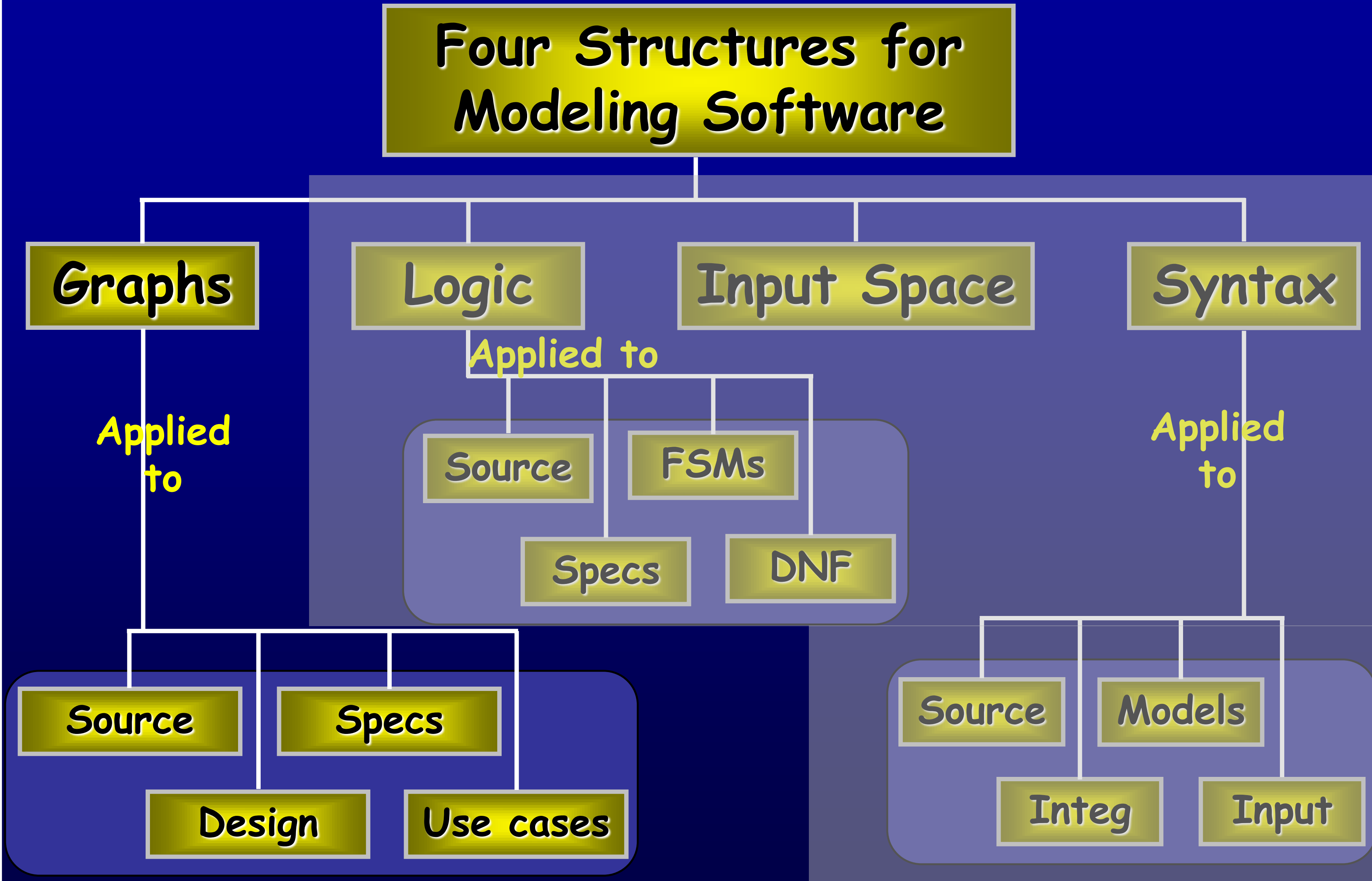
Overview Graph Coverage Criteria

Graph Coverage



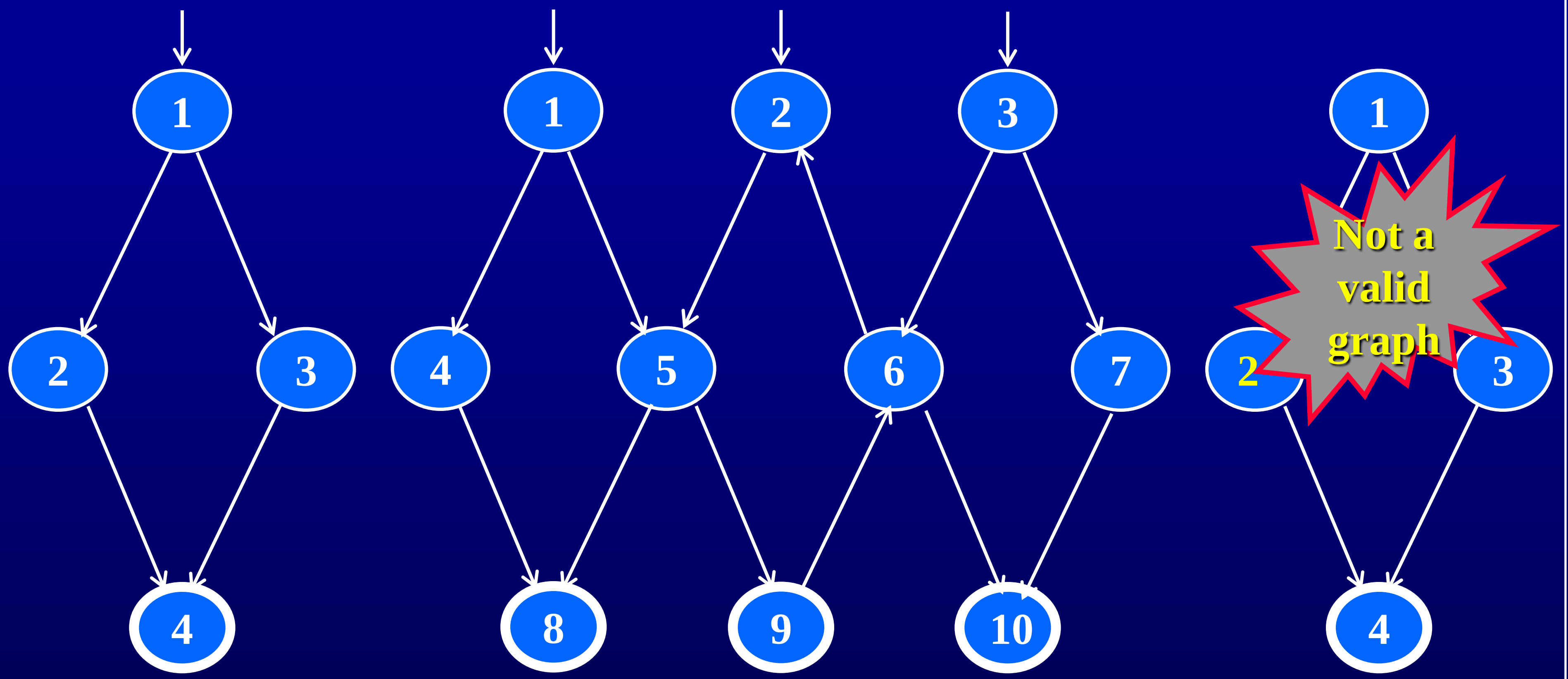
Covering Graphs

- Graphs are the most commonly used structure for testing
- Graphs can come from many sources
  - Control flow graphs
  - Design structure
  - FSMs and statecharts
  - Use cases
- Tests usually are intended to "cover" the graph in some way

Definition of a Graph

- A set N of nodes, N is not empty
- A set N_0 of initial nodes, N_0 is not empty
- A set N_f of final nodes, N_f is not empty
- A set E of edges, each edge from one node to another
  - (n_i , n_j), i is predecessor, j is successor

Three Example Graphs



$N_0 = \{ 1 \}$

$N_f = \{ 4 \}$

$N_0 = \{ 1, 2, 3 \}$

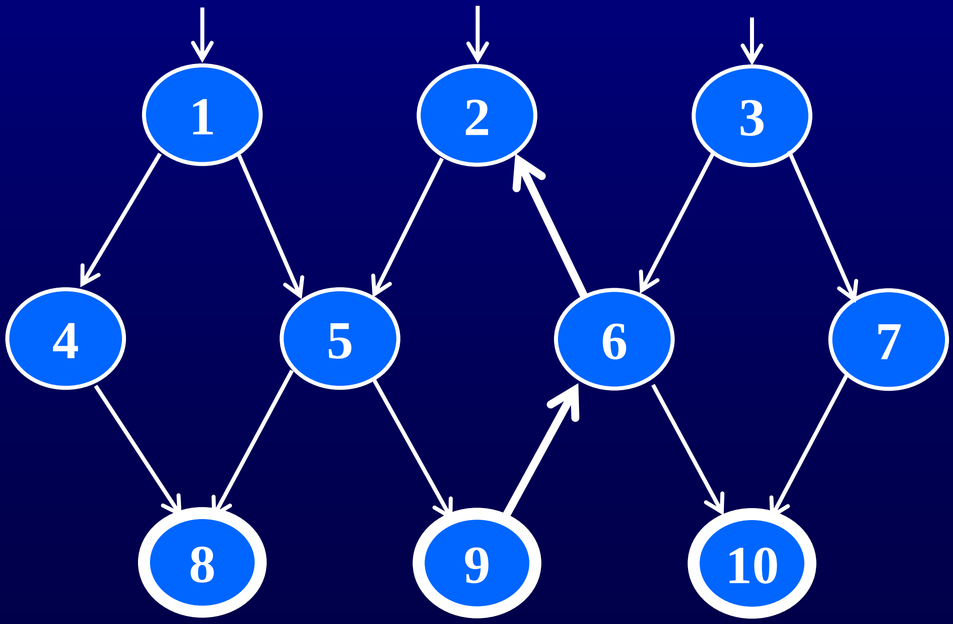
$N_f = \{ 8, 9, 10 \}$

$N_0 = \{ \}$

$N_f = \{ 4 \}$

Paths in Graphs

- **Path** : A sequence of nodes – $[n_1, n_2, \ldots, n_M]$
  - Each pair of nodes is an edge
- **Length** : The number of edges
  - A single node is a path of length 0
- **Subpath** : A subsequence of nodes in *p* is a subpath of *p*
- **Reach** (*n*) : Subgraph that can be reached from *n*



