Lecture 8: Structural Testing

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Every developer must answer:

Are our tests are any good?

More importantly… Are they good enough to stop writing new tests?

Have We Done a Good Job?

What we want:

- We've found all the faults.
  - Impossible.

What we (usually) get:

- We compiled and it worked.
- We run out of time or budget.
  - Inadequate.

Test Adequacy Metrics

Instead - can we **compromise between the impossible and the inadequate**?

- Can we measure “good testing”?
  - Test adequacy metrics “score” testing efforts by measuring the completion of a set of **test obligations**.
    - Properties that must be met by our test cases.

(In)Adequacy Metrics

- We do not know what faults exist before testing, so we rely on an approximation of “we found all of the faults”.
- Criteria identify **in**adequacies in the tests.
  - If the test does not reach a statement, it is *inadequate* for finding faults in that statement.
  - If the requirements discuss two outcomes of a function, but the tests only cover one, then the tests are *inadequate* for verifying that requirement.

Adequacy Metrics

- Adequacy Metrics based on coverage of factors correlated to finding faults (hopefully).
  - Widely used in industry - easy to understand, cheap to calculate, offer a checklist.
  - Some metrics based on coverage of requirement statements, used for verification.
  - Majority based on exercising elements of the source code in ways that might trigger faults.
    - This is the basis of ***structural testing***.

We Will Cover

- Structural Testing:
  - Derive tests from the program structure, directed by a chosen adequacy metric.
- Common structural coverage metrics:
  - Statement coverage
  - Branch coverage
  - Condition coverage
  - Path coverage

Structural Testing

- The structure of the software itself is a valuable source of information.
- Structural testing is the practice of using that structure to derive test cases.
- Sometime called white-box testing
  - Functional = black-box.

Structural Testing

- Uses a family of metrics that define how and what code is to be executed.
- Goal is to exercise a certain percentage of the code.
  - Why??

```
while (*eptr){
    char c;
    c = *eptr;
    if(c == ‘+’){
        *dptr = ‘ ‘;
    } else{
        *dptr = *eptr;
    }
}
```

The basic idea:
You can’t find all of the faults without exercising all of the code.

Structural Testing - Motivation

- Requirements-based tests should execute *most* code, but will rarely execute all of it.
  - Helper functions
  - Error-handling code
  - Requirements missing outcomes
- Structural testing compliments functional testing by requiring that code elements are exercised in prescribed ways.

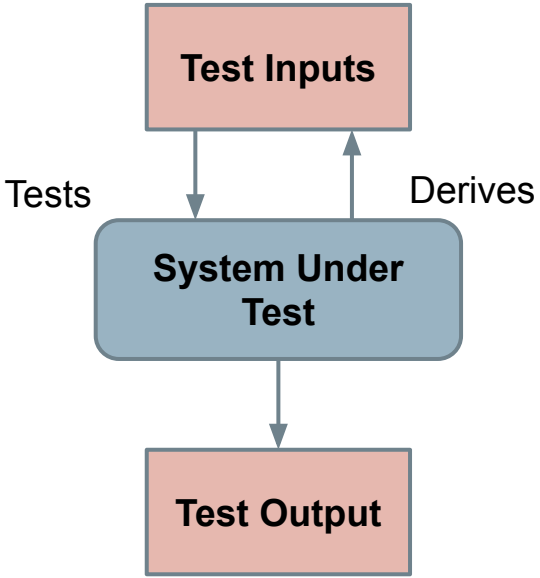
Structural Does Not Replace Functional

- Structural testing should not be the basis for “How do I choose tests?”
  - Structure-based tests do not directly make an argument for verification or expose missing functionality.
  - Structural testing is useful for supplementing functional tests to help reveal faults.
    - Functional tests are good at exposing conceptual faults. Structural tests are good at exposing coding mistakes.

Structural Testing Usage

Take code, derive information about structure, use obligation information to:

- Create Tests
  - Design tests that satisfy obligations.
- Measure Adequacy of Existing Tests
  - Measure coverage of existing tests, fill in gaps.

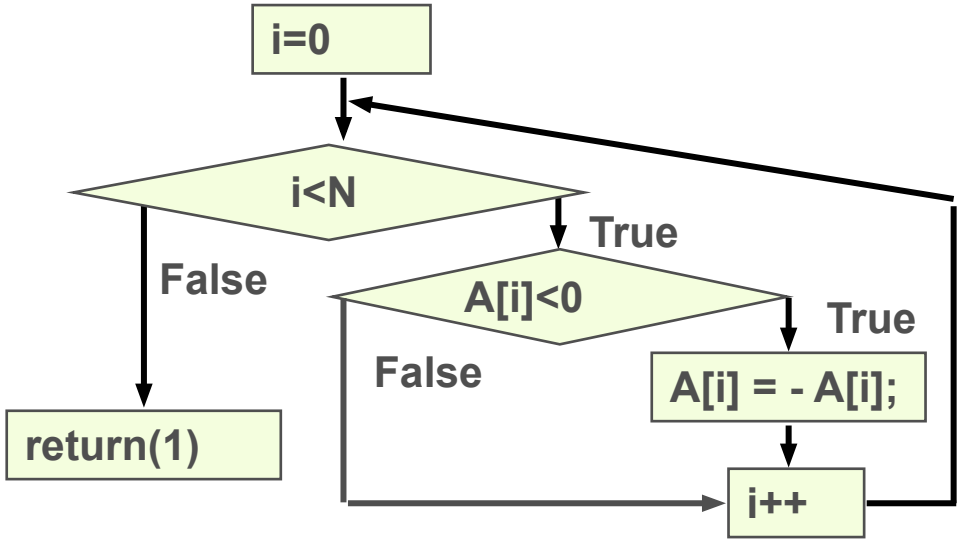


Control and Data Flow

- We need context on how system executes.
- Code is rarely sequential - conditional statements result in branches in execution, jumping between blocks of code.
  - Control flow is information on how control passes between blocks of code.
- Data flow is information on how variables are used in other expressions.

Control-Flow Graphs

- A directed graph representing the flow of control through the program.
- Nodes represent sequential blocks of program commands.
- Edges connect nodes in the sequence they are executed. Multiple edges indicate conditional statements (loops, if statements, switches).



