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

# Overview Graph Coverage Criteria

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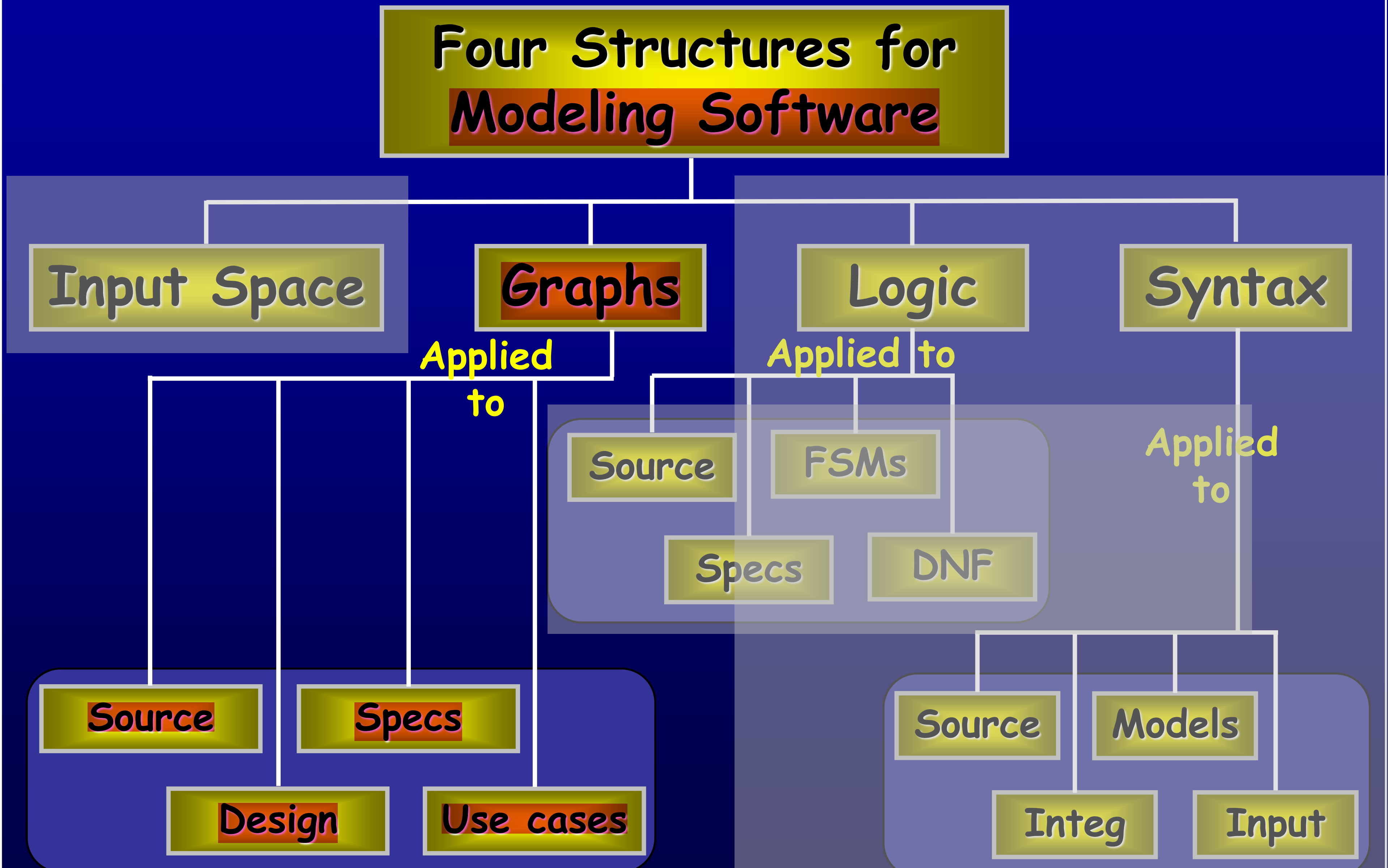
# Ch. 7 : Graph Coverage



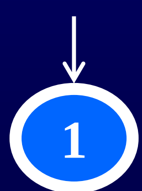
# Covering Graphs (7.1)

- 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

Is this a graph?



