SENG3320/6320: Software Verification and Validation

Basis Path Coverage

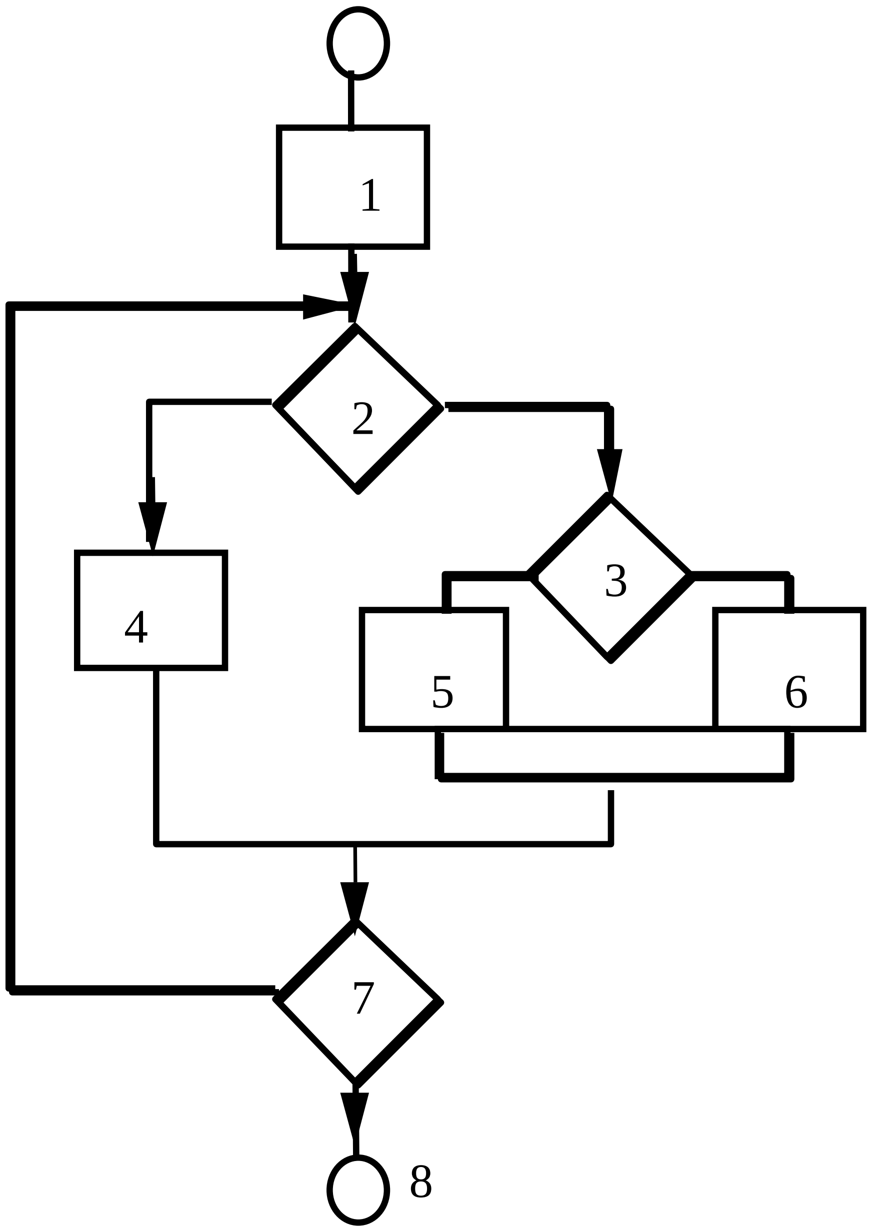
Basis Path Testing

- A testing mechanism proposed by McCabe.
- A testing criterion between branch coverage and all path coverage.
- Basis Path testing is a software testing that fulfills the requirements of branch testing & also tests all of the **independent paths** that could be used to construct **any arbitrary path** through the computer program. [NIST]

Arthur H. Watson and Thomas J. McCabe (1996). "Structured Testing: A Testing Methodology Using the Cyclomatic Complexity Metric". NIST Special Publication 500-235.

Thomas J. McCabe: A Complexity Measure. IEEE Trans. Software Eng. 2(4): 308-320 (1976)

Independent Path



A path through the system is independent from other paths only if it includes some vertices or edges that are not covered in the other path.

