Introduction to Software Testing
Chapter 7.3
Graph Coverage for Source Code

Paul Ammann & Jeff Offutt

http://www.cs.gmu.edu/~offutt/softwaretest/

Update March 2016

Overview

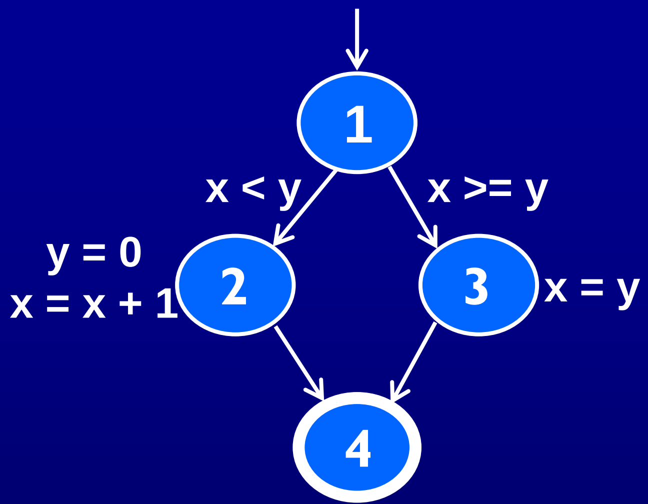
- A common application of graph criteria is to program **source**
- **Graph** : Usually the control flow graph (CFG)
- **Node coverage** : Execute every statement
- **Edge coverage** : Execute every branch
- **Loops** : Looping structures such as for loops, while loops, etc.
- **Data flow coverage**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

Control Flow Graphs

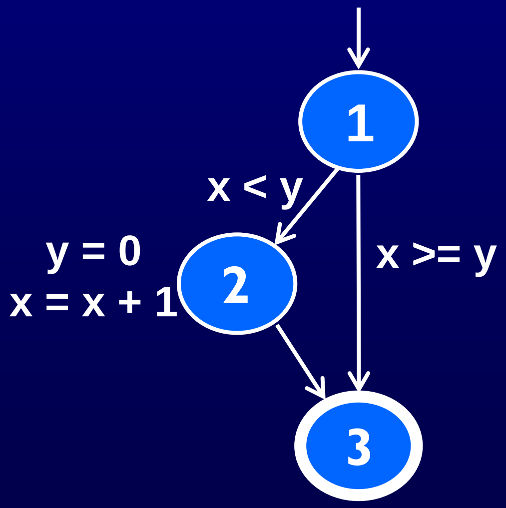
- A CFG models all executions of a method by describing control structures
- Nodes : Statements or sequences of statements (basic blocks)
- Edges : Transfers of control
- Basic Block : A sequence of statements such that if the first statement is executed, all statements will be (no branches)
- CFGs are 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;
}
```

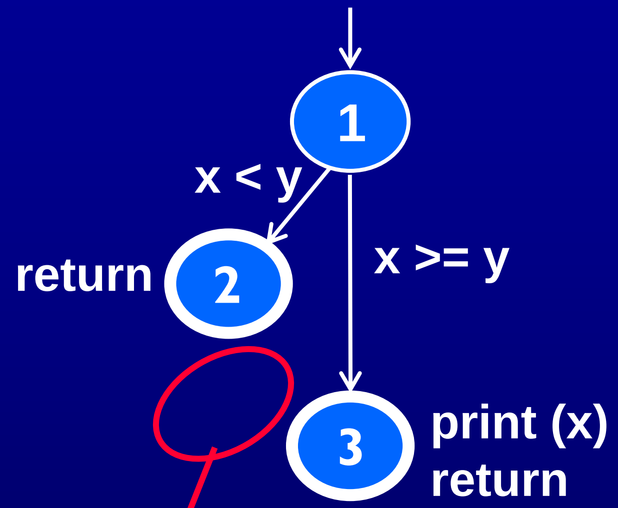



