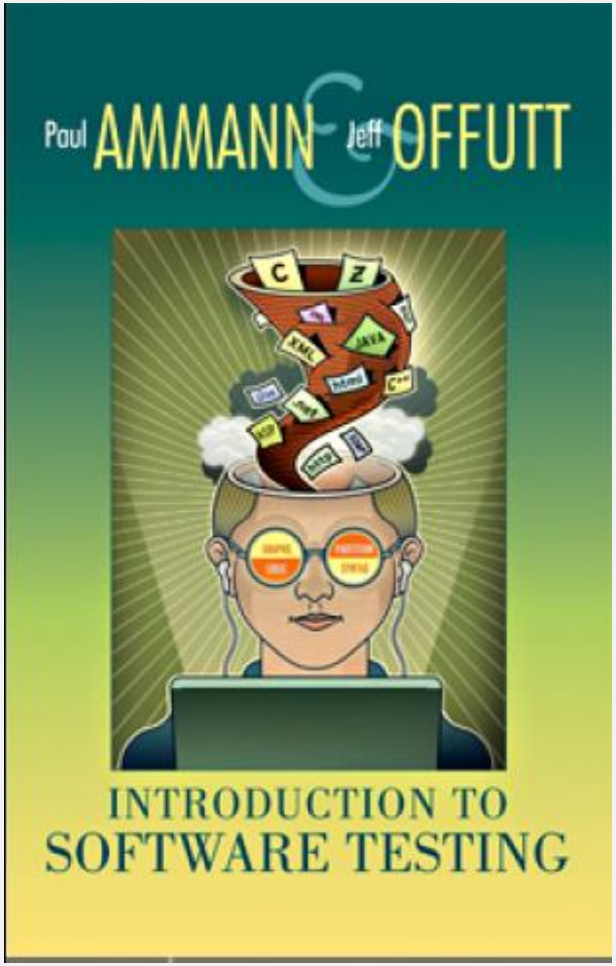
Software Testing



Lecture 20

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

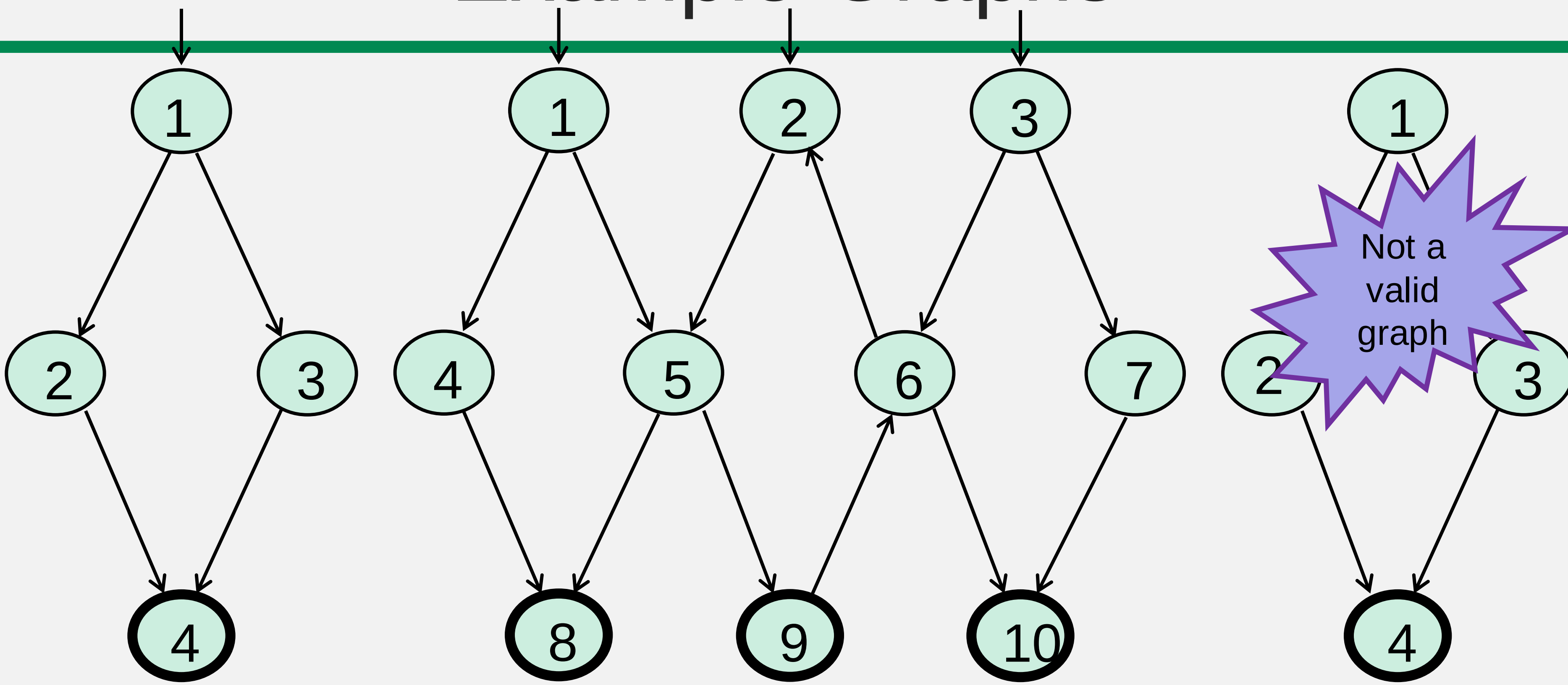
A set N_0 of initial nodes, N_0 is not empty

