Testing: Coverage and Structural Coverage

Testing, Quality Assurance, and Maintenance
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based on slides by Prof. Marsha Chechik and Prof. Lin Tan

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Introduction to Software Testing

How would you test this program?

floor(x) is the largest integer not greater than x.

```
def Foo (x, y):
“”” requires: x and y are int
    ensures: returns floor(max(x,y)/min(x, y))”””
   if x > y:
      return x / y
   else
      return y / x
```

Testing

Static Testing [at compile time]

- Static Analysis
- Review
  - Walk-through [informal]
  - Code inspection [formal]

Dynamic Testing [at run time]

- Black-box testing
- White-box testing

Commonly, testing refers to dynamic testing.

Complete Testing?

Poorly defined terms: “complete testing”, “exhaustive testing”, “full coverage”

The number of potential inputs are infinite.

Impossible to completely test a nontrivial system

- Practical limitations: Complete testing is prohibitive in time and cost [e.g., 30 branches, 50 branches, ...]
- Theoretical limitations: e.g. Halting problem

Need testing criteria

Test Case

Test Case: [informally]

- What you feed to software; and
- What the software should output in response.

Test Set: A set of test cases

Test Case: input values, expected results, prefix values, and postfix values necessary to evaluate software under test

Expected Results: The result that will be produced when executing the test if and only if the program satisfies its intended behaviour

Test Requirement & Coverage Criterion

Test Requirement: A test requirement is a specific element of a software artifact that a test case must satisfy or cover.

- Ice cream cone flavors: vanilla, chocolate, mint
- One test requirement: test one chocolate cone
- **TR** denotes a set of test requirements

A coverage criterion is a rule or collection of rules that impose test requirements on a test set.

  - Coverage criterion is a recipe for generating TR in a systematic way.
- Flavor criterion [cover all flavors]
- TR = {flavor=chocolate, flavor=vanilla, flavor=mint}

Adequacy criteria

Adequacy criterion = set of test requirements

A test suite satisfies an adequacy criterion if

- all the tests succeed (pass)
- every test requirement in the criterion is satisfied by at least one of the test cases in the test suite.

Example:

the statement coverage adequacy criterion is satisfied by test suite S for program P if each executable statement in P is executed by at least one test case in S, and the outcome of each test execution was “pass”

Adequacy Criteria as Design Rules

Many design disciplines employ design rules

- e.g.: “traces (on a chip, on a circuit board) must be at least ___ wide and separated by at least ___”
- “Interstate highways must not have a grade greater than 6% without special review and approval”

Design rules do not guarantee good designs

- Good design depends on talented, creative, disciplined designers; design rules help them avoid or spot flaws

Test design is no different

Where do test requirements come from?

Functional (black box, specification-based): from software specifications

- Example: If spec requires robust recovery from power failure, test requirements should include simulated power failure

Structural (white or glass box): from code

- Example: Traverse each program loop one or more times.

Model-based: from model of system

- Models used in specification or design, or derived from code
- Example: Exercise all transitions in communication protocol model

Fault-based: from hypothesized faults (common bugs)

- example: Check for buffer overflow handling (common vulnerability) by testing on very large inputs

Code Coverage

Introduced by Miller and Maloney in 1963

Coverage Criteria

Basic Coverage

- Line coverage
- Statement
- Function/Method coverage
- Branch coverage
- Decision coverage
- Condition coverage
- Condition/decision coverage
- Modified condition/decision coverage
- Path coverage
- Loop coverage
- Mutation adequacy
- …

Advanced Coverage

Line Coverage

Percentage of source code lines executed by test cases.

- For developer easiest to work with

- Precise percentage depends on layout?
  - `int x = 10; if (z++ < x) y = x+z;`

- Requires mapping back from binary?

In practice, coverage not based on lines, but on control flow graph

Control Flow Graph (CFG)

Represents the flow of execution in the program

G = (N, E, S, T) where

- the nodes N represent executable instructions (statement, statement fragments, or basic blocks);
- the edges E represent the potential transfer of control;
- S is a designated start node;
- T is a designated final node
- E = { (n_i, n_j) | syntactically, the execution of n_j follows the execution of n_i}

Nodes may correspond to single statements, parts of statements, or several statements (i.e., basic blocks)

Execution of a node means that the instructions associated with a node are executed in order from the first instruction to the last

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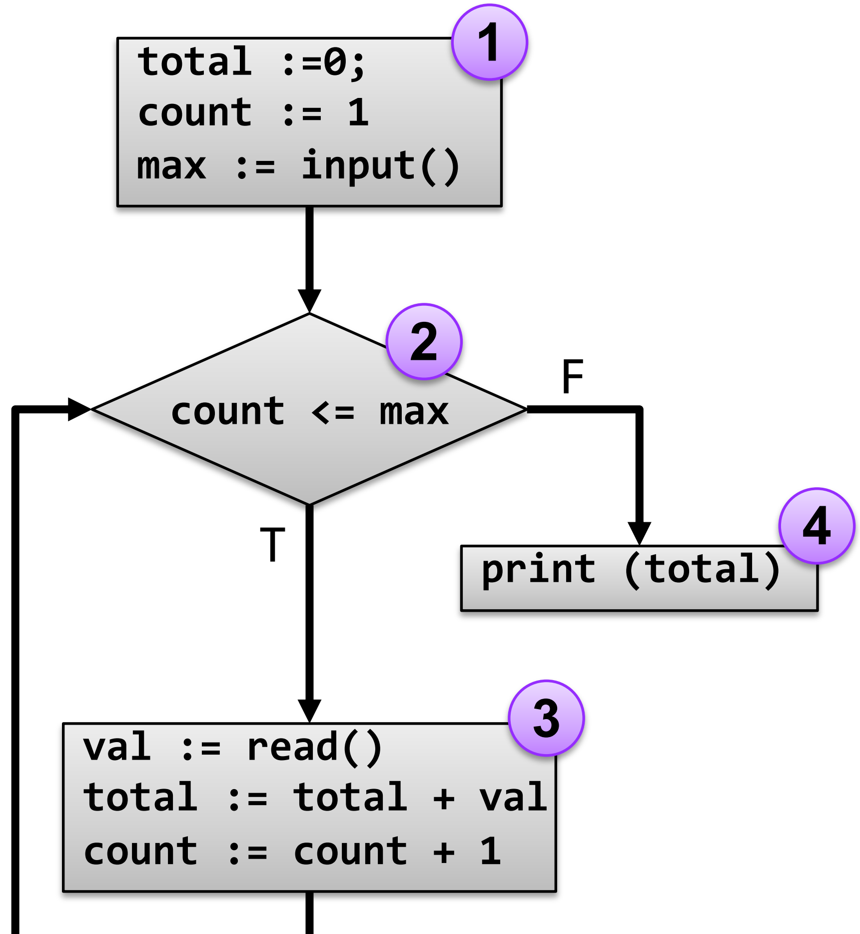
Example of a Control Flow Graph

```
total := 0;
count := 1;
max := input();
while (count <= max)
 do {
  val := input();
  total := total+val;
  count := count+1};
print (total)
```



Control Flow Graph

A CFG is a graph of basic blocks

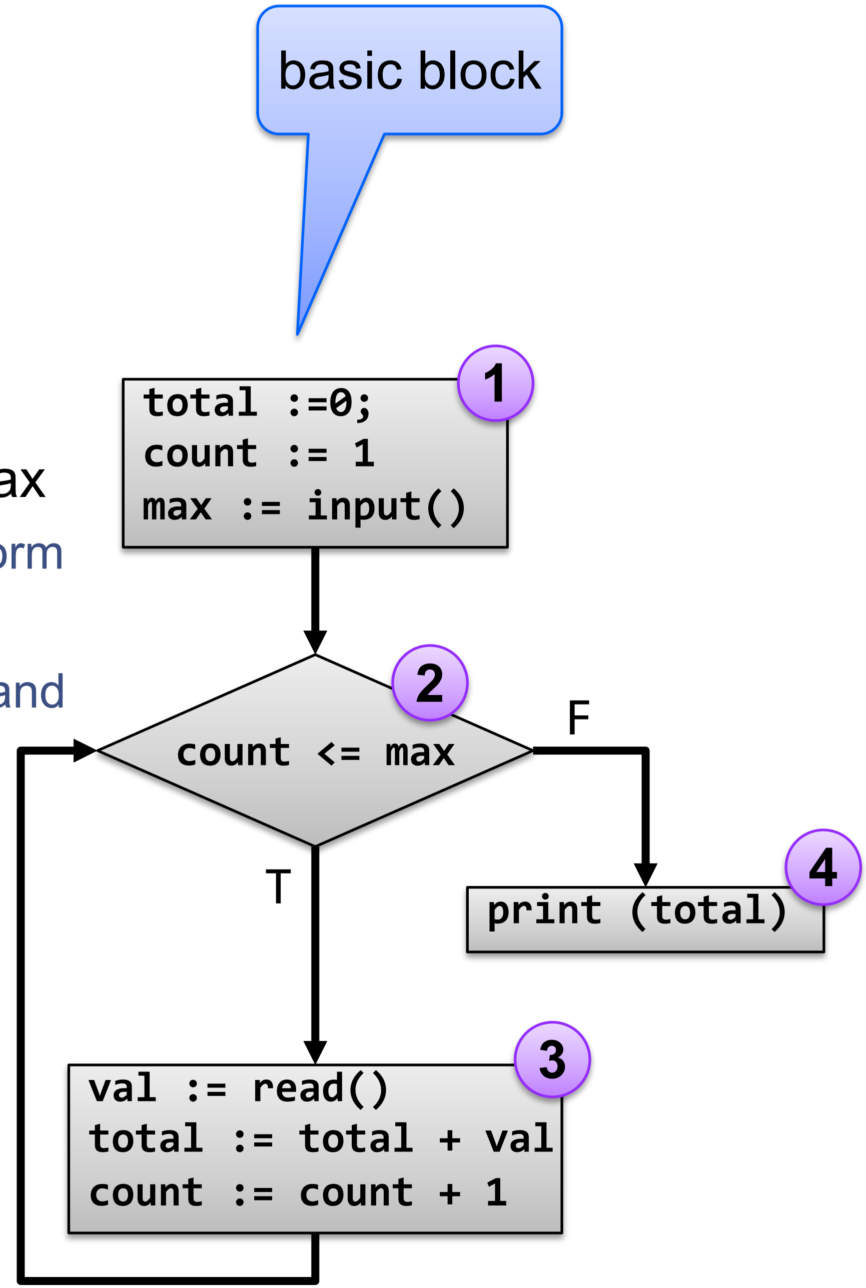
- edges represent different control flow

A CFG corresponds to a program syntax

- where statements are restricted to the form

  L_i:S ; goto L_j

  and S is control-free (i.e., assignments and procedure calls)



