

Testing: Coverage and Structural Coverage

Testing, Quality Assurance, and Maintenance
Fall 2023

Prof. Arie Gurfinkel

based on slides by Prof. Marsha Chechik and Prof. Lin Tan, and Prof.
Patrick Lam



Introduction to Software Testing



How would you test this program?

$\text{floor}(x)$ 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
```

Complete Testing?

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

The number of potential inputs is astronomical.

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

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]
- $TR = \{\text{flavor}=\text{chocolate}, \text{flavor}=\text{vanilla}, \text{flavor}=\text{mint}\}$

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

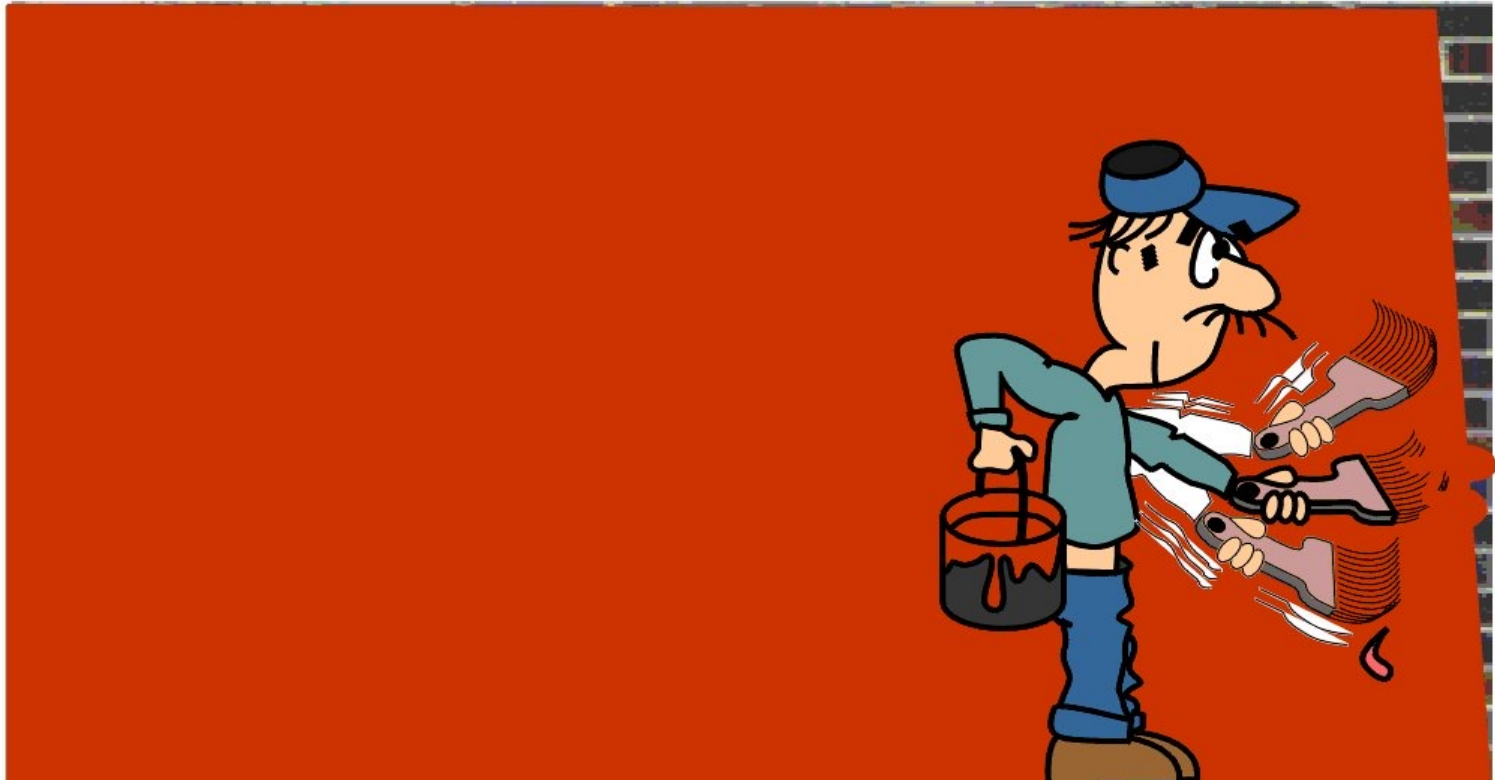
- Models used in specification or design, or derived from code
- Example: Exercise all transitions in communication protocol model

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



Advanced 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
- ...

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 basic blocks of control flow graph

Control Flow Graph (CFG)

Represents the flow of execution in the program

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

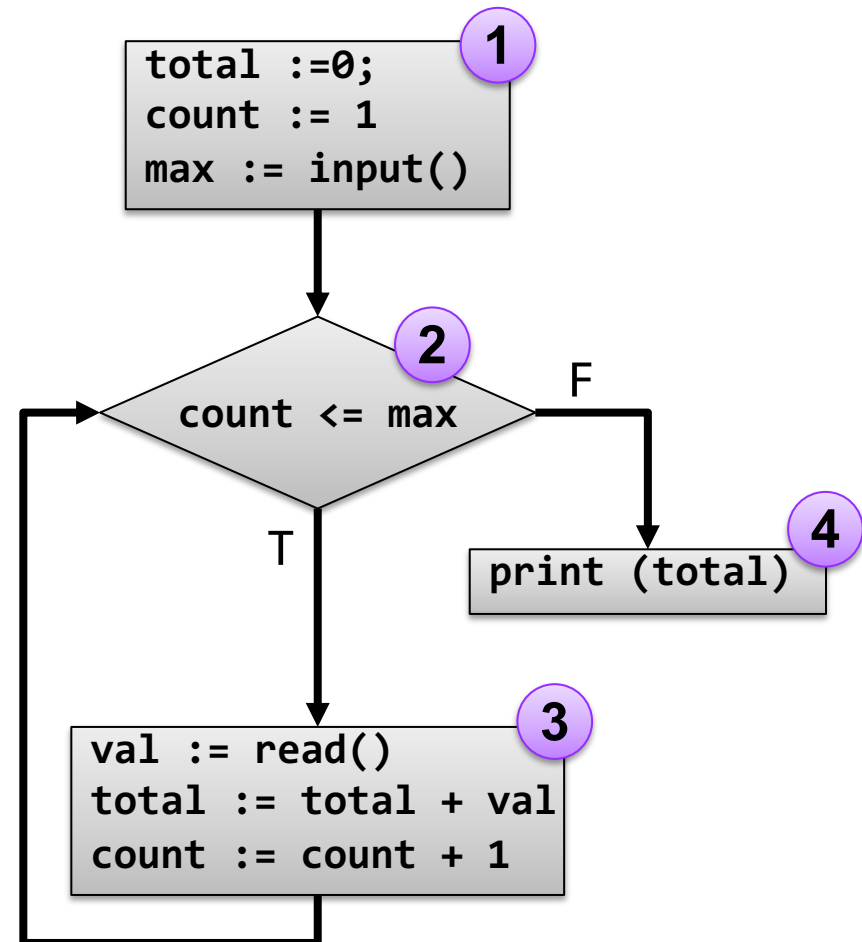
