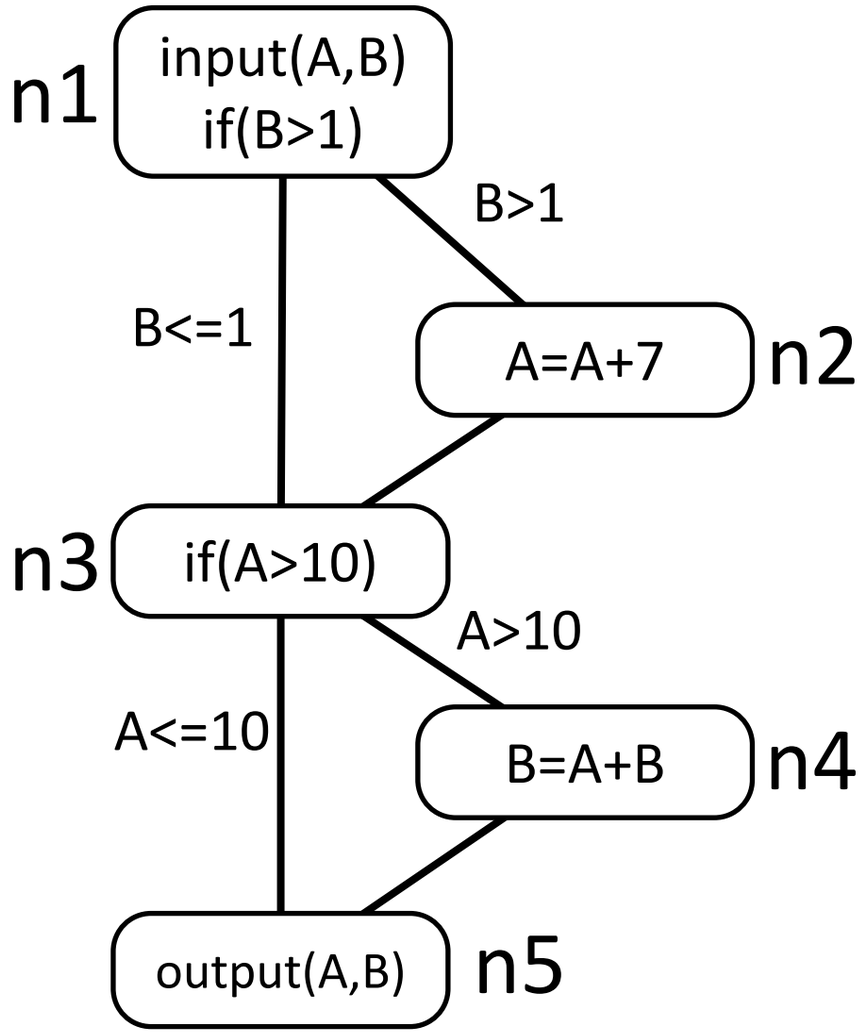
Identifying du-pairs – variable **A**

du-pair	**path(s)**
(1,2)	<1,2>
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4>
(2,5)	<2,3,4,5>
	<2,3,5>
(2,<3,4>)	<2,3,4>
(2,<3,5>)	**<2,3,5>**



Identifying du-pairs – variable **B**

du-pair	**path(s)**
(1,4)	<1,2,3,4>
	<1,3,4>
(1,5)	<1,2,3,5>
	<1,3,5>
(1,<1,2>)	<1,2>
(1,<1,3>)	<1,3>
(4,5)	<4,5>



Dataflow test coverage criteria

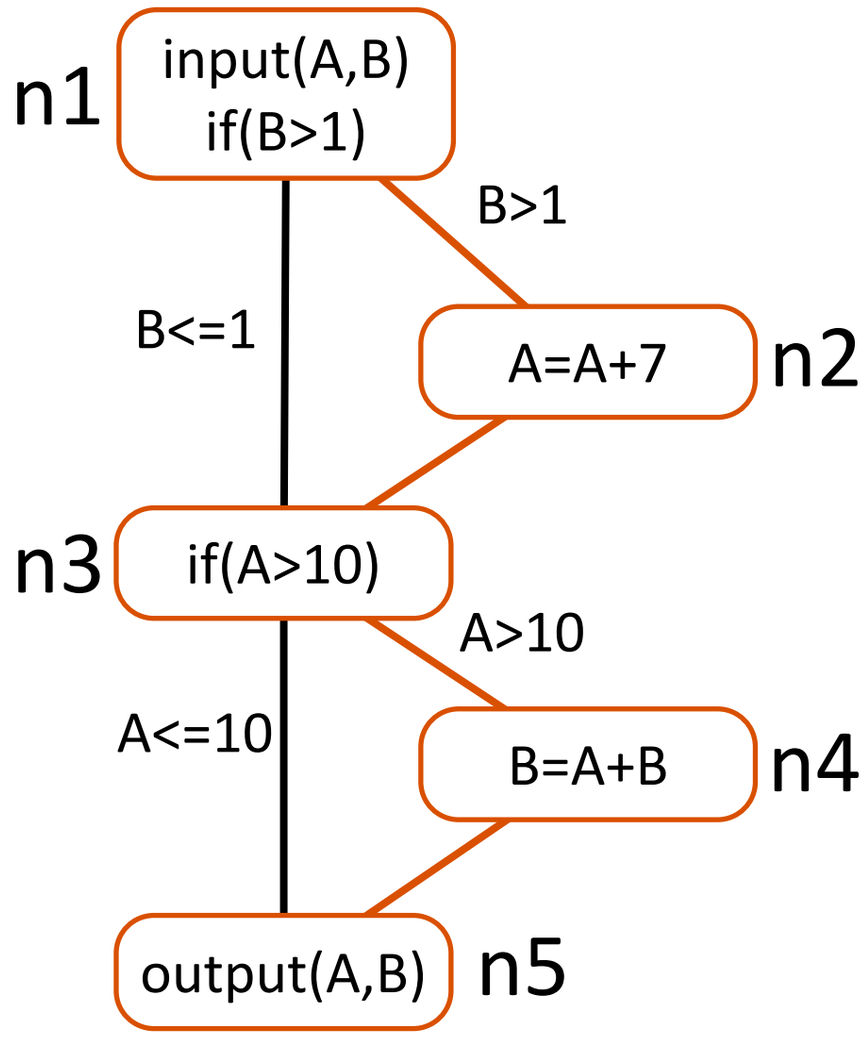
- **All-Defs**
  - for every program variable **v**, at least one def-clear path from every definition of **v** to at least one c-use or one p-use of **v** must be covered

Dataflow test coverage criteria

- Consider a test case executing path:
  - t1: <1,2,3,4,5>
- Identify all def-clear paths covered (i.e., subsumed) by this path for each variable
- Are all definitions for each variable associated with at least one of the subsumed def-clear paths?