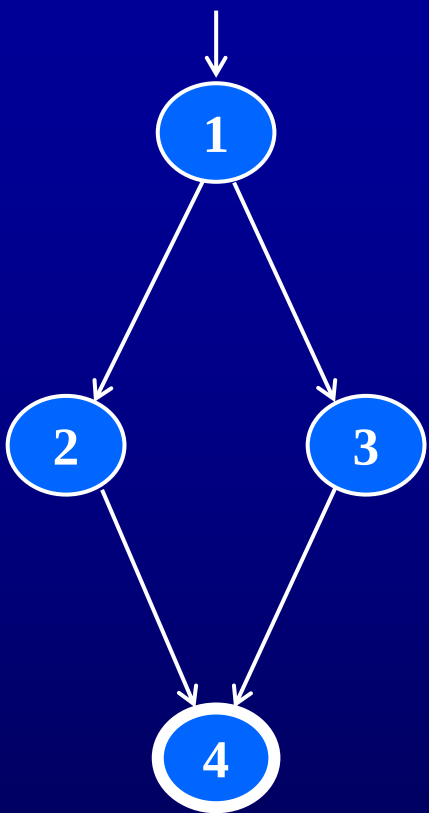

$N_0 = \{ 1 \}$

$N_f = \{ 1 \}$

$E = \{ \}$

Yes

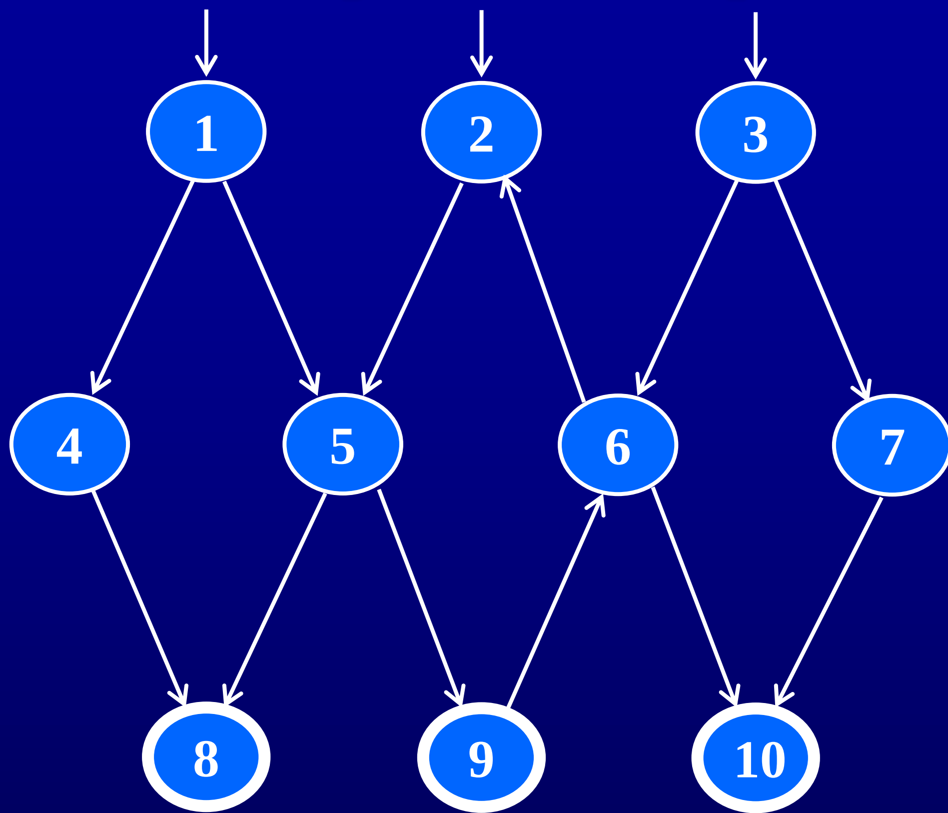
# Example Graphs



$N_0$ = { 1 }

$N_f$ = { 4 }

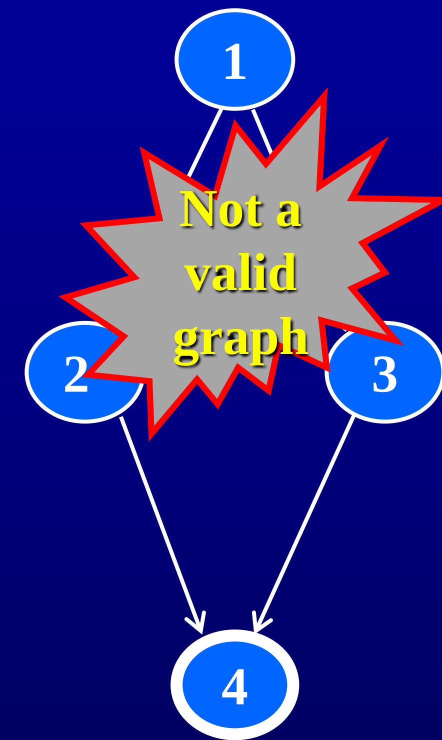
E = { (1,2), (1,3), (2,4), (3,4) }



$N_0$ = { 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) }



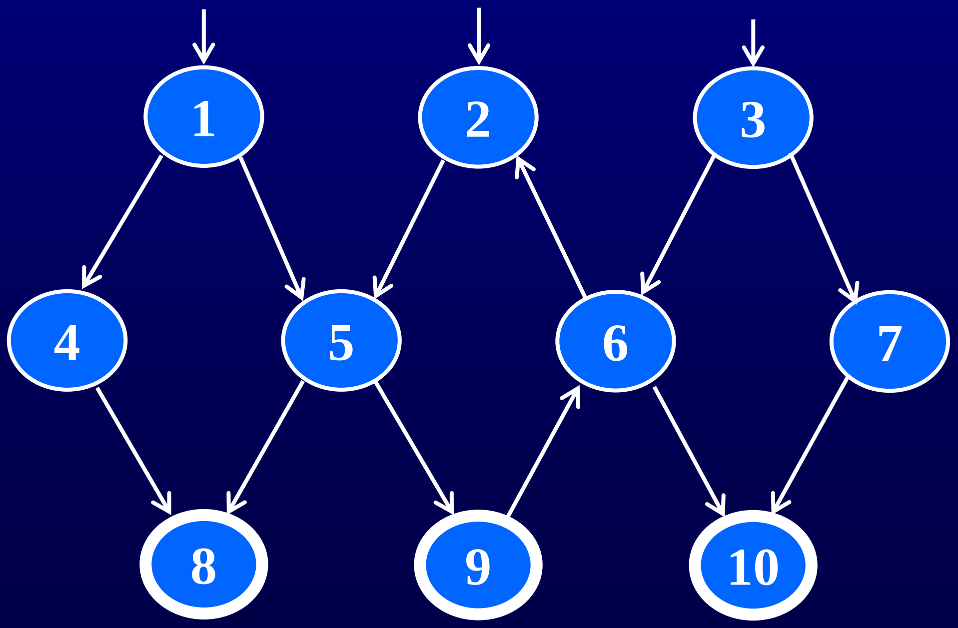

$N_0$ = { }

$N_f$ = { 4 }

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

# Paths in Graphs

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

