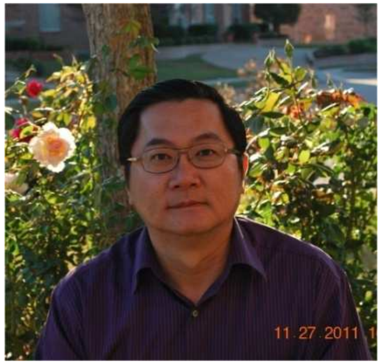
Controlflow-based Coverage Criteria

W. Eric Wong
Department of Computer Science
The University of Texas at Dallas
ewong@utdallas.edu
http://www.utdallas.edu/~ewong

Speaker Biographical Sketch



- Professor & Director of International Outreach
  Department of Computer Science
  University of Texas at Dallas
- Guest Researcher
  Computer Security Division
  National Institute of Standards and Technology (NIST)
- Vice President, IEEE Reliability Society
- Secretary, ACM SIGAPP (Special Interest Group on Applied Computing)
- Principal Investigator, NSF TUES (Transforming Undergraduate Education in Science, Technology, Engineering and Mathematics) Project
  - *Incorporating Software Testing into Multiple Computer Science and Software Engineering Undergraduate Courses*
- Founder & Steering Committee co-Chair for the SERE conference (*IEEE International Conference on Software Security and Reliability*) (http://paris.utdallas.edu/sere13)

Outline

- Block/Statement Coverage
- Decision Coverage
- Condition Coverage
- Multiple Condition Coverage

Statement and Block Coverage

Declarations and Basic Blocks

- Any program written in a procedural language consists of a sequence of statements. Some of these statements are *declarative*, such as the *#define* and *int* statements in C, while others are *executable*, such as the *assignment*, *if*, and *while* statements in C and Java.
- Recall that a basic block is a sequence of consecutive statements that has exactly one entry point and one exit point.
  – For any procedural language, adequacy with respect to the statement coverage and block coverage criteria are defined next.
- Notation: (*P*, *R*) denotes program *P* subject to requirement *R*.

Statement Coverage

- The statement coverage of *T* with respect to (*P*, *R*) is computed as $S_c / (S_e - S_i)$, where S_c is the number of statements covered, S_i is the number of *unreachable statements*, and S_e is the *total number of executable statements* in the program, i.e., the size of the coverage domain.

- *T* is considered adequate with respect to the statement coverage criterion if the statement coverage of *T* with respect to (*P*, *R*) is 1.

Block Coverage

- The block coverage of *T* with respect to (*P*, *R*) is computed as $B_c / (B_e - B_i)$, where B_c is the number of blocks covered, B_i is the number of *unreachable blocks*, and B_e is the total number of *executable blocks* in the program, i.e., the size of the block coverage domain.
- *T* is considered adequate with respect to the block coverage criterion if the statement coverage of *T* with respect to (*P*, *R*) is 1.