Path 1: 1,2,3,6,7,8
Path 2: 1,2,3,5,7,8
Path 3: 1,2,4,7,8
Path 4: 1,2,4,7,2,4,...7,8

Cyclomatic Complexity

- A program's complexity can be measured by the cyclomatic number of the program flowgraph
- For a program with the program flowgraph *G*, the cyclomatic complexity *v(G)* is measured as:

$$\boldsymbol{v(G) = e - n + 2p}$$

  - *e* : number of edges
    - Representing branches and cycles
  - *n* : number of nodes
    - Representing block of sequential code
  - *p* : number of connected components
    - For a single component, *p=1*

Simplified Complexity Calculation

- For a program with the program flowgraph *G*, the cyclomatic complexity *v(G)* is measured as:

  $$v(G) = 1 + d$$

  - *d* : number of predicate nodes (i.e., nodes with out-degree other than 1)
    - *d* represents number of loops in the graph

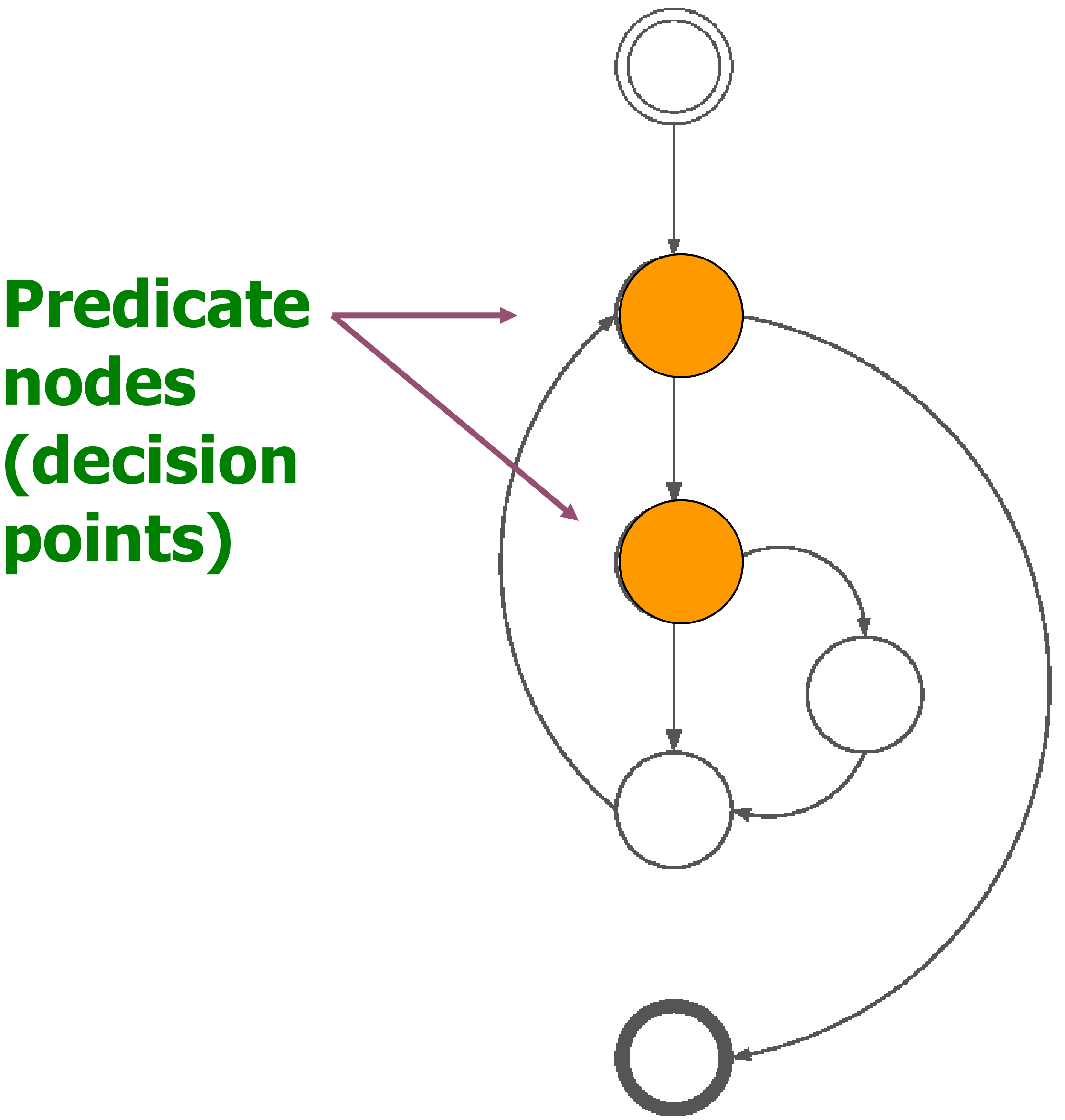
      or number of decision points in the program

