CS/CE/SE 6367 Software Testing, Validation and Verification

Lecture 4
Code Coverage (II)

UTD

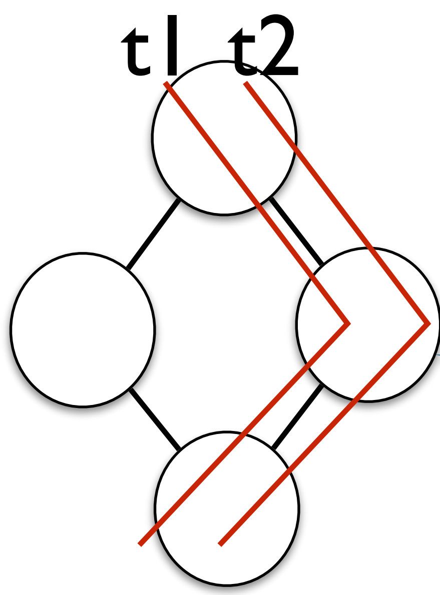
Last Class

- Code coverage
  - Control-flow coverage
    - Statement coverage
    - Branch coverage
    - Path coverage
  - Coverage Collection Tools
    - EclEmma

This Class

- Code coverage
  - Data-flow coverage
    - All-Defs
    - All-Uses
    - All-DU-Paths
    - All-P-Uses/Some-C-Uses
    - All-C-Uses/Some-P-Uses
    - All-P-Uses
    - All-C-Uses

Motivation



Control-flow graph

Are t1 and t2 identical?

although the paths are the same, different tests may have different variable values defined/used

- Basic idea:
  - Existing control-flow coverage criteria only consider the execution path (structure)
  - In the program paths, which variables are defined and then used should also be covered (data)
- A family of dataflow criteria is then defined, each providing a different degree of data coverage

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 (garbage collection helps here)

Uninitialized

```
...
List l;
l.add("1");
...
```

```
Exception in thread "main" java.lang.NullPointerException
	at dataflow.Temp.main(Temp.java:21)
```