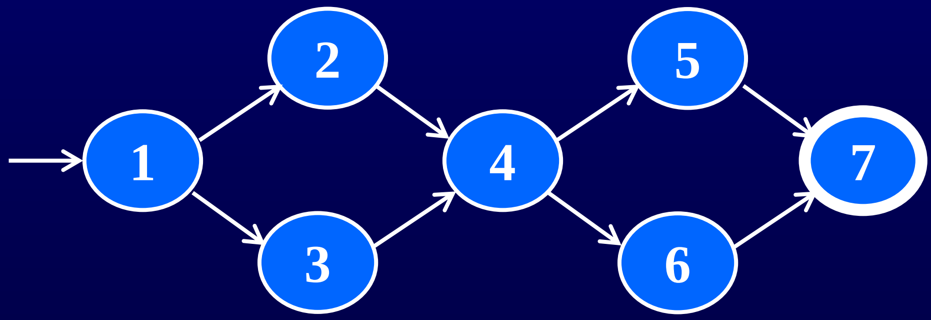
[ 1, 4, 8 ]

[ 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

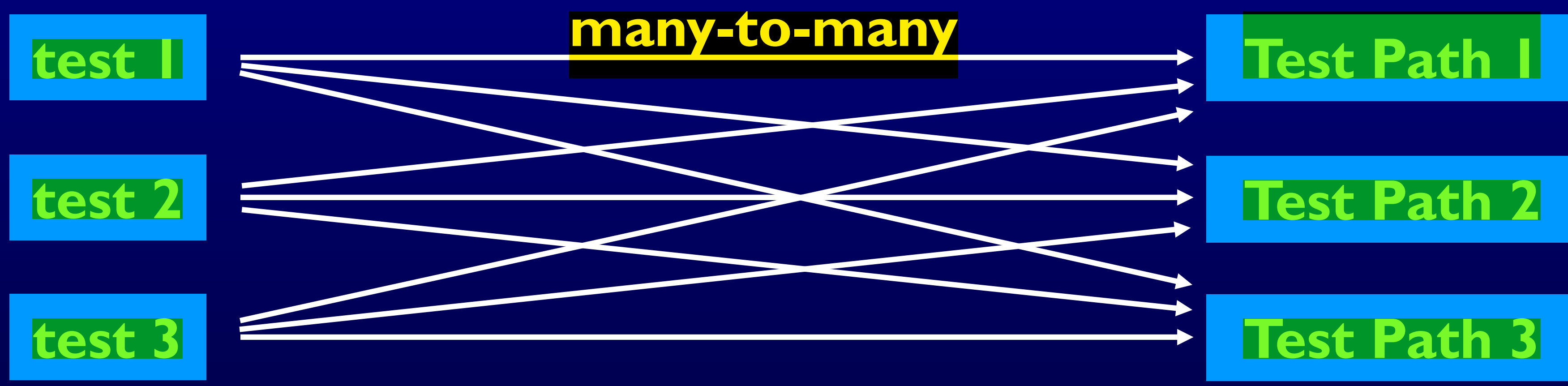
- path (*t*) : The test path executed by test *t*
- path (*T*) : The set of test paths executed by the set of tests *T*
- Each test executes one and only one test path
  - – Complete execution from a start node to an final node
- A location in a graph (node or edge) can be reached from another location 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
  - – This distinction will become important in section 7.3

