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Lecture 9: Test Adequacy and Structural Testing

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DIT636/DAT560 - February 12, 2024

We Will Cover

- Test Adequacy Criteria
- Structural Testing:
  - Use structural coverage to judge tests, create new tests.
  - Statement, Branch, Condition, Path Coverage

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.

What we (usually) get:

- We compiled and it worked.
- We run out of time or budget.
  - **(Inadequate testing)**.

Test Adequacy Criteria

Can we **compromise between the impossible and the inadequate**?

- Measure “good testing”
- **Test adequacy criteria** “score” tests by measuring completion of **test obligations**.
  - Checklists of properties that must be met by test cases.

(In)Adequacy Criteria

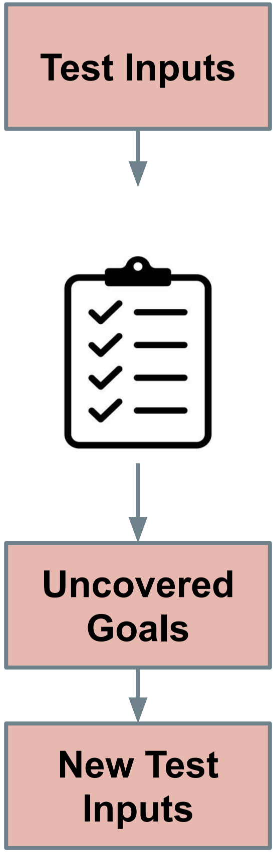
- Criteria identify **inadequacies** in the tests.
  - If no test reaches a statement, test suite is inadequate for finding faults in that statement.
  - If we plant a fake fault and no test exposes it, our tests are inadequate at detecting that fault.
- Tests may still miss faults, but maximizing criteria shows that tests *at least* meet certain goals.

Adequacy Criteria

- Adequacy Criteria based on coverage of factors correlated to finding faults (*hopefully*).
  - Exercising elements of source code (**structural testing**).
  - Detection of planted faults (**mutation testing**)
- Widely used in industry - easy to understand, cheap to calculate, offer a checklist.
  - Enable tracking of “testing completion”
  - Can be measured in IntelliJ, Eclipse, etc.

Use of Criteria

- Measure adequacy of existing tests
  - Create additional tests to cover missed obligations.
- Create tests directly
  - Choose specific obligations, create tests to cover those.
  - Targets for automated test generation.



Structural Testing

Structural Testing

- The structure of software is valuable information.
- Prescribe how code elements should be executed, and measure coverage of execution.
  - If-statements, Boolean expressions, loops, switches, paths between statements...

```
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 A;
}
```

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 covering gaps in the source code.

Structural Does Not Replace Functional

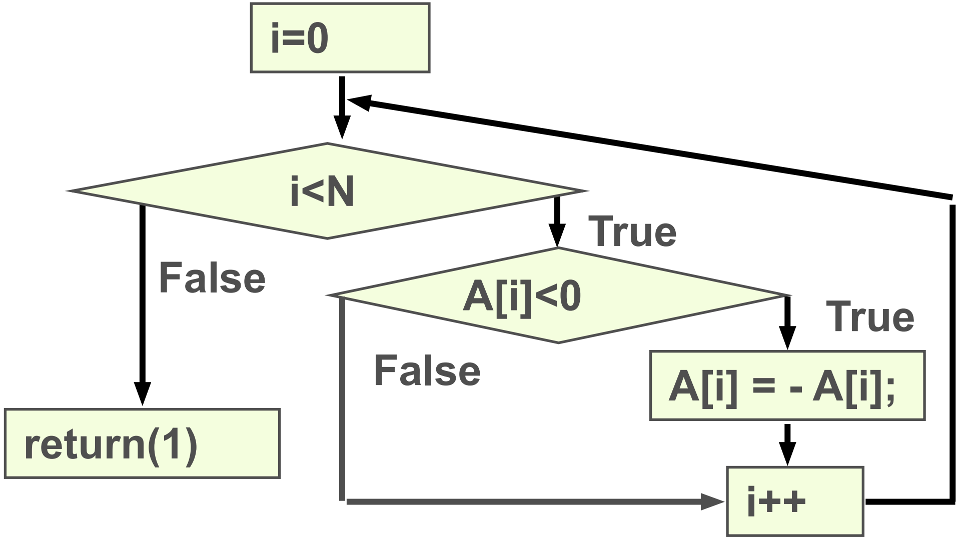
- **Should not be the basis for all test cases!!!!!**
- Harder to make verification argument.
  - May not map directly to requirements.
- Does not expose missing functionality.
- Useful for supplementing functional tests.
  - Functional tests good at exposing *conceptual faults*.
  - Structural tests good at exposing *coding mistakes*.