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);
}
```

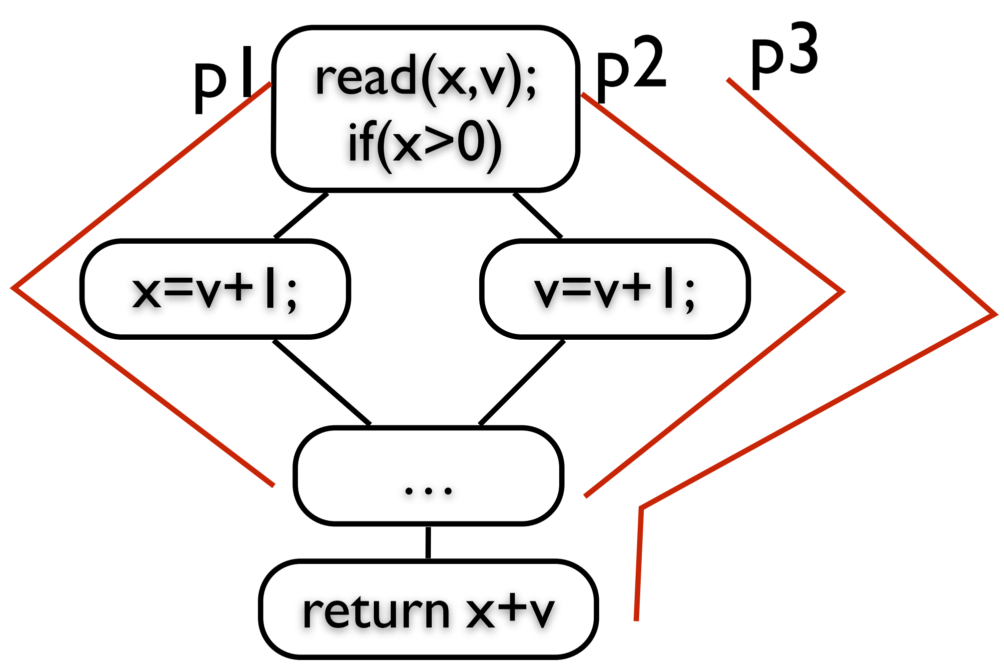
There is a p-use of x and a c-use of y

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**)

More Dataflow Terms and Definitions

- 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
- A **complete path** is a path whose initial node is a entry node and whose final node is an exit node



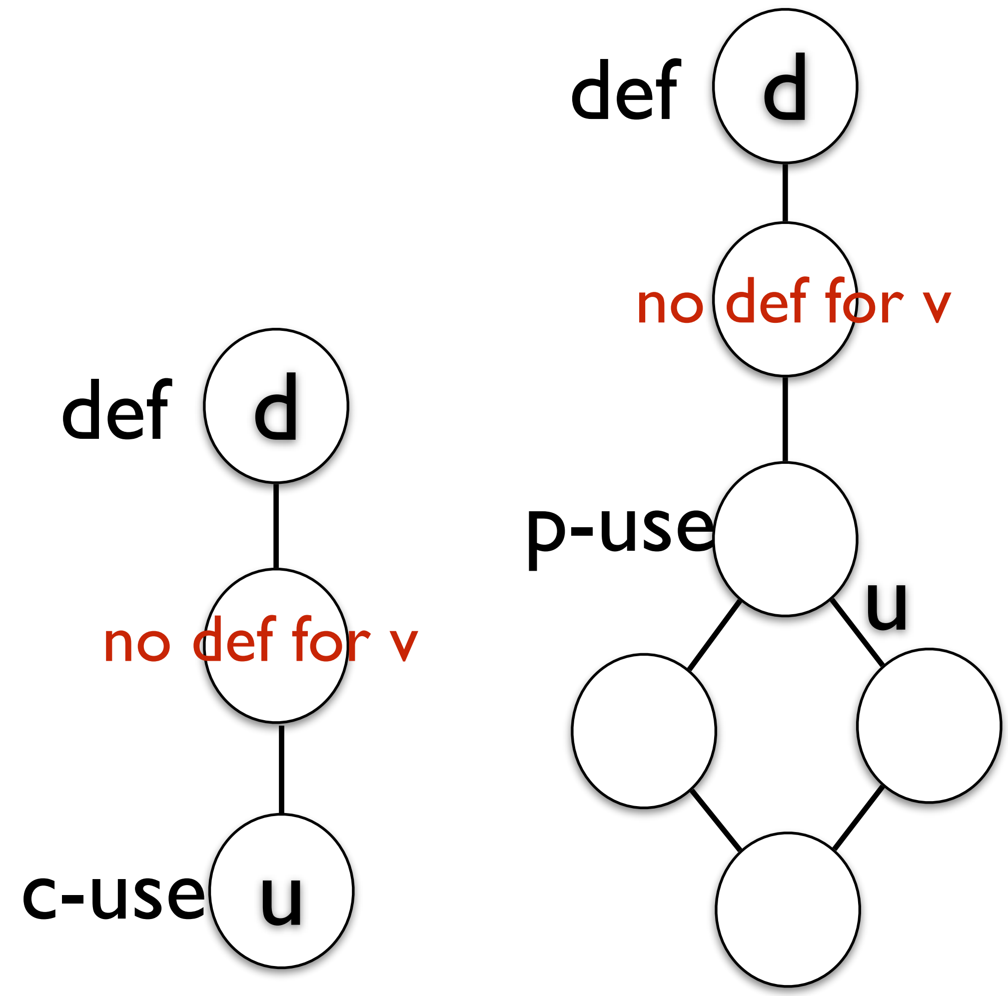
Control-flow graph

p1 is def-clear for **v**, while p2 is not

p1, p2 are not complete, while p3 is

Definition-Use Pair (DU-Pair)

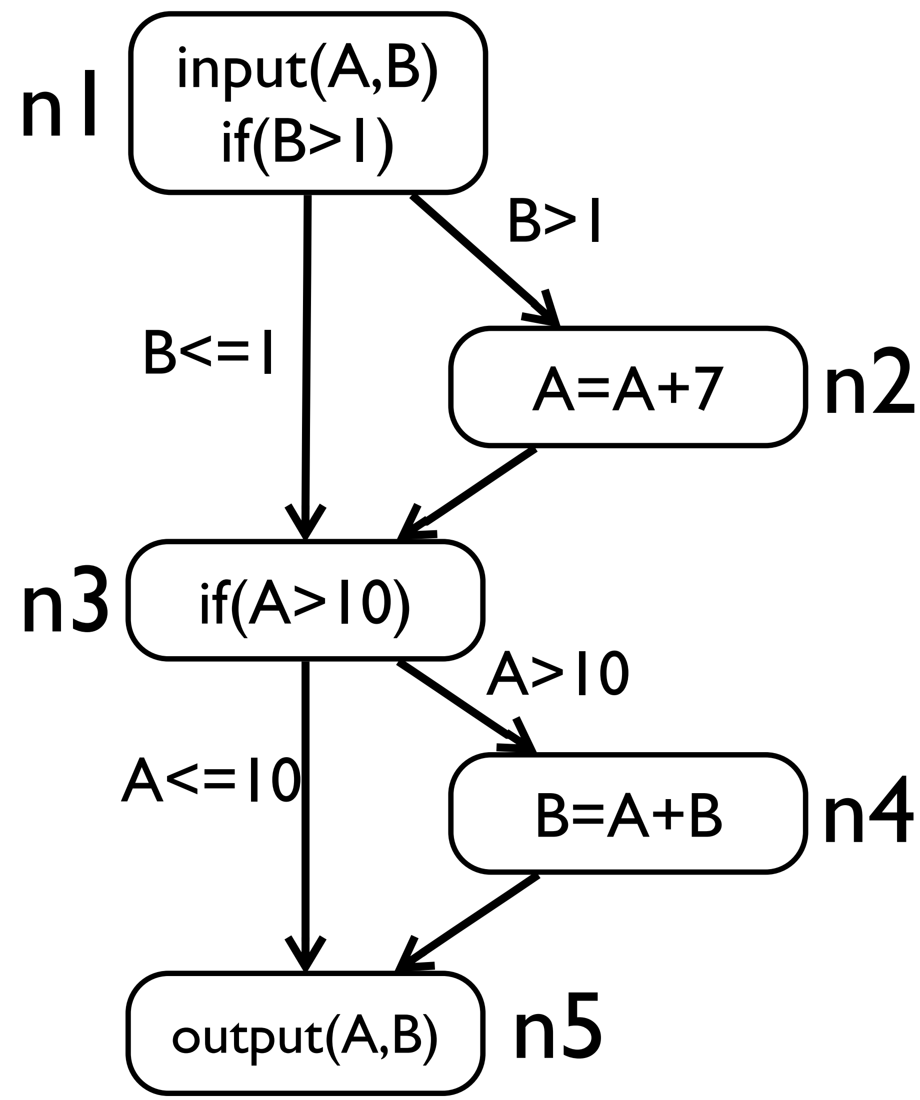
- A **definition-use pair** ("du-pair") with respect to a variable **v** is a pair (**d**,**u**) such that
  - **d** is a node defining **v**
  - **u** is a node or edge using **v**
    - when it is a p-use of **v**, **u** is an outgoing edge of the predicate statement
  - there is a def-clear path with respect to **v** from **d** to **u**



