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Software Testing and Quality Assurance

Theory and Practice

Chapter 4

Control Flow Testing

Outline of the Chapter

- Basic Idea
- Outline of Control Flow Testing
- Control Flow Graph
- Paths in a Control Flow Graph
- Path Selection Criteria
- Generating Test Input
- Containing Infeasible Paths
- Summary

Basic Idea

- Two kinds of basic program statements:
  - Assignment statements (Ex. x = 2*y;)
  - Conditional statements (Ex. if(), for(), while(), …)
- Control flow
  - Successive execution of program statements is viewed as flow of control.
  - Conditional statements alter the default flow.
- Program path
  - A program path is a sequence of statements from entry to exit.
  - There can be a large number of paths in a program.
  - There is an (input, expected output) pair for each path.
  - Executing a path requires invoking the program unit with the right test input.
  - Paths are chosen by using the concepts of path selection criteria.
- Tools: Automatically generate test inputs from program paths.

Outline of Control Flow Testing

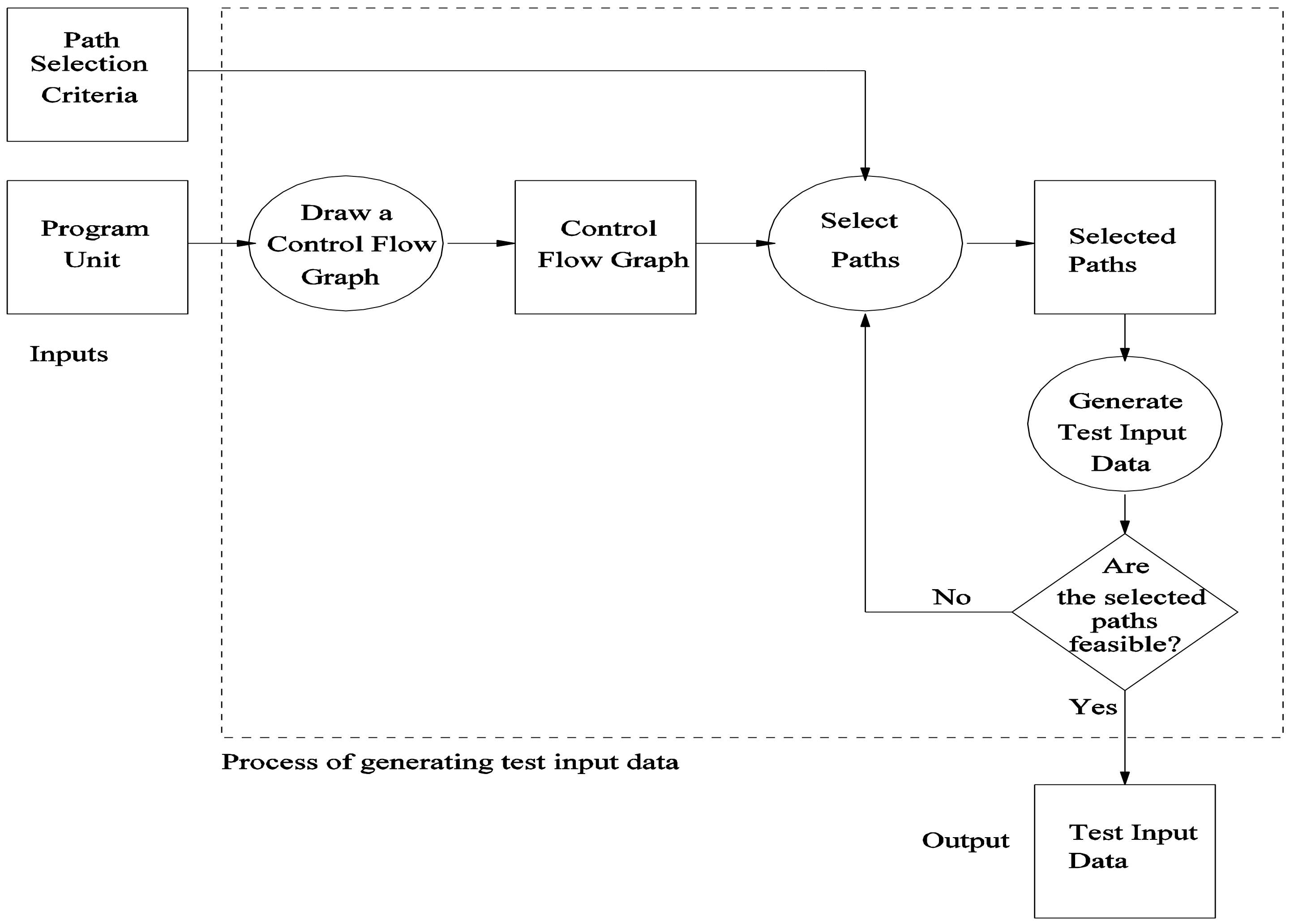


Figure 4.1: The process of generating test input data for control flow testing.

Outline of Control Flow Testing

- Control Flow Assumptions
  - We have correct specifications
  - Definitions of data are correct
  - Data can be accessed correctly
  - All known bugs have been resolved
    - Except for the one that affect control flow
- Application
  - New software
  - Unit testing
- Control Flow Graph
  - Graphical representation of a program's control structure

Outline of Control Flow Testing

- Complete Path
  - Path the begins at the entry to a routine and ends at its exit
  - Also called Entry - Exit Path
- Complete Paths are useful
  - It is difficult to start execution at an arbitrary statement
  - It is difficult to stop execution at an arbitrary statement
    - Without modifying code
- There can be many paths between entry and exit
  - Even small/short routines can have a large number of paths

Control Flow Graph

- Symbols in a CFG

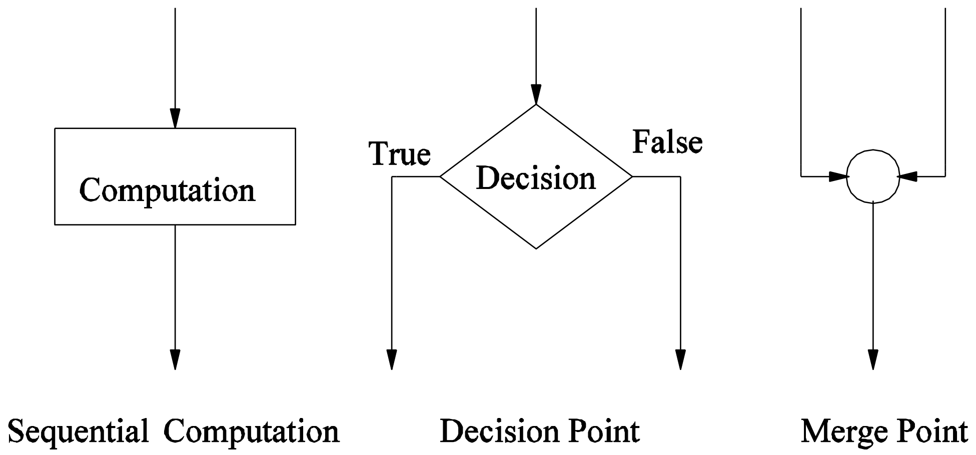
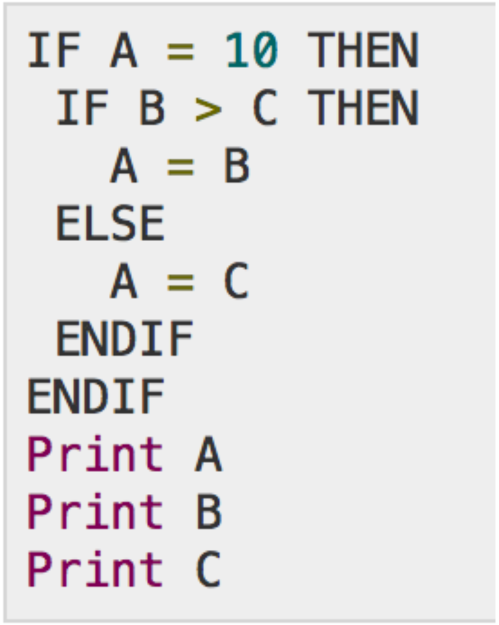