Control and Data Flow

- We need to understand how system executes.
  - Conditional statements result in branches in execution, jumping between blocks of code.
- **Control flow**: how control passes through code.
  - Which code is executed, and when.
- **Data flow**: how data passes through code.
  - How variables are used in different expressions.

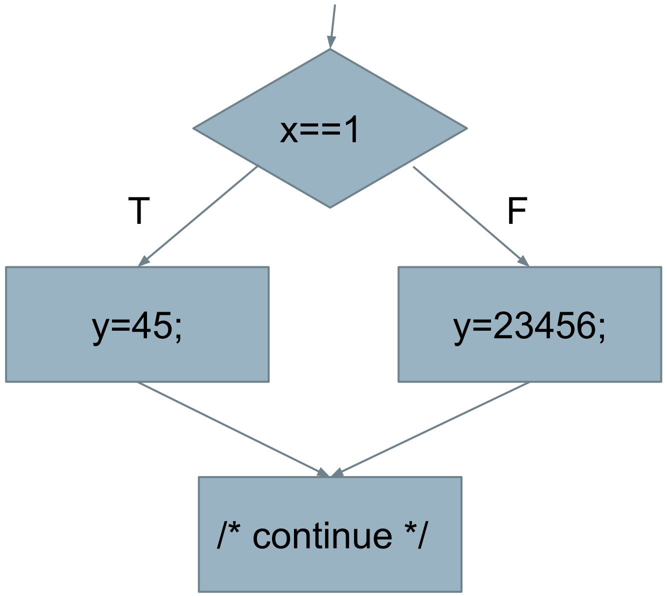
Control-Flow Graphs

- Directed graph representing flow of control.
- Nodes represent blocks of sequential statements.
- Edges connect nodes in the sequence they are executed.
  - Multiple edges indicate conditional statements.



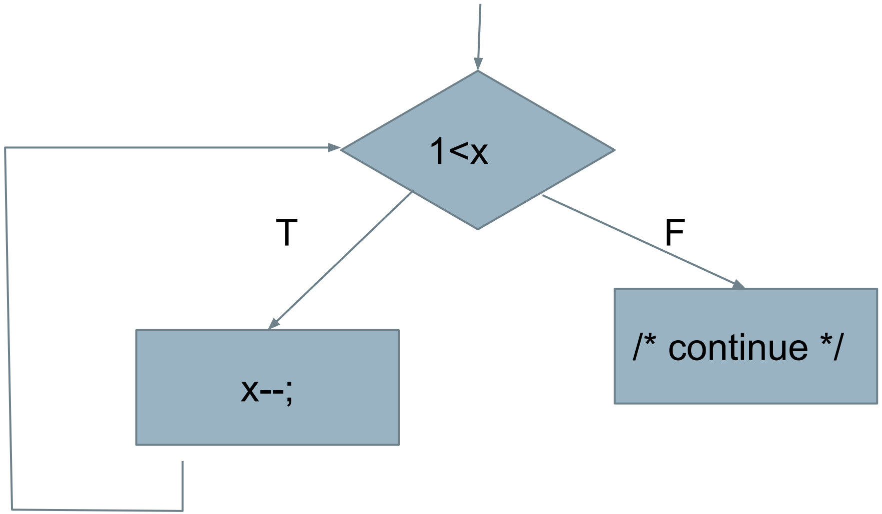
Control Flow: If-then-else

```
if (x==1) {
        y=45;
}else {
        y=23456;
}
/* continue */
```