# Tests and Test Paths

many-to-one


**Deterministic software–test always executes the same test path**

many-to-many




**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 *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

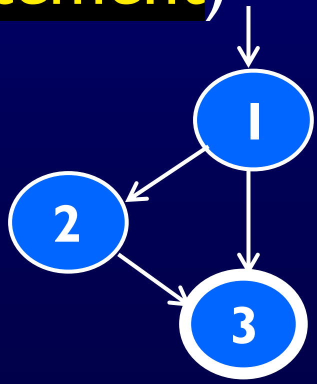
**Node Coverage (NC) : TR contains each reachable node in G.**

# 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)

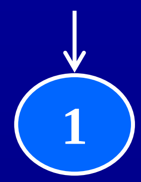



**Node Coverage : TR = { 1, 2, 3 }**
**Test Path = [ 1, 2, 3 ]**

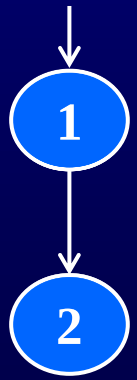
**Edge Coverage : TR = { (1, 2), (1, 3), (2, 3) }**
**Test Paths = [ 1, 2, 3 ]**
**[ 1, 3 ]**

# 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 …

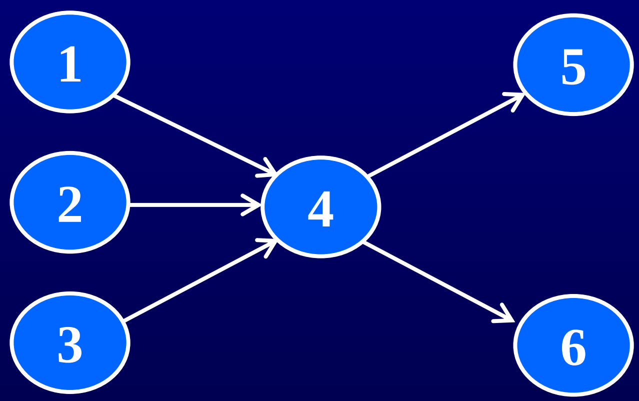


# Covering Multiple Edges

- 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 …

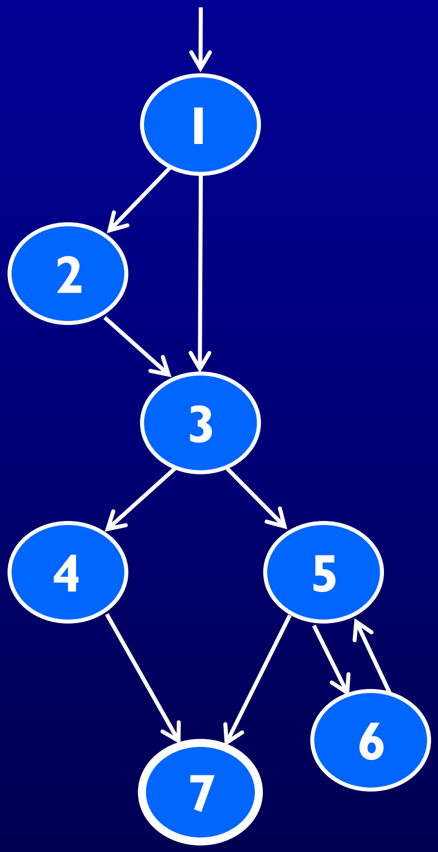
# Covering Multiple Edges

**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

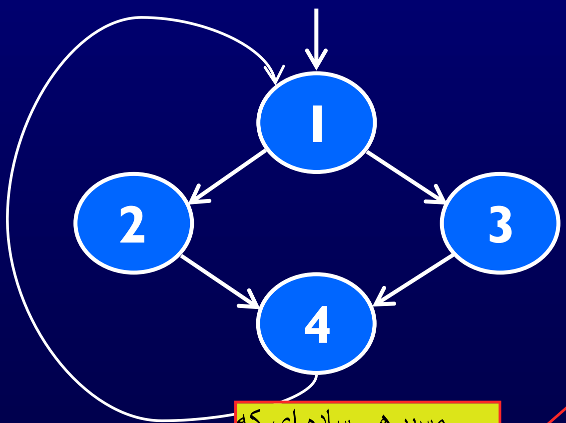
- If a graph contains a loop, it has an infinite number of paths
- Thus, CPC is not feasible
- SPC is not satisfactory because the results are subjective and vary with the tester
- Attempts to "deal with" loops:
  - 1970s : Execute cycles once ([4, 5, 4] in previous example, informal)
  - 1980s : Execute 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 ni to nj 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

در تعریف مسیرهای ساده:
مسیرهای به طول صفرکه نودهامون هستن ومسیر به طول یک که یال هامونه و ... را داریم

- **Prime Path** : A *simple path that does not appear as a proper subpath of any other simple path*




مسیرهی ساده ای که بیشترین طول را دارند

**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]

ماکس تعداد نودی که در این مسیرها میبینیم به تعدادنودهای گرافمون است

# Prime Path Coverage

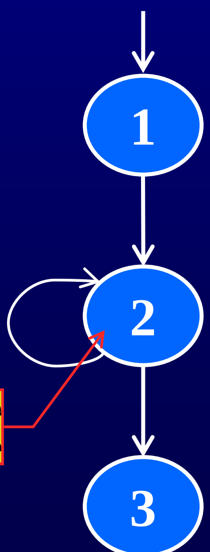
- A simple, elegant and finite criterion that requires loops to be executed as well as skipped