```
if (x < y)
{
   y = 0;
   x = x + 1;
}
```



CFG : The if-Return Statement

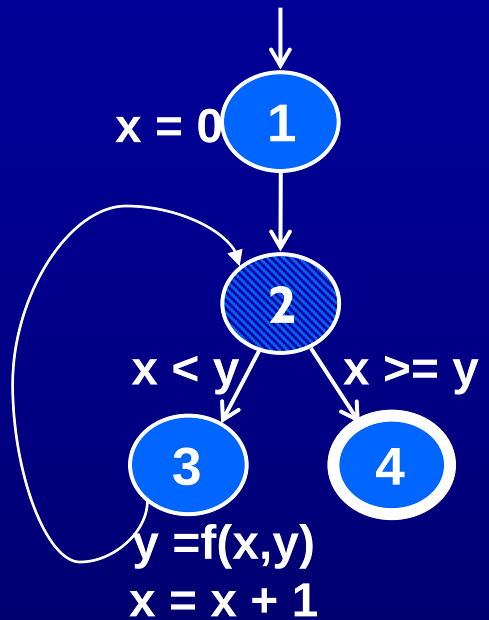
```
if (x < y)
{
   return;
}
print (x);
return;
```



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

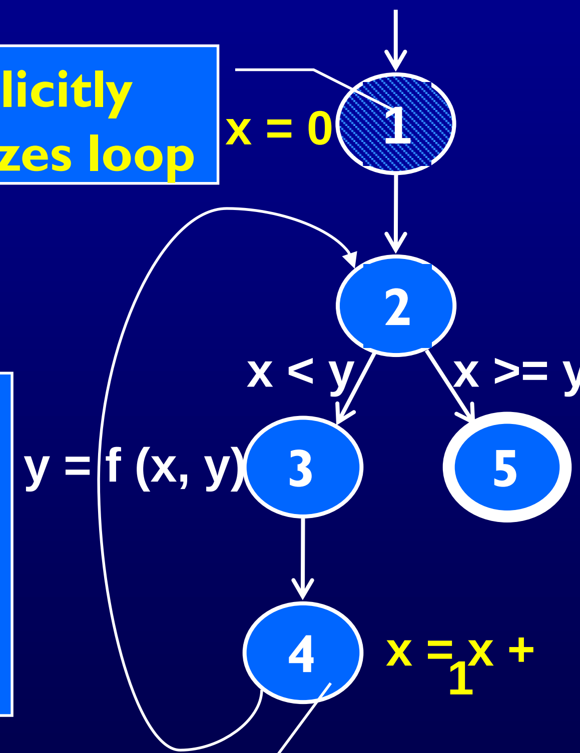
CFG : while and for Loops

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




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

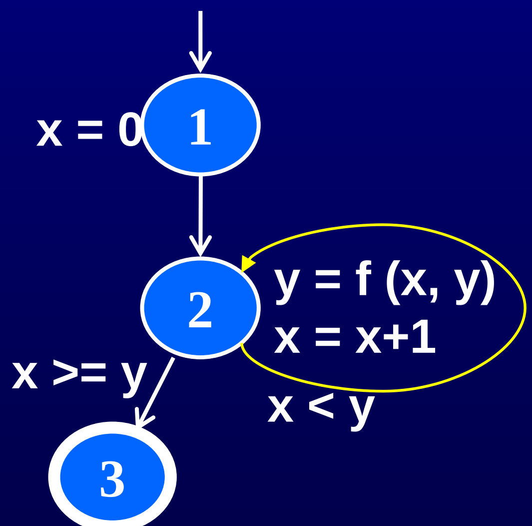
implicitly initializes loop



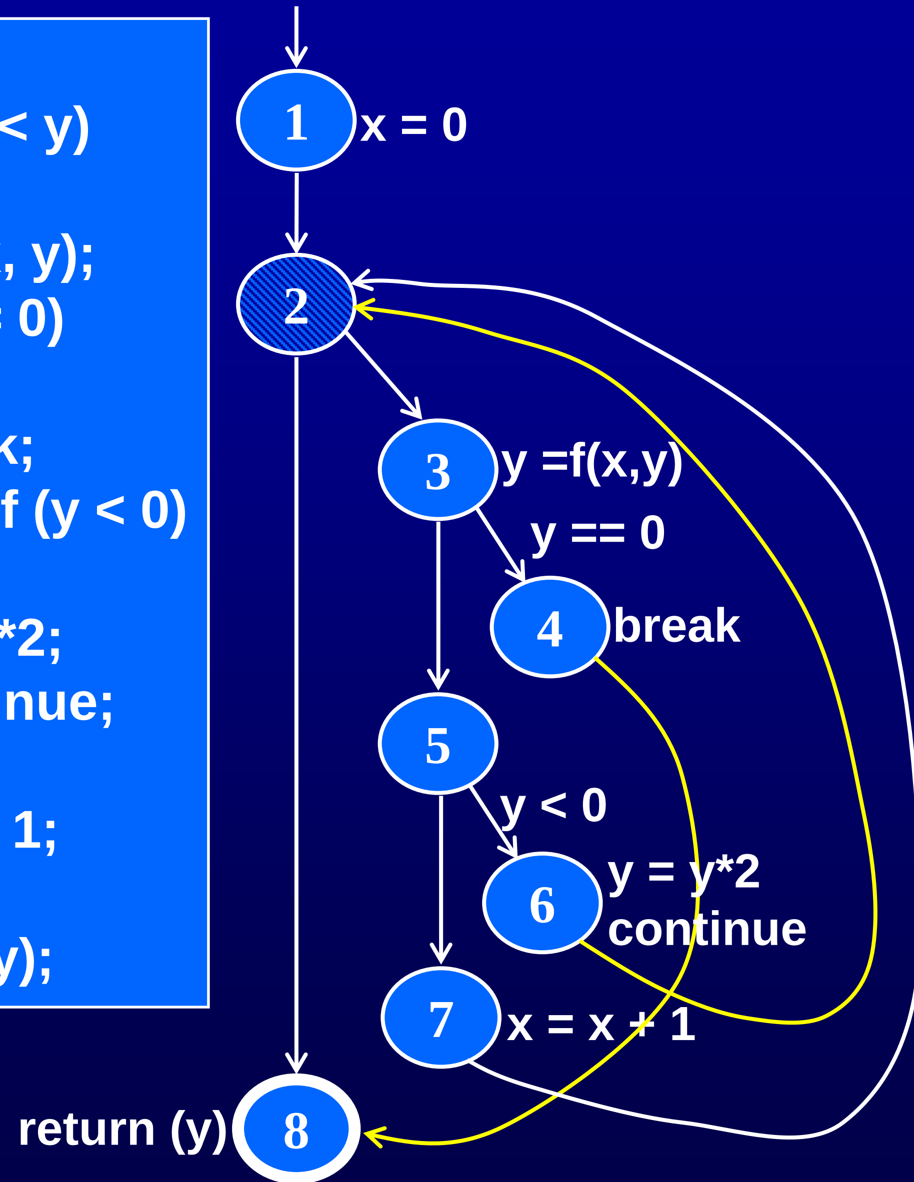
implicitly increments loop

CFG : do Loop, break and continue

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

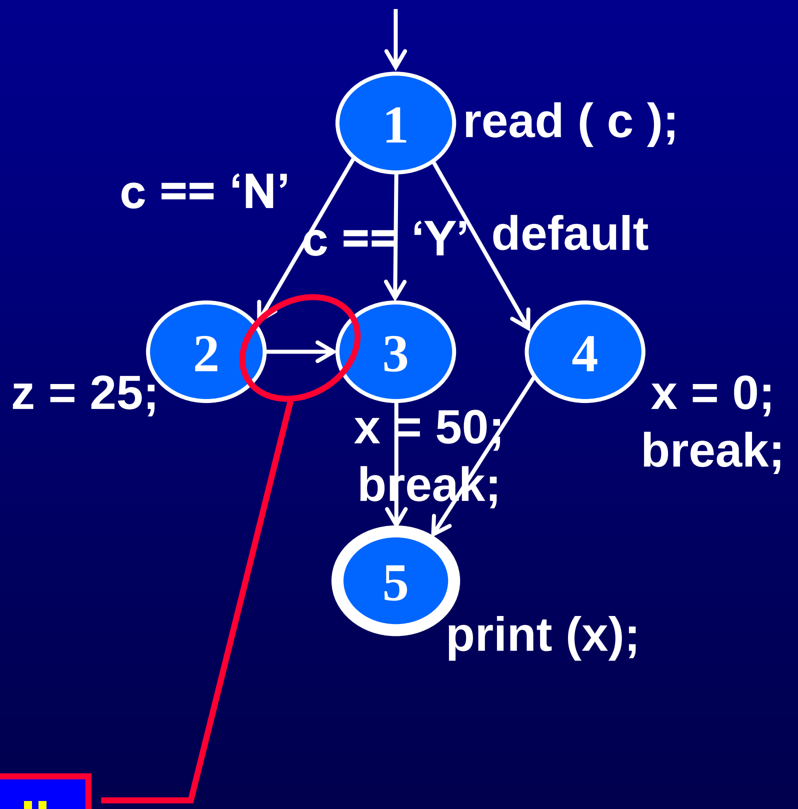