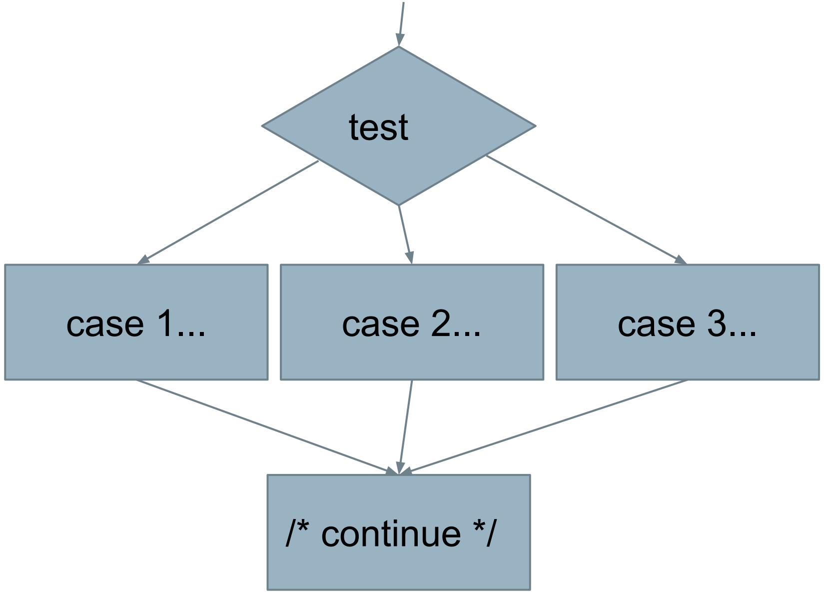
Loop

```
while (1<x) {
        x--;
}
/* continue */
```



Case

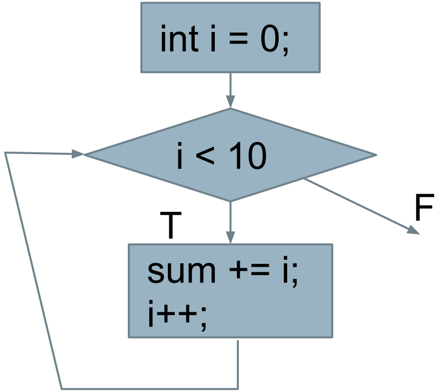
```
switch (test) {
        case 1 : ...
        case 2 : ...
    case 3 : ...
}
/* continue */
```



Basic Blocks

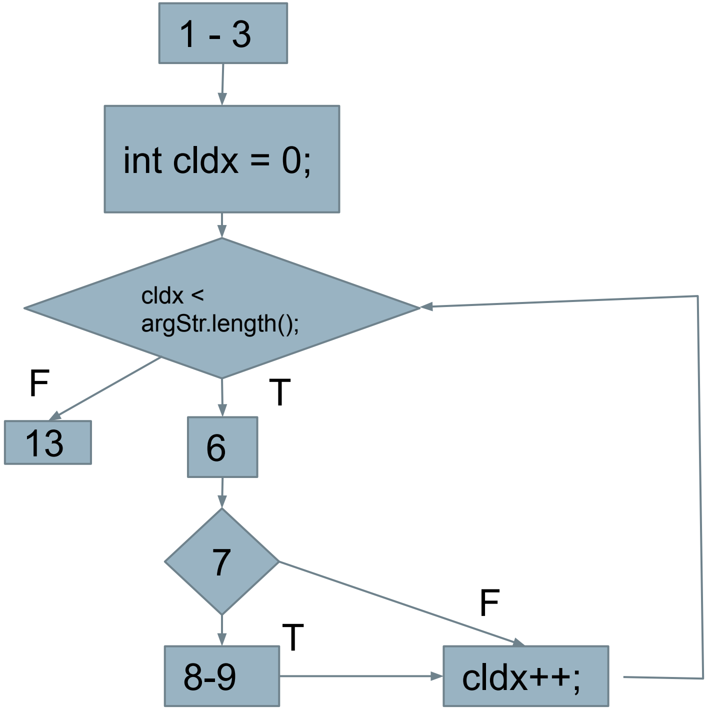
- Nodes are basic blocks.
  - Sequential instructions with one entry and exit.
- Typically adjacent statements
  - One line might be broken up (e.g., loop setup is really three statements).

```
for(int i=0; i < 10; i++){
    sum += i;
}
```



Control Flow Graph Example

```
1. public static String collapseNewlines(String argSt){
2.    char last = argStr.charAt(0);
3.    StringBuffer argBuf = new StringBuffer();
4.
5.    for(int cldx = 0; cldx < argStr.length(); cldx++){
6.          char ch = argStr.charAt(cldx);
7.          if (ch != ‘\n’ || last != ‘\n’){
8.                argBuf.append(ch);
9.                last = ch;
10.         {
11.   }
12.
13.   return argBuf.toString();
14. }
```



