Unit 7. Control Flow Testing

1. **Introduction**
2. **Control Flow Graph**
3. **Test Coverage Analysis**

Reading: TB-Chapters 4 (4.1-4.9)

1. Introduction

-Control Flow Testing (CFT) and Data Flow Testing (DFT) are structural (i.e. White-box) techniques suitable for small units of source code, e.g., a function.

-CFT and DFT help with interactions along the execution path and interactions among data items in execution, respectively.

-CFT and DFT use as test models ***control flow graphs (CFG)***, which give an abstract representation of the code.

-CFG is also used as main model for ***code coverage analysis***.

2. Control Flow Graph

Code Segments

-A **code segment** consists of one or several contiguous statements with no conditionally executed statements.

- That means once a segment is entered, ***all the statements involved will execute***.
- The last statement in the segment must be another predicate, a method exit, a loop control, a break, or a goto.
- The ***last part of a segment includes the predicate or exit expression*** that selects another segment but does not include any of subsequent segment's code.

-A **predicate** expression contains one or many conditions that evaluate to true or false. One **condition** corresponds to each boolean operator in the predicate expression.

- Predicates are used in control statements: if, case, do, while, do until, for, and so on.
- The evaluation of a predicate results in transfer of control to one or many **code segments**.
- A predicate with multiple conditions is called a **compound predicate.**

Examples: Code segments in Canonical loop structures

For Loop

```
buffer= new char[nchar + 1];                  A
for (n=0; | n< nchars; | ++n) {               B, D
            buffer[n] = newChar;              C
}
```

While Loop

```
buffer= new char[nchar + 1];                  A
int n =0;
while ( n< nchars) {                          B
            buffer[n] = newChar;              C
            ++n;
}
```

Until Loop

```
buffer= new char[nchar + 1];                  A
int n =0;
do {                                          B
            buffer[n] = newChar;
            ++n;
}
While (n < nchars);                           C
```

Representation

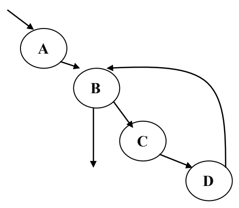
-A **control flow graph (CFG)** describes code segments and their sequencing in a program. It is a directed graph in which:

- A **node** corresponds to a code segment; nodes are labeled using letters or numbers
- An **edge** corresponds to a conditional transfer of control between code segments; edges are represented as arrows
- **Entry node:** the entry point of a method, represented with a node with no inbound edges.
- **Exit node:** the exit point of a method, represented with a node with no outbound edges.
- **Decision node**: more than one outgoing edge
- **Junction node**: more than one incoming edge
- **Processing node**: one incoming and one outgoing edge

Flow graphs for canonical loop structures

For Loop

```
buffer= new char[nchar + 1];                  A
for (n=0; | n< nchars; | ++n) {               B, D
            buffer[n] = newChar;              C
}
```

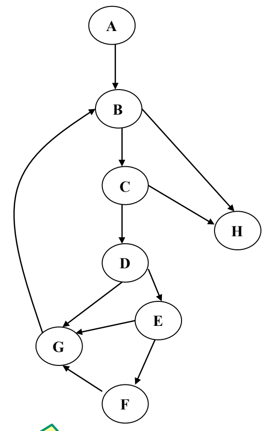


Example: CFG for a method

public class Authenticator {
final int MAX = 10000;
String [] userids = new String [MAX];
String [] passwords = new String [MAX];
…

		Segments
public boolean verify (String uid, String pwd) { *boolean result=false;* *int i = 0;*		A
while ((result==false)	*&& (i < MAX)) {*	B, C
if ((userids[i]==uid)	*&& (passwords[i] == pwd))*	D, E
result=true;		F
++i; *}*		G
return result; *}*		H

//…Other methods
} //Class end



Identify each node as: decision, junction, processing, entry, or exit

Is there any harm in merging two neighbor nodes in a CFG?

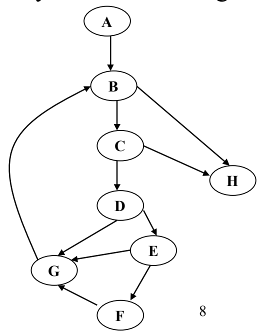
Path Expressions

-A ***path*** corresponds to a sequence of segments connected by arrows.
- A path is denoted by the nodes that comprise the path; e.g., path *ABH*.
- Loops are represented by segments within parentheses, followed by an asterisk to show that this group may iterate from zero to *n* times, e.g., path *A(BCDEFG)*BH*.

