

Introduction to Software Testing (2nd edition) Chapter 7.1, 7.2

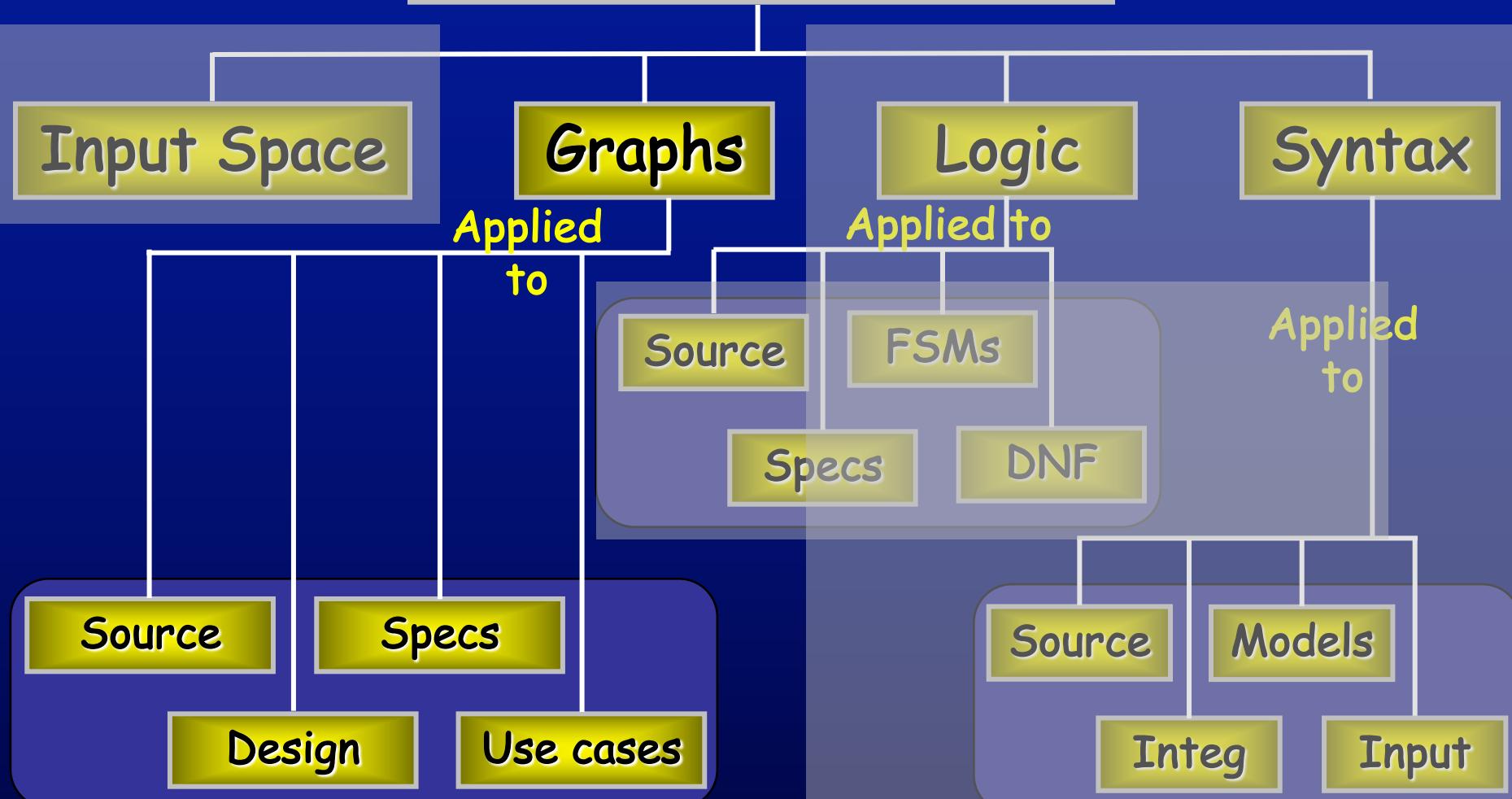
Overview Graph Coverage Criteria

Paul Ammann & Jeff Offutt

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

Ch. 7 : Graph Coverage