Structural Coverage Criteria

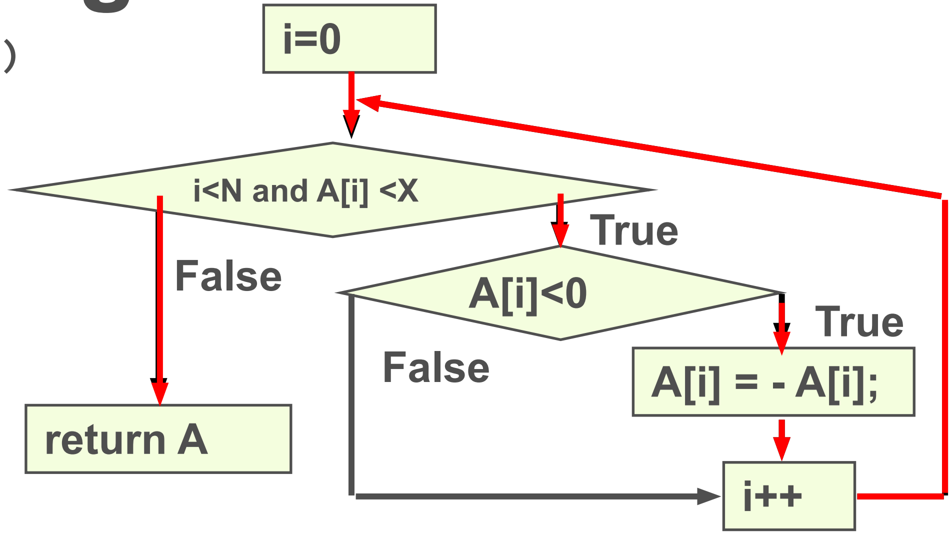
- Criteria based on exercising:
  - Statements (nodes of CFG)
  - Branches (edges of CFG)
  - Conditions
  - Paths
  - … and many more
- Measurements used as adequacy criteria

Statement Coverage

- 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.
- 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 A;
}
```



Can cover in one test: [-1], 1, 10

A Note on Test Suite Size

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

Test Suite Size

- **Design small targeted tests**, not long tests.
  - If test targets few obligations, it is easier to debug.
  - If a test covers many obligations, harder to understand the purpose, harder to locate and fix faults.
  - Exception - if cost to execute each test is high.

Branch Coverage

- Do tests execute all outcomes of control-diverging statements (`loop`, `if`, `switch`)?
  - 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

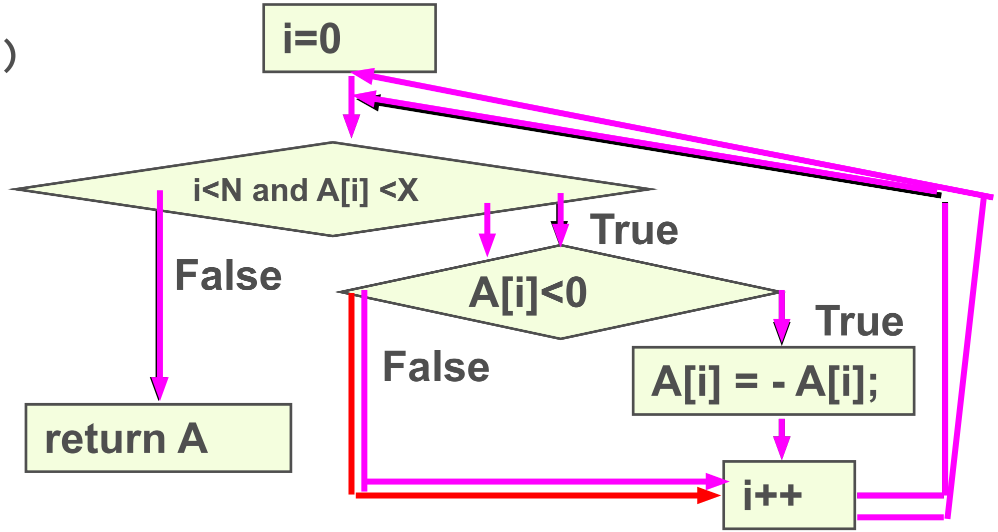
- Criterion A **subsumes** Criterion B if, for every program P, every test suite satisfying A also satisfies B on P.
  - *If we satisfy A, we have satisfied B*.
- Branch coverage **subsumes** statement coverage.
  - Covering all edges in CFG requires covering all nodes.

Subsumption

- Shouldn’t we always choose the stronger metric?
- Not always…
  - Typically requires **more** obligations.
    - (so, you have to come up with more tests)
  - Or **tougher** obligations.
    - (making it harder to come up with the tests).
  - May end up with **unsatisfiable** obligations.
    - (no test can cover these 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 A;
}
```



- ([-1], 1, 10) leaves one edge uncovered.
- ([-1, 1], 2, 10) achieves Branch Coverage.