Example: Statement Coverage

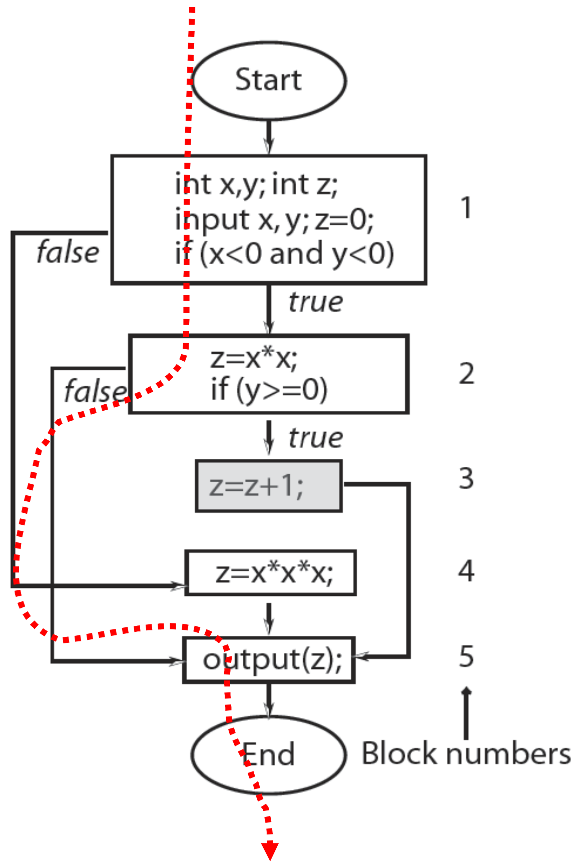
- Coverage domain: $S_e = \{4, 5, 6, 7, 8, 9, 12, 13\}$ Let $T_1 = \{t_1: < x = -1, y = -1 >, t_2: < x = 1, y = 1 >\}$
- Statements covered:
  - t_1: 4, 5, 6, 7, 8 and 13
  - t_2: 4, 5, 6, 12, and 13
- $S_c = 7$, $S_i = 1$, $S_e = 8$. The statement coverage for T_1 is $7 / (8 - 1) = 1$. Hence we conclude that T_1 is adequate for (P, R) with respect to the statement coverage criterion. Note: *9 is unreachable*.

```
1       begin
2         int X, Y;
3         int Z;
4         input (X, Y);
5         Z = 0;
6         if (X < 0 and Y < 0) {
7            Z = X*X;
8            if (Y >= 0)
9               Z = Z + 1;
10        }
11        else
12           Z = X*X*X;
13        output (Z);
14      end
```

Example: Block Coverage (1)

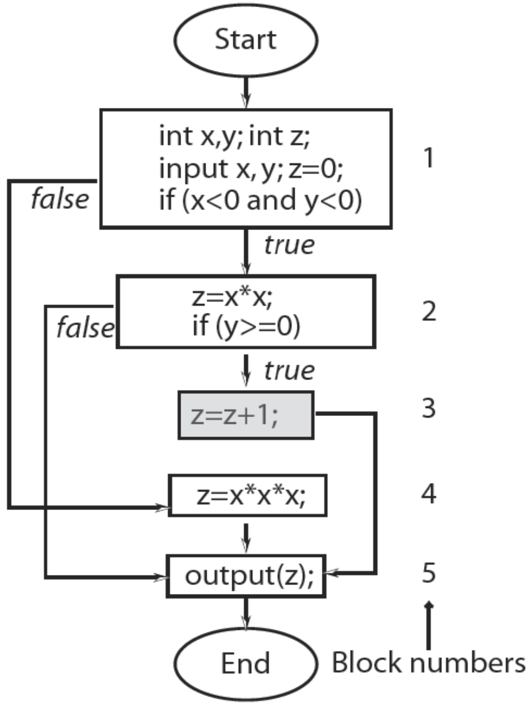
- Coverage domain: B_e={1, 2, 3, 4, 5}
- Blocks covered:
  - t_1: Blocks 1, 2, 5
  - t_2, t_3: same coverage as of t_1.
- $B_e = 5$, $B_c = 3$, $B_i = 1$.
  - Block coverage for T_2= 3 / (5 − 1) = 0.75.
  - Hence T_2 is not adequate for (P, R) with respect to the block coverage criterion.

$$T_2 = \left\{ \begin{array}{lll} t_1: & < x = -1 & y = -1 > \\ t_2: & < x = -3 & y = -1 > \\ t_3: & < x = -1 & y = -3 > \end{array} \right\}$$



Example: Block Coverage (2)

- T_1 is adequate w.r.t. block coverage criterion. Verify this statement!
- Also, if test t_2 in T_1 is added to T_2, we obtain a test set adequate with respect to the block coverage criterion for the program under consideration.
- Verify this statement!



Coverage Values

- The formulae given for computing various types of code coverage yield *a coverage value between* 0 *and* 1. However, while specifying a coverage value, *one might instead use percentages*. For example, a statement coverage of 0.65 is the same as 65% statement coverage.