Four Structures for Modeling Software



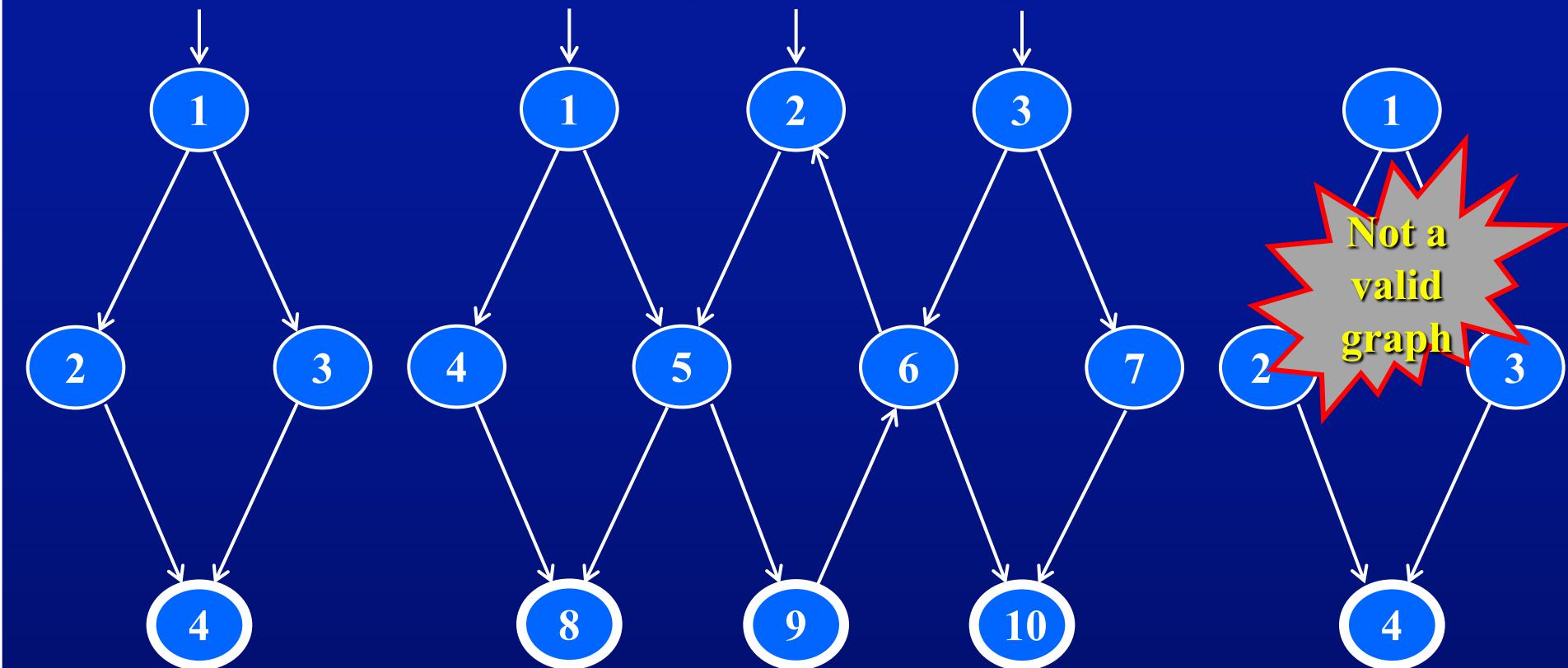
Covering Graphs (7.1)

- 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**

Example 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)

