CS 5154: Software Testing

Graph Coverage

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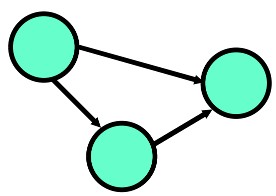
Fall 2021

Recall the four software models in this course

Input Domains

A: {0, 1, >1}
B: {600, 700, 800}
C: {cs, ece, is, sds}

Graphs



Logic Expressions

(!x | !y) & a & b

Syntax

```
if (x > y)
    z = x - y;
else
    z = 2 * x;
```

Why learn about graph coverage?

- Some of the most widely-used coverage criteria

- The “R” in the RIPR model

- Graph coverage criteria help create tests that reach different parts of code

Roadmap on Graph-based MDTD

- Today: establish a vocabulary for talking about graph coverage

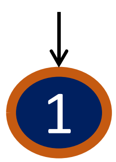
- Next: apply graph coverage to source code

What is a graph?

Graph G is a tuple (N, N_0, N_f, E), where

- N is a non-empty set of nodes
- $N_0 \subset N$ is a non-empty set of initial nodes
- $N_f \subset N$ is a non-empty set of final nodes
- E is a set of pairs (n_i, n_j) where an edge exists from node n_i to node n_j in G
  - n_i : predecessor, n_j : successor

Based on the definition, is this a graph?