Condition and Decision Coverage

Conditions

- Any expression that evaluates to true or false constitutes a condition. Such an expression is also known as a predicate.
- Given that A, B, and D are Boolean variables, and x and y are integers, A, $x > y$, A OR B, A AND ($x < y$), (A AND B) are sample conditions.
- Note that in programming language C, x and $x + y$ are valid conditions, and the *constants* 1 *and* 0 correspond to, respectively, *true and false*.

Simple and Compound Conditions

- *A simple condition does not use any Boolean operators except for the* not *operator*. It is made up of variables and *at most one* relational operator from the set {<, ≤, >, ≥, ==, ≠}.
- *Simple conditions* are also referred to as atomic or elementary conditions because they cannot be parsed any further into two or more conditions.
- A *compound condition* is made up of two or more simple conditions joined by one or more Boolean operators.

Conditions as Decisions

- *Any condition can serve as a decision* in an appropriate context within a program. Most high level languages provide *if*, *while*, and *switch* statements to serve as contexts for decisions.

```
if (A)                    while(A)                    switch (e)
    task if A is true;        task while A is true;       task for e=e1
else                                                    else
    task if A is false;                                    task for e=e2
                                                              ⋮
                                                        else
                                                           task for e=en
                                                        else
                                                           default task
```

(a) (b) (c)

Outcomes of a Decision

- A decision can have three possible outcomes: true, false, and undefined.
- In some cases the evaluation of a condition might fail in which case the corresponding decision's outcome is undefined.

Undefined Condition

- The condition inside the if statement on line 6 will remain undefined *because the loop at lines 2-4 will never end*. Thus the decision on line 6 evaluates to undefined.

```
1   bool foo(int a_parameter){
2     while (true) {     // An infinite loop.
3       a_parameter=0;
4     }
5   }     // End of function foo().
⋮

6   if(x< y and foo(y)){     // foo() does not terminate.
7     compute(x,y);
⋮
```

Coupled Conditions

- How many simple conditions are there in the compound condition: D = (A AND B) OR (C AND A)? *The first occurrence of A is said to be* coupled *to its second occurrence*.
- Does D contain *three or four simple conditions*? Both answers are correct depending on one's point of view. Indeed, there are three distinct conditions A , B, and C. The answer is four when one is interested in the number of occurrences of simple conditions in a compound condition.

Conditions within Assignments

- Strictly speaking, a condition becomes a decision only when it is used in the appropriate context such as within an if statement.
- At line 4, $x < y$ does not constitute a decision and neither does $A \times B$.
  1. A = $x < y$; // A simple condition assigned to a Boolean variable A.
  2. $X = P$ or Q; // A compound condition assigned to a Boolean variable x
  3. $x = y + z \times s$; if(x)…// The condition will be true if $x = 1$ and false otherwise
  4. A = $x < y$; x = A $\times$ B; // *A* is used in a subsequent expression for x but not as a decision

Decision Coverage

- A decision is considered covered if the flow of control has been diverted to all possible destinations that correspond to this decision, i.e., *all outcomes of the decision have been taken.*
- This implies that, for example, the expression in the if or a while statement has evaluated to true in some execution of the program under test and to false in the same or another execution.

Decision Coverage: Switch Statement

- Decision implied by *the switch statement* is considered covered if during one or more executions of the program under test the flow of control has been *diverted to all possible destinations*.

Decision Coverage: Example (1)

- Requirement:
  - The following code inputs an integer *x*, and if *x* < 0, transforms it into a positive value before invoking foo-1 to compute the output *z*.
  - It is supposed to compute z using foo-2 when *x* ≥ 0.
  - It has a bug.

```
begin
  int x, z;
  input (x);
  if(x<0)
   x =-x;
  z=foo-1(x);
  output(z);
end
```

There should have been an else clause before this statement.