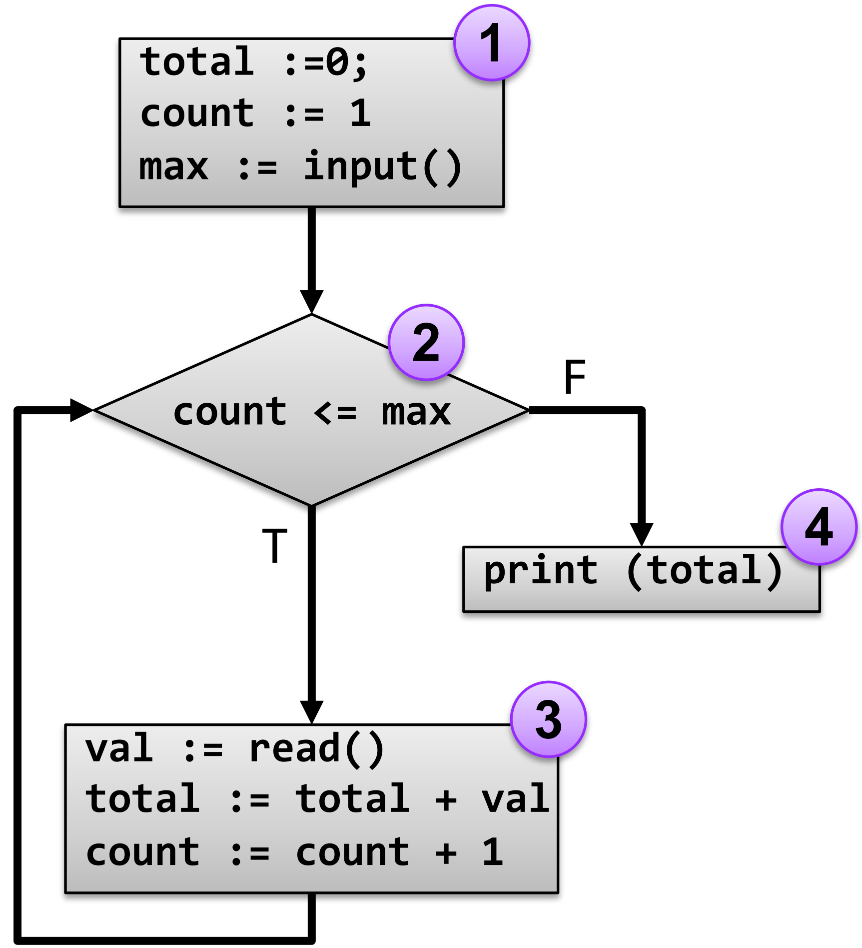
Control Flow Graph as a Goto Program

```
1: total:=0; count := 1;
   max = input(); goto 2

2: if count <= max
   then goto 3 else goto 4

3: val := read();
   total := total + val;
   count := count + 1; goto 2

4: print(total)
```

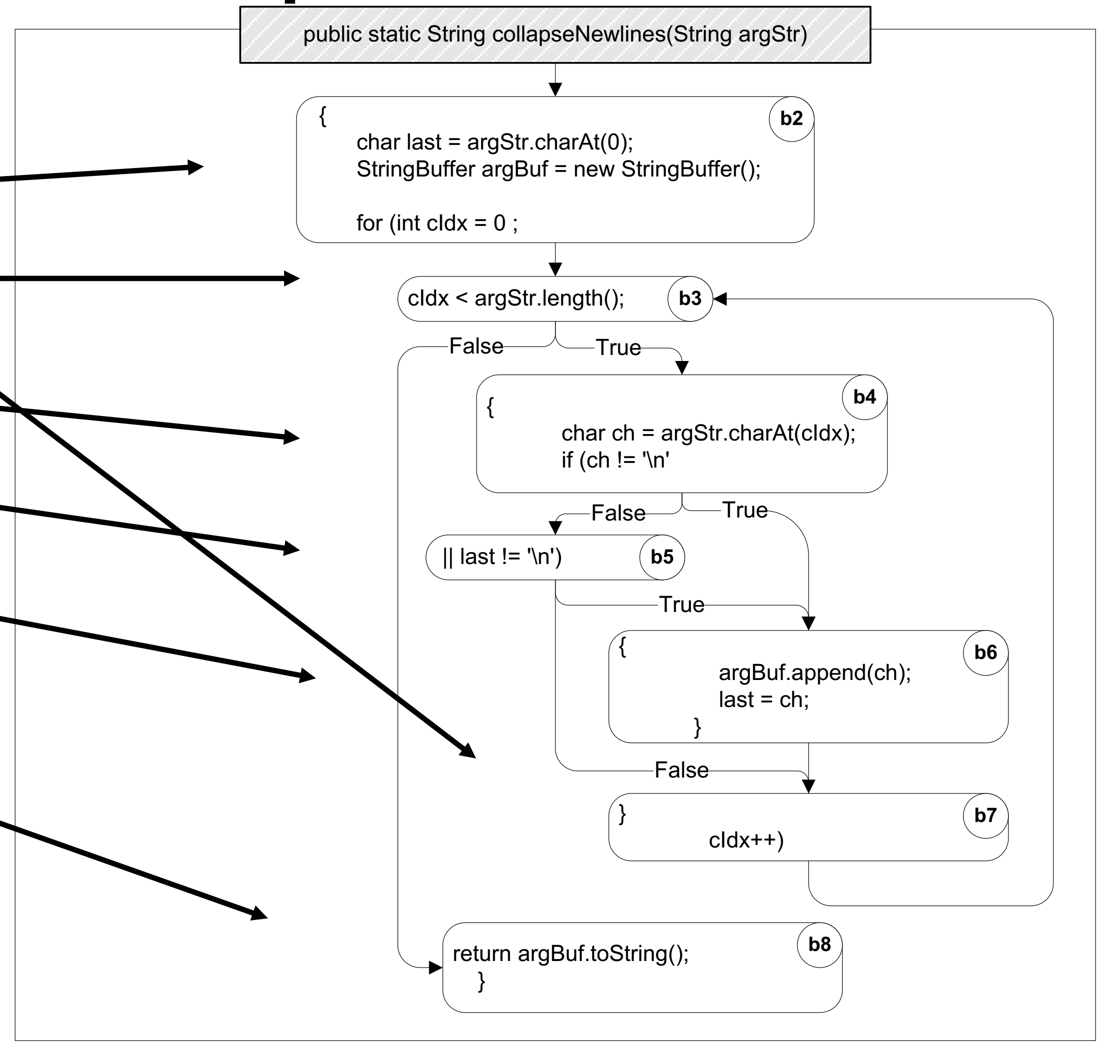


Deriving a Control Flow Graph

```
public static String collapseNewlines(String argStr)
  {
    char last = argStr.charAt(0);
    StringBuffer argBuf = new StringBuffer();

    for (int cIdx = 0; cIdx < argStr.length(); cIdx++)
    {
      char ch = argStr.charAt(cIdx);
      if (ch != '\n' || last != '\n')
      {
        argBuf.append(ch);
        last = ch;
      }
    }

    return argBuf.toString();
  }
```



Splitting multiple conditions depends on goal of analysis

Infeasible Paths

Every executable sequence in the represented component corresponds to a path in G

Not all paths correspond to executable sequences

- requires additional semantic information
- “infeasible paths” are not an indication of a fault

CFG usually overestimates the executable behavior

Statement or Node Coverage

Adequacy criterion: each statement (or node in the CFG) must be executed at least once

```
void foo (int z) {
  int x = 10;
  if (z++ < x) {
    x=+ z;
 }
}
```

Coverage:

$$\frac{\#\text{ executed statements}}{\#\text{ statements}}$$

Statement or Node Coverage

Adequacy criterion: each statement (or node in the CFG) must be executed at least once

```
void foo (int z) {
  int x = 10;
  if (z++ < x) {
    x=+ z;
 }
}
```

```
@Test
void testFoo() {
  foo(10);
}
```

Coverage:

$$\frac{\text{\# executed statements}}{\text{\# statements}}$$

Statement or Node Coverage

Adequacy criterion: each statement (or node in the CFG) must be executed at least once

```
void foo (int z) {
  int x = 10;
  if (z++ < x) {
    x=+ z;
 }
}
```

```
@Test
void testFoo() {
  foo(10);
}
```

Coverage:

$$\frac{\text{\# executed statements}}{\text{\# statements}}$$

Statement or Node Coverage

Adequacy criterion: each statement (or node in the CFG) must be executed at least once

```
void foo (int z) {
  int x = 10;
  if (z++ < x) {
    x=+ z;
  }
}
```

```
@Test
void testFoo() {
  foo(5);
}
// 100% Statement coverage
```

Coverage Level:

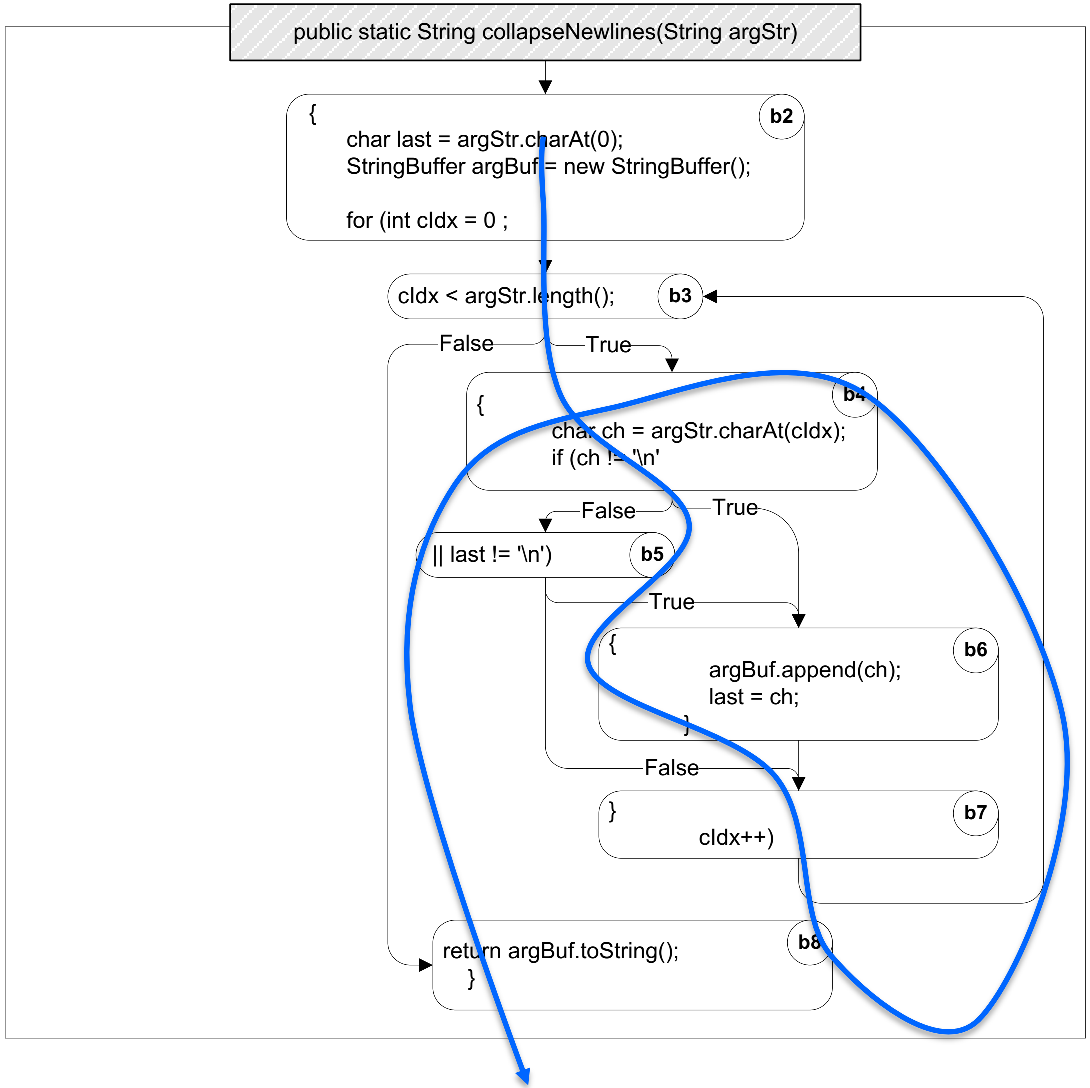
$$\frac{\text{\# executed statements}}{\text{\# statements}}$$

Control Flow Based Adequacy Criteria

Every block / Statement?

