Intro to Software Testing
chapter 7

Graph Coverage

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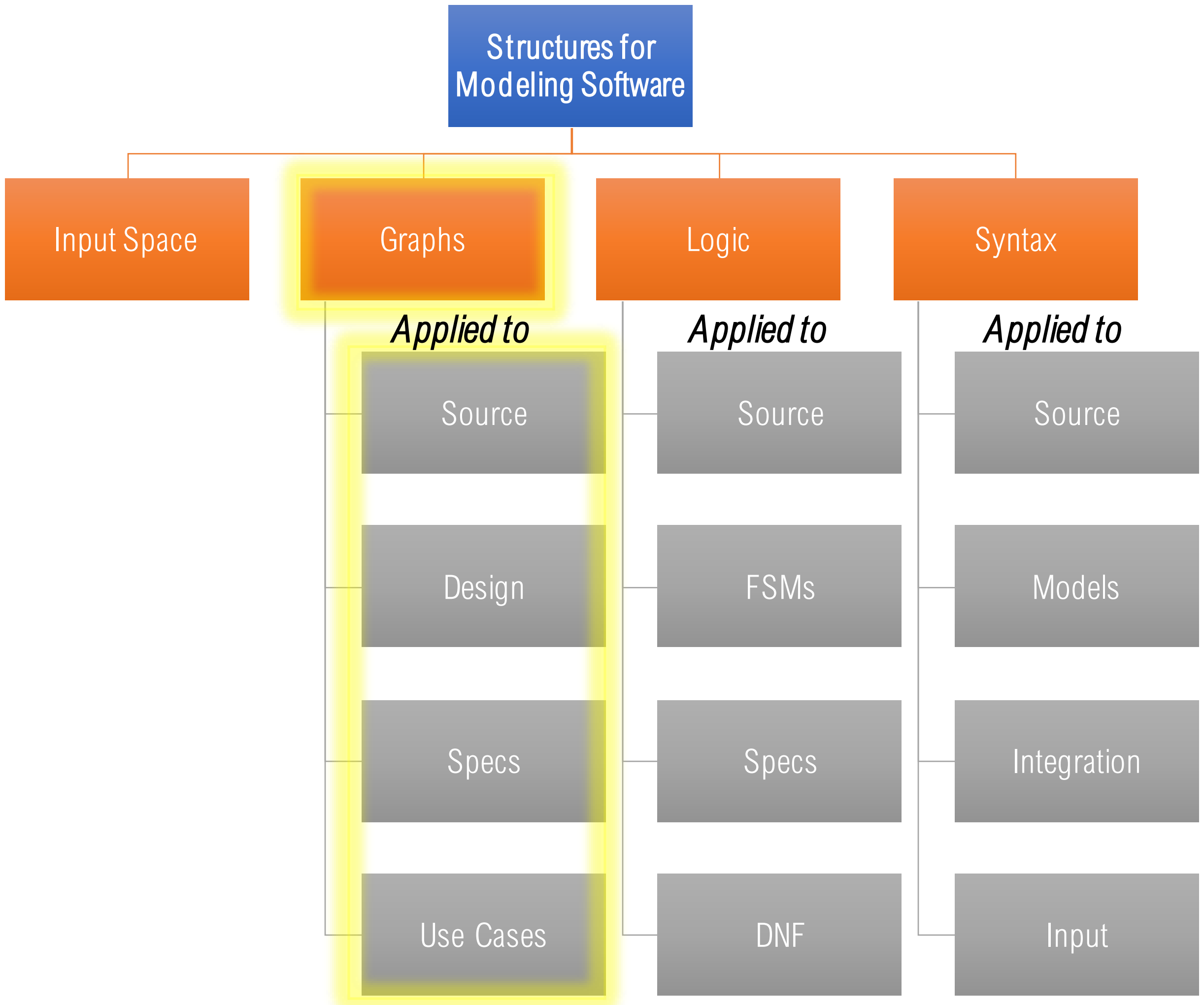
(Dr. B for short)

https://go.gmu.edu/SWE637

Adapted from slides by Jeff Offutt and Bob Kurtz

Graph Coverage



Covering Graphs

Graphs are the most commonly used structure for testing

Graphs can come from many sources

- Control flow graphs
- Design structure
- Finite state machines and state charts
- Use cases

Implementation knowledge is usually needed ("white box")