Decision Coverage: Example (2)

- Consider the test set $T = \{t_1\!:\,< x = -5 >\}$.
  - It is adequate with respect to *statement and block* coverage criteria, but does not reveal the bug.
- Another test set $T' = \{t_1\!:\,< x = -5 >\ \ t_2\!:\,< x = 3 >\}$ does reveal the bug. It covers the decision whereas T does not. Check!
- This example illustrates *how and why decision coverage might help in revealing a bug that is not revealed* by a test set adequate with respect to *statement and block coverage*.

```
begin
  int x, z;
  input (x);
  if(x<0)
   x =-x;
  z=foo-1(x);
  output(z);
end
```

There should have been an `else` clause before this statement.

Decision Coverage: Computation

- The decision coverage of *T* with respect to (*P*, *R*) is computed as $D_c / (D_e - D_i)$, where D_c is the number of decisions covered.
- D_i is the number of infeasible decisions, and D_e is the total number of decisions in the program, i.e., the size of the decision coverage domain.
- *T is considered adequate* with respect to the decision coverage criterion if the decision coverage of *T with respect to* (*P*, *R*) *is* 1.

Decision Coverage: Domain

- The domain of decision coverage consists of *all decisions in the program under test.*

Condition Coverage

- A decision can be composed of *a simple condition* such as $x < 0$, or of *a more complex condition*, such as (($x < 0$ AND $y < 0$) OR ($p \geq q$)).
- AND, OR, XOR are the *logical operators* that connect two or more simple conditions to form a *compound condition*.
- *A simple condition is considered covered if it evaluates to true and false in one or more executions* of the program in which it occurs.
- A compound condition is considered covered if each simple condition it is comprised of is also covered.

Decision and Condition Coverage (1)

- Decision coverage is concerned with *the coverage of decisions regardless of* whether or not a decision corresponds to *a simple or a compound* condition. Thus in the statement

```
1.   if (x < 0 and y < 0) {
2.       z = foo(x, y)
```

<u>Question</u>

```
if (x < 0)
    if (y < 0)
        z=foo(x, y);
```

How many decision?

- There is *only one decision* that leads control to line 2 if the compound condition inside the *if* evaluates to true.
- However, a compound condition might evaluate to true or false *in one of several ways*.

Decision and Condition Coverage (2)

- Referring to the following code

  1. *if* ($x < 0$ and $y < 0$) {
  2. $z = \text{foo}(x, y)$

- The condition at line 1 evaluates to false when $x \geq 0$ regardless of the value of y.
- Another condition, such as ($x < 0$ OR $y < 0$), evaluates to true regardless of the value of y, when $x < 0$.
- With this evaluation characteristic in view, compilers often generate code that uses short circuit evaluation of compound conditions.

Decision and Condition Coverage (3)

- Here is a possible translation:

```
1    if (x < 0 and y < 0) {
2      z=foo(x,y);
```

→

```
1    if (x<0)
2      if (y<0)
3        z=foo(x,y);
```

- We now see two decisions, one corresponding to each simple condition in the *if* statement.

Condition Coverage

- The *condition coverage* of T with respect to (P, R) is computed as $C_c / (C_e - C_i)$, where
  - C_c is the number of simple conditions covered,
  - C_i is the number of infeasible simple conditions, and
  - C_e is the total number of simple conditions in the program.
- T is considered adequate with respect to the condition coverage criterion if the condition coverage of T with respect to (P, R) is 1.
- An alternate formula where each simple condition contributes 2, 1, or 0 to C_c depending on whether it is covered, partially covered, or not covered, respectively, is:

$$\frac{C_c}{2 \times (C_e - C_i)}$$

Condition Coverage: Example (1)

- Partial specifications for computing *z*

x< 0	y< 0	Output (z)
true	true	foo1(x,y)
true	false	foo2(x,y)
false	true	foo2(x,y)
false	false	foo1(x,y)

```
begin
  int x, y, z;
  input (x, y);
  if(x<0 and y<0)
    z=foo1(x,y);
  else
    z=foo2(x,y);
  output(z);
end
```

This program has a bug based on the specification.