Input: “a”

Trace: b2,b3,b4,b5,b6,b7,b3,b8



Branch / Edge Coverage

Every branch going out of node executed at least once

- Decision-, all-edges-, coverage
- Coverage: percentage of edges hit.

Each branch predicate must be both true and false

Branch Coverage

One longer input:

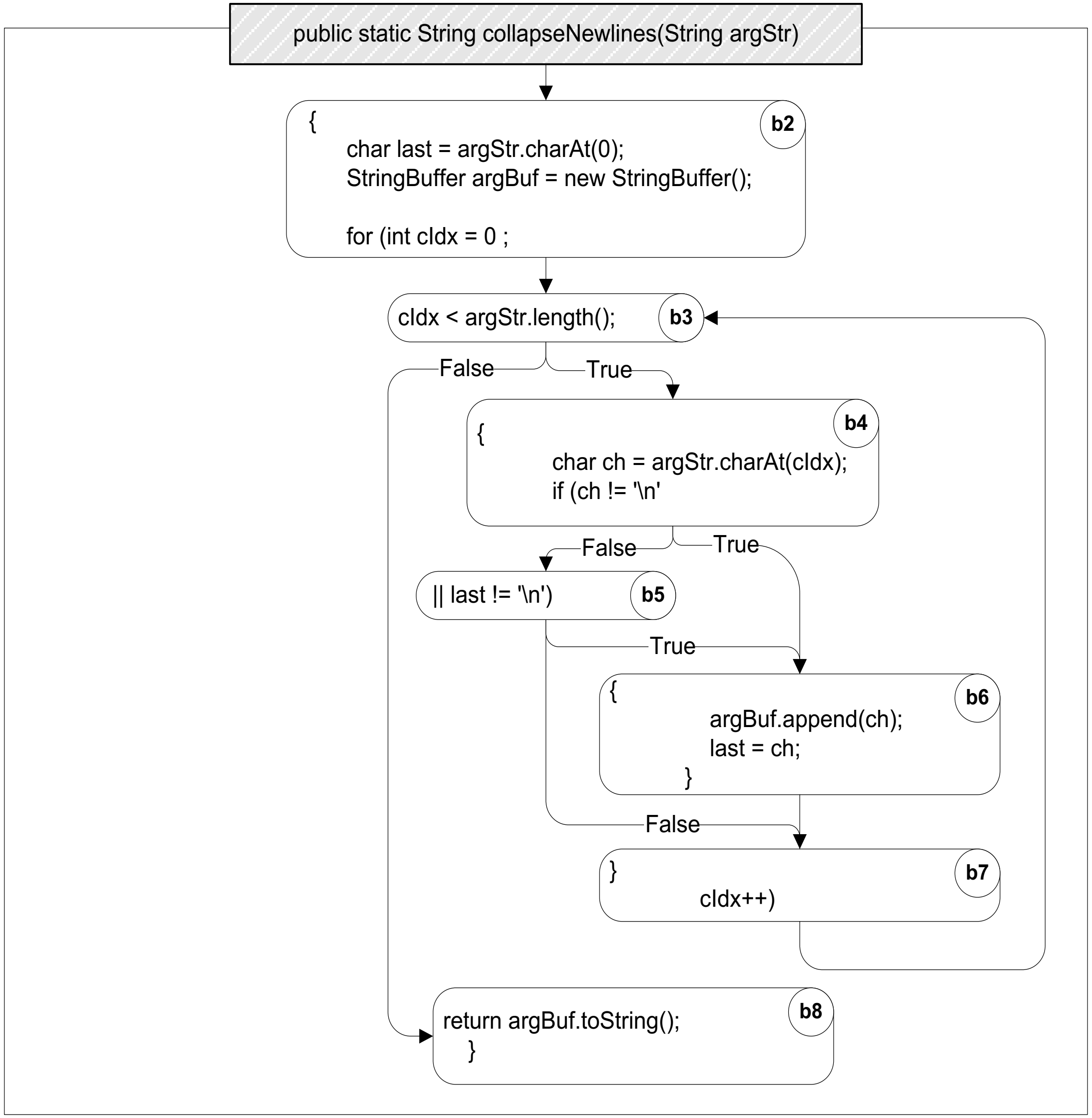
"a\n\n"

Alternatively:

Block ("a") and

"\n" and

"\n\n"



Infeasible Test Requirements

```
if (false)
  unreachableCall();
```

Real code from the Linux kernel:

```
while (0)
  {local_irq_disable();}
```

Statement coverage criterion cannot be satisfied for many programs.

Coverage Level

Given a set of test requirements **TR** and a test set **T**, the *coverage level* is the ratio of the number of test requirements satisfied by **T** to the size of **TR**.

TR = {flavor=chocolate, flavor=vanilla, flavor=mint}

Test set 1 T1 = {3 chocolate cones, 1 vanilla cone}

Coverage Level = 2/3 = 66.7%

Coverage levels helps evaluate the goodness of a test set, especially in the presence of infeasible test requirements.

Unit Testing

A *unit test* exercises a unit of functionality to test its behavior

A *unit test framework* provides a standard mechanism for

- specifying a test (setup, execution, expected result, teardown)
- executing a test
- generating test reports

Python includes a Unit Test framework called unittest

- https://docs.python.org/2/library/unittest.html

It is important to design your code with testing in mind

- e.g., a code that simply reads and writes to standard input and output is harder to test than code that provides a more structured interaction

Anatomy of a Unit Test

include module

A test case is a collection of tests

A method is a test

Calls to `assertXXX()` methods indicate test results

Entry point for the test when ran from command line

```
import unittest

class TestStringMethods(unittest.TestCase):

    def test_upper(self):
        self.assertEqual('foo'.upper(), 'FOO')

    def test_isupper(self):
        self.assertTrue('FOO'.isupper())
        self.assertFalse('Foo'.isupper())

    def test_split(self):
        s = 'hello world'
        self.assertEqual(s.split(), ['hello', 'world'])
        # check that s.split fails when the separator is not a string
        with self.assertRaises(TypeError):
            s.split(2)

if __name__ == '__main__':
    unittest.main()
```

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Designing for Testing

Factor the program into meaningful units / components

- e.g., parser, command processor, components, data structures, etc.

Each unit should have a well defined specification

- what are legal inputs
- what are legal outputs
- how inputs and outputs are passed around

Avoid monolithic design that reads standard input and writes standard output

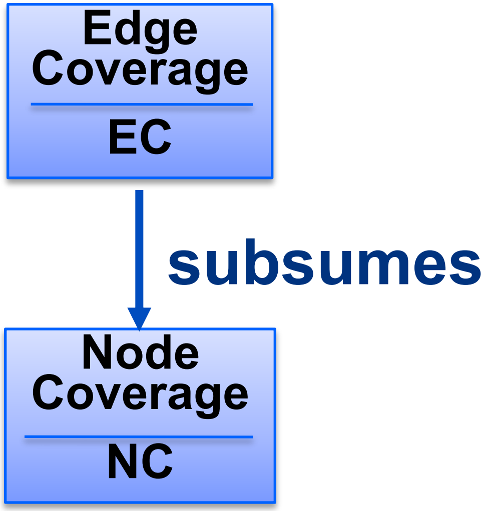
Good design requires more work

- additional functionality specifically for testing / debugging purposes
- but ultimately will save time of the overall development

Subsumption

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

Must be true for **every set** of test cases



Which one is stronger?

Subsumption is a rough guide for comparing criteria, although it's hard to use in practice.

More powerful coverage criterion helps find more bugs!

```
int d[2];

N1: if (x >= 0 && x < 2)
       { N2: print (x); }
N3: if (y > 0)
       { N4: print (d[x] + y); }
N5: exit (0);
```

Path [N1, N2, N3, N4, N5]:
  satisfies node coverage but not edge coverage.
  The corresponding test case passes. No bug found.

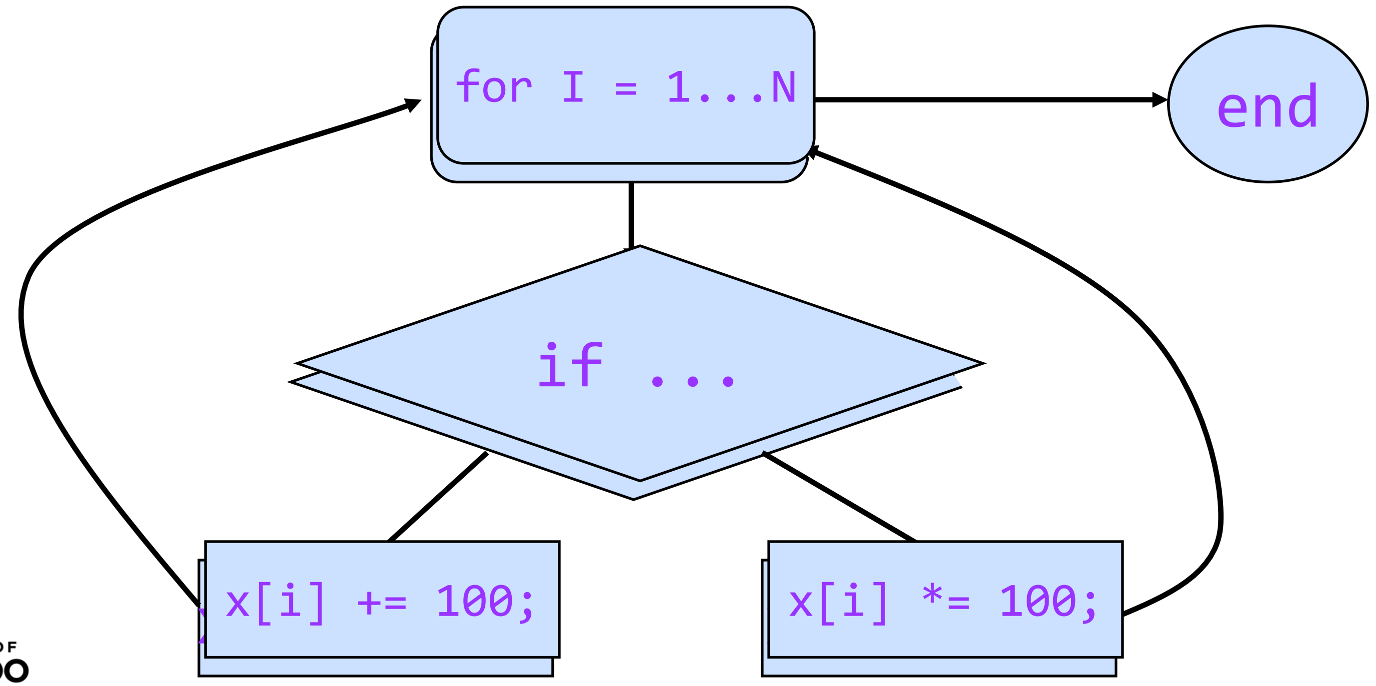
Path [N1, N3, N4, N5]: buffer overflow bug!