c-use example p-use example

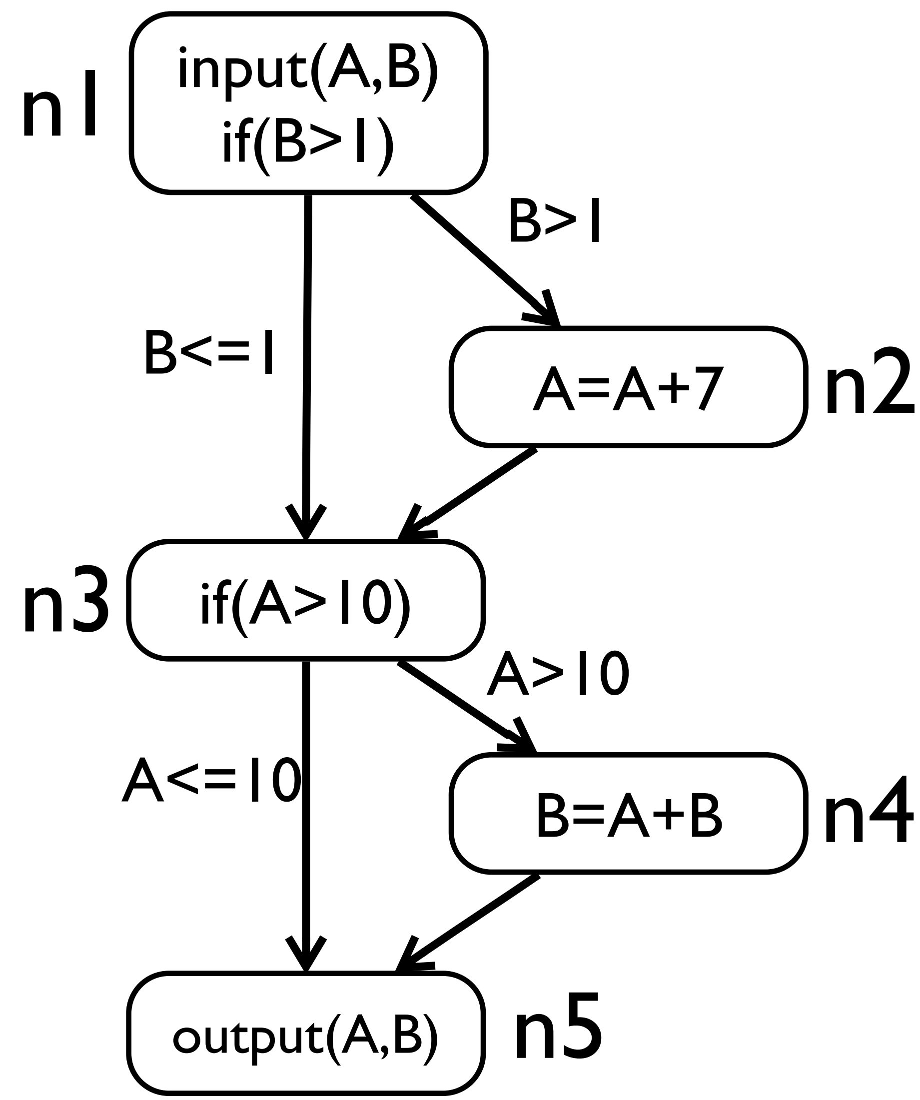
DU-Pair: Example 1

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



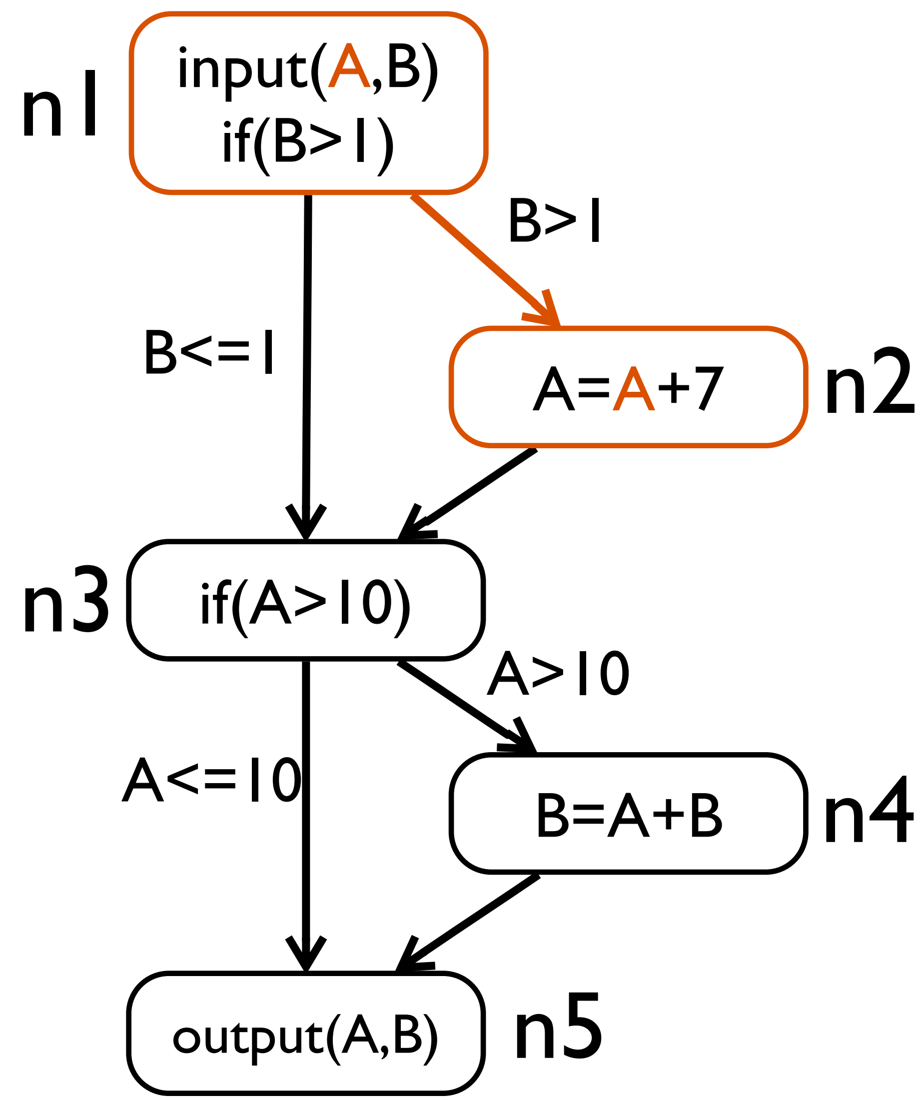
Identifying DU-Pairs – Variable **A**

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>



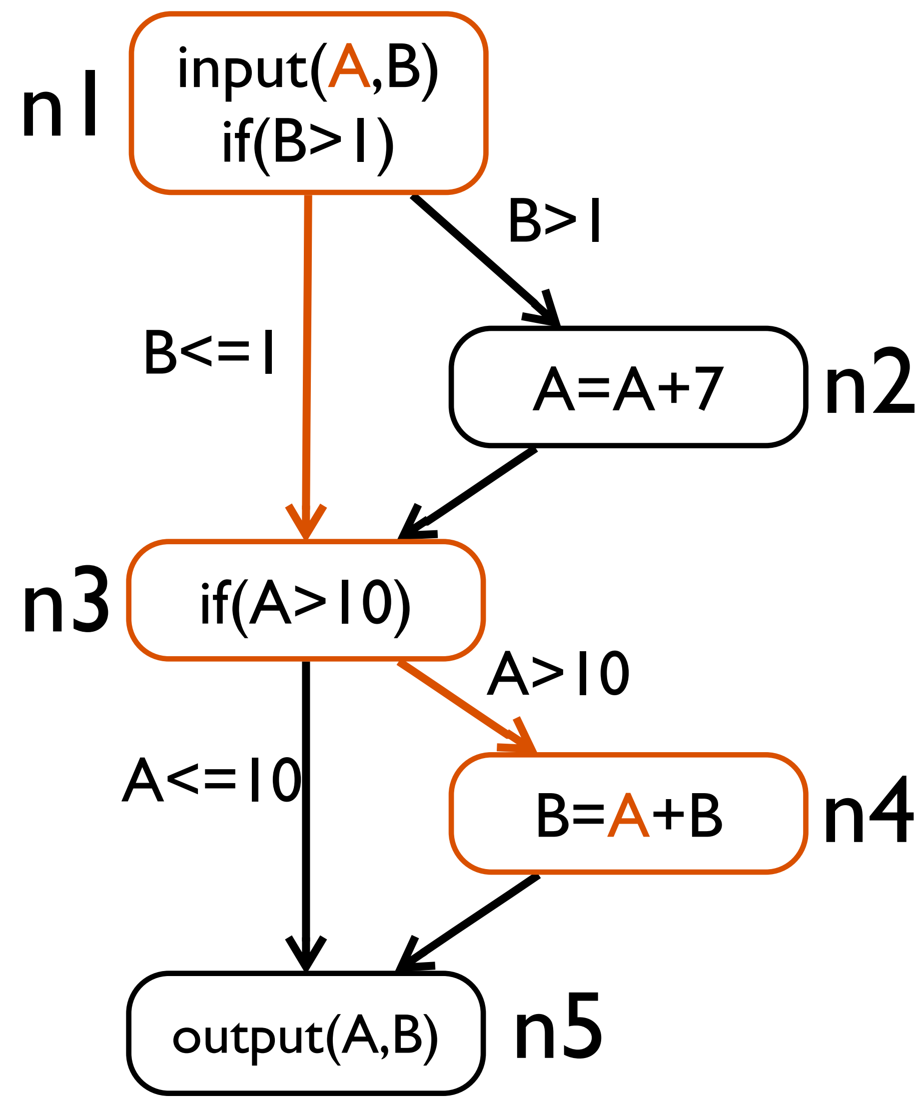
Identifying DU-Pairs – Variable **A**

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>



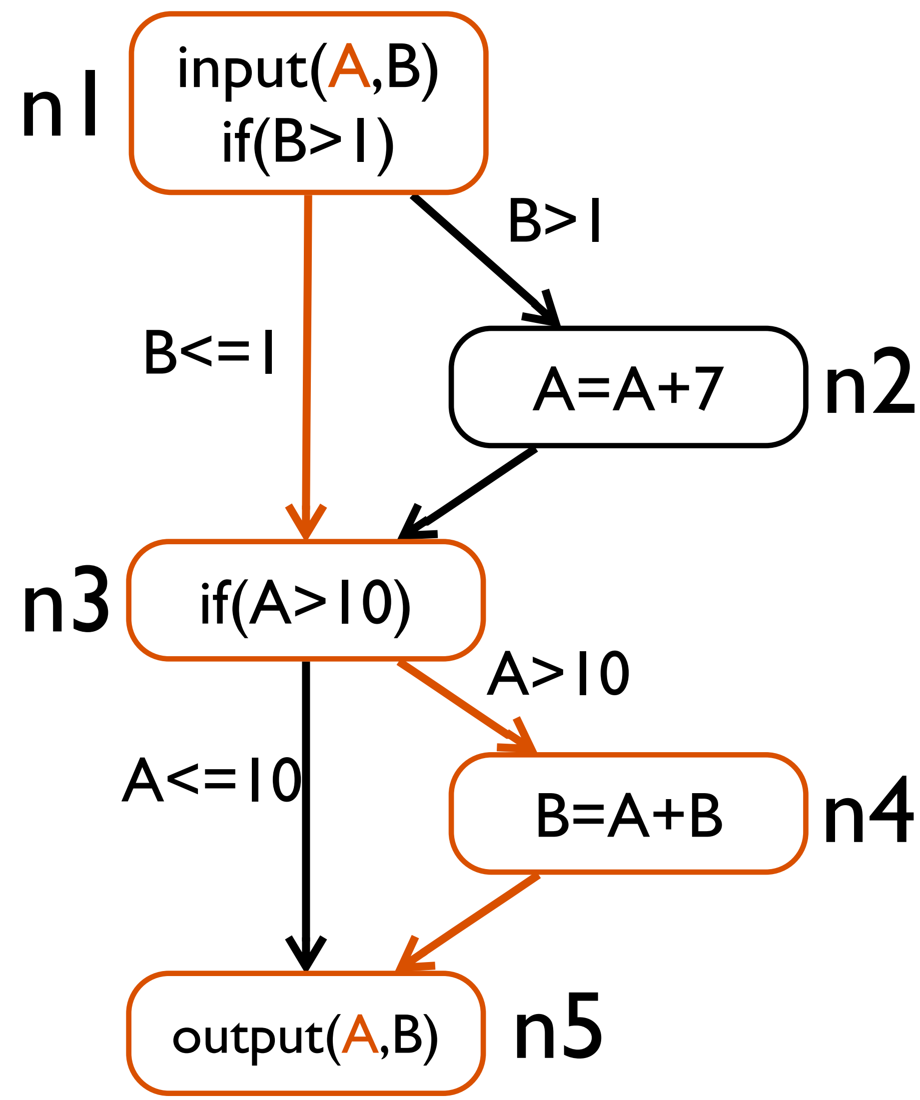
Identifying DU-Pairs – Variable **A**

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>



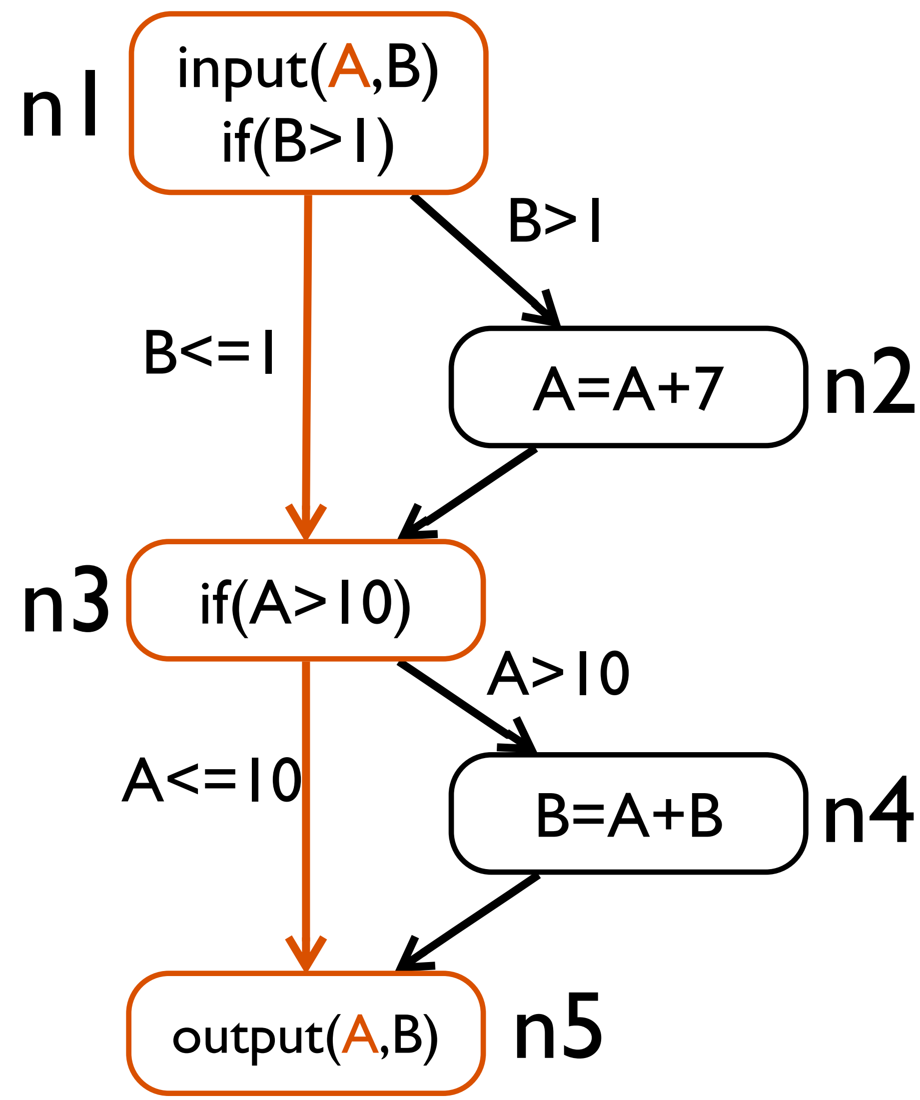
Identifying DU-Pairs – Variable **A**

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>



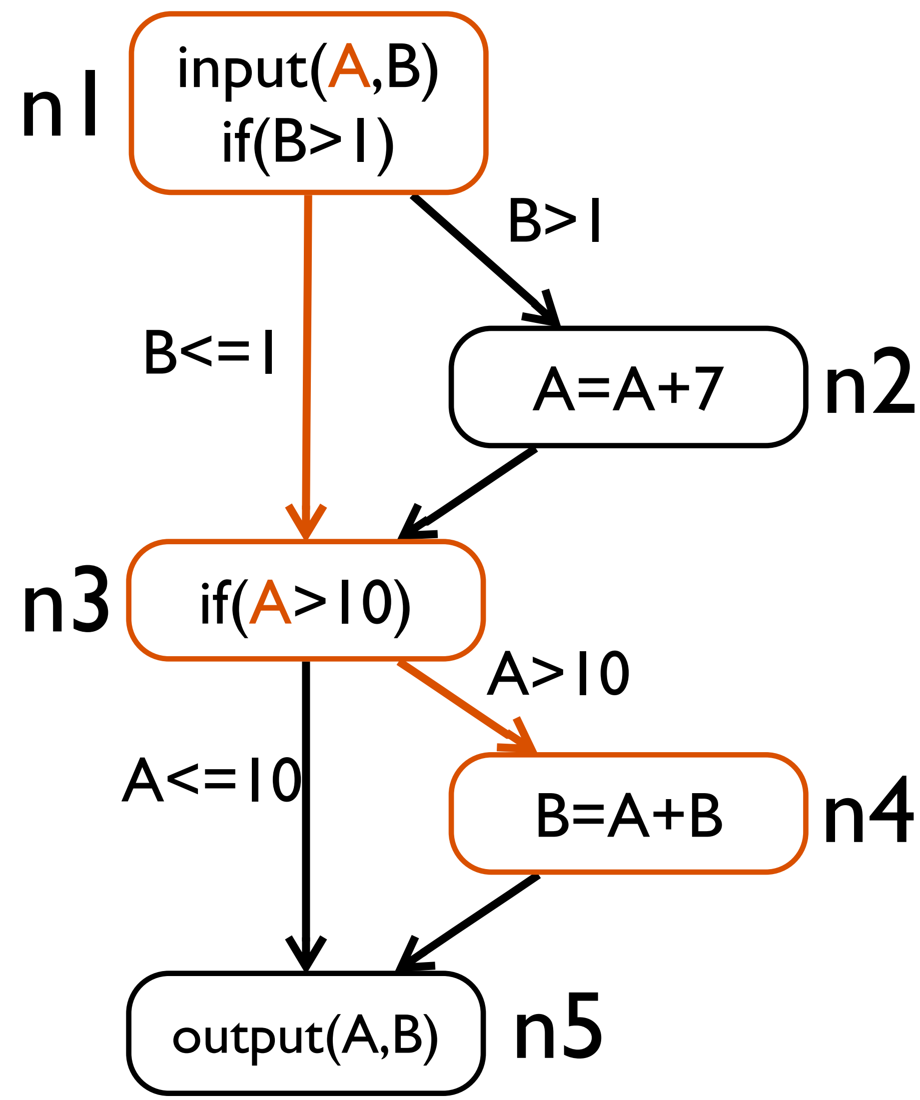
Identifying DU-Pairs – Variable **A**

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>



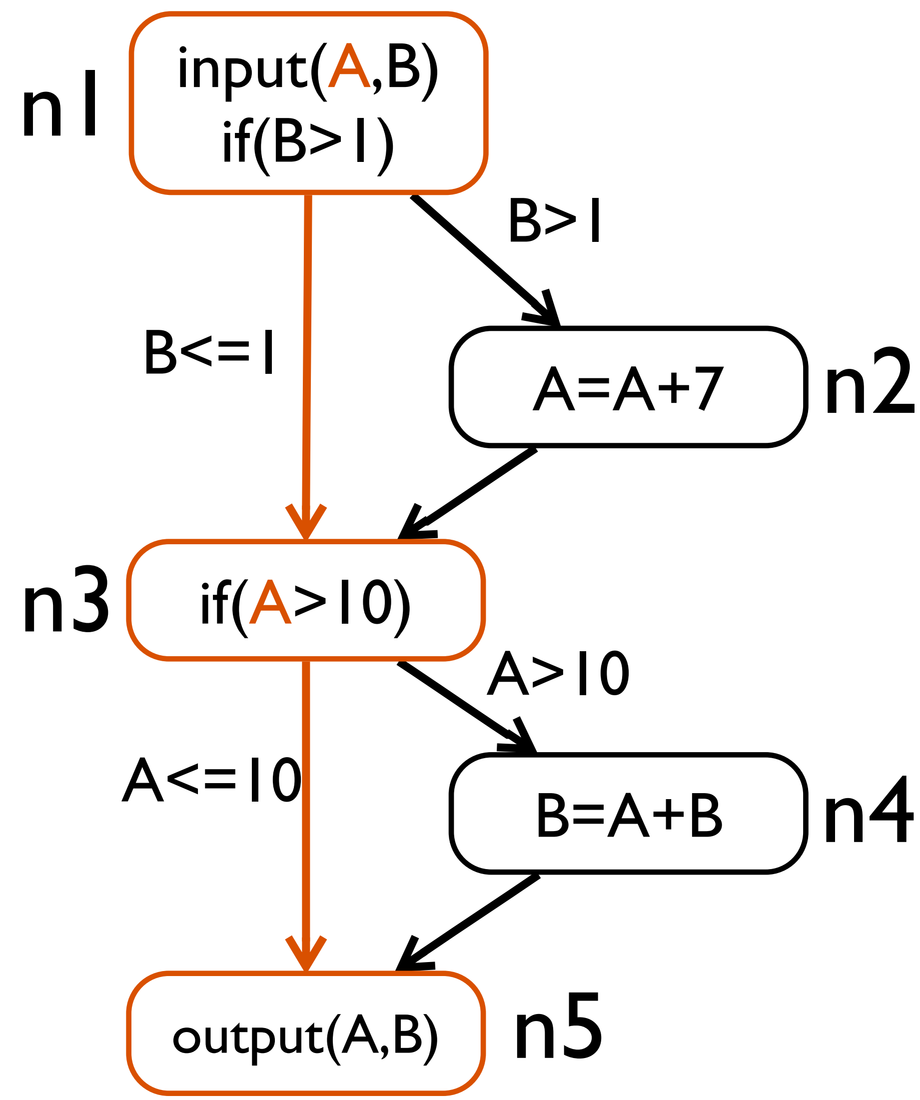
Identifying DU-Pairs – Variable **A**

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>