-An ***entry-exit path*** is a path starting with the entry node and ending with the exit node

Examples of Entry/Exit Paths:

-ABH
-ABCH
-A(BCDEFG)*BH
-A(BCDEG)*BH
-A(BCDG)*BH
-A(BCDG)*BCH



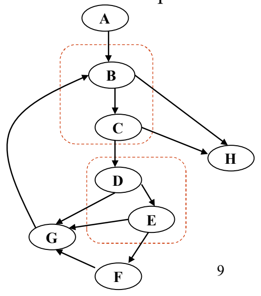
Compound Predicates

-Modeled separately by specifying ***a node for each individual predicate*** involved.

-All true-false combinations in a compound predicate should be analyzed, and the effects of ***short circuit boolean evaluation*** should be made explicit.
- For instance: C++, Java, and Objective-C use C semantics- short circuit boolean evaluation is automatically applied to all multiple-condition boolean expressions.

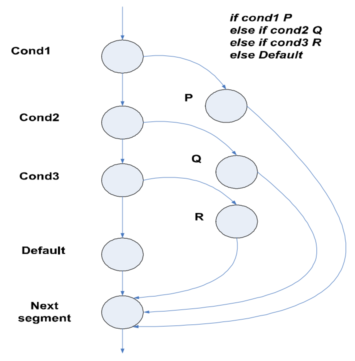
- Example:

```
    …
while ((result==false)    && (i < MAX)) {

    if ((userids[i]==uid)   && (passwords[i] = pwd ))

        result=true;

        ++i;
}
    …
```



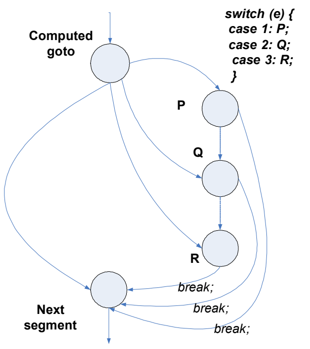
Case and Multiple-if Statements

-Modeled by specifying a ***separate node for each predicate***, each ***conditional action***, and the ***default action***.



Switch Statements

-Modeled by specifying a ***node for the switch*** expression, and a ***separate node for each action***.



3. Test Coverage Analysis

Test Coverage Overview

-Test coverage attempts to address questions about ***when to stop testing***, or the amount of testing that is enough for a given program.

-Ideal testing is to ***explore exhaustively the entire test domain***, which in general is ***impossible***.
- Some code may never be executed due to the possibility of missing test cases.
- Effectiveness of test suites can be established only by knowing what code is, or isn't executed.

-A **code coverage model** calls out the parts of an implementation that must be exercised to satisfy an implementation-based test model.
- Coverage, as a metric, is the percentage of these parts exercised by a test suite.

Test Coverage Overview (ctd.)

-Hundreds of coverage models have been published and used since the late 1960s.

•Most coverage models rely on ***control flow graphs (CFG)*** to provide an abstract representation of the code.

-Recommended not to use a code coverage model as a test model.

•Instead, ***established test strategies*** (e.g., equivalence, domain) should be used to devise test suites, while ***coverage metrics are used at the same time*** to analyze generated test suites adequacy.
•***Coverage reports*** can point out a grossly inadequate test suite.

-**Common coverage criteria include**:
•Statement coverage
•Branch coverage
•Condition/Multiple conditions coverage
•Basis-path coverage
•Data flow coverage

Common Code Coverage Criteria

Statement coverage

-Achieved when all statements in a method have been executed at least once.

•Also known as ***line coverage***, ***segment coverage***, or basic ***block coverage***.

•Segment and basic block coverages count segments instead of individual statements.

•Segment coverage ensures that all code segments defined in the CFG are covered.

-Example:

```
int foo(int x) {
   if (a==b) { ++x; }
   else { --x;}
   return x;
}
```

$\longrightarrow$ Statement coverage is achieved by having test cases involving both:

1. *a==b*
2. *a != b*

Statement coverage (ctd.)

•If a bug exists in a statement, and that statement is not executed, there is almost no chance of revealing that bug; hence statement coverage is the ***minimum coverage required by IEEE SENG standards***.

•However, it is a ***very weak criterion*** and should be viewed as the ***barest minimum***.

•Example:

```
      void foo () {
              char* c = NULL;
              if (x == y) {
                      c = &aString;
              }
              *c = “test code”;
      }
```

$\longrightarrow$ Statement coverage is achieved for *foo()* by setting *x* equal *y*; however, when the condition is false, the code generates an incorrect pointer and crashes.