Structural Coverage Criteria

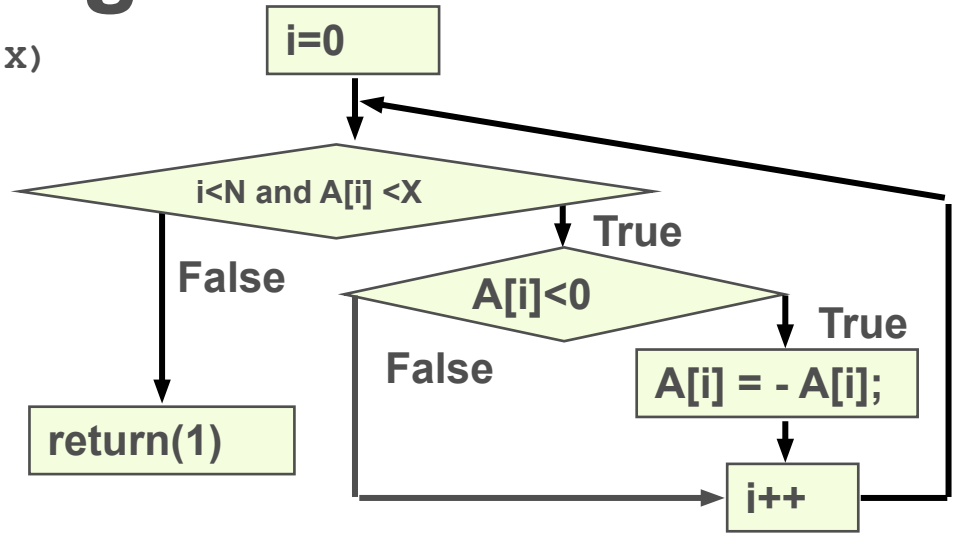
- Criteria based on exercising of:
  - Statements (nodes of CFG)
  - Branches (edges of CFG)
  - Conditions
  - Paths
  - … and many more
- Measurements used as (in)adequacy criteria
  - If significant parts of the program are not tested, testing is surely inadequate.

Statement Coverage

- The most intuitive criteria. Did we execute every statement at least once?
  - Cover each node of the CFG.
- The idea: a fault in a statement cannot be revealed unless we execute the statement.
- $$\text{Coverage} = \frac{\text{Number of Statements Covered}}{\text{Number of Total Statements}}$$

Statement Coverage

```
int flipSome(int A[], int N, int X)
{
     int i=0;
     while (i<N and A[i] <X)
     {
          if (A[i]<0)
               A[i] = - A[i];
          i++;
     }
     return(1);
}
```



How many tests do we need to provide coverage?
What kind of faults could we miss?
Where would we want to use statement coverage?

A Note on Test Suite Size

- Level of coverage is not strictly correlated to test suite size.
  - Coverage depends on whether obligations are met. Some tests might not cover new code.
- However, larger suites often find more faults.
  - They exercise the code more thoroughly.
  - *How* code is executed is often more important than *whether* it was executed.

Test Suite Size

- Generally, favor a large number of *targeted* tests over a small suite that hits many statements.
  - If a test targets a smaller number of obligations, it is easier to tell where a fault is.
  - If a test executes everything and covers a large number of obligations, we get higher coverage, but at the cost of being able to identify and fix faults.
  - The exception - cost to execute each test is high.

Branch Coverage

- Do we have tests that take all of the control branches at some point?
  - Cover each edge of the CFG.
- Helps identify faults in decision statements.
- Coverage = $\frac{\text{Number of Branches Covered}}{\text{Number of Total Branches}}$

Subsumption

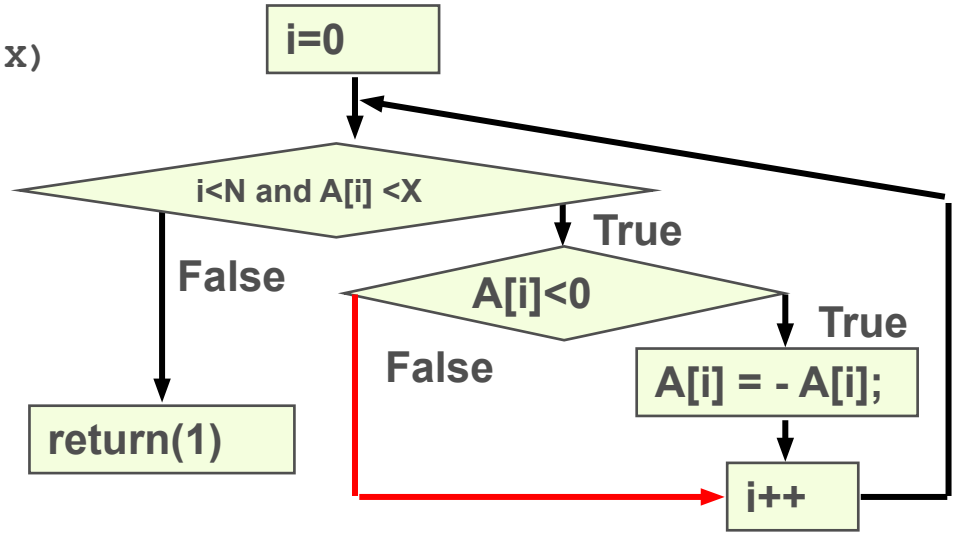
- Coverage metric (*A*) *subsumes* another metric (*B*) if, for every program *P*, every test suite satisfying *A* also satisfies *B* with respect to *P*.
  - If we satisfy A, there is no point in measuring B.
  - Branch coverage subsumes statement coverage.
    - Covering all edges requires covering all nodes in a graph.

Subsumption

- Shouldn’t we always choose the stronger metric?
  - Not always…
    - Typically require more obligations (so, you have to come up with more tests)
    - Or, at least, tougher obligations - making it harder to come up with the test cases.
    - May end up with a large number of *unsatisfiable* obligations

Branch Coverage

```
int flipSome(int A[], int N, int X)
{
     int i=0;
     while (i<N and A[i] <X)
     {
          if (A[i]<0)
               A[i] = - A[i];
          i++;
     }
     return(1);
}
```



What test obligations must be covered?
How does fault detection potential change?
Where would we want to use branch coverage?

Decisions and Conditions

- A *decision* is a complex Boolean expression.
  - Often cause control-flow branching:
    - `if ((a && b) || !c) { ...`
  - But not always:
    - `Boolean x = ((a && b) || !c);`

Decisions and Conditions

- A *decision* is a complex Boolean expression.
  - Made up of *conditions* connected with Boolean operators (and, or, xor, not):
    - Simple Boolean connectives.
      - Boolean variables: `Boolean b = false;`
      - Subexpressions that evaluate to true/false involving (<, >, <=, >=, ==, and !=): `Boolean x = (y < 12);`

Decision Coverage

- Branch Coverage deals with a subset of *decisions*.
  - Branching decisions that decide how control is routed through the program.
- Decision coverage requires that all boolean decisions evaluate to true and false.
- $$\text{Coverage} = \frac{\text{Number of Decisions Covered}}{\text{Number of Total Decisions}}$$

Basic Condition Coverage

- Several coverage metrics examine the individual *conditions* that make up a *decision*.
- Identify faults in decision statements.