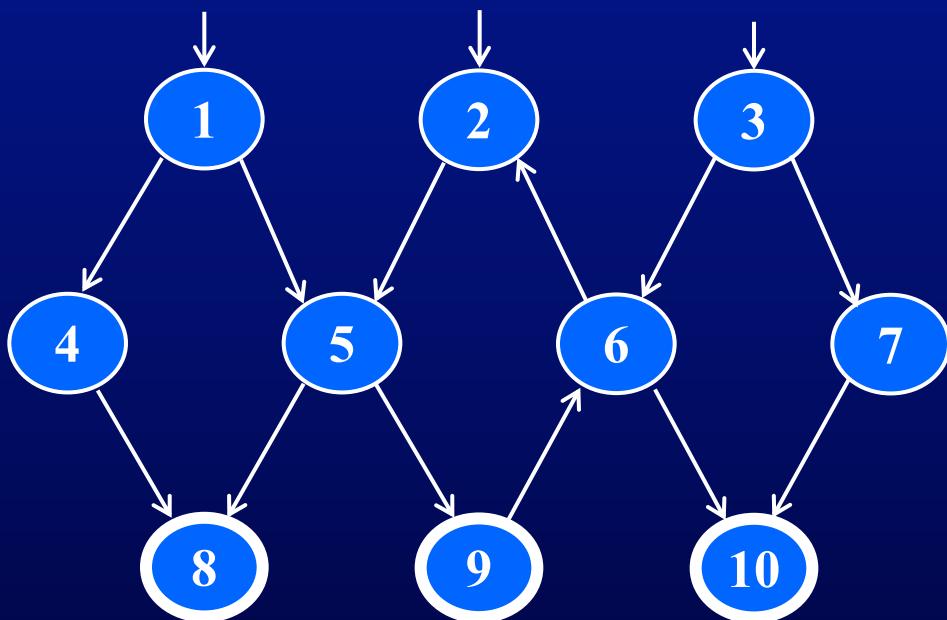
$$N_0 = \{ \ }$$

$$N_f = \{ 4 \}$$

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

Paths in Graphs

- **Path** : A sequence of nodes – $[n_1, n_2, \dots, n_M]$
 - 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



A Few Paths

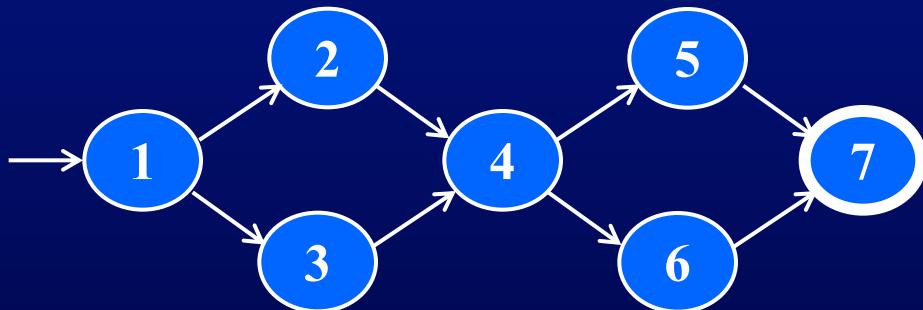
[1, 4, 8]

[2, 5, 9, 6, 2]

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

(Also, each edge is technically a subpath)

Tests and Test Paths

- $\text{path}(t)$: The test path executed by test t
- $\text{path}(T)$: The set of test paths executed by the set of tests T
- Each test executes one and only one test path
 - Complete execution from a start node to an final node
- 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
 - This distinction will become important in section 7.3

Tests and Test Paths

test 1

many-to-one

test 2

test 3

Test Path

Deterministic software-test always executes the same test path

test 1

many-to-many

test 2

test 3

Test Path 1

Test Path 2

Test Path 3

Non-deterministic software—the same test can execute different test paths

Testing and Covering Graphs (7.2)

- We use graphs in testing as follows :
 - Develop a model of the software as a graph
 - Require 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 $\text{path}(T)$ such that p visits n .

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

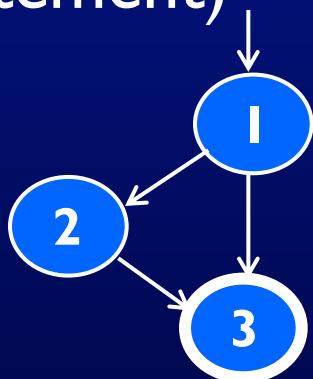
Node Coverage (NC) : TR contains each reachable node in G.

Node and Edge Coverage

- Edge coverage is slightly stronger than node coverage

Edge Coverage (EC) : TR contains each reachable path of length up to l , inclusive, in G .

- The phrase “length up to l ” 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)



Node Coverage : $TR = \{ 1, 2, 3 \}$
Test Path = [1, 2, 3]

Edge Coverage : $TR = \{ (1, 2), (1, 3), (2, 3) \}$
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 ...