Definition of a graph

A set $\boldsymbol{N}$ of *nodes*, where $\boldsymbol{N} \neq \emptyset$

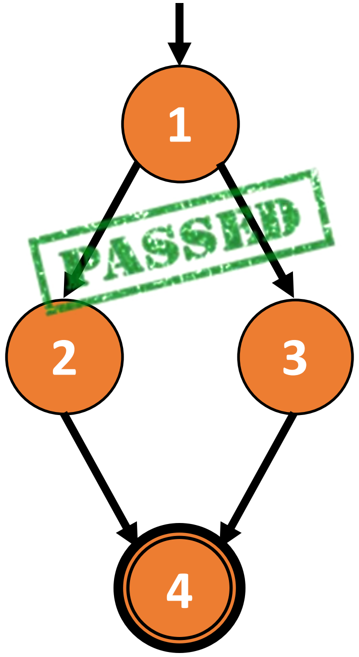
A set $\boldsymbol{N_0}$ of *initial nodes*, where $\boldsymbol{N_0} \subseteq \boldsymbol{N}$

A set $\boldsymbol{N_f}$ of *final nodes*, where $\boldsymbol{N_f} \subseteq \boldsymbol{N}$

A set $\boldsymbol{E}$ of *edges*, where each edge connects one node to another

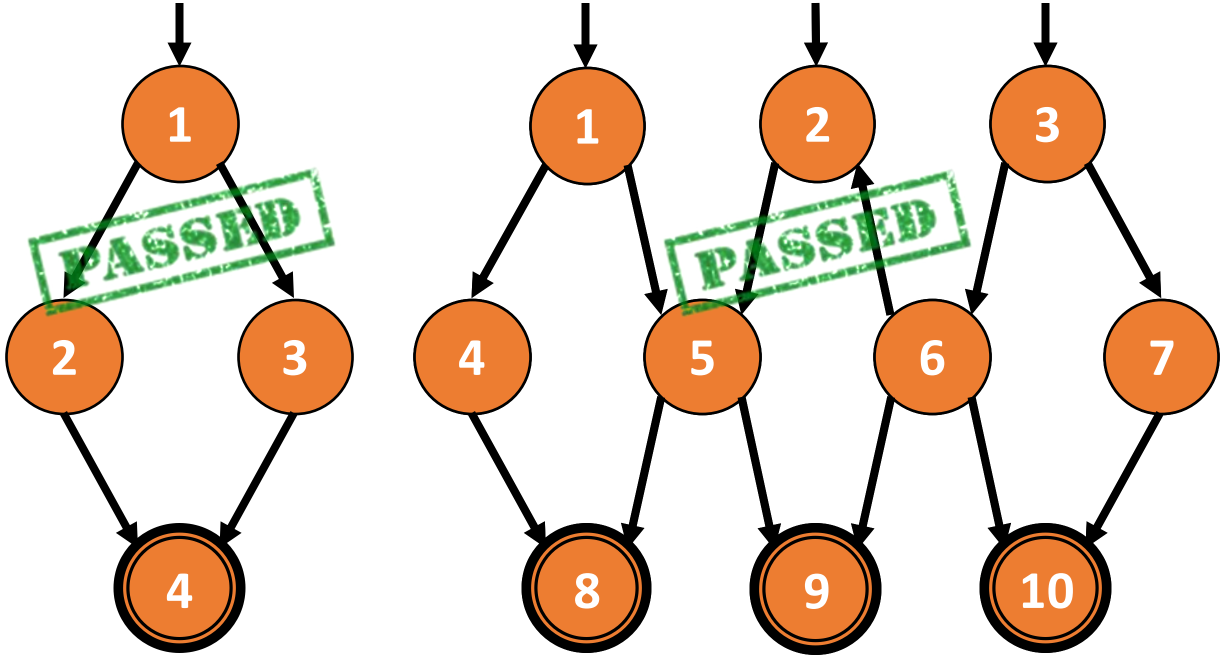
Denoted (n_i, n_j) where i is the *predecessor* node and j is the *successor* node