$N = \{ 1 \}$

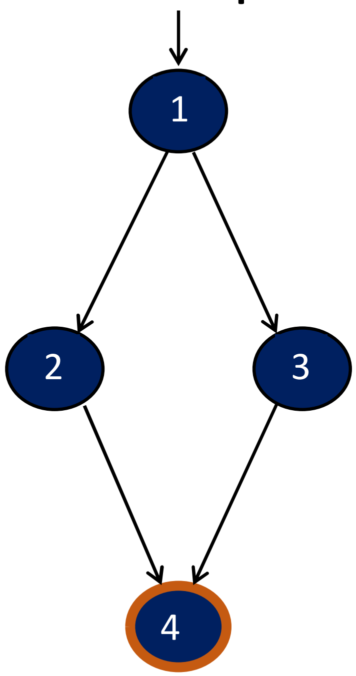
$N_0 = \{ 1 \}$

$N_f = \{ 1 \}$

$E = \{ \}$

Yes

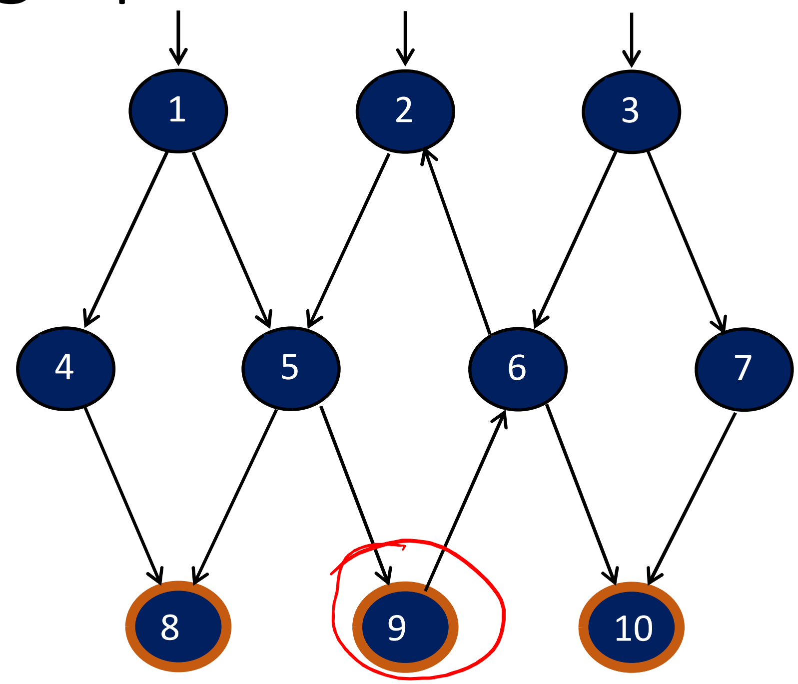
Examples of graphs



N_0 = { 1 }

N_f = { 4 }

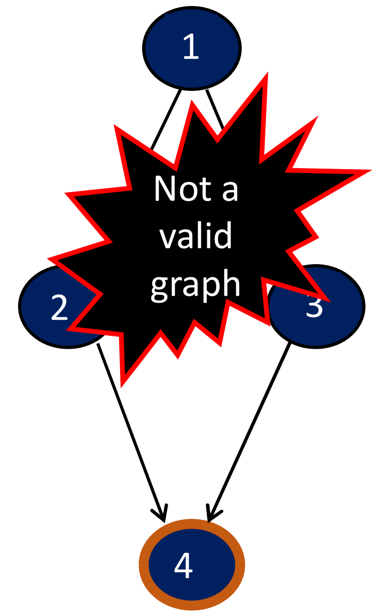
E = { (1, 2), (1,3), (2,4), (3,4) }



N_0 = { 1, 2, 3 }

N_f = { 8, 9, 10 }

E = { (1,4), (1,5), (2,5), (3,6), (3, 7), (4, 8), (5,8), (5,9), (6,2), (6,10), (7,10) (9,6) }

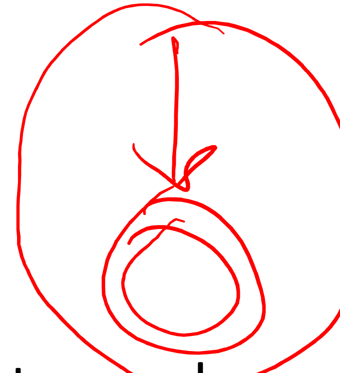


N_0 = { }

N_f = { 4 }

E = { (1,2), (1,3), (2,4), (3,4) }

Graph coverage criteria are usually about paths in G



Imprecise

- Path : A sequence, *p*, of nodes [n_1, n_2, …, n_M] such that there exists an edge between each pair of nodes in *p*

[1, 2, 3, 4]

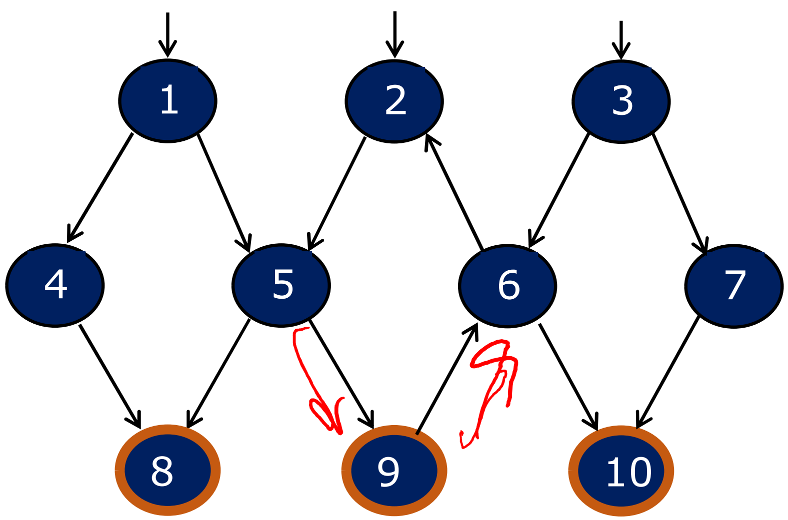
[1, 3]

- Length of a path : The number of edges in *p*
  - A single node is a path of length 0
- Subpath : A subsequence of nodes in *p* is a subpath of *p*

Graph coverage criteria are usually about paths in G

- Path : A sequence, *p*, of nodes $[n_1, n_2, \ldots, n_M]$ such that there exists an edge between each pair of adjacent nodes (n_i, n_{i+1}), $1 \le i < M$
- Length of a path : The number of edges in *p*
  - A single node is a path of length 0
- Subpath : A subsequence of nodes in *p* is a subpath of *p*

Identify some paths in this graph



A Few Paths

[1, 4, 8]

[2, 5, 9, 6, 2]

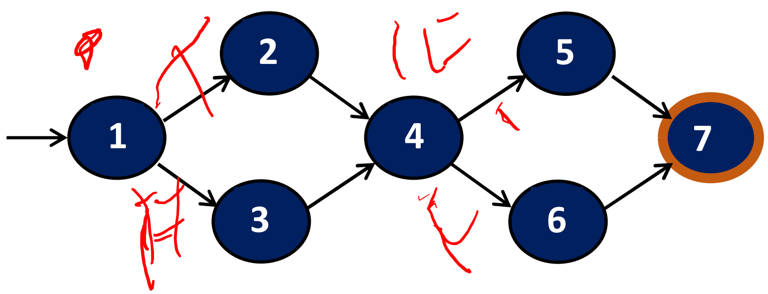
[3, 7, 10]

Tests must start at $n_i \in N_0$ and end at $n_j \in N_f$

- Test Path : A path that starts at an initial node and ends at a final node

- Single entry, single exit (SESE) graphs :
  - N_0 and N_f have exactly one node
  - All test paths start at $n \in N_0$ and end at $m \in N_f$

Identify all the test paths in this graph



Four test paths

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

What does it mean for tests to "cover" graphs?

