Graph Coverage for Source Code

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Inspiration

"You must be a constructive schizophrenic. Be clear about the difference between your role as a programmer and as a tester. The tester in you must be suspicious, uncompromising, hostile, and compulsively obsessed with destroying, utterly destroying, the programmer's software. The tester in you is your Mr. Hyde – your Incredible Hulk. He must exercise what Gruenberger calls 'low cunning." – Boris Beizer

Outcomes

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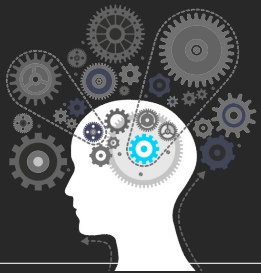
After today's lecture you will be able to:

- Develop CFGs for given source code
- Connect concepts from graph coverage to CFGs



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

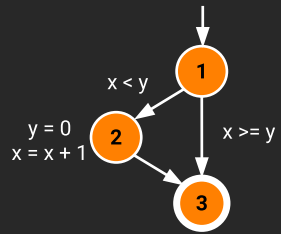
Control Flow Graphs

- 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

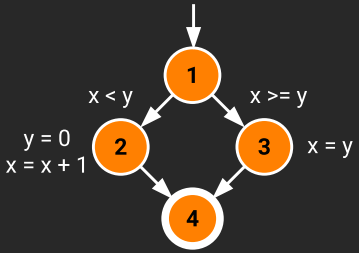
Basic If

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



If/Else

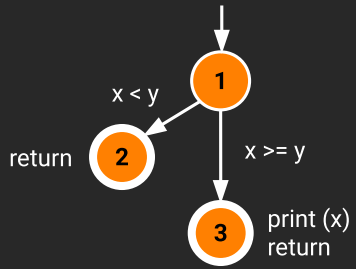
```
if (x < y) {
  y = 0;
  x = x + 1;
} else {
  x = y;
}
```



CFG: The If-Return Statement

If with Return

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



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

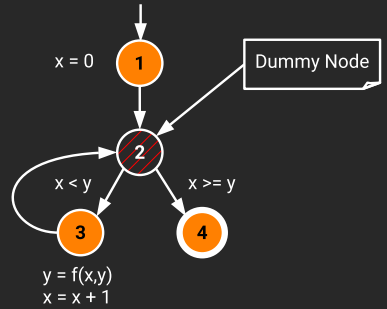
Loops

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

CFG: while Loops

While Loop

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



CFG: for Loops

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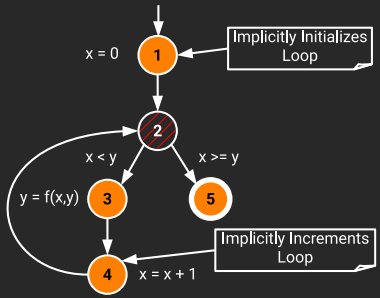
For Loop

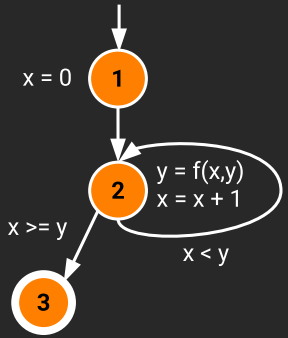
```
for (x = 0; x < y; x++) {
  y = f(x, y);
}
return(x);
```



CFG: do Loop

Do Loop}

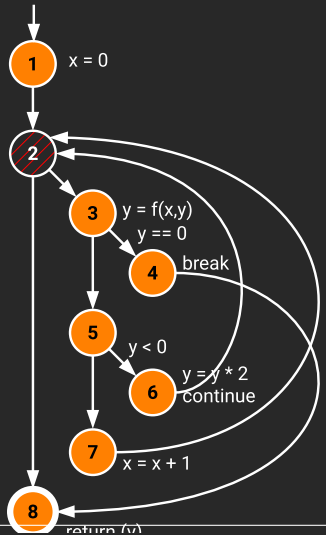
```
x = 0;
do {
  y = f(x, y);
  x = x + 1;
} while (x < y);
return(y);
```