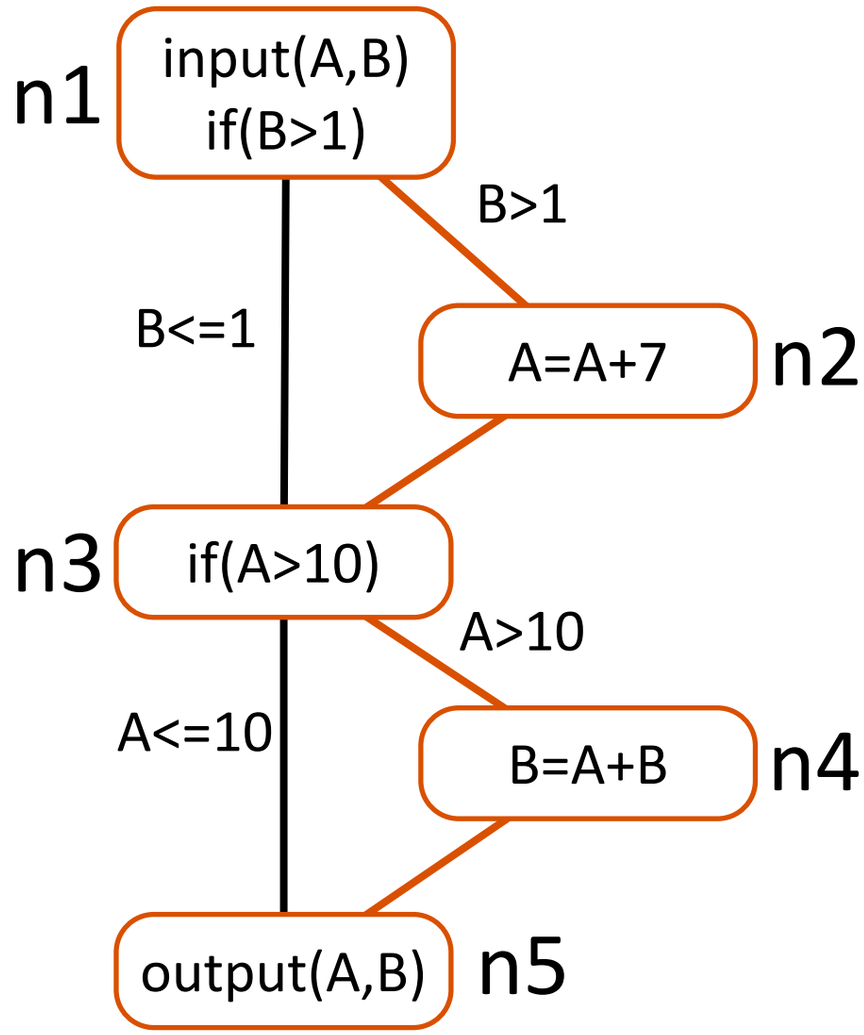
Def-clear paths subsumed by <1,2,3,4,5> for variable **A**

du-pair	path(s)
(1,2)	<1,2> ✔
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4> ✔
(2,5)	<2,3,4,5> ✔
	<2,3,5>
(2,<3,4>)	<2,3,4> ✔
(2,<3,5>)	<2,3,5>



Def-clear paths subsumed by <1,2,3,4,5> for variable **B**

du-pair	path(s)
(1,4)	<1,2,3,4> ✔
	<1,3,4>
(1,5)	<1,2,3,5>
	<1,3,5>
(1,<1,2>)	<1,2> ✔
(1,<1,3>)	<1,3>
(4,5)	<4,5> ✔



Dataflow test coverage criteria

- Since <1,2,3,4,5> covers at least one def-clear path from every definition of **A** or **B** to at least one c-use or p-use of **A** or **B**, All-Defs coverage is achieved

Dataflow test coverage criteria

- **All-P-Uses**:
  for every program variable **v**, at least one def-clear path from every definition of **v** to every p-use of **v** must be covered

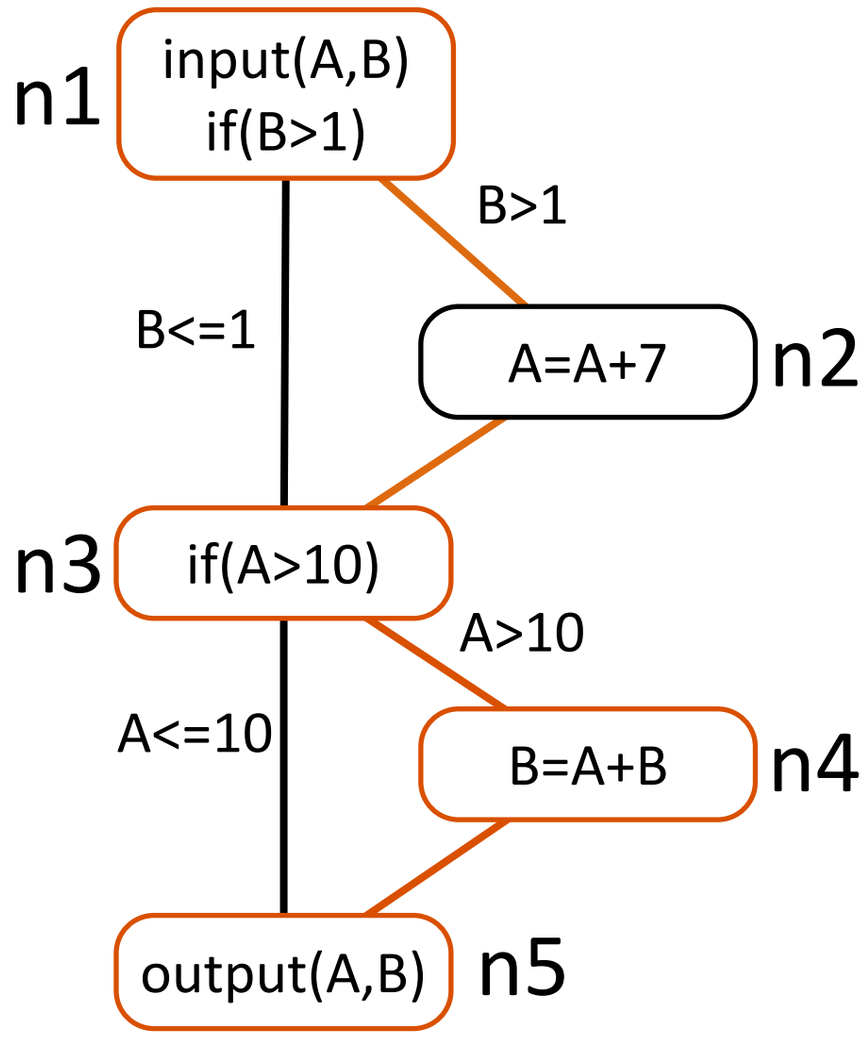
- **All-C-Uses**:
  for every program variable **v**, at least one def-clear path from every definition of **v** to every c-use of **v** must be covered

Dataflow test coverage criteria

- **All-Uses**:
  - for every program variable **v**, at least one def-clear path from every definition of **v** to every c-use and every p-use (including all outgoing edges of the predicate statement) of **v** must be covered
    - Requires that all du-pairs covered
- Consider the test cases executing paths:
  - t1: <1,2,3,4,5>
  - t2: <1,3,4,5>
  - t3: <1,2,3,5>
- Do all three test cases provide All-Uses coverage?

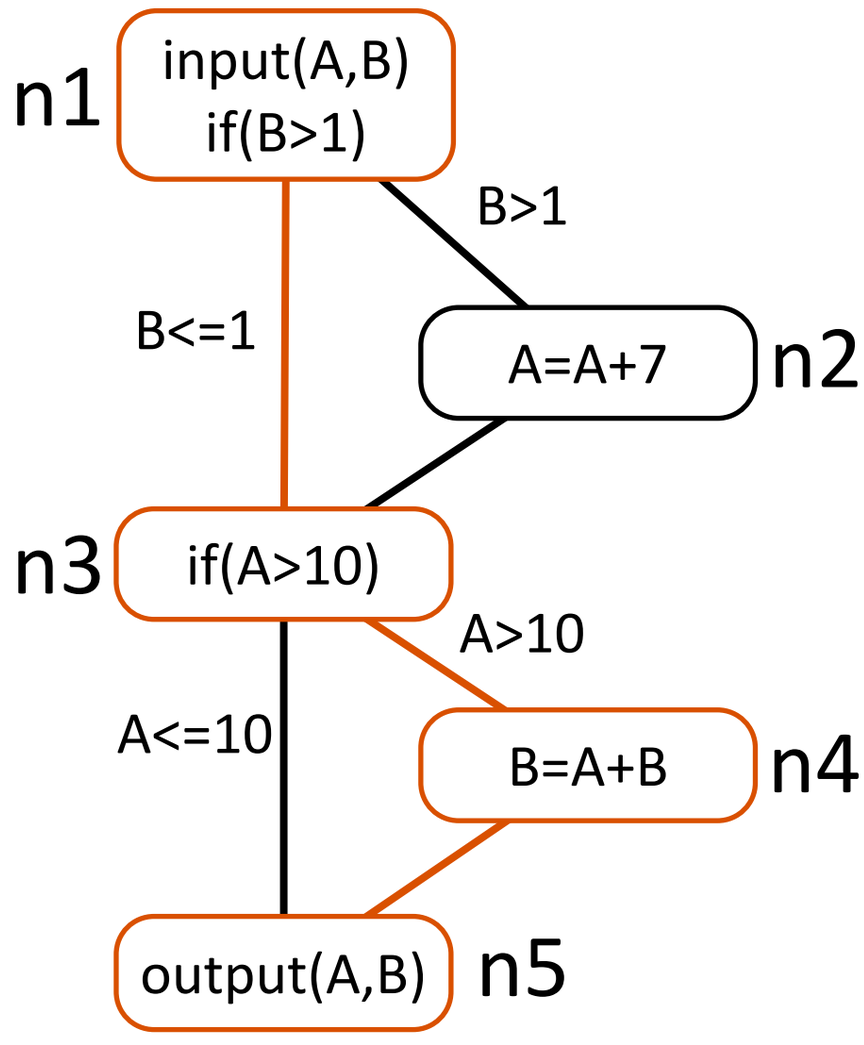
Def-clear paths subsumed by <1,2,3,4,5> for variable **A**