  `(a == 1 || b == -1)` instead of `(a == -1 || b == -1)`

- Most basic form: make each condition T/F.
- Coverage = $\frac{\text{Number of Truth Values for All Conditions}}{\text{2x Number of Conditions}}$

Basic Condition Coverage

- Make each condition both True and False

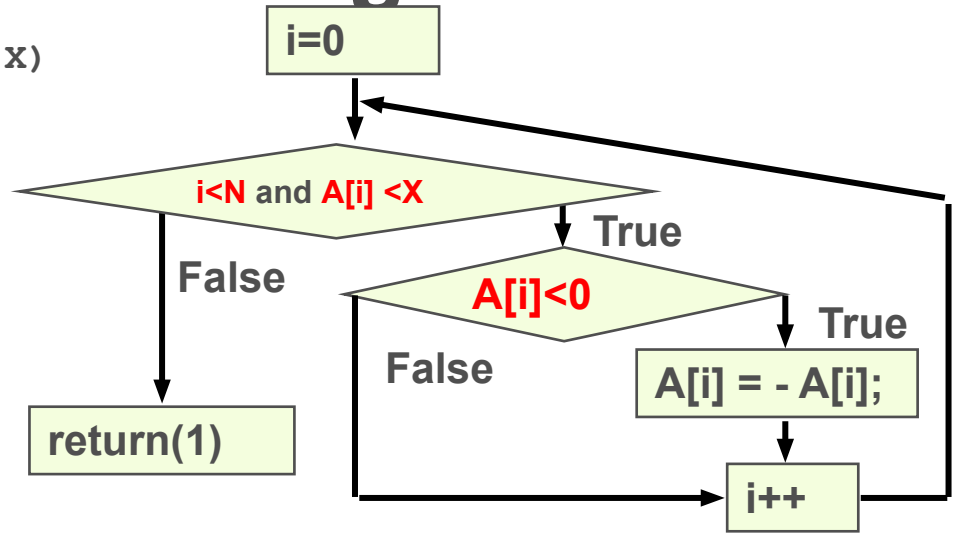
(A and B)

Test Case	A	B
1	True	False
2	False	True

- Does not require hitting both branches.
  - Does not subsume branch coverage.
  - In this case, false branch is taken for both tests

Basic Condition Coverage

```
int flipSome(int A[], int N, int X)
{
     int i=0;
     while (i<N and A[i] <X)
     {
          if (A[i]<0)
               A[i] = - A[i];
          i++;
     }
     return(1);
}
```



What test obligations must be covered?
How does fault detection potential change?
Where would we want to use condition coverage?

Compound Condition Coverage

- Evaluate every combination of the conditions

(A and B)

Test Case	A	B
1	True	True
2	True	False
3	False	True
4	False	False

- Subsumes branch coverage, as all outcomes are now tried.
- Can be expensive in practice.

Compound Condition Coverage

- Requires **many** test cases.

(A and (B and (C and D))))

Test Case	A	B	C	D
1	True	True	True	True
2	True	True	True	False
3	True	True	False	True
4	True	True	False	False
5	True	False	True	True
6	True	False	True	False
7	True	False	False	True
8	True	False	False	False
9	False	True	True	True
10	False	True	True	False
11	False	True	False	True
12	False	True	False	False
13	False	False	True	True
14	False	False	True	False
15	False	False	False	True
16	False	False	False	False

Short-Circuit Evaluation

- In many languages, if the first condition determines the result of the entire decision, then fewer tests are required.
  - If A is false, B is never evaluated.

(A and B)

Test Case	A	B
1	True	True
2	True	False
3	False	-

Modified Condition/Decision Coverage(MC/DC)

- Requires:
  - Each **condition** evaluates to true/false
  - Each **decision** evaluates to true/false
  - Each condition shown to **independently affect outcome** of each decision it appears in.

Test Case	A	B	(A and B)
1	True	True	True
2	True	False	False
3	False	True	False
~~4~~	~~False~~	~~False~~	~~False~~

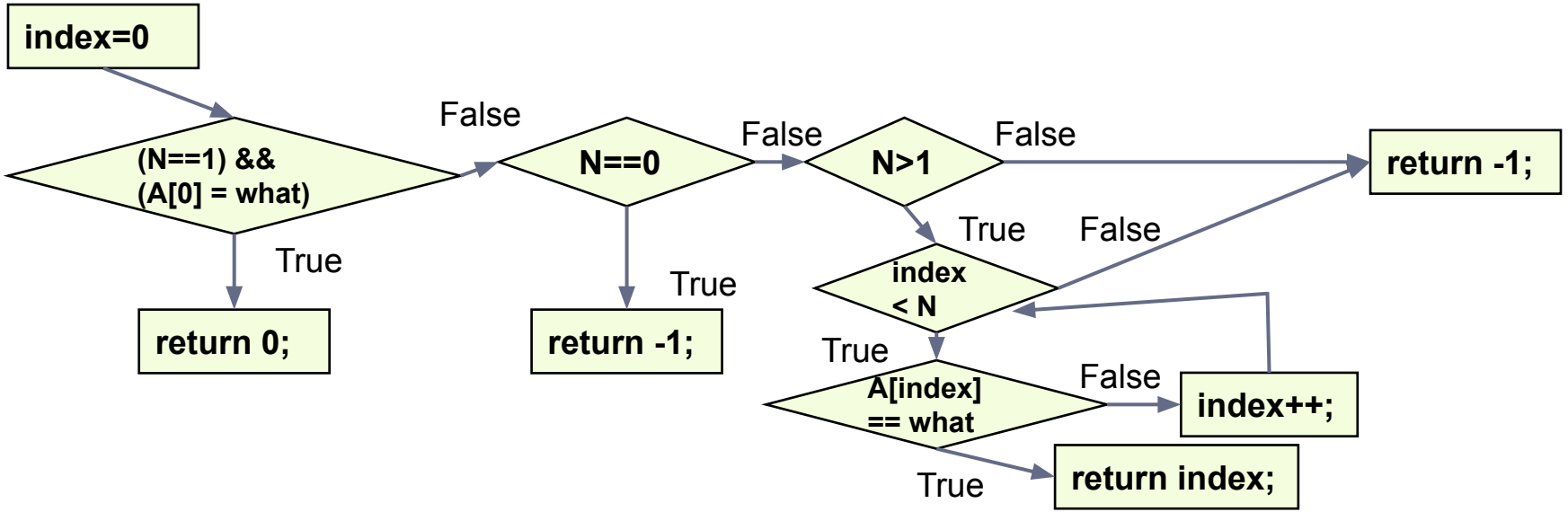
Let’s take a break.