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

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

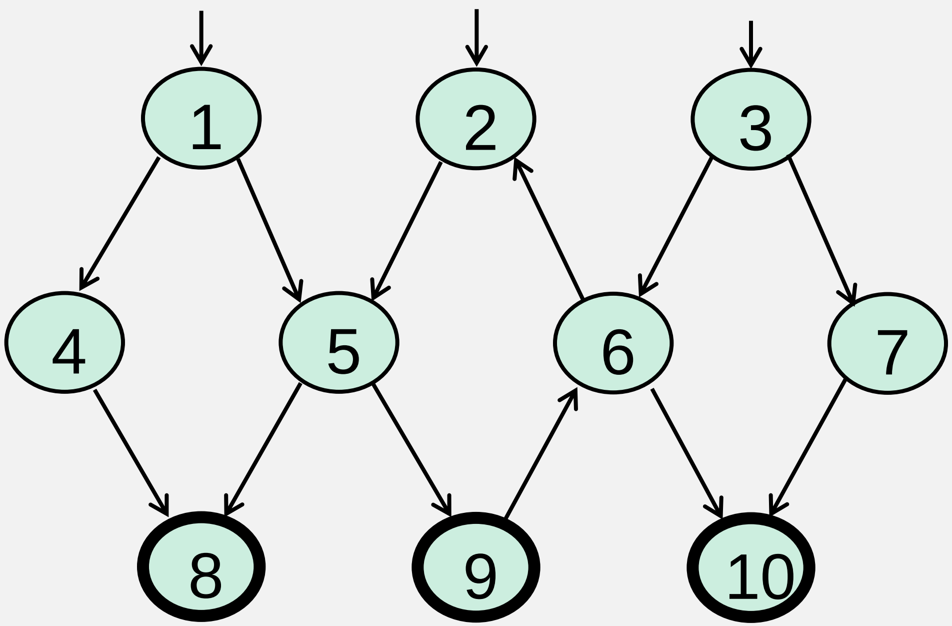
Path : A sequence of nodes – [n_1, n_2, …, n_M]