Example Graphs



$N_0 = \{ 1 \}$
$N_f = \{ 4 \}$
$E = \{ (1,2), (1,3), (2,4), (3,4) \}$

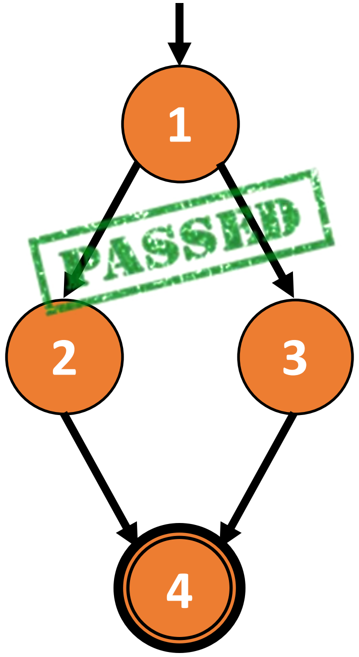
Example Graphs



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), (6,9), (6,10), (7,10) }

Example Graphs



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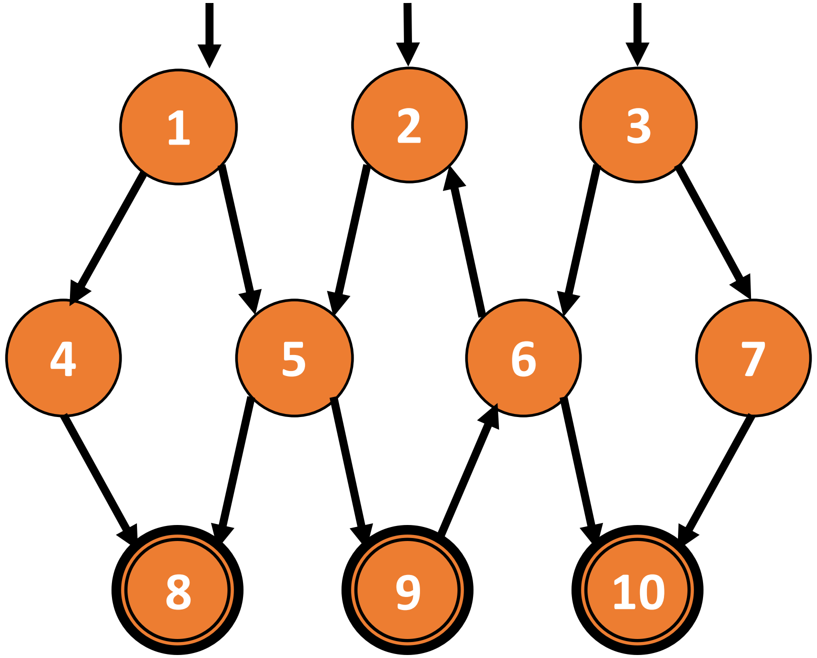
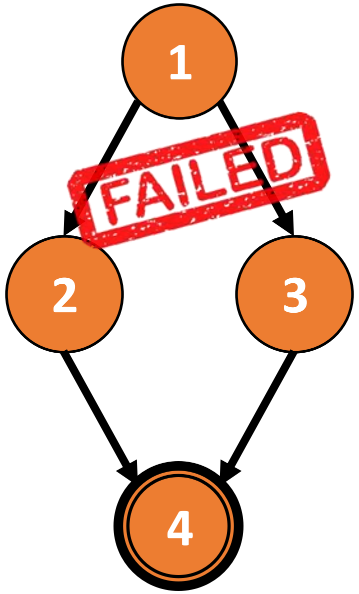


$N_0 = \{ 1, 2, 3 \}$
$N_f = \{ 8, 9, 10 \}$
$E = \{ (1,4), (1,5), (2,5), (3,6), (3,7), (4,8), (5,8), (5,9), (6,2), (6,9), (6,10), (7,10) \}$



$N_0 = \{ \}$
$N_f = \{ 4 \}$
$E = \{ (1,2), (1,3), (2,4), (3,4) \}$

Example Graphs

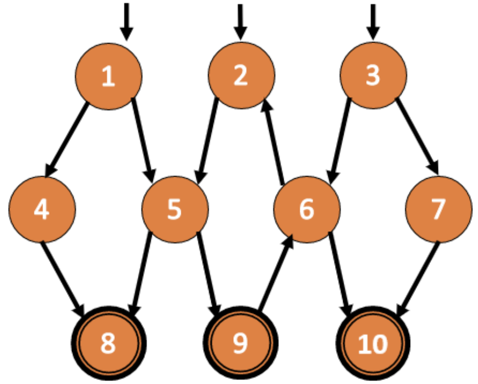
Path: a sequence of nodes [n1, n2, … nM]

Recall that 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]

[5, 9, 6, 10]