Let’s take a break.

Decisions and Conditions

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

Decisions and Conditions

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

Decision Coverage

- Branch Coverage covers a *subset* of decisions.
    - Branching decisions that decide how control is routed through the program.
- Decision coverage requires that ***all*** decisions evaluate to all outcomes.
- 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

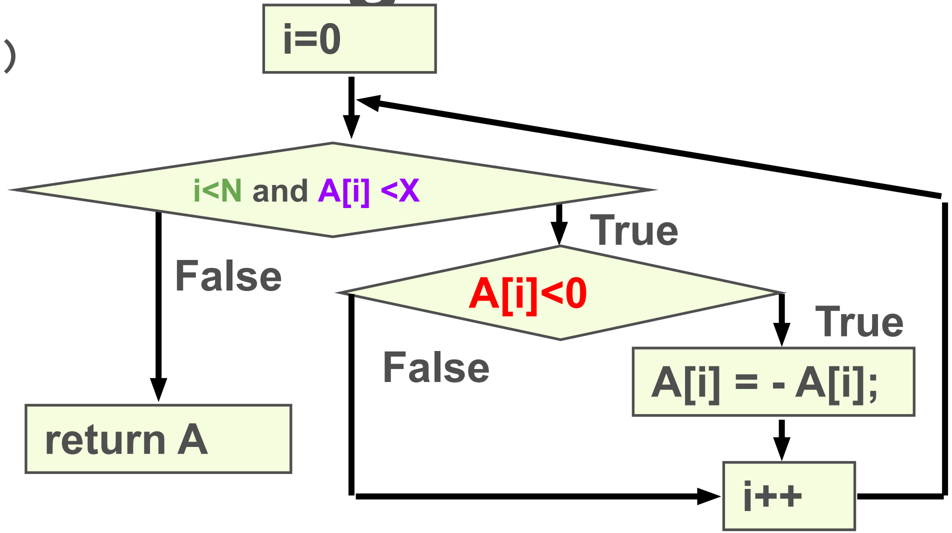
(A and B)