- the nodes N represent executable instructions (statement, statement fragments, or basic blocks);
- the edges E represent the **potential** transfer of control;
- S is a designated start node;
- T is a designated final node
- $E = \{ (n_i, n_j) \mid \text{syntactically, the execution of } n_j \text{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

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

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

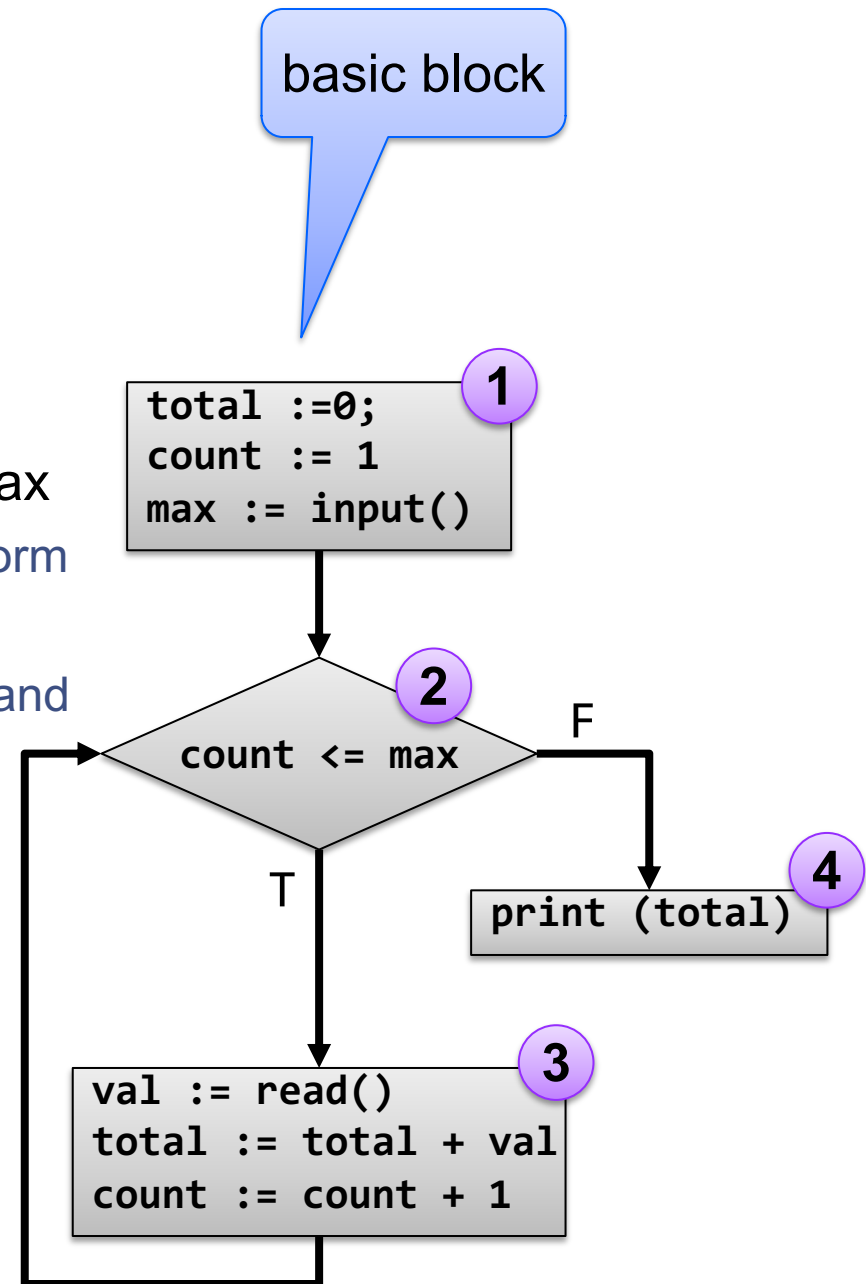
- edges represent different control flow

A CFG corresponds to a program syntax

- where statements are restricted to the form

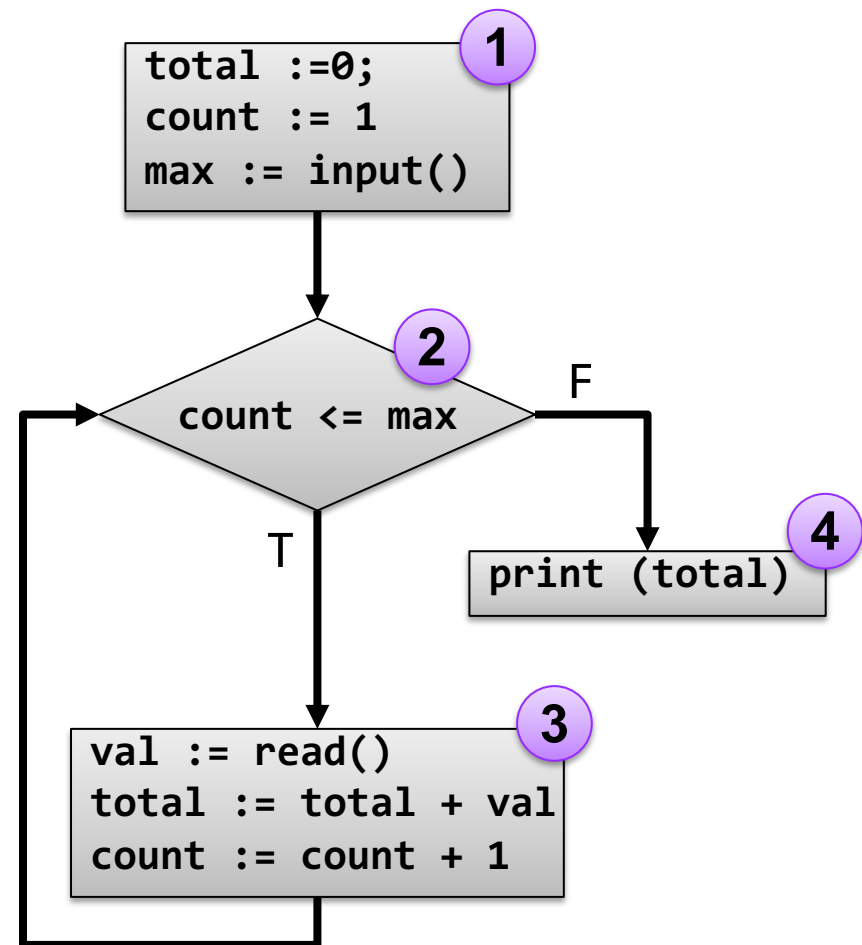
$L_i:S ; \text{goto } L_j$

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 cldx = 0; cldx < argStr.length(); cldx++)
```

```
    {  
        char ch = argStr.charAt(cldx);  
        if (ch != '\n' || last != '\n')
```

```
        {  
            argBuf.append(ch);  
            last = ch;
```

```
        }  
    }  
    return argBuf.toString();  
}
```

```
public static String collapseNewlines(String argStr)
```

```
{  
    char last = argStr.charAt(0);  
    StringBuffer argBuf = new StringBuffer();  
    for (int cldx = 0 ;
```

```
        cldx < argStr.length();
```

```
        False      True