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

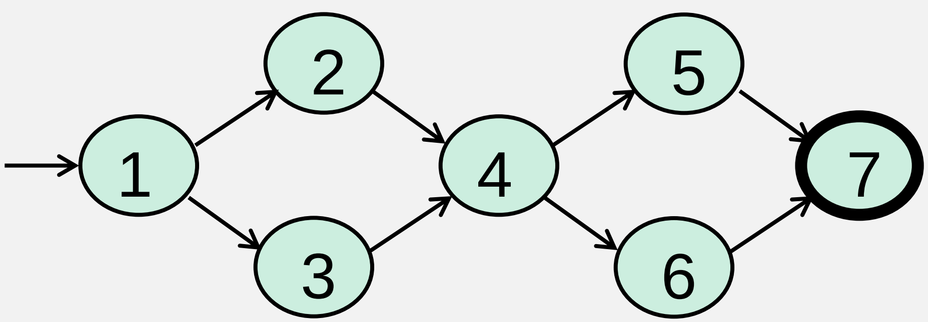
Test Path : A path that starts at an initial node and ends at a final node

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
- N_0 and N_f 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

path (*t*) : The test path executed by test *t*

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

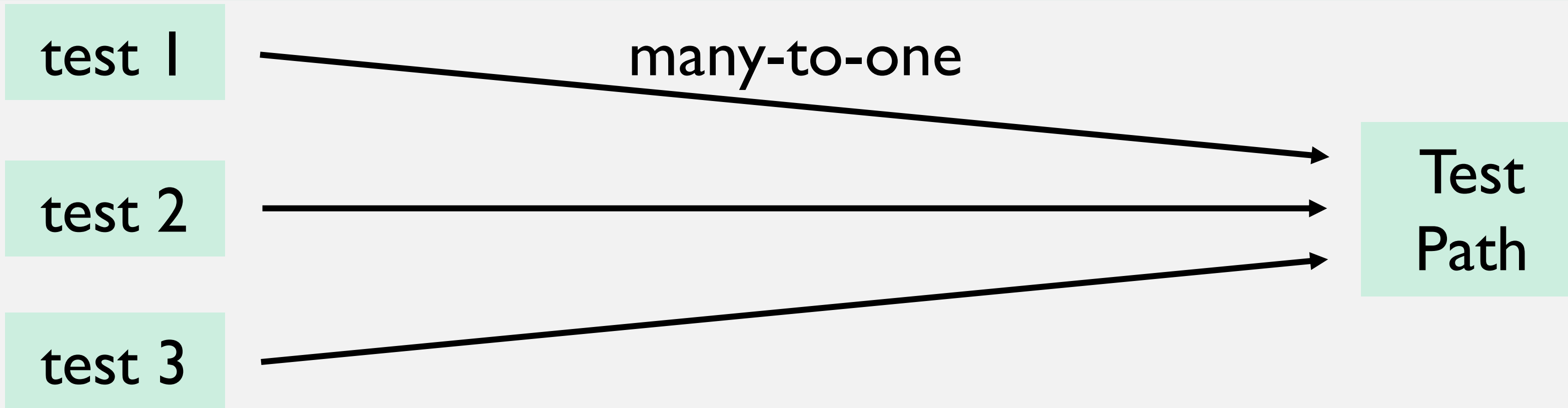
Each test executes one and only one test path

- Complete execution from a start node to an final node

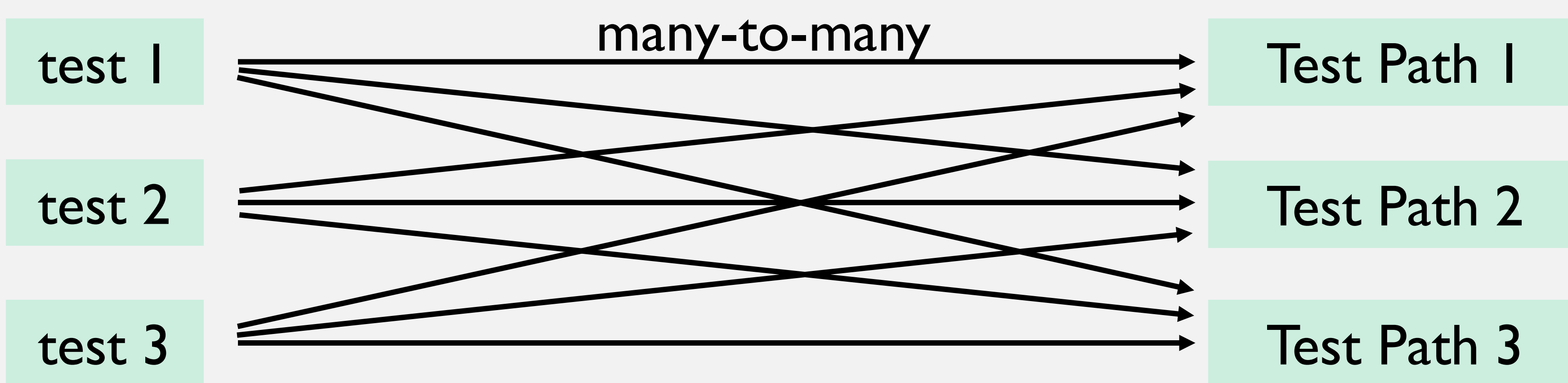
A location in a graph (node or edge) can be **reached** from another location if there is a sequence of edges from the first location to the second