CFG: break and continue

While with Break/Cont

```
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

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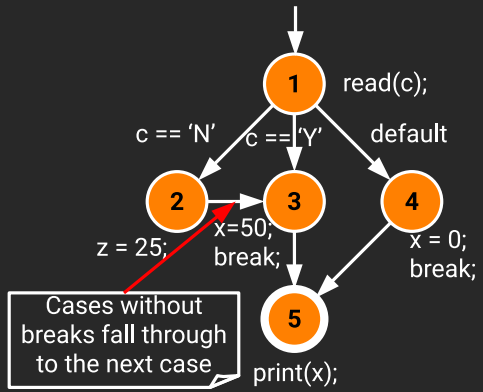
Switch

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



CFG: Exceptions (try-catch)

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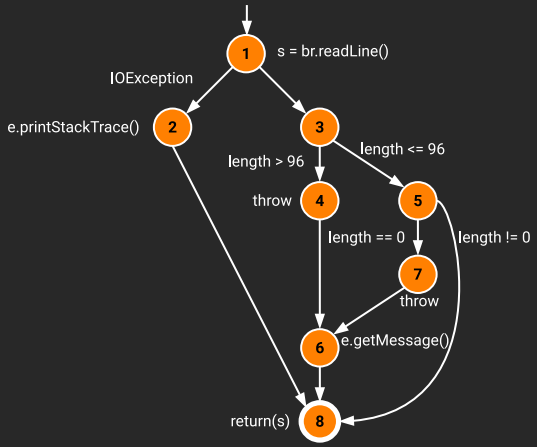
Exception Handling

```
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

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Draw the graph and label the edges

```
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 = 0.0;
     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);
}
```

Example Control Flow - Stats

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public static void computeStats (int[] numbers) {
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     }
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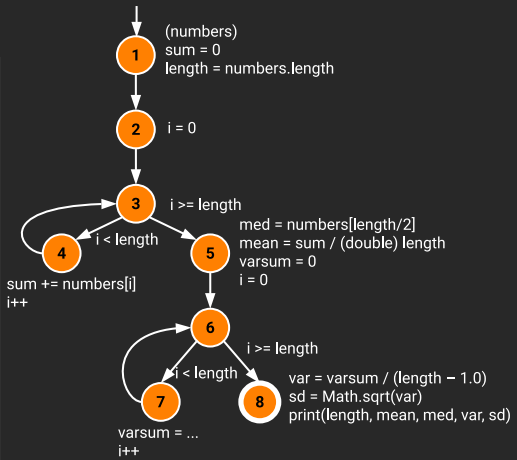
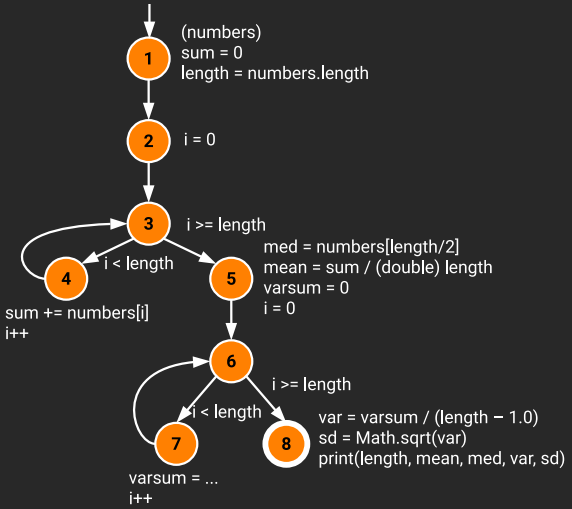
     System.out.println("length:              " + length);
     System.out.println("mean:                " + mean);
     System.out.println("median:              " + med);
     System.out.println("variance:            " + var);
     System.out.println("standard deviation:  " + sd);
}
```



Control Flow TRs and Test Paths - EC



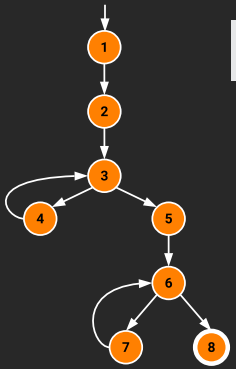
Edge Coverage

TRs

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]

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

Control Flow TRs and Test Paths - EPC



Edge-Pair Coverage

TRs

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]

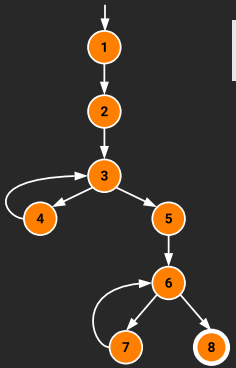
Test Paths:

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~~	C, H
ii	A,C,E,H	
iii	A,B,D,E,F,G,I,J,K,L	C, H

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

Control Flow TRs and Test Paths - PPC



Prime Path Coverage

TRs:
A. [3, 4, 3] **B.** [4, 3, 4] **C.** [7, 6, 7]
D. [6, 7, 6] **E.** [1, 2, 3, 4] **F.** [4, 3, 5, 6, 7]
G. [4, 3, 5, 6, 8] **H.** [4, 3, 5, 6, 8]
I. [1, 2, 3, 5, 6 ,7] **J.** [1, 2, 3, 5, 6, 8]

Test Paths:
i. [1,2,3,4,3,5,6,7,6,8]
ii. [1,2,3,4,3,4,3,5,6,7,6,7,6,8]
iii. [1,2,3,4,3,5,6,8]
iv. [1,2,3,5,6,7,6,8]
v. [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

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- **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

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1. Create the basic CFG Graph