Activity

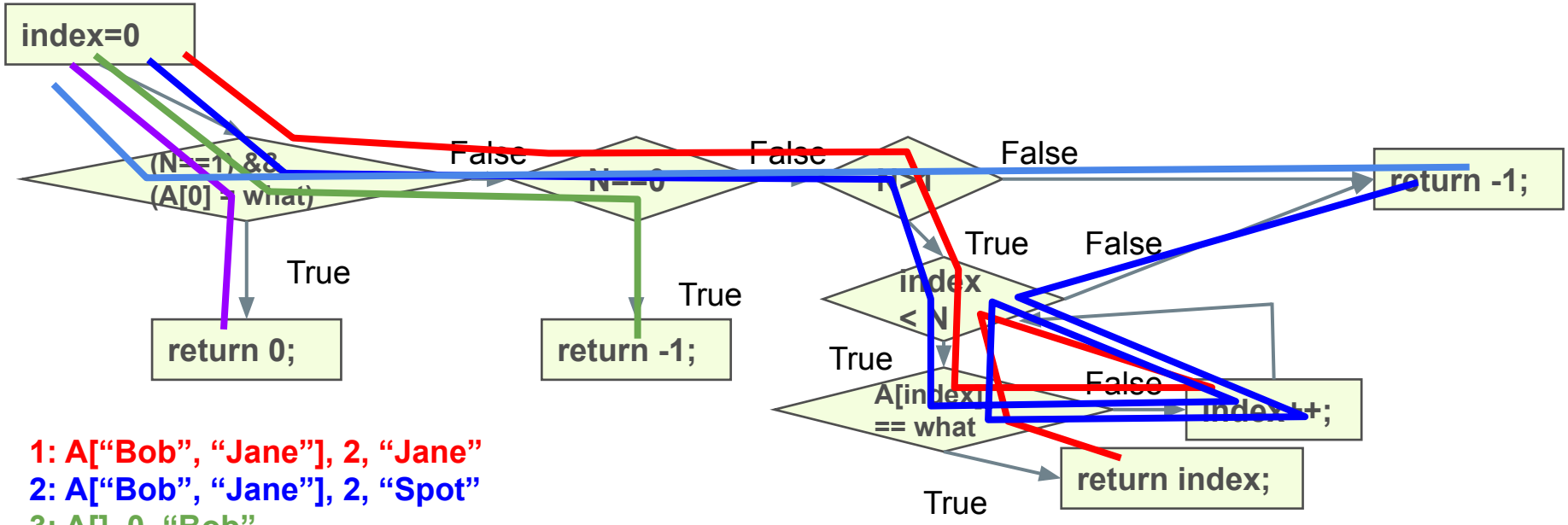
Draw the CFG and write tests that provide statement, branch, and basic condition coverage over the following code:

```
int search(string A[], int N, string what){
    int index = 0;
    if ((N == 1) && (A[0] == what)){
           return 0;
    } else if (N == 0){
        return -1;
    } else if (N > 1){
        while(index < N){
            if (A[index] == what)
               return index;
            else
                index++;
        }
    }
    return -1;
}
```

Activity


index=0
(N==1) &&
(A[0] = what)
False
True
return 0;
N==0
False
True
return -1;
N>1
False
True
return -1;
index
< N
False
True
A[index]
== what
False
index++;
True
return index;

Activity - Possible Solution



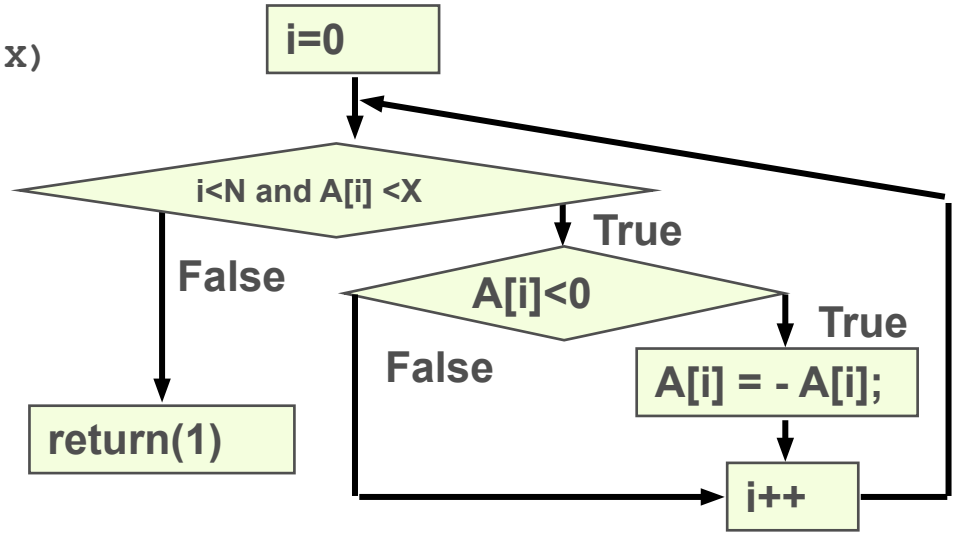
1: A[“Bob”, “Jane”], 2, “Jane”
2: A[“Bob”, “Jane”], 2, “Spot”
3: A[], 0, “Bob”
4. A[“Bob”], 1, “Bob”
5. A[“Bob”], 1, “Spot”

Path Coverage

- Other criteria focus on single elements.
  - However, all tests execute a sequence of elements - a path through the program.
  - Combination of elements matters - interaction sequences are the root of many faults.
- Path coverage requires that all paths through the CFG are covered.
- $$\text{Coverage} = \frac{\text{Number of Paths Covered}}{\text{Number of Total Paths}}$$

Path Coverage

```
int flipSome(int A[], int N, int X)
{
     int i=0;
     while (i<N and A[i] <X)
     {
          if (A[i]<0)
               A[i] = - A[i];
          i++;
     }
     return(1);
}
```