Test Case	A	B
1	True	False
2	False	True

- Does not require covering both outcomes.
  - Does not subsume branch or decision coverage.
  - (In this case, false outcome 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 A;
}
```



- ([-1, 1], 2, 10)
  - Negative value in array
  - Positive value (but < X)
- ([11], 1, 10)
  - Positive, but > X
- Both eventually cause i < N to be false.

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 and decision coverage.
  - 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~~

- Tests 1, 3 show independent impact of A.
- Tests 1, 2 show independent impact of B.
- Test 4 adds nothing and can be skipped.

Activity

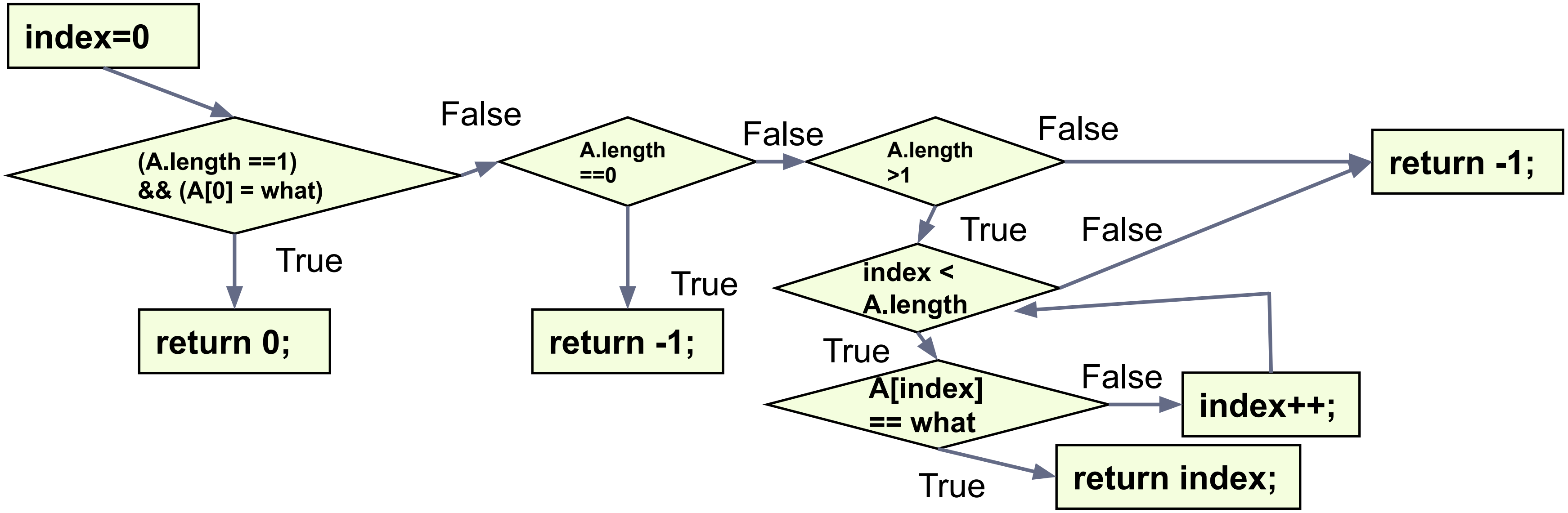
Draw the CFG and write tests that provide statement, branch, and basic condition coverage over the following code:

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

[ ] (empty array), "Bob"

Executes lines:
1, 2, 3,
(Branch 3-F),
5,
(Branch 5-T),
6

Activity - Control Flow Graph



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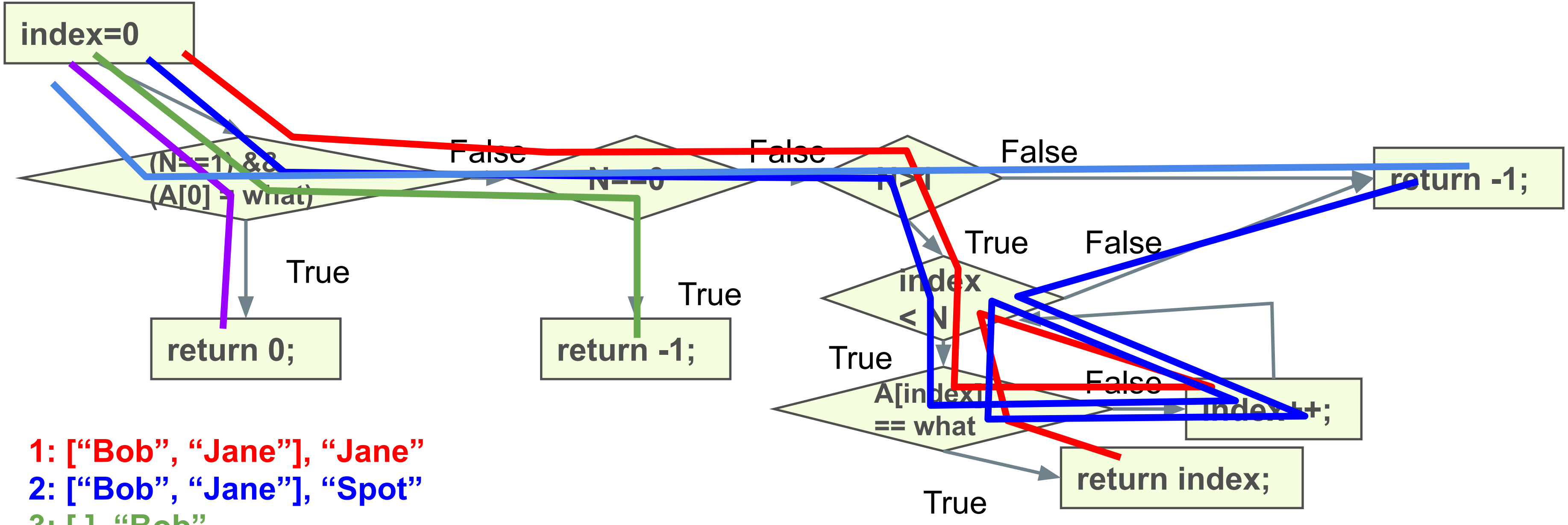
Activity - Possible Solution



1: [“Bob”, “Jane”], “Jane”

2: [“Bob”, “Jane”], “Spot”

3: [ ], “Bob”

4. [“Bob”], “Bob”

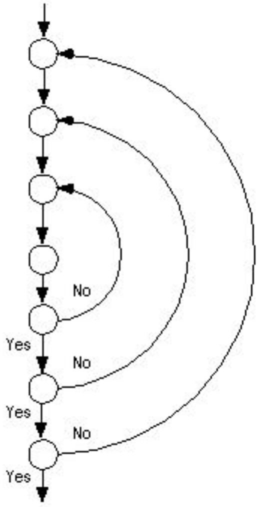