Figure 4.2: Symbols in a control flow graph

- Decision point – where control can diverge
- Process block – statements uninterrupted by decisions or junctions
- Junction point – where control flow merges

Example



```
IF A = 10 THEN
 IF B > C THEN
   A = B
 ELSE
   A = C
 ENDIF
ENDIF
Print A
Print B
Print C
```

Example

```
int evensum(int i)
{
  int sum = 0;

  while (i <= 10) {
    if (i/2 == 0)
      sum = sum + i;
    i++;
  }
  return sum;

}
```

Control Flow Graph

- **Example code: openfiles()**

```
FILE *fptr1, *fptr2, *fptr3; /* These are global variables. */
int openfiles(){
  /*
    This function tries to open files "file1", "file2", and "file3"
    for read access, and returns the number of files successfully
    opened. The file pointers of the opened files are put in the
    global variables.
  */
   int i = 0;
   if(
      ((( fptr1 = fopen("file1", "r")) != NULL) && (i++) && (0)) ||
      ((( fptr2 = fopen("file2", "r")) != NULL) && (i++) && (0)) ||
      ((( fptr3 = fopen("file3", "r")) != NULL) && (i++))
   );
   return(i);
}
```

Figure 4.3: A function to open three files.

Control Flow Graph

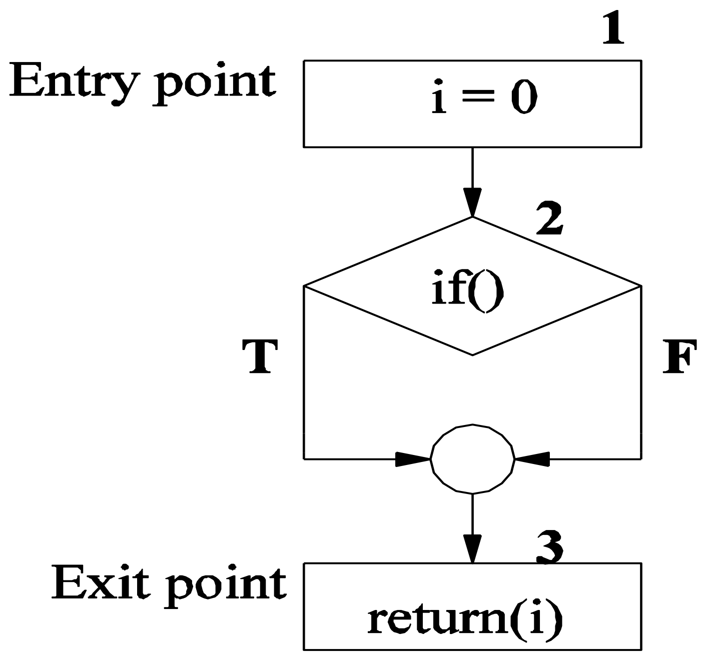


Figure 4.4: A high-level CFG representation of openfiles().