```
x = 0;
while (x < y)
{
   y = f (x, y);
   if (y == 0)
   {
      break;
   } else if (y < 0)
   {
      y = y*2;
      continue;
   }
   x = x + 1;
}
return  (y);
```



CFG : The case (switch) Structure

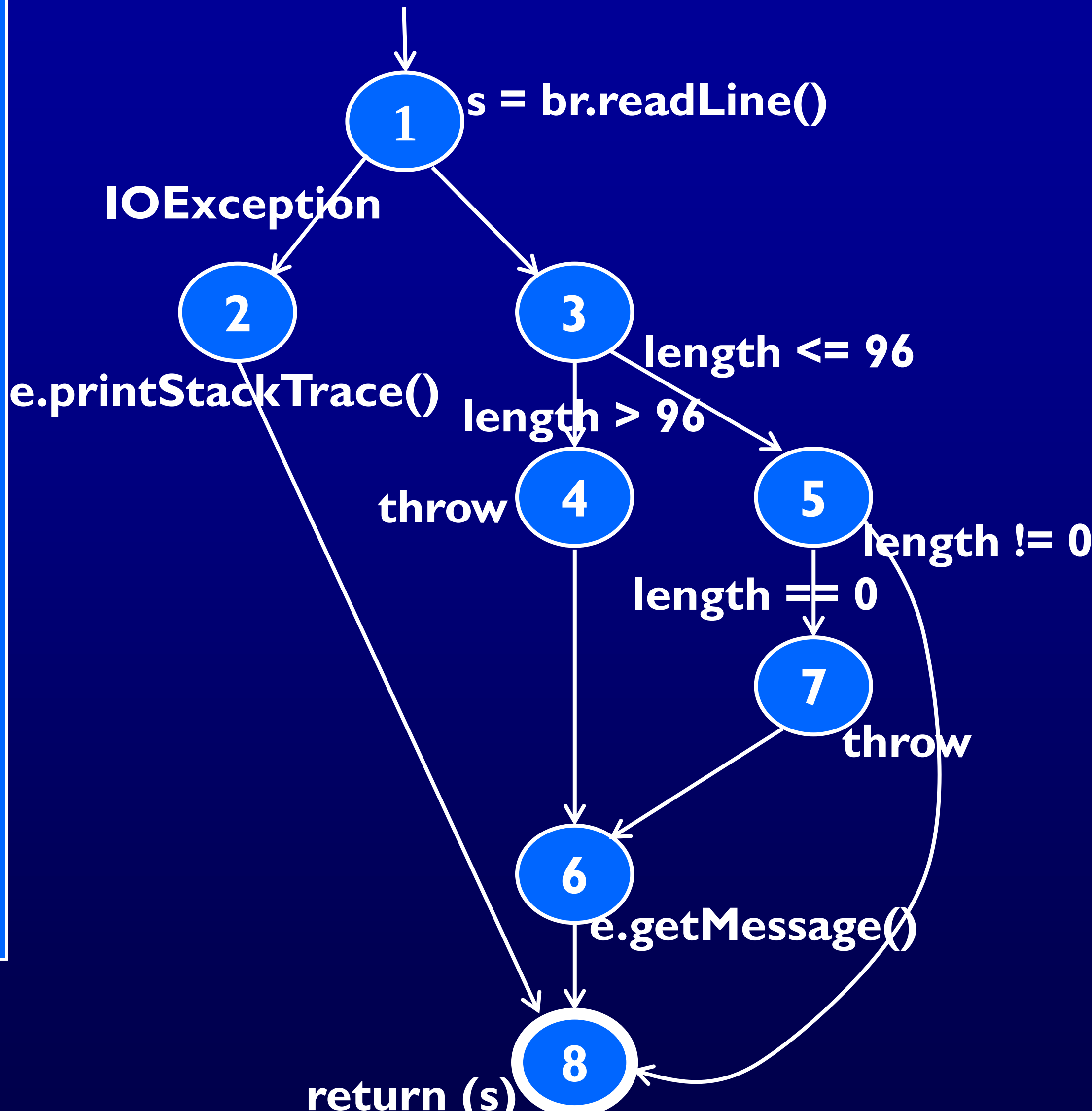
```
read ( c) ;
switch ( c )
{
  case 'N':
    z = 25;
  case 'Y':
    x = 50;
    break;
  default:
    x = 0;
    break;
}
print (x);
```



Cases without breaks fall through to the next case

CFG : Exceptions (try-catch)