Path Coverage

Adequacy criterion: each path must be executed at least once

Coverage:

$$\frac{\#\ \text{executed paths}}{\#\ \text{paths}}$$



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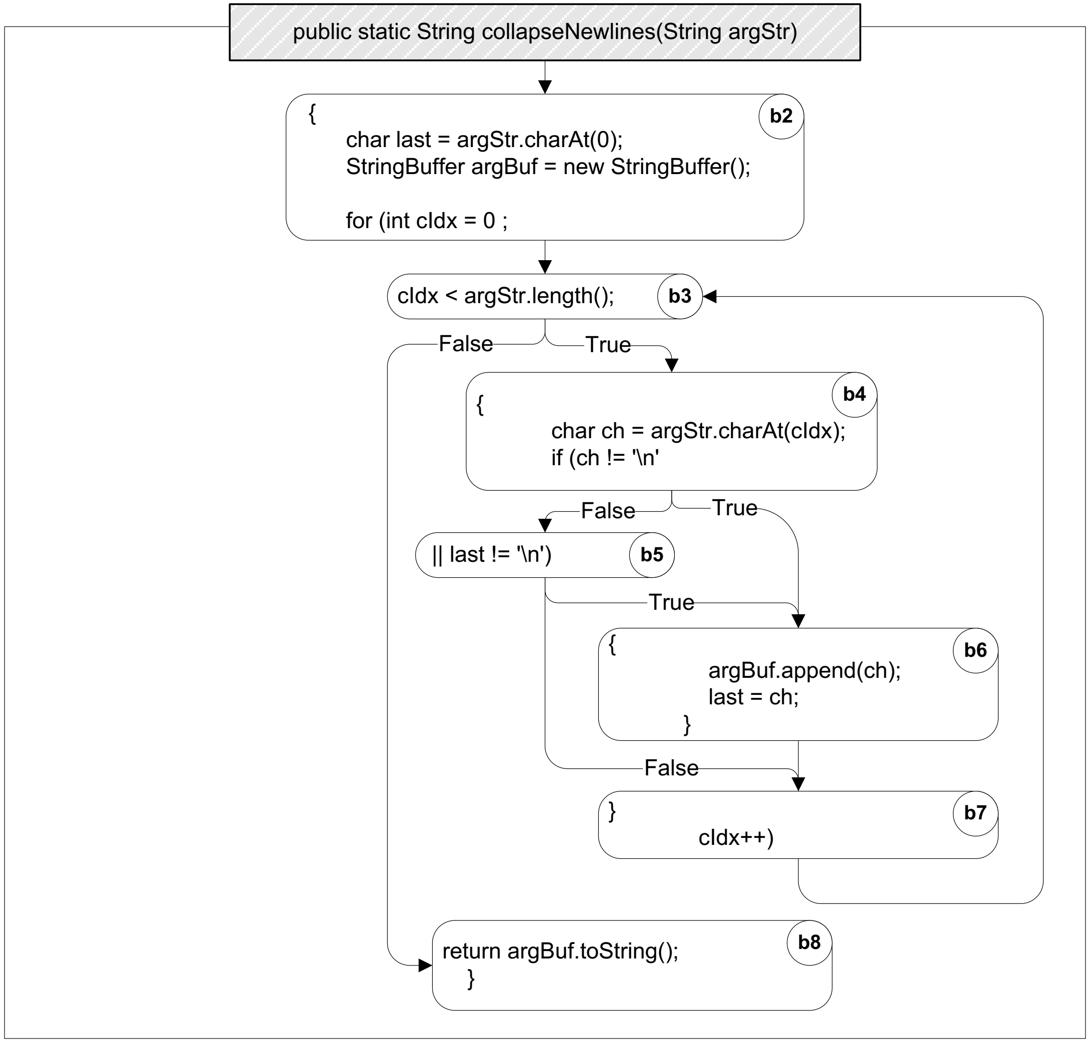
Path-based criteria?

All paths?

Which paths?



Branch vs Path Coverage

```
if( cond1 )
   f1();
else
   f2();

if( cond2 )
   f3();
else
   f4();
```

How many test cases to achieve branch coverage?

Branch vs Path Coverage

```
if( cond1 )
   f1();
else
   f2();

if( cond2 )
   f3();
else
   f4();
```

How many test cases to achieve branch coverage?

Two, for example:

1. cond1: true, cond2: true
2. cond1: false, cond2: false

Branch vs Path Coverage

```
if( cond1 )
   f1();
else
   f2();

if( cond2 )
   f3();
else
   f4();
```

How about path coverage?

Branch vs Path Coverage

```
if( cond1 )
   f1();
else
   f2();

if( cond2 )
   f3();
else
   f4();
```

How about path coverage?

Four:

1. cond1: true, cond2: true
2. cond1: false, cond2: true
3. cond1: true, cond2: false
4. cond1: false, cond2: false

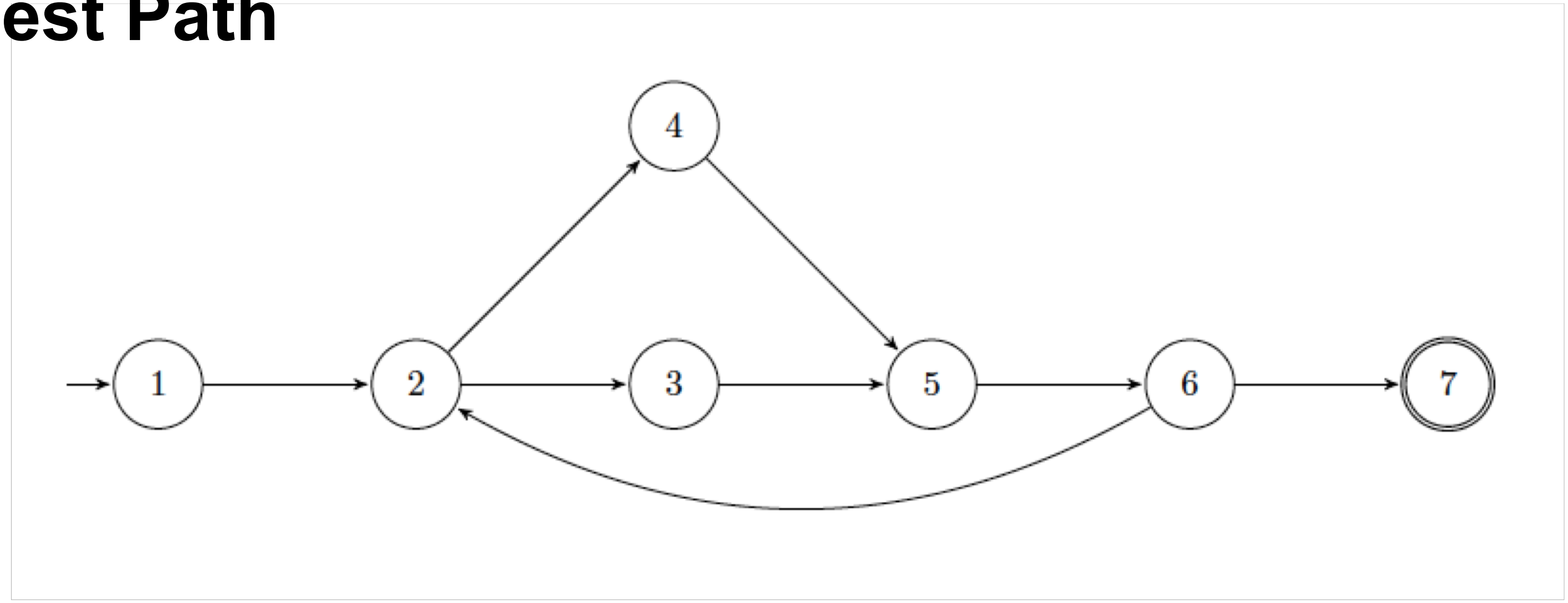
Branch vs Path Coverage

```
if( cond1 )
   f1();
else
   f2();
if( cond2 )
   f3();
else
   f4();
if( cond3 )
   f5();
else
   f6();
if( cond4 )
   f7();
else
   f8();
if( cond5 )
   f9();
else
   f10();
if( cond6 )
   f11();
else
   f12();
if( cond7 )
   f13();
else
   f14();
```

How many test cases for path coverage?

2^n test cases, where n is the number of conditions

Test Path

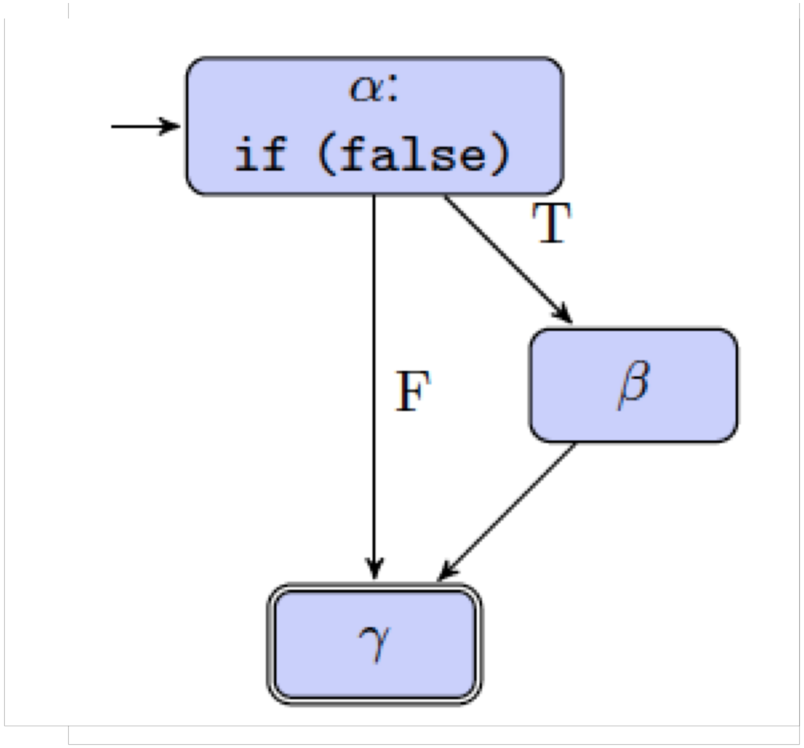


A test path is a path p [possibly of length 0] that starts at some node in N_0 and ends at some node in N_f.