Branch Coverage

-Achieved when every branch from a node is executed at least once by a test suite.

•Also known as ***decision coverage*** or ***all-edge coverage***.

•***Improve on statement coverage*** by requiring that each branch be taken at least once. Hence each outcome of a predicate expression is exercised at least once (i.e., true and false).

•However, it is limited by the fact that it ***treats a compound predicate as a single statement***: branch coverage may be achieved without exercising all of the conditions

Branch Coverage (ctd.)

-Example

```
int foo(int x) {
      if (a==b || (x==y && isEmpty())) {
                  ++x;
      }
      else {
                  --x;
      }
      return x;
}
```

$\longrightarrow$ Branch coverage may be Achieved using:

1. a ==b
2. a !=b and x !=y

Without ever exercising *this.isEmpty()*

• Branch coverage misses several of the possible entry-exit paths.

Condition coverage/Multiple condition coverage

-**Condition coverage** requires that each condition be evaluated as true and false at least once.

-**Multiple-condition coverage** requires that all true-false combinations of simple conditions be exercised at least once.

•There at most 2^n true-false combinations for a compound predicate with *n* simple conditions.

•Multiple-condition coverage ensures that all statements, branches, and conditions are covered, ***but not all paths***.

•Reaching all condition combinations may be impossible due to short circuit evaluation.

•Mutually exclusive conditions spanning several predicate expressions may preclude certain combinations.

Basis-Path Model

Cyclomatic Complexity Metric

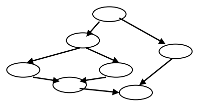
-Defined as the number of edges minus the number of nodes plus 2:

$$C = e - n + 2$$

- Where *e* and *n* stand for the number of edges and the number of nodes in corresponding CFG, respectively.

-Also called **McCabe complexity** metric
- Evaluate the ***complexity of algorithms*** involved in a method.
- Give a count of the minimum number of test cases needed to test a method comprehensively.
- Low C value means reduced testing, and better maintainability.

-Example:



CC= e- n + 2 = 8 – 7 + 2 = 3

The Basis-Path Test Model

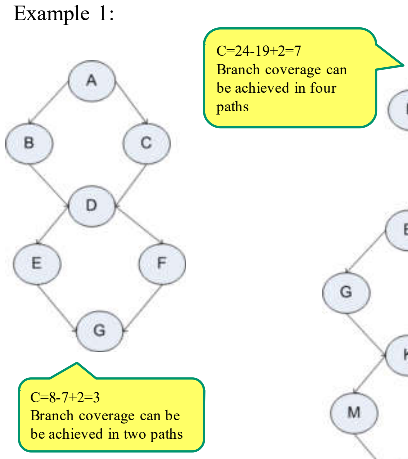
-Call for testing ***C* distinct entry-exit paths**.
- A test suite is developed by finding C distinct entry-exit paths and producing test cases by **path sensitization**.
- Traditionally, it is suggested that the longest entry-exit path be included in the test suite.
- **Basis-path coverage** is achieved when C distinct entry-exit paths have been exercised.

-The basis-path model is appealing because it is simple and pragmatic.

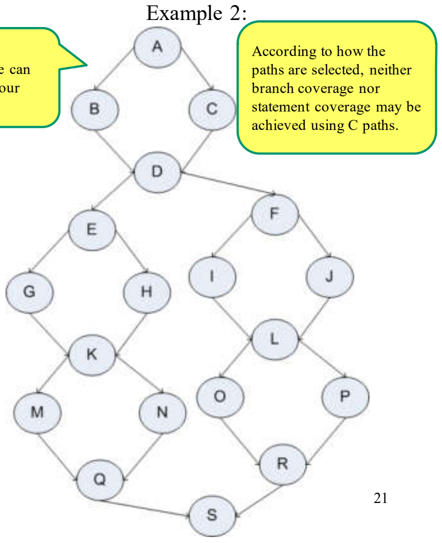
-However it is ***unreliable as a coverage metric***, because it can be satisfied without meeting the barest minimum generally accepted standards of code coverage:
- On one hand branch coverage may be achieved with less than C paths in some methods.
- On the other hand it is possible to select C entry-exit paths and achieve neither statement coverage nor branch coverage.

The Basis-Path Test Model (ctd.)