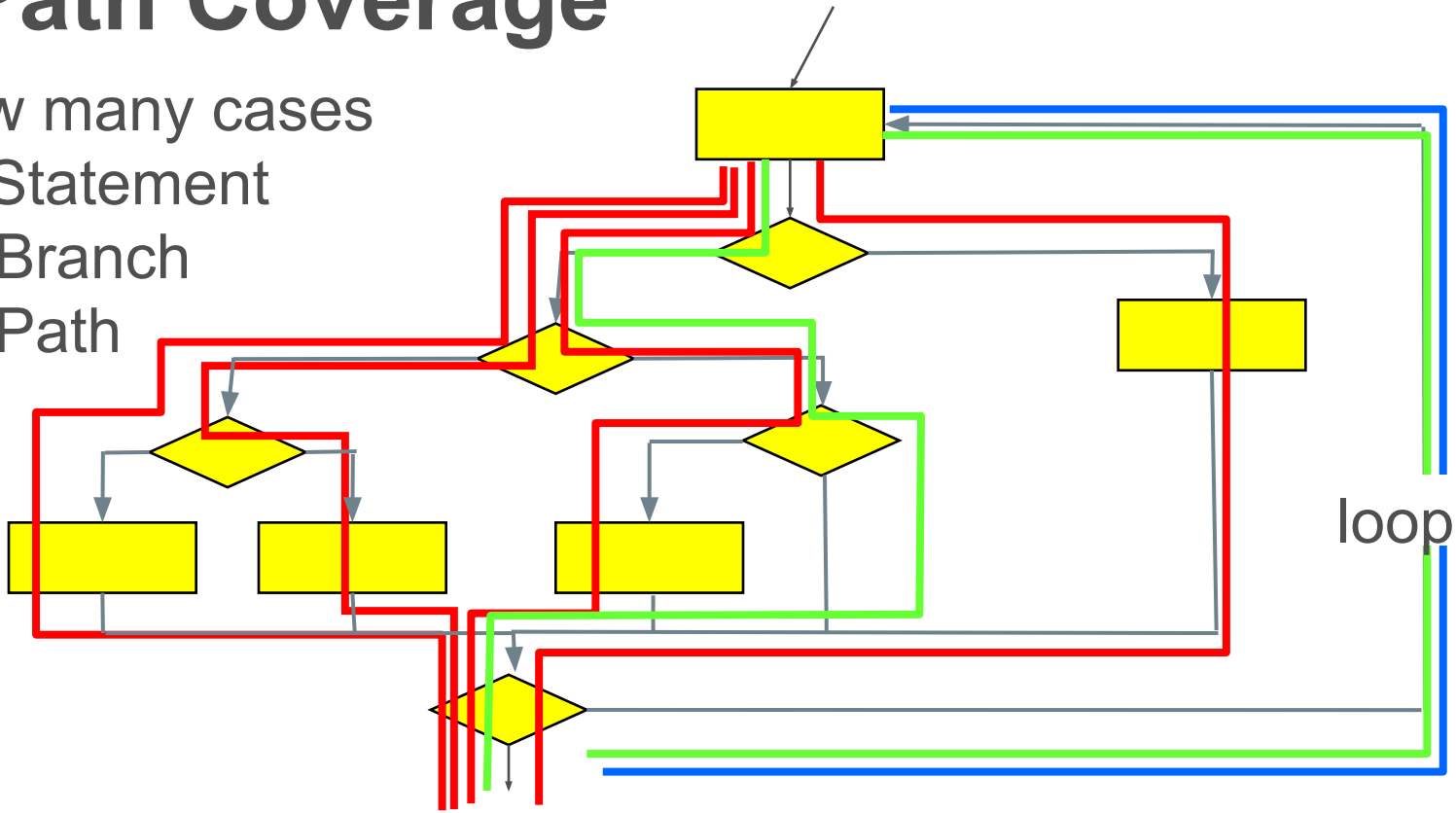


In theory, path coverage is the ultimate coverage metric.
In practice, it is impractical.

- **How many paths does this program have?**

Path Coverage

How many cases
for Statement
Branch
Path



Number of Tests

Path coverage for that loop bound requires: **3,656,158,440,062,976** test cases

If you run 1000 tests per second, this will take **116,000 years**.

However, there are ways to get some of the benefits of path coverage without the cost...

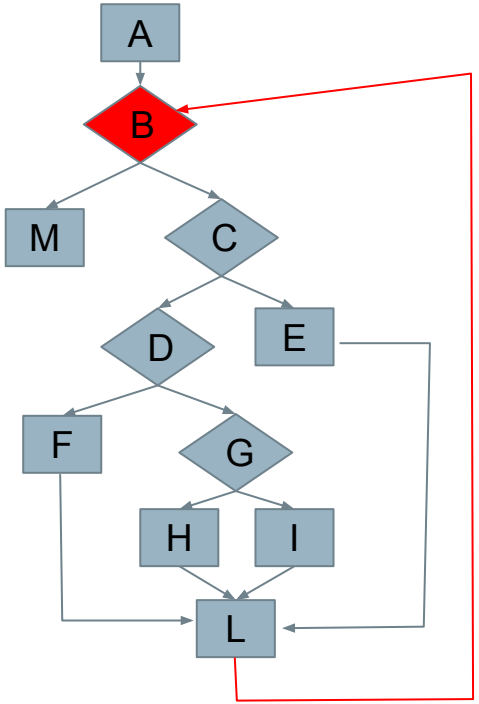
Path Coverage

- Theoretically, the strongest coverage metric.
  - Many faults emerge through sequences of interactions.
- But… Generally impossible to achieve.
  - Loops result in an infinite number of path variations.
  - Even bounding number of loop executions leaves an infeasible number of tests.

Boundary Interior Coverage

- Need to partition the infinite set of paths into a finite number of classes.
- **Boundary Interior Coverage** groups paths that differ only in the subpath they follow when repeating the body of a loop.
  - Executing a loop 20 times is a different path than executing it twice, but the same *subsequences* of statements repeat over and over.

Boundary Interior Coverage



B -> M
B -> C -> E -> L -> B
B -> C -> D -> F -> L -> B
B -> C -> D -> G -> H -> L -> B
B -> C -> D -> G -> I -> L -> B

Number of Paths

- Boundary Interior Coverage removes the problem of infinite loop-based paths.
- However, the number of paths through this code can still be exponential.
  - N non-loop branches results in 2^N paths.
- Additional limitations may need to be imposed on the paths tested.

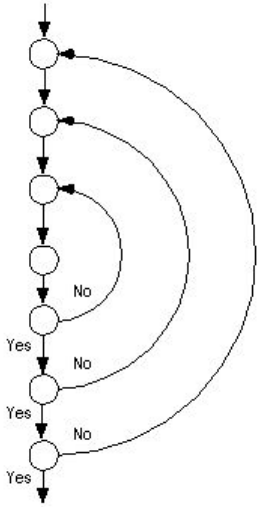
```
if (a)      S1;
if (b)      S2;
if (c)      S3;
…
if (x)      SN;
```

Loop Boundary Coverage

- Focus on problems related to loops.
  - Cover *scenarios representative of how loops might be executed*.
- For simple loops, write tests that:
  - Skip the loop entirely.
  - Take exactly one pass through the loop.
  - Take two or more passes through the loop.
  - (optional) Choose an upper bound N, and:
    - M passes, where 2 < M < N
    - (N-1), N, and (N+1) passes

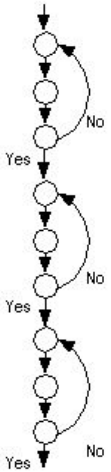
Nested Loops

- Often, loops are nested within other loops.
  - For each level, you should execute similar strategies to simple loops.
- In addition:
  - Test innermost loop first with outer loops executed minimum number of times.
  - Move one loops out, keep the inner loop at “typical” iteration numbers, and test this layer as you did the previous layer.
  - Continue until the outermost loop tested.