A Few Paths

[1, 4, 8]

[2, 5, 9, 6, 2]

[3, 7, 10]

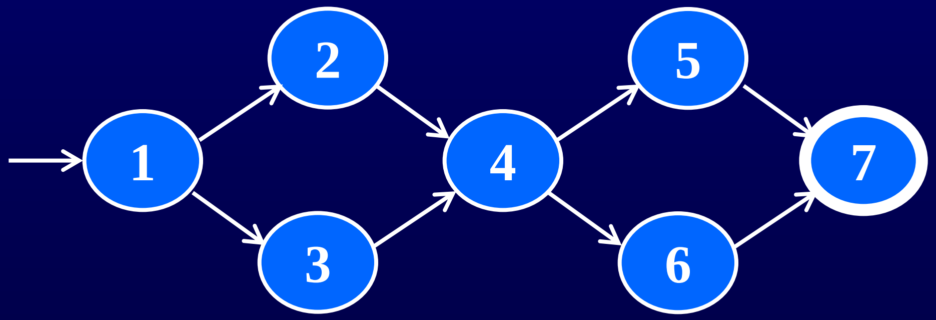
Reach (1) = { 1, 4, 5, 8, 9, 6, 2, 10 }

Reach ({1, 3}) = G

Reach([3,7]) = {3, 7, 10}

Test Paths and SESEs

- Test Path : A path that starts at an initial node and ends at a final node
- Test paths represent execution of test cases
  - Some test paths can be executed by many tests
  - Some test paths cannot be executed by any tests
- SESE graphs : All test paths start at a single node and end at another node
  - Single-entry, single-exit
  - N0 and Nf have exactly one node



Double-diamond graph

Four test paths

[1, 2, 4, 5, 7]

[1, 2, 4, 6, 7]

[1, 3, 4, 5, 7]

[1, 3, 4, 6, 7]

Visiting and Touring

- Visit : A test path *p* *visits* node *n* if *n* is in *p*

  A test path *p* *visits* edge e if e is in *p*
- Tour : A test path *p* *tours* subpath *q* if *q* is a subpath of *p*

Path [1, 2, 4, 5, 7]

Visits nodes 1, 2, 4, 5, 7

Visits edges (1, 2), (2, 4), (4, 5), (5, 7)

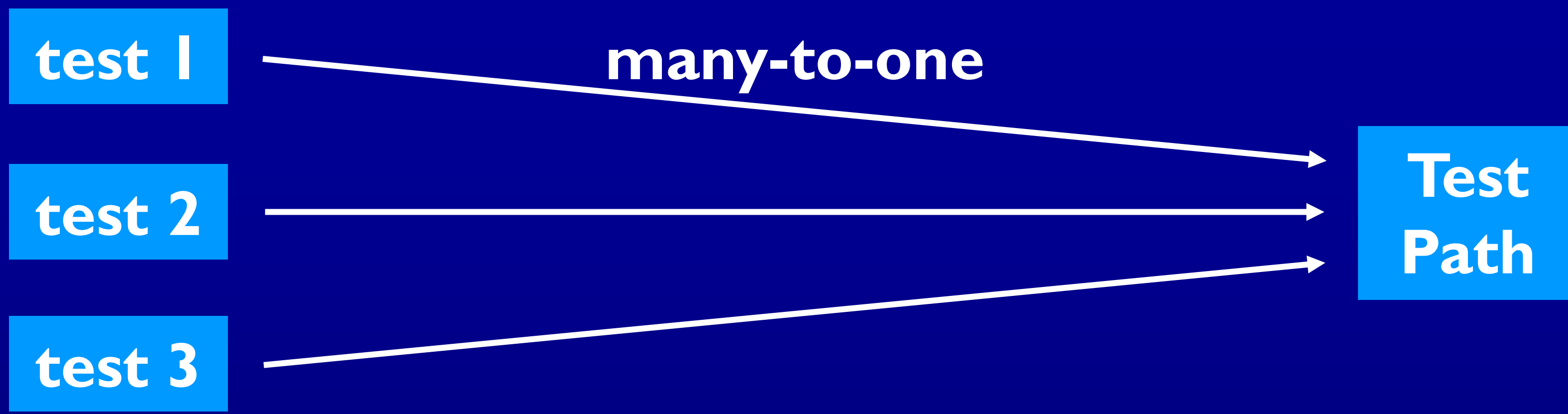
Tours subpaths [1, 2, 4], [2, 4, 5], [4, 5, 7], [1, 2, 4, 5], [2, 4, 5, 7]

Tests and Test Paths

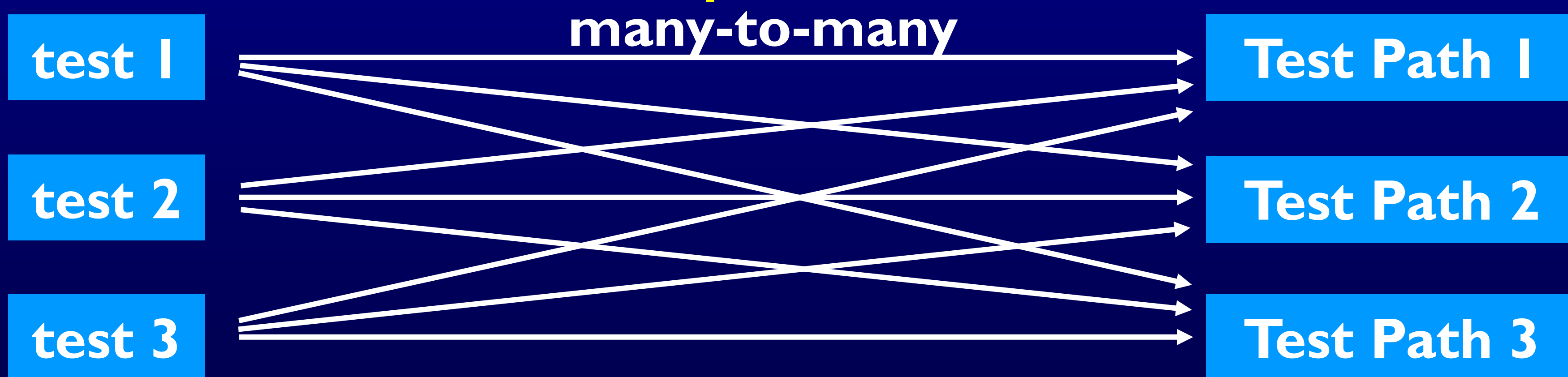
- path (*t*) : The test path executed by test *t*
- path (*T*) : The set of test paths executed by the set of tests *T*

- Each test executes one and only one test path
- A location in a graph (node or edge) can be reached from another location if there is a sequence of edges from the first location to the second
  - *Syntactic reach* : A subpath exists in the graph
  - *Semantic reach* : A test exists that can execute that subpath

Tests and Test Paths



Deterministic software–a test always executes the same test path



Non-deterministic software–a test can execute different test paths

Testing and Covering Graphs (6.2)

- We use graphs in testing as follows :
  - Developing a model of the software as a graph
  - Requiring tests to visit or tour specific sets of nodes, edges or subpaths
- Test Requirements (TR) : Describe properties of test paths
- Test Criterion : Rules that define test requirements
- Satisfaction : *Given a set TR of test requirements for a criterion C, a set of tests T satisfies C on a graph if and only if for every test requirement in TR, there is a test path in path(T) that meets the test requirement tr*

- Structural Coverage Criteria : Defined on a graph just in terms of nodes and edges
- Data Flow Coverage Criteria : Requires a graph to be annotated with references to variables

Node and Edge Coverage

- The first (and simplest) two criteria require that each node and edge in a graph be executed

Node Coverage (NC) : Test set *T* satisfies node coverage on graph *G* iff for every syntactically reachable node *n* in *N*, there is some path *p* in *path(T)* such that *p* visits *n*.

- **This statement is a bit cumbersome, so we abbreviate it in terms of the set of test requirements**

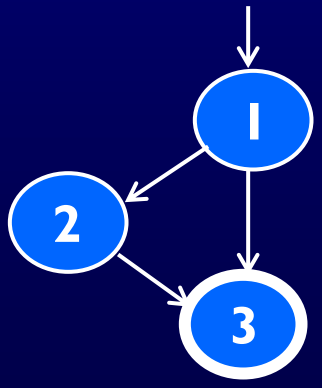
Node Coverage (NC) : TR contains each reachable node in G.