Test paths and SESE Graphs

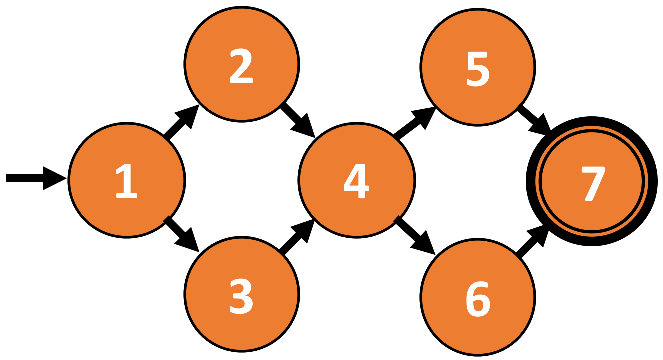
Test Path: a path that starts at an *initial node* and ends at a *final node*

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

Single-Entry Single-Exit (SESE) Graphs: all test paths start at one node and end at one node

- N_0 and N_f each 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***

Given test path ***p*** = [1, 2, 4, 5, 7]

p visits nodes 1, 2, 4, 5, 7

p visits edges (1,2), (2,4), (4,5), (5,7)

p tours subpaths [1, 2], [2, 4], [4, 5], [5, 7],
[1, 2, 4], [2, 4, 5], [4, 5, 7], [1, 2, 4, 5], [2, 4, 5, 7],
[1, 2, 4, 5, 7]

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 *exactly one* test path

It is the complete execution from some initial node to some final node

Reaching Graph Locations

A location (node or edge) in a graph 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 from the first location to the second

This is based only on the graph structure

Semantic reach: a *test* exists that can execute that subpath

This considers the actual implementation logic

Covering Graphs

We use graphs in testing to:

- Develop a model of the software (as a graph)
- Require tests to visit or tour nodes, edges, or subpaths

Test requirements (TRs) describe the properties of test paths

Test criteria are rules that define the test requirements

DEFINITION

Satisfaction – given a set of test requirements ***TR*** for a criterion ***C***, a set of tests ***T*** satisfies ***C*** on a graph if and only if for each test requirement ***tr*** in ***TR***, there is a test path in ***path(T)*** that meets the test requirement ***tr***.

Structural Coverage Criteria

Structural coverage criteria are defined on a graph only in terms of nodes and edges

- The goal of structural coverage is to ensure that control flow executes successfully

Node Coverage

The first (and simplest) structural coverage criteria requires that each node in a graph be executed

DEFINITION

Node Coverage (NC) – 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***.

Or, in terms of test requirements

DEFINITION

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

Is node coverage the same as "statement coverage"?

Edge Coverage

Edge coverage is slightly stronger than NC

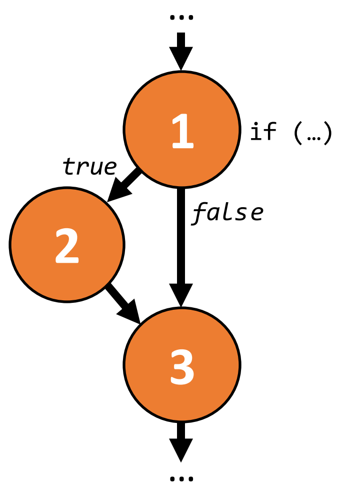
DEFINITION

Edge Coverage (EC) – *TR* contains each reachable path of length up to 1, inclusive, in *G*.

"length up to 1" allows for graphs with one node and no edges

EC TRs differ from NC TRs only when there is a path with length>1 and a path with length=1 between two nodes

Example: if-then statement

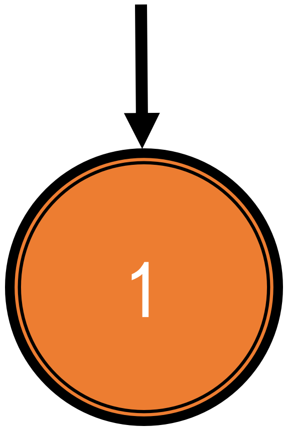


Is edge coverage the same as "branch coverage"?

Path length "up to 1"?

A path with only one node has no edges

- It may seem trivial, but formally edge coverage must require node coverage on this graph, otherwise EC will not subsume NC
- We will see the same issue later for edge-pair coverage when a graph has only one edge



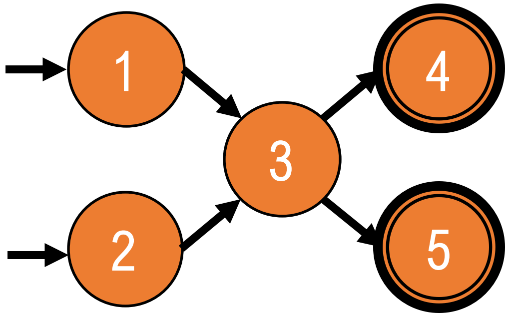
Covering Multiple Edges

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

DEFINITION

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

“length up to 2” allows for graphs with two nodes and one edge



Edge-Pair Coverage:

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

Covering Multiple Edges

This suggests an obvious extension to…

DEFINITION

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

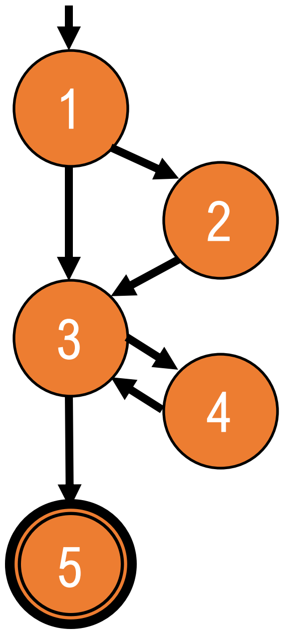
But this is impossible if the graph has a loop

A weak compromise is to let the tester decide which paths to test

DEFINITION

Specified Path Coverage (SPC) – ***TR*** contains a set ***S*** of test paths, where S is supplied as a parameter.

Structural Coverage Example

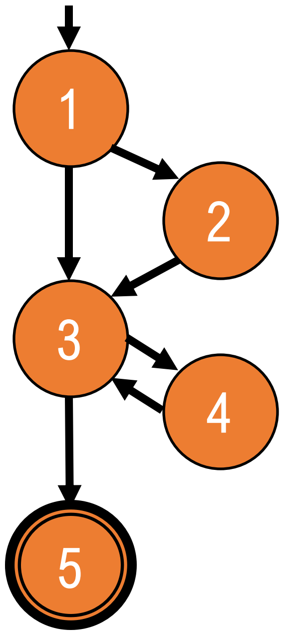


Node Coverage:
TR = { 1, 2, 3, 4, 5 }
Test paths = [1, 2, 3, 4, 3, 5]

Edge Coverage:
TR = { (1,2), (1,3), (2,3), (3,4), (4,3), (3,5) }
Test paths = [1, 2, 3, 4, 3, 5], [1, 3, 5]

Edge-Pair Coverage:
TR = { [1,2,3], [1,3,4], [1,3,5], [2,3,4], [2,3,5], [3,4,3], [4,3,4], [4,3,5] }
Test paths = [1, 2, 3, 4, 3, 5], [1, 3, 4, 3, 4, 3, 5], [1, 3, 5], [1, 2, 3, 5]

Structural Coverage Example



Complete Path Coverage:

Test paths = [1, 3, 5], [1, 2, 3, 5],
[1, 2, 3, 4, 3, 5],
[1, 2, 3, 4, 3, 4, 3, 5],
[1, 2, 3, 4, 3, 4, 3, 4, 3, 5],
[1, 2, 3, 4, 3, 4, 3, 4, 3, 4, 3, 5],
…

Handling Loops in Graphs

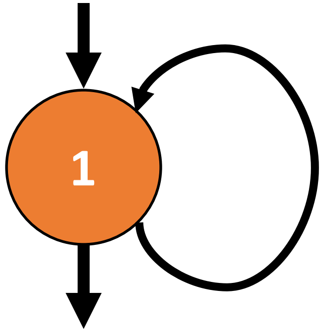
If a graph contains a loop, then it has an *infinite number* of paths

- Complete path coverage is infeasible

SPC is not satisfactory because the results are *subjective* and vary with the tester

Attempts to deal with loops

- 1980s: execute loops exactly once
- 1990s: execute loops 0, 1, >1 times
- 2000s: prime paths (touring, sidetrips, detours)

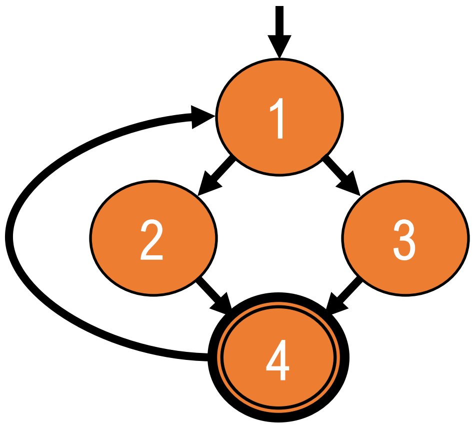


Simple Paths and Prime Paths

Simple path: a path from node *ni* to *nj* is *simple* if no node appears more than once, except that the first and last nodes may be the same