Condition Coverage: Example **(2)**

- Consider the test set

  $T = \{t_1 :< x = -3, y = -2 > \ t_2 :< x = -4, y = -2 >\}$

- Check that T is adequate with respect to the *statement, block, and decision* coverage criteria and the program behaves correctly against t_1 and t_2.

- $C_c = 1$, $C_e = 2$, $C_i = 0$. Hence, condition coverage for $T = 0.5$.

```
begin
  int x, y, z;
  input (x, y);
  if(x<0 and y<0)
    z=foo1(x,y);
  else
    z=foo2(x,y);
  output(z);
end
```

Condition Coverage: Example (3)

- Add the following test case to T: t_3: $< x = 3, y = 4 >$
- Check that the enhanced test set T is adequate with respect to the *condition coverage criterion* and possibly reveals a bug in the program.
  - The programs shows z = foo2(x, y)
  - But the specifications says z = foo1(x, y)
- Under what conditions will the bug be revealed by t_3?

```
begin
  int x, y, z;
  input (x, y);
  if(x<0 and y<0)
    z=foo1(x,y);
  else
    z=foo2(x,y);
  output(z);
end
```

Condition/Decision Coverage

- When a decision is composed of a compound condition, decision coverage does not imply that each simple condition within a compound condition has taken both values true and false.
- Condition coverage ensures that each component simple condition within a condition has taken both values true and false.
- Question: Does the condition coverage require each decision to take all its outcomes?

Condition/Decision Coverage: Example

- Consider the following program and two test sets.

```
begin
  int x, y, z;
  input (x, y);
  if(x<0 or y<0)
    z=foo-1(x,y);
  else
    z=foo-2(x,y);
  output(z);
end
```

$$T_1 = \left\{ \begin{array}{lll} t_1: & < x = -3 & y = -2 > \\ t_2: & < x = 4 & y = -2 > \end{array} \right\}$$

$$T_2 = \left\{ \begin{array}{lll} t_1: & < x = -3 & y = 2 > \\ t_2: & < x = 4 & y = -2 > \end{array} \right\}$$

- In-class exercise:
  - Is T_1 is adequate with respect to decision coverage?
  - Is T_1 is adequate with respect to condition coverage?
  - How about T_2?

Condition/Decision Coverage: Definition

- The condition/decision coverage of *T* with respect to (*P*, *R*) is computed as $(C_c + D_c) / ((C_e - C_i) + (D_e - D_i))$, where
  - C_c is the number of simple conditions covered
  - D_c is the number of decisions covered,
  - C_e and D_e are the number of simple conditions and decisions respectively
  - C_i and D_i are the number of infeasible simple conditions and decisions, respectively.

Condition/Decision Coverage: Example

- In-class exercise: Is *T* adequate with respect to the condition/decision coverage criterion?

```
begin
  int x, y, z;
  input (x, y);
  if(x<0 or y<0)
    z=foo-1(x,y);
  else
    z=foo-2(x,y);
  output(z);
end
```

$$T = \left\{ \begin{array}{lll} t_1: & < x = -3 & y = -2 > \\ t_2: & < x = 4 & y = 2 > \end{array} \right\}$$

Multiple Condition Coverage

Multiple Condition Coverage

- Consider *a compound condition with two or more simple conditions*. Using condition coverage on some compound condition C implies that each simple condition within C needs to be evaluated to true and false.
- However, does it imply that all combinations_of the values of the individual simple conditions in C have been exercised?

Multiple Condition Coverage/Simple Condition Coverage

- Multiple condition coverage versus simple condition coverage is similar to uni-dimensional equivalence class partitioning versus multi-dimensional equivalence partitioning.
  ➔ *considered separately* versus *considered simultaneously*

Multiple Condition Coverage: Example

- Consider D = (A < B) OR (A > C) composed of two simple conditions A < B and A > C. The four possible combinations of the outcomes of these two simple conditions are enumerated in the table.
  - Check: Is *T* 100% w.r.t. the decision coverage?
  - Check: Is *T* 100% w.r.t. the condition coverage?
  - Check: Does *T* cover all four combinations?
  - Check: Does *T'* cover all four combinations?