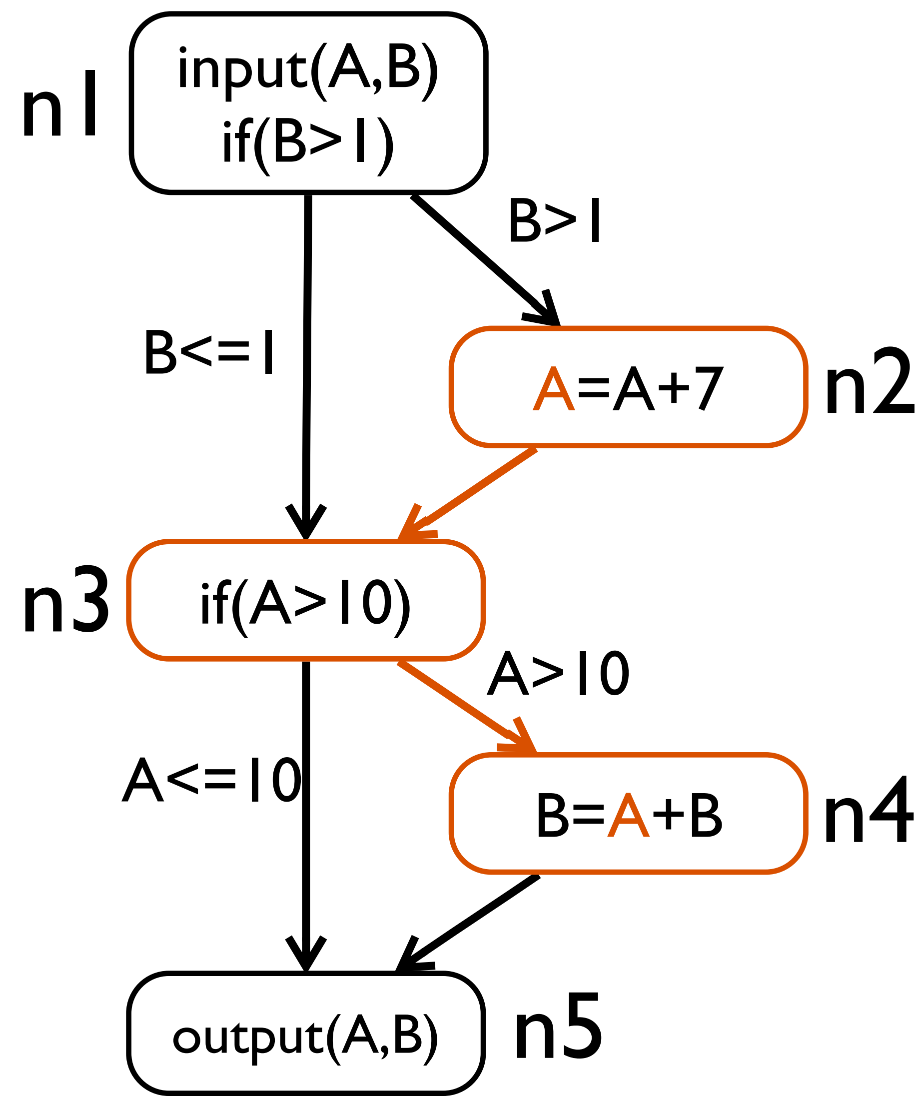
Identifying DU-Pairs – Variable **A**

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>



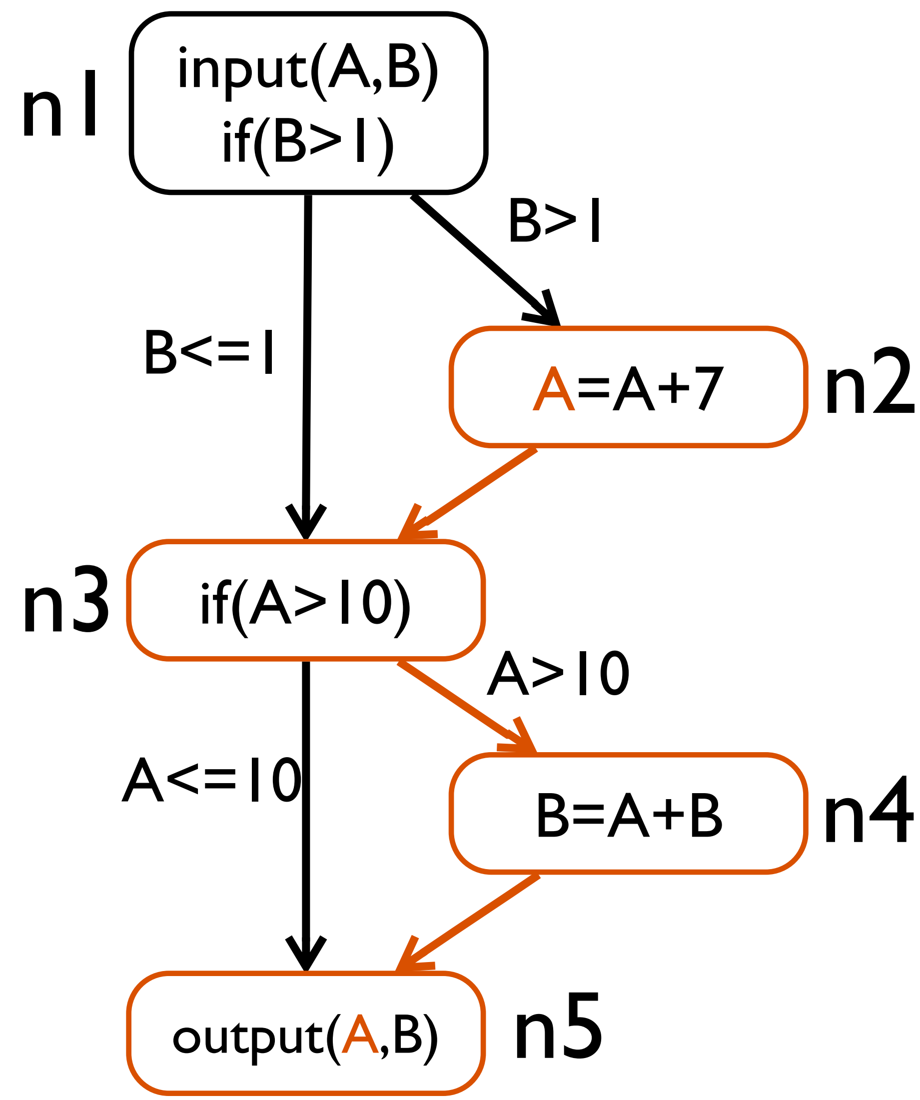
Identifying DU-Pairs – Variable **A**

<u>du-pair</u>	<u>path(s)</u>
(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>



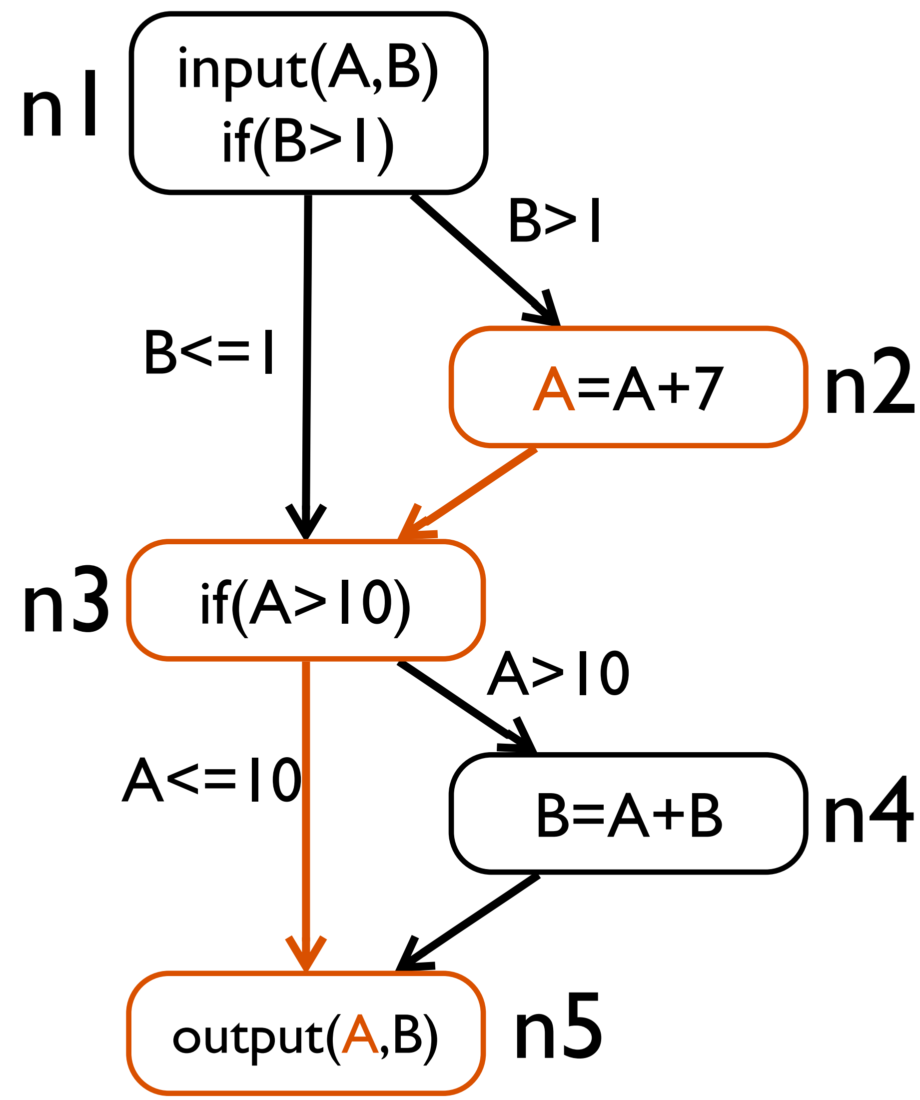
Identifying DU-Pairs – Variable **A**

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>



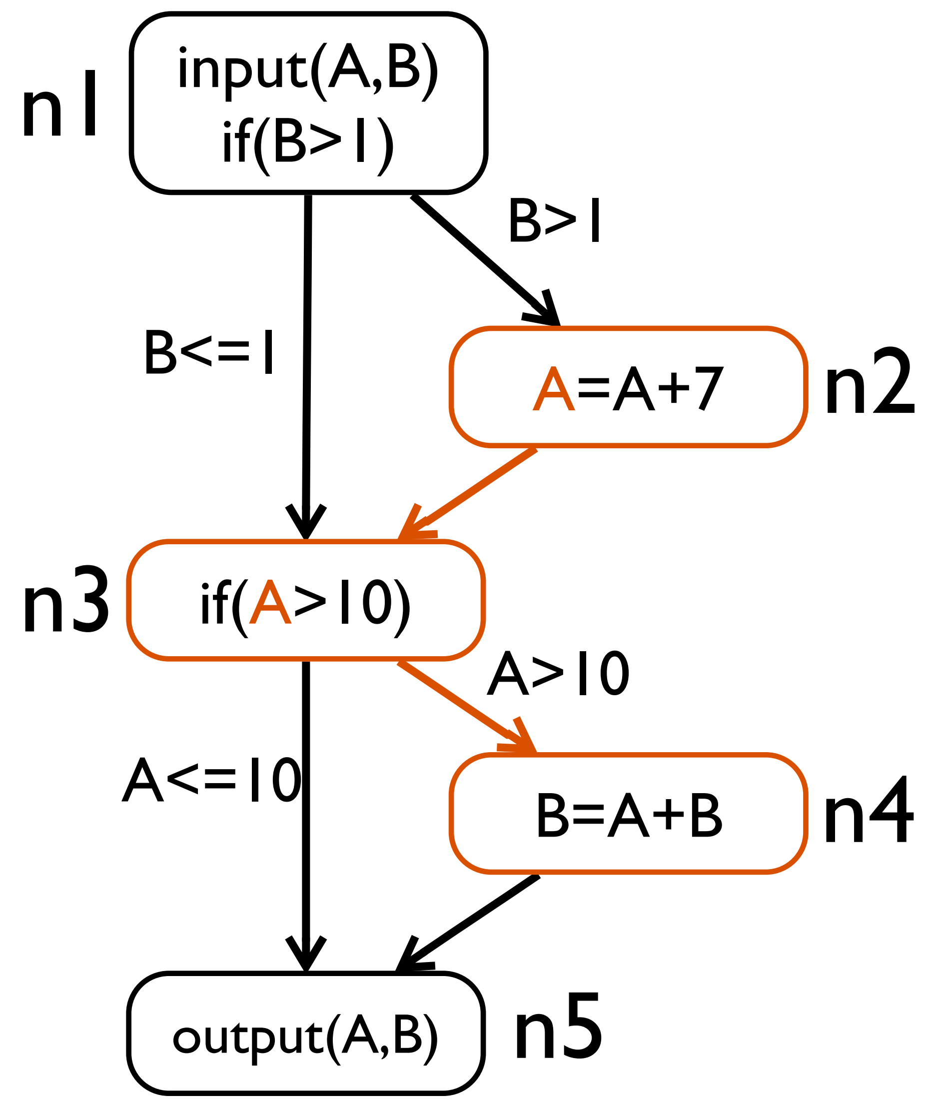
Identifying DU-Pairs – Variable **A**

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>



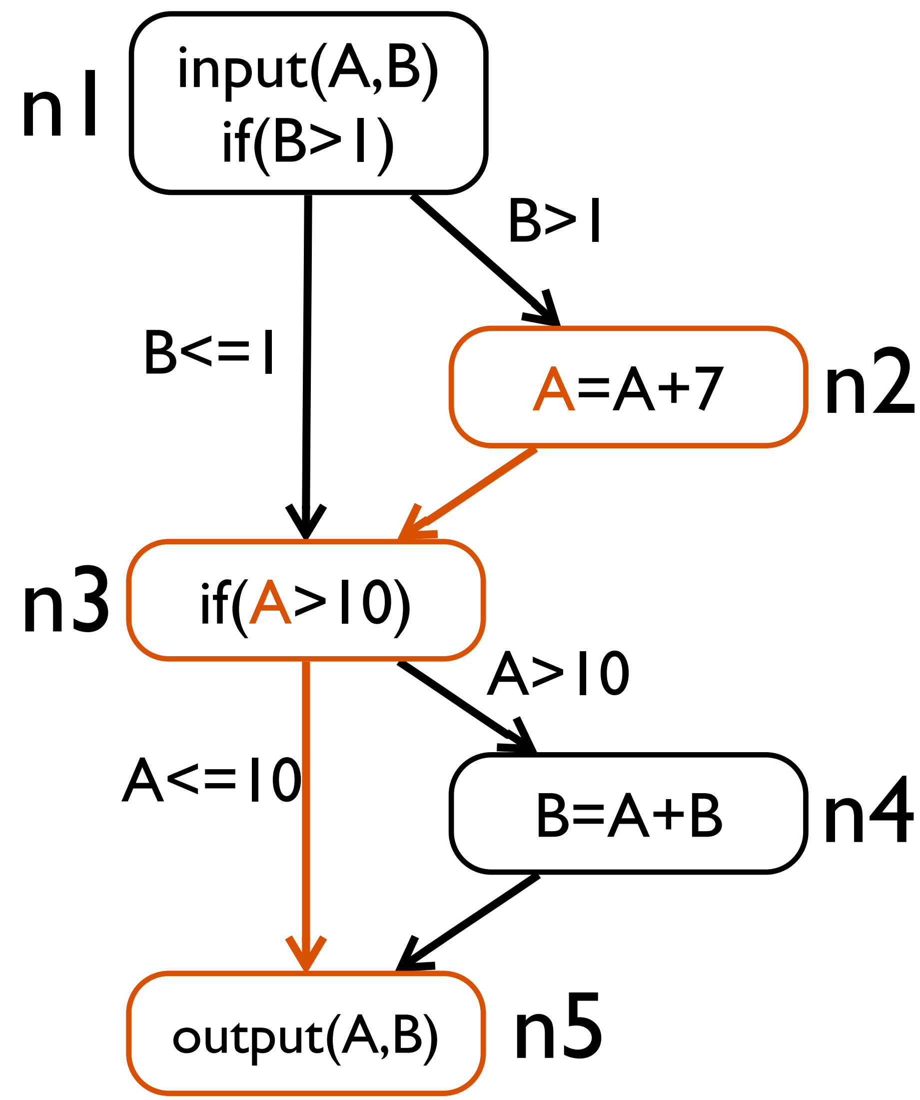
Identifying DU-Pairs – Variable **A**

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>



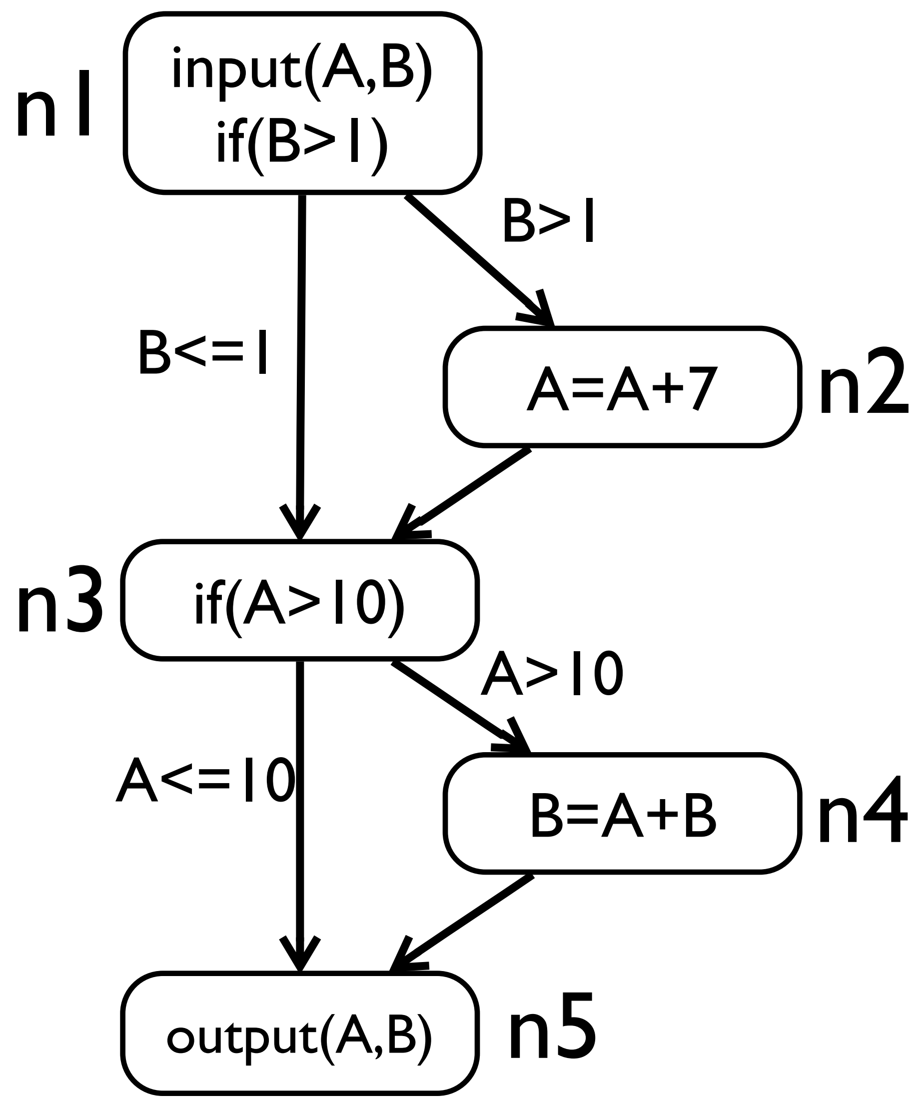
Identifying DU-Pairs – Variable **A**

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>**



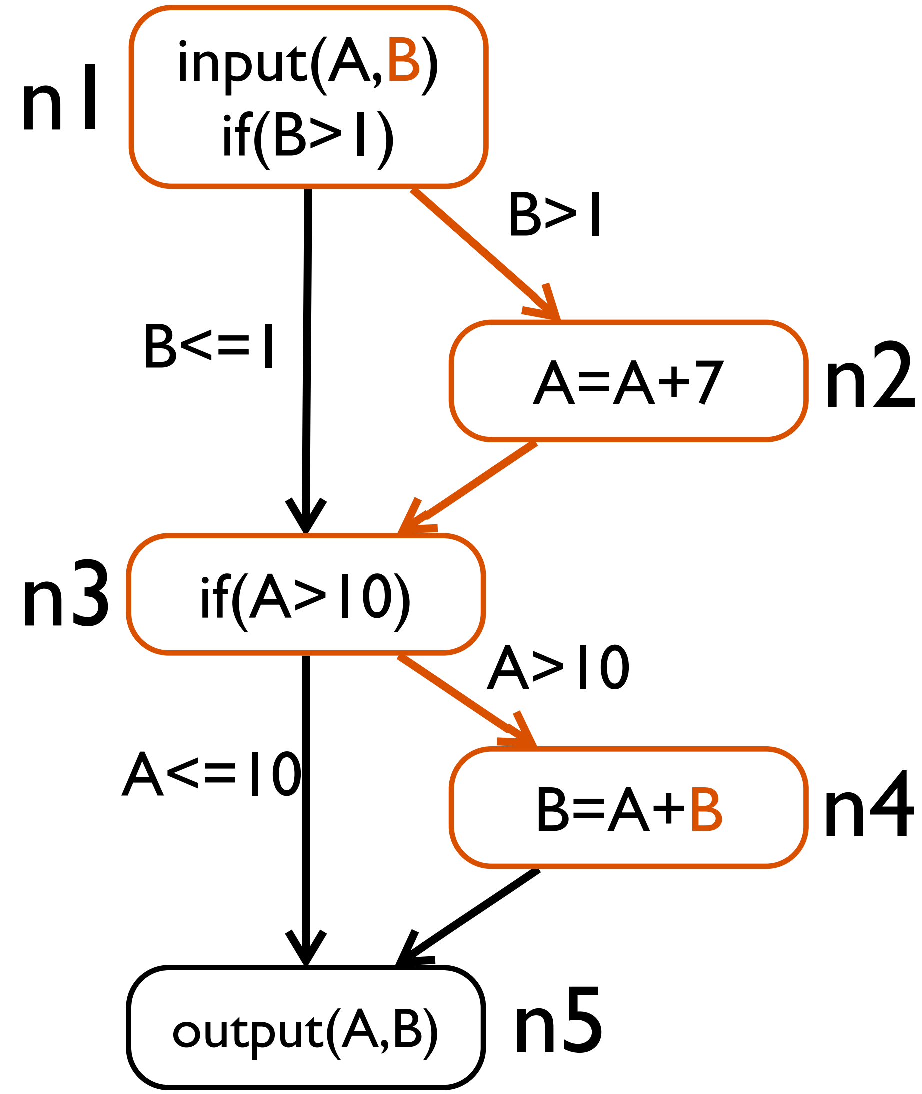
Identifying DU-Pairs – Variable **B**