A simple path has no loops within it, but a loop is itself 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], [1,3], [2,4], [3,4], [4,1],
[1,2,4], [1,3,4], [2,4,1], [3,4,1], [4,1,2], [4,1,3],
[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]

Prime 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]

Prime Path Coverage

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

DEFINITION

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

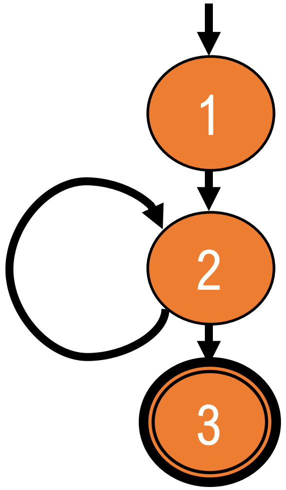
Will tour all paths of length 0, 1, … , N

Subsumes node and edge coverage

PPC Does Not Subsume EPC

If a node *j* has an edge to itself (a *self edge*), then edge-pair coverage requires [*i*, *j*, *j*] and [*j*, *j*, *k*]

Neither [*i*, *j*, *j*] nor [*j*, *j*, *k*] are *simple paths* and thus not *prime paths*



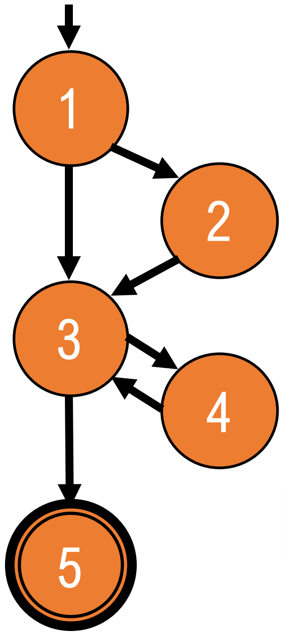
EPC Requirements:

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

PPC Requirements:

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

Prime Path Example



Simple Paths (16):
[1,2], [1,3], [2,3], [3,4], [3,5], [4,3],
[1,2,3], [1,3,4], [1,3,5], [2,3,4], [2,3,5],
[3,4,3], [4,3,4], [4,3,5],
[1,2,3,4], [1,2,3,5]

Prime Paths (7):
[1,3,4],
[1,3,5],
[3,4,3],
[4,3,4],
[4,3,5],
[1,2,3,4],
[1,2,3,5]

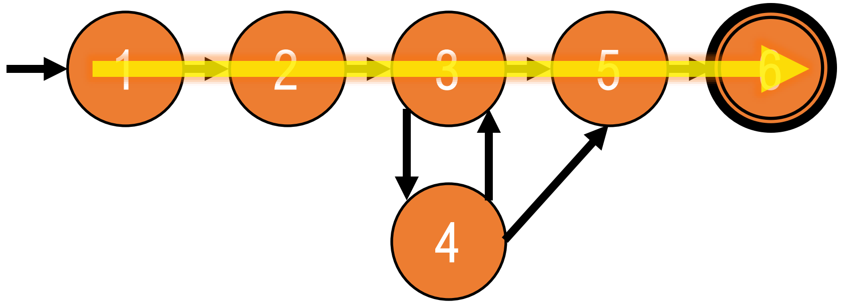
Loop at least once

Loop 0 times

Loop more than once

Touring

Tour: a test path ***p*** tours subpath ***q*** if ***q*** is a subpath of ***p***

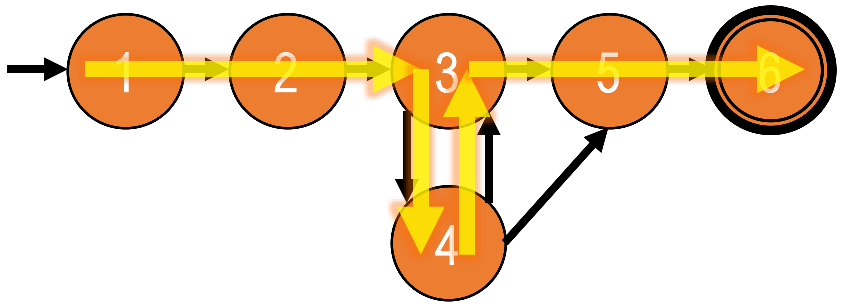


Touring the prime path [1,2,3,5,6]
without sidetrips or detours

Touring with Sidetrips

Tour with sidetrips: a test path ***p*** tours subpath ***q*** with sidetrips if and only if every *edge* in ***q*** is also in ***p*** in the same order