**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)




در گراف نودی داریم که طوقه داره

**EPC Requirements :**

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

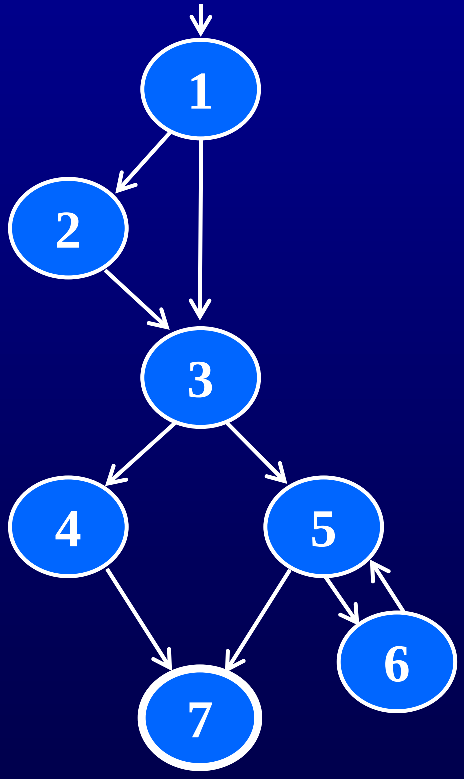
یال های مجاورهم رو باید داشته باشیم

**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**

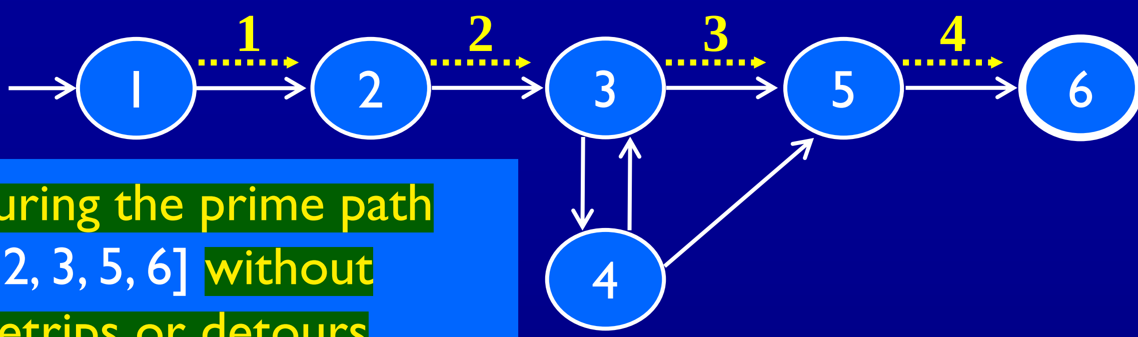
**Execute loop once**

**Execute loop more than once**

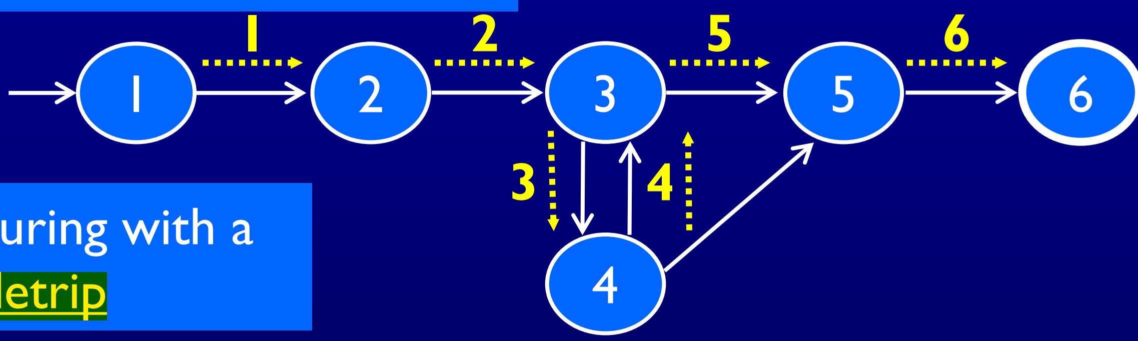
# Touring, Sidetrips, and Detours

- Prime paths do not have internal loops … test paths might (page 170)
- 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 *ni*, as long as it comes back to the prime path at a successor of *ni*

# Sidetrips and Detours Example

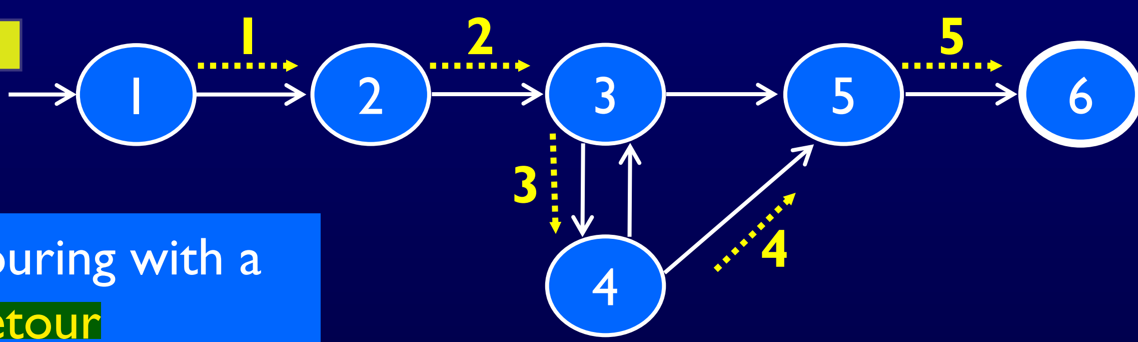


Touring the prime path [1, 2, 3, 5, 6] without sidetrips or detours