Example 1

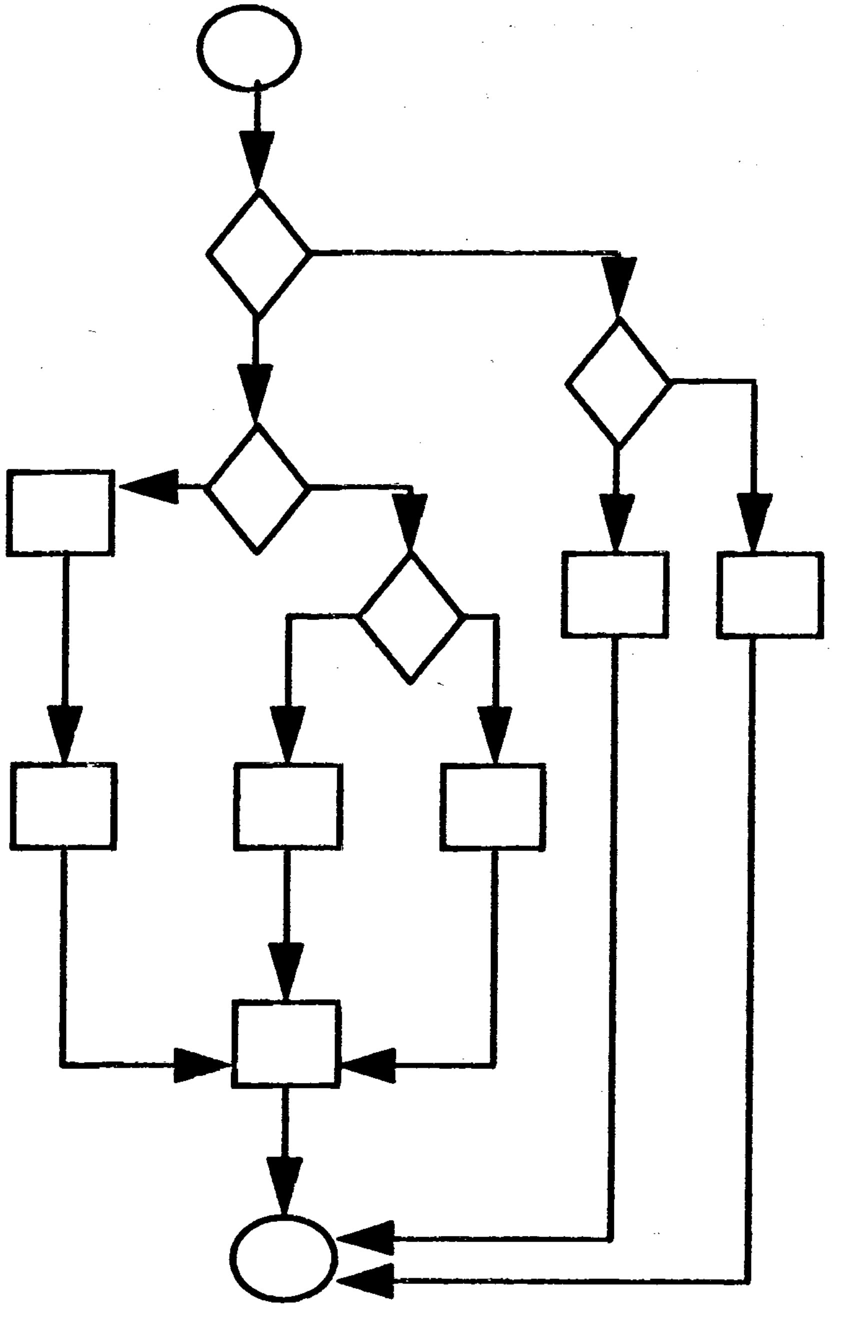
$$v(G) = e - n + 2p$$
$$= 7 - 6 + 2 \times 1$$
$$= 3$$