```
try
{
  s = br.readLine();
  if (s.length() > 96)
    throw new Exception
      ("too long");
  if (s.length() == 0)
    throw new Exception
      ("too short");
} (catch IOException e) {
  e.printStackTrace();
} (catch Exception e) {
  e.getMessage();
}
return (s);
```



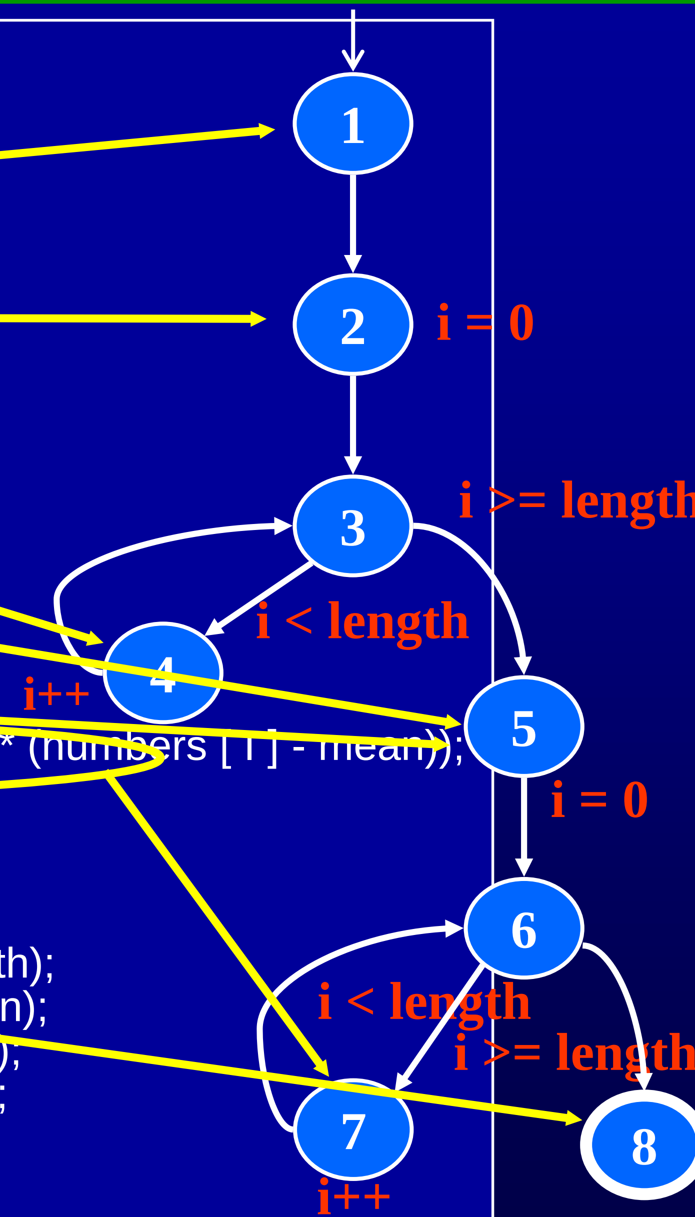
Example Control Flow – Stats