Example 1:


A
B
C
D
E
F
G
C=24-19+2=7
Branch coverage can be achieved in four paths
C=8-7+2=3
Branch coverage can be achieved in two paths

Example 2:


A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
According to how the paths are selected, neither branch coverage nor statement coverage may be achieved using C paths.

Example: Binary Search Routine

Code

```
Class BinSearch {
        public static void search(int key, int[] elemArray, Result r) {
                int bottom = 0;
                int top = elemArray.length – 1;
                int mid;
                r.found = false; r.index=-1;
                while (bottom <= top) {
                        mid = (top + bottom)/2;
                        if (elemArray [mid] == key) {
                                r.index = mid;
                                r.found = true;
                                return;
                        }
                        else {
                                if (elemArray[mid] < key) bottom = mid + 1;
                                else top = mid – 1;
                        }
                }
        }
}
```

Class BinSearch {
 	
public static void search(int key, int[] elemArray, Result r) {
int bottom = 0;
int top = elemArray.length – 1;
int mid;
r.found = false; r.index=-1;
	A

while (bottom <= top) {	**B**
mid = (top + bottom)/2;	**C**
if (elemArray [mid] == key) {	**D**

r.index = mid;
r.found = true;
return;
}
	E

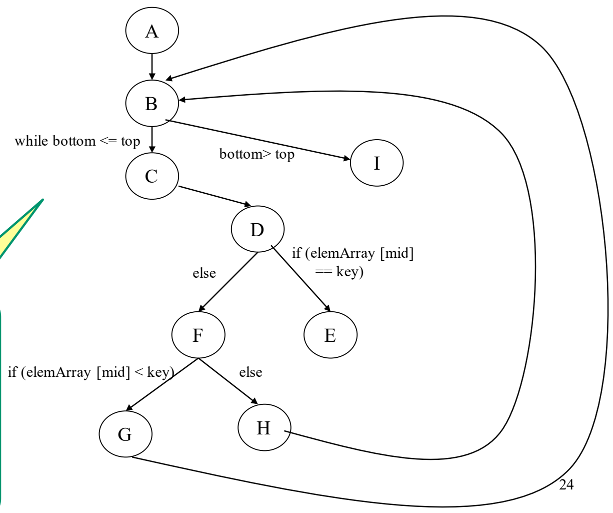
else {
if (elemArray[mid] < key)
	F

bottom = mid + 1;	**G**

else top = mid – 1;
}
}
	H

} }	**I**

Flow Graph



Derive 3 test cases:
ABI
ABCDE
ABCDFGBI

Is this enough?

Independent Paths and Number of Test cases

ABI
ABCDEI
A(BCDFG)*BI
A(BCDFH)*BI

-The minimum number of test cases required according to the Basis path criterion is equal to the cyclomatic complexity (CC).

CC = Number (edges) – Number (nodes) + 2 = 10 – 9 + 2 = 3

Path Sensitization

-Process of determining argument and instance variable values that will cause a particular path to be taken.

-Path sensitization is undecidable; no algorithm can solve this problem in all cases.

-Instead it must be solved heuristically:

- For small, well-structured methods, this task is usually not difficult.
- It becomes increasingly more difficult as size and complexity increase.

-Approach:

1. Use initially other test strategies (e.g., domain analysis etc.) to select test inputs (this reduces the amount of work required).
2. Then find additional test values to exercise the missing paths to meet the coverage goal.

Test Coverage, in Practice

-In practice, the three basic criteria most commonly used are *statement coverage, branch coverage* and *condition coverage*.

- It has been suggested that the combination of these three criteria can achieve 80-90 % or more coverage needs in most cases.

-Important to note that test coverage is not enough by itself:

- 100% test coverage cannot guarantee achieving error-free software.

-However, test coverage in combination with appropriate test strategies can mitigate the impact of uncovered code during software testing.

- Help the tester find some rational points at which to stop testing.

Review Questions:

Mark each of the following as true or false:

(1) Segment coverage implies statement coverage	**T**
(2) Branch coverage implies segment coverage	**T**
(3) Branch coverage implies multiple conditional coverage	**F**
(4) Multiple conditional coverage implies branch coverage	**T**
(5) Path coverage implies branch coverage	**T**

-Example

```
int foo(int x) {
        if (a==b || (x==y && isEmpty())) {
                    ++x;
        }
        else {
                    --x;
        }
        return x;
}
```

-What test cases will give 100% branch coverage? **a==b, a!=b && x!=y**
-Does this achieve 100% multiple conditional coverage? **No**
-Which coverage criteria should be used here to maximize coverage?