The tour can sidetrip from node n_i as long as it comes back to n_i

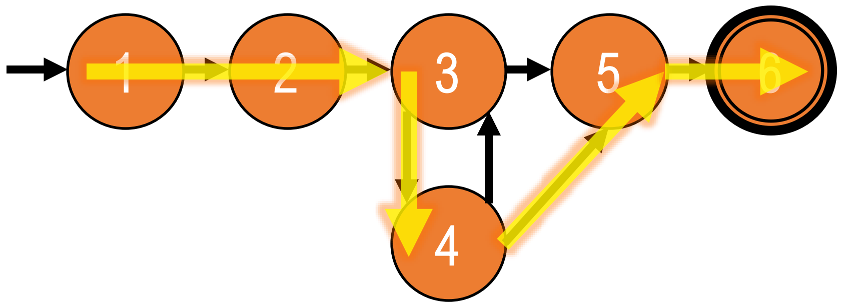


Touring the prime path [1,2,3,5,6] with a sidetrip to node 4

Touring with Detours

Tour with detours: a test path ***p*** tours subpath ***q*** with detours if and only if every *node* in ***q*** is also in ***p*** in the same order

A tour can detour from node n_i as long as it comes back to the prime path at a successor of n_i



Touring the prime path [1,2,3,5,6] with a detour to node 4

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, structural criteria typically have *more* infeasible requirements

- However, allowing sidetrips weakens the test criteria

Best effort Touring

Best effort touring is a practical compromise

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

Data Flow Coverage

Data flow coverage criteria also require the graph to be annotated with references to variables

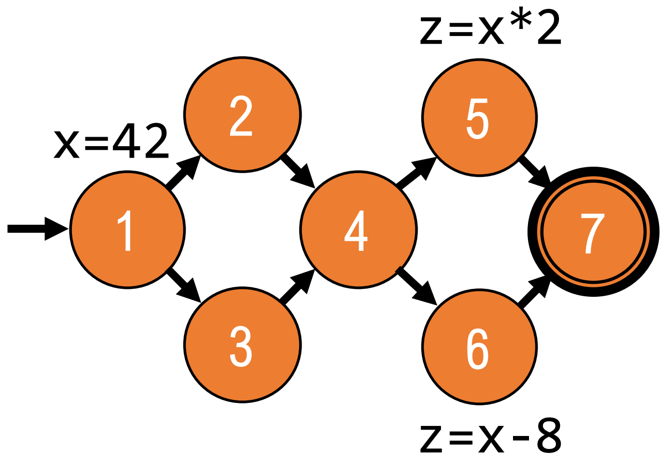
The goal of data flow coverage is to ensure that values are computed and used correctly

Definition (Def): a location where a variable's value is set

Use: a location where a variable's value is accessed

Def-Use

The values set in each *def* should *reach* at least one, some, or all possible *uses*.



Defs:

def(1) = { x }
def(5) = { z }
def(6) = { z }

Uses:

use(5) = { x }
use(6) = { x }

DU Pairs

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

DU Paths

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 of 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 of ***v*** 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***

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 as with previous touring

Three obvious criteria

- Use every def
- Get to every use
- Follow all DU-paths

Data flow test criteria

First, ensure every def reaches a use

DEFINITION

All-Defs Coverage (ADC) – for each set of DU-paths *S=du(n,v)*, *TR* contains at least one path *d* in *S*.

Then, ensure every def reaches all uses

DEFINITION

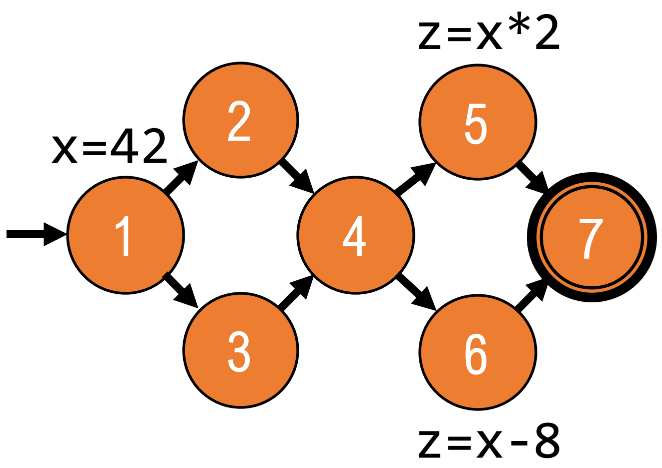
All-Uses Coverage (AUC) – for each set of DU-paths to uses $S=du(n_i,n_j,v)$, *TR* contains at least one path *d* in *S*.