	$A < B$	$A > C$	D
1	true	true	true
2	true	false	true
3	false	true	true
4	false	false	false

$$T = \left\{ \begin{array}{llll} t_1: & <A=2 & B=3 & C=1> \\ t_2: & <A=2 & B=1 & C=3> \end{array} \right\}$$

$$T' = \left\{ \begin{array}{llll} t_1: & <A=2 & B=3 & C=1> \\ t_2: & <A=2 & B=1 & C=3> \\ t_3: & <A=2 & B=3 & C=5> \\ t_4: & <A=2 & B=1 & C=5> \end{array} \right\}$$

Multiple Condition Coverage: Definition **(1)**

- Suppose that the program under test contains a total of n decisions. Assume also that each decision contains k_1, k_2, …, k_n simple conditions. Each decision has several combinations of values of its constituent simple conditions.
- For example, decision i will have a total of 2^{k_i} combinations. Thus the total number of combinations to be covered is

$$\sum_{i=1}^{n} 2^{k_i}$$

Multiple Condition Coverage: Definition (2)

- The multiple condition coverage of *T* with respect to (*P*, *R*) is computed as $C_c / (C_e - C_i)$, where:
  - C_c is the number of combinations covered,
  - C_i is the number of infeasible simple combinations, and
  - C_e is the total number of combinations in the program.
- *T* is considered adequate with respect to the multiple condition coverage criterion if the condition coverage of *T* with respect to (*P*, *R*) is 1.

Multiple Condition Coverage: Example **(1)**

- Consider the following program with specifications in the table.

```
begin
  int A, B, C, S=0;
  input (A, B, C);
  if(A<B and A>C) S=f1(A, B, C);
  if(A<B and A≤C) S=f2(A, B, C);
  if(A≥B and A≤C) S=f4(A, B, C);
  output(S);
end
```

	$A < B$	$A > C$	S
1	true	true	$f1(P, Q, R)$
2	true	false	$f2(P, Q, R)$
3	false	true	$f3(P, Q, R)$
4	false	false	$f4(P, Q, R)$

- There is an obvious bug in the program: computation of S for one of the four combinations, line 3 in the table, has been left out.

Multiple Condition Coverage: Example **(2)**

- Is *T* adequate w.r.t. decision coverage?
- Multiple condition coverage?
- Does it reveal the bug?

```
begin
  int A, B, C, S=0;
  input (A, B, C);
  if(A<B and A>C) S=f1(A, B, C);
  if(A<B and A≤C) S=f2(A, B, C);
  if(A≥B and A≤C) S=f4(A, B, C);
  output(S);
end
```

$$T = \left\{ \begin{array}{lllll} t_1 : & < A = 2 & B = 3 & C = 1 > \\ t_2 : & < A = 2 & B = 1 & C = 3 > \end{array} \right\}$$

Multiple Condition Coverage: Example **(3)**

- Is *T*' 100% with respect to the decision coverage?
- Does *T*' reveal the bug?

```
begin
  int A, B, C, S=0;
  input (A, B, C);
  if(A<B and A>C) S=f1(A, B, C);
  if(A<B and A≤C) S=f2(A, B, C);
  if(A≥B and A≤C) S=f4(A, B, C);
  output(S);
end
```

$$T' = \left\{ \begin{array}{lll} t_1: & < A = 2, B = 3, C = 1 > \\ t_2: & < A = 2, B = 1, C = 3 > \\ t_3: & < A = 2, B = 3, C = 5 > \end{array} \right\}$$

Multiple Condition Coverage: Example **(4)**

- In-class exercise:
  - Is *T*'100% w.r.t. simple condition coverage?
  - Is *T*'100% w.r.t. multiple condition coverage?
- Now add a test to *T*' to cover the uncovered combinations.
  - Does your test reveal the bug?
  - If yes, then under what conditions?