- *Syntactic reach* : A subpath exists in the graph
- *Semantic reach* : A test exists that can execute that subpath

Tests and Test Paths



Deterministic software–test always executes the same test path



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

Testing and Covering Graphs

We use graphs in testing as follows :

1. Develop a model of the software as a graph
2. 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 *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

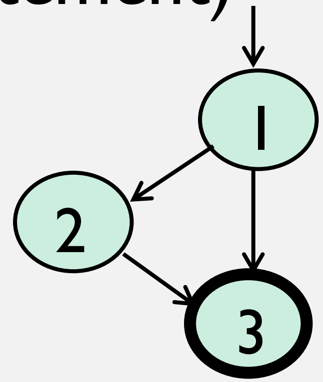
Node Coverage (NC) : TR contains each reachable node in G.

Node and Edge Coverage

Edge coverage is slightly stronger than node coverage

> Edge Coverage (EC) : TR contains each reachable path of length up to 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)



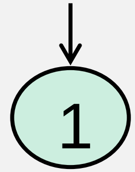
Node Coverage : TR = { 1, 2, 3 }
Test Path = [1, 2, 3]

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

12

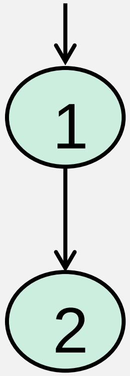
Paths of Length 1 and 0

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 …

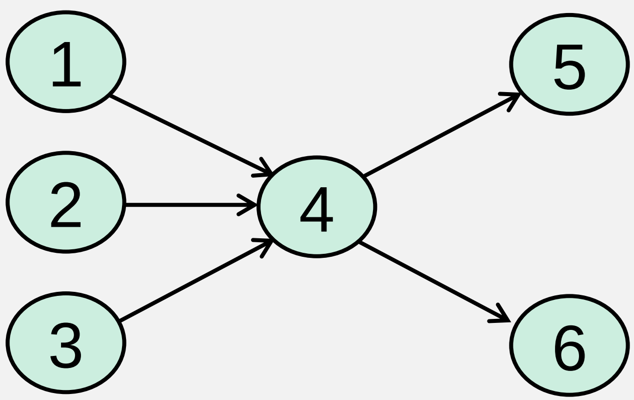


Covering Multiple Edges

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 …

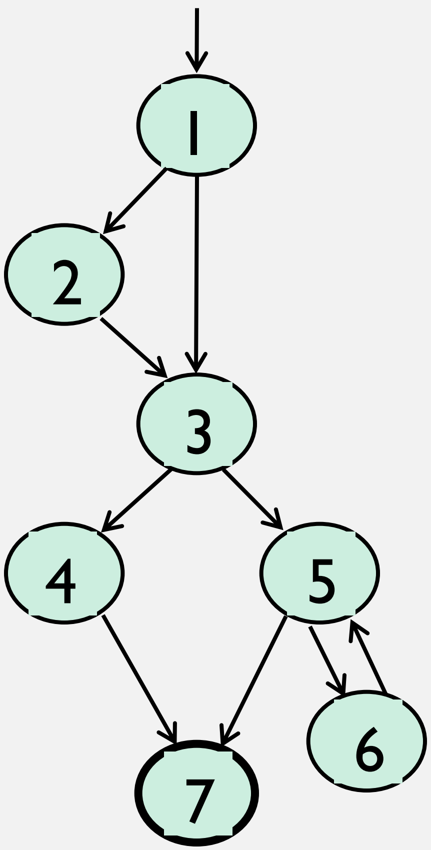
Covering Multiple Edges

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, 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:

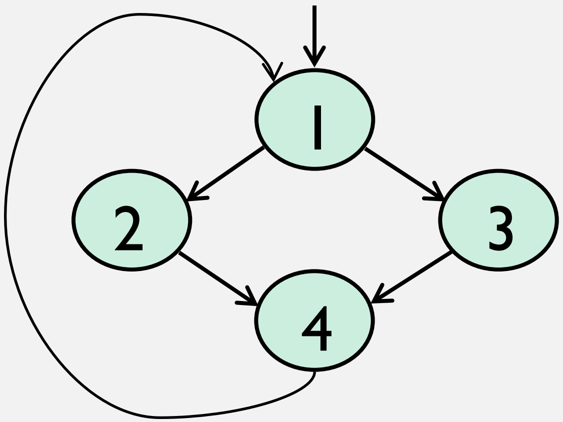
- 1970s : Execute cycles once ([4, 5, 4] in previous example, informal)
- 1980s : Execute each loop, exactly once (formalized)
- 1990s : Execute loops 0 times, once, more than once (informal description)
- 2000s : Prime paths (touring, sidetrips, and detours)

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

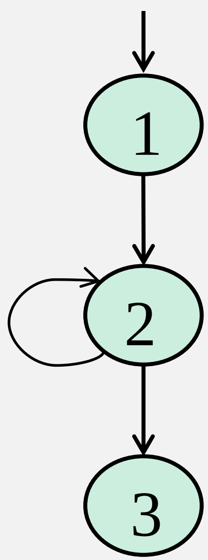
A simple, elegant and finite criterion that requires loops to be executed as well as skipped

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] }

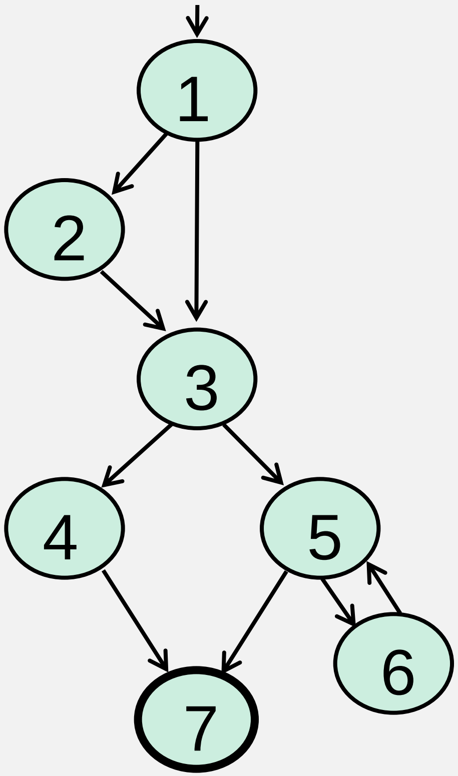
PPC Requirements :