Node and Edge Coverage

- Edge coverage is slightly stronger than node coverage

<u>Edge Coverage (EC)</u> : TR contains each reachable path of length up to 1, inclusive, in G.

- The phrase "*length up to 1*" allows for graphs with one node and no edges
- NC and EC are only different when there is an edge and another subpath between a pair of nodes (as in an "if-else" statement)

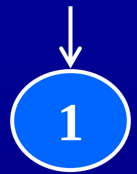


<u>Node Coverage</u> : TR = { 1, 2, 3 }
Test Path = [1, 2, 3]

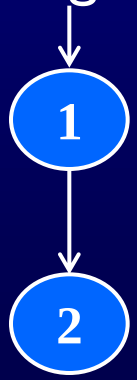
<u>Edge Coverage</u> : TR = { (1, 2), (1, 3), (2, 3) }
Test Paths = [1, 2, 3]
[1, 3]

Paths of Length 1 and 0

- A graph with only one node will not have any edges



- It may seem trivial, but formally, Edge Coverage needs to require Node Coverage on this graph
- Otherwise, Edge Coverage will not subsume Node Coverage
  - So we define "length up to 1" instead of simply "length 1"
- We have the same issue with graphs that only have one edge – for Edge Pair Coverage …



Covering Multiple Edges

- Edge-pair coverage requires pairs of edges, or subpaths of length 2

<u>Edge-Pair Coverage (EPC)</u> : TR contains each reachable path of length up to 2, inclusive, in G.

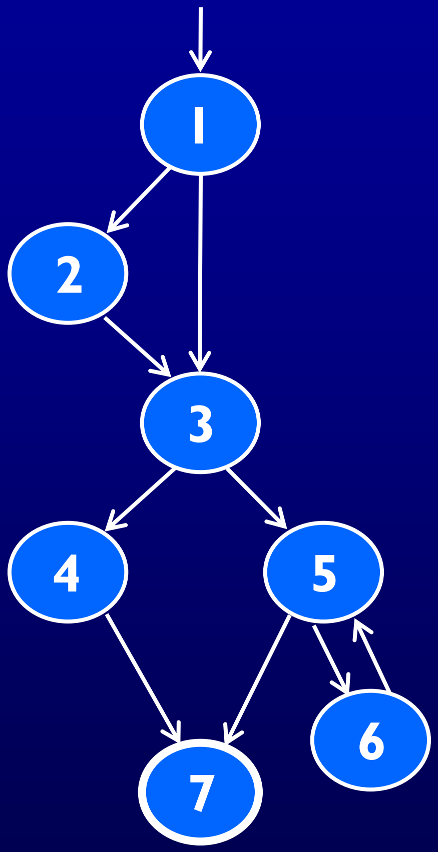
- The phrase "length up to 2" is used to include graphs that have less than 2 edges
- The logical extension is to require all paths …

<u>Complete Path Coverage (CPC)</u> : TR contains all paths in G.

- Unfortunately, this is impossible if the graph has a loop, so a weak compromise is to make the tester decide which paths:

<u>Specified Path Coverage (SPC)</u> : TR contains a set S of test paths, where S is supplied as a parameter.

Structural Coverage Example



Node Coverage

TR = { 1, 2, 3, 4, 5, 6, 7 }

Test Paths: [1, 2, 3, 4, 7] [1, 2, 3, 5, 6, 5, 7]

Edge Coverage

TR = { (1,2), (1, 3), (2, 3), (3, 4), (3, 5), (4, 7), (5, 6), (5, 7), (6, 5) }

Test Paths: [1, 2, 3, 4, 7] [1, 3, 5, 6, 5, 7]

Edge-Pair Coverage

TR = {[1,2,3], [1,3,4], [1,3,5], [2,3,4], [2,3,5], [3,4,7], [3,5,6], [3,5,7], [5,6,5], [6,5,6], [6,5,7] }

Test Paths: [1, 2, 3, 4, 7] [1, 2, 3, 5, 7] [1, 3, 4, 7] [1, 3, 5, 6, 5, 6, 5, 7]

Complete Path Coverage

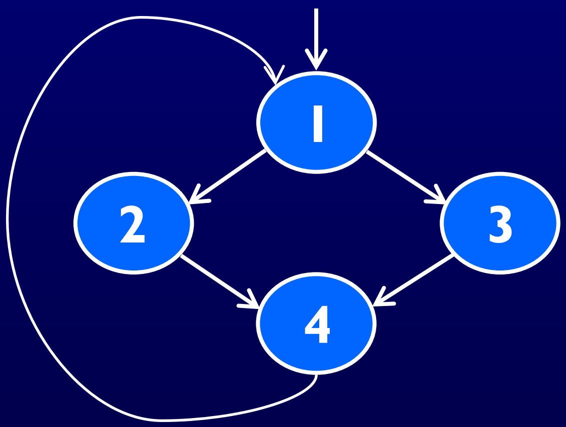
Test Paths: [1, 2, 3, 4, 7] [1, 2, 3, 5, 7] [1, 2, 3, 5, 6, 5, 6] [1, 2, 3, 5, 6, 5, 6, 5, 7] [1, 2, 3, 5, 6, 5, 6, 5, 6, 5, 7] …

Loops in Graphs

- If a graph contains a loop, it has an infinite number of paths
- Thus, CPC is not feasible
- SPC is not satisfactory because the results are subjective and vary with the tester
- Attempts to "deal with" loops:
  - 1970s : Execute cycles once ([4, 5, 4] in previous example, informal)
  - 1980s : Execute each loop, exactly once (formalized)
  - 1990s : Execute loops 0 times, once, more than once (informal description)
  - 2000s : Prime paths

Simple Paths and Prime Paths

- **Simple Path** : *A path from node ni to nj is simple if no node appears more than once, except possibly the first and last nodes are the same*
  - No internal loops
  - A loop is a simple path
- **Prime Path** : *A simple path that does not appear as a proper subpath of any other simple path*



Simple Paths : [1,2,4,1], [1,3,4,1], [2,4,1,2], [2,4,1,3], [3,4,1,2], [3,4,1,3], [4,1,2,4], [4,1,3,4], [1,2,4], [1,3,4], [2,4,1], [3,4,1], [4,1,2], [4,1,3], [1,2], [1,3], [2,4], [3,4], [4,1], [1], [2], [3], [4]

Prime Paths : [2,4,1,2], [2,4,1,3], [1,3,4,1], [1,2,4,1], [3,4,1,2], [4,1,3,4], [4,1,2,4], [3,4,1,3]

Prime Path Coverage

- A simple, elegant and finite criterion that requires loops to be executed as well as skipped

<u>Prime Path Coverage (PPC)</u> : TR contains each prime path in G.

- Will tour all paths of length 0, 1, …
- That is, it subsumes node and edge coverage
- PPC does NOT subsume EPC
  - If a node *n* has an edge to itself, EPC will require [*n, n, m*]
  - [*n, n, m*] is not prime

Round Trips

- Round-Trip Path : *A prime path that starts and ends at the same node*

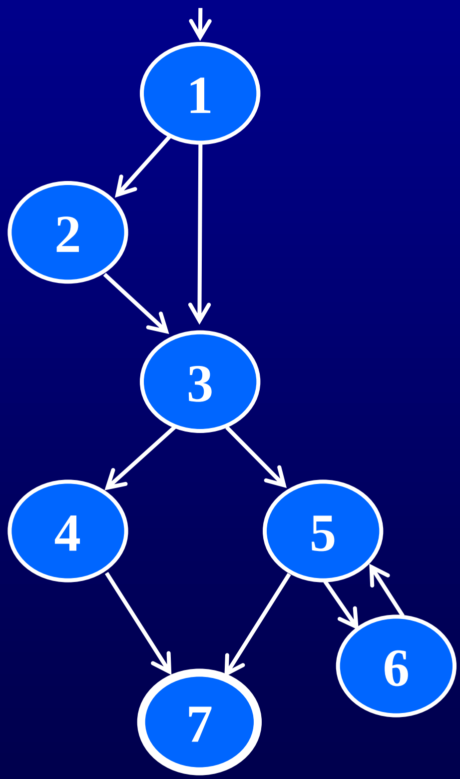
<u>Simple Round Trip Coverage (SRTC)</u> : TR contains at least one round-trip path for each reachable node in G that begins and ends a round-trip path.

<u>Complete Round Trip Coverage (CRTC)</u> : TR contains all round-trip paths for each reachable node in G.