Touring with a sidetrip

حفظ ترتیب یال ها



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**

# Round Trips

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

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

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

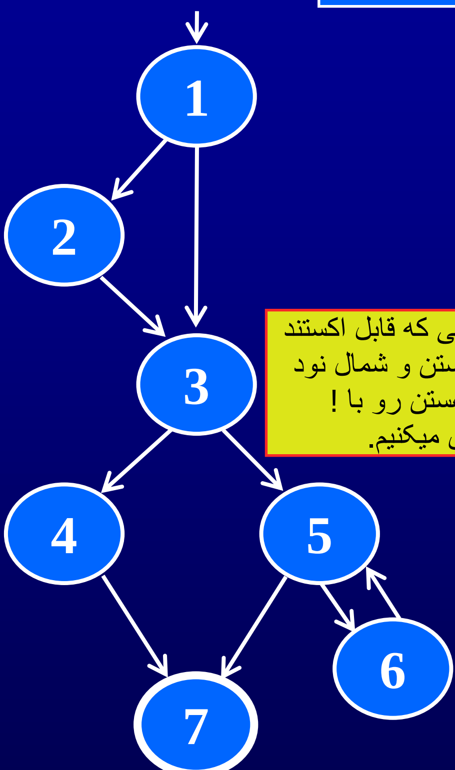
- These criteria omit nodes and edges that are not in round trips
- Thus, they do not subsume edge-pair, edge, or node coverage

# Simple & Prime Path Example

همه ی نودها در گراف

همه ی یال ها

**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]

**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] *

**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] !

سیرهایی که قابل اکستند شدن نیستن و شمال نود فاینال هستن رو با ! مشخص میکنیم.