5. [“Bob”], “Spot”

Loop Boundary Coverage

- Focus on problems related to loops.
- For each loop, write tests that:
  - Skip the loop entirely.
  - Take exactly one pass through the loop.
  - Take two or more passes through the loop.

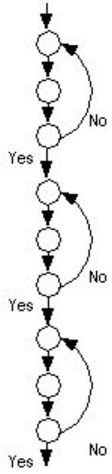
Nested Loops

- Often, loops are nested within other loops.
  - For each level, execute 0, 1, 2+ times
- 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. Next line of code starts a new loop. These are generally independent.
- If not, follow a similar strategy to nested loops.
  - Start with bottom loop, hold higher loops at minimal iterations
  - Work up towards the top, holding lower loops at "typical" iteration numbers.



Why These Loop Strategies?

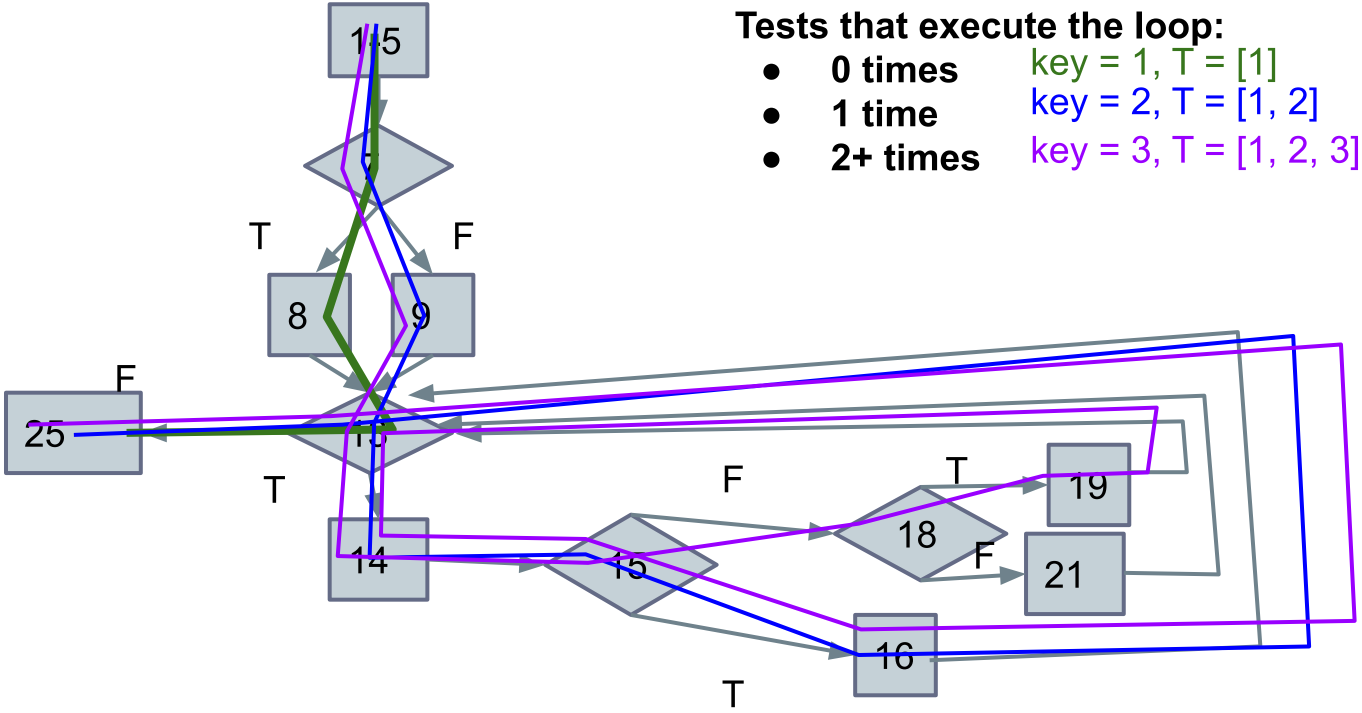
- If proving correctness, we establish preconditions, postconditions, and invariants that are true on each execution of loop.
  - The loop executes zero times when the postconditions are true in advance.
  - The loop invariant is true on loop entry (one), then each loop iteration maintains the invariant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

Activity: Binary Search

For the binary-search code:

1. Draw the control-flow graph for the method.