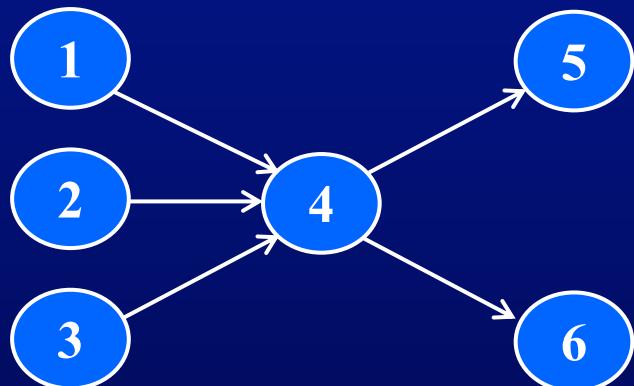


Covering Multiple Edges

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

Edge-Pair Coverage (EPC) : 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



Edge-Pair Coverage :

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

- The logical extension is to require all paths ...

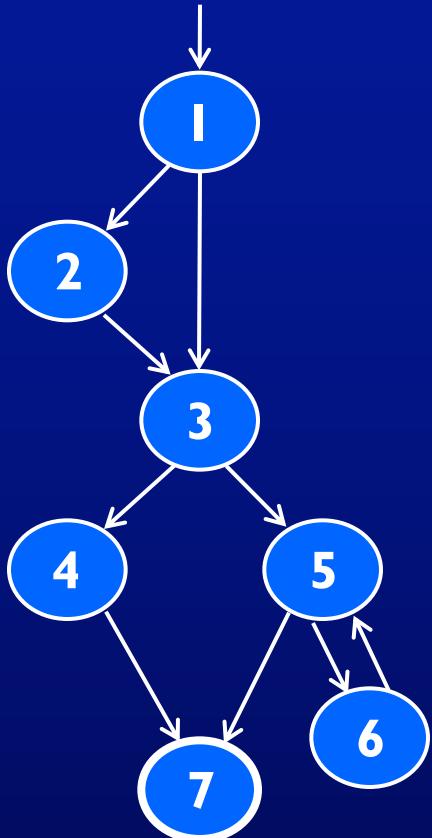
Covering Multiple Edges

Complete Path Coverage (CPC) : TR contains all paths in G.

Unfortunately, this is **impossible** if the graph has a loop, so a weak compromise makes the tester decide which paths:

Specified Path Coverage (SPC) : 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

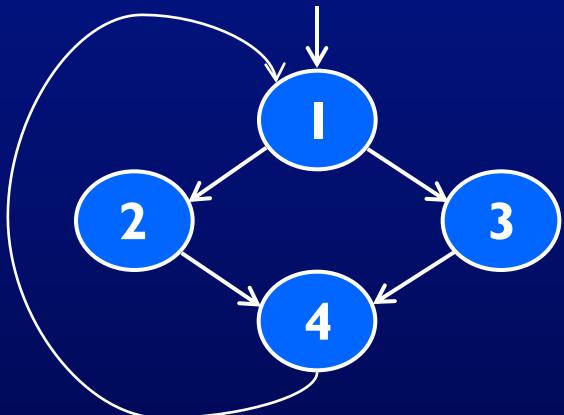
Test Paths: [1, 2, 3, 4, 7] [1, 2, 3, 5, 7] [1, 2, 3, 5, 6, 5, 6] [1, 2, 3, 5, 6, 5, 6, 5, 7] [1, 2, 3, 5, 6, 5, 6, 5, 7] ...

Handling 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 (touring, sidetrips, and detours)

Simple Paths and Prime Paths

- **Simple Path** : A path from node n_i to n_j 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

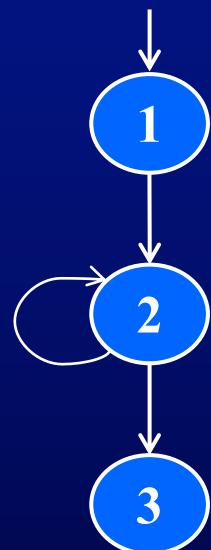
- A simple, elegant and finite criterion that requires loops to be executed as well as skipped

Prime Path Coverage (PPC) : TR contains each prime path in G.

- Will tour all paths of length 0, 1, ...
- That is, it **subsumes** node and edge coverage
- PPC almost, but **not quite**, subsumes EPC ...