TR = { [1,2,3], [2,2] }

Prime Path Example

The previous example has 38 simple paths

Only nine *prime paths*



<u>Prime Paths</u>

[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

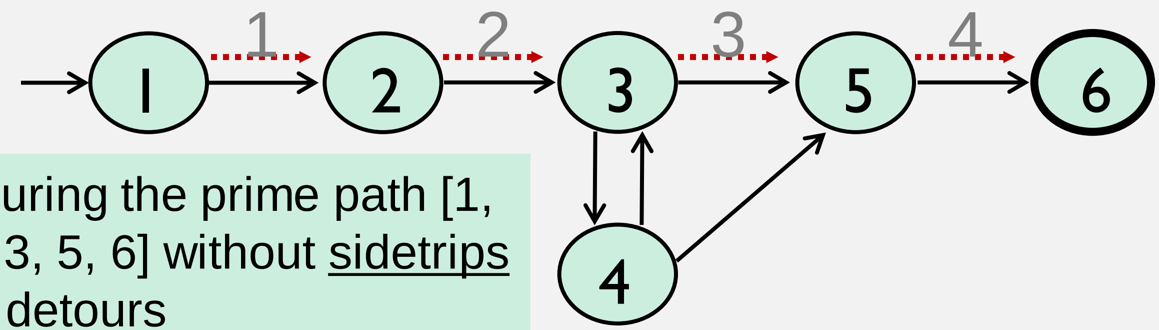
Execute loop more than once

Touring, Sidetrips, and Detours

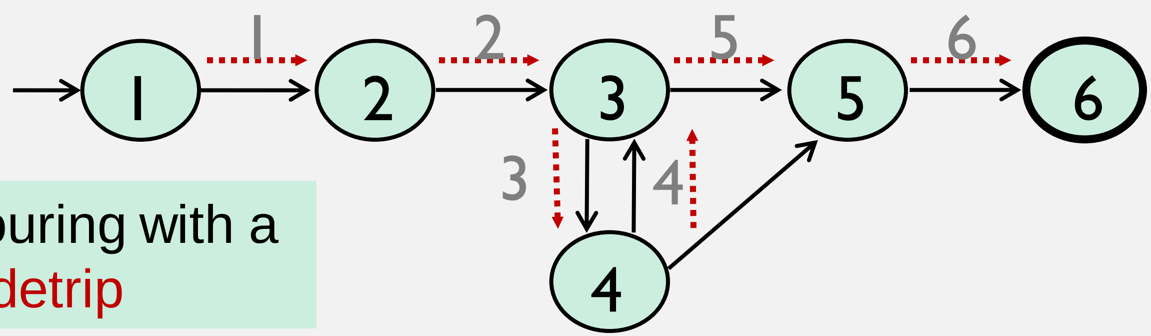
Prime paths do not have internal loops … test paths might

- Tour : *A test path p tours subpath q if q is a subpath of p*
- Tour With Sidetrips : *A test path p tours subpath q with sidetrips iff every edge in q is also in p 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 p tours subpath q with detours iff every node in q is also in p in the same order*
  - The tour can include a detour from node n_i, as long as it comes back to the prime path at a successor of n_i

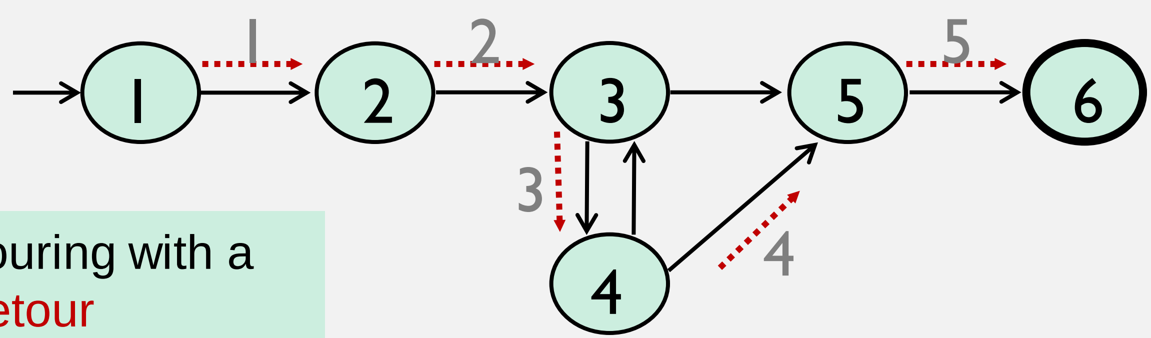
Sidetrips and Detours Example



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



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 $X < 0$)