```
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);
}
```

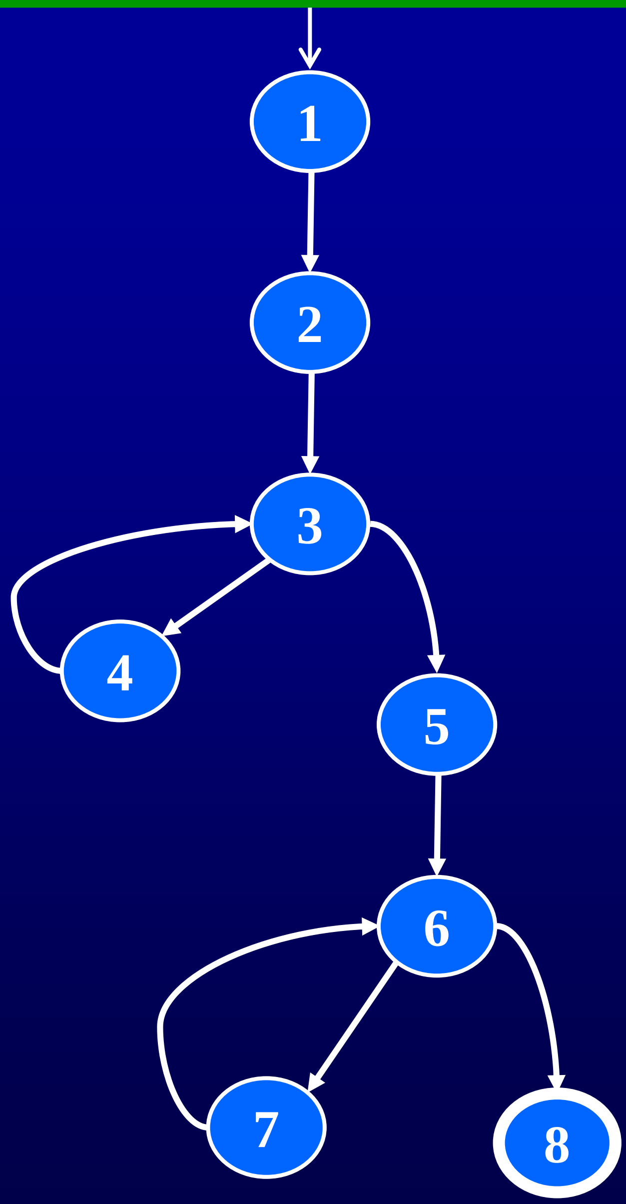
Standard Deviation Formula $= \sqrt{\dfrac{\Sigma_{i-1}^{n} (x_i - \bar{x})^2}{N - 1}}$

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);
}
```