- These criteria omit nodes and edges that are not in round trips
- That is, they do not subsume edge-pair, edge, or node coverage

Prime Path Example

- The previous example has 38 simple paths
- Only nine *prime paths*



Prime Paths

[1, 2, 3, 4, 7]
[1, 2, 3, 5, 7]
[1, 2, 3, 5, 6]
[1, 3, 4, 7]
[1, 3, 5, 7]
[1, 3, 5, 6]
[6, 5, 7]
[6, 5, 6]
[5, 6, 5]

Execute loop 0 times

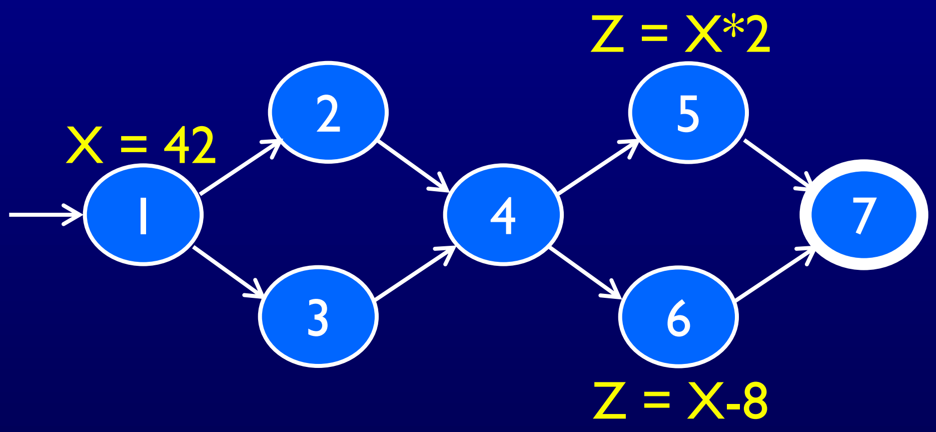
Execute loop once

Execute loop more than once

Data Flow Criteria

<u>Goal</u>: Try to ensure that values are computed and used correctly

- Definition (def) : A location where a value for a variable is stored into memory
- Use : A location where a variable's value is accessed



<u>Defs</u>: def (1) = {X}

def (5) = {Z}

def (6) = {Z}

<u>Uses</u>: use (5) = {X}

use (6) = {X}

The values given in defs should reach at least one, some, or all possible uses

DU Pairs and DU Paths

- def (n) or def (e) : The set of variables that are defined by node n or edge e
- use (n) or use (e) : The set of variables that are used by node n or edge e

- DU pair : A pair of locations (l_i, l_j) such that a variable *v* is defined at l_i and used at l_j

- Def-clear : A path from l_i to l_j is *def-clear* with respect to variable *v* if *v* is not given another value on any of the nodes or edges in the path
- Reach : If there is a def-clear path from l_i to l_j with respect to *v*, the def of *v* at l_i reaches the use at l_j

- du-path : A simple subpath that is def-clear with respect to *v* from a def of *v* to a use of *v*
- du (n_i, n_j, *v*) – the set of du-paths from n_i to n_j
- du (n_i, *v*) – the set of du-paths that start at n_i

Data Flow Test Criteria

- First, we make sure every def reaches a use

<u>All-defs coverage (ADC)</u> : For each set of du-paths *S* = *du* (*n*, *v*), TR contains at least one path *d* in *S*.

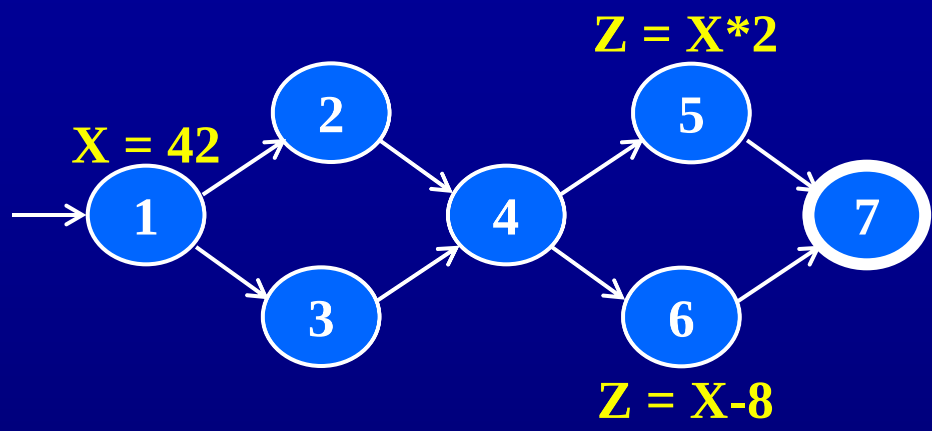
- Then we make sure that every def reaches all possible uses

<u>All-uses coverage (AUC)</u> : For each set of du-paths to uses *S* = *du* (n_i, n_j, *v*), TR contains at least one path *d* in *S*.

- Finally, we cover all the paths between defs and uses

<u>All-du-paths coverage (ADUPC)</u> : For each set *S* = *du* (*ni*, *nj*, *v*), TR contains every path *d* in *S*.

Data Flow Testing Example



All-defs for *X*
[1, 2, 4, 5]

All-uses for *X*
[1, 2, 4, 5]
[1, 2, 4, 6]

All-du-paths for *X*
[1, 2, 4, 5]
[1, 3, 4, 5]
[1, 2, 4, 6]
[1, 3, 4, 6]

Graph Coverage for Source Code

Overview

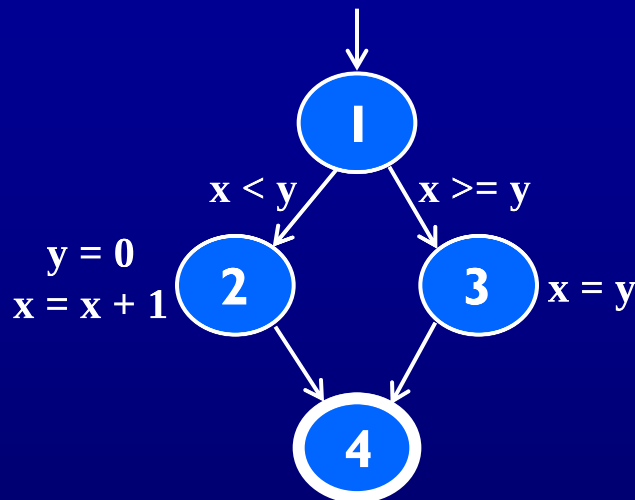
- A common application of graph criteria is to program source
- Graph : Usually the control flow graph (CFG)
- Node coverage : Execute every statement
- Edge coverage : Execute every branch
- Loops : Looping structures such as for loops, while loops, etc.
- Data flow coverage : Augment the CFG
  - defs are statements that assign values to variables
  - uses are statements that use variables

Control Flow Graphs

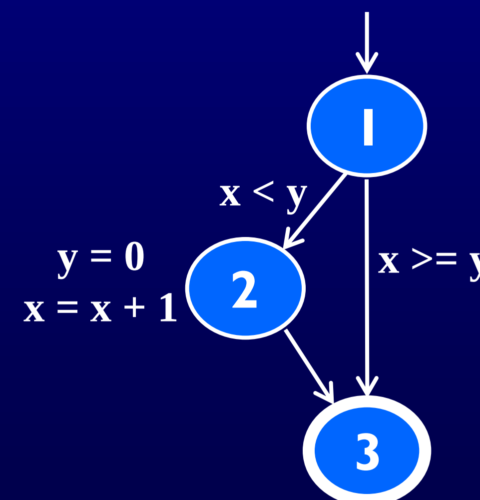
- A CFG models all executions of a method by describing control structures
- Nodes : Statements or sequences of statements (basic blocks)
- Edges : Transfers of control
- Basic Block : A sequence of statements such that if the first statement is executed, all statements will be (no branches)
- CFGs are sometimes annotated with extra information
  - branch predicates
  - defs
  - uses
- Rules for translating statements into graphs …

CFG : The if Statement

```
if (x < y)
{
  y = 0;
  x = x + 1;
}
else
{
  x = y;
}
```

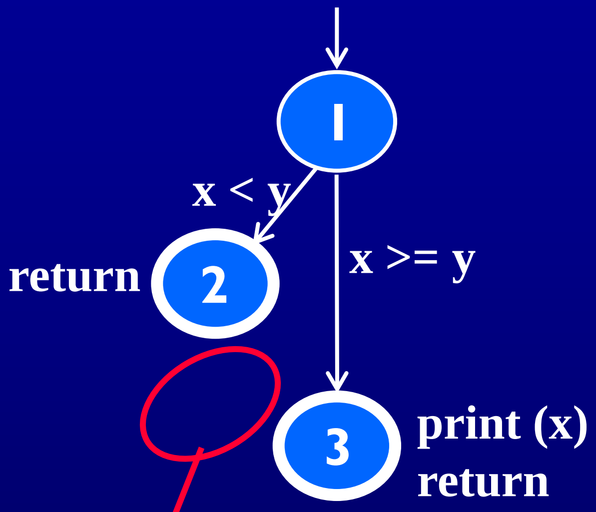



```
if (x < y)
{
  y = 0;
  x = x + 1;
}
```



CFG : The if-Return Statement

```
if (x < y)
{
   return;
}
print (x);
return;
```



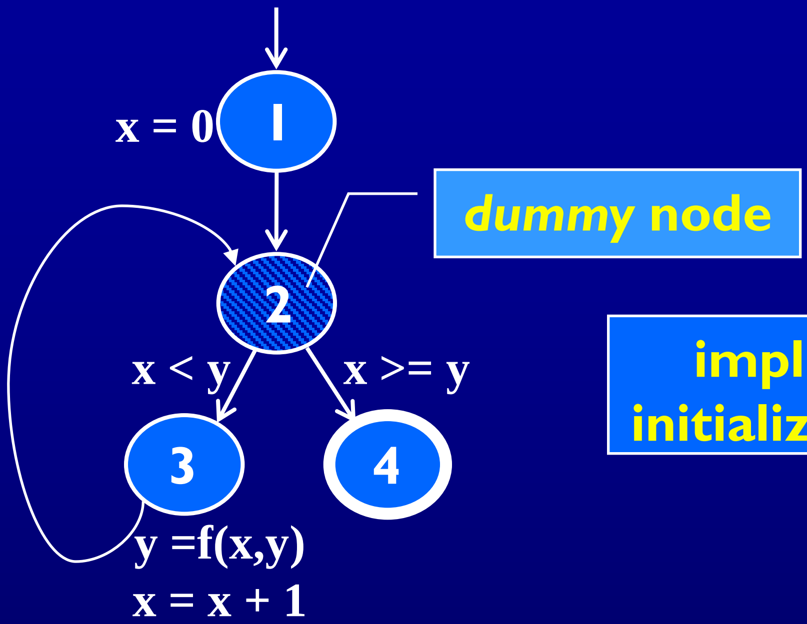
No edge from node 2 to 3.
The return nodes must be distinct.