Test path examples:

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

Paths and Semantics



β is never executed!

Some paths in a control flow graph may not correspond to program *semantics*.

In path coverage, we generally only talk about the *syntax* of a graph -- its nodes and edges -- and not its *semantics*.

Syntactical and Semantic Reachability

A node n is *syntactically* reachable from m if there exists a path from m to n.

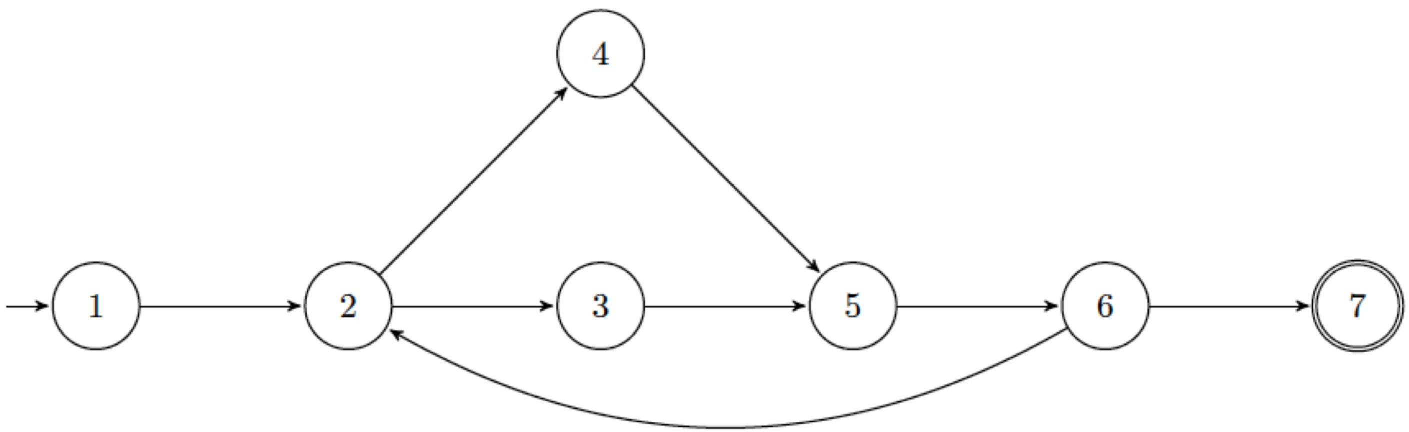
A node n is *semantically* reachable if one of the paths from m to n can be reached on some input.

Standard graph algorithms when applied to Control Flow Graph can only compute syntactic reachability.

Semantic reachability is undecidable.

Reachability

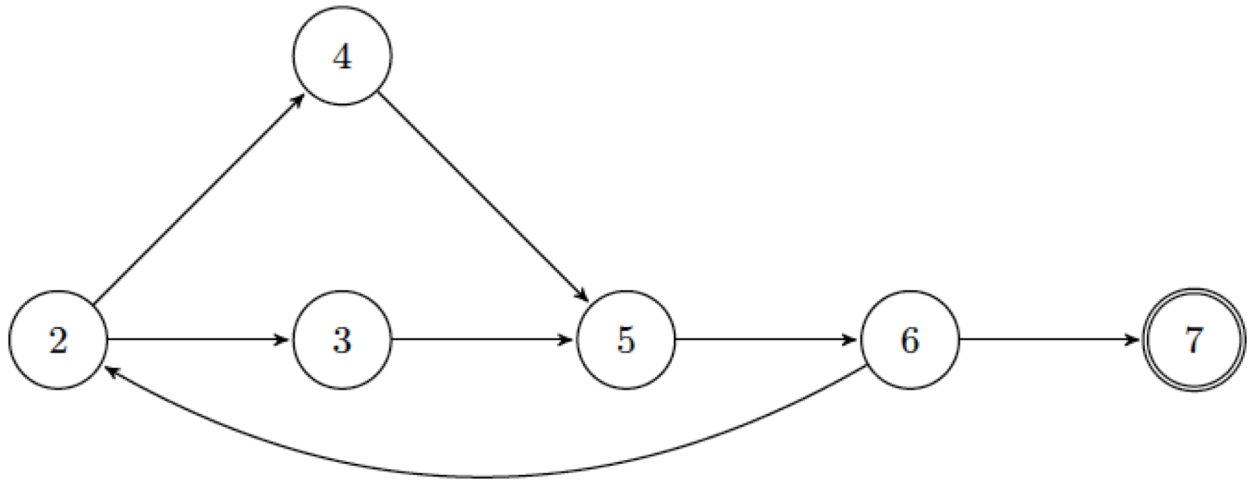
Let $reach_G(X)$ denote the sub-graph of G that is (syntactically) reachable from X, where X is either a node, an edge, a set of nodes, or a set of edges.



In this example, $reach_G(1)$ is the whole graph G.

Syntactical Reachability

- $\text{reach}_{G\#}(2)$ is the subgraph that is syntactically reachable from node 2.



- $\text{reach}_{G\#}(7)$ is:

Connect Test Cases and Test Paths

Connect test cases and test paths with a mapping $path_G$ from test cases to test paths

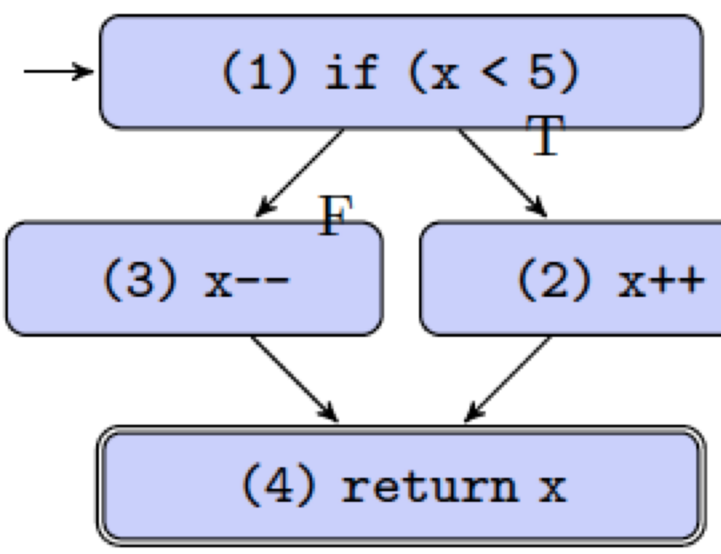
- e.g., $path_G[t]$ is the set of test paths corresponding to test case t.
- Usually just write *path,* as G is obvious from the context
- Lift the definition of path to test set T by defining path(T)

$$\text{path}(T) = \{\text{path}(t) | t \in T\}.$$

- Each test case gives at least one test path. If the software is deterministic, then each test case gives exactly one test path; otherwise, multiple test cases may arise from one test path.

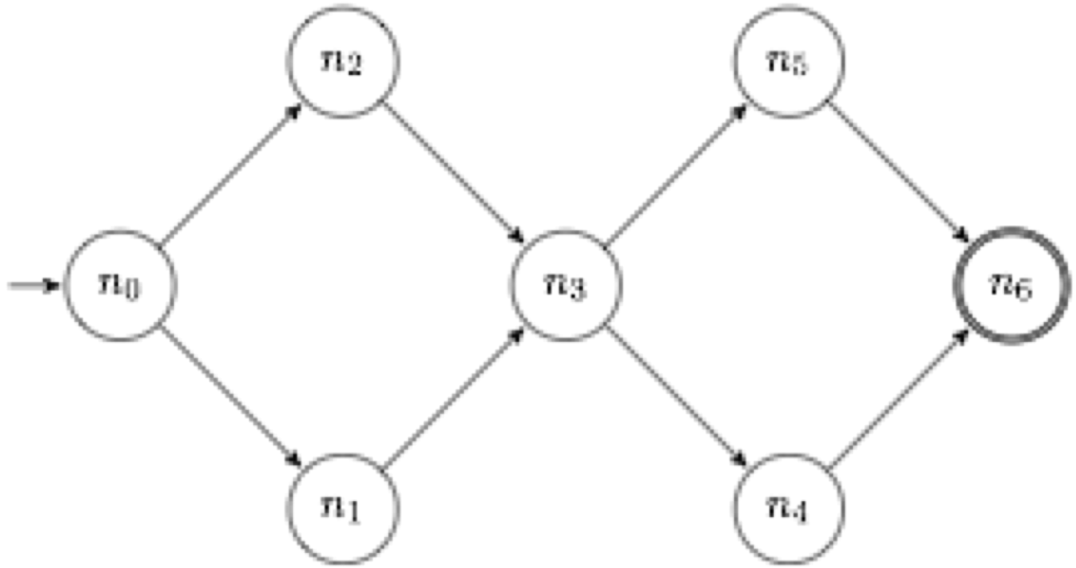
Connecting Test Cases, Test Paths, and CFG

```
int foo(int x) {
  if (x < 5) {
    x ++;
  } else {
    x --;
  }
  return x;
}
```



- Test case: $x = 5$; test path: $[(1),(3),(4)]$.
- Test case: $x = 2$; test path: $[(1),(2),(4)]$.

Node Coverage



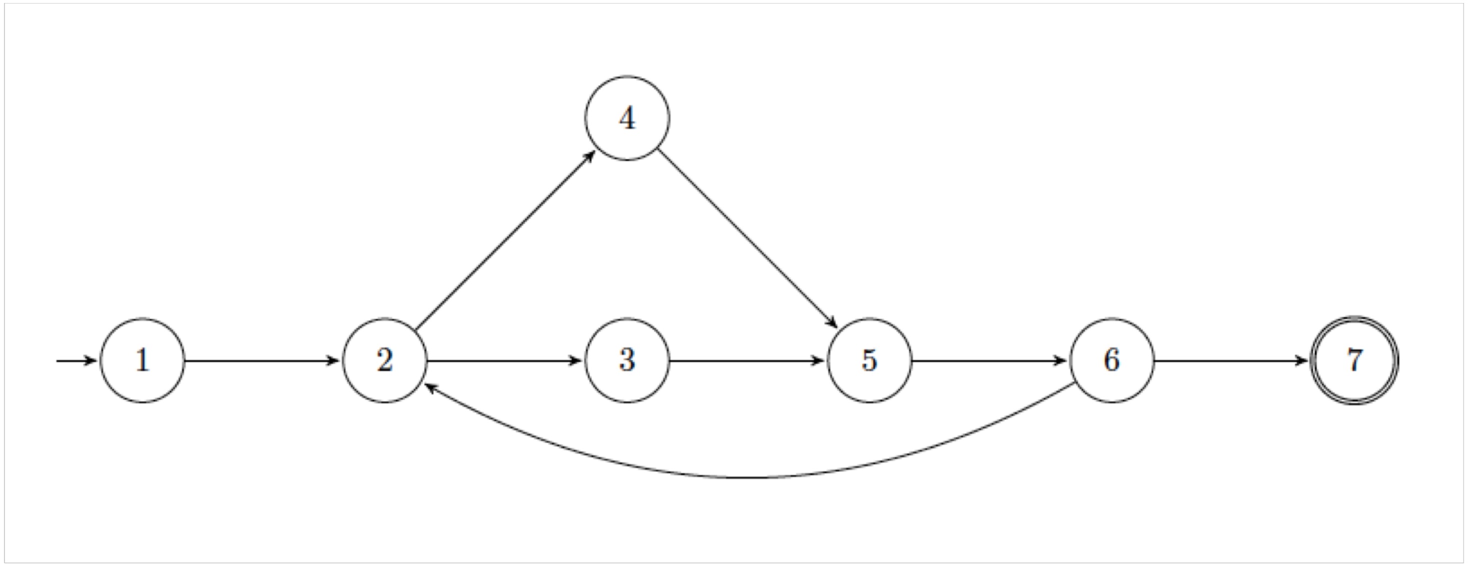
Node coverage: For each node $n \in reachG[N_0]$, TR contains a requirement to visit node n.