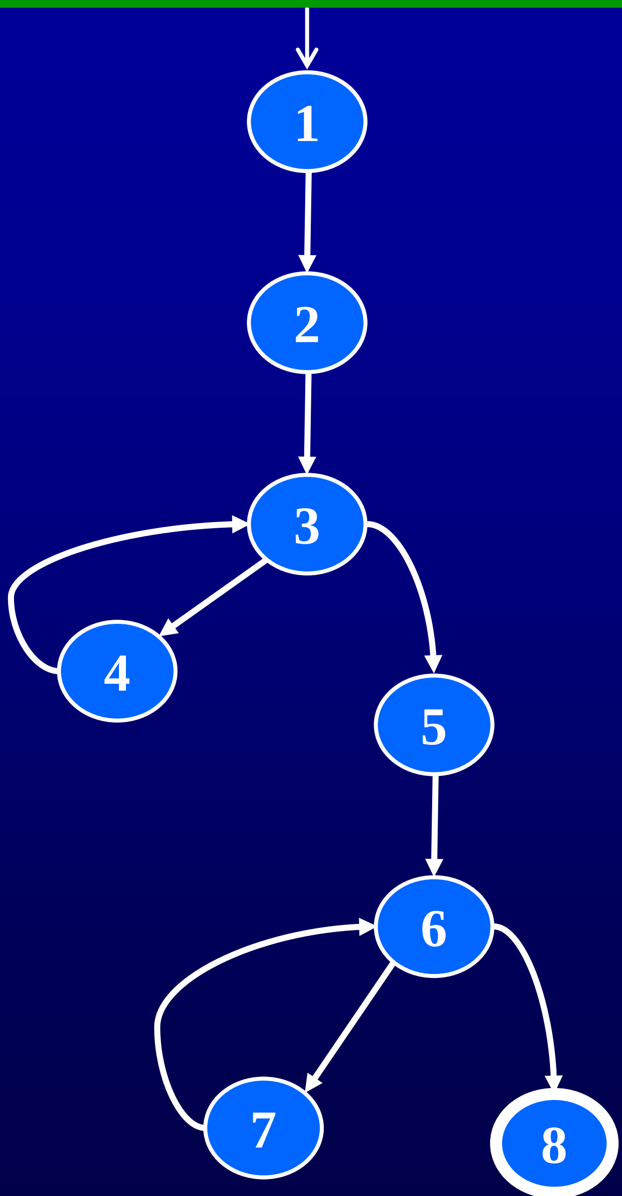


Control Flow TRs and Test Paths—EC



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

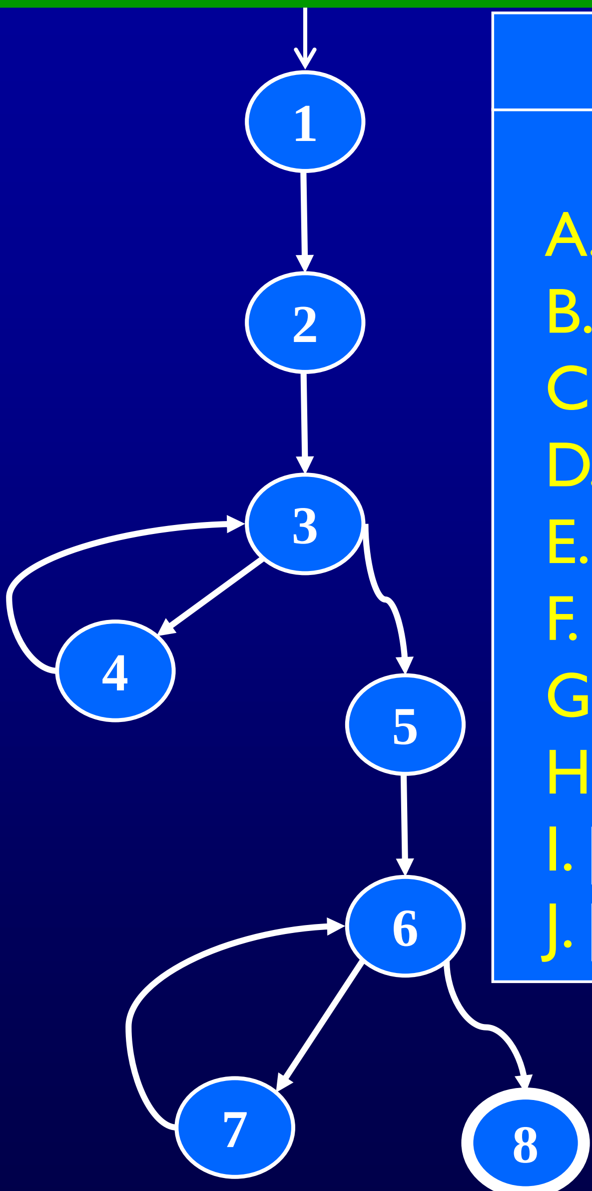


Edge-Pair Coverage	
TR	**Test Paths**
A. [1, 2, 3] B. [2, 3, 4] C. [2, 3, 5] D. [3, 4, 3] E. [3, 5, 6] F. [4, 3, 5] G. [5, 6, 7] H. [5, 6, 8] I. [6, 7, 6] J. [7, 6, 8] K. [4, 3, 4] L. [7, 6, 7]	i. [1, 2, 3, 4, 3, 5, 6, 7, 6, 8] ii. [1, 2, 3, 5, 6, 8] iii. [1, 2, 3, 4, 3, 4, 3, 5, 6, 7, 6, 7, 6, 8]

TP	TRs toured	*sidetrips*
~~i~~	~~A, B, D, E, F, G, I, J~~	C, H
ii	A, C, E, H	
iii	A, B, D, E, F, G, I, J, K, L	C, H

TP iii makes TP i redundant. A *minimal* set of TPs is cheaper.

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]	

TP	TRs toured	*sidetrips*
~~i~~	~~A, D, E, F, G~~	~~H, I, J~~
ii	A, **B**, **C**, D, E, F, G,	H, I, J
iii	A, F, **H**	J
iv	D, E, F, **I**	J
v	**J**	

TP ii makes TP i redundant.

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 input to a program
    - For example: cin >> x;
  - x is a formal parameter of a method (implicit def when method starts)
    - Call by value
  - x is an actual parameter in a call and the method changes its value
    - Call by reference

Data Flow Coverage for Source

- 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
    - For example: cout << x;
  - x is an output of a method in a return statement

Formal parameter vs Actual parameter

Call by value

```
void increment(int a)      Def a
 {
   a++;                    def & use a
 }
                           Formal Parameter
 int main()
 {
   int x = 5;              Def x
   increment(x);           Use x
 }                         Actual Parameter
```

Call by reference

```
#include <iostream>
using namespace std;

//Value of x is shared with a
void increment(int &a){
    a++;                   def & use x (or a)
    cout << "Value in Function increment: "<< a <<endl;
}

int main()
{
    int x = 5;             Def x
    increment(x);          Use x
    cout << "Value in Function main: "<< x <<endl;
    return 0;
}
```