PPC Does Not Subsume EPC

- If a node n has an edge to itself (self edge), EPC requires $[n, n, m]$ and $[m, n, n]$
- $[n, n, m]$ is not prime
- Neither $[n, n, m]$ nor $[m, n, n]$ are simple paths (not prime)

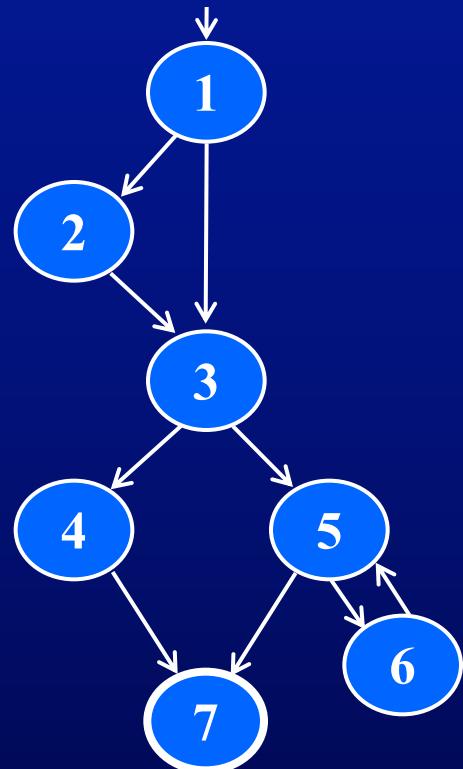


EPC Requirements :
 $TR = \{ [1,2,3], [1,2,2], [2,2,3], [2,2,2] \}$

PPC Requirements :
 $TR = \{ [1,2,3], [2,2] \}$

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

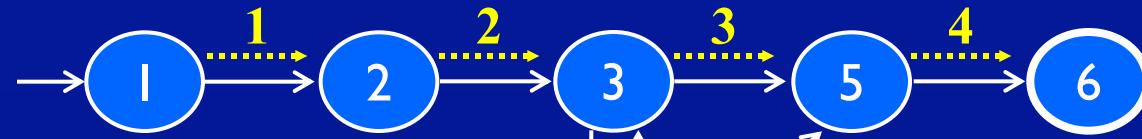
Execute
loop once

Execute loop
more than once

Touring, Sidetrips, and Detours

- Prime paths do not have **internal loops** ... test paths might
- **Tour** : A test path ρ tours subpath q if q is a subpath of ρ
- **Tour With Sidetrips** : A test path ρ tours subpath q with sidetrips iff every edge in q is also in ρ in the same order
 - The tour can include a sidetrip, as long as it comes back to the same node
- **Tour With Detours** : A test path ρ tours subpath q with detours iff every node in q is also in ρ in the same order
 - The tour can include a detour from node ni , as long as it comes back to the prime path at a successor of ni

Sidetrips and Detours Example



Touring the prime path
[1, 2, 3, 5, 6] without
sidetrips or detours



Touring with a
sidetrip



Touring with a
detour

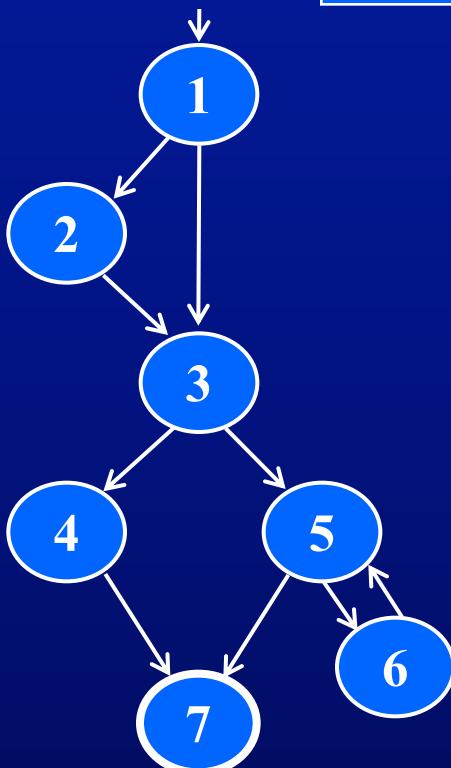
Infeasible Test Requirements

- An **infeasible** test requirement cannot be satisfied
 - Unreachable statement (dead code)
 - Subpath that can only be executed with a contradiction ($X > 0$ and $X < 0$)
- Most test **criteria** have some infeasible test requirements
- It is usually **undecidable** whether all test requirements are feasible
- When sidetrips are not allowed, many structural criteria have **more infeasible test requirements**
- However, always allowing **sidetrips** weakens the test criteria