```

```
{  
    char ch = argStr.charAt(cldx);  
    if (ch != '\n'
```

```
        False      True  
        || last != '\n')
```

```
{  
    argBuf.append(ch);  
    last = ch;
```

```
        False
```

```
        }  
        cldx++;
```

```
    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:

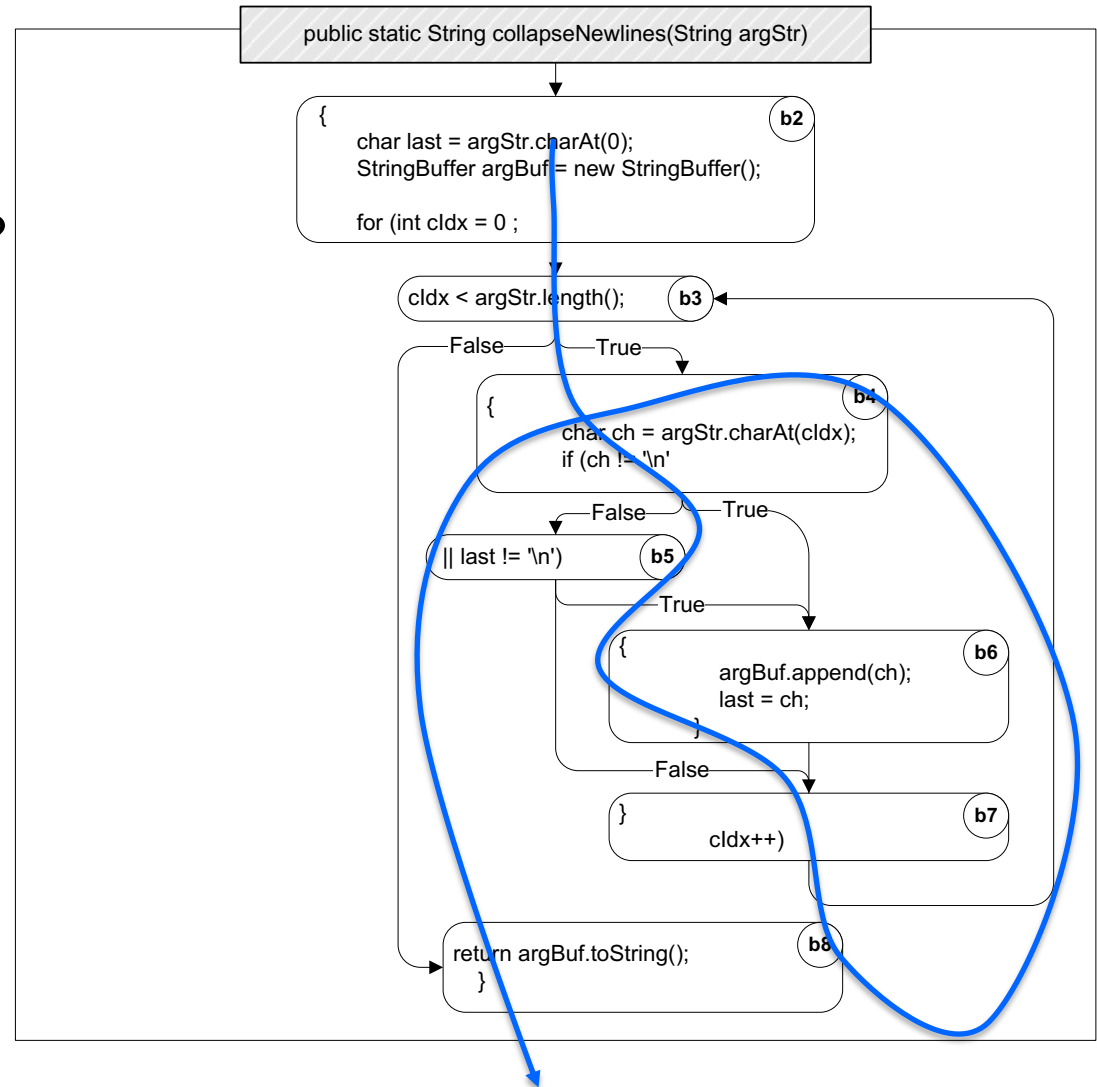
$$\frac{\text{\# executed statements}}{\text{\# statements}}$$

Control Flow Based Adequacy Criteria

How many inputs needed
to cover every basic block?

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:

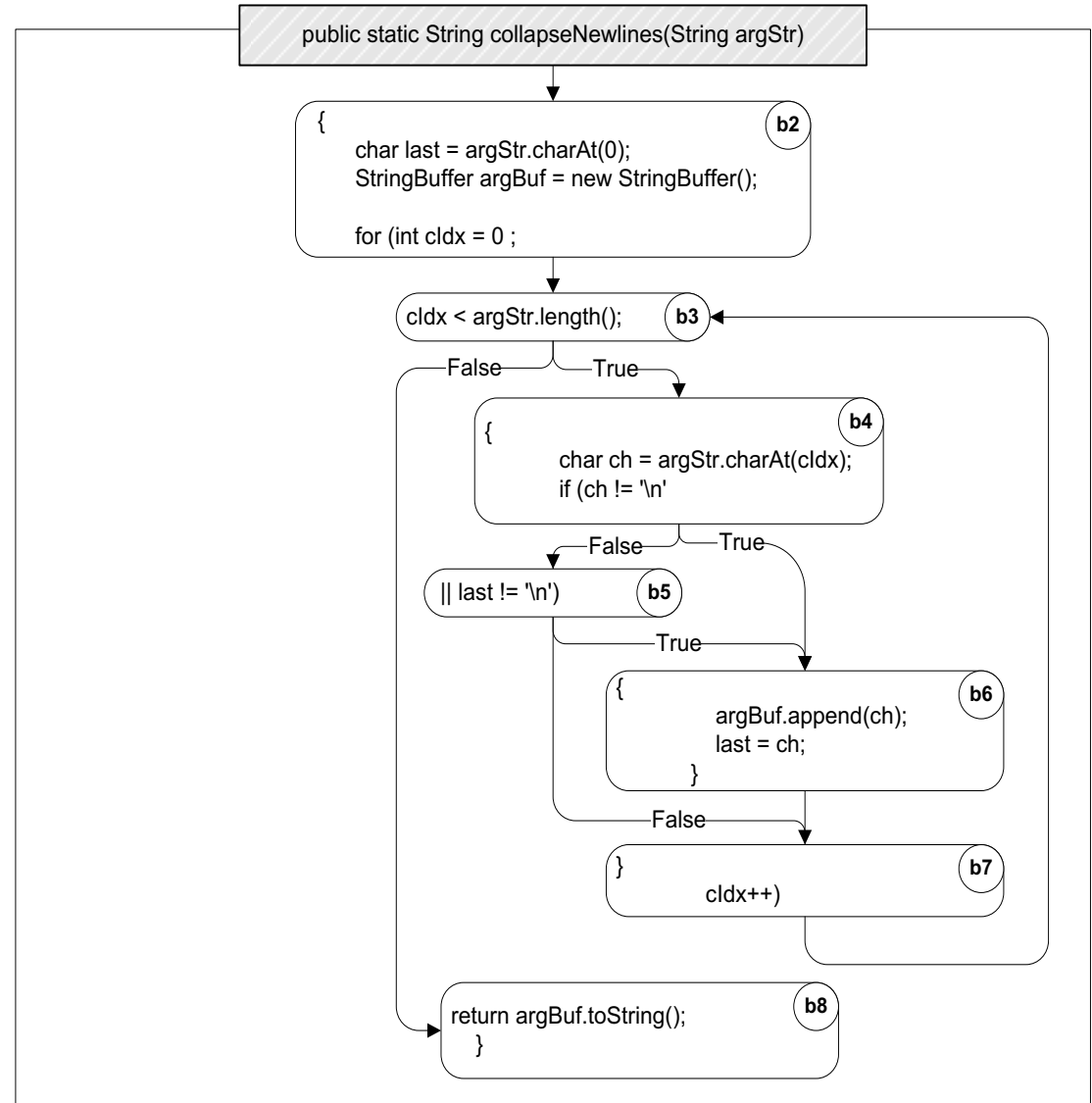
“a\n\n”

Alternatively:

Block (“a”) and

“\n” and

“\n\n”



Infeasible Test Requirements

Real programs almost always contain unreachable code

- Automatically generated code that is not used
- Defensive programming creates dead code
- Macro expansion, inlining, ...
- Testing code
- ...

Therefore, complete statement coverage is impossible for most real programs

More generally, not all test requirements are feasible

- Test requirements that are not possible are called **infeasible**
- In practice, identifying infeasible TRs can be very hard
- Whenever possible, they have to be explained and lack of coverage justified

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