Data Flow Coverage for Source

- 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

def comes before use, is not a DU-pair

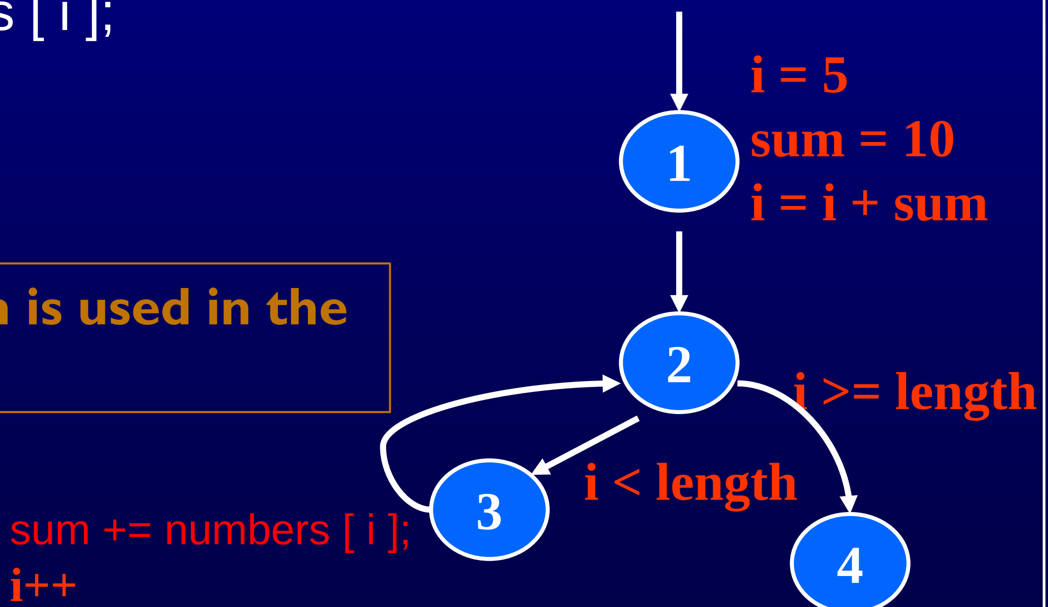
```
i = 5;
sum = 10;
i = i + sum;
while (i < length)
{
    sum += numbers [ i ];
    i = i +1;
}
```

node is not in a loop, is not a DU-pair

Du-pair

Du-pair

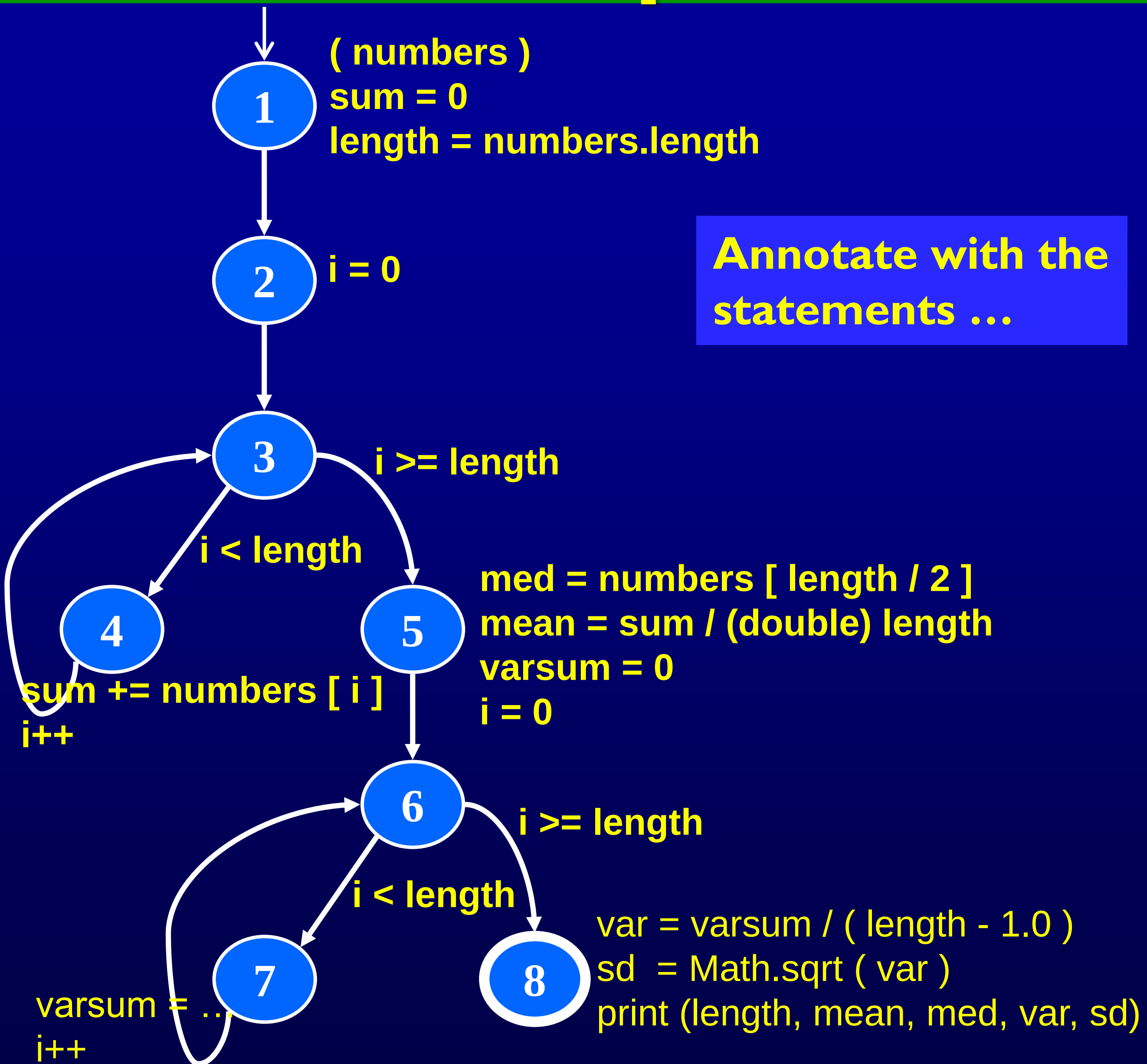
DU-pair (a def in an iteration is used in the next iteration)