du-pair	path(s)
(1,2)	<1,2> ✔
(1,4)	<1,3,4>
(1,5)	<1,3,4,5>
	<1,3,5>
(1,<3,4>)	<1,3,4>
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4> ✔
(2,5)	<2,3,4,5> ✔
	<2,3,5>
(2,<3,4>)	<2,3,4> ✔
(2,<3,5>)	<2,3,5>



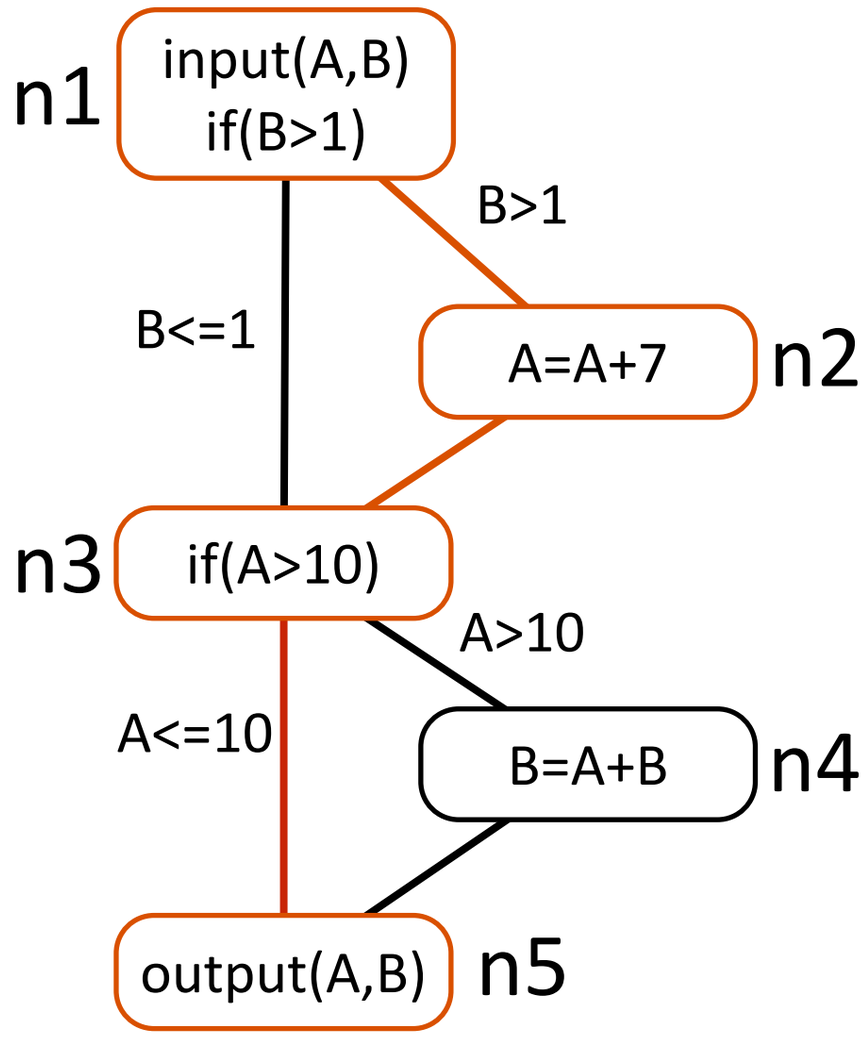
Def-clear paths subsumed by <1,3,4,5> for variable **A**

du-pair	path(s)
(1,2)	<1,2> ✔
(1,4)	<1,3,4> ✔
(1,5)	<1,3,4,5> ✔
	<1,3,5>
(1,<3,4>)	<1,3,4> ✔
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4> ✔
(2,5)	<2,3,4,5> ✔
	<2,3,5>
(2,<3,4>)	<2,3,4> ✔
(2,<3,5>)	<2,3,5>



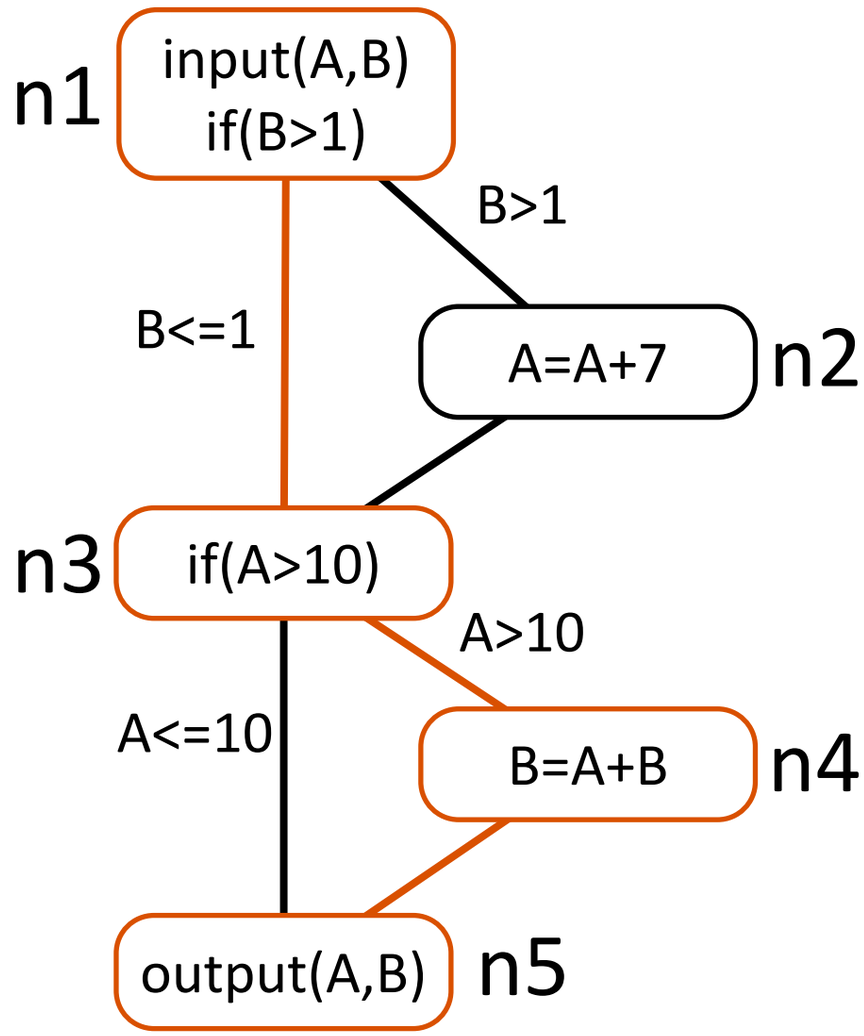
Def-clear paths subsumed by <1,2,3,5> for variable **A**

du-pair	path(s)
(1,2)	<1,2> ✓ ✓
(1,4)	<1,3,4> ✓
(1,5)	<1,3,4,5> ✓
	<1,3,5>
(1,<3,4>)	<1,3,4> ✓
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4> ✓
(2,5)	<2,3,4,5> ✓
	<2,3,5> ✓
(2,<3,4>)	<2,3,4> ✓
(2,<3,5>)	<2,3,5> ✓