- 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*

Test path [1, 2, 4, 5, 7]

Visits nodes ? 1, 2, 4, 5, 7

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

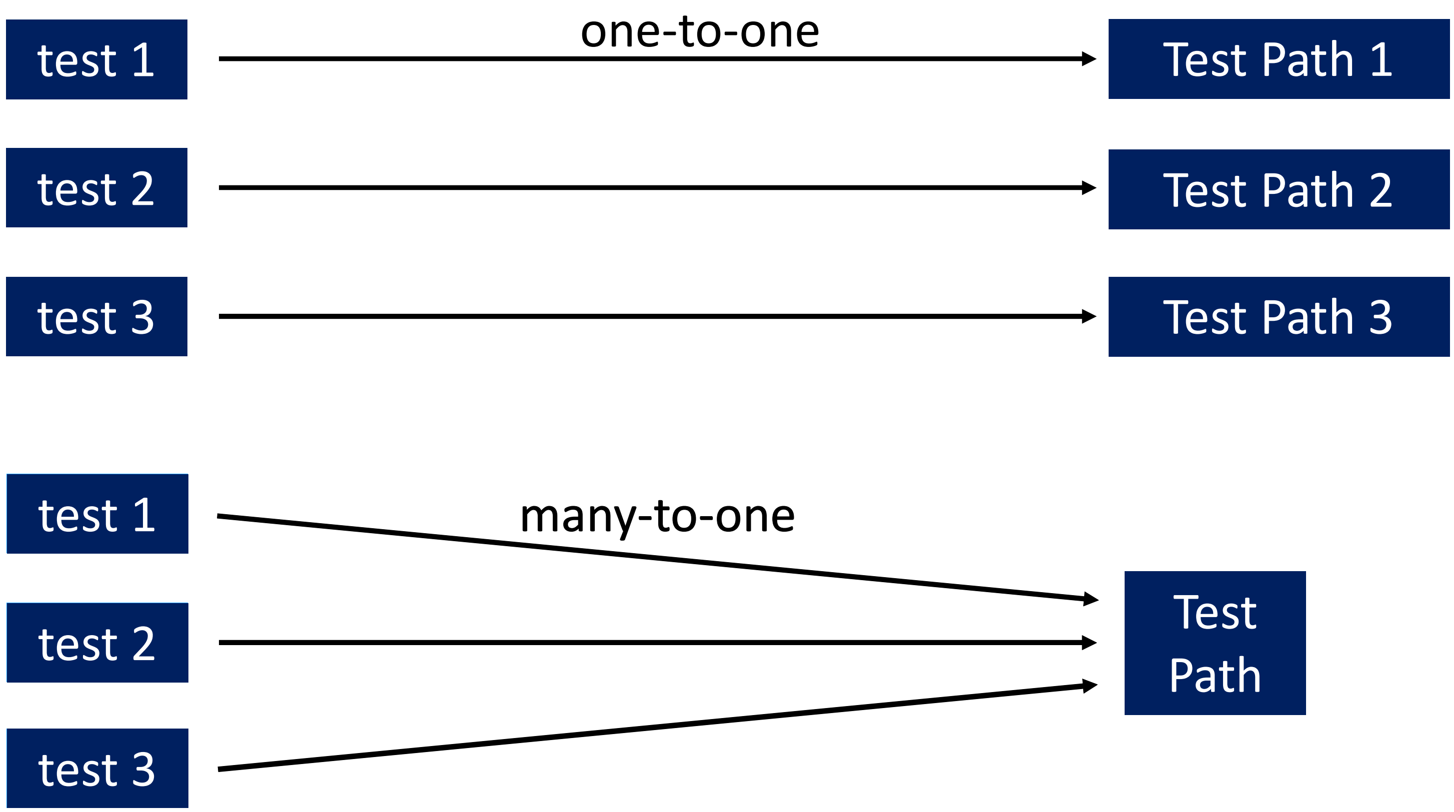
Tours subpaths ? [1,2,4], [2,4,5], [4,5,7], [1,2,4,5], [2,4,5,7], [1,2,4,5,7]