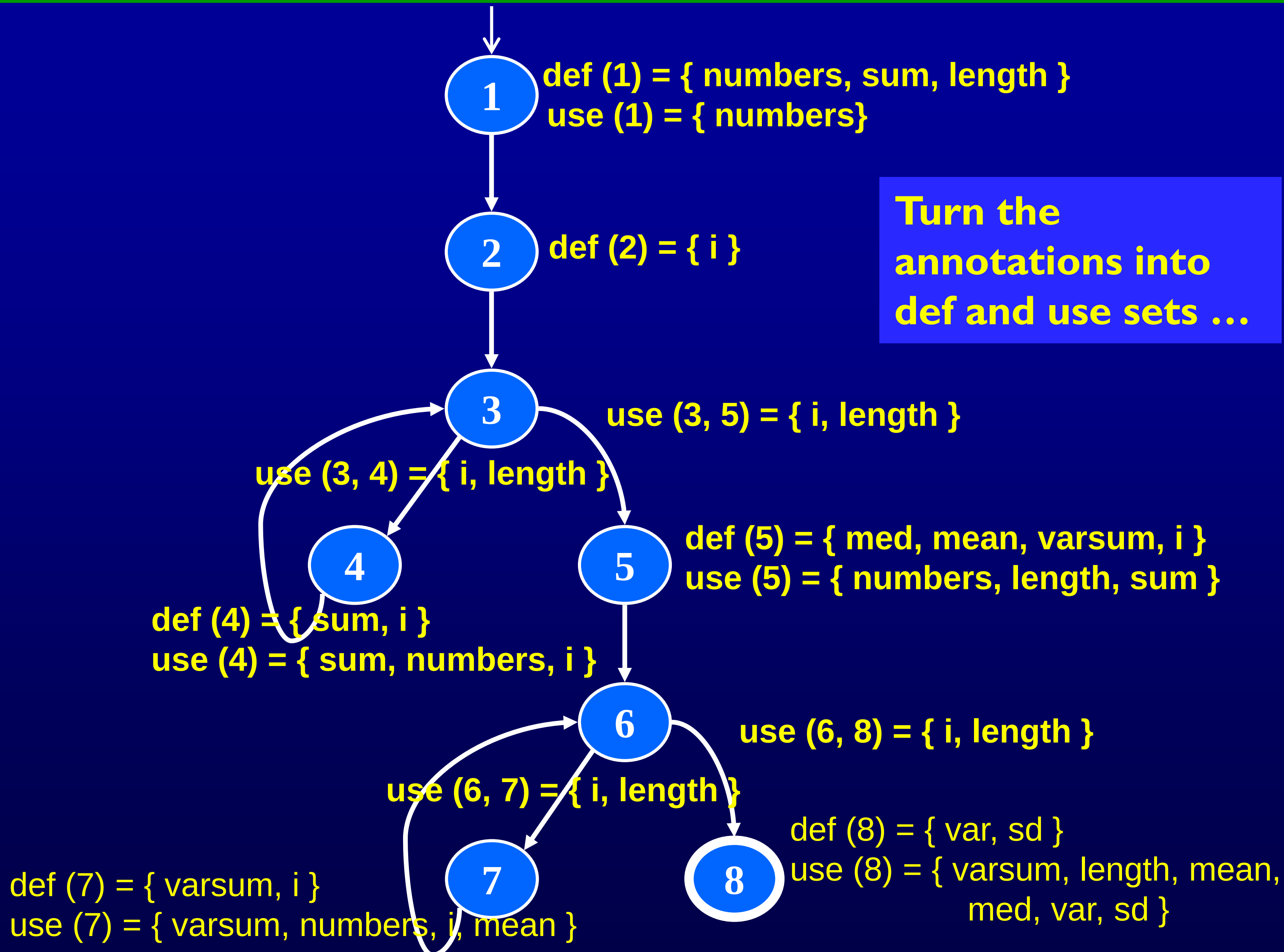
Example Data Flow – Stats

```
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



Turn the annotations into def and use sets …

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	(1,1) (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

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	-	-
sd	-	-
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
    - Larger graphs