Practical recommendation—Best Effort Touring

- Satisfy as many test requirements as possible without sidetrips
- Allow sidetrips to try to satisfy remaining test requirements

Simple & Prime Path Example



Simple paths

Len 0

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

Len 1

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

“!” means path
es

Len 2

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

Len 3

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

is path
es

Len 4

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

Prime Paths

Round Trips

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

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

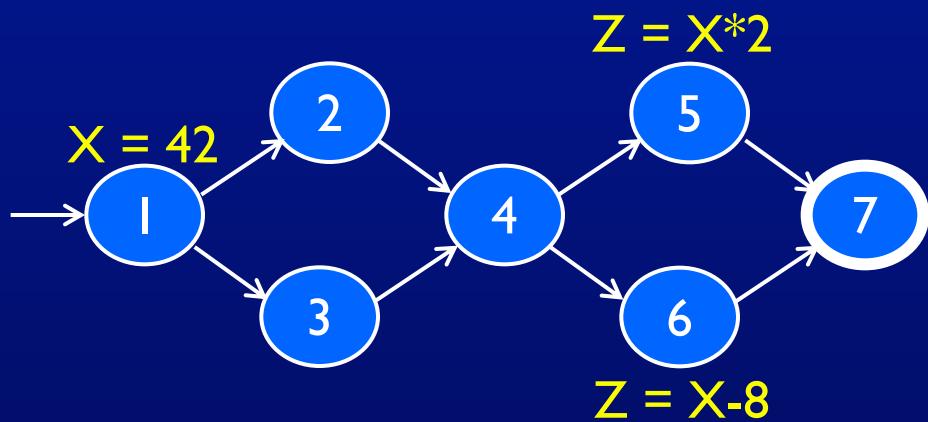
Complete Round Trip Coverage (CRTC) : TR contains all round-trip paths for each reachable node in G.

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

Data Flow Criteria

Goal: 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



Defs: def (1) = {X}

def (5) = {Z}

def (6) = {Z}

Uses: 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

Touring DU-Paths

- A test path p *du-tours* subpath d with respect to v if p tours d and the subpath taken is def-clear with respect to v
- **Sidetrips** can be used, just as with previous touring
- Three criteria
 - Use every def
 - Get to every use
 - Follow all du-paths

Data Flow Test Criteria

- First, we make sure **every def reaches a use**

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

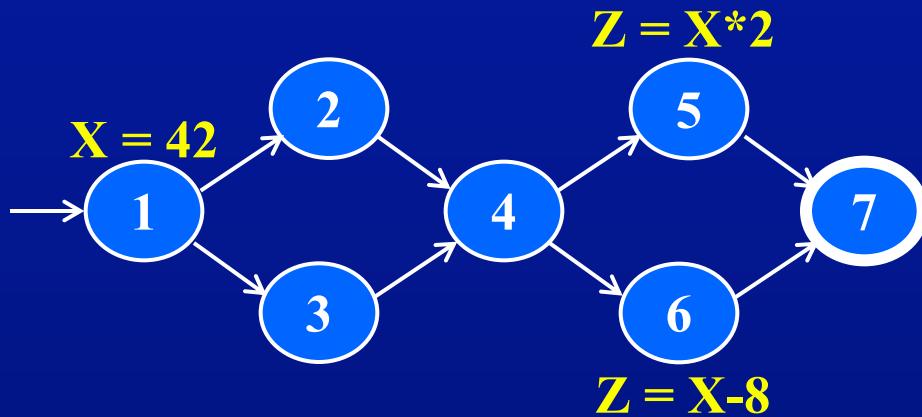
- Then we make sure that **every def reaches all possible uses**

All-uses coverage (AUC) : 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**

All-du-paths coverage (ADUPC) : For each set $S = du(n_i, n_j, v)$, 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