Concatenated Loops

- One loop executes. The next line of code starts a new loop.
- These are generally independent.
  - Most of the time...
- If not, follow a similar strategy to nested loops.
  - Start with bottom loop, hold higher loops at minimal iteration numbers.
  - Work up towards the top, holding lower loops at “typical” iteration numbers.



Why These Loop Strategies?

- In proving formal correctness of a loop, we would establish preconditions, postconditions, and invariants that are true on each execution of the loop, then prove that these hold.
  - The loop executes **zero** times when the postconditions are true in advance.
  - The loop invariant is true on loop entry (**one**), then each loop iteration maintains the invariant (**many**).
    - (invariant and !(loop condition) implies postconditions)
- Loop testing strategies echo these cases.

The Infeasibility Problem

Sometimes, **no** test can satisfy an obligation.

- Impossible combinations of conditions.
- Unreachable statements as part of defensive programming.
  - Error-handling code for conditions that can’t actually occur in practice.
- Dead code in legacy applications.
- Inaccessible portions of off-the-shelf systems.

The Infeasibility Problem

Stronger criteria call for potentially infeasible combinations of elements.

```
(a > 0 && a < 10)
```

It is not possible for both conditions to be false.

Problem compounded for path-based coverage criteria.

Not possible to traverse the path where both if-statements evaluate to true.

```
if (a < 0)  a = 0;
if (a > 10) a = 10;
```

The Infeasibility Problem

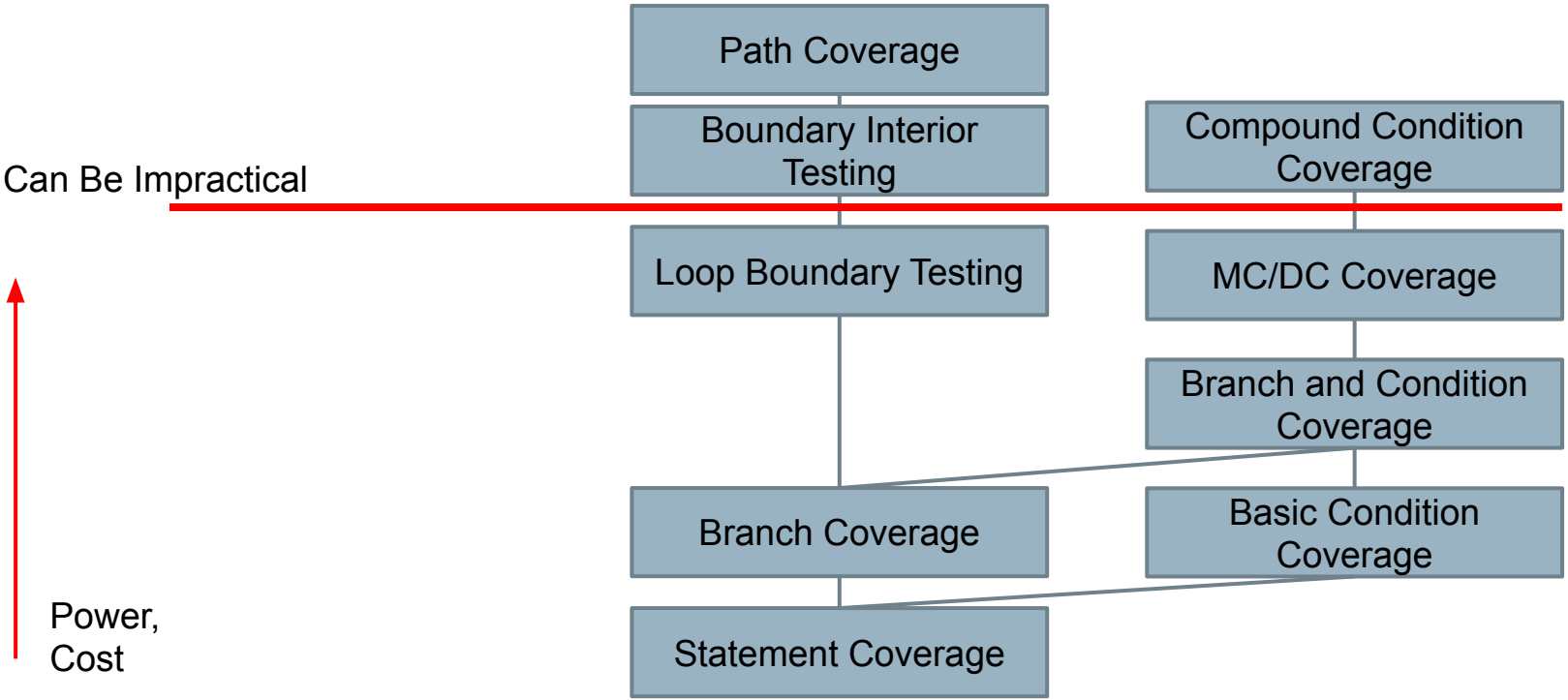
How this is usually addressed:

- Adequacy “scores” based on coverage.
  - 95% branch coverage, 80% MC/DC coverage, etc.
  - Decide to stop once a threshold is reached.
  - Unsatisfactory solution - elements are not equally important for fault-finding.
- Manual justification for omitting each impossible test obligation.
  - Helps refine code and testing efforts.
  - … but **very** time-consuming.

In Practice.. Budget Coverage

- Industry's answer to "when is testing done"
  - When the money is used up
  - When the deadline is reached
- This is sometimes a rational approach!
  - Implication 1:
    - Adequacy criteria answer the wrong question. Selection is more important.
  - Implication 2:
    - Practical comparison of approaches must consider the cost of test case selection

Which Coverage Metric Should I Use?