Or

$$v(G) = 1 + d$$
$$= 1 + 2 = 3$$



Example 2



v(G) = 16 – 13 + 2 = 5

or

v(G) = 4 +1 = 5

Cyclomatic Complexity: Usage

- **A useful indicator of software quality**
  - McCabe (1976) suggested that a module may be problematic if *v(G)* exceeds 10.
  - Grady (1994) concluded that 15 should be maximum value of *v(G)*
  - Bennett (1994) suggested that a modules be rejected if its *v(G)* exceeds 20.
- **Useful in white-box testing**
  - It provides an upper bound on the number of test cases that will be required to guarantee coverage of all program statements.

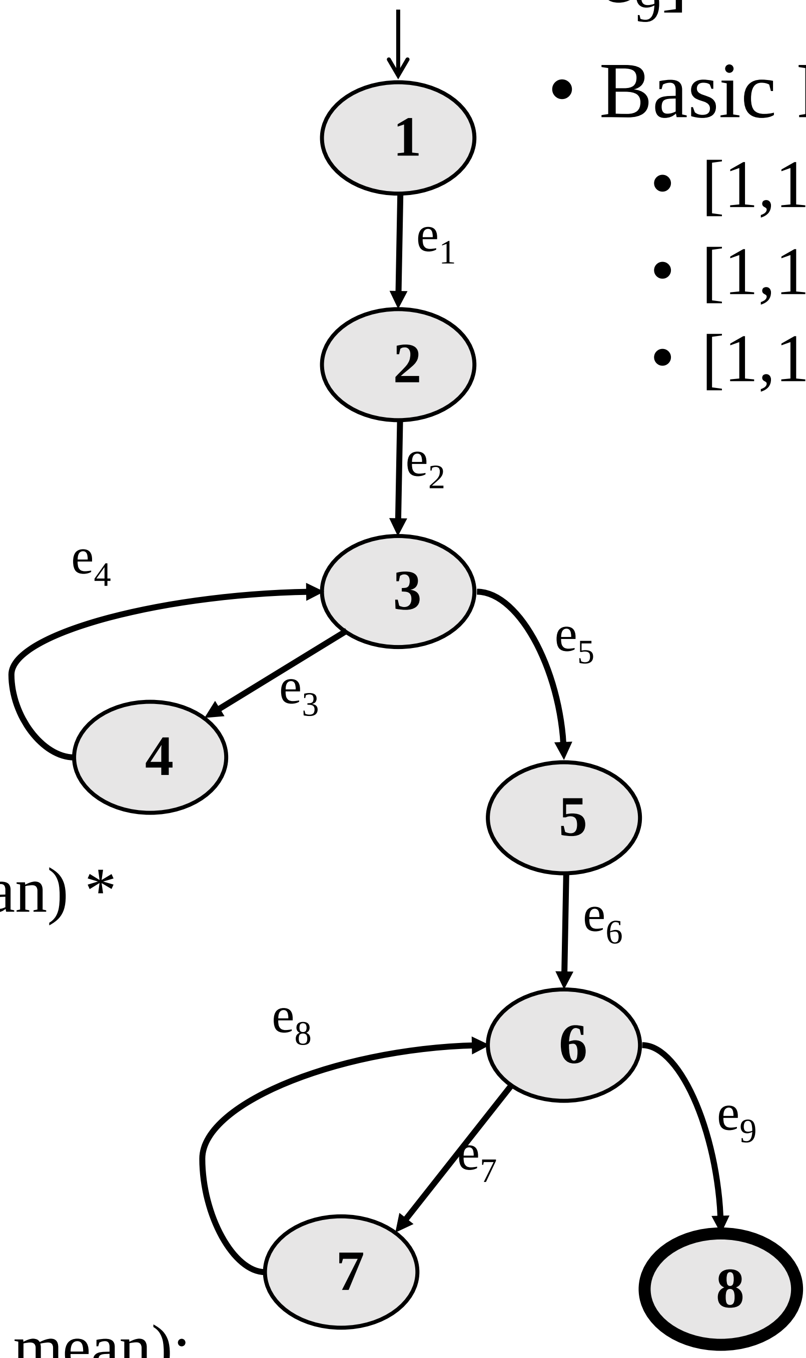
McCabe's Basis Path Testing

1. Generate control flow graph
2. Compute cyclomatic complexity
3. Determine a basis set of linearly independent paths
4. Generate tests for the basis paths