‘!’ means path terminates

‘*’ means path cycles

این چندتا چون زیرمسیر یه مسیر دیگه هستن نمیتونن prime path باشن.

حلقه ها هم قابل توسعه نیستند چون اگه یه نود دیگه اضافه کنیم مسیر دیگه ساده نیست

این مسیر هم قابل توسعه نیست چون بعد از نود۶ فقط میشه به نود۵ بریم که دیگه مسیرمون ساده نمیشه و شرط ساده بودن نقض میشه

***Prime Paths***

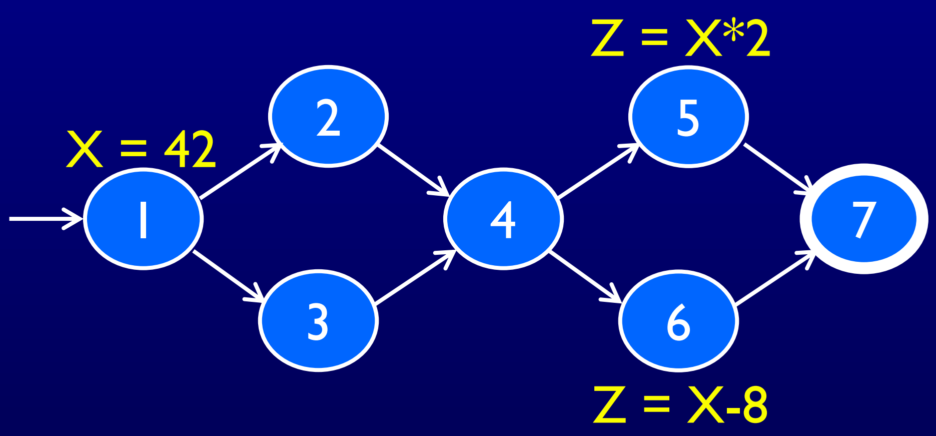
الگوریتم تعداد بی نهایت ایتریشن یا تکرار نداره چرا؟
چون ماکس طول مسیر ما مثلا اینجا ۴ است و یکی از تعداد نودهای گرافمون کمتره

برای پیداکردن prime pathها، از طولانی ترین مسیر ها شروع میکنیم و این مسیر ها نباید جزو مسیر دیگه ای باشند یعنی نباید sub-path مسیردیگه ای باشند پس اون مسیرهایی که قابل توسعه بودن یعنی sub-path یه مسیرساده بودن پس نمیتونن prime path باشند.

# 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

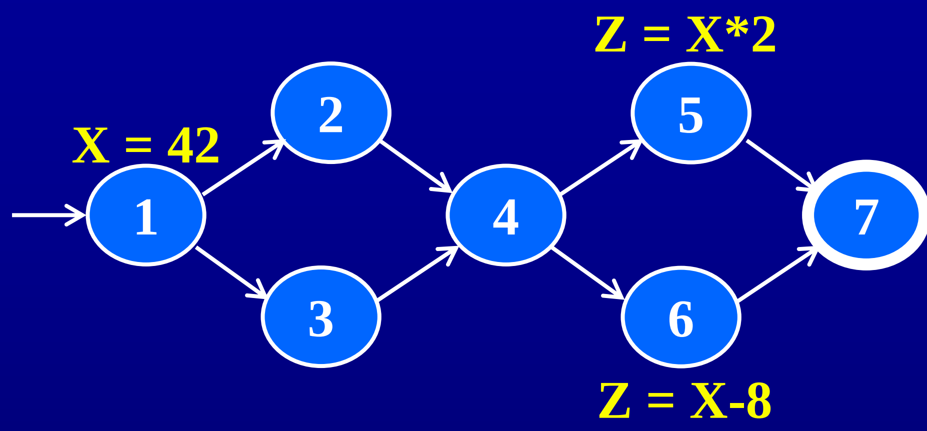
**All-uses coverage (AUC) : For each set of du-paths to uses *S* = *du* ($n_i$, $n_j$, *v*), TR contains at least one path *d* in *S*.**

- Finally, we cover all the paths between defs and uses

**All-du-paths coverage (ADUPC) : For each set *S* = *du* (*ni*, *nj*, *v*), TR contains every path *d* in *S*.**

هر defای به هر useای که برای یک متغیر است
دسترسی و مسیر داشته باشه

# Data Flow Testing Example




**All-defs for *X***

[ 1, 2, 4, 5 ]

برای هر def حداقل یک use بررسی شه

**All-uses for *X***

[ 1, 2, 4, 5 ]