```
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()
```

Calls to
assertXXX()
methods indicate
test results

Entry point for the
test when ran from
command line

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

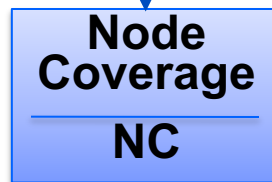
Subsumption

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



subsumes



Which one is stronger?

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

More powerful coverage criterion MIGHT 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.

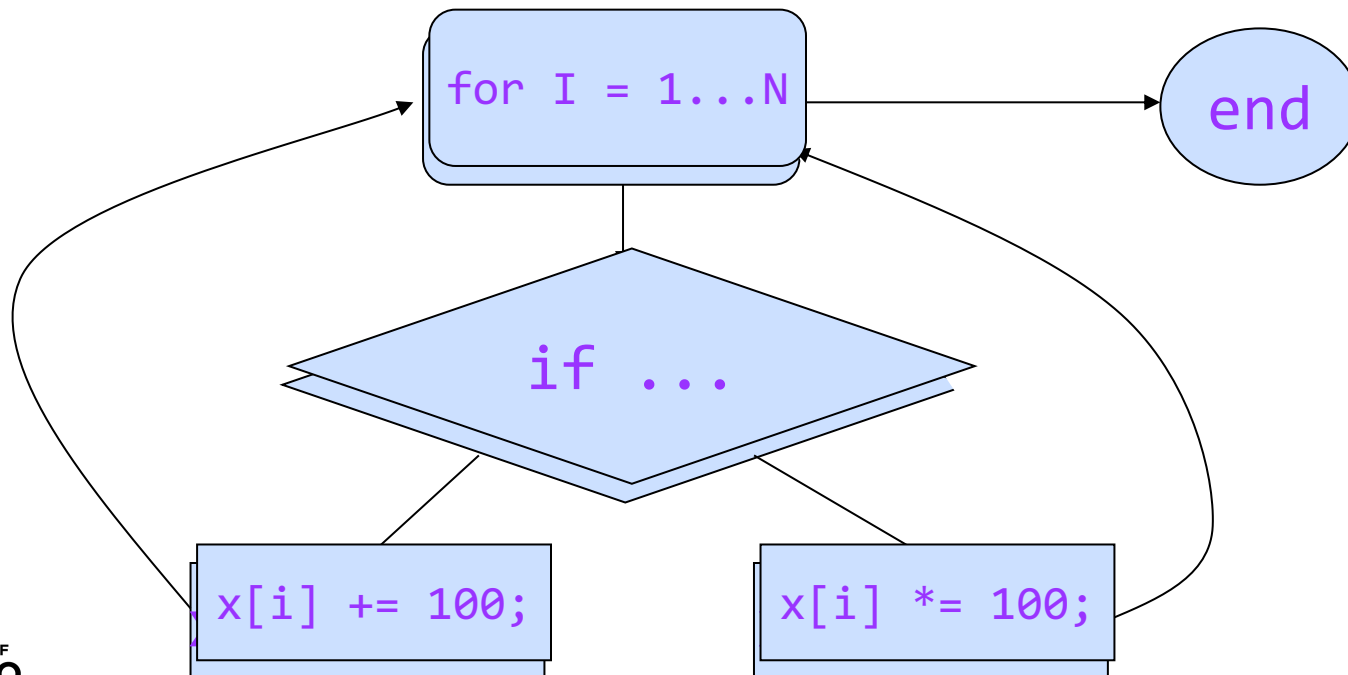
Path [N1, N3, N4, N5]: buffer overflow bug!

Path Coverage

Adequacy criterion: each path must be executed at least once

Coverage:

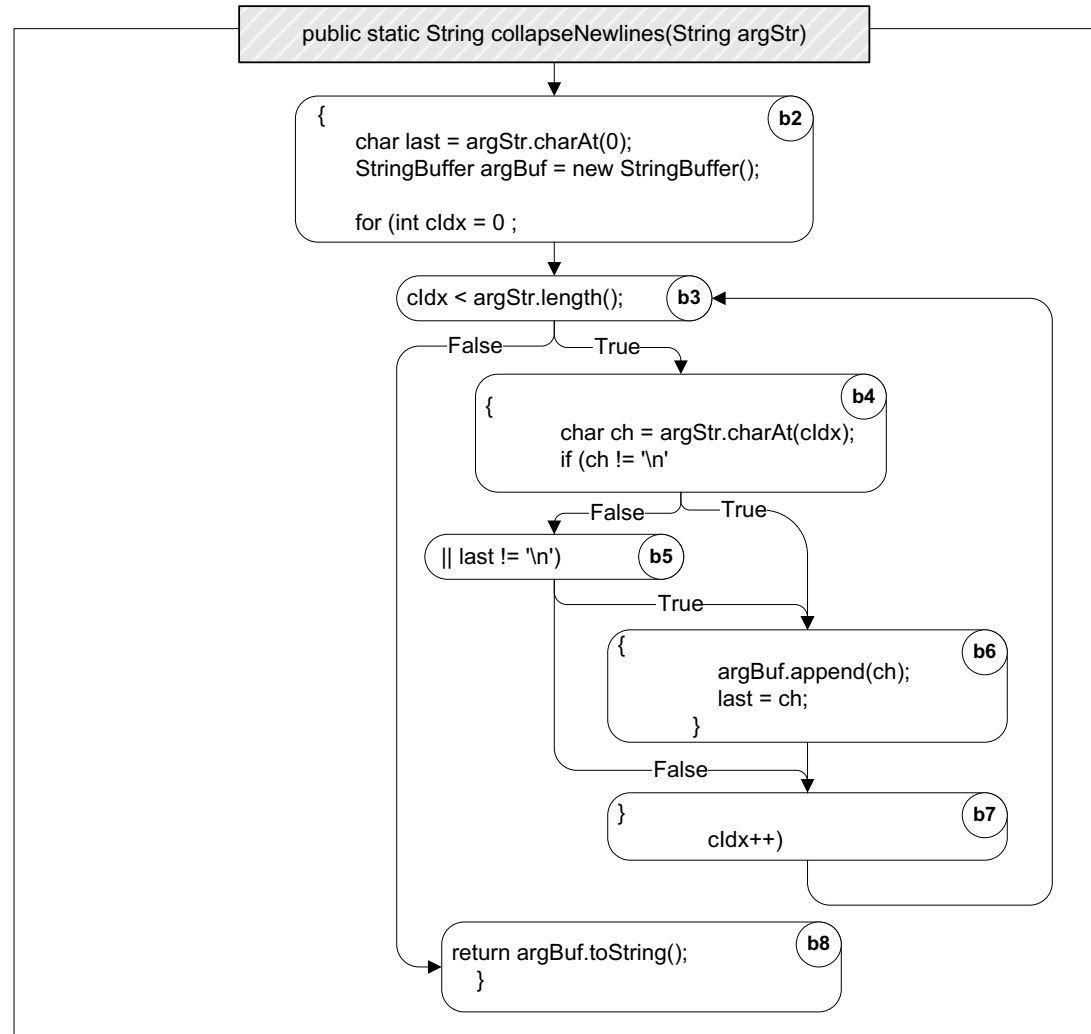
$$\frac{\text{\# executed paths}}{\text{\# paths}}$$



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();
```