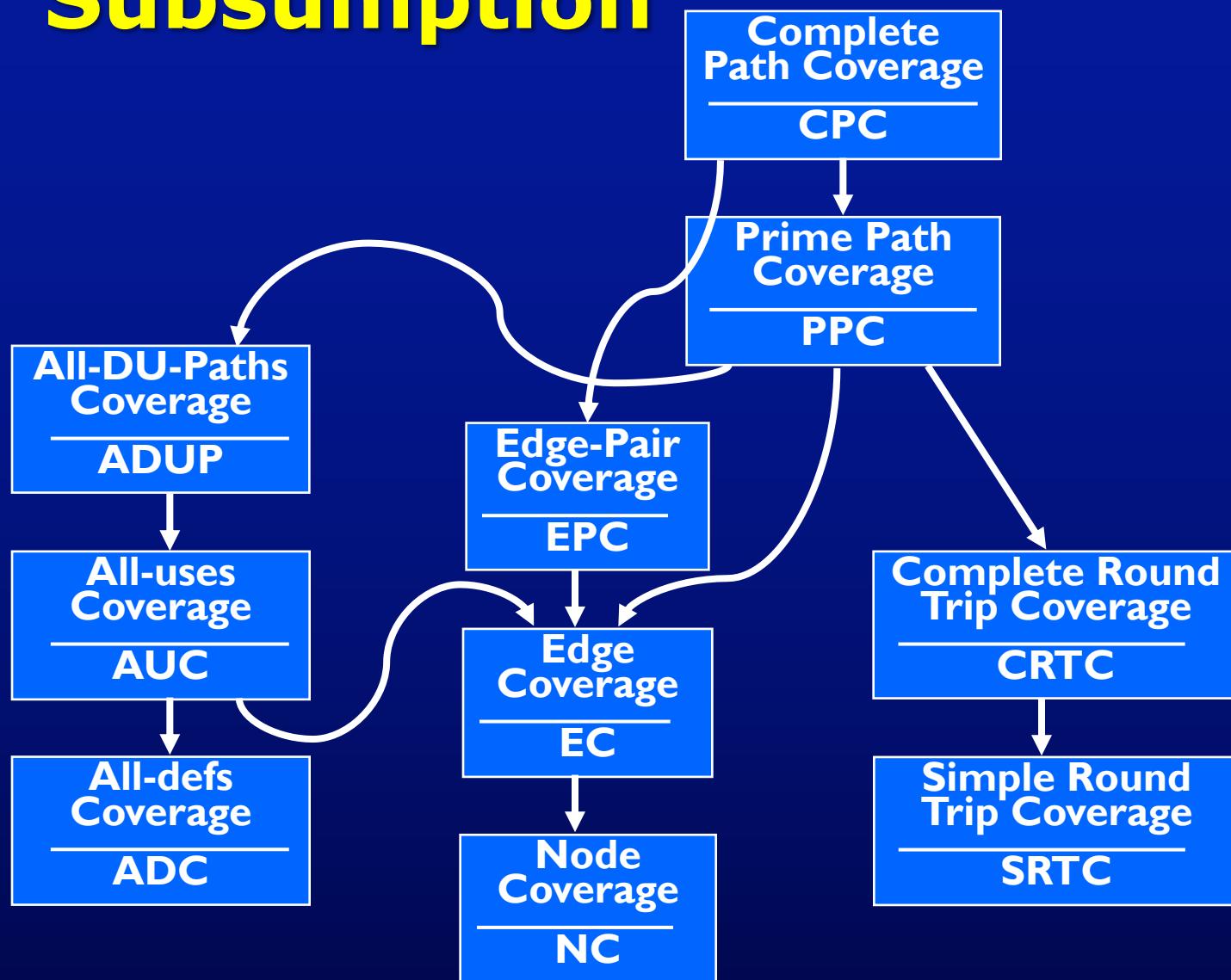
[1, 2, 4, 5]

[1, 3, 4, 5]

[1, 2, 4, 6]

[1, 3, 4, 6]

Graph Coverage Criteria Subsumption



Summary 7.1-7.2

- Graphs are a very powerful abstraction for designing tests
- The various criteria allow lots of cost / benefit tradeoffs
- These two sections are entirely at the “design abstraction level” from chapter 2
- Graphs appear in many situations in software
 - As discussed in the rest of chapter 7