All Path Testing>=Basis Path Testing>=Branch Testing

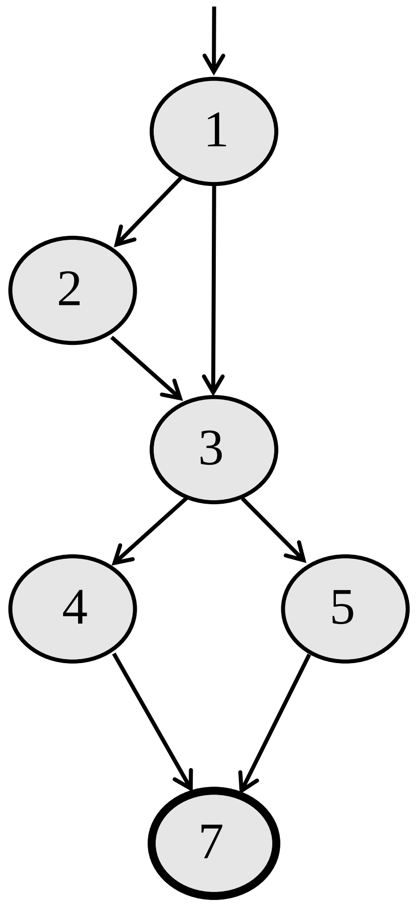
Basis Path Testing

```
public static void CSta (int [ ] numbers)
{
    int length = numbers.length;
    double var, mean, sum, varsum;

    sum = 0.0;
    for (int i = 0; i < length; i++)
    {
        sum += numbers [ i ];
    }
    mean = sum / (double) length;

    varsum = 0.0;
    for (int i = 0; i < length; i++)
    {
        varsum = varsum  + ((numbers [i] - mean) *
(numbers [i] - mean));
    }
    var = varsum / ( length - 1.0 );

    System.out.println ("length:                    " +
length);
    System.out.println ("mean:                      " + mean);
    System.out.println ("variance:                  " + var);
}
```