*Node Coverage [NC]: TR contains each **reachable** node in G.*

TR = {n0,n1,n2,n3,n4,n5,n6}

a.k.a. statement coverage

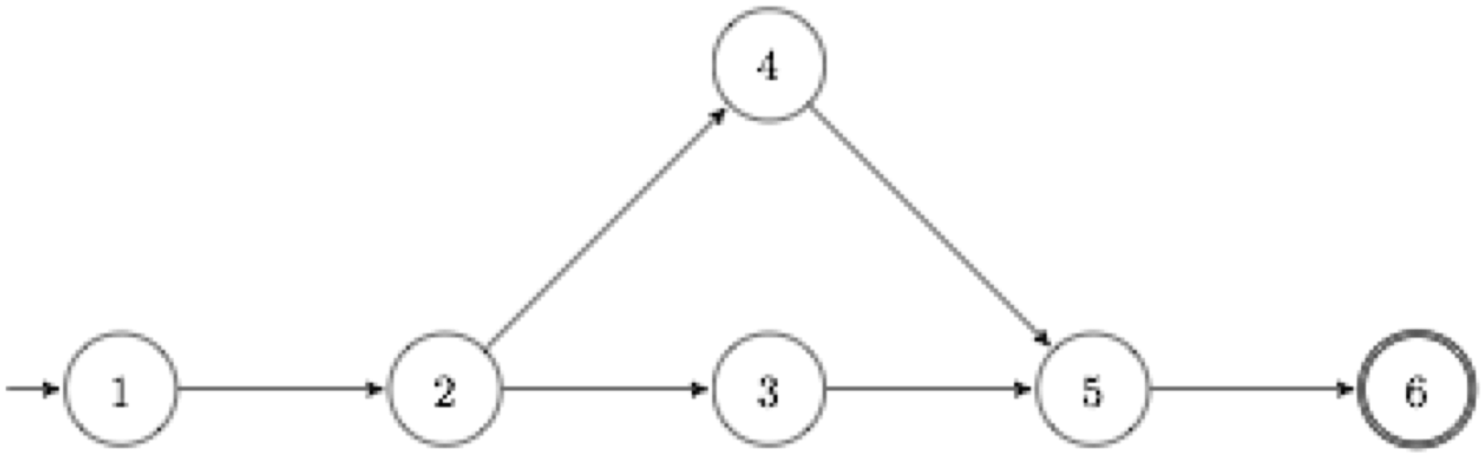
Edge Coverage (a.k.a. Branch Coverage)



*Edge Coverage [EC]: TR contains each **reachable** path of length up to 1, inclusive, in G.*

TR = {[1,2], [2,4], [2,3], [3,5], [4,5], [5,6] [6,7], [6,2]}

Edge Pair Coverage



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

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

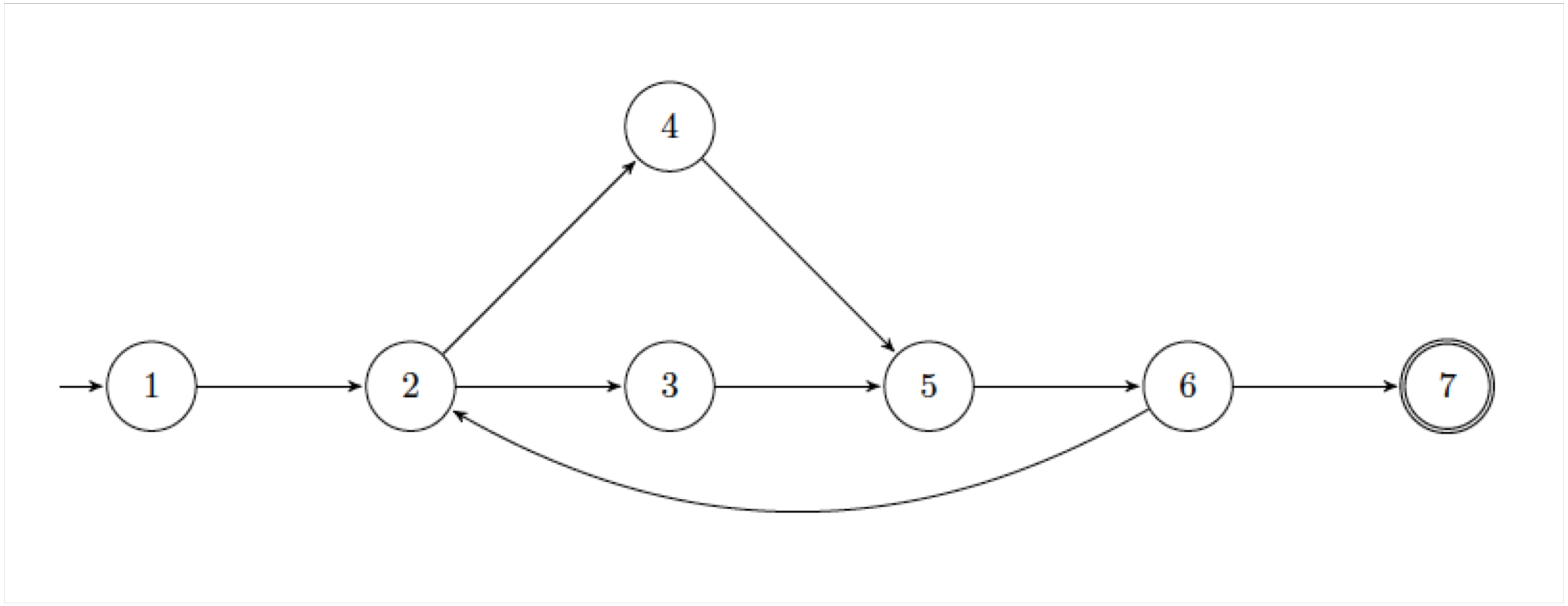
Simple Path

A path is simple if no node appears more than once in the path, except that the first and last nodes may be the same.

Some properties of simple paths:

- no internal loops;
- can bound their length;
- can create any path by composing simple paths; and
- many simple paths exist [too many!]

Simple Path Examples



Simple path examples:

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

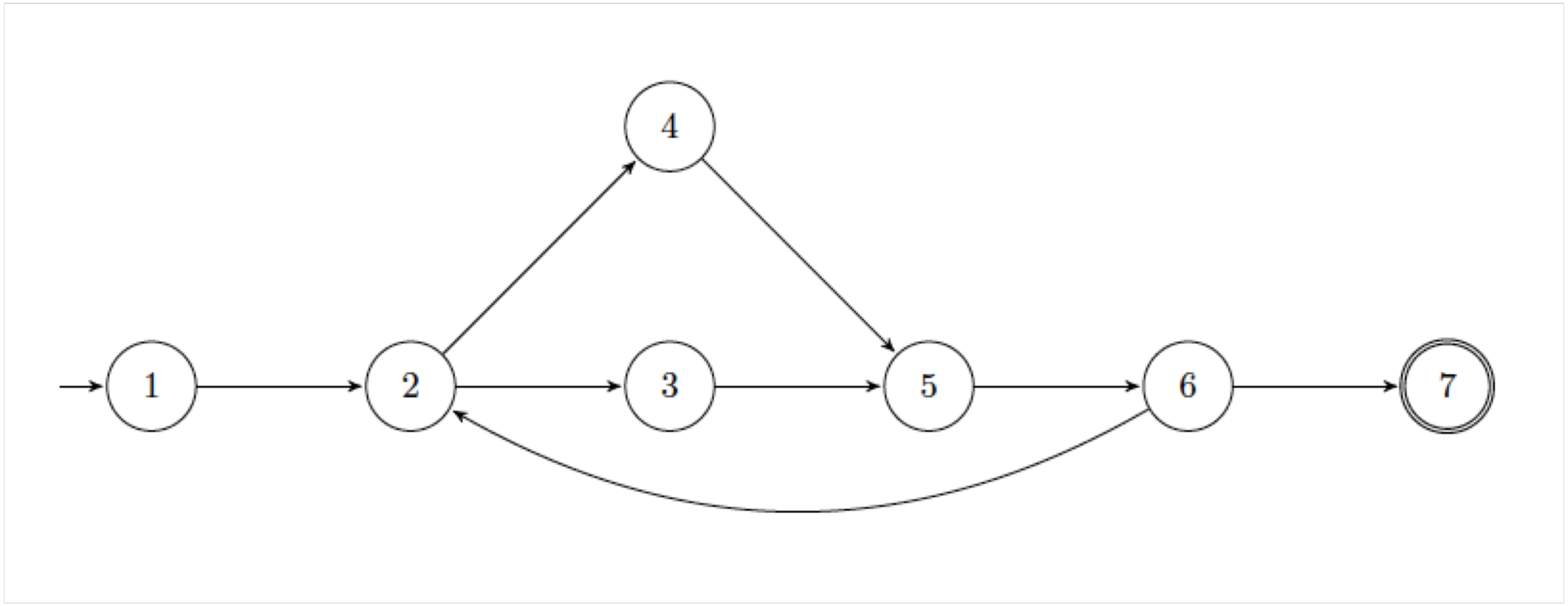
Not simple Path: [1,2,3,5,6,2,4]

Prime Path

Because there are so many simple paths, let's instead consider prime paths, which are simple paths of maximal length.

A path is prime if it is simple and does not appear as a proper subpath of any other simple path.

Prime Path Examples



Prime path examples:

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

Not a prime path: [3, 5, 6, 7]

Prime Path Coverage

Prime Path Coverage [PPC]: TR contains each prime path in G.

There is a problem with using PPC as a coverage criterion: a prime path may be infeasible but contains feasible simple paths.