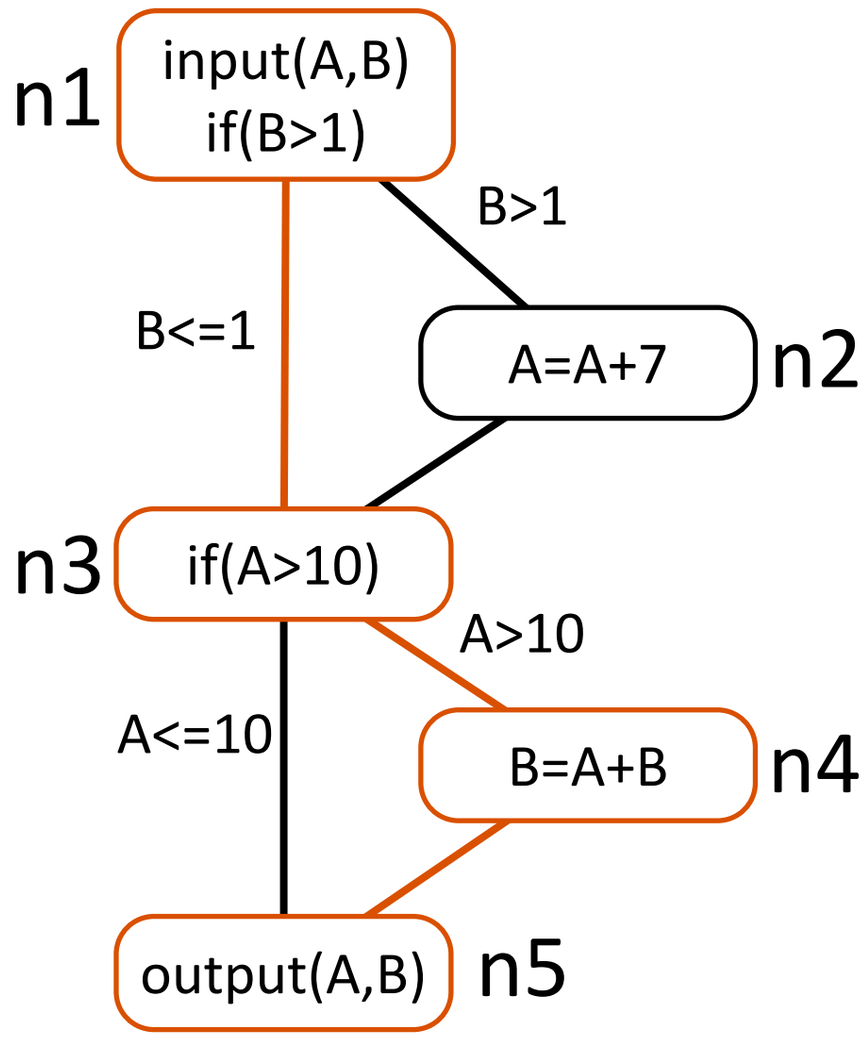
Def-clear paths subsumed by <1,2,3,4,5> for variable **B**

du-pair	path(s)
(1,4)	<1,2,3,4> ✔
	<1,3,4>
(1,5)	<1,2,3,5>
	<1,3,5>
(1,<1,2>)	<1,2> ✔
(1,<1,3>)	<1,3>
(4,5)	<4,5> ✔



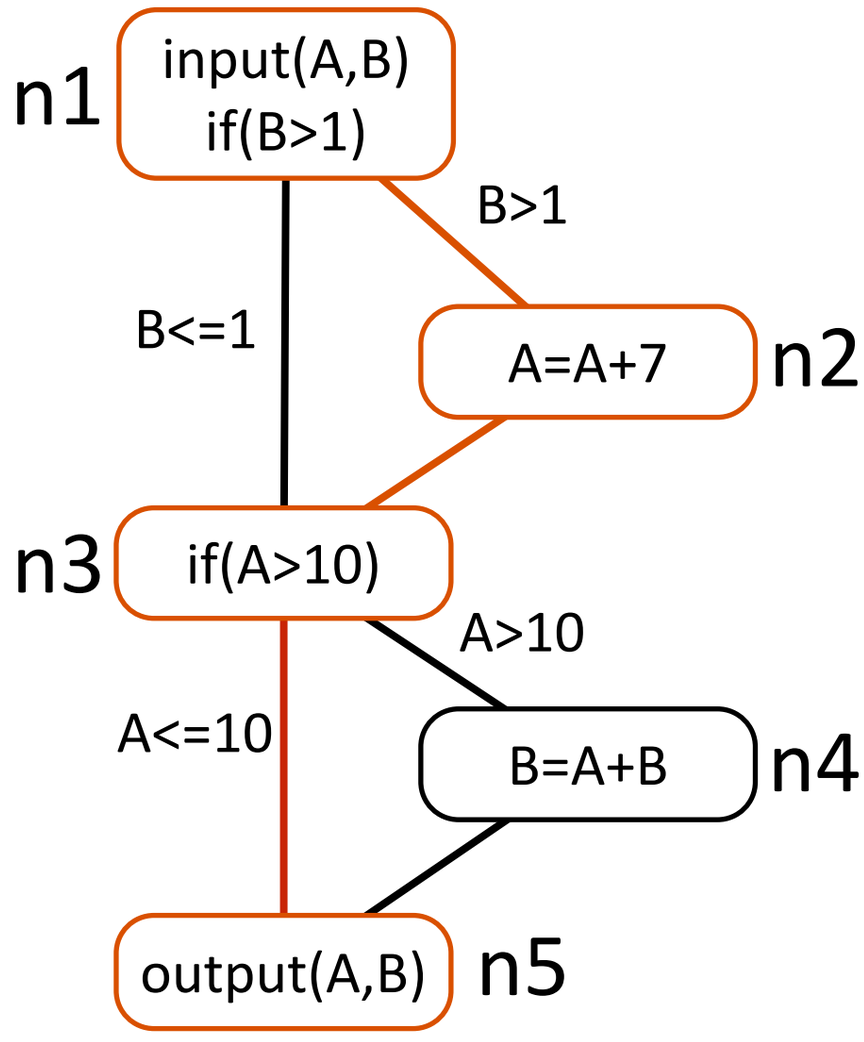
Def-clear paths subsumed by <1,3,4,5> for variable **B**

du-pair	path(s)
(1,4)	<1,2,3,4> ✔
	<1,3,4> ✔
(1,5)	<1,2,3,5>
	<1,3,5>
(1,<1,2>)	<1,2> ✔
(1,<1,3>)	<1,3> ✔
(4,5)	<4,5> ✔ ✔