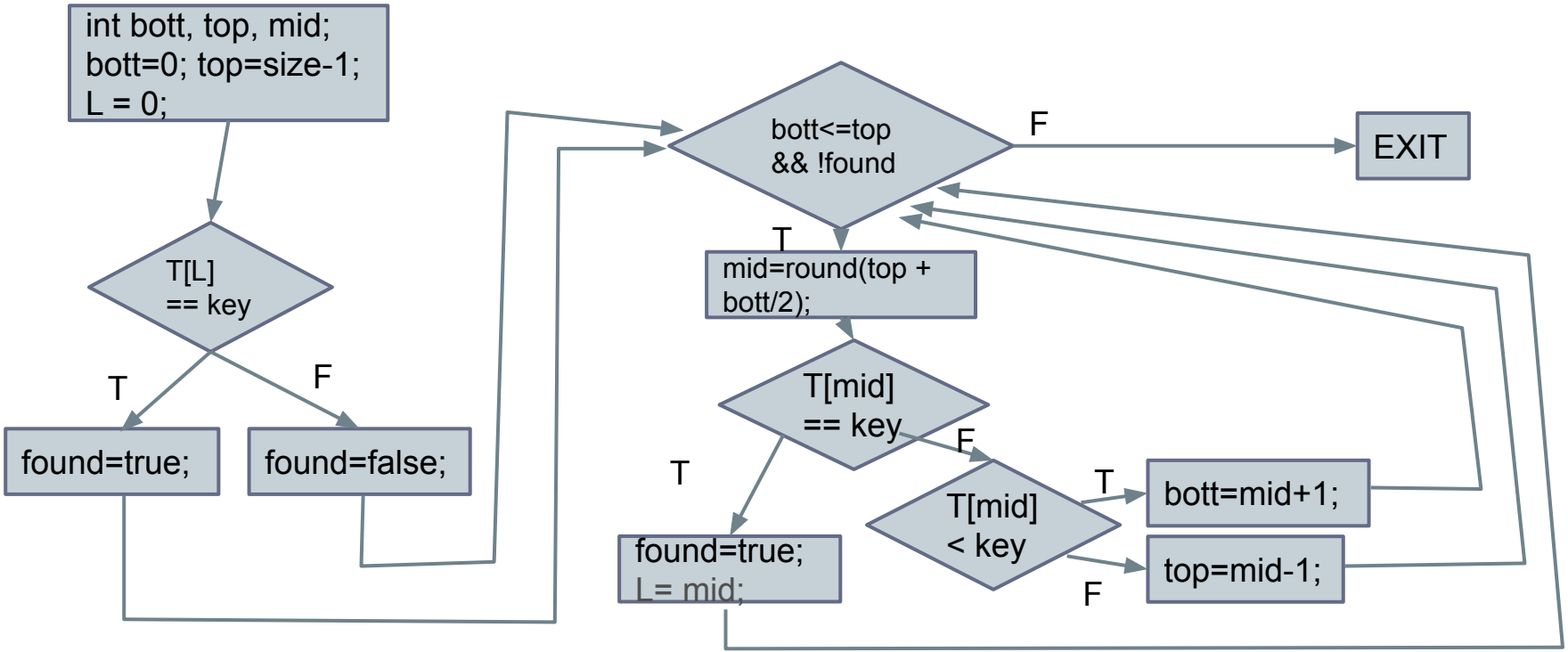


Activity: Loop-Covering Tests

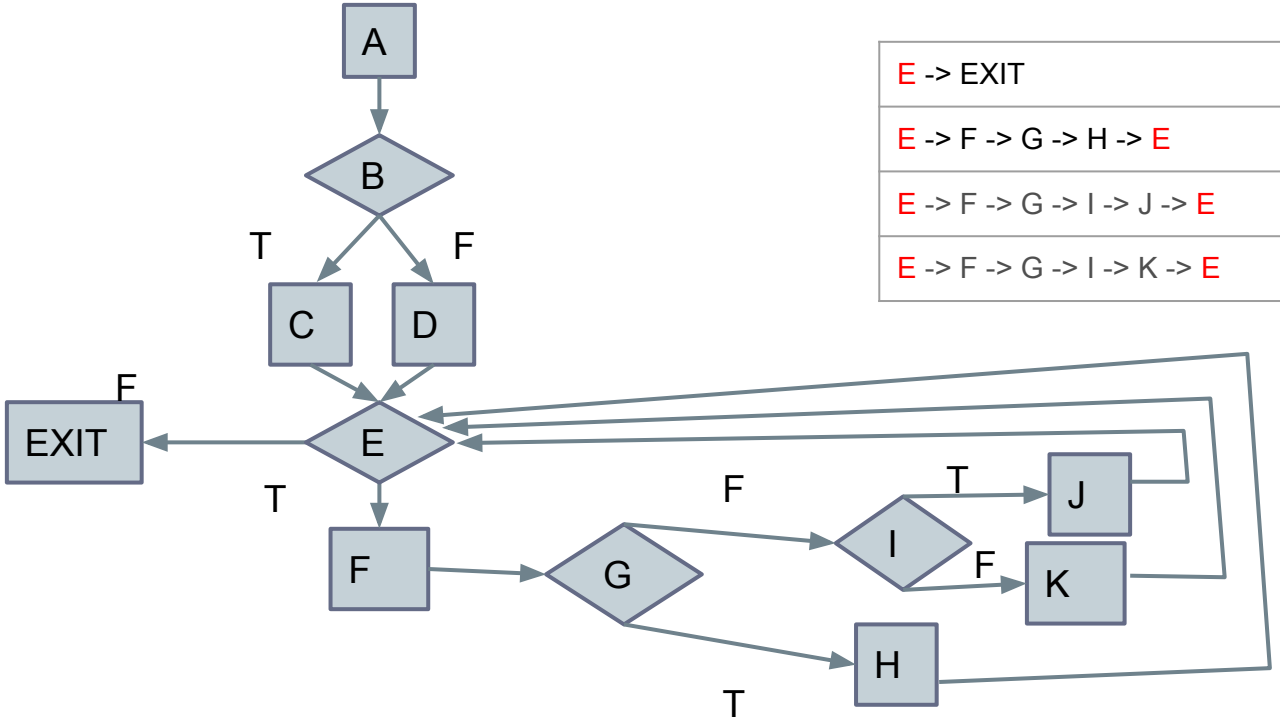
For the binary-search code:

1. Draw the control-flow graph for the method.
2. Identify the subpaths through the loop and draw the unfolded CFG for boundary interior testing.
3. Develop a test suite that achieves loop boundary coverage.