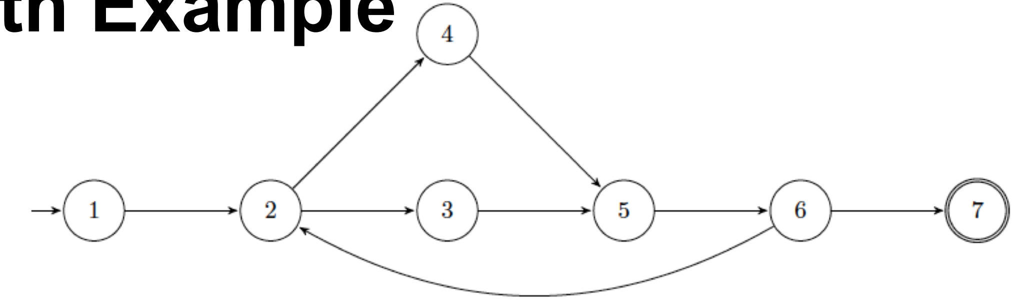
- How to address this issue?

More Path Coverage Criterions

Complete Path Coverage [CPC]: TR contains all paths in G.

Specified Path Coverage [SPC]: TR contains a specified set S of paths.

Prime Path Example



Simple paths

Len 0	Len 1	Len 2	Len 3	Len 4	Len 5
[1]	[1,2]				
[2]	[2,4]				
[3]	[2,3]				
[4]	[3,5]				
[5]	[4,5]				
[6]	[5,6]				
[7]!	[6,7]!				
	[6,2]				

53 Simple Paths
12 Prime Paths

! means path terminates

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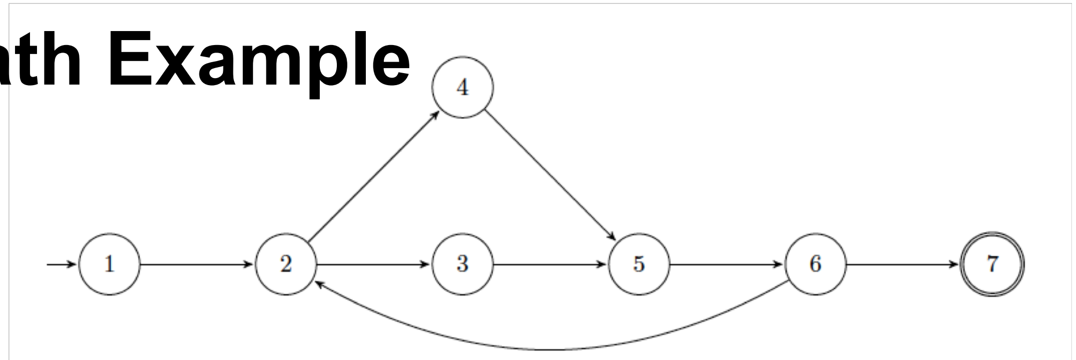
Prime Path Example



Simple paths

Len 0

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

Len 1

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

Len 2

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

Len 3

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

Len 4

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

Len 5

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

! means path terminates.

x means not prime paths.

* denotes path cycles.

Check paths without a x or *:

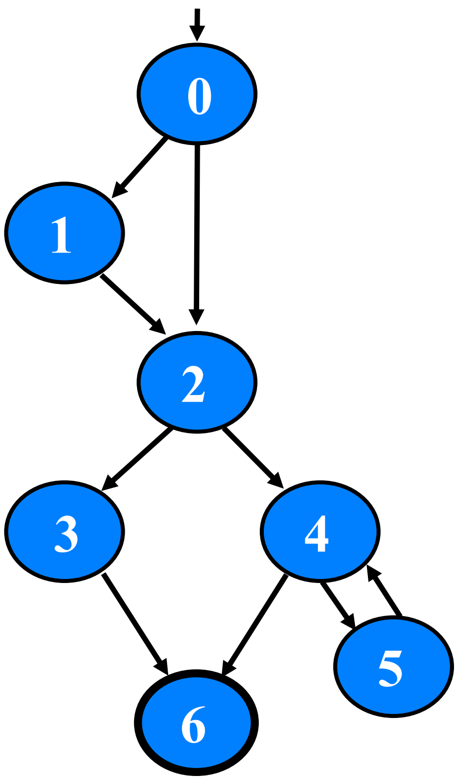
12 Prime Paths

53 Simple Paths

Prime Path Example (2)

This graph has 38 simple paths

Only 9 *prime paths*



Prime Paths

[0, 1, 2, 3, 6]
[0, 1, 2, 4, 5]
[0, 1, 2, 4, 6]
[0, 2, 3, 6]
[0, 2, 4, 5]
[0, 2, 4, 6]
[5, 4, 6]
[4, 5, 4]
[5, 4, 5]

Prime Path Example (2)

! means path terminates

Simple paths

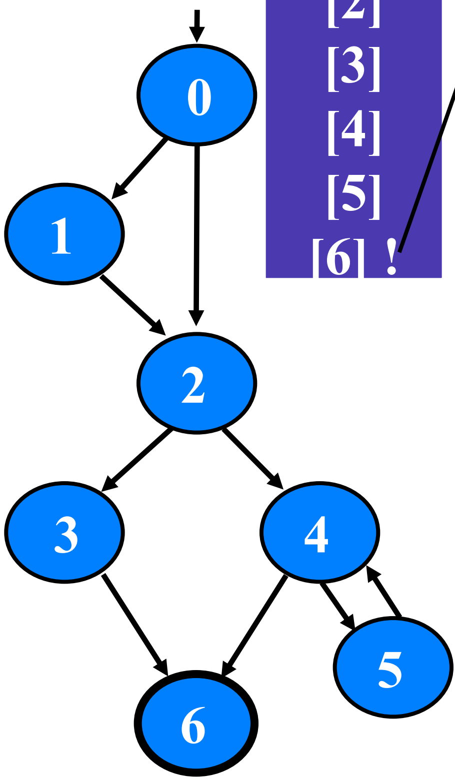
Len 0
- [0]
- [1]
- [2]
- [3]
- [4]
- [5]
- [6] !

Len 1
- [0, 1]
- [0, 2]
- [1, 2]
- [2, 3]
- [2, 4]
- [3, 6] !
- [4, 6] !
- [4, 5]
- [5, 4]

Len 2
- [0, 1, 2]
- [0, 2, 3]
- [0, 2, 4]
- [1, 2, 3]
- [1, 2, 4]
- [2, 3, 6] !
- [2, 4, 6] !
- [2, 4, 5] !
- [4, 5, 4] *
- [5, 4, 6] !
- [5, 4, 5] *

Len 3
- [0, 1, 2, 3]
- [0, 1, 2, 4]
- [0, 2, 3, 6] !
- [0, 2, 4, 6] !
- [0, 2, 4, 5] !
- [1, 2, 3, 6] !
- [1, 2, 4, 5] !
- [1, 2, 4, 6] !

Len 4
- [0, 1, 2, 3, 6] !
- [0, 1, 2, 4, 6] !
- [0, 1, 2, 4, 5] !



* denotes path cycles

9 Prime Paths

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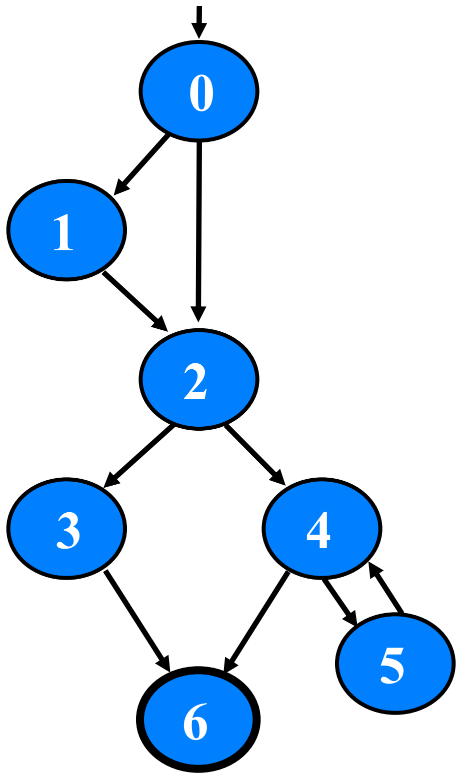
Examples of NC, EC, EPC, CPC



Node Coverage

TR = { 0, 1, 2, 3, 4, 5, 6 }

Test Paths: [0, 1, 2, 3, 6] [0, 1, 2, 4, 5, 4, 6]

Edge Coverage

TR = { [0,1], [0,2], [1,2], [2,3], [2,4], [3,6], [4,5], [4,6], [5,4] }

Test Paths: [0, 1, 2, 3, 6] [0, 2, 4, 5, 4, 6]

Edge-Pair Coverage

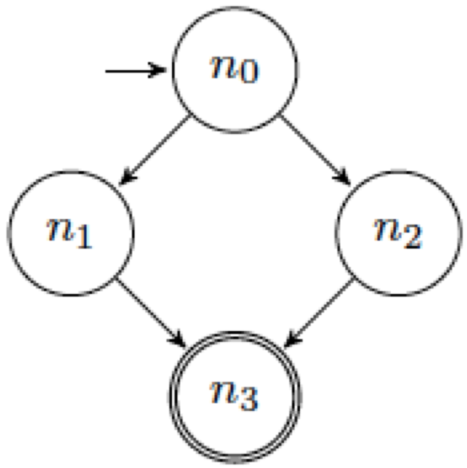
TR = { [0,1,2], [0,2,3], [0,2,4], [1,2,3], [1,2,4], [2,3,6], [2,4,5], [2,4,6], [4,5,4], [5,4,5], [5,4,6] }

Test Paths: [0, 1, 2, 3, 6] [0, 2, 3, 6] [0, 2, 4, 5, 4, 5, 4, 6] [

Complete Path Coverage

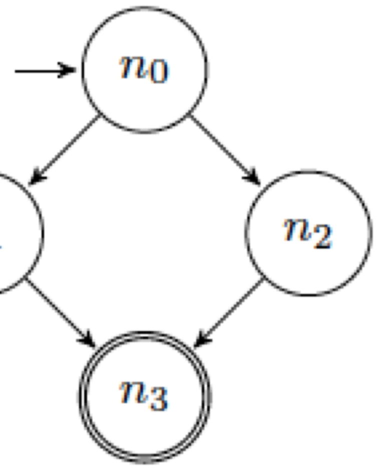
Test Paths: [0, 1, 2, 3, 6] [0, 1, 2, 4, 6] [0, 1, 2, 4, 5, 4, 6] [0, 1, 2, 4, 5, 4, 5, 4, 6] [0, 1, 2, 4, 5, 4, 5, 4, 5, 4, 6] …

Prime Path Coverage vs. Complete Path Coverage



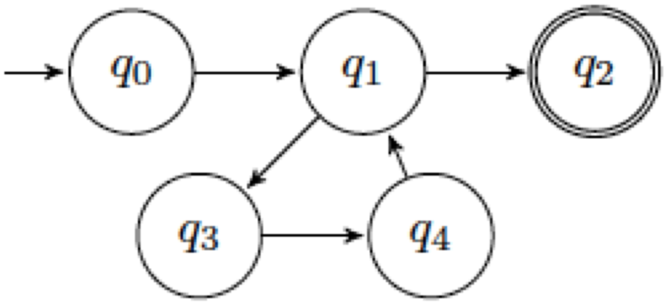
- Prime paths:
- $\text{path}(t_1) =$
- $\text{path}(t_2) =$
- $T_1 = \{t_1, t_2\}$ satisfies both PPC and CPC.