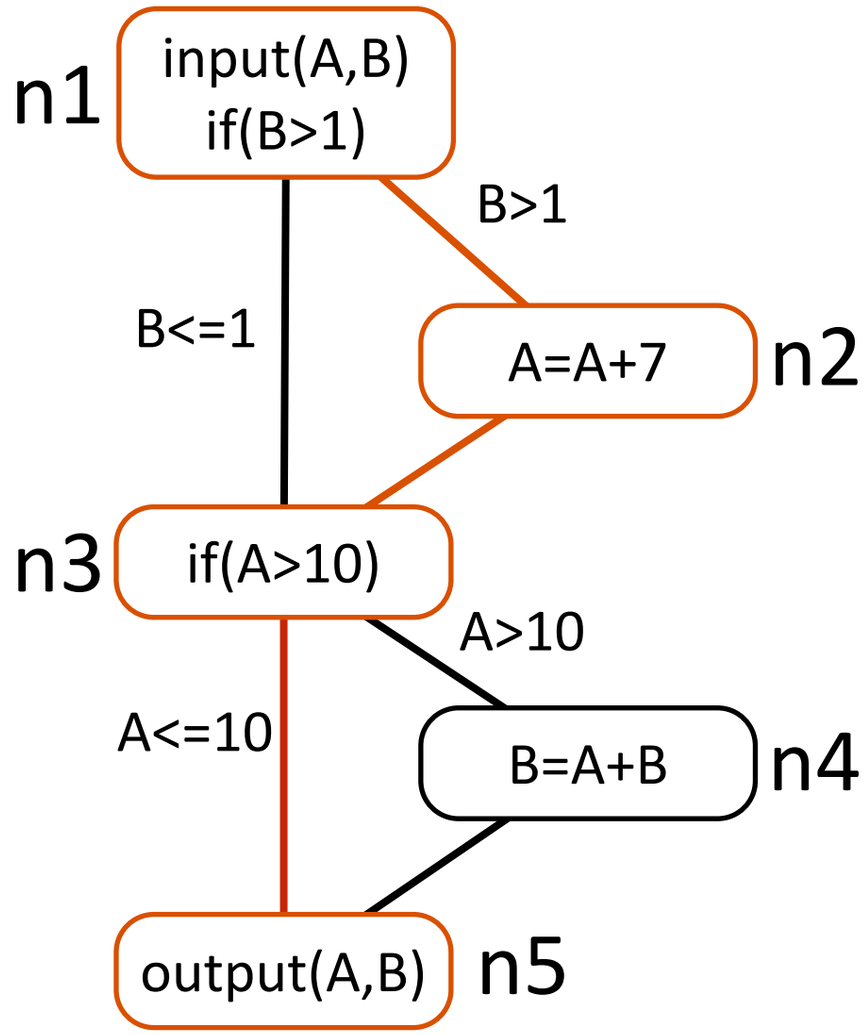
Def-clear paths subsumed by <1,2,3,5> for variable **A**

du-pair	path(s)
(1,2)	<1,2> ✔ ✔
(1,4)	<1,3,4> ✔
(1,5)	<1,3,4,5> ✔
	<1,3,5>
(1,<3,4>)	<1,3,4> ✔
(1,<3,5>)	<1,3,5>
(2,4)	<2,3,4> ✔
(2,5)	<2,3,4,5> ✔
	<2,3,5> ✔
(2,<3,4>)	<2,3,4> ✔
(2,<3,5>)	<2,3,5> ✔



Def-clear paths subsumed by <1,2,3,5> for variable **B**

du-pair	path(s)
(1,4)	<1,2,3,4> ✔
	<1,3,4> ✔
(1,5)	<1,2,3,5> ✔
	<1,3,5>
(1,<1,2>)	<1,2> ✔ ✔
(1,<1,3>)	<1,3> ✔
(4,5)	<4,5> ✔ ✔

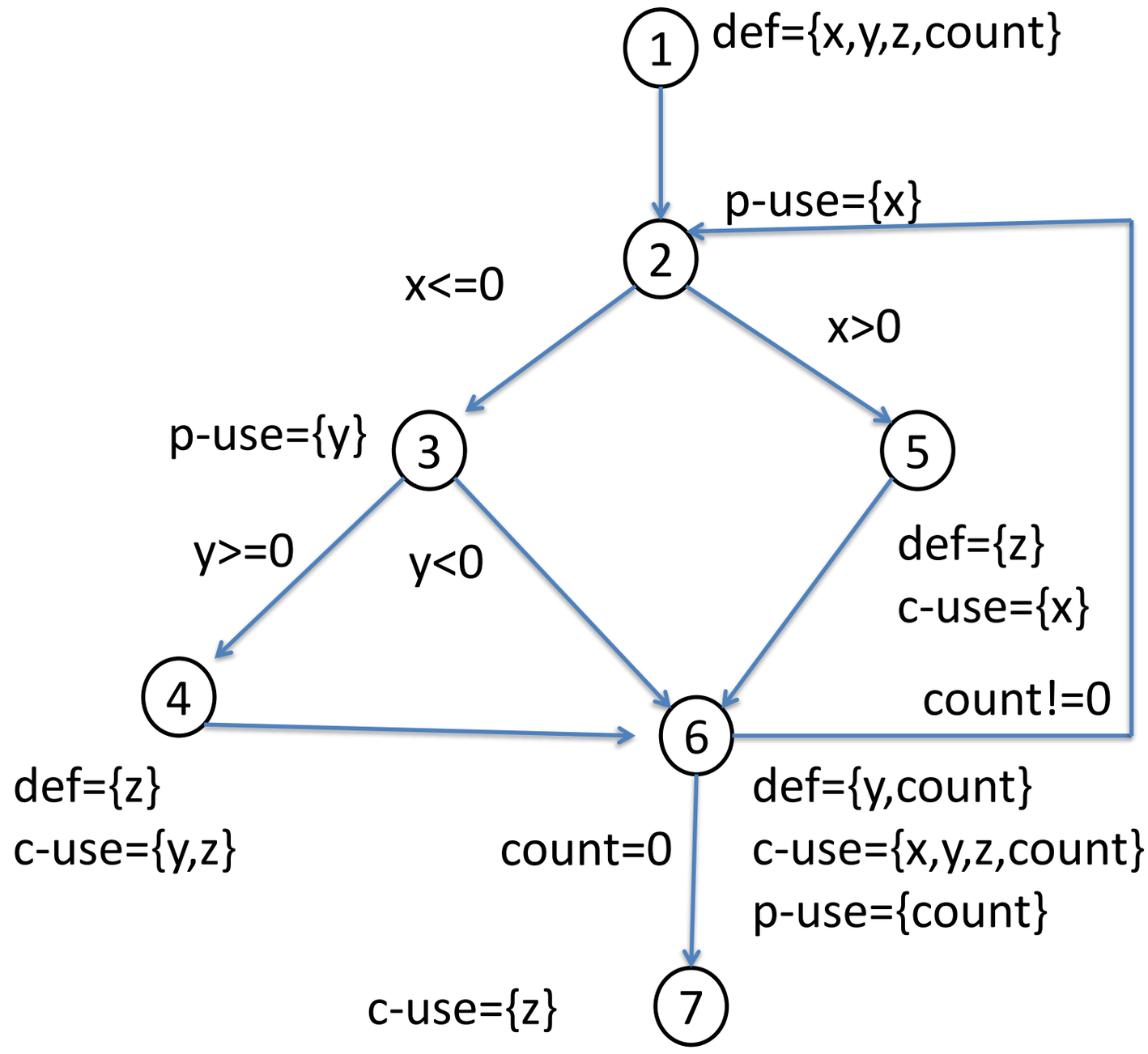


Dataflow test coverage criteria

- None of the three test cases covers the du-pair (1,<3,5>) for variable **A**,
- All-Uses Coverage is not achieved