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>



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

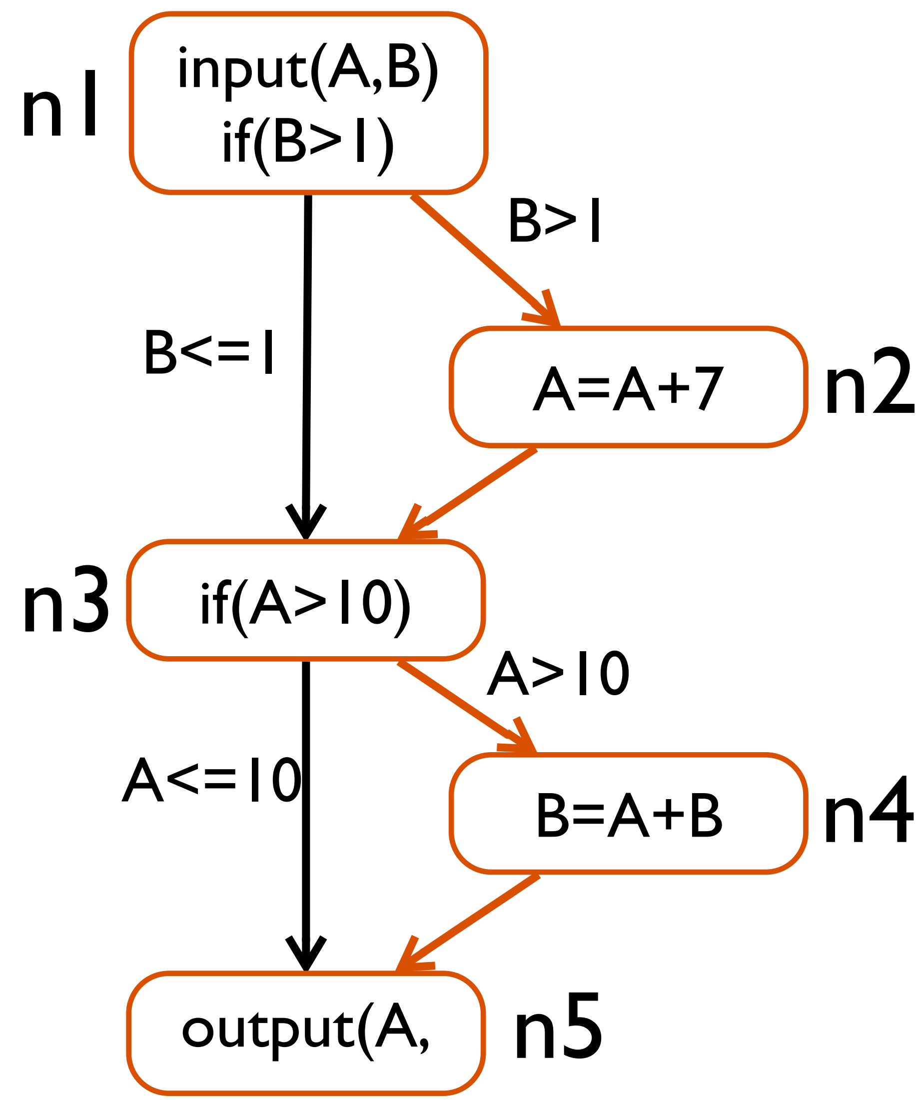
- **All-Defs**
  - for every program variable **v**, at least one def-clear path from every definition of **v** to at least one c-use or one p-use of **v** must be covered

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?

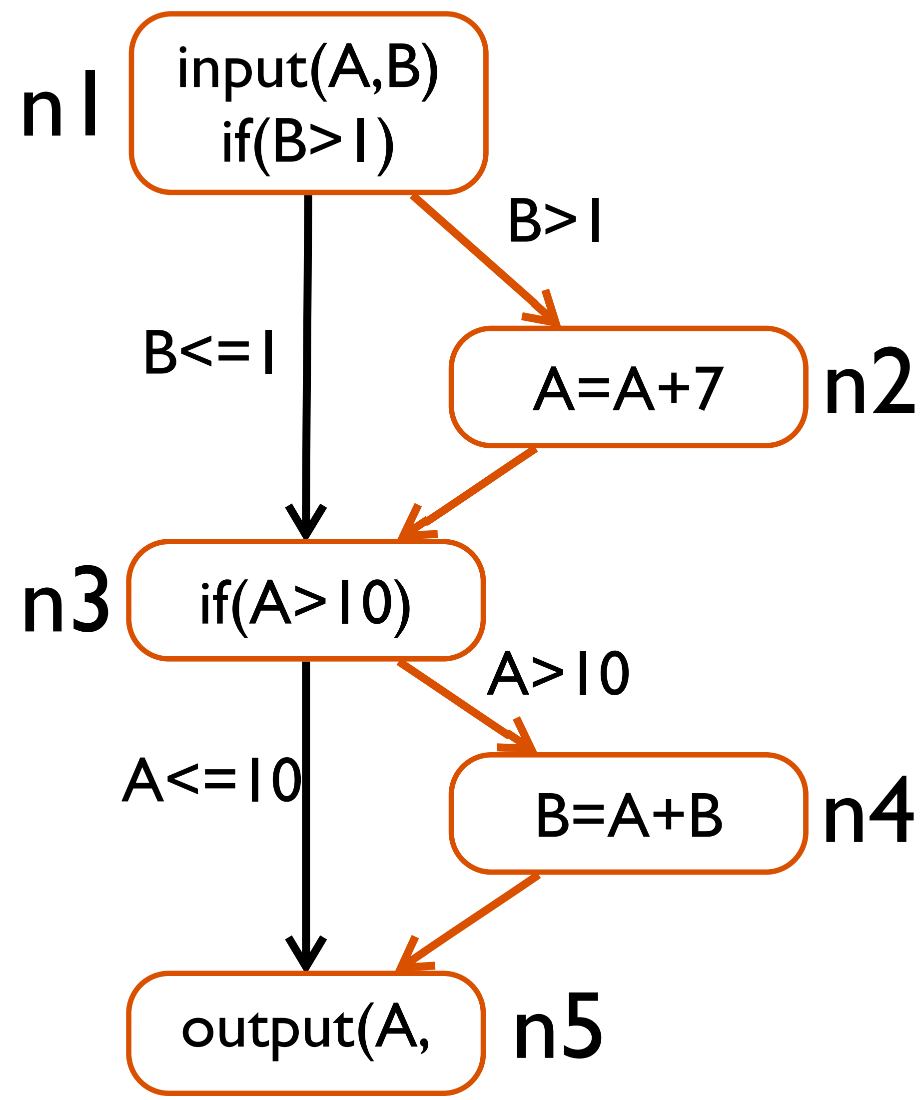
Def-Clear Paths subsumed by <1,2,3,4,5> for Variable **A**

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



Dataflow Test Coverage Criteria

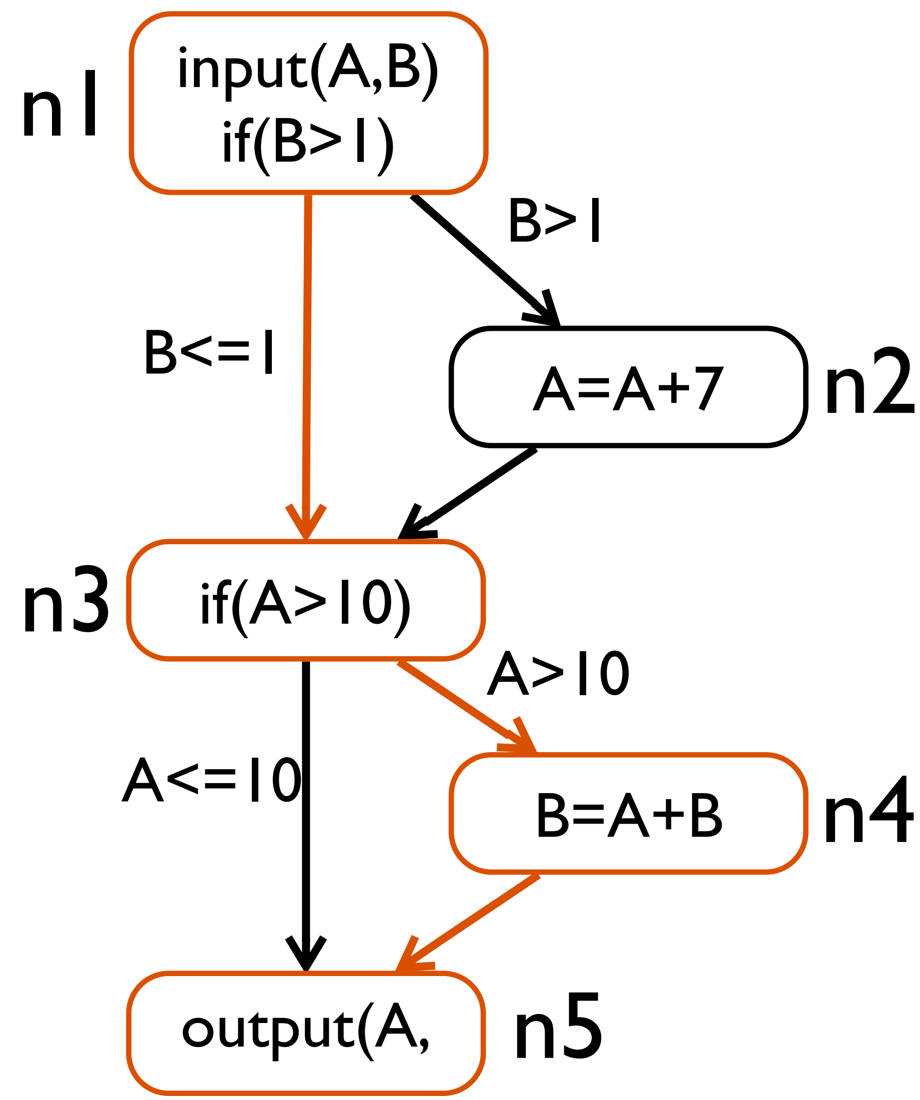
- Since <1,2,3,4,5> covers at least one def-clear path from every definition of **A** or **B** to at least one c-use or p-use of **A** or **B**, All-Defs coverage is achieved

Dataflow Test Coverage Criteria

- **All-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 additional test cases executing paths:
  - t2: <1,3,4,5>
  - t3: <1,2,3,5>
- Do all three test cases provide All-Uses coverage?