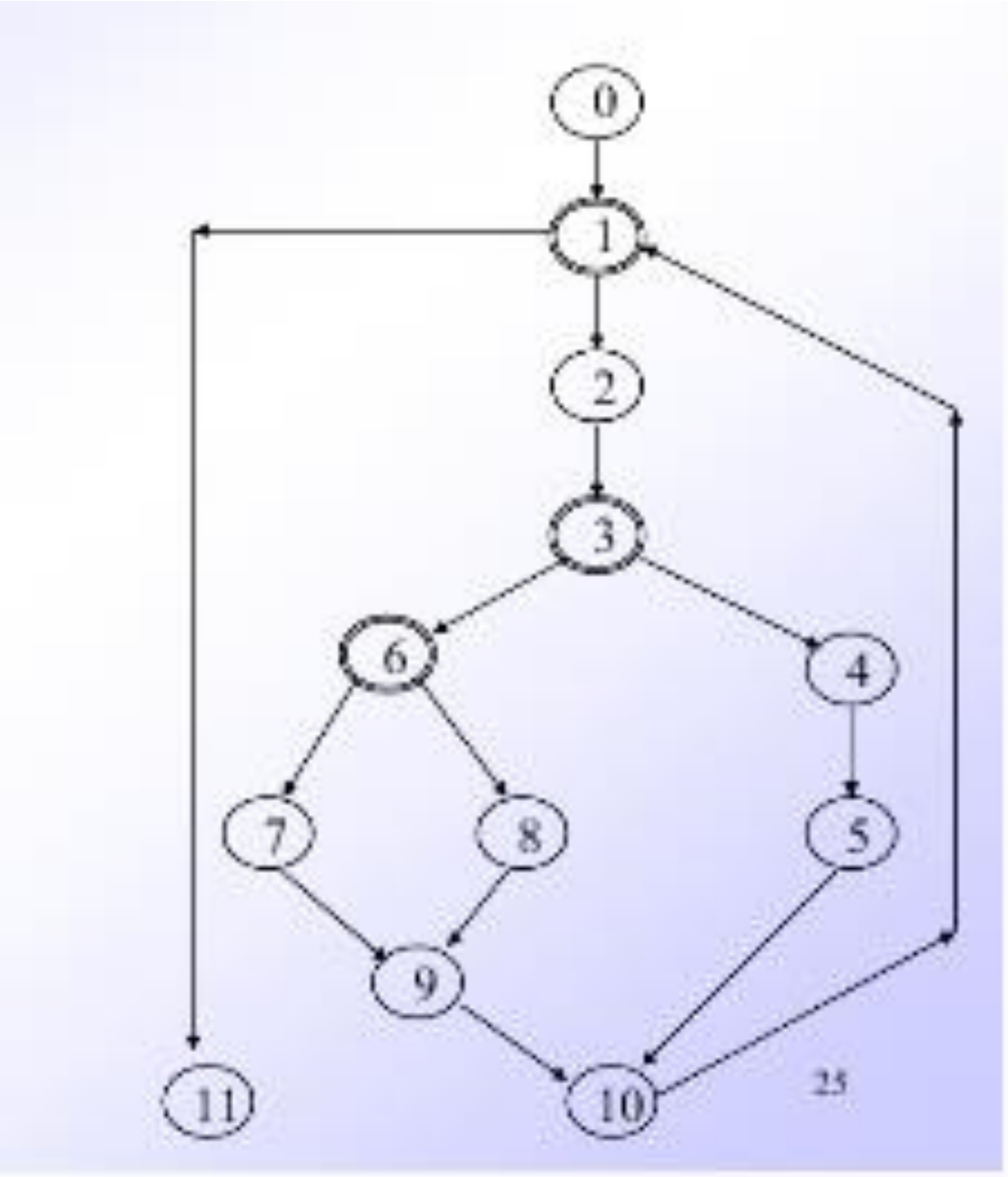


- $V(g) = 9-8+2=3$
- $[e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8, e_9]$
- Basic Path Set
  - [1,1,0,0,1,1,0,0,1]
  - [1,1,1,1,1,1,0,0,1]
  - [1,1,0,0,1,1,1,1,1]

Quiz



Basis Path Set ?



Quiz

```
#include <stdio.h>
main()
{
int a ;
scanf (“%d”, &a);
if ( a >= 10 )
  if ( a < 20 )
      printf ("10 < a< 20 %d\n" , a);
  else
      printf ("a >= 20    %d\n" , a);
else
   printf ("a <= 10    %d\n" , a);
}
```

Basis Path Set ?

Decision and Condition Coverage

Logic in Program

((x>5) && (y>0))

Decision Condition

Decision Coverage

- Decision Coverage (DC):
  Executing *true* and *false* of decision.
- Also called Branch Decision Coverage