[ 1, 2, 4, 6 ]

برای هر def همه ی use ها بررسی بشن

**All-du-paths for *X***

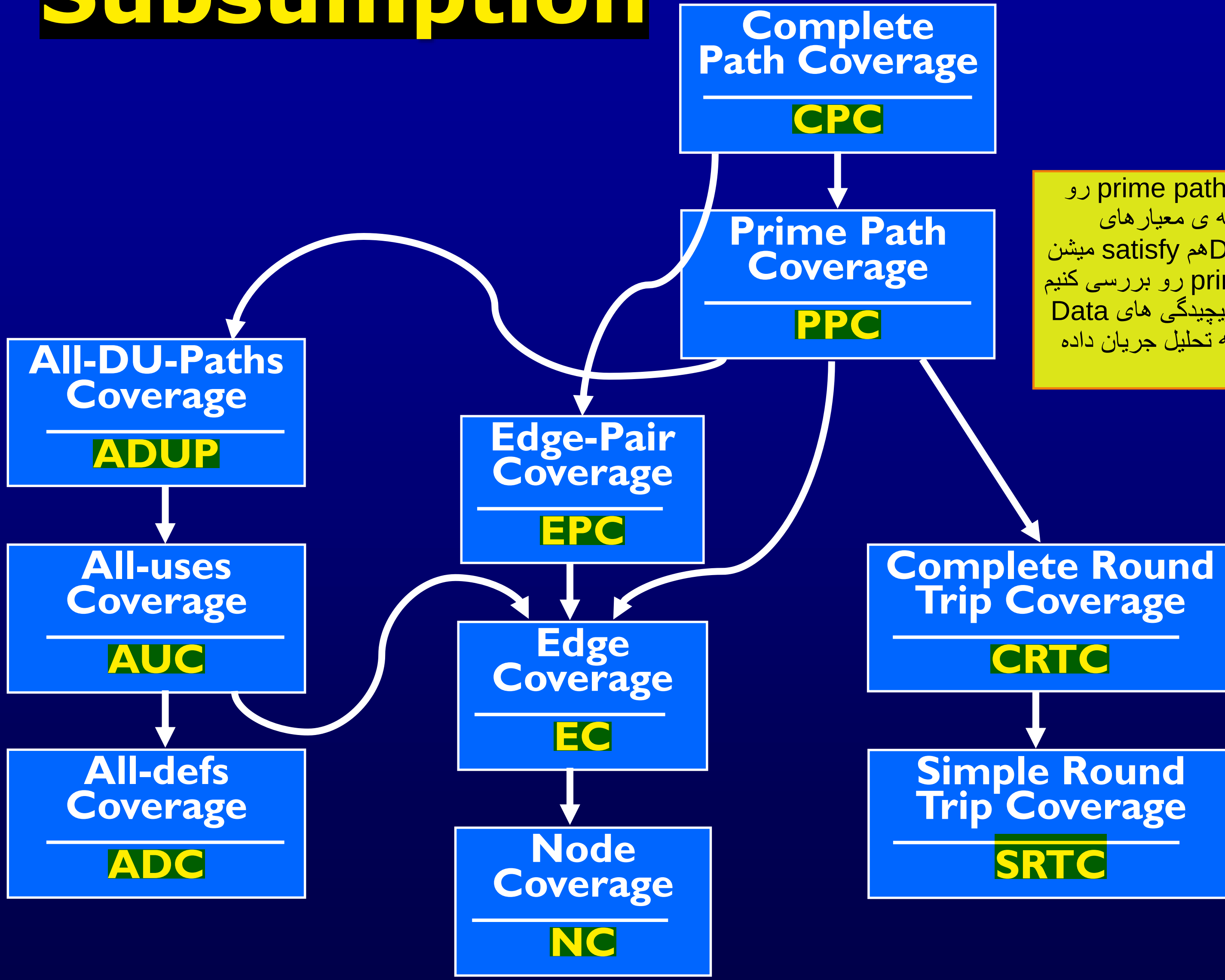
[ 1, 2, 4, 5 ]

[ 1, 3, 4, 5 ]

[ 1, 2, 4, 6 ]

[ 1, 3, 4, 6 ]

# Graph Coverage Criteria Subsumption




اگه ما prime path coverage رو
برقرار کنیم دیگه همه ی معیارهای
ربوط به Data flowهم satisfy میشن
پس وقتی prime path رو بررسی کنیم
میتونیم دیگه درگیر پیچیدگی های Data
flow نشیم مگه اینکه تحلیل جریان داده
مهم باشه

# 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