(*Also, each edge is technically a subpath*)

Terminology for discussing test cases and test paths

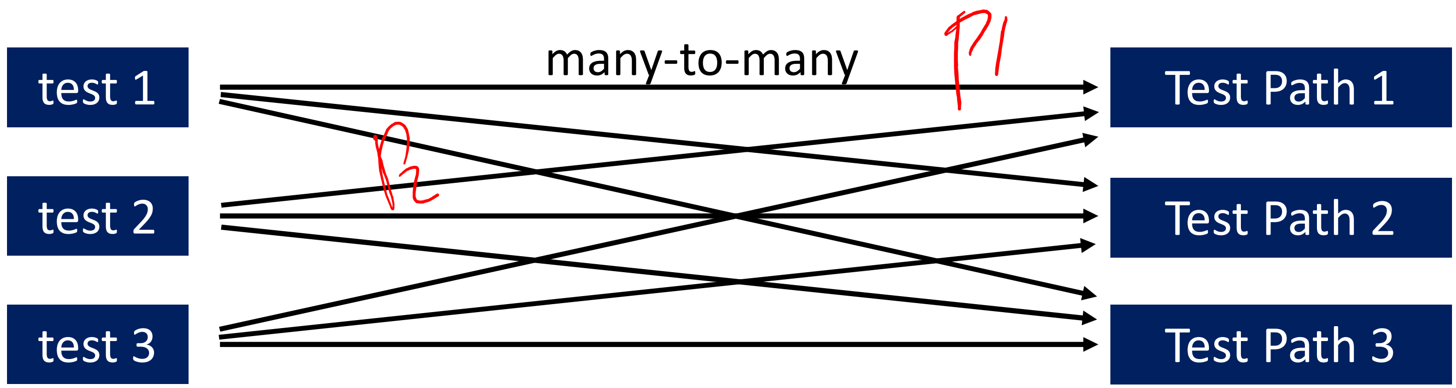
- path (*t*) : The test path executed by test case *t*
- path (*T*) : The set of test paths executed by set of test cases *T*
- Each test case executes one and only one test path
  - Is the previous statement really true?

Relationship among test cases and test paths



Relationship among test cases and test paths

path(t)



path(T)

Terminology for discussing test cases and test paths

- path (t) : The test path executed by test case t
- path (T) : The set of test paths executed by set of test cases T
- ~~Each test case executes one and only one test path~~
  - Is the previous statement really true? No
- Each test case executes one and only one test path at once

More terminology on test cases and test paths

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

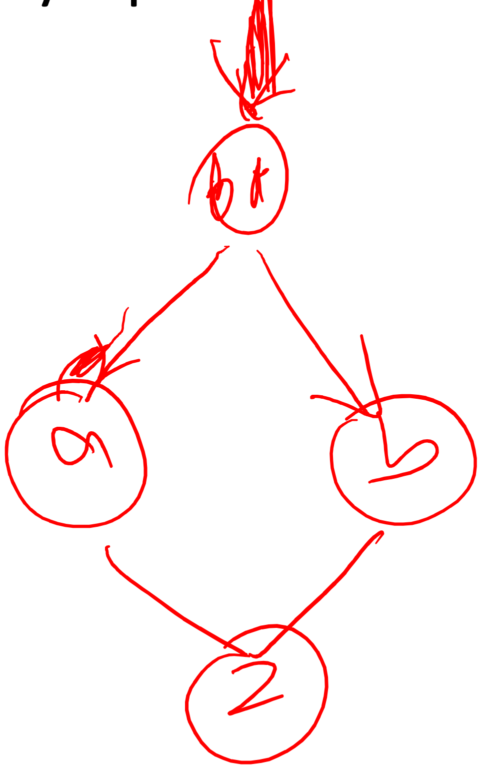
1. *Syntactic reach* : A subpath exists in the graph

2. *Semantic reach* : A test exists that can execute the subpath in (1)

3. Semantic vs syntactic reach is important when applied to source code

HW0: You all computed syntactic reachability on a given graph!