CFG

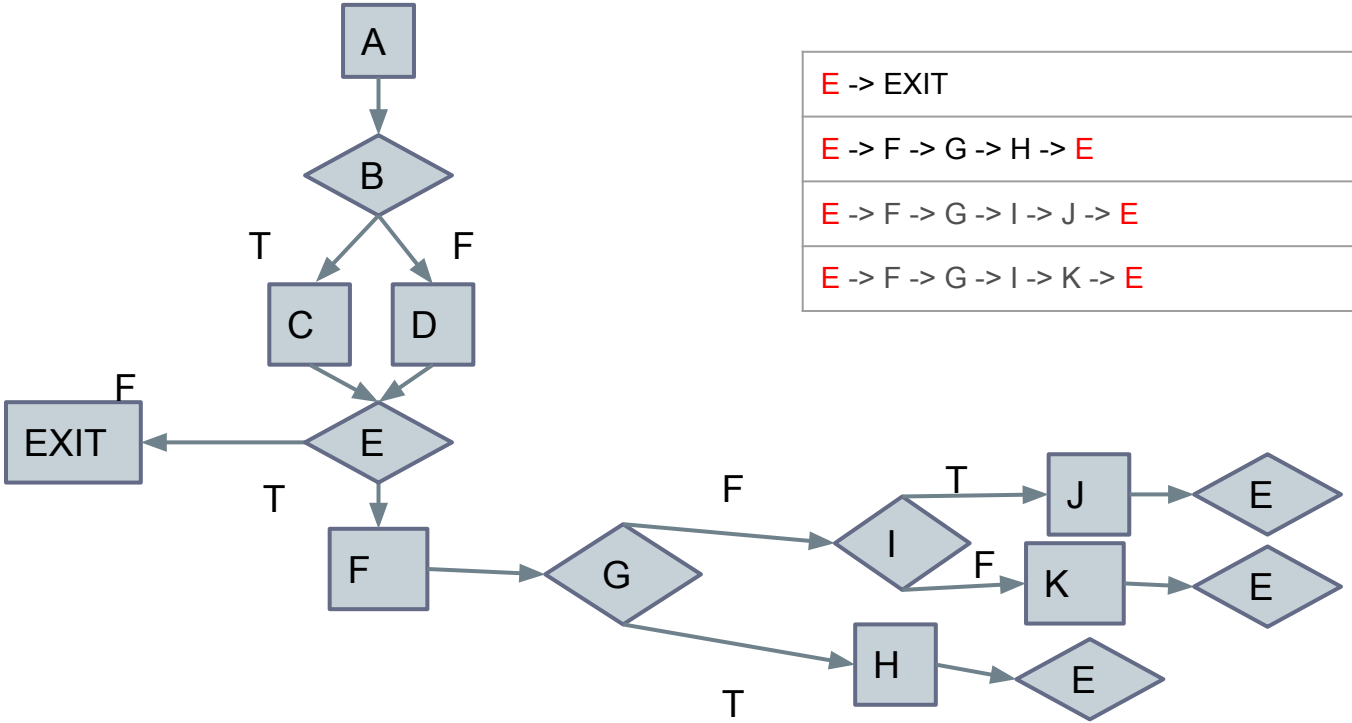

int bott, top, mid;
bott=0; top=size-1;
L = 0;
T[L]
== key
T
F
found=true;
found=false;
bott<=top
&& !found
F
EXIT
T
mid=round(top +
bott/2);
T[mid]
== key
T
F
found=true;
L= mid;
T[mid]
< key
T
F
bott=mid+1;
top=mid-1;

CFG



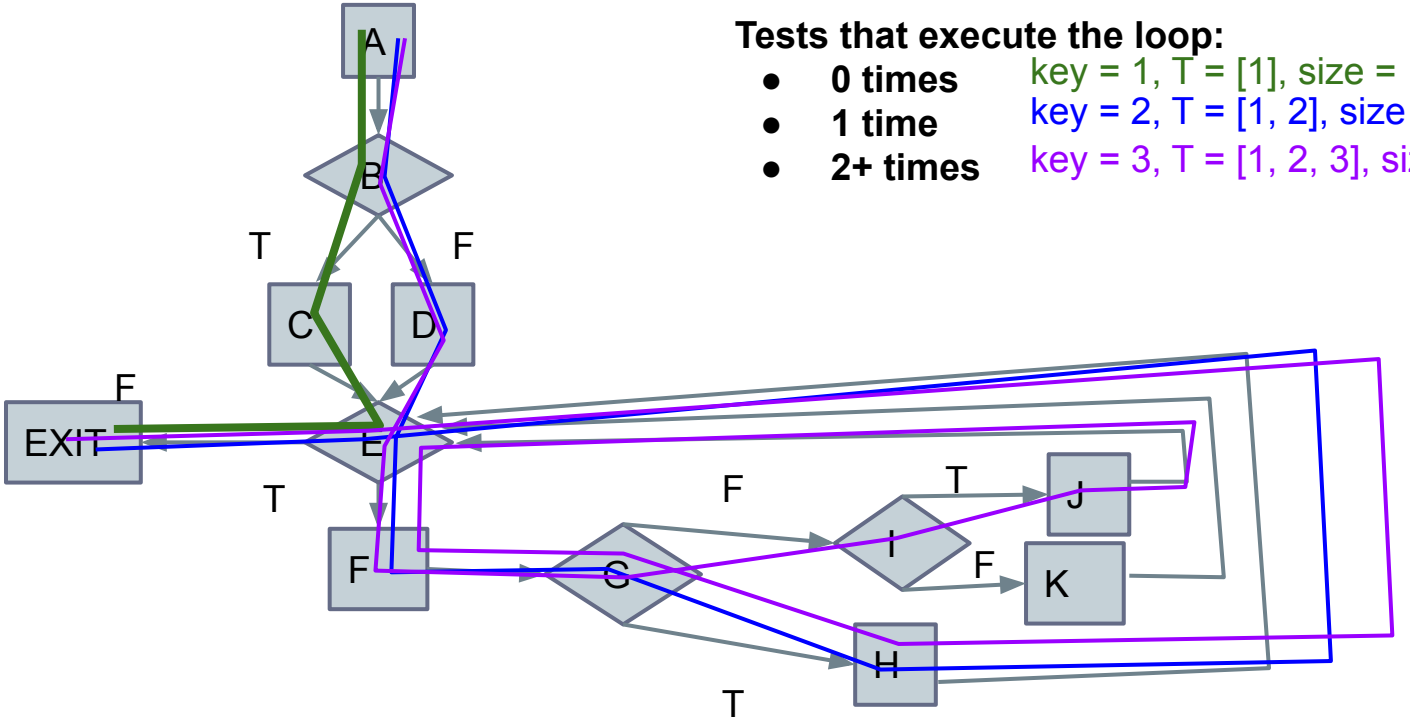
E -> EXIT
E -> F -> G -> H -> E
E -> F -> G -> I -> J -> E
E -> F -> G -> I -> K -> E

CFG



E -> EXIT
E -> F -> G -> H -> E
E -> F -> G -> I -> J -> E
E -> F -> G -> I -> K -> E

CFG



Tests that execute the loop:

- **0 times** key = 1, T = [1], size = 1
- **1 time** key = 2, T = [1, 2], size = 2
- **2+ times** key = 3, T = [1, 2, 3], size = 3

We Have Learned

- Test adequacy metrics let us “measure” how good our testing efforts are.
  - They prescribe test obligations that can be used to remove inadequacies from test suites.
- Code structure is used in many adequacy metrics. Many different criteria, based on:
  - Statements, branches, conditions, paths, etc.

We Have Learned

- Coverage metrics tuned towards particular types of faults. Some are theoretically stronger than others, but are also more expensive and difficult to satisfy.
- Full path coverage is impractical
  - However, there are strategies to get the benefits of path coverage without the cost.
  - These strategies are based on covering “important” paths or subpaths.

Next Time

- Exercise Today: Functional Testing
- Next class: Data-Flow Testing
  - Optional Reading - Pezze and Young, Chapters 6 and 13

- Homework - Assignment 1 due Sunday, Feb 16

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