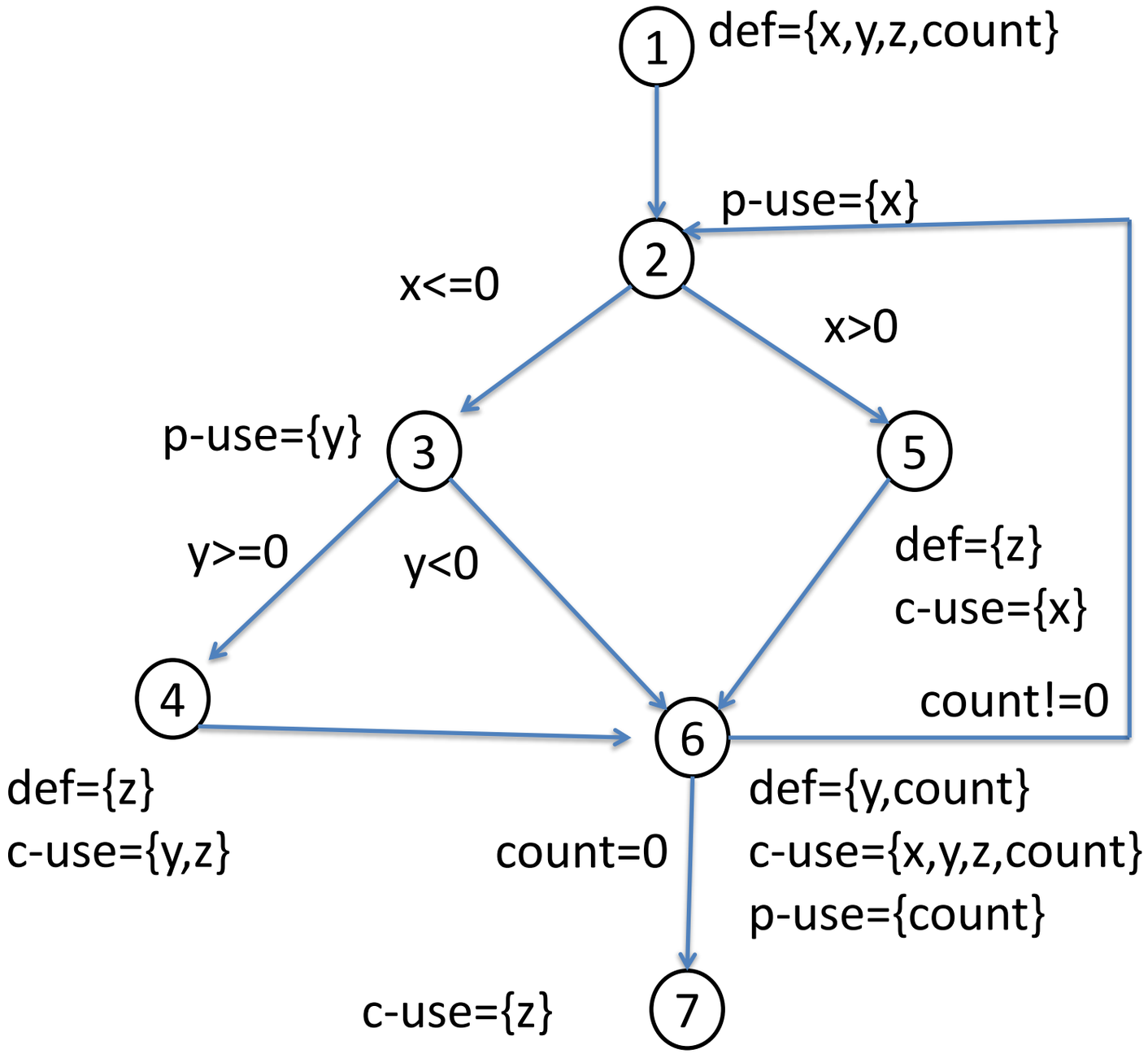
Another Example

```
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
```