Loops

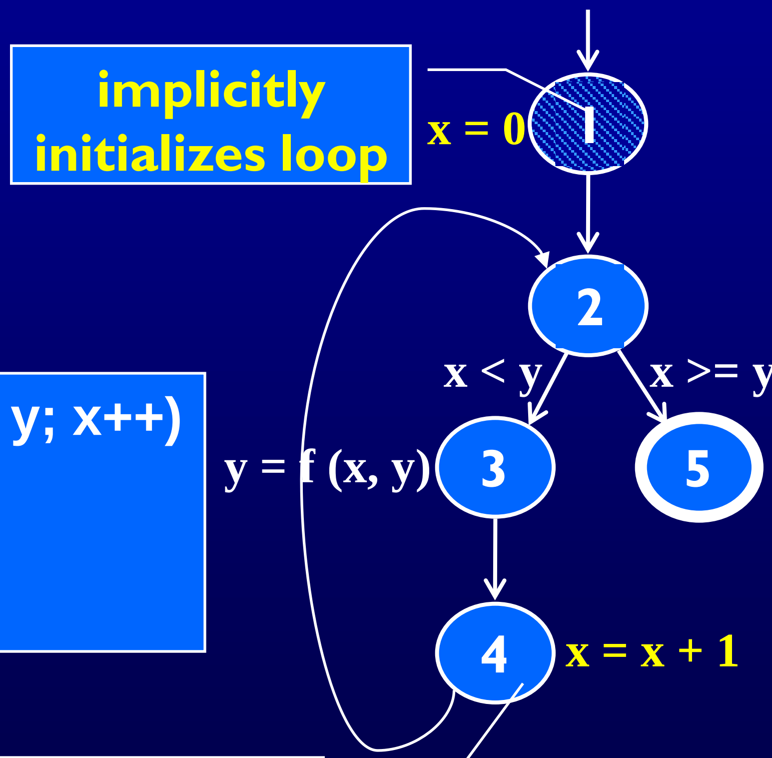
- Loops require "*extra*" nodes to be added
- Nodes that do not represent statements or basic blocks

CFG : while and for Loops

```
x = 0;
while (x < y)
{
   y = f (x, y);
   x = x + 1;
}
```

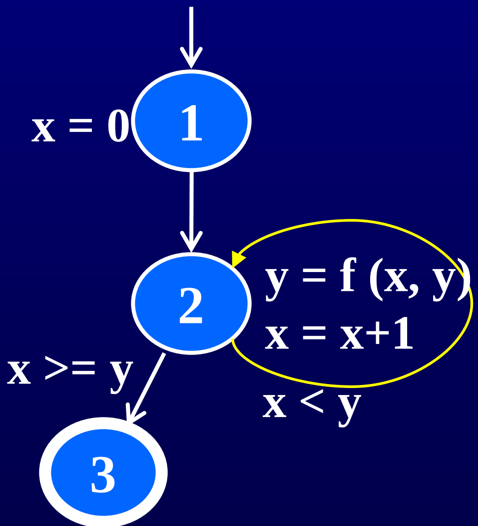



```
for (x = 0; x < y; x++)
{
   y = f (x, y);
}
```

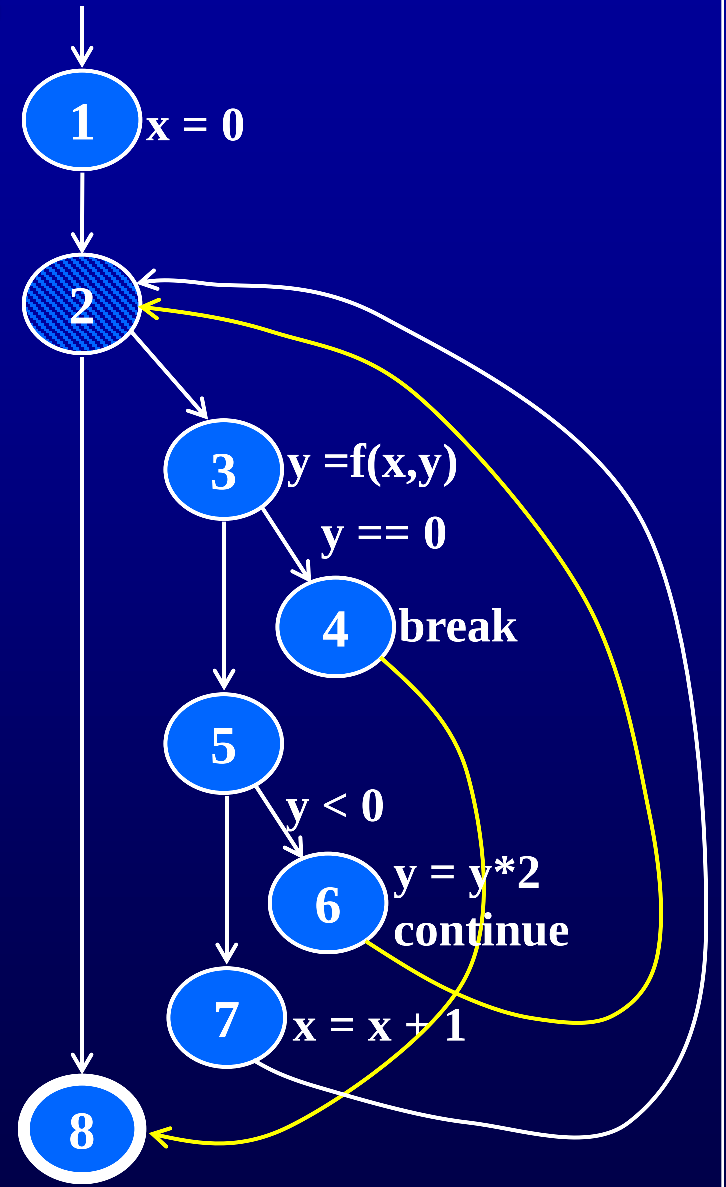


CFG : do Loop, break and continue

```
x = 0;
do
{
   y = f (x, y);
   x = x + 1;
} while (x < y);
println (y)
```

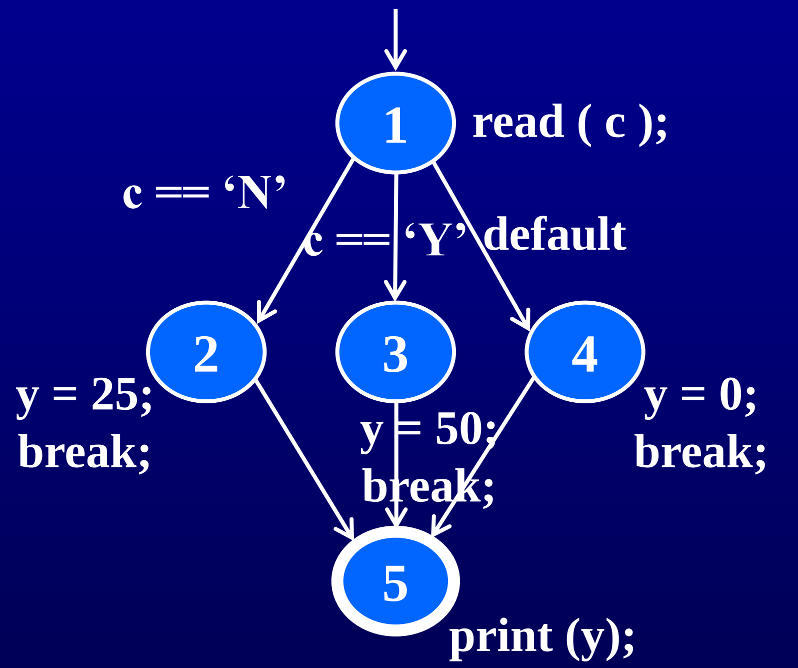



```
x = 0;
while (x < y)
{
   y = f (x, y);
   if (y == 0)
   {
      break;
   } else if y < 0)
   {
      y = y*2;
      continue;
   }
   x = x + 1;
}
print (y);
```



CFG : The case (switch) Structure

```
read ( c) ;
switch ( c )
{
   case 'N':
      y = 25;
      break;
   case 'Y':
      y = 50;
      break;
   default:
      y = 0;
      break;
}
print (y);
```