Any questions so far



?

if (true && false)
a;
else
b;

Implementing Graph-based MDTD

- Develop a model of the software as a graph
- Require tests to visit/tour sets of nodes, edges, or sub-paths
- Choose inputs that satisfy the test requirements
- Implement and automate tests based on the inputs chosen

Recall these three general concepts?

- **Test Requirement** : A software element that a test must satisfy or cover
- **Coverage Criterion** : A rule or collection of rules that impose test requirements on a set of tests
- **Coverage** : Given a set of test requirements *TR* for coverage criterion *C*, a test set *T* satisfies *C* if and only if for every test requirement *tr* in *TR*, there is at least one test *t* in *T* such that *t* satisfies *tr*

Defining these three concepts on Graphs

- Test Requirements (TR) : Describe properties of test paths

- Coverage Criterion : Rules that define test requirements.
  - We discuss some of those next

- Coverage : 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 *tr* in *TR*, there is a test path in *path(T)* that meets the test requirement *tr*

Two kinds of graph coverage criteria

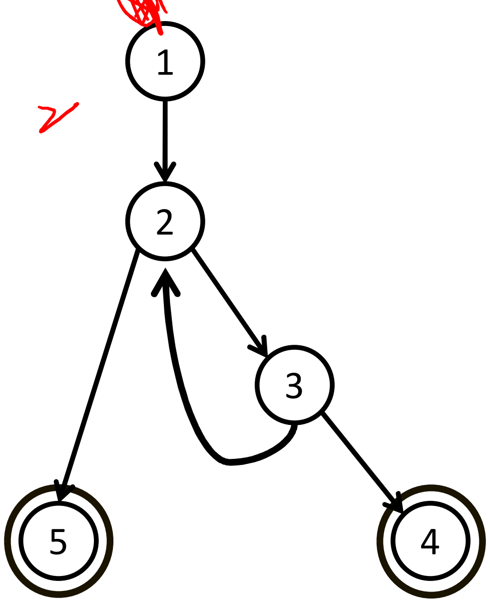
1. Structural Coverage Criteria : Defined on a graph just in terms of nodes and edges

2. Data Flow Coverage Criteria : Defined on a graph that is annotated with variable definitions and uses (i.e., *def-use* pairs)
   a. Do tests cover every use of each variable definition?
   b. Are there variable definitions that are not covered by any test?

We will not cover Data Flow Coverage Criteria this semester

Recall: we saw structural coverage criteria before

Graph: abstract version



Edges
1 2
2 3
3 2
3 4
2 5
Initial Node: 1
Final Nodes: 4, 5

6 requirements for Edge-Pair Coverage
1. [1, 2, 3]
2. [1, 2, 5]
3. [2, 3, 4]
4. [2, 3, 2]
5. [3, 2, 3]
6. [3, 2, 5]

Test Paths
[1, 2, 5]
[1, 2, 3, 2, 5]
[1, 2, 3, 2, 3, 4]

Convention :

([1,2],[2,3]) = [1,2,3]

Structural Coverage Criteria

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

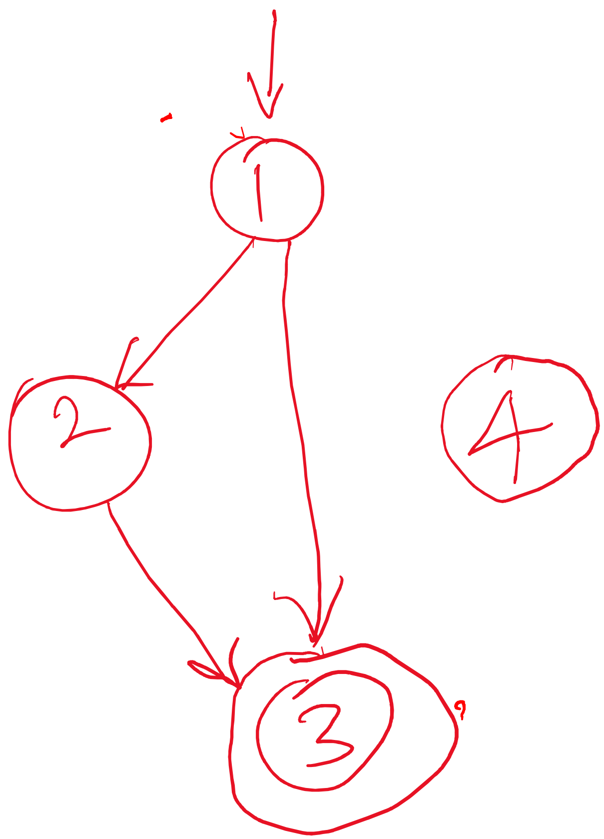
Node Coverage

<u>Node Coverage (NC)</u> : Test set *T* satisfies node coverage on graph *G* if and only if 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