2. Develop a test suite that achieves loop boundary coverage (executes while loop 0, 1, 2+ times).

Activity: Binary Search



Tests that execute the loop:

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

The Infeasibility Problem

Sometimes, no test can satisfy an obligation.

- Impossible combinations of conditions.
- Error-handling for problems that can't really occur.
- Dead code.

The Infeasibility Problem

- Stronger criteria call for potentially infeasible combinations of elements.

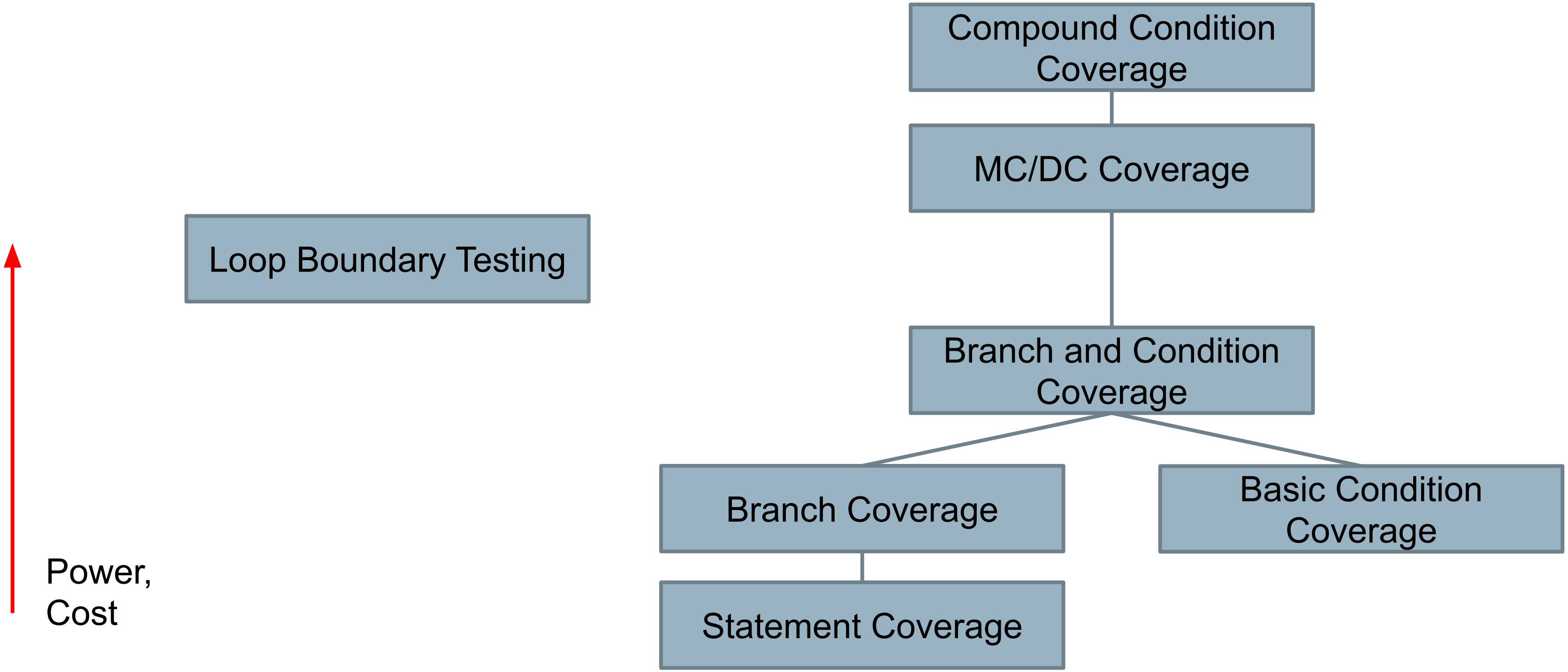
```
(a > 0 && a < 10)
```

- It is not possible for both conditions to be false.
  - A would negative and greater than 10
- Loop boundary coverage
  - Maybe a loop can’t be skipped.

The Infeasibility Problem

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

Which Coverage Criterion Should I Use?



We Have Learned

- Test adequacy “measures” how good our tests are.
  - Covering obligations removes inadequacies from suites.
- Code structure is used in many adequacy criteria.
  - Based on statements, branches, conditions, loops, etc.

Next Time

- Next class: Path-based coverage and data-flow
- Thursday Exercise Session: Structural Coverage

- Homework - Assignment 2 due Feb 25

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