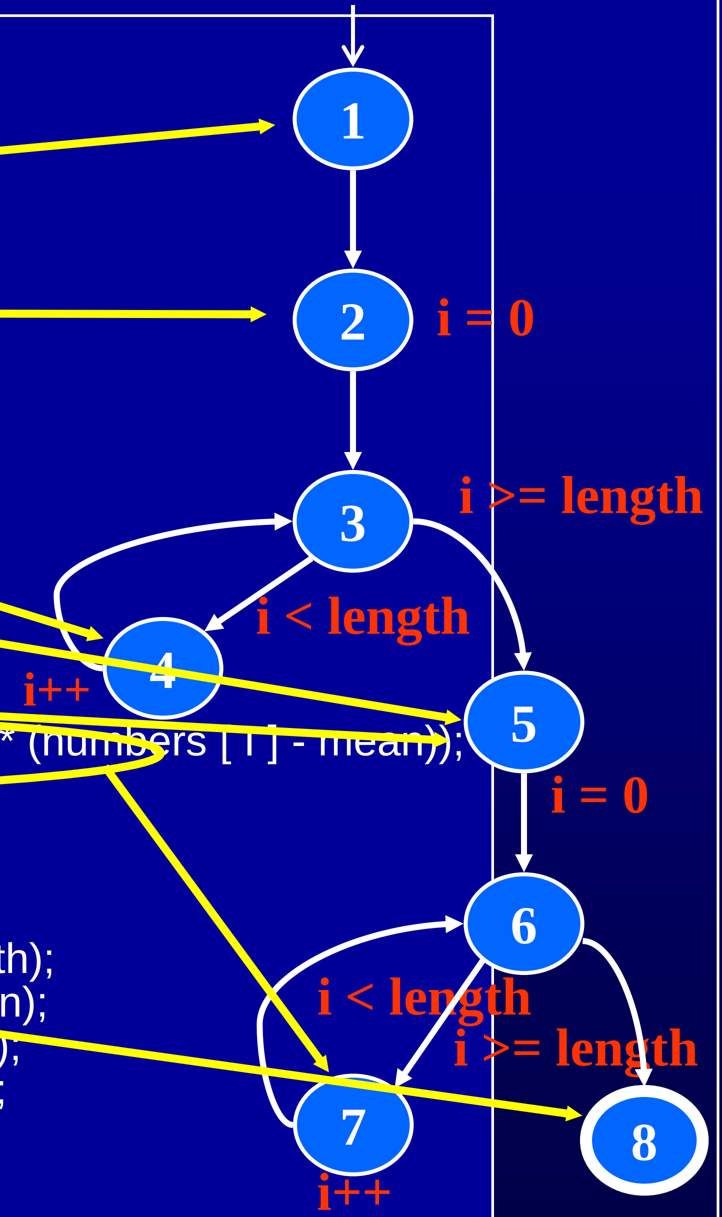


Example Control Flow – Stats

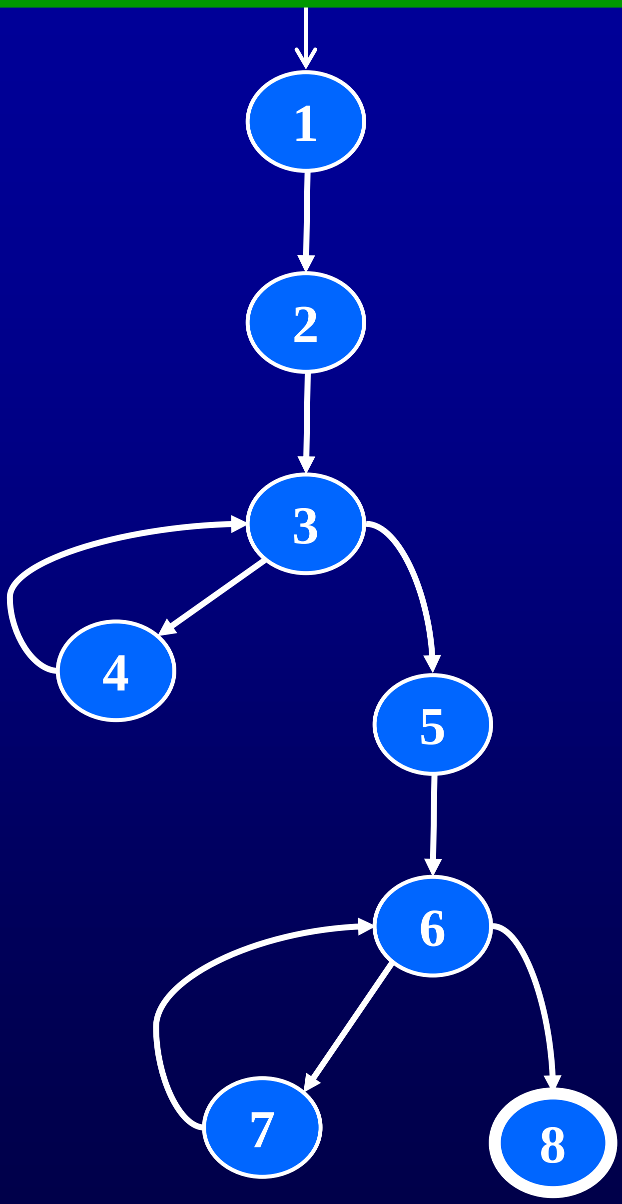
```
public static void computeStats (int [ ] numbers)
{
    int length = numbers.length;
    double med, var, sd, mean, sum, varsum;

    sum = 0;
    for (int i = 0; i < length; i++)
    {
        sum += numbers [ i ];
    }
    med   = numbers [ length / 2];
    mean = sum / (double) length;

    varsum = 0;
    for (int i = 0; i < length; i++)
    {
        varsum = varsum  + ((numbers [ I ] - mean) * (numbers [ I ] - mean));
    }
    var = varsum / ( length - 1.0 );
    sd  = Math.sqrt ( var );

    System.out.println ("length:                " + length);
    System.out.println ("mean:                  " + mean);
    System.out.println ("median:                " + med);
    System.out.println ("variance:              " + var);
    System.out.println ("standard deviation: " + sd);
}
```

Control Flow Graph for Stats

```
public static void computeStats (int [ ] numbers)
{
     int length = numbers.length;
     double med, var, sd, mean, sum, varsum;

     sum = 0;
     for (int i = 0; i < length; i++)
     {
          sum += numbers [ i ];
     }
     med   = numbers [ length / 2];
     mean = sum / (double) length;

     varsum = 0;
     for (int i = 0; i < length; i++)
     {
          varsum = varsum  + ((numbers [ I ] - mean) * (numbers [ I ] - mean));
     }
     var = varsum / ( length - 1.0 );
     sd  = Math.sqrt ( var );

     System.out.println ("length:                    " + length);
     System.out.println ("mean:                      " + mean);
     System.out.println ("median:                    " + med);
     System.out.println ("variance:                  " + var);
     System.out.println ("standard deviation: " + sd);
}
```

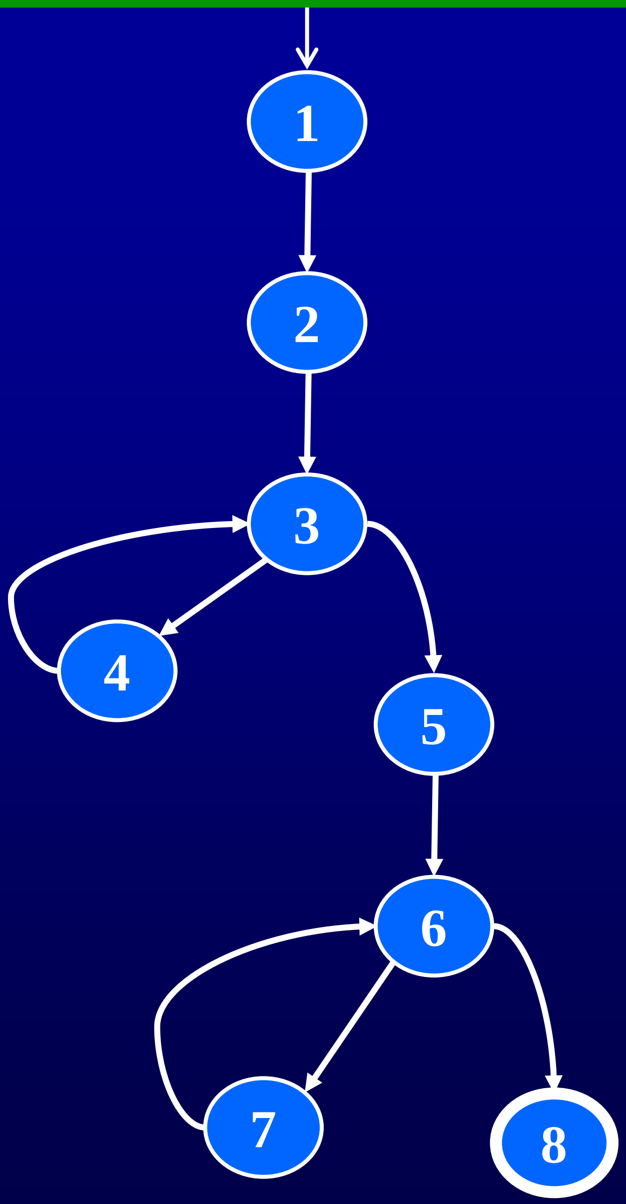


Control Flow TRs and Test Paths—EC



Edge Coverage	
TR	**Test Path**
A. [1, 2] B. [2, 3] C. [3, 4] D. [3, 5] E. [4, 3] F. [5, 6] G. [6, 7] H. [6, 8] I. [7, 6]	[1, 2, 3, 4, 3, 5, 6, 7, 6, 8]