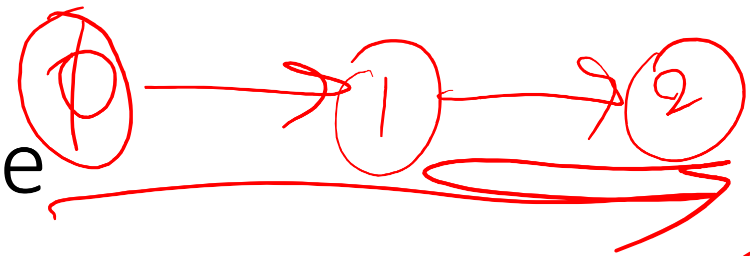
<u>Node Coverage (NC)</u> : TR contains each reachable node in G.

Example on Node Coverage



How many TRs are there?

Edge coverage



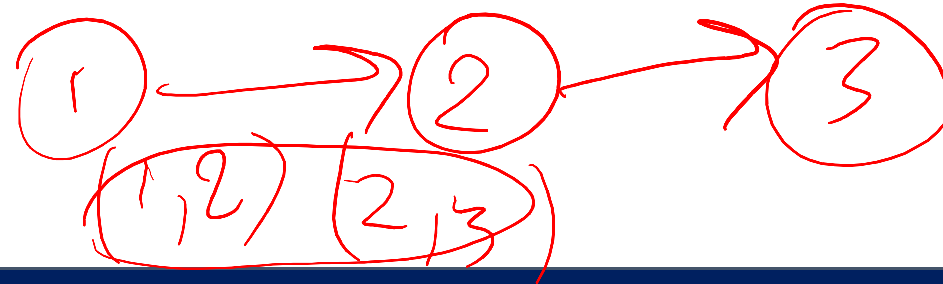
[1, 2]

<u>Edge Coverage (EC)</u> : TR contains each reachable path of length 2 in G.

- What is wrong with this definition?

(1) (2) (3)

Edge coverage



Edge Coverage (EC) : TR contains each reachable path of length 1 in G.

- In theory, should Edge Coverage subsume Node Coverage?
- Given the definition above, does Edge Coverage subsume Node Coverage?
- What is wrong with this definition of Edge Coverage?

Edge coverage

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

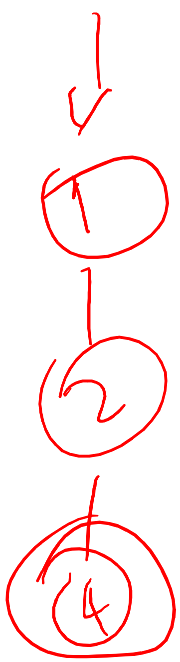
- The phrase “*length up to 1*” allows for graphs with one node and no edges

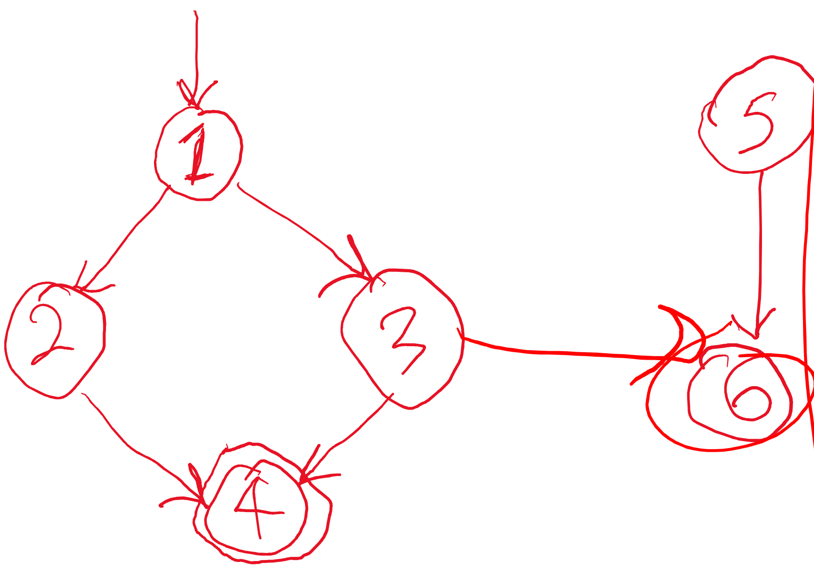
[1,2,4]