```
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 = 0.0;
     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);
}
```

Example Data Flow - Stats

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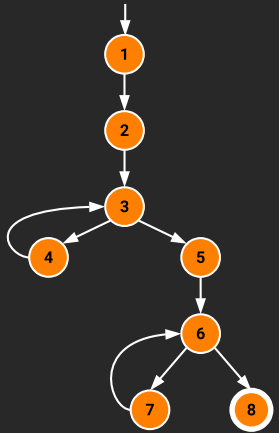
```
public static void computeStats (int[] numbers) {
     int length = numbers.length;
     double med, var, sd, mean, sum, varsum;

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

     varsum = 0.0;
     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);
}
```



2. Annotate with the statements...

Example Data Flow - Stats

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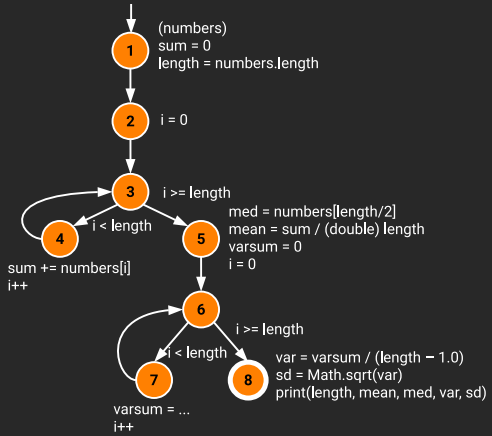
```
public static void computeStats (int[] numbers) {
     int length = numbers.length;
     double med, var, sd, mean, sum, varsum;

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

     varsum = 0.0;
     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);
}
```



3. Turn the annotations into defs and use sets...

Example Data Flow - Stats

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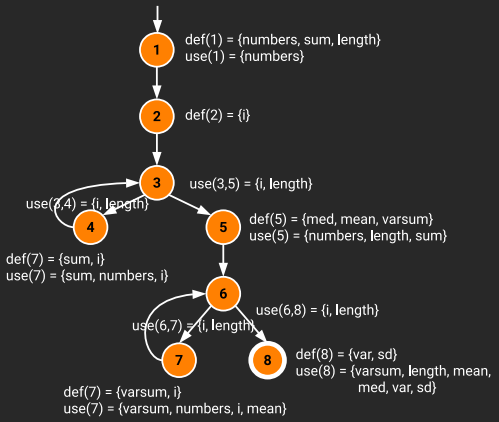
```
public static void computeStats (int[] numbers) {
     int length = numbers.length;
     double med, var, sd, mean, sum, varsum;

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

     varsum = 0.0;
     for (int i = 0; i < length; i++) {
          varsum = varsum + ((numbers[i] - mean) * (numbers[i] - mean));
     }
     var = varsum / (length - 1);
     sd  = Math.sqrt (var);