Prime Path Coverage vs. Complete Path Coverage



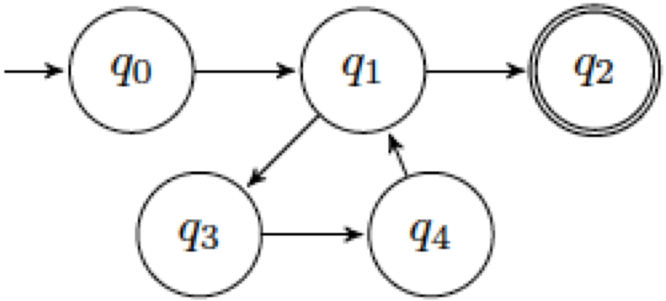
- Prime paths: [n0, n1, n3], [n0, n2, n3]
- $\text{path}(t_1) =$ [n0, n1, n3]
- $\text{path}(t_2) =$ [n0, n2, n3]
- $T_1 = \{t_1, t_2\}$ satisfies both PPC and CPC.

Prime Path Coverage vs. Complete Path Coverage (2)



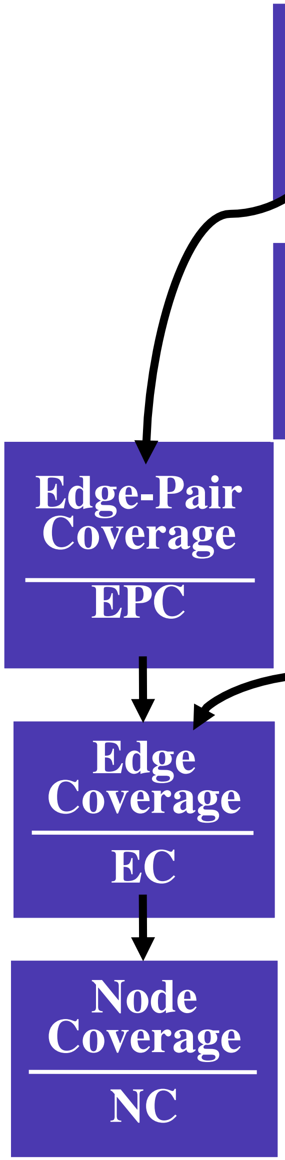
- Prime paths:
- $\text{path}(t_3) =$
- $\text{path}(t_4) =$
- $T_1 = \{t_3, t_4\}$ satisfies PPC but not CPC.

Prime Path Coverage vs. Complete Path Coverage (2)



- Prime paths: [q0, q1, q2], [q0, q1, q3, q4], [q3, q4, q1, q2], [q1, q3, q4, q1], [q3, q4, q1, q3], [q4, q1, q3, q4]
- $\text{path}(t_3) =$ [q0, q1, q2]
- $\text{path}(t_4) =$ [q0, q1, q3, q4, q1, q3, q4, q1, q2]
- $T_1 = \{t_3, t_4\}$ satisfies PPC but not CPC.

Graph Coverage Criteria Subsumption

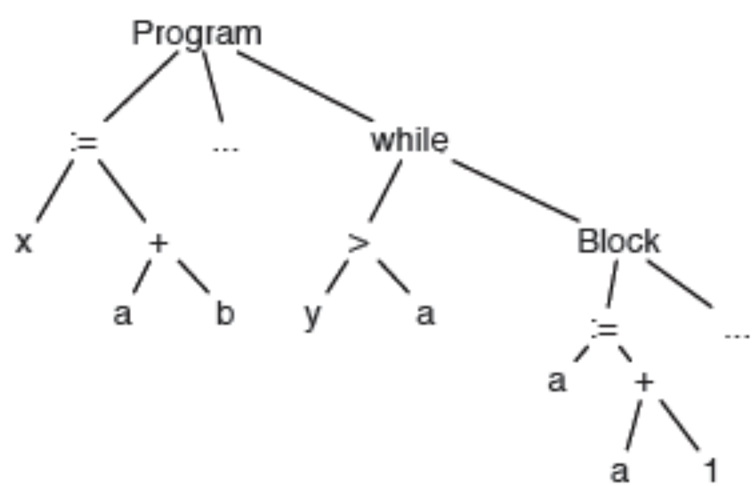


How do we measure coverage?

First:

1. Parse the source code to build an Abstract Syntax Tree (AST)
2. Analyze the AST to build a Control Flow Graph (CFG)
3. Count points of interest
   - (total # of statements, branches, etc.)
4. Instrument the AST using the CFG
   - add tracing statements in the code

```
x := a + b;
y := a * b;
while (y > a) {
    a := a + 1;
    x := a + b
}
```



How do we measure coverage?

Then:

1. Transform AST back to instrumented code
2. Recompile and run the test suite on the recompiled code
3. Collect tracing data
   - (line 1 executed, line 3 executed, etc.)
4. Calculate coverage:
   - # traced points / total # points

Coverage May Affect Test Outcomes

Heisenberg effect

- *the act of observing a system inevitably alters its state.*

Coverage analysis changes the code by adding tracing statements

Instrumentation can change program behaviour

Enabled In-code Assertions Mess Up Branch Coverage Reporting

assert P
Turned into:

```
if assertion-enabled then
    if P then skip()
    else abort()
else skip()
```

Thus 4 branches!

Reported as such

Assertions shouldn't fail

Resulting branch coverage reports:

- Not useful with assertion checking enabled
- Without it, they miss invariants

Coverage: Useful or Harmful?

Measuring coverage (% of satisfied test obligations) can be a useful indicator ...

- Of progress toward a thorough test suite, of trouble spots requiring more attention

... or a dangerous seduction

- Coverage is only a proxy for thoroughness or adequacy
- It's easy to improve coverage without improving a test suite (much easier than designing good test cases)

The only measure that really matters is **effectiveness**

EXERCISES

Exercise 1: Bridge Coverage

Bridge Coverage (BC): If removing an edge adds unreachable nodes to the graph, then this edge is a bridge. The set of test requirements for BC contains all bridges.

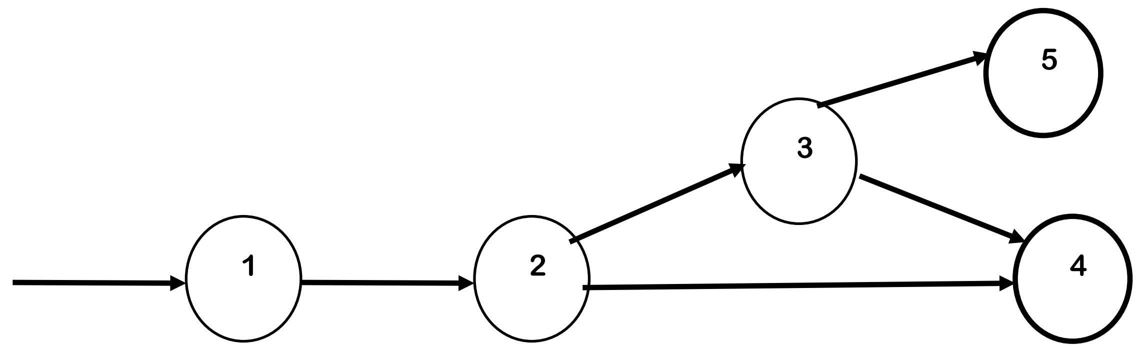
Assume that a graph contains at least two nodes, and all nodes in a graph are reachable from the initial nodes.

(a) Does BC subsume Node Coverage (NC). If yes, justify your answer. If no, give a counterexample.

(b) Does NC subsume BC? If yes, justify your answer. If no, give a counterexample

Bridge Coverage: Part (a)

Bridge Coverage does not subsume Node Coverage.



TR$_{BC}$ = {[1,2], [2,3], [3,5]}

TR$_{NC}$ = {[1, 2, 3,4, 5}

Test path [1,2,3,5] satisfies BC, but not NC because node 4 is not visited.

Bridge Coverage: Part (b)

NC subsumes BC

Key points for the proof:

- For any bridge [a, b], any test case that visits b must also visit the edge [a, b] (can be proved by contradiction).

- Any test set that satisfies NC must visit node b (TR of NC contains all nodes, including node b). Therefore, for any bridge [a, b], the test set will visit it. Therefore, NC subsumes BC.

Exercise 2 (1/2)

Answer questions [a]-[g] for the graph defined by the following sets:

- N ={1, 2, 3, 4, 5, 6, 7}
- N0 = {1}
- Nf = {7}
- E = {[1, 2], [1, 7], [2, 3], [2, 4], [3, 2], [4, 5], [4, 6], [5, 6], [6, 1]}

Also consider the following test paths:

- t0 = [1, 2, 4, 5, 6, 1, 7]
- t1 = [1, 2, 3, 2, 4, 6, 1, 7]

Exercise 2 (2/2)

[a] Draw the graph.

[b] List the test requirements for EPC. [Hint: You should get 12 requirements of length 2].

[c] Does the given set of test paths satisfy EPC? If not, identify what is missing.

[d] List the test requirements for NC, EC and PPC on the graph.

[e] List a test path that achieve NC but not EC on the graph.

[f] List a test path that achieve EC but not PPC on the graph.

Exercise 2: Partial Solutions (1/2)

[a] Draw the graph.

[b] List the test requirements for EPC. [Hint: You should get 12 requirements of length 2].

- The edge pairs are: {[1, 2, 3], [1, 2, 4], [2, 3, 2], [2, 4, 5], [2, 4, 6], [3, 2, 3], [3, 2, 4], [4, 5, 6], [4, 6, 1], [5, 6, 1], [6, 1, 2], [6, 1, 7] }

[c] Does the given set of test paths satisfy EPC? If not, identify what is missing.

- No. Neither t0 nor t1 visits the following edge-pairs: {[3, 2, 3], [6, 1, 2]}

Exercise 2: Partial Solutions (2/2)

[d] TR for NC, EC, and PPC.

- TR_{NC} =
- TR_{EC} =
- TR_{PPC} = {[3, 2, 4, 6, 1, 7], [3, 2, 4, 5, 6, 1, 7], [4, 6, 1, 2, 3], [4, 5, 6, 1, 2, 3], [3, 2, 3], [2, 3, 2], [1, 2, 4, 5, 6, 1], [1, 2, 4, 6, 1], [2, 4, 6, 1, 2], [2, 4, 5, 6, 1, 2], [4, 6, 1, 2, 4], [4, 5, 6, 1, 2, 4], [5, 6, 1, 2, 4, 5], [6, 1, 2, 4, 6], [6, 1, 2, 4, 5, 6]}

[e] A test path that achieve NC but not EC.

- [1, 2, 3, 2, 4, 5, 6, 1, 7] does not cover edge [4, 6].

[f] A test path that achieve EC but not PPC.

- [1, 2, 3, 2, 4, 5, 6, 1, 2, 4, 6, 1, 7] does not cover prime paths such as [3,2,3].