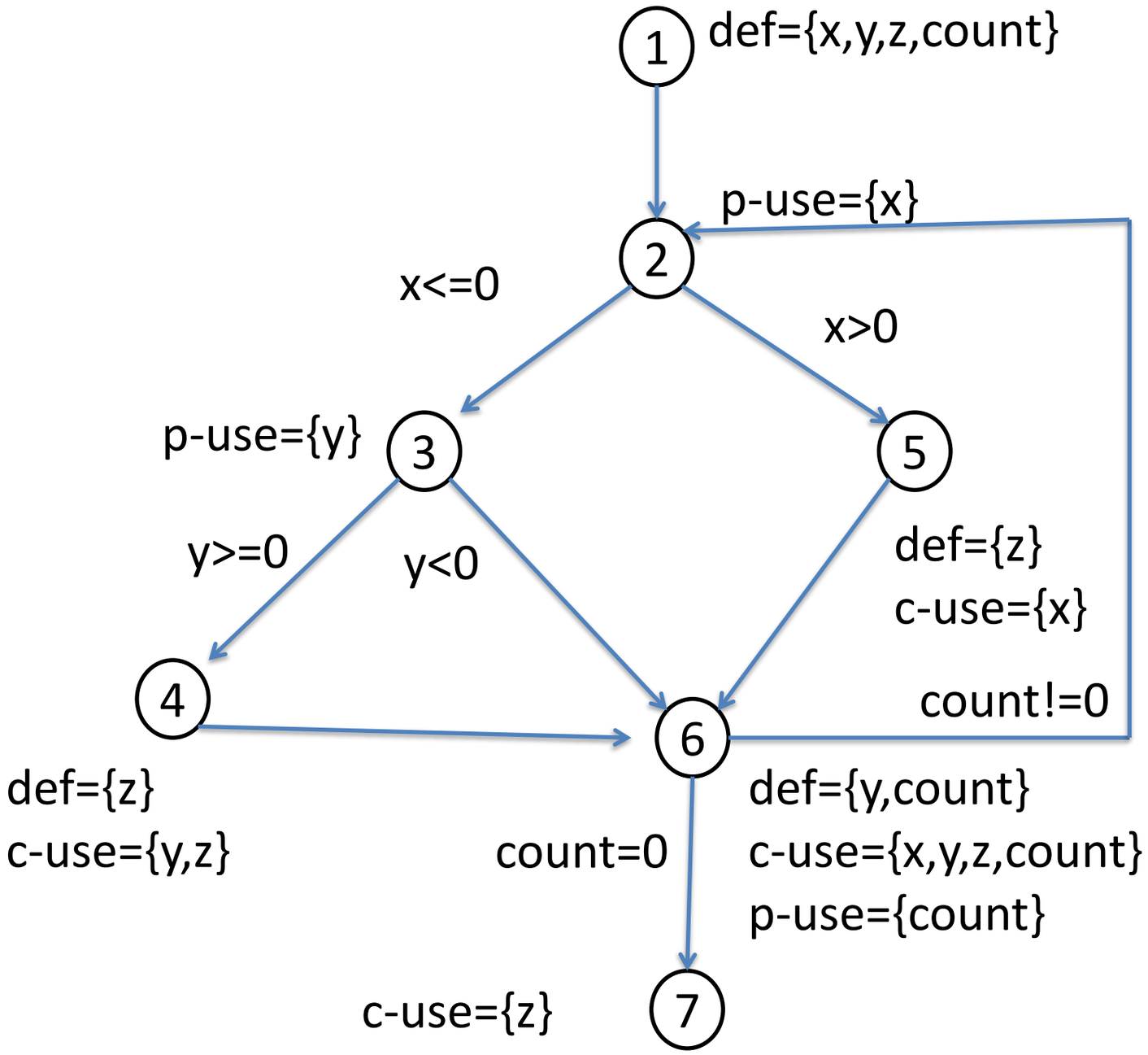


Some Notations

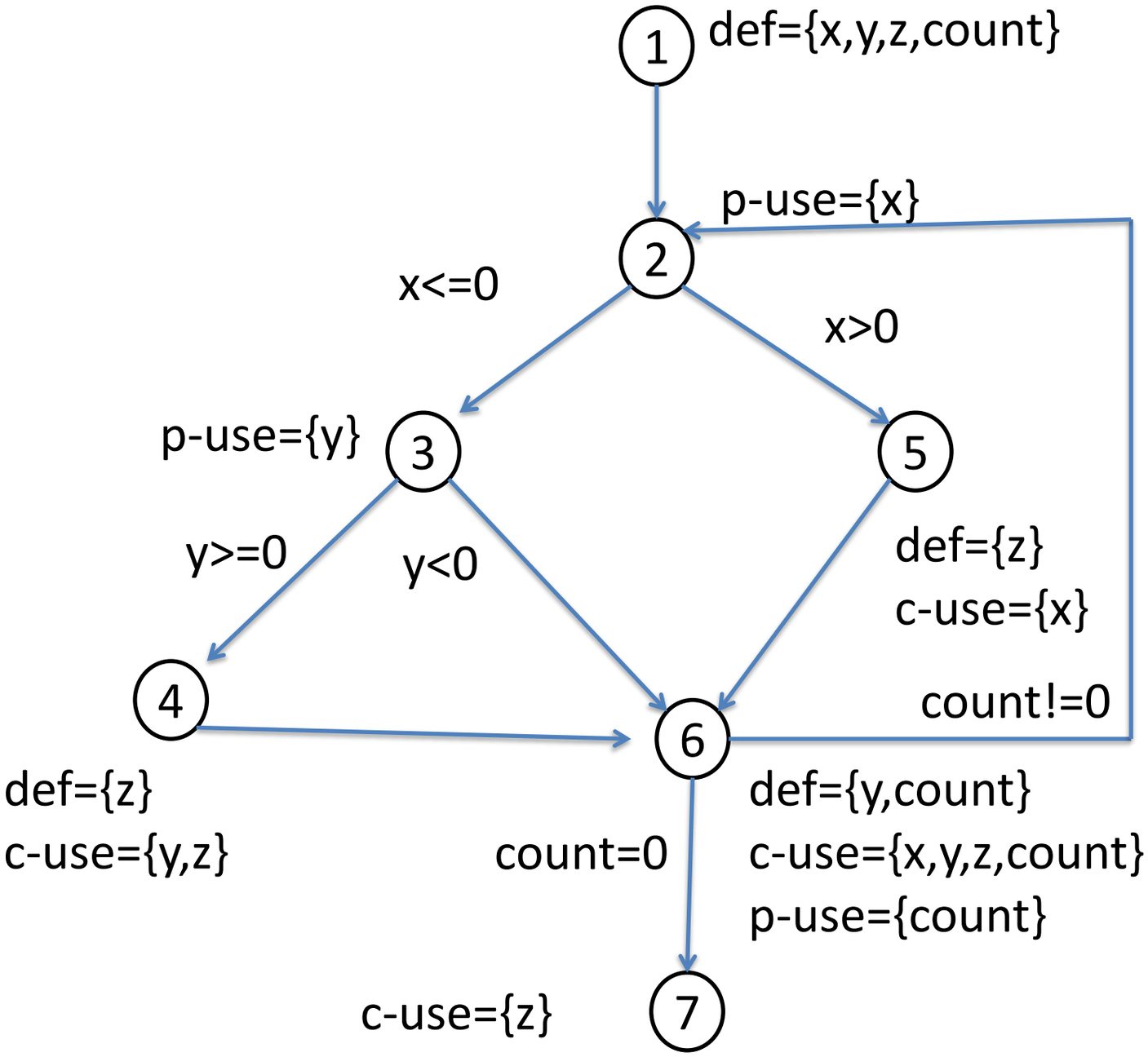
- $d_i(x)$： The definition of variable x in node i
- $u_i(x)$： The use of variable x in node i
- dcu ($d_i(x)$)： The set of c-uses with respect to $d_i(x)$.
  - dcu($d_i(x)$) is also denoted as *dcu(x,i)*
- dpu ($d_i(x)$)： The set of p-uses with respect to $d_i(x)$.
  - dpu($d_i(x)$) is also denoted as *dpu(x,i)*



Variable v	Note n	dcu(v,n)	dpu(v,n)
x	1	{5,6}	{(2,3),(2,5)}
y	1	{4,6}	{(3,4),(3,6)}
…	…	…	…



- **dcu(y,1)={4,6}， dcu(z,1)={4,6,7}**
- **dcu(z,1) subsumes dcu(y,1)**



$$CU = \sum_{i=1}^{n} \sum_{j=1}^{d_i} |dcu(v_i, n_j)|$$

$$PU = \sum_{i=1}^{n} \sum_{j=1}^{d_i} |dpu(v_i, n_j)|$$

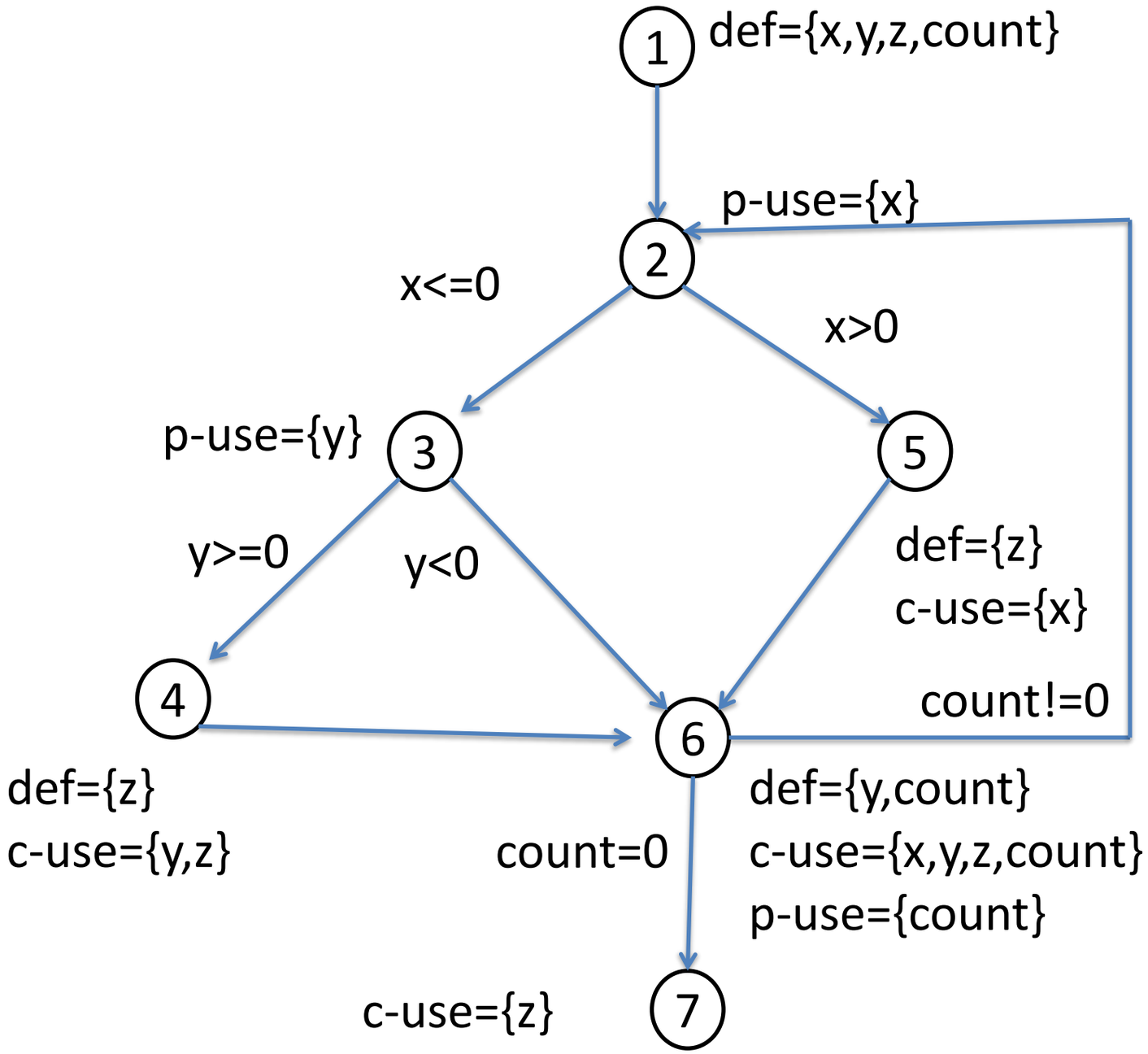
- **n=4,d1=1,d2=2,d3=3,d4=2**
- **The size of All-C-Uses (CU): 17**
- **The size of All-P-Uses (PU): 10**

```
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
```