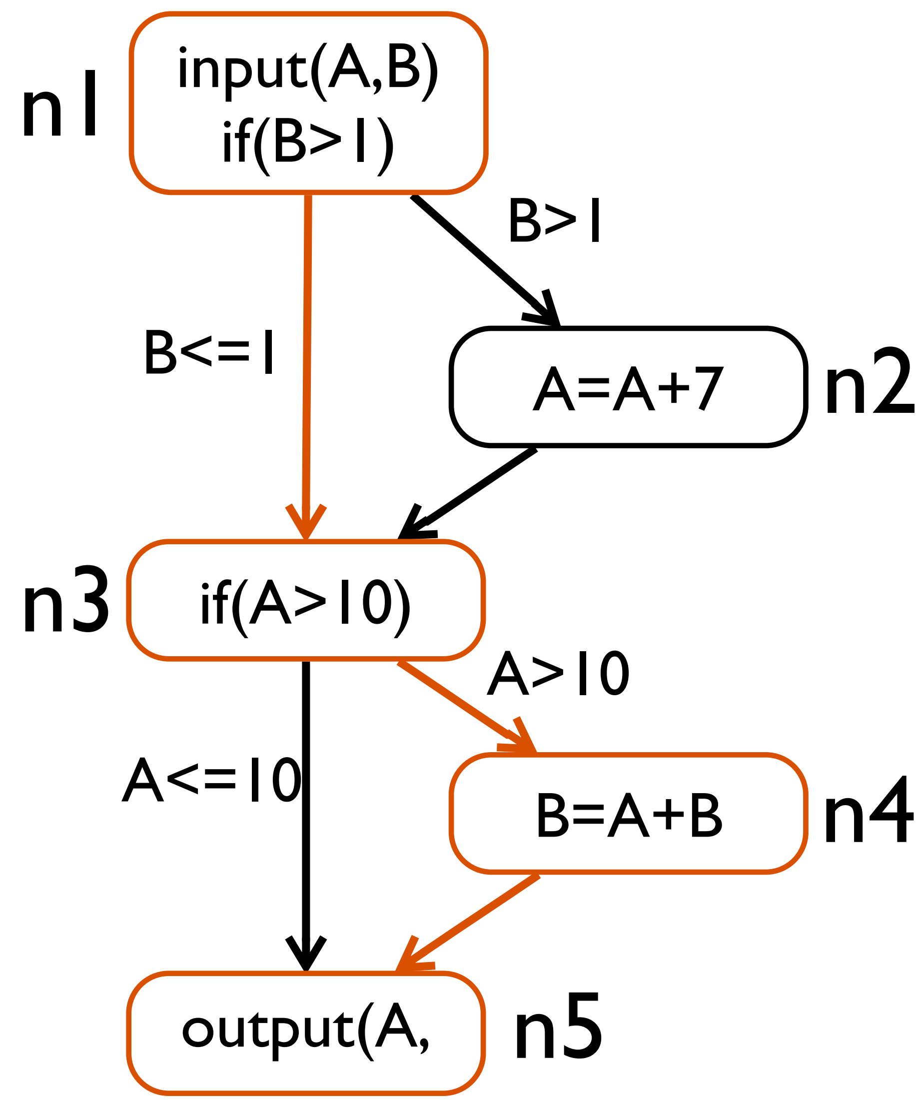
Def-Clear Paths Subsumed by <1,3,4,5> for Variable **A**

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



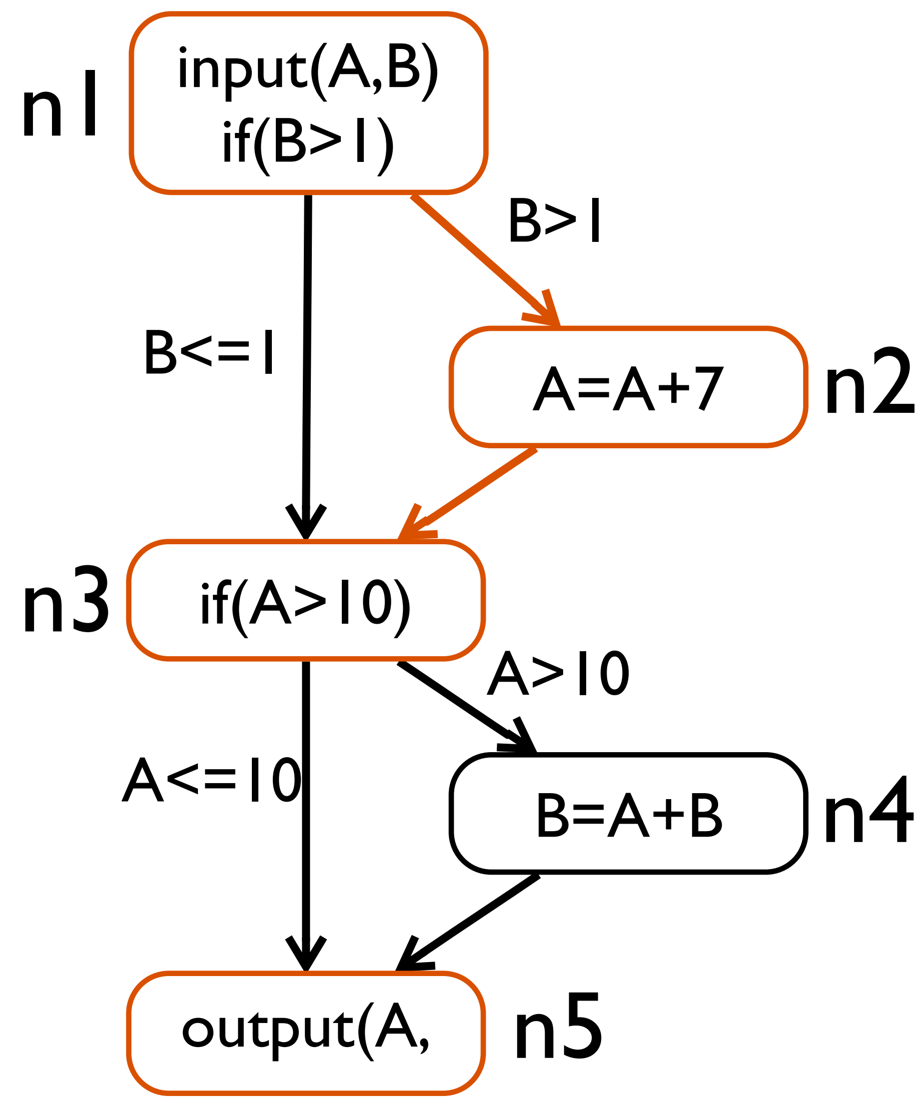
Def-Clear Paths Subsumed by <1,3,4,5> for Variable **B**

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



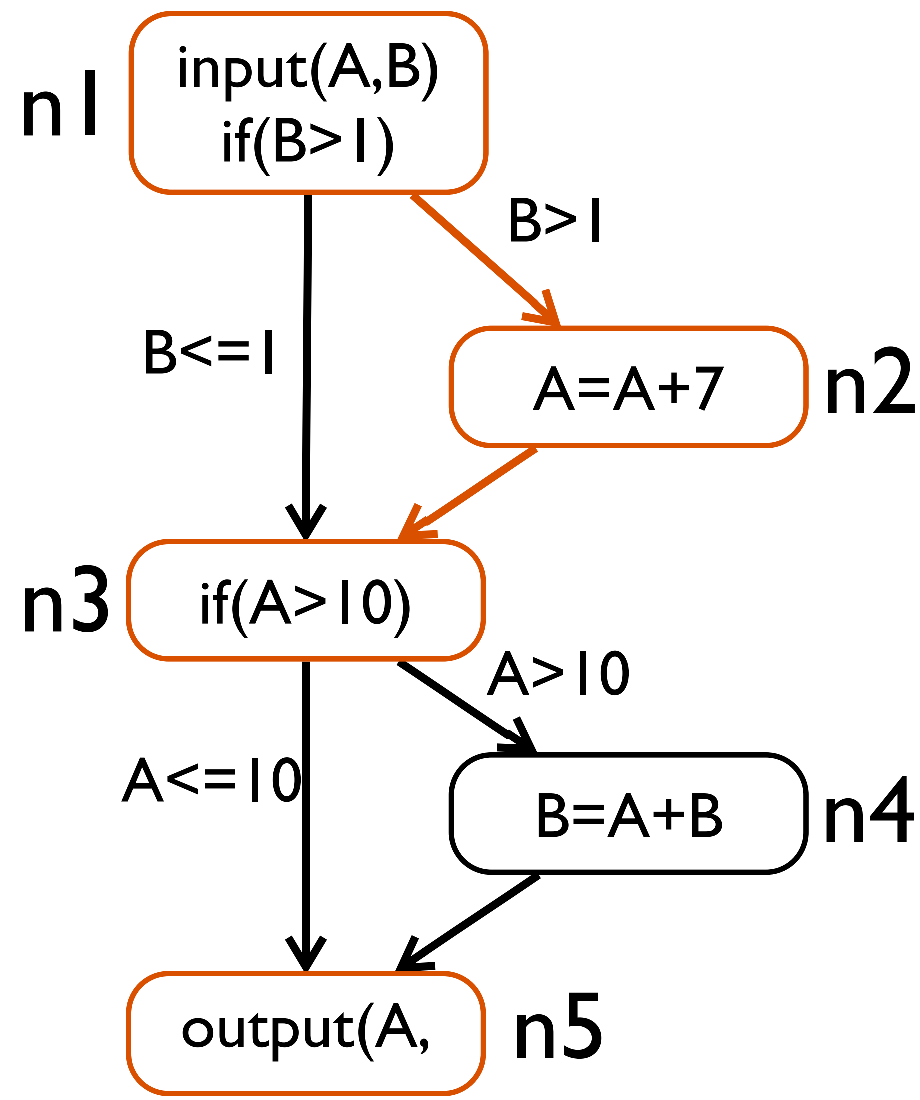
Def-Clear Paths Subsumed by <1,2,3,5> for Variable **A**

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



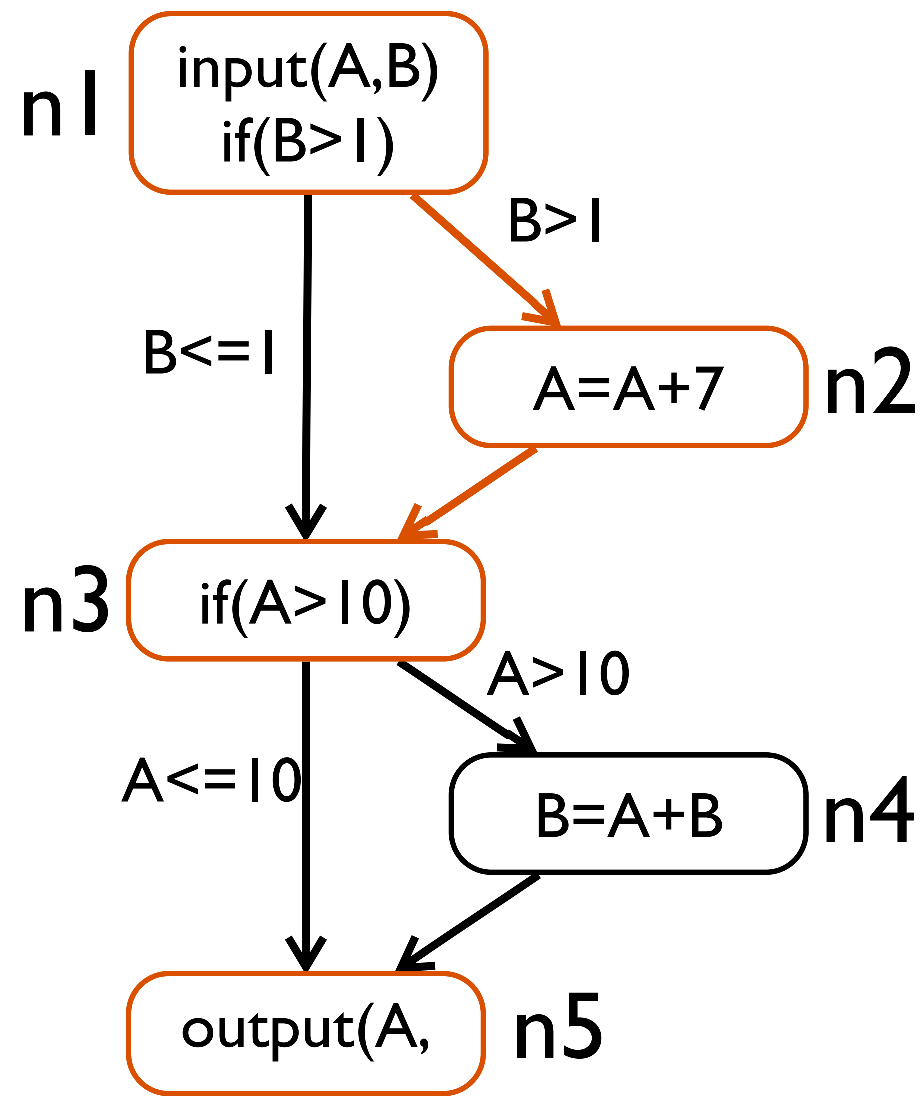
Def-Clear Paths Subsumed by <1,2,3,5> for Variable **A**

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



Def-Clear Paths Subsumed by <1,2,3,5> for Variable **B**

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

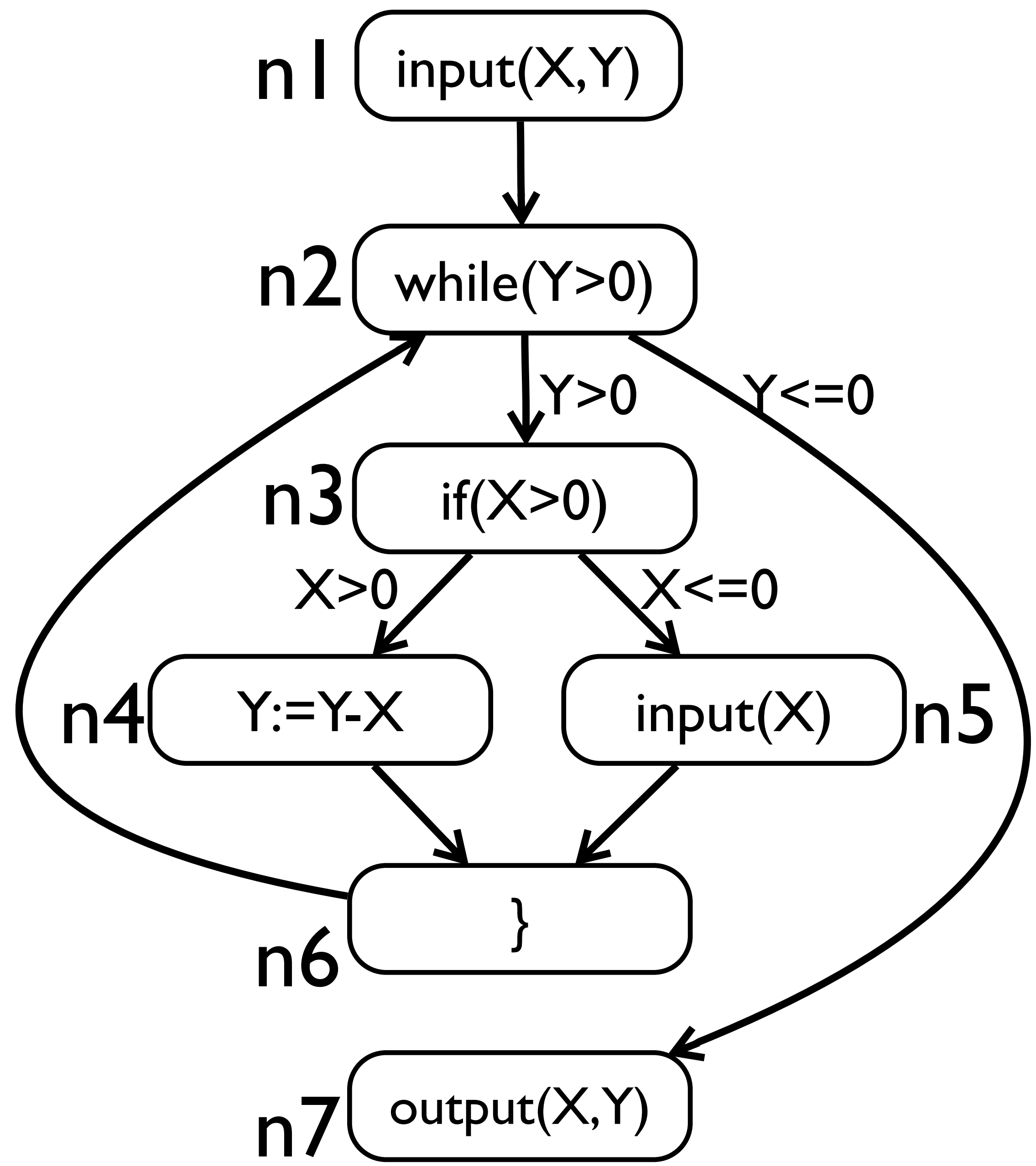


Dataflow Test Coverage Criteria

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

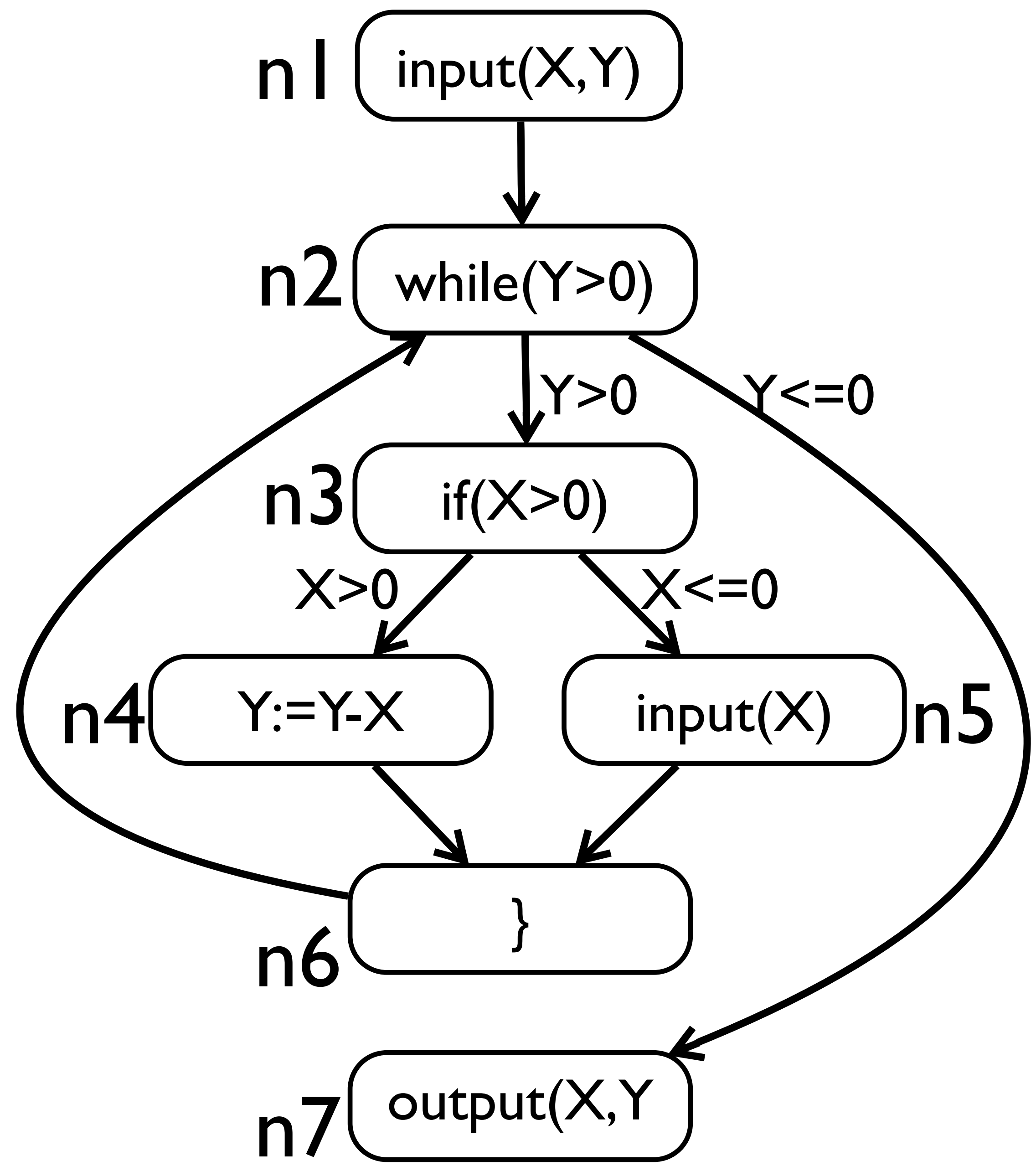
DU-Pair: More Complicated Example