Control Flow Graph

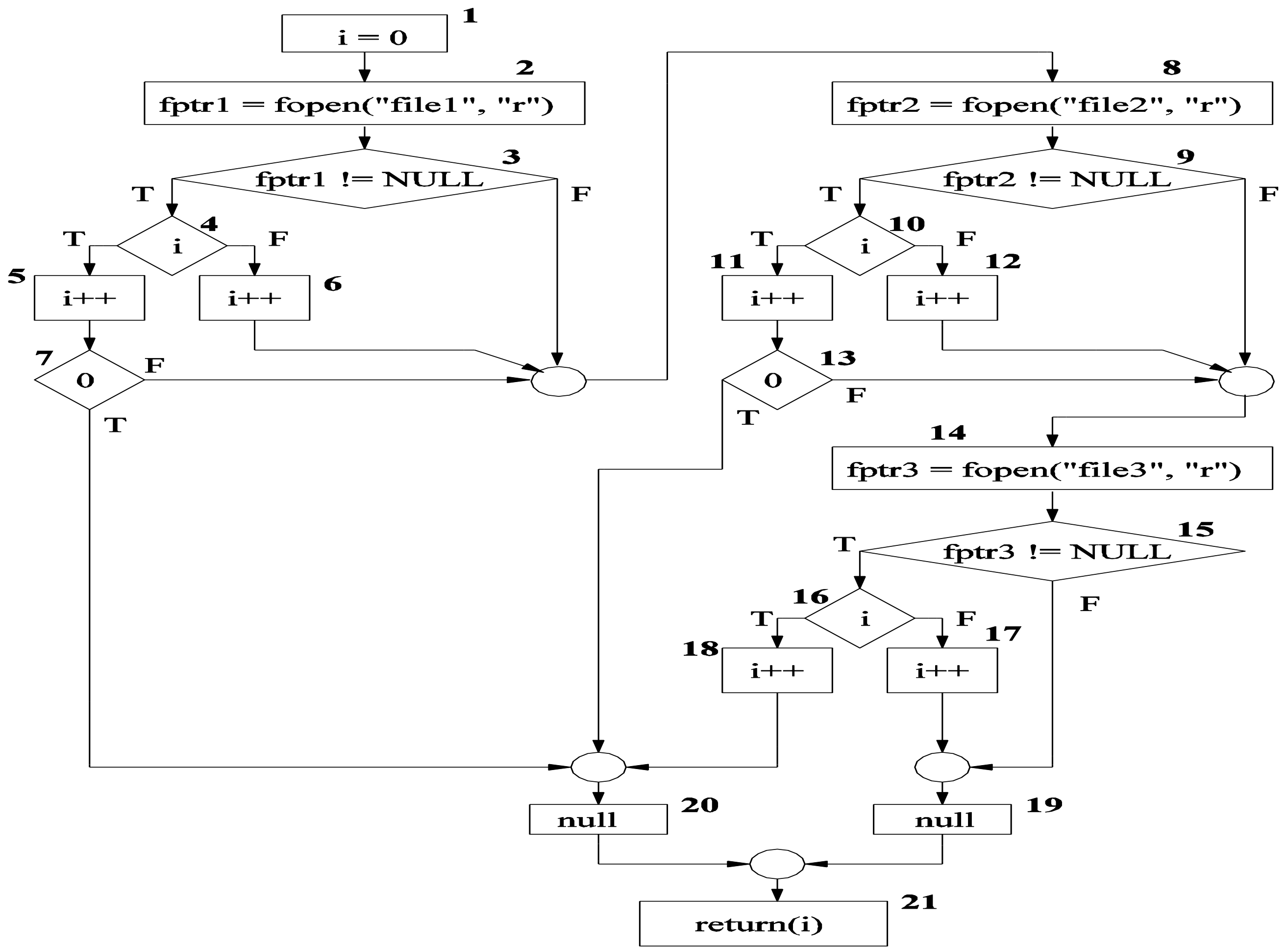


Figure 4.5: A detailed CFG representation of openfiles().

Control Flow Graph

- **Example code: ReturnAverage()**

```
public static double ReturnAverage(int value[],  int AS, int MIN, int MAX){
   /* Function: ReturnAverage  Computes the  average of all  those  numbers in the  input array  in
      the  positive  range  [MIN, MAX]. The  maximum size  of the array is AS.  But, the   array size
      could be smaller than AS in which case the end of input is represented by -999. */

      int i, ti, tv, sum;
      double av;
      i = 0; ti = 0; tv = 0; sum = 0;
      while (ti < AS && value[i] != -999) {
         ti++;
         if (value[i] >= MIN && value[i] <= MAX) {
            tv++;
            sum = sum + value[i];
         }
         i++;
      }
      if (tv > 0)
         av = (double)sum/tv;
      else
         av = (double) -999;
      return (av);
   }
```

Figure 4.6: A function to compute the average of selected integers in an array.

