Software Testing, Quality Assurance and Maintenance Winter 2019

Lecture 8 — January 23, 2019

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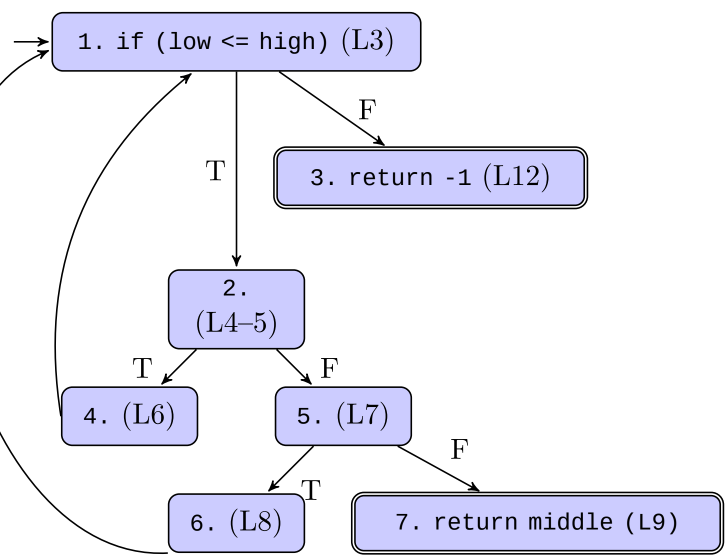
Larger CFG example. You can draw a 7-node CFG for this program:

```
1  /** Binary search for target in sorted subarray a[low..high] */
2  int binary_search(int[] a, int low, int high, int target) {
3    while (low <= high) {
4      int middle = low + (high-low)/2;
5      if (target < a[middle)
6        high = middle - 1;
7      else if (target > a[middle])
8        low = middle + 1;
9      else
10       return middle;
11   }
12   return -1; /* not found in a[low..high] */
13 }
```



Here are more exercise programs that you can draw CFGs for.

```
/* effects: if x==null, throw NullPointerException
            otherwise, return number of elements in x that are odd, positive or both. */
int oddOrPos(int[] x) {
  int count = 0;
  for (int i = 0; i < x.length; i++) {
    if (x[i]%2 == 1 || x[i] > 0) {
      count++;
    }
  }
  return count;
}

// example test case: input: x=[-3, -2, 0, 1, 4]; output: 3
```

Finally, we have a really poorly-designed API (I'd give it a D at most, maybe an F) because it's impossible to succinctly describe what it does. **Do not design functions with interfaces like this.** But we can still draw a CFG, no matter how bad the code is.

```java
/** Returns the mean of the first maxSize numbers in the array,
    if they are between min and max. Otherwise, skip the numbers. */
double computeMean(int[] value, int maxSize, int min, int max) {
  int i, ti, tv, sum;

  i = 0; ti = 0; tv = 0; sum = 0;
  while (ti < maxSize) {
    ti++;
    if (value[i] >= min && value[i] <= max) {
      tv++;
      sum += value[i];
    }
    i++;
  }
  if (tv > 0)
    return (double)sum/tv;
  else
    throw new IllegalArgumentException();
}
```

Statement and Branch Coverage

We defined Control-Flow Graphs so that we can give principled definitions of statement and branch coverage. We can start with the definition of a test path:

Definition 1 *A* test path *is a path p (possibly of length 0) that starts at some initial node (i.e. in N_0) and ends at some final node (i.e. in N_f).*

Here's a definition of coverage for graphs:

Definition 2 *Given a set of test requirements* TR *for a graph criterion C, a test set T satisfies C on graph G iff for every test requirement* tr *in* TR*, at least one test path p in path(T) exists such that p satisfies* tr*.*

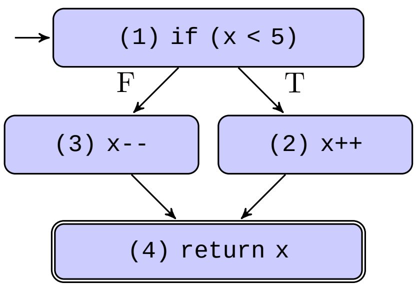
We'll use this notion to define a number of standard testing coverage criteria. But first, what are test paths?

Test cases and test paths. We connect test cases and test paths with a mapping path_G from test cases to test paths; e.g. $\text{path}_G(t)$ is the set of test paths corresponding to test case t.

- usually we just write path since G is obvious from the context.
- we can lift the definition of path to test sets T by defining $\text{path}(T) = \{\text{path}(t) | t \in T\}$.
- 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.

Example. Here is a short method, the associated control-flow graph, and some test cases and test paths.