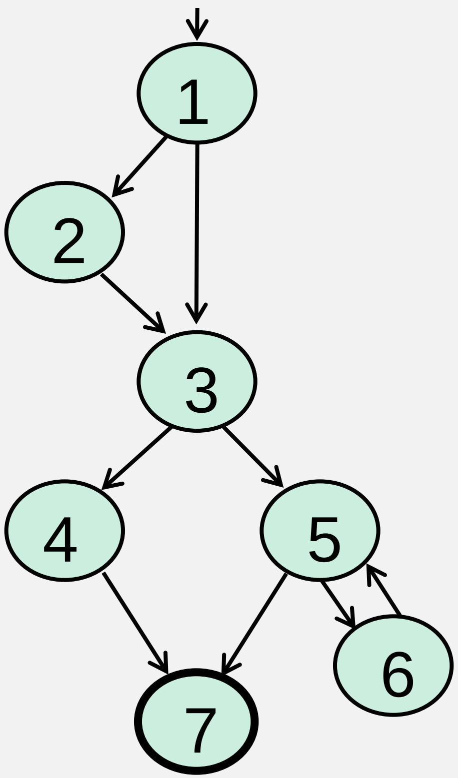
- Most test criteria have some infeasible test requirements
- It is usually undecidable whether all test requirements are feasible
- When sidetrips are not allowed, many structural criteria have more infeasible test requirements
- However, always allowing sidetrips weakens the test criteria

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] !
[5, 6, 5] *
[6, 5, 7] !
[6, 5, 6] *

s path
es

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] !

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.

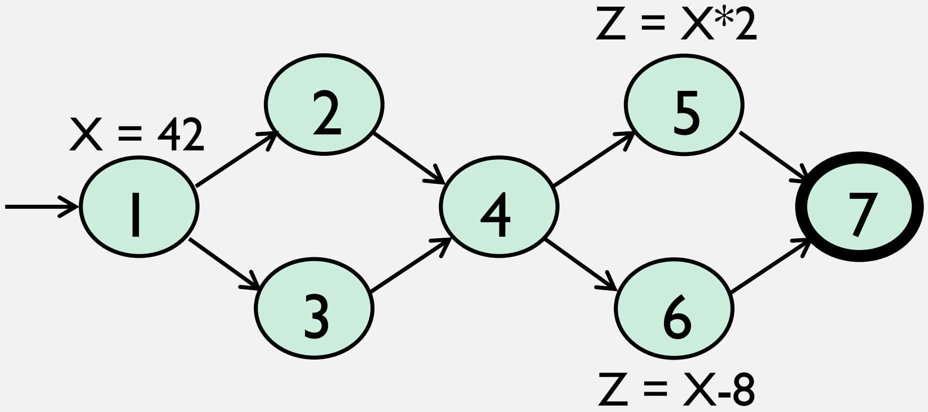
- These criteria omit nodes and edges that are not in round trips
- Thus, they do not subsume edge-pair, edge, or node coverage

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

1. Use every def
2. Get to every use
3. 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.

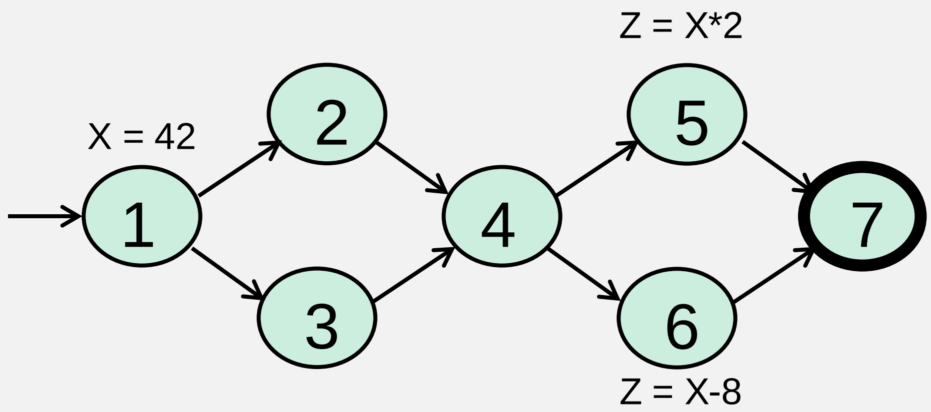
- Then we make sure that every def reaches all possible uses

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 $S = du(ni, nj, v)$, TR contains every path d in S.