Control Flow Graph

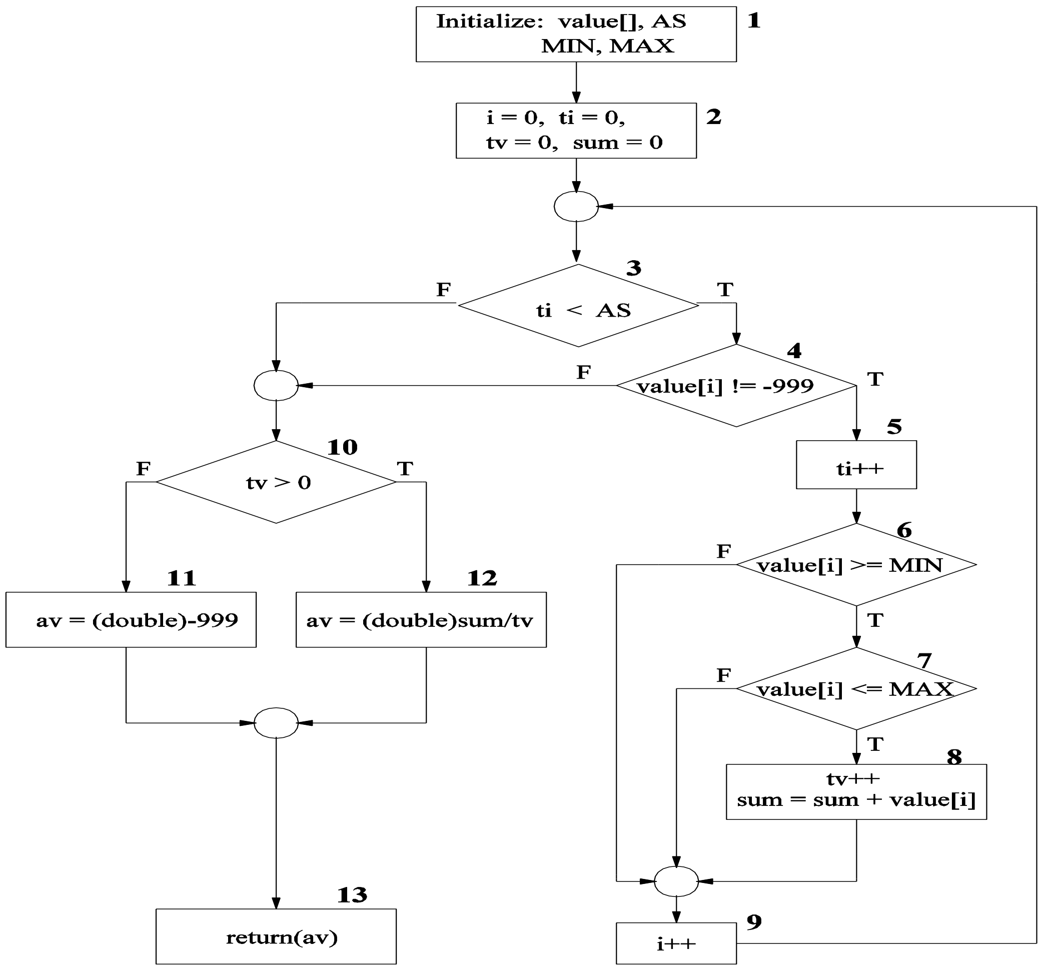


Figure 4.7: A CFG representation of ReturnAverage().

Paths in a Control Flow Graph

- A few paths in Figure 4.7. (Table 4.1)
  - Path 1: 1-2-3(F)-10(T)-12-13
  - Path 2: 1-2-3(F)-10(F)-11-13
  - Path 3: 1-2-3(T)-4(T)-5-6(T)-7(T)-8-9-3(F)-10(T)-12-13
  - Path 4: 1-2-3(T)-4(T)-5-6-7(T)-8-9-3(T)-4(T)-5-6(T)-7(T)-8-9-3(F)-10(T)-12-13

Outline of Control Flow Testing

- Complete Testing