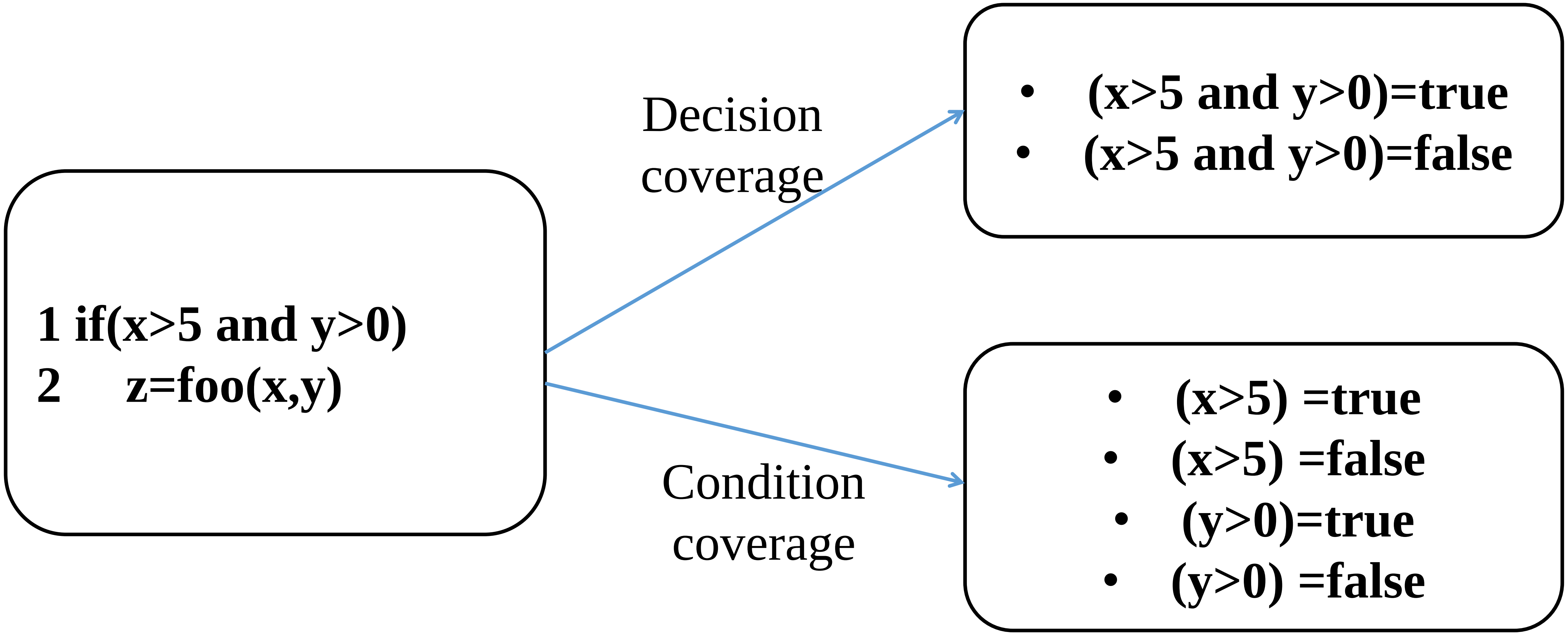
Example: ((x>5) && (y>0)): *true* and *false*

```
// {(6, 1), (1,1)} --- 100% Decision Coverage
int foo(int x, int y) {
        int z = y;
        if ((x>5) && (y>0)) {
                z = x;
        }
        return x*z;
}
```

Condition Coverage

- Condition Coverage (CC):
  Executing *true* and *false* of each condition
- (x>5) ： *true* and *false*
- (y>0) ： *true* and *false*

```
// {(6, 0), (0,1)} --- 100% Condition Coverage
int foo(int x, int y) {
        int z = y;
        if ((x>5) && (y>0)) {
                z = x;
        }
        return x*z;
}
```


1 if(x>5 and y>0)
2 z=foo(x,y)
Decision coverage
• (x>5 and y>0)=true
• (x>5 and y>0)=false
Condition coverage
• (x>5) =true
• (x>5) =false
• (y>0)=true
• (y>0) =false

An Example

```
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
```

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

- **Decision coverage?**
- **Condition coverage?**

- **100% Condition coverage does not mean 100% Decision coverage**

```
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
```

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

- **Decision coverage?**
- **Condition coverage = 100%**

- **100% Decision coverage does not mean 100% Condition coverage**

```
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
```

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

- **Decision coverage = 100%**
- **Condition coverage?**

Condition/Decision Coverage

- Condition/Decision Coverage (C/DC): Combing DC and CC.
- Overcomes the limitation of Decision Coverage (DC) and Condition Coverage (CC)
  - C/DC ≥ CC
  - C/DC ≥ DC

```
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
```

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

- **Decision coverage = 100%**
- **Condition coverage = 100%**

Multiple Condition Coverage

- Multiple condition coverage (MCC) reports whether every possible combination of Boolean sub-expressions occurs.
- The test cases required for full multiple condition coverage of a condition are essentially given by the logical operator truth table for the condition.

D=(A<B) or (A>C)

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

T={t1:<A=2,B=3,C=1>, t2:<A=2,B=1,C=3>}

- **Covers all decisions and conditions**
- **Covers only two combinations of Boolean sub-expressions.**

An Example

- Requirements for a program:

Given three integers A, B, and C, produce S according to the following table:

	A<B	A>C	S
1	**true**	**true**	**f1(A,B,C)**
2	**true**	**false**	**f2(A,B,C)**
3	**false**	**true**	**f3(A,B,C)**
4	**false**	**false**	**f4(A,B,C)**

```
1 begin
2      int A,B,C,S=0;
3      input(A,B,C);
4      if(A<B and A>C)
       S=f1(A,B,C);
5      if(A<B and A≤C)
       S=f2(A,B,C);
6      if(A≥B and A≤C)
       S=f4(A,B,C);
7      output(S);
9 end
```