How many test cases to achieve branch coverage?

Two, for example:

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

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

Branch vs Path Coverage

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

How about path
coverage?

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

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

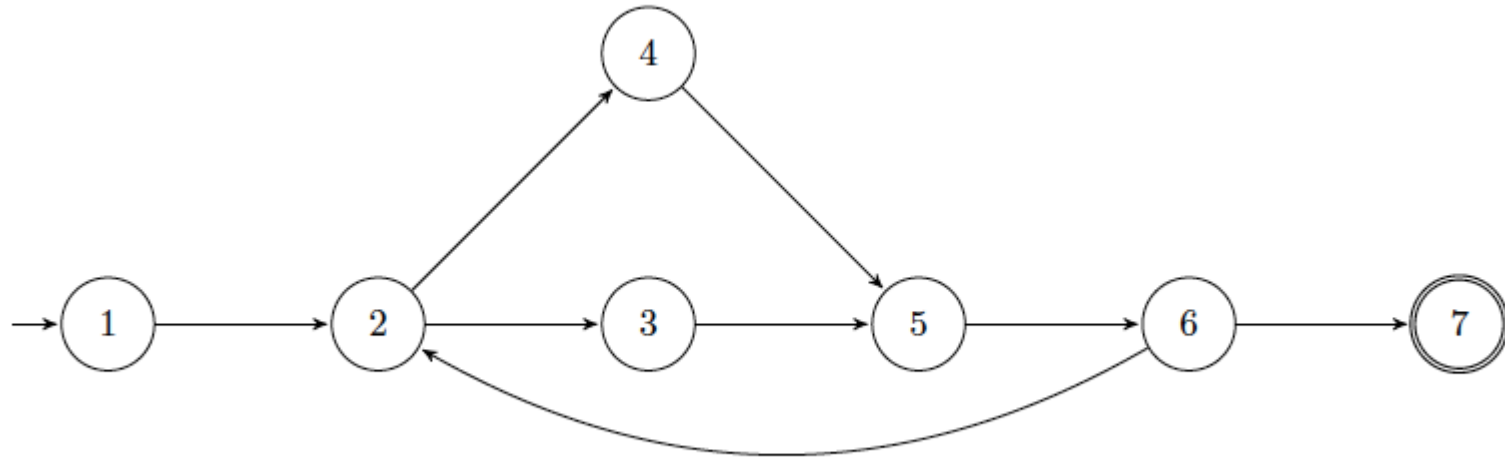
Branch vs Path Coverage

```
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

Path and Test Path



A sequence of nodes connected by edges is called a **path**

A **test path** is a path p [possibly of length 0] that starts at some node in N_0 (initial node) and ends at some node in N_f (the final node)

Test path examples:

- $[1, 2, 3, 5, 6, 7]$ $[1, 2, 3, 5, 6, 2, 3, 5, 6, 7]$
- Path, but not test path: $[2, 4, 5, 6]$

Syntactical and Semantic Reachability

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

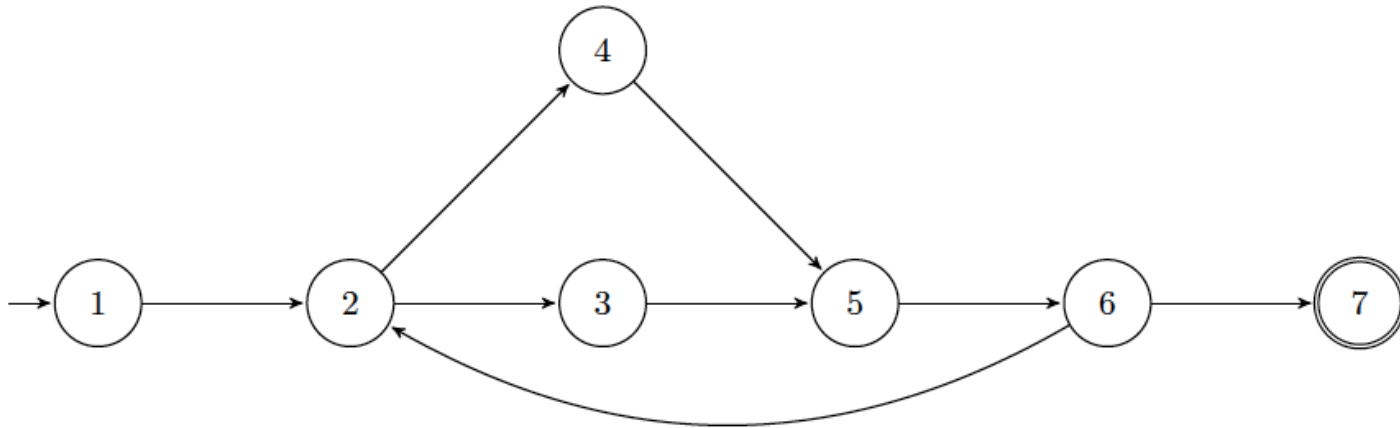
A node n is *semantically* reachable if one of the paths from m to n can be reached on some input.

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

Semantic reachability is undecidable.

Reachability

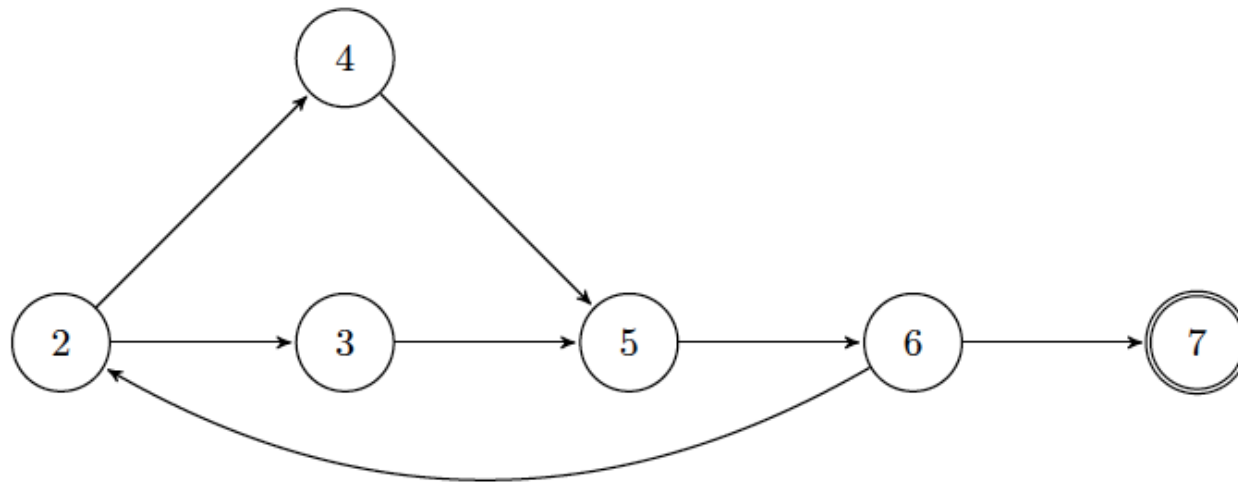
Let $\text{reach}_G(X)$ denote the sub-graph of G that is (syntactically) reachable from X , where X is either a node, an edge, a set of nodes, or a set of edges.



In this example, $\text{reach}_G(1)$ 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

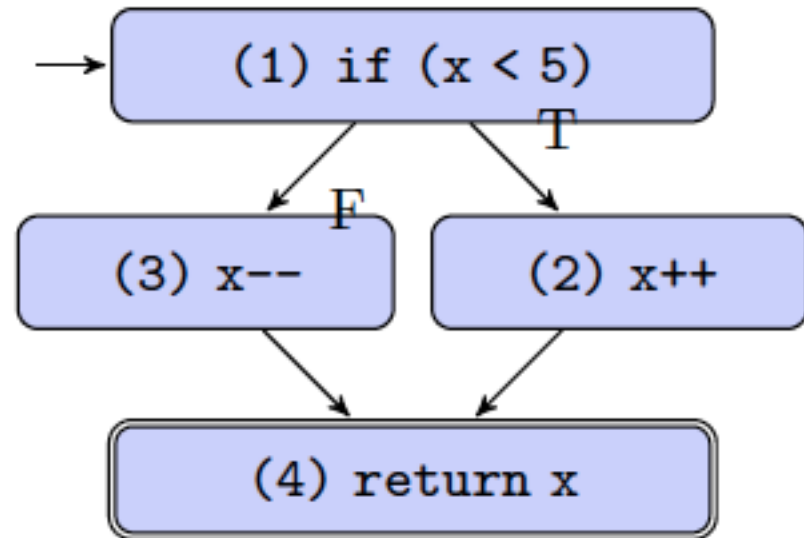
- e.g., $path_G[t]$ is the set of test paths corresponding to a test case t
 - the set of all paths in G that are executed when input t is evaluated
- Usually just write $path(t)$, as G is obvious from the context
- Lift the definition of path to test set T by defining $path(T)$

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

- 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.

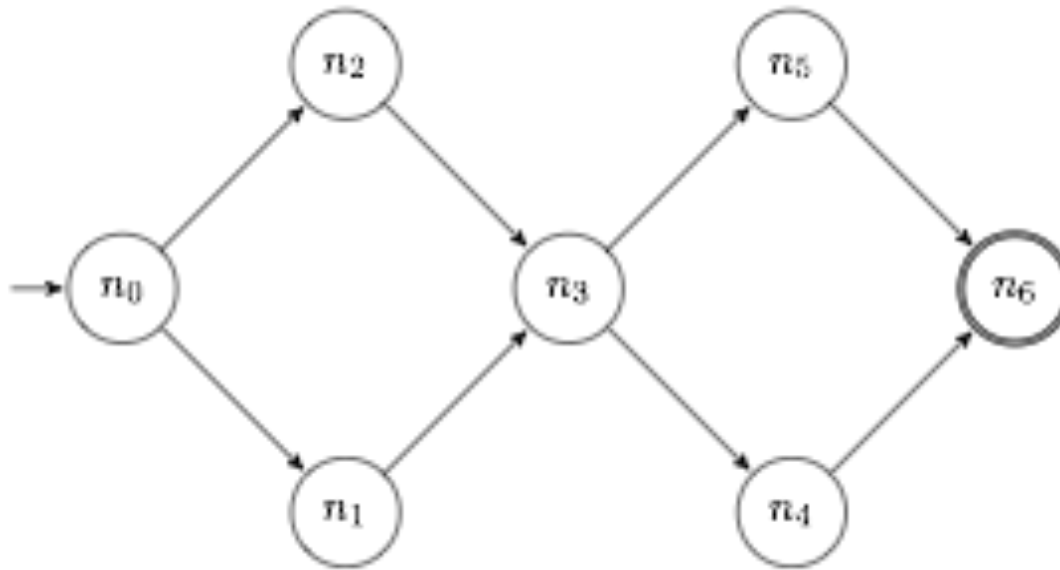
Connecting Test Cases, Test Paths, and CFG

```
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



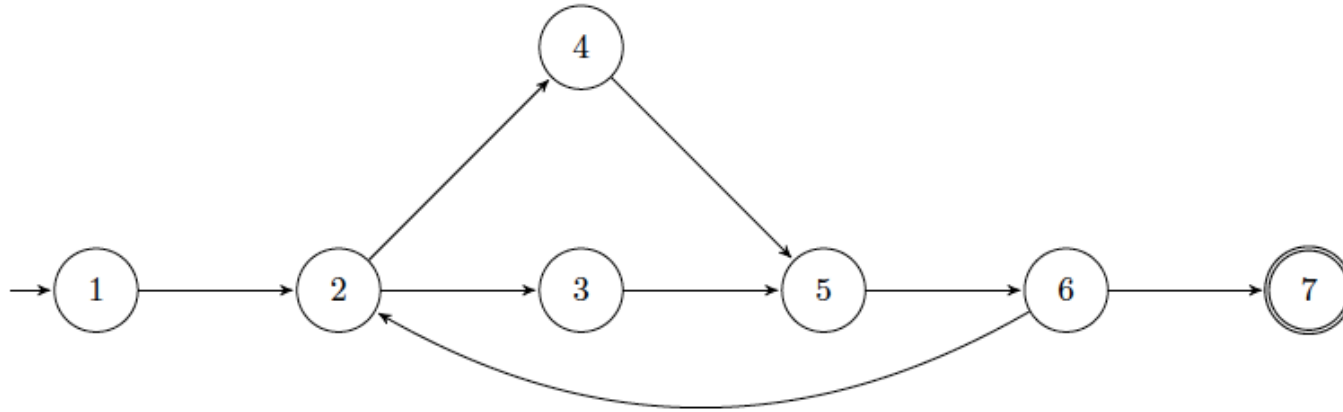
Node coverage: For each node $n \in \text{reachG}[N_0]$, TR contains a requirement to visit node n .