Data Flow Testing Example

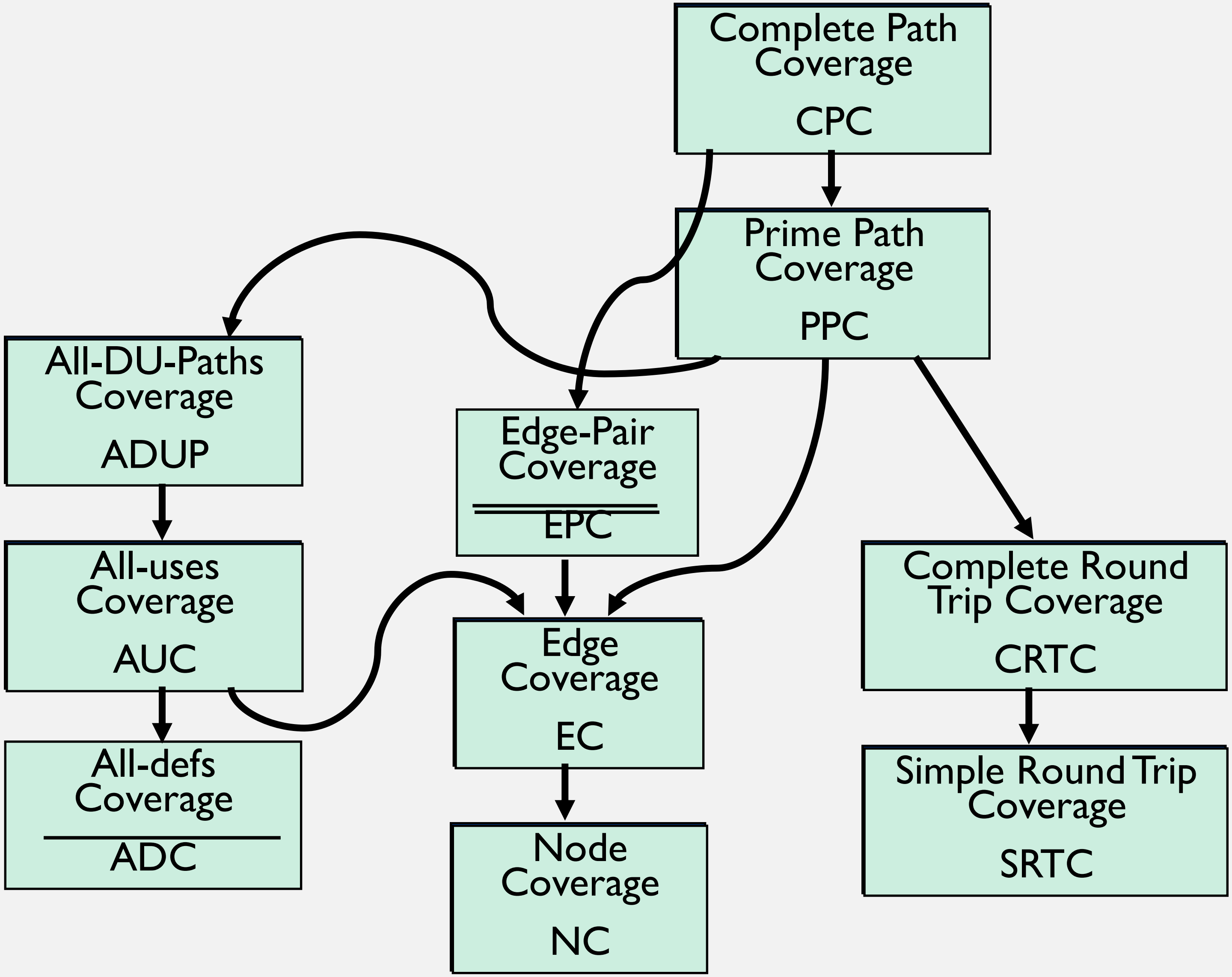


All-defs for *X*
[1, 2, 4, 5]

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 Criteria Subsumption



Summary

- Graphs are a very powerful abstraction for designing tests
- The various criteria allow lots of cost / benefit tradeoffs

Thank You