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

A buggy implementation !

```
1 begin
2     int A,B,C,S=0;
3     input(A,B,C);
4     if(A<B and A>C)
      S=f1(A,B,C);
5     if(A<B and A≤C)
      S=f2(A,B,C);
6     if(A≥B and A≤C)
      S=f4(A,B,C);
7     output(S);
9 end
```

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

$T=\{t_1:<A=2,B=3,C=1>, t_2:<A=2,B=1,C=3>\}$

- 100% condition coverage
- Bug not found

```
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(A,B,C)
2	true	false	f2(A,B,C)
3	false	true	f3(A,B,C)
4	false	false	f4(A,B,C)

$T=\{t_1:<A=2,B=3,C=1>,$
$t_2:<A=2,B=1,C=3>,$
$t_3:<A=2,B=3,C=5>\}$

- 100% condition coverage
- 100% decision coverage
- Bug not found

```
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
```

$T=\{t_1:\langle A=2,B=3,C=1\rangle,$
$t_2:\langle A=2,B=1,C=3\rangle,$
$t_3:\langle A=2,B=3,C=5\rangle,$
$t_4:\langle A=2,B=1,C=1\rangle\}$

- 100% Multiple Condition Coverage
- **Bug found**

	$A<B$	$A>C$	T	$A<B$	$A \le C$	T	$A \ge B$	$A \le C$	T
1	true	true	t1	true	true	t3	true	true	t2
2	true	false	t3	true	false	t1	true	false	t4
3	false	true	t4	false	true	t2	false	true	t3
4	false	false	t2	false	false	t4	false	false	t1

Quiz – C/DC

How to achieve 100% condition/decision coverage?

```
// ??
int foo(int x, int y) {
        int z = y;
        if ((x>5) && (y>0)) {
                z = x; }
        return x*z;
}
```

Quiz- MCC

How to achieve 100% multiple condition coverage?

```
// ??
int foo(int x, int y) {
        int z = y;
        if ((x>5) && (y>0)) {
                z = x; }
        return x*z;
}
```

Limitation of MCC

- Assuming n conditions, 2^n test cases are required.
- Assuming each test case needs 1ms to execute:

Conditions n	Test cases 2^n	Test case execution time
1	2	2ms
4	16	16ms
8	256	256ms
16	65536	65.5s
32	4294967296	49.5 days

Modified condition/decision (MC/DC)

- Motivation: Effectively test important combinations of conditions, without exponential blowup in test suite size
  - "Important" combinations means: Each basic condition independently affects the outcome of each decision
  - MC/DC $\geq$ C/DC

- Requires:
  - For each basic condition C, two test cases,
  - values of all evaluated conditions except C are the same
  - compound condition as a whole evaluates to true for one and false for the other

Modified condition/decision (MC/DC)

- **MC/DC coverage:**
  - Each entry and exit point is invoked
  - Each decision takes every possible outcome
  - Each condition in a decision takes every possible outcome
  - Each condition in a decision is shown to independently affect the outcome of the decision.
  - Independence of a condition is shown by proving that only one condition changes at a time.
- MC/DC is used in avionics software development guidance DO-178B and DO-178C to ensure adequate testing of the most critical (Level A) software.

https://en.wikipedia.org/wiki/Modified_condition/decision_coverage

MC/DC

- ((x>5) && (y>0))   Decision

T	T	T
T	F	F
F	T	F
F	F	F

```
// ??
int foo(int x, int y) {
        int z = y;
        if ((x>5) && (y>0)) {
                z = x; }
        return x*z;
}
```

Comparison

Table 1. Types of Structural Coverage

Coverage Criteria	Statement Coverage	Decision Coverage	Condition Coverage	Condition/ Decision Coverage	MC/DC	Multiple Condition Coverage
Every point of entry and exit in the program has been invoked at least once		•	•	•	•	•
Every statement in the program has been invoked at least once	•					
Every decision in the program has taken all possible outcomes at least once		•		•	•	•
Every condition in a decision in the program has taken all possible outcomes at least once			•	•	•	•
Every condition in a decision has been shown to independently affect that decision's outcome					•	•[8]
Every combination of condition outcomes within a decision has been invoked at least once						•

References

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Thanks!


Testing
Software
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team
bug