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

$\text{TR} = \{n_0, n_1, n_2, n_3, n_4, n_5, n_6\}$

a.k.a. statement coverage or basic block coverage

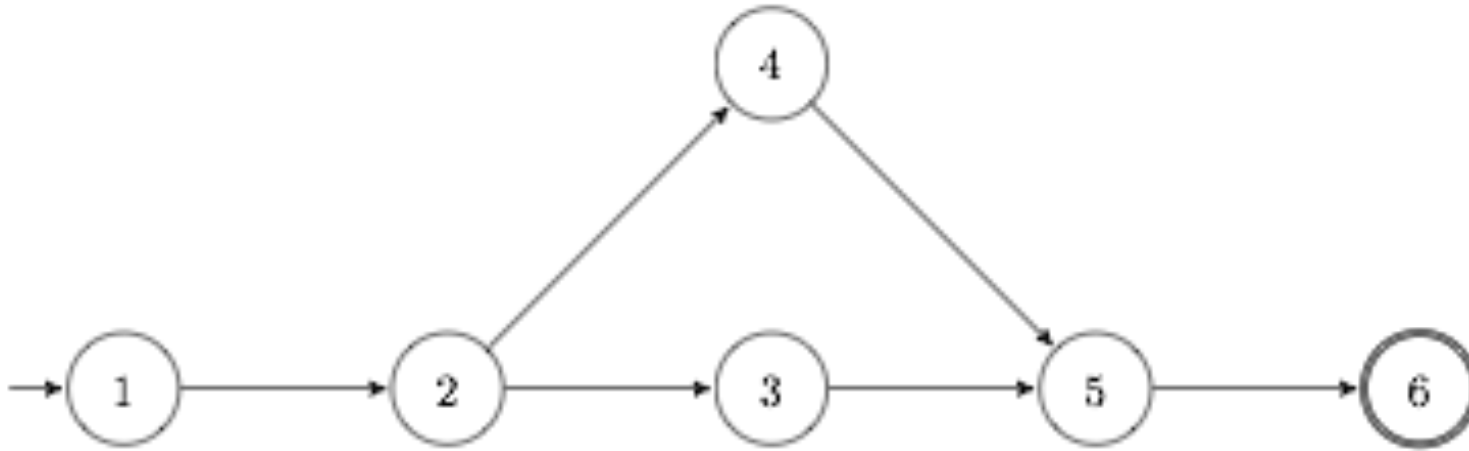
Edge Coverage (a.k.a. Branch Coverage)



*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.*

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

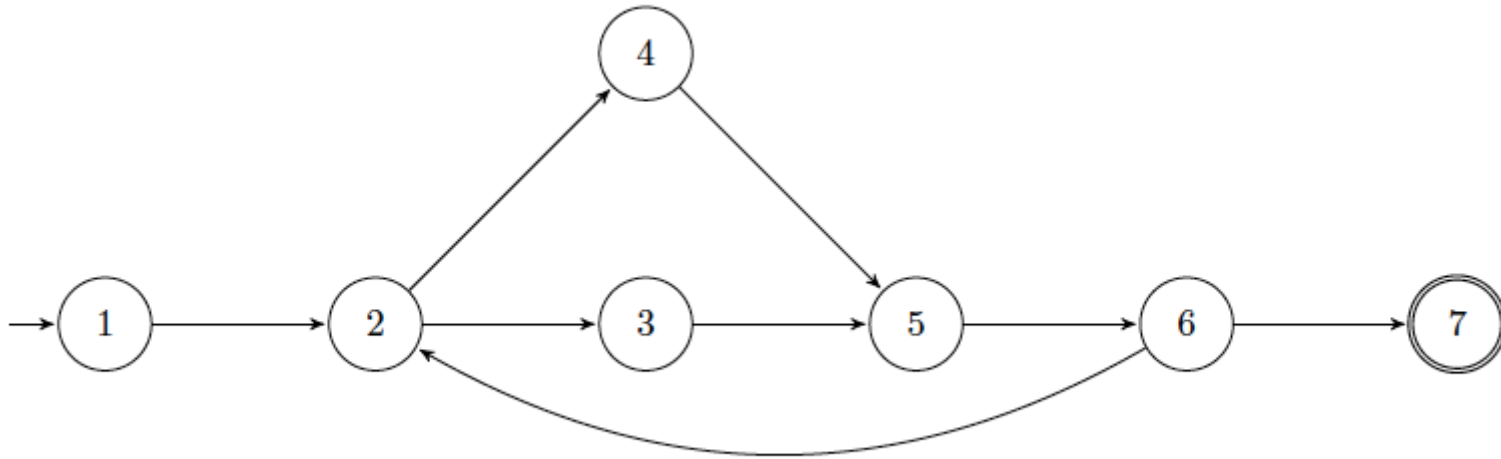
Simple Path

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]

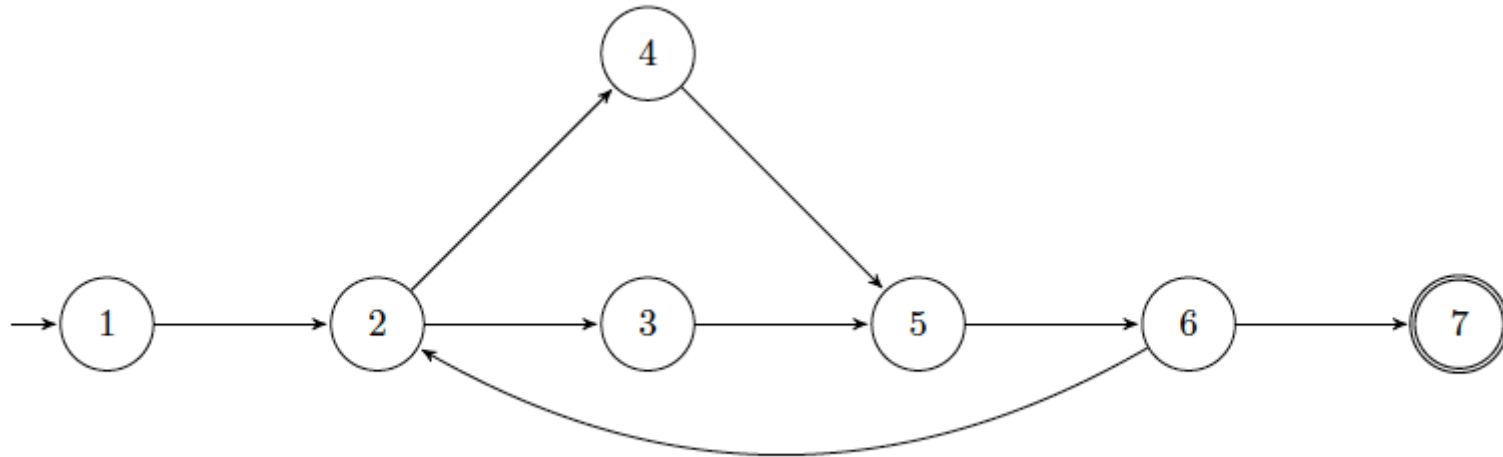
Not simple Path: [1, 2, 3, 5, 6, 2, 4]

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

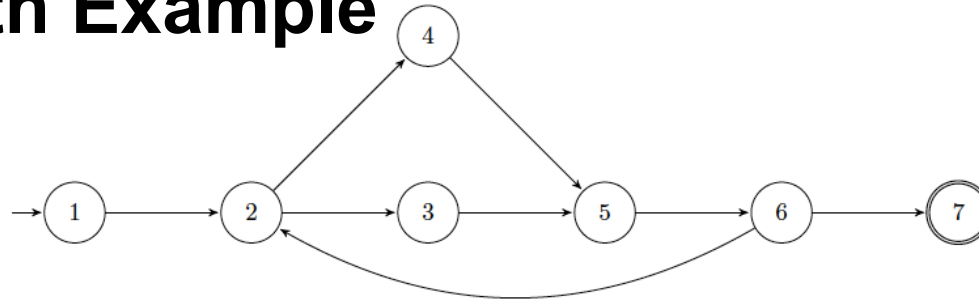
Prime Path Coverage [PPC]: TR contains each prime path in G .

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?

Prime Path Example

Simple
paths



Len 0

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

Len 1

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

Len 2

Len 3

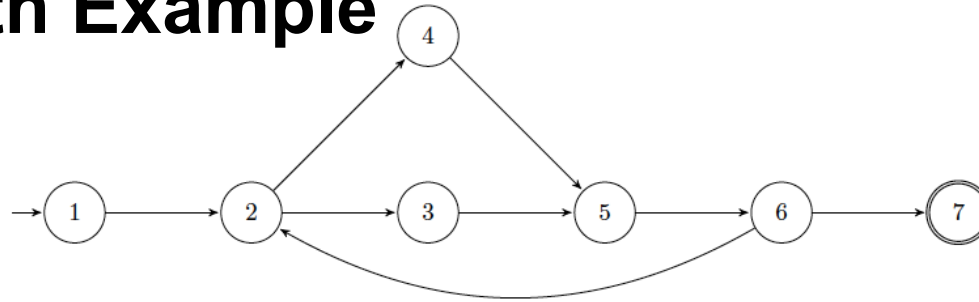
Len 4

Len 5

! means path terminates

53 Simple Paths
12 Prime Paths

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] !

**Check paths
without a x or *:**

12 Prime Paths

53 Simple Paths

! means path terminates.