Node Coverage review

5

- How many test requirements does **Node Coverage** impose on the tests for this graph:



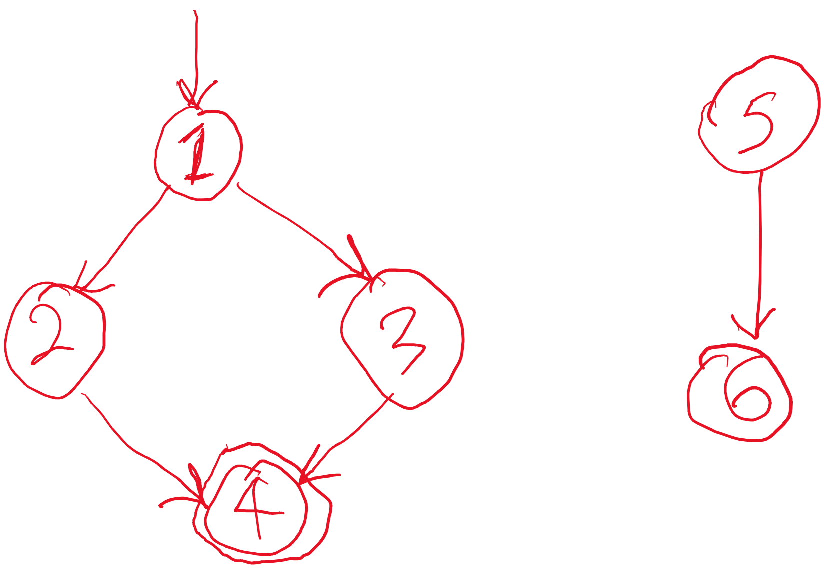


[1,2]
[1,3]
[2,4]
[3,4]

[1]
[2]
[3]
[4]

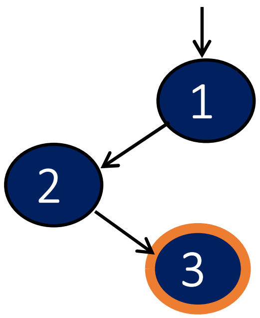
Edge Coverage review

- How many test requirements does **Edge Coverage** impose on the tests for this graph:



[1,3,4]

Examples on Node and Edge Coverage

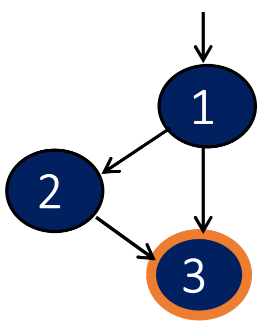


TRs for Node Coverage: 1, 2, 3

Test Paths for Node Coverage: [1, 2, 3]

TRs for Edge Coverage: [1, 2], [2, 3]

Test Paths for Edge Coverage: [1, 2, 3]



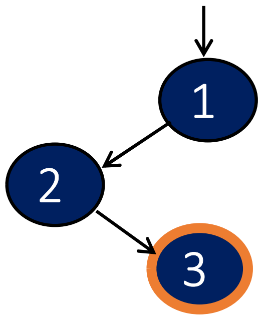
TRs for Node Coverage: 1, 2, 3

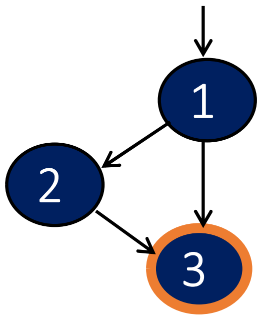
Test Paths for Node Coverage: [1, 2, 3]

TRs for Edge Coverage: [1, 2] [2, 3], [1, 3]

Test Paths for Edge Coverage:

When do Node Coverage and Edge Coverage differ?