Test Case t: <x=5,y=-1, count=1>

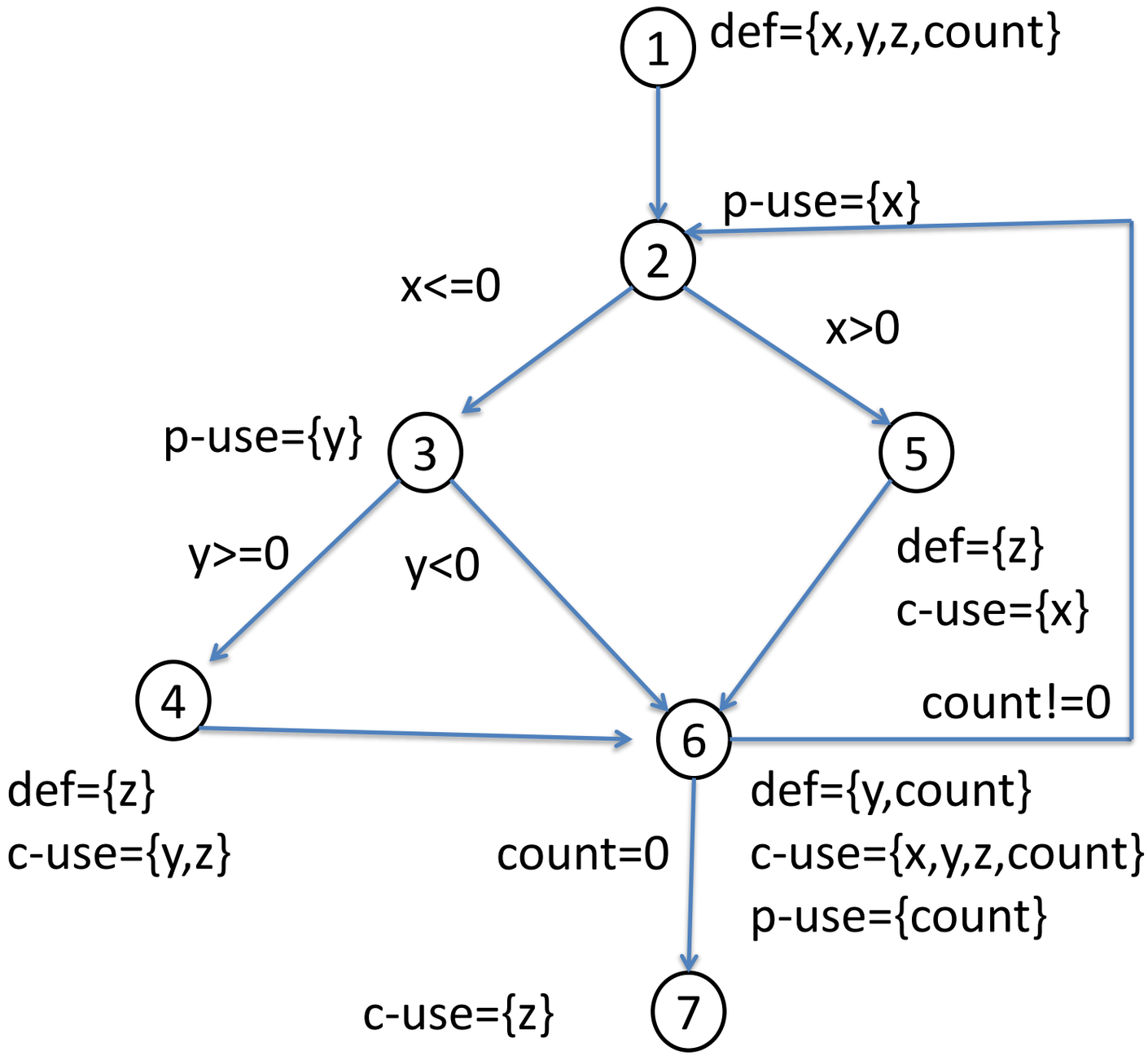
Path： 1-2-5-6-7

- **C-uses (achieved by this test case): 6**
- **All-C-Uses (CU): 17**
- **C-use Coverage: 6/17<1**

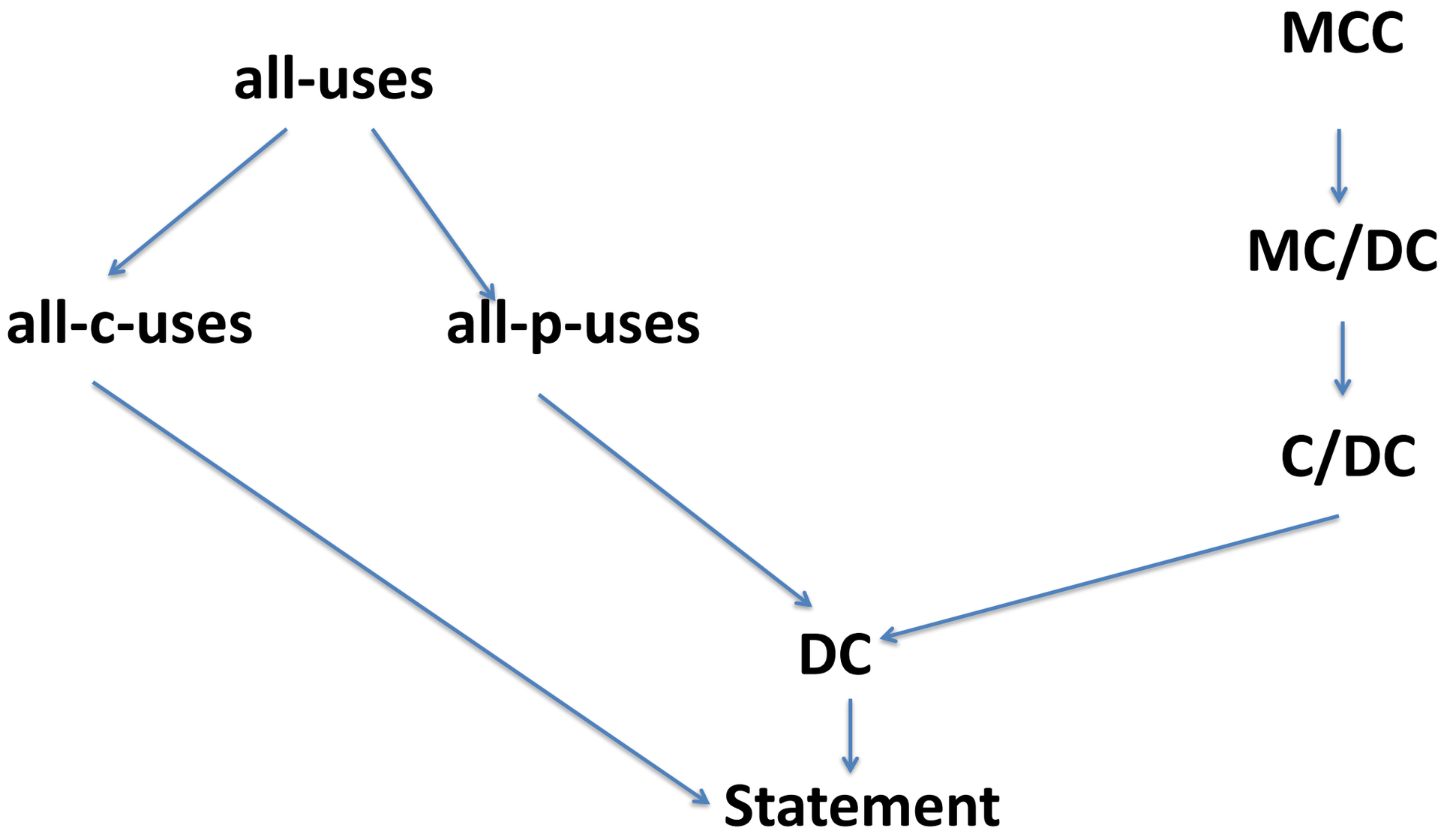


```
1 begin
2     float x,y,z=0.0;
3     int count;
4     input(x,y,count);
5     do{
6       if(x≤0) {
7         if(y≥0)  {
8           z=y*z+1;
9         }
10      }
11     else{
12      z=1/x;
13     }
14     y=x*y+z;
15     count=count-1;}
16   while(count>0)
17   output(z);
18 end
```

- T:{t1:<x=5,y=-1,count=1>,t2:<x=-2,y=-1,count=3>}
  t1 path：1-2-5-6-7
  t2 path：1-2-3-6_1-2-3-4-6_2-2-3-6_3-7
- P-use coverage: 100%



Relationships among some of the coverage criteria



Quiz

```
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)  //should be y!=0 and x!=0
9         z=z/x;
10      else z=z*x;
11      output(z):
12 end
```

- How to achieve All-Uses coverage?

Test case	x	y	z
t1	0	0	0.0
t2	1	1	1.0
..	..	..	..

References and Acknowledgement

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- P. Frankl and E. Weyuker. An Applicable Family of Data Flow Testing Criteria. IEE Transaction on software eng., vol.14, no.10, October 1988.
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Thanks!


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