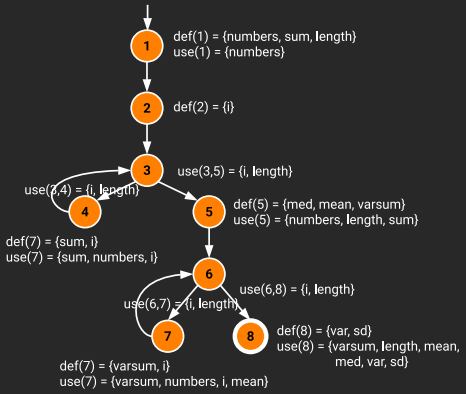
     System.out.println("length:              " + length);
     System.out.println("mean:                " + mean);
     System.out.println("median:              " + med);
     System.out.println("variance:            " + var);
     System.out.println("standard deviation:  " + sd);
}
```



Defs and Uses Tables for Stats

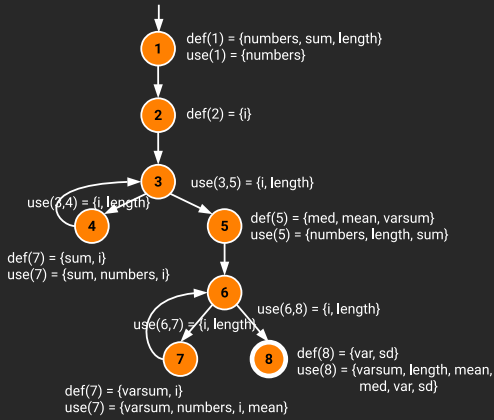
Node	Def	Use
1	{numbers, sum, length}	{numbers}
2	{i}	
3		
4	{sum, i}	{numbers, i, sum}
5	{med, mean, varsum, i}	{numbers, length, sum}
6		
7	{varsum, i}	{varsum, numbers, i, mean}
8	{var, sd}	{varsum, length, var, mean, med, var, sd}

Edge	Use
(3, 4)	{i, length}
(1, 2)	
(2, 3)	
(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)** def comes before use, not a DU pair
sd	**(8,8)** def comes before use, not a DU pair
mean	(5,7) (5,8)
sum	(1,4) (1,5) **(4,4)** (4,5) def after use in loop -> DU pair
varsum	(5,7) (5,8) **(7,7)** (7,8) no def-clear path
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)) no def-clear path



DU Paths for Stats

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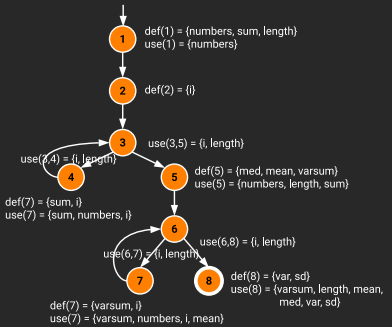
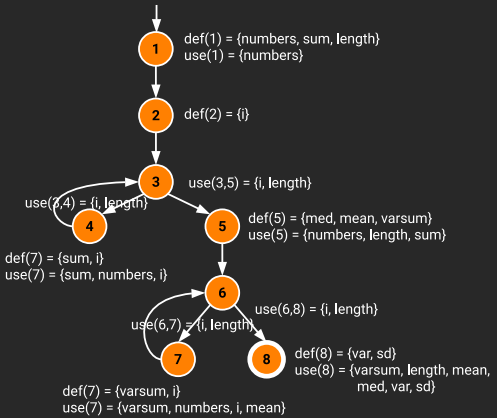
variable	DU Pairs	DU Paths
numbers	(1,4)	[1,2,3,4]
	(1,5)	[1,2,3,5]
	(1,7)	[1,2,3,5,6,7]
length	(1,5)	[1,2,3,5]
	(1,8)	[1,2,3,5,6,8]
	(1, (3,4))	[1,2,3,4]
	(1, (3,5))	[1,2,3,4]
	(1, (6,7))	[1,2,3,4,5,7]
	(1, (6,8))	[1,2,3,5,6,8]
med	(5,8)	[5,6,8]
var	(8,8)	no path needed
sd	(8,8)	no path needed
sum	(1,4)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

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



DU Paths for Stats–No Duplicates



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

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

6 require at least one iteration of a loop

4 Expect a loop not to be "entered"

2 require at least two iterations of a loop

Test Cases and Test Paths

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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];`

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

For Next Time

- Review the Reading
- Review this Lecture
- Come to Class

Are there any questions?