```
1. input(X,Y)
2. while (Y>0) {
3.    if (X>0)
4.          Y := Y-X
       else
5.          input(X)
6.    }
7. output(X,Y)
```



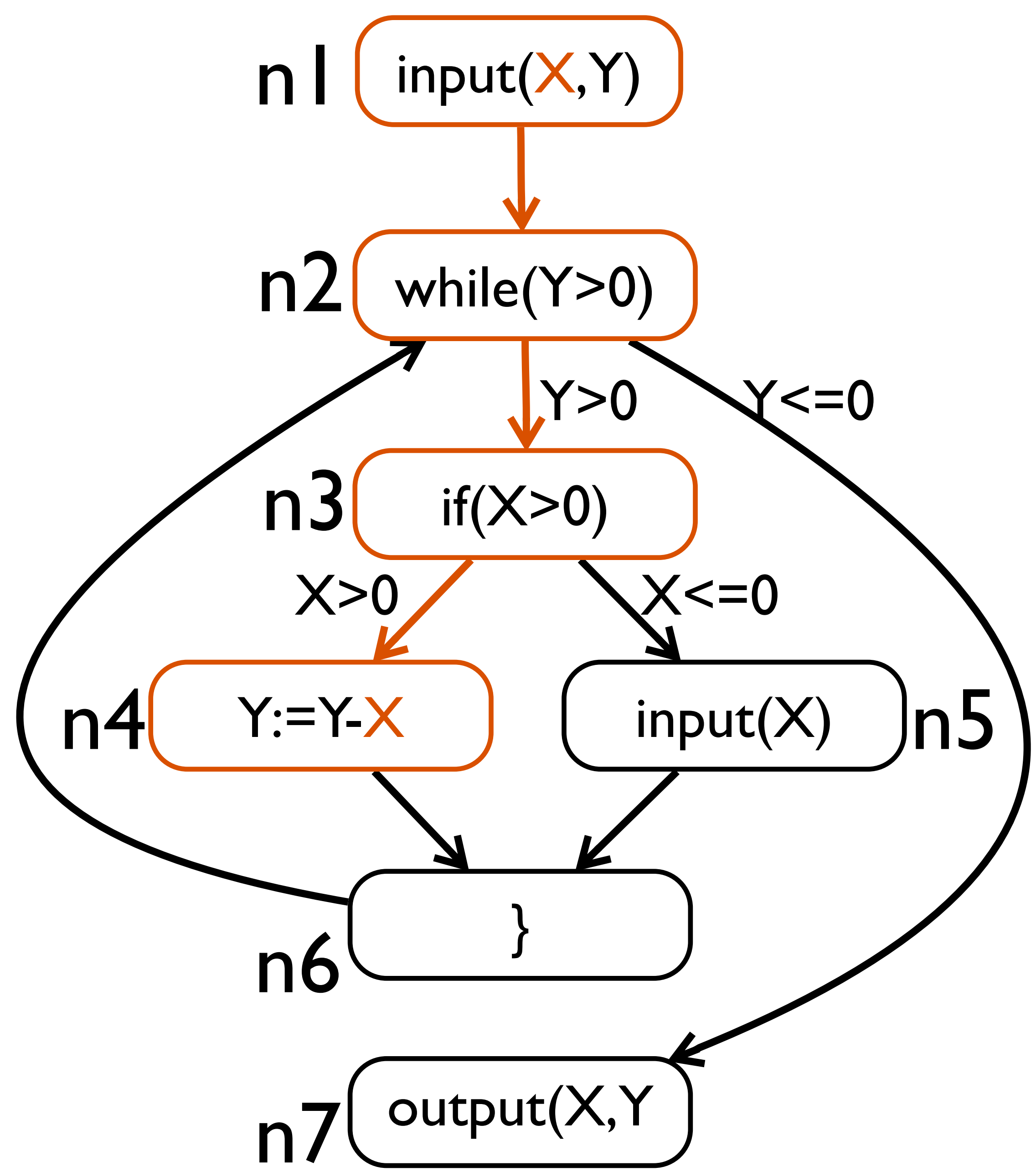
airs – Variable **X**

du-pair	**path(s)**
(1,4)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,7)	<1,2,7>
	<1,2,(3,4,6, 2)*,7>
(1,<3,4>)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,<3,5>)	<1,2,3,5>
	<1,2,3,5,(6,2,3,5)*>
(5,4)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,7)	<5,6,2,7>
	<5,6,2,(3,4,6,2)*,7>
(5,<3,4>)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,<3,5>)	<5,6,2,3,5>
	<5,6,2,(3,4,6,2)*,3,5>



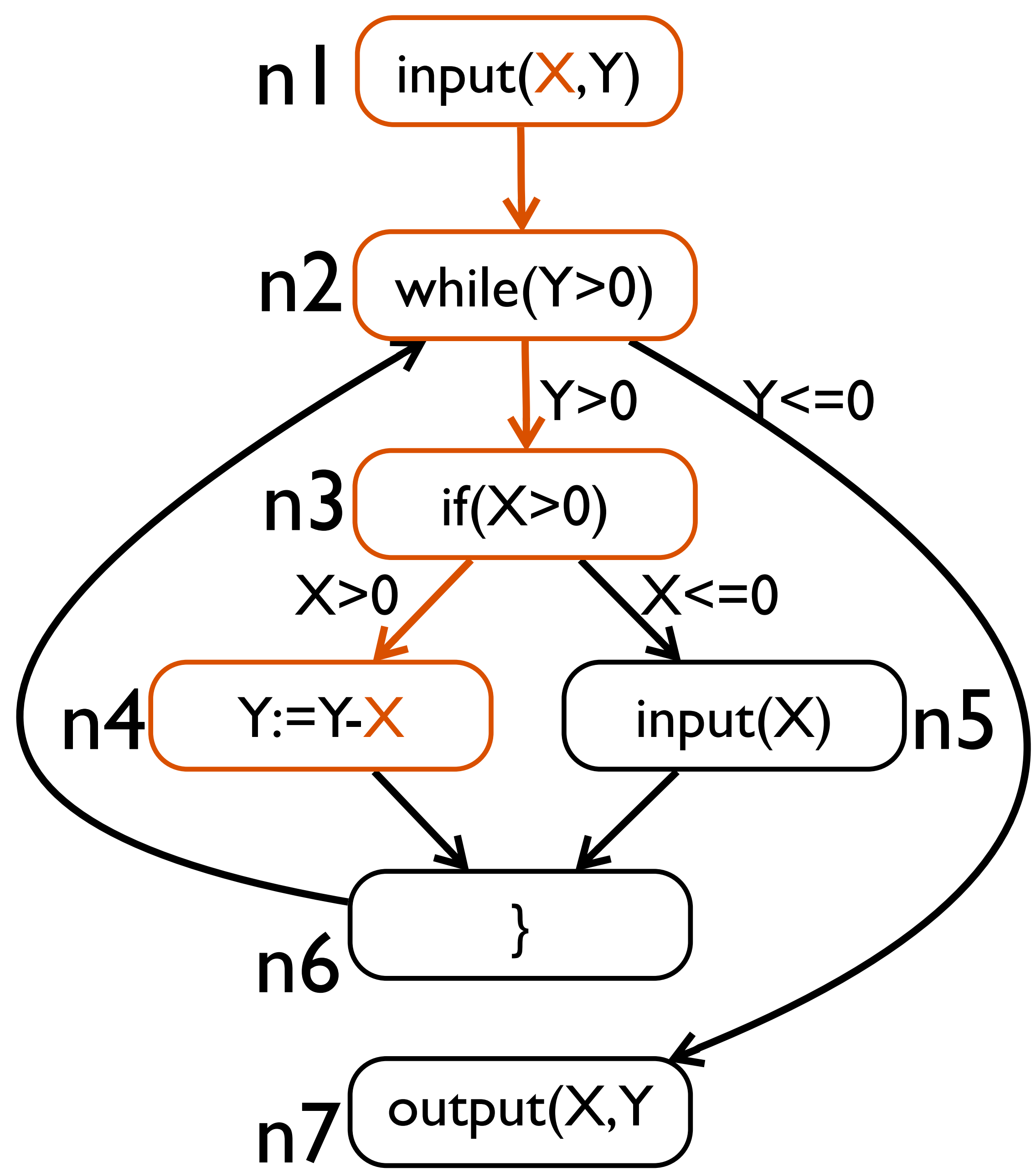
airs – Variable **X**

du-pair	path(s)
(1,4)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,7)	<1,2,7>
	<1,2,(3,4,6, 2)*,7>
(1,<3,4>)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,<3,5>)	<1,2,3,5>
	<1,2,3,5,(6,2,3,5)*>
(5,4)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,7)	<5,6,2,7>
	<5,6,2,(3,4,6,2)*,7>
(5,<3,4>)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,<3,5>)	<5,6,2,3,5>
	<5,6,2,(3,4,6,2)*,3,5>



airs – Variable **X**

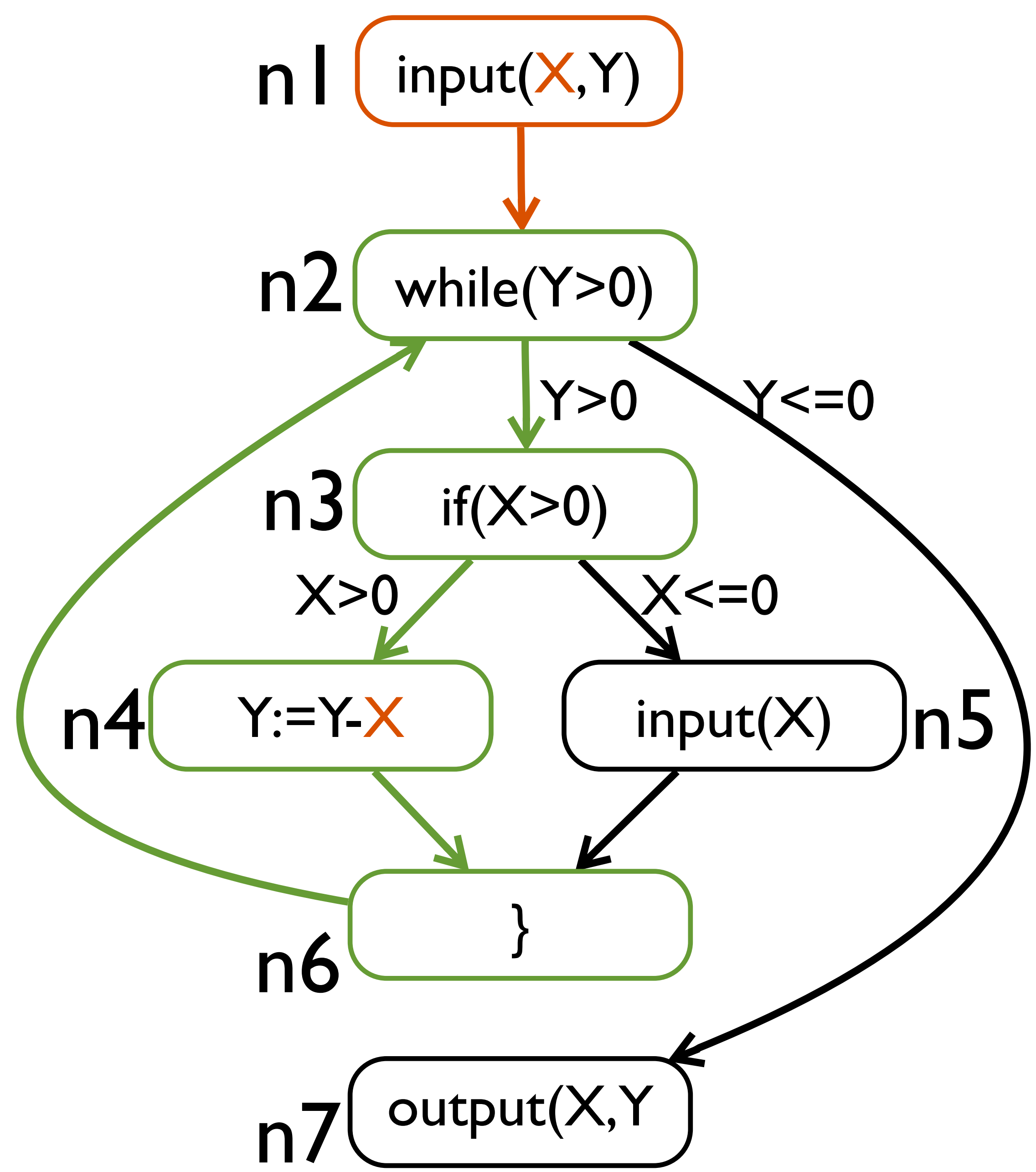
du-pair	path(s)
(1,4)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,7)	<1,2,7>
	<1,2,(3,4,6, 2)*,7>
(1,<3,4>)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,<3,5>)	<1,2,3,5>
	<1,2,3,5,(6,2,3,5)*>
(5,4)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,7)	<5,6,2,7>
	<5,6,2,(3,4,6,2)*,7>
(5,<3,4>)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,<3,5>)	<5,6,2,3,5>
	<5,6,2,(3,4,6,2)*,3,5>



(a)* means “a” will be repeated for >=1 times

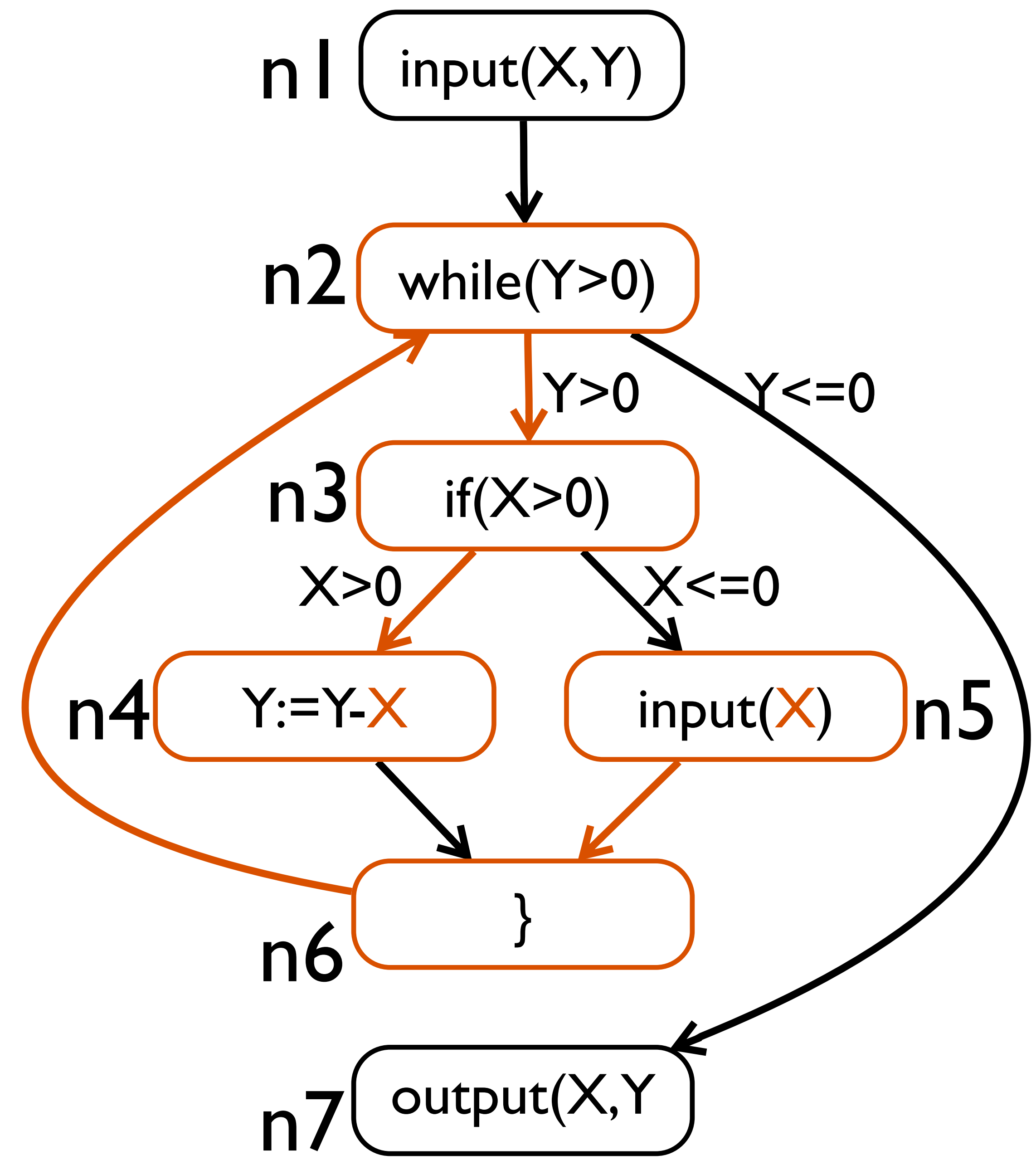
airs – Variable **X**

du-pair	**path(s)**
(1,4)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,7)	<1,2,7>
	<1,2,(3,4,6, 2)*,7>
(1,<3,4>)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,<3,5>)	<1,2,3,5>
	<1,2,3,5,(6,2,3,5)*>
(5,4)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,7)	<5,6,2,7>
	<5,6,2,(3,4,6,2)*,7>
(5,<3,4>)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,<3,5>)	<5,6,2,3,5>
	<5,6,2,(3,4,6,2)*,3,5>



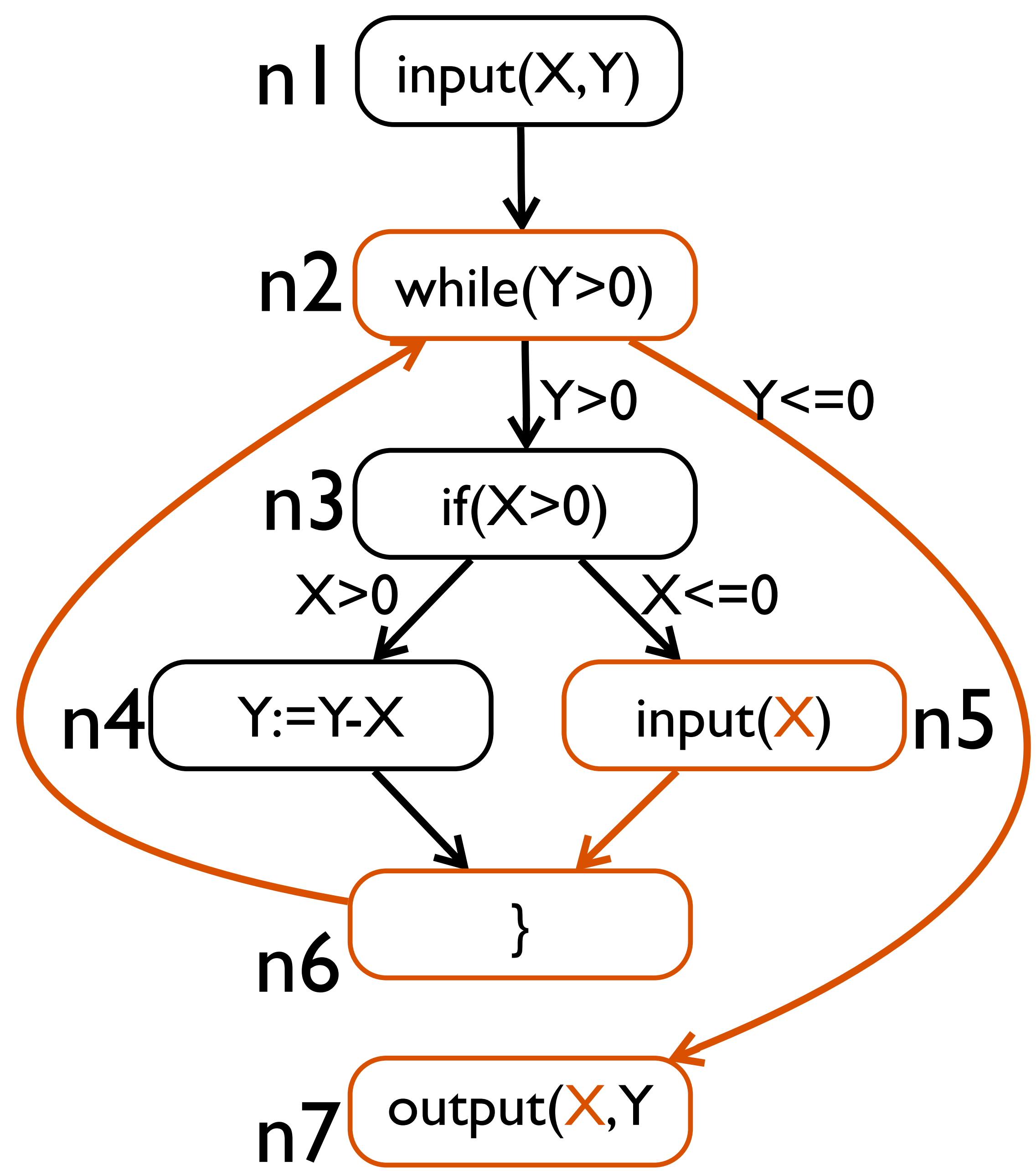
…airs – Variable **X**

du-pair	path(s)
(1,4)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,7)	<1,2,7>
	<1,2,(3,4,6, 2)*,7>
(1,<3,4>)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,<3,5>)	<1,2,3,5>
	<1,2,3,5,(6,2,3,5)*>
(5,4)	**<5,6,2,3,4>**
	<5,6,2,3,4,(6,2,3,4)*>
(5,7)	<5,6,2,7>
	<5,6,2,(3,4,6,2)*,7>
(5,<3,4>)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,<3,5>)	<5,6,2,3,5>
	<5,6,2,(3,4,6,2)*,3,5>



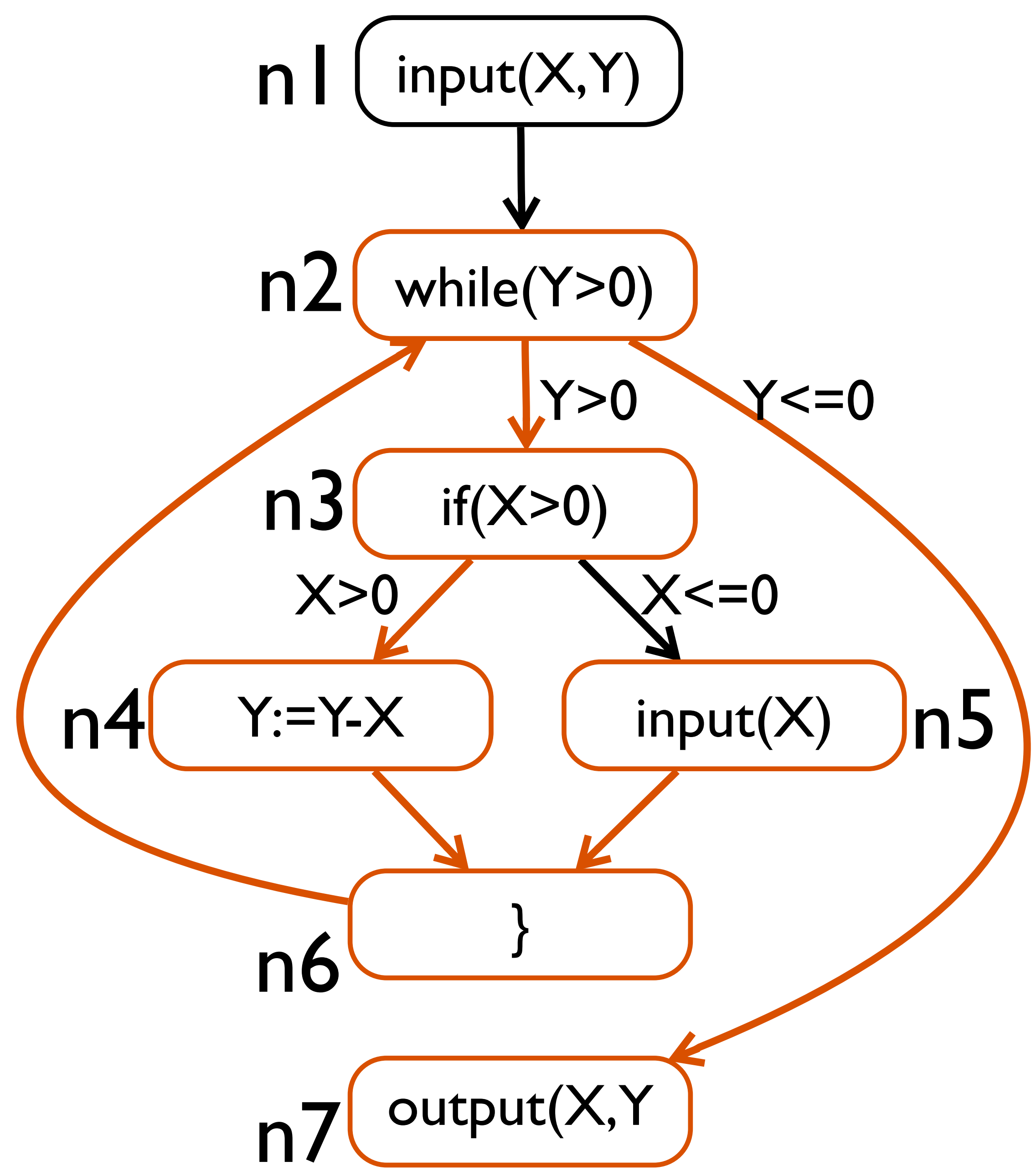
Note that the definition of a du-pair does not require the existence of a feasible def-clear path from **d** to **u**

du-pair	path(s)
(1,4)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,7)	<1,2,7>
	<1,2,(3,4,6, 2)*,7>
(1,<3,4>)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,<3,5>)	<1,2,3,5>
	<1,2,3,5,(6,2,3,5)*>
(5,4)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,7)	<5,6,2,7> Infeasible!
	<5,6,2,(3,4,6,2)*,7>
(5,<3,4>)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,<3,5>)	<5,6,2,3,5>