Node Coverage and Edge Coverage are only different when there is more than one path between a pair of nodes (as in an “if-else” statement)

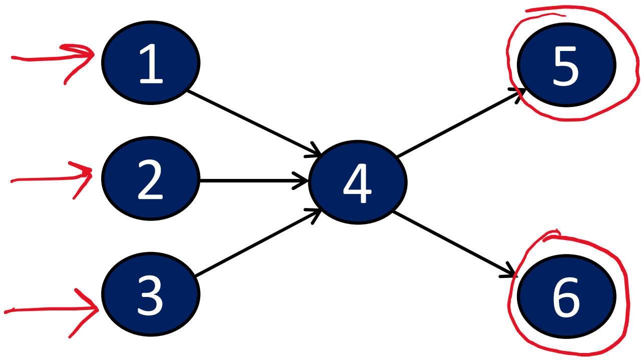
What if we want tests to cover multiple edges?

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

- Why do we need the phrase, "length up to 2"?

- "length up to 2" captures graphs that have less than 2 edges

Example on Edge-Pair Coverage



<u>Edge-Pair Coverage</u> : ?

TR = { …}

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

What if we want tests to cover more than two edges?

Should we play the same game as in ISP?

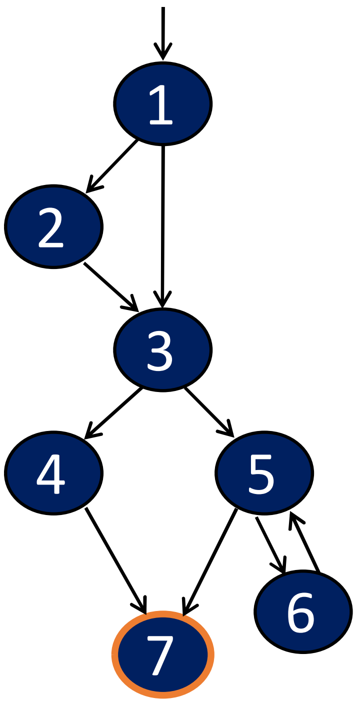
- **Pair-Wise Coverage (PWC) Criterion** : A value from each block for each characteristic must be combined with a value from every block for all other characteristics.

- **t-Wise Coverage (TWC) Criterion** : A value from each block for each group of t characteristics must be combined

Covering all edges

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

In-class exercise…



Node Coverage

TR =

Test Paths:

Edge Coverage

TR =

Test Paths:

Edge-Pair Coverage

TR =

Test Paths:

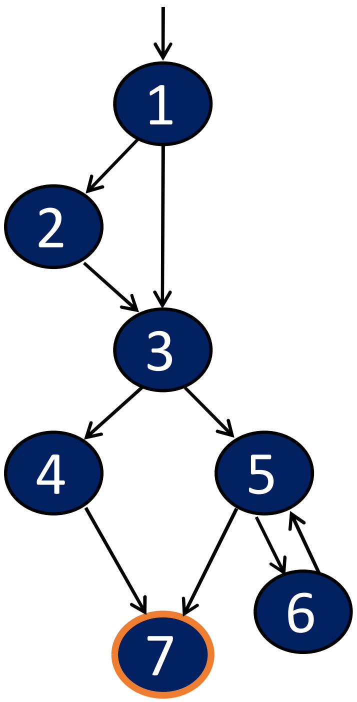
Complete Path Coverage

TR:

Test Paths:

Write down the TRs and Test Paths for these criteria

In-class exercise solution



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) }

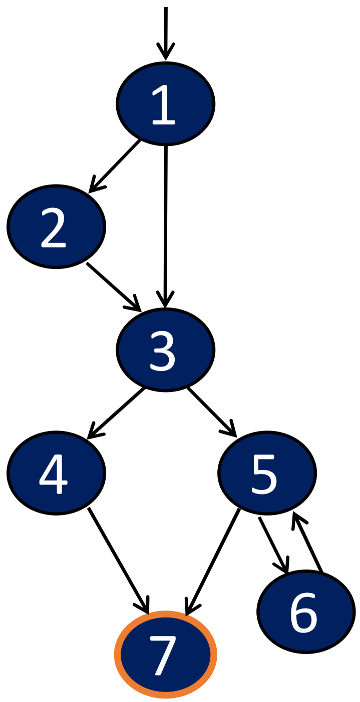
Test Paths: [1, 2, 3, 4, 7] [1, 3, 5, 6, 5, 7]

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]

In-class exercise solution (2)



Complete Path Coverage

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

Unfortunately, CPC is **impossible** to satisfy if G has a loop

What we covered so far

- Basic definition of Graphs
- Terminology that we will use to talk about Graph Coverage
- Your first few Graph Coverage Criteria
- Complete Path Coverage is infeasible!

Next

- How to handle loops in Graph Coverage