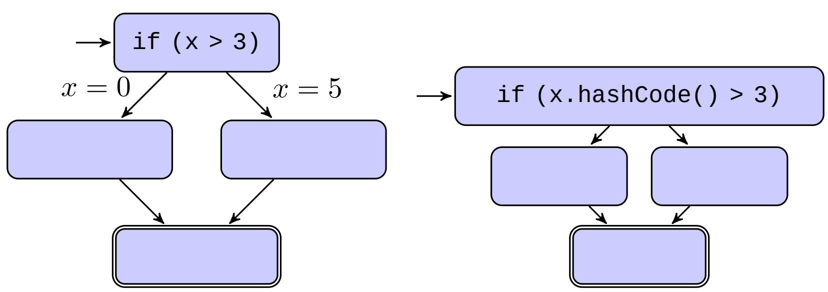
```
int foo(int x) {
  if (x < 5) {
    x ++;
  } else {
    x --;
  }
  return x;
}
```



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

Note that (1) we can deduce properties of the test case from the test path; and (2) in this example, since our method is deterministic, the test case determines the test path.

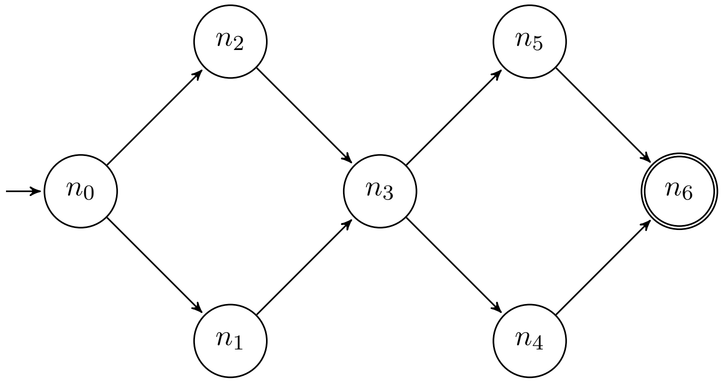
Nondeterminism. I mentioned the mapping between test cases and test paths above. The mapping is not one-to-one for nondeterminstic code. Here's an example of deterministic and non-deterministic control-flow graphs:



Causes of nondeterminism include dependence on inputs; on the thread scheduler; and on memory addresses, for instance as seen in calls to the default Java `hashCode()` implementation.

Nondeterminism makes it hard to check test case output, since more than one output might be a valid result of a single test input.

As another (more abstract) example, consider the double-diamond graph D.



Here are the four test paths in D:

$$[n_0, n_1, n_3, n_4, n_6]$$
$$[n_0, n_1, n_3, n_5, n_6]$$
$$[n_0, n_2, n_3, n_4, n_6]$$
$$[n_0, n_2, n_3, n_5, n_6]$$

For the *statement coverage* criterion, we get the following test requirements:

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

That is, any test set T which satisfies statement coverage on D must include test cases t; the cases t give rise to test paths path(t), and some path must include each node from n_0 to n_6. (No single path must include all of these nodes; the requirement applies to the set of test paths.)

Let's formally define statement coverage.

Definition 3 *Statement coverage: For each node $n \in reach_G(N_0)$,* TR *contains a requirement to visit node n.*

For our example,

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

Let's consider an example of a test set which satisfies statement coverage on D.

Start with a test case t_1; assume that executing t_1 gives the test path

$$\text{path}(t_1) = p_1 = [n_0, n_1, n_3, n_4, n_6].$$

Then test set $\{t_1\}$ does not give statement coverage on D, because no test case covers node n_2 or n_5. If we can find a test case t_2 with test path

$$\text{path}(t_2) = p_2 = [n_0, n_2, n_3, n_5, n_6],$$

then the test set $T = \{t_1, t_2\}$ satisfies statement coverage on D.

What is another test set which satisfies statement coverage on D?

Here is a more verbose definition of statement coverage.

Definition 4 *Test set T satisfies* statement coverage *on graph G if and only if for every syntactically reachable node $n \in N$, there is some path p in path(T) such that p visits n.*

A second standard criterion is that of branch coverage.

Criterion 1 Branch Coverage. *TR contains each reachable path of length up to 1, inclusive, in G.*

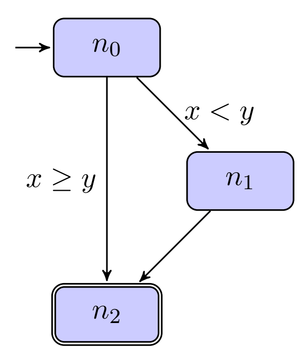
Here are some examples of paths of length ≤ 1:

Note that since we're not talking about *test paths*, these reachable paths need not start in N_0.

In general, paths of length ≤ 1 consist of nodes and edges. (Why not just say edges?)

Saying "edges" on the above graph would not be the same as saying "paths of length ≤ 1".

Another example. Here is a more involved example:



Let's define

$$
\begin{aligned}
\text{path}(t_1) &= [n_0, n_1, n_2] \\
\text{path}(t_2) &= [n_0, n_2]
\end{aligned}
$$

Then

$$
\begin{aligned}
T_1 &= \langle ? \rangle && \text{satisfies statement coverage} \\
T_2 &= \langle ? \rangle && \text{satisfies branch coverage}
\end{aligned}
$$