	<5,6,2,(3,4,6,2)*,3,5>



airs – Variable **X**

du-pair	path(s)
(1,4)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,7)	<1,2,7>
	<1,2,(3,4,6, 2)*,7>
(1,<3,4>)	<1,2,3,4>
	<1,2,3,4,(6,2,3,4)*>
(1,<3,5>)	<1,2,3,5>
	<1,2,3,5,(6,2,3,5)*>
(5,4)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,7)	<5,6,2,7>
	<5,6,2,(3,4,6,2)*,7>
(5,<3,4>)	<5,6,2,3,4>
	<5,6,2,3,4,(6,2,3,4)*>
(5,<3,5>)	<5,6,2,3,5>
	<5,6,2,(3,4,6,2)*,3,5>



More Dataflow Terms and Definitions

- A path (either partial or complete) is **simple** if all edges within the path are distinct, *i.e.,* different
- A path is **loop-free** if all nodes within the path are distinct, *i.e.,* different

Simple and Loop-Free Paths

path	Simple?	Loop-free?
<1,3,4,2>	a	a
<1,2,3,2>	a	
<1,2,3,1,2>		
<1,2,3,2,4>	a	

DU-Path

- A path <n1,n2,...,nj,nk> is a **du-path** with respect to a variable **v,** if **v** is defined at node **n1** and either:
  - there is a c-use of **v** at node **nk** and <n1,n2,...,nj,nk> is a def-clear simple path, or
  - there is a p-use of **v** at edge <nj,nk> and <n1,n2,...nj> is a def-clear loop-free path.

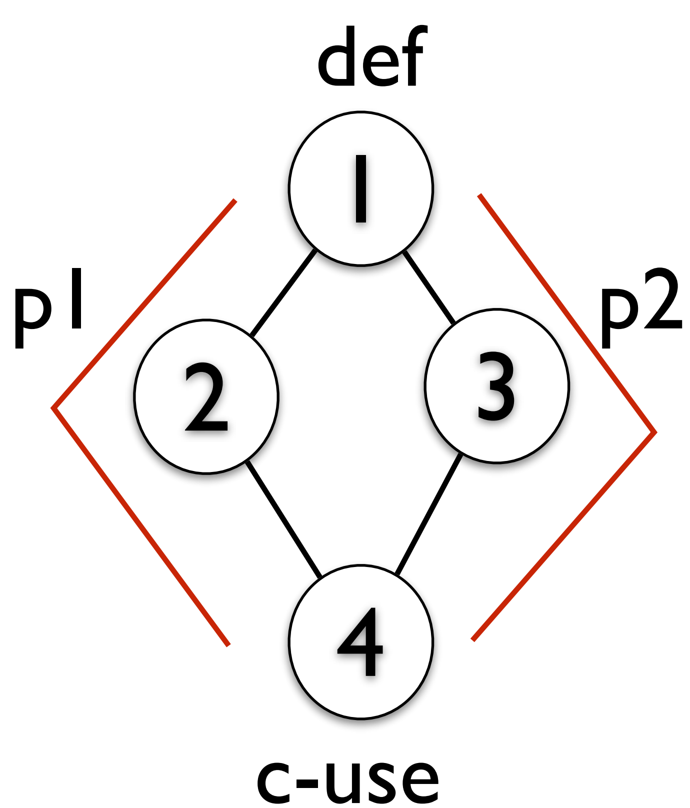
NOTE!

Identifying DU-Paths

du-pair	**path(s)**	**du-path?**
(5,4)	<5,6,2,3,4>	a
	<5,6,2,3,4,(6,2,3,4)*>	
(5,7)	<5,6,2,7>	a
	<5,6,2,(3,4,6,2)*,7>	
(5,<3,4>)	<5,6,2,3,4>	a
	<5,6,2,3,4,(6,2,3,4)*>	
(5,<3,5>)	<5,6,2,3,5>	a
	<5,6,2,(3,4,6,2)*,3,5>	

Another Dataflow Test Coverage Criterion

- **All-DU-Paths**:
  - for every program variable **v**, every du-path from every definition of **v** to every c-use and every p-use of **v** must be covered



node 1 is the only def node, and 4 is the only use node for v

p1 satisfies all-defs and all-uses, but not all-du-paths

p1 and p2 together satisfy all-du-paths

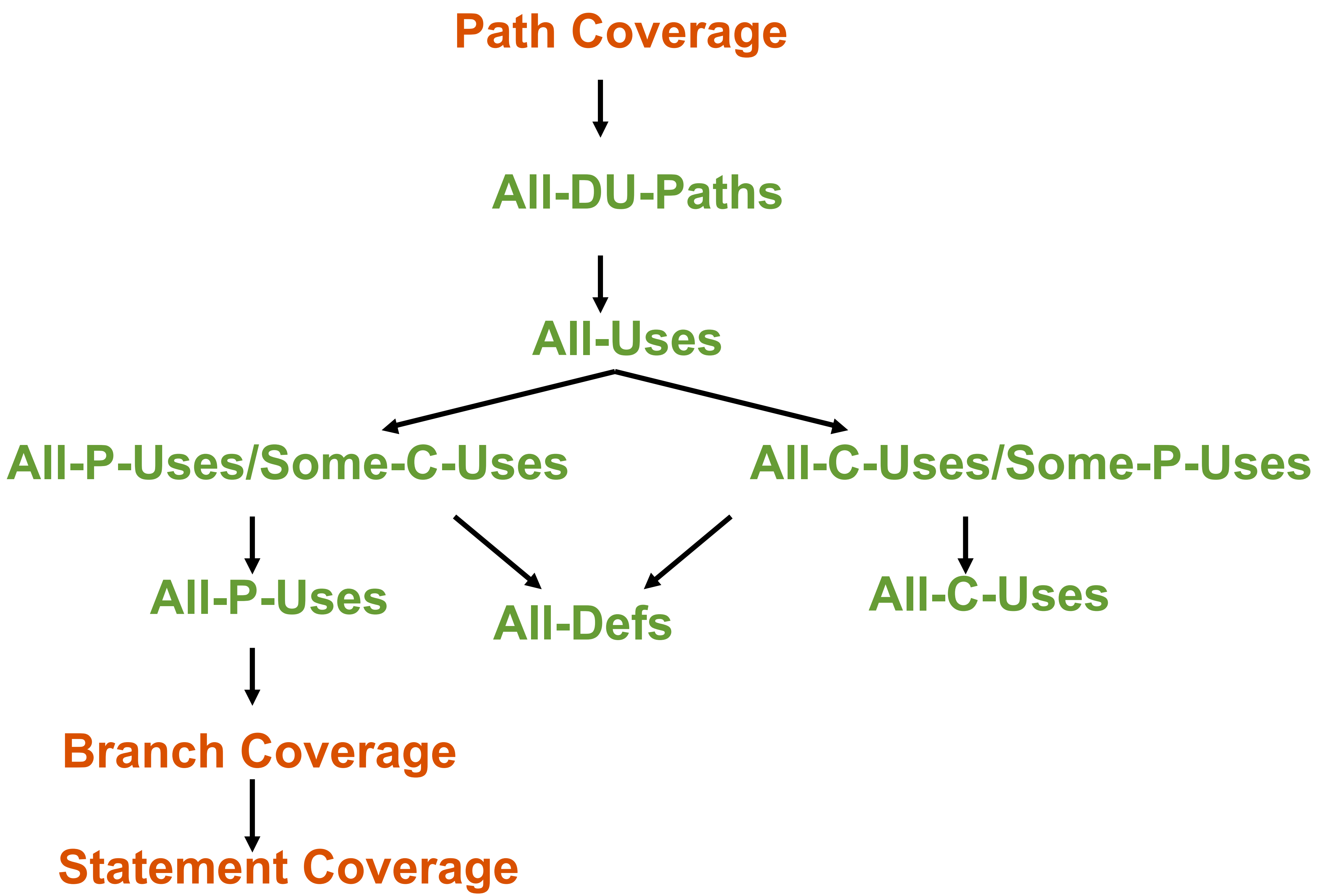
More Dataflow Test Coverage Criteria

- **All-P-Uses/Some-C-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
  - If no p-use of **v** is available, at least one def-clear path to a c-use of **v** must be covered
- **All-C-Uses/Some-P-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
  - If no c-use of **v** is available, at least one def-clear path to a p-use of **v** must be covered

More Dataflow Test Coverage Criteria (2)

- **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

Summary


Path Coverage
All-DU-Paths
All-Uses
All-P-Uses/Some-C-Uses
All-C-Uses/Some-P-Uses
All-P-Uses
All-Defs
All-C-Uses
Branch Coverage
Statement Coverage

Suggested Readings

- Sandra Rapps and Elaine J. Weyuker. Selecting Software Test Data Using Data Flow Information. IEEE Transactions on Software Engineering, 11(4), April 1985, pp. 367-375. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1702019
- P. Frankl and E. Weyuker. An Applicable Family of Data Flow Testing Criteria. IEE Transaction on software eng., vol.14, no.10, October 1988.
- E. Weyuker. The evaluation of Program-based software test data adequacy criteria. Communication of the ACM, vol.31, no.6, June 1988.
- Software Testing: A Craftsman's Approach.2nd CRC publication, 2002

Thanks