Finally, cover all the paths between defs and uses

DEFINITION

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|3, 4, 5|6]

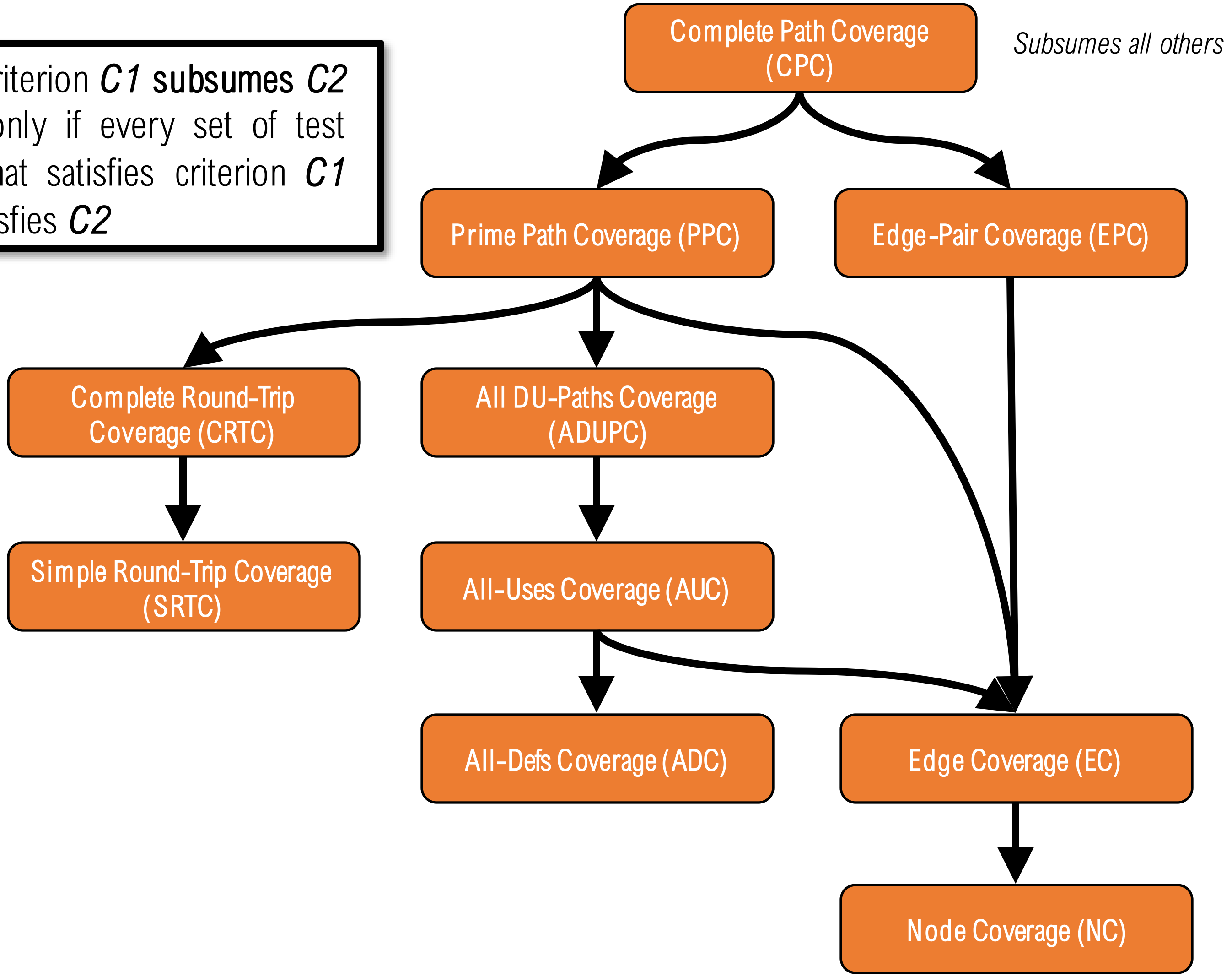
All-uses for x:
[1, 2|3, 4, 5],
[1, 2|3, 4, 6]

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

DEFINITION

A test criterion *C1* **subsumes** *C2* if and only if every set of test cases that satisfies criterion *C1* also satisfies *C2*



Summary

Graphs are a *powerful abstraction* for designing tests

Various criteria allow *cost/benefit* trades

Graphs appear in *many situations* in software

We'll explore this further next week