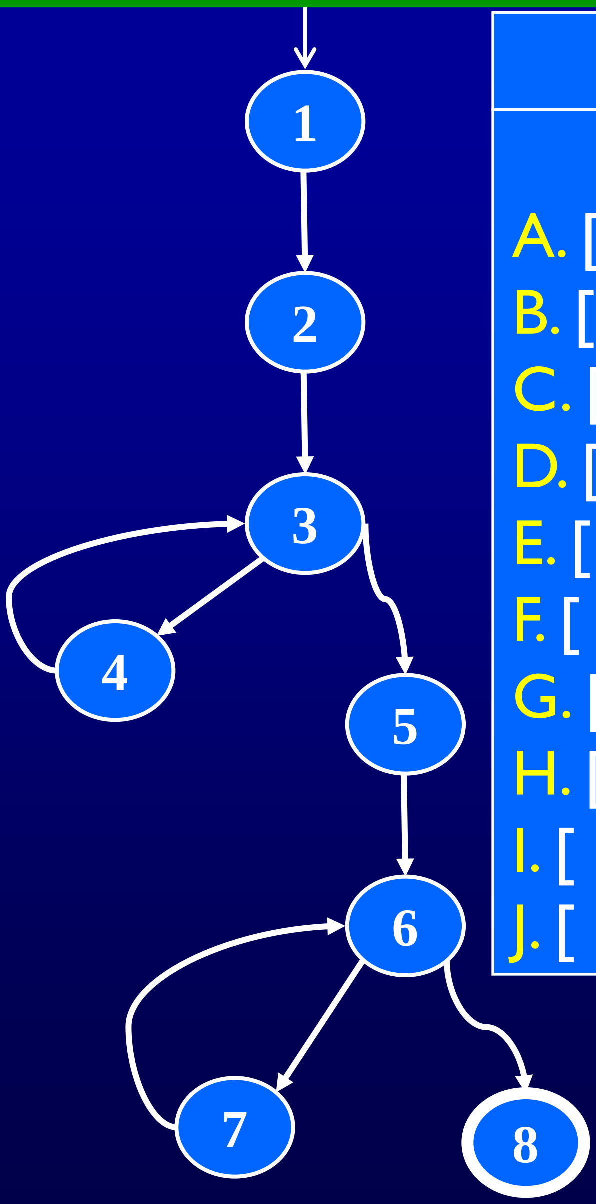
Control Flow TRs and Test Paths—EPC



Edge-Pair Coverage

TR	Test Paths
A. [1, 2, 3]	i. [1, 2, 3, 4, 3, 5, 6, 7, 6, 8]
B. [2, 3, 4]	ii. [1, 2, 3, 5, 6, 8]
C. [2, 3, 5]	iii. [1, 2, 3, 4, 3, 4, 3, 5, 6, 7, 6, 7, 6, 8]
D. [3, 4, 3]	
E. [3, 5, 6]	
F. [4, 3, 5]	
G. [5, 6, 7]	
H. [5, 6, 8]	
I. [6, 7, 6]	
J. [7, 6, 8]	
K. [4, 3, 4]	
L. [7, 6, 7]	

Control Flow TRs and Test Paths—PPC



Prime Path Coverage

TR	Test Paths
A. [3, 4, 3]	i. [1, 2, 3, 4, 3, 5, 6, 7, 6, 8]
B. [4, 3, 4]	ii. [1, 2, 3, 4, 3, 4, 3, 5, 6, 7, 6, 7, 6, 8]
C. [7, 6, 7]	iii. [1, 2, 3, 4, 3, 5, 6, 8]
D. [7, 6, 8]	iv. [1, 2, 3, 5, 6, 7, 6, 8]
E. [6, 7, 6]	v. [1, 2, 3, 5, 6, 8]
F. [1, 2, 3, 4]	
G. [4, 3, 5, 6, 7]	
H. [4, 3, 5, 6, 8]	
I. [1, 2, 3, 5, 6, 7]	
J. [1, 2, 3, 5, 6, 8]	

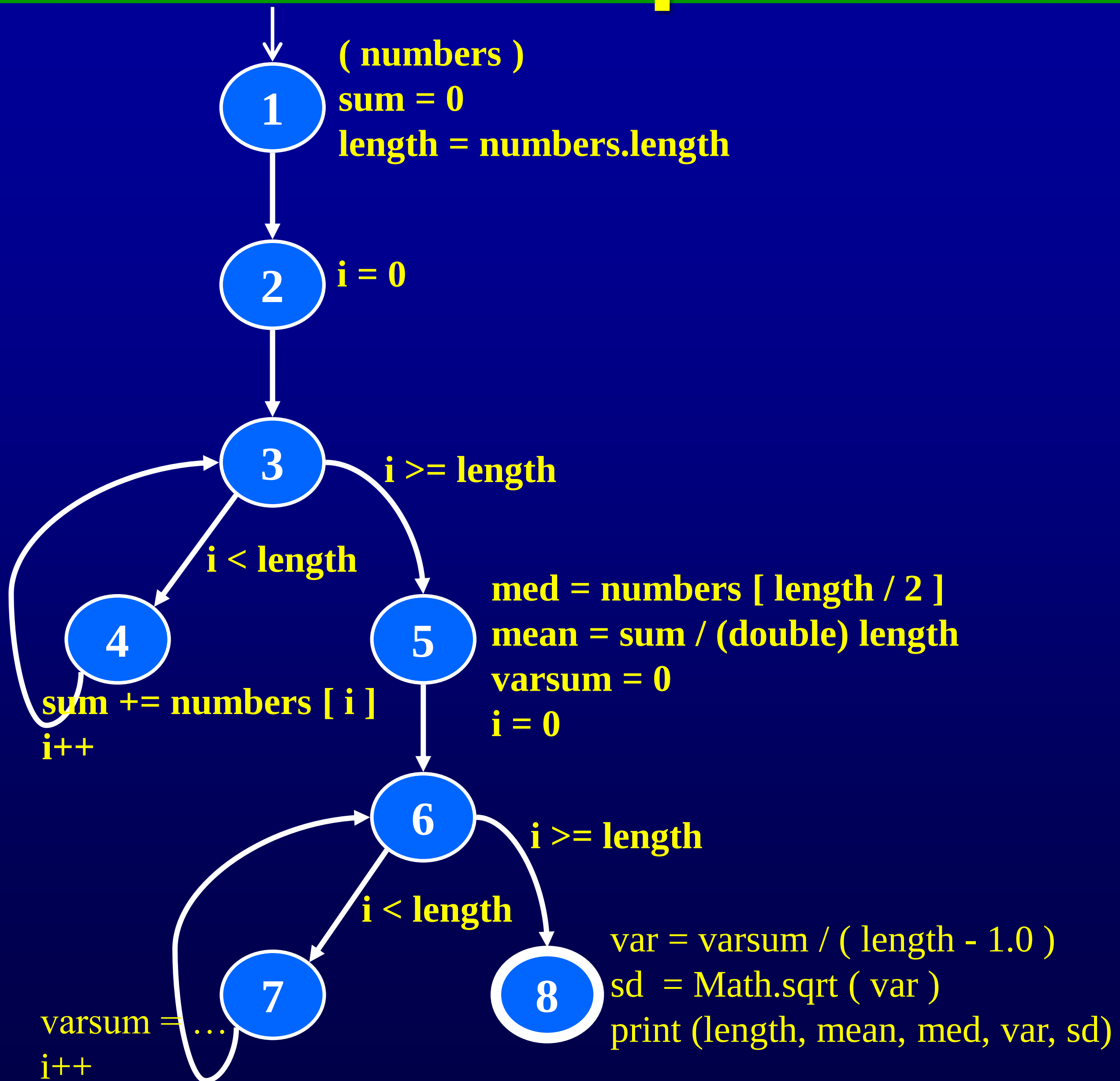
Data Flow Coverage for Source

- def : a location where a value is stored into memory
  - x appears on the left side of an assignment (x = 44;)
  - x is an actual parameter in a call and the method changes its value
  - x is a formal parameter of a method (implicit def when method starts)
  - x is an input to a program
- use : a location where variable's value is accessed
  - x appears on the right side of an assignment
  - x appears in a conditional test
  - x is an actual parameter to a method
  - x is an output of the program
  - x is an output of a method in a return statement
- If a def and a use appear on the same node, then it is only a DU-pair if the def occurs after the use and the node is in a loop