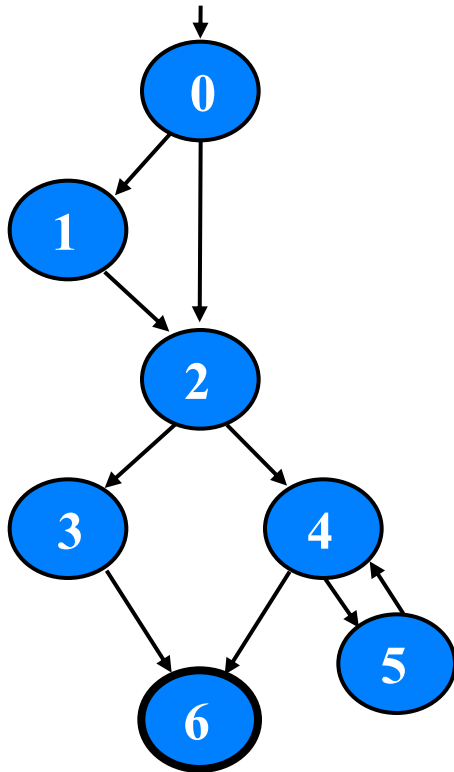
x means not prime paths.

* denotes path cycles.

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]

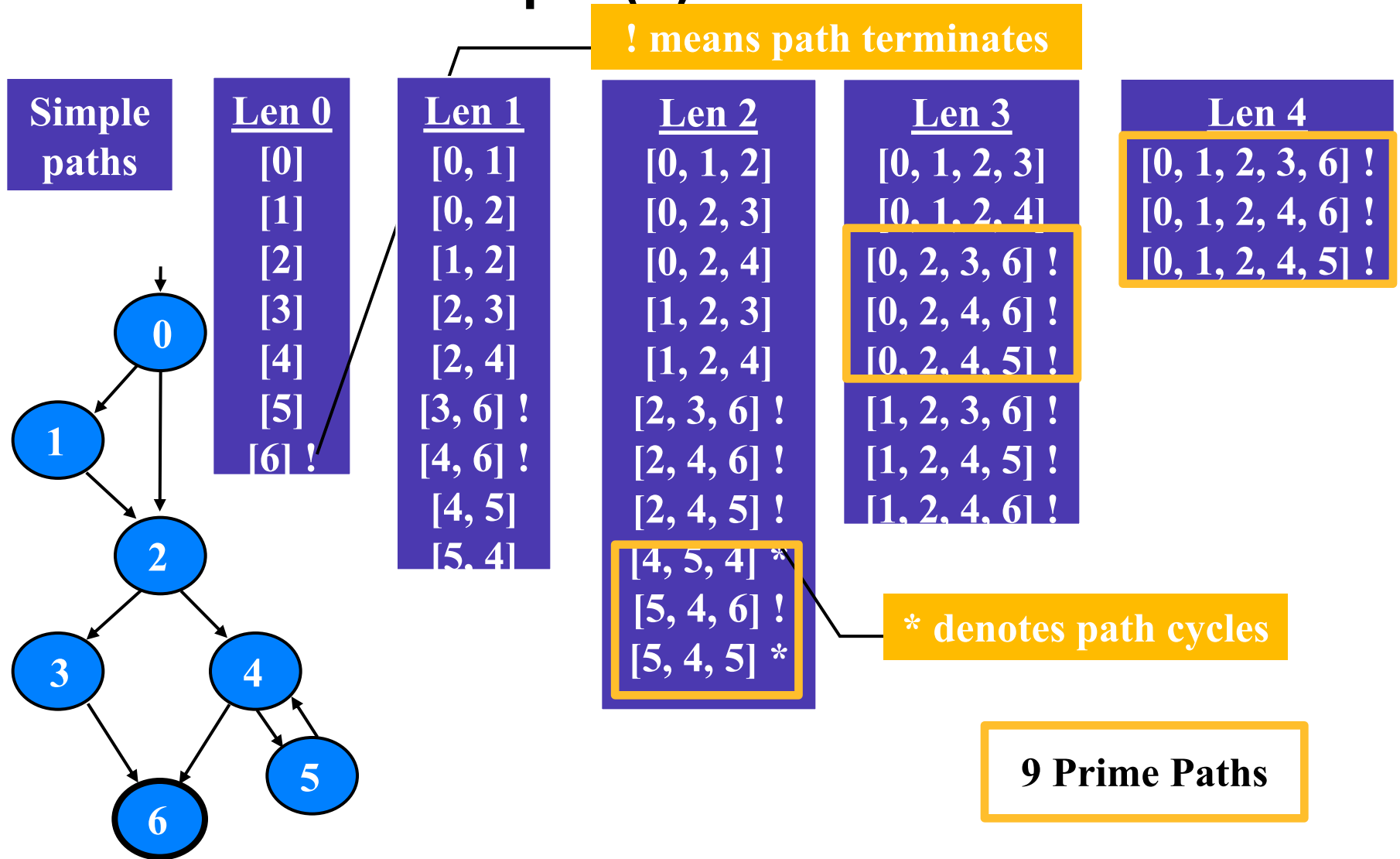
[0, 2, 4, 6]

[5, 4, 6]

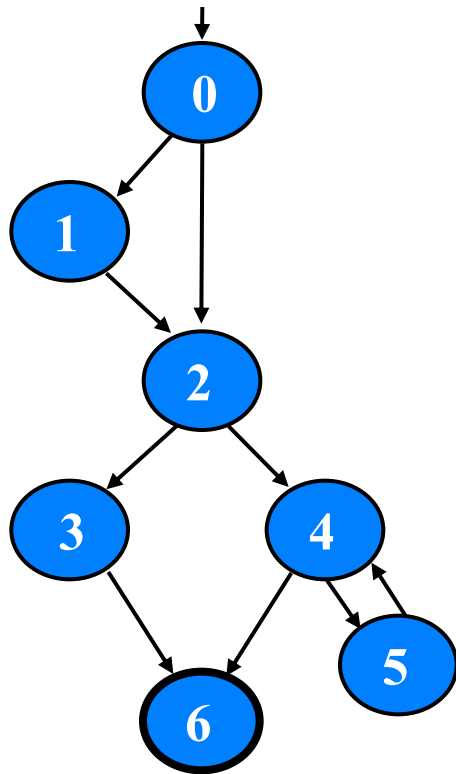
[4, 5, 4]

[5, 4, 5]

Prime Path Example (2)



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

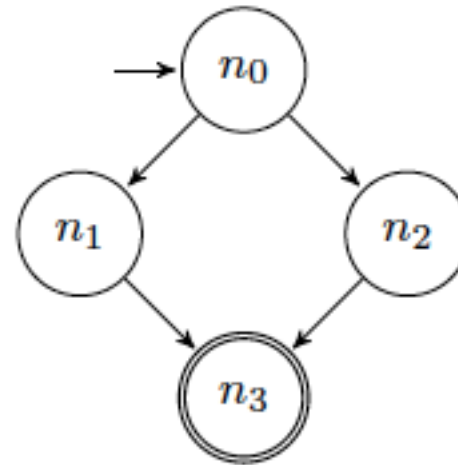
TR = { [0,1,2], [0,2,3], [0,2,4], [1,2,3], [1,2,4], [2,3,6],
[2,4,5], [2,4,6], [4,5,4], [5,4,5], [5,4,6] }

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

Complete Path Coverage

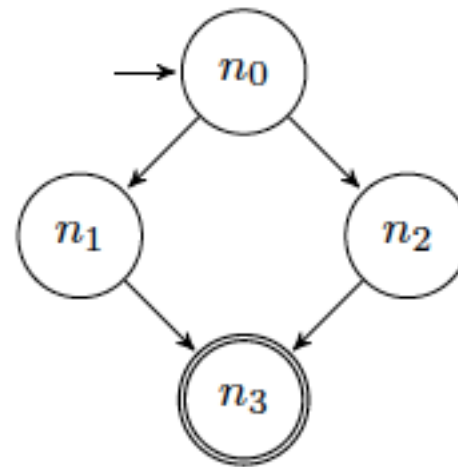
Test Paths: [0, 1, 2, 3, 6] [0, 1, 2, 4, 6] [0, 1, 2, 4, 5, 4, 6]
[0, 1, 2, 4, 5, 4, 5, 4, 6] [0, 1, 2, 4, 5, 4, 5, 4, 5, 4, 6] ...