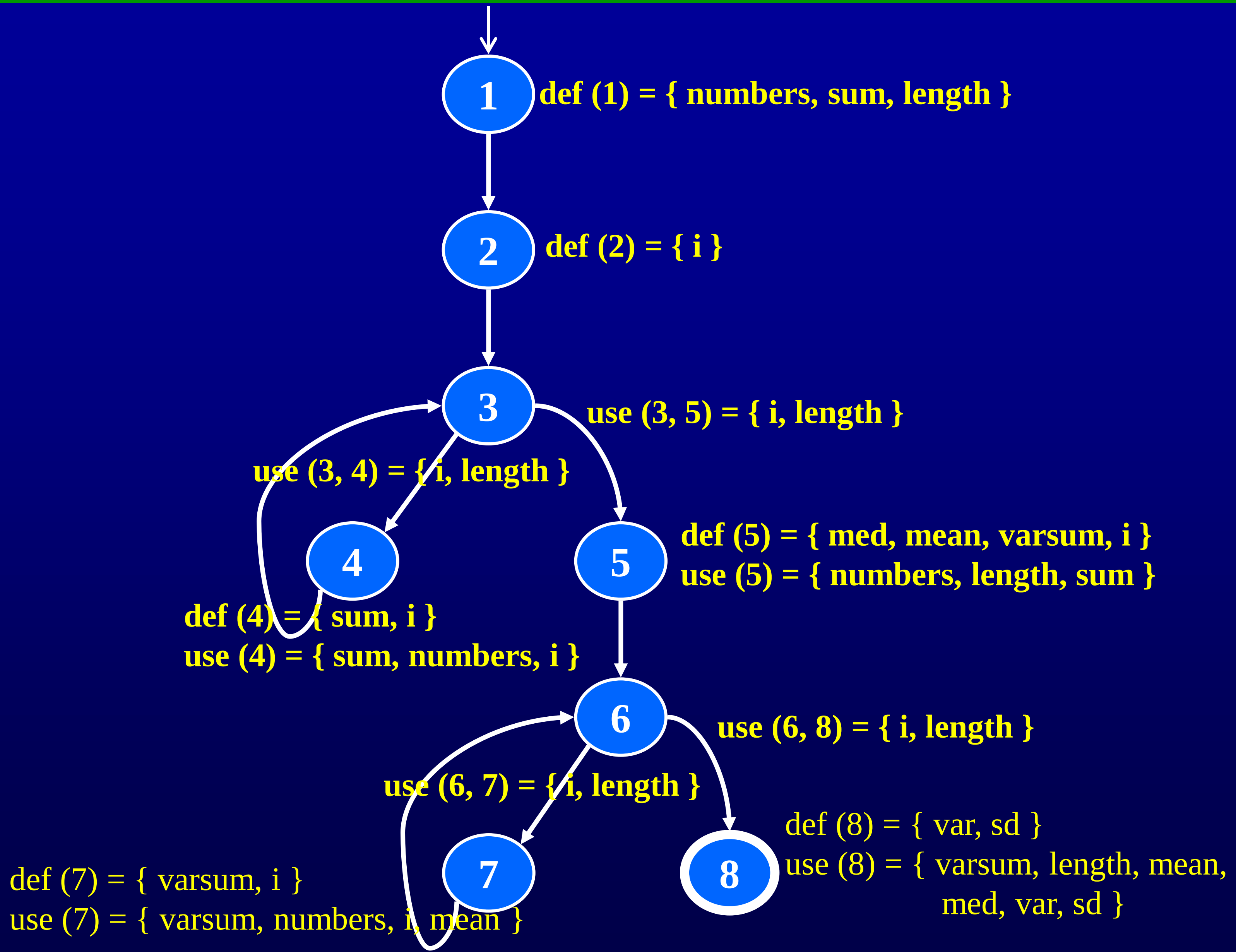
Example Data Flow – Stats

```
public static void computeStats (int [ ] numbers)
{
    int length = numbers.length;
    double med, var, sd, mean, sum, varsum;

    sum = 0.0;
    for (int i = 0; i < length; i++)
    {
        sum += numbers [ i ];
    }
    med   = numbers [ length / 2 ];
    mean = sum / (double) length;

    varsum = 0.o;
    for (int i = 0; i < length; i++)
    {
        varsum = varsum  + ((numbers [ i ] - mean) * (numbers [ i ] - mean));
    }
    var = varsum / ( length - 1 );
    sd  = Math.sqrt ( var );

    System.out.println ("length:                   " + length);
    System.out.println ("mean:                     " + mean);
    System.out.println ("median:                   " + med);
    System.out.println ("variance:                 " + var);
    System.out.println ("standard deviation: " + sd);
}
```

Control Flow Graph for Stats



CFG for Stats – With Defs & Uses



Defs and Uses Tables for Stats

Node	Def	Use
1	{ numbers, sum, length }	{ numbers }
2	{ i }	
3		
4	{ sum, i }	{ numbers, i, sum }
5	{ med, mean, varsum, i }	{ numbers, length, sum }
6		
7	{ varsum, i }	{ varsum, numbers, i, mean }
8	{ var, sd }	{ varsum, length, var, mean, med, var, sd }

Edge	Use
(1, 2)	
(2, 3)	
(3, 4)	{ i, length }
(4, 3)	
(3, 5)	{ i, length }
(5, 6)	
(6, 7)	{ i, length }
(7, 6)	
(6, 8)	{ i, length }

DU Pairs for Stats

variable	DU Pairs
numbers	(1, 4) (1, 5) (1, 7)
length	(1, 5) (1, 8) (1, (3,4)) (1, (3,5)) (1, (6,7)) (1, (6,8))
med	(5, 8)
var	(8, 8)
sd	(8, 8)
mean	(5, 7) (5, 8)
sum	(1, 4) (1, 5) (4, 4) (4, 5)
varsum	(5, 7) (5, 8) (7, 7) (7, 8)
i	(2, 4) (2, (3,4)) (2, (3,5)) ~~(2, 7) (2, (6,7)) (2, (6,8))~~ (4, 4) (4, (3,4)) (4, (3,5)) ~~(4, 7) (4, (6,7)) (4, (6,8))~~ (5, 7) (5, (6,7)) (5, (6,8)) (7, 7) (7, (6,7)) (7, (6,8))

defs come before uses, do not count as DU pairs

defs after use in loop, these are valid DU pairs

No def-clear path … different scope for i

No path through graph from nodes 5 and 7 to 4 or 3

DU Paths for Stats

variable	DU Pairs	DU Paths
numbers	(1, 4) (1, 5) (1, 7)	[1, 2, 3, 4] [1, 2, 3, 5] [1, 2, 3, 5, 6, 7]
length	(1, 5) (1, 8) (1, (3,4)) (1, (3,5)) (1, (6,7)) (1, (6,8))	[1, 2, 3, 5] [1, 2, 3, 5, 6, 8] [1, 2, 3, 4] [1, 2, 3, 5] [1, 2, 3, 5, 6, 7] [1, 2, 3, 5, 6, 8]
med	(5, 8)	[5, 6, 8]
var	(8, 8)	*No path needed*
sd	(8, 8)	*No path needed*
sum	(1, 4) (1, 5) (4, 4) (4, 5)	[1, 2, 3, 4] [1, 2, 3, 5] [4, 3, 4] [4, 3, 5]

variable	DU Pairs	DU Paths
mean	(5, 7) (5, 8)	[5, 6, 7] [5, 6, 8]
varsum	(5, 7) (5, 8) (7, 7) (7, 8)	[5, 6, 7] [5, 6, 8] [7, 6, 7] [7, 6, 8]
i	(2, 4) (2, (3,4)) (2, (3,5)) (4, 4) (4, (3,4)) (4, (3,5)) (5, 7) (5, (6,7)) (5, (6,8)) (7, 7) (7, (6,7)) (7, (6,8))	[2, 3, 4] [2, 3, 4] [2, 3, 5] [4, 3, 4] [4, 3, 4] [4, 3, 5] [5, 6, 7] [5, 6, 7] [5, 6, 8] [7, 6, 7] [7, 6, 7] [7, 6, 8]

DU Paths for Stats—No Duplicates

There are 38 DU paths for Stats, but only 12 unique

[1, 2, 3, 4]	[4, 3, 4]
[1, 2, 3, 5]	[4, 3, 5]
[1, 2, 3, 5, 6, 7]	[5, 6, 7]
[1, 2, 3, 5, 6, 8]	[5, 6, 8]
[2, 3, 4]	[7, 6, 7]
[2, 3, 5]	[7, 6, 8]

4 expect a loop not to be "entered"

6 require at least one iteration of a loop

2 require at least <u>two</u> iterations of a loop

Test Cases and Test Paths

Test Case : numbers = (44) ; length = 1

Test Path : [1, 2, 3, 4, 3, 5, 6, 7, 6, 8]

Additional DU Paths covered (no sidetrips)

[1, 2, 3, 4]   [2, 3, 4]   [4, 3, 5]   [5, 6, 7]   [7, 6, 8]

The five stars that require at least one iteration of a loop

Test Case : numbers = (2, 10, 15) ; length = 3

Test Path : [1, 2, 3, 4, 3, 4, 3, 4, 3, 5, 6, 7, 6, 7, 6, 7, 6, 8]

DU Paths covered (no sidetrips)

[4, 3, 4]   [7, 6, 7]

The two stars that require at least two iterations of a loop

Other DU paths require arrays with length 0 to skip loops

But the method fails with index out of bounds exception…

```
med = numbers [length / 2];
```

A fault was found

Summary

- Applying the graph test criteria to control flow graphs is relatively straightforward
  - Most of the developmental research work was done with CFGs
- A few subtle decisions must be made to translate control structures into the graph
- Some tools will assign each statement to a unique node
  - These slides and the book uses basic blocks
  - Coverage is the same, although the bookkeeping will differ