Prime Path Coverage vs. Complete Path Coverage



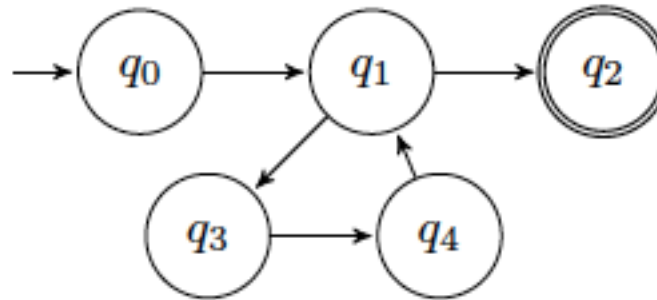
- Prime paths:
- $\text{path}(t_1) =$
- $\text{path}(t_2) =$
- $T_1 = \{t_1, t_2\}$ satisfies both PPC and CPC.

Prime Path Coverage vs. Complete Path Coverage



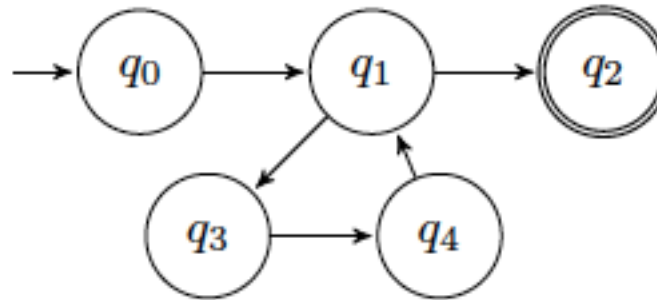
- Prime paths: $[n_0, n_1, n_3], [n_0, n_2, n_3]$
- $\text{path}(t_1) = [n_0, n_1, n_3]$
- $\text{path}(t_2) = [n_0, n_2, n_3]$
- $T_1 = \{t_1, t_2\}$ satisfies both PPC and CPC.

Prime Path Coverage vs. Complete Path Coverage (2)



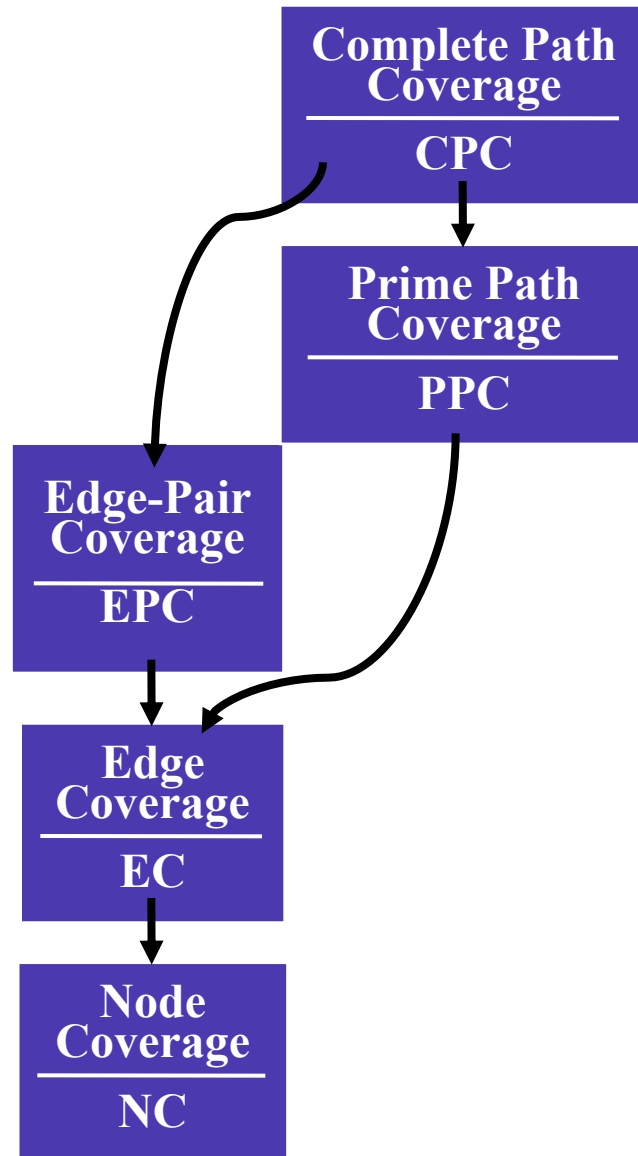
- Prime paths:
- $\text{path}(t_3) =$
- $\text{path}(t_4) =$
- $T_1 = \{t_3, t_4\}$ satisfies PPC but not CPC.

Prime Path Coverage vs. Complete Path Coverage (2)



- Prime paths: $[q_0, q_1, q_2]$, $[q_0, q_1, q_3, q_4]$, $[q_3, q_4, q_1, q_2]$,
 $[q_1, q_3, q_4, q_1]$, $[q_3, q_4, q_1, q_3]$, $[q_4, q_1, q_3, q_4]$
- $\text{path}(t_3) = [q_0, q_1, q_2]$
- $\text{path}(t_4) = [q_0, q_1, q_3, q_4, q_1, q_3, q_4, q_1, q_2]$
- $T_1 = \{t_3, t_4\}$ satisfies PPC but not CPC.

Graph Coverage Criteria Subsumption

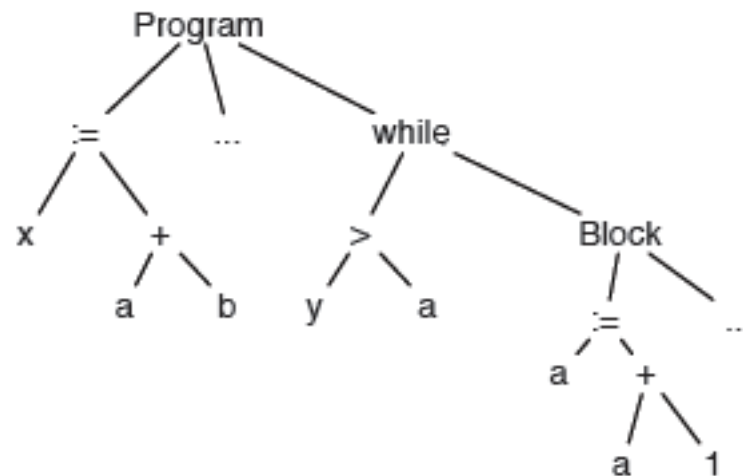


How do we measure coverage?

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:
 - $\# \text{ traced points} / \text{total } \# \text{ points}$

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 a 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

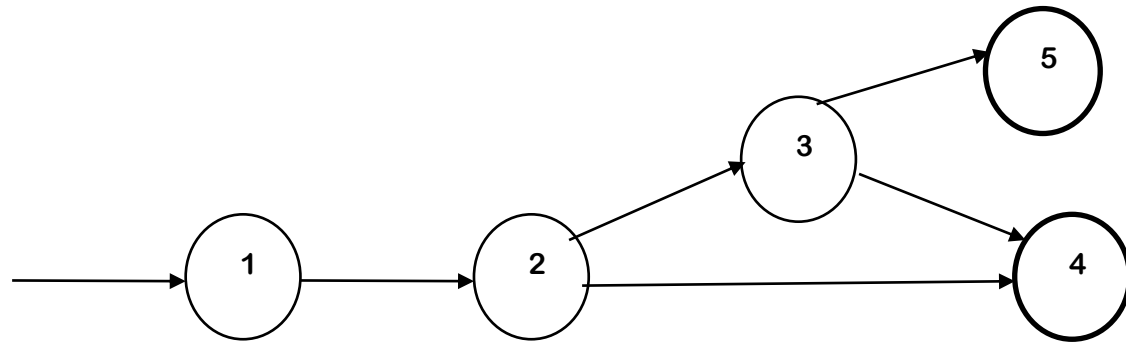
Bridge Coverage (BC): If removing an edge adds unreachable nodes to the graph, then this edge is a bridge. The set of test requirements for BC contains all bridges.

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.



TRBC = {[1,2], [2,3], [3,5]}

TRNC = {[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:

- $N = \{1, 2, 3, 4, 5, 6, 7\}$
- $N_0 = \{1\}$
- $N_f = \{7\}$
- $E = \{[1, 2], [1, 7], [2, 3], [2, 4], [3, 2], [4, 5], [4, 6], [5, 6], [6, 1]\}$

Also consider the following test paths:

- $t_0 = [1, 2, 4, 5, 6, 1, 7]$
- $t_1 = [1, 2, 3, 2, 4, 6, 1, 7]$

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 t_0 nor t_1 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 $[3, 2, 3]$.

On the Danger of Coverage Directed Test Case Generation

Matt Staats
KAIST

Gregory Gay, Michael Whalen, Mats Heimdahl
University of Minnesota



Suggested reading for STQAM 2023



Story Outline

- **Industry problem:** MCDC, branch coverage adopted as certification criteria for avionics system
 - Expensive, slow
- **Research solution:** Counterexample based test generation
 - Achieves 100% coverage
- **Unintended side-effect:** Using the solution, in the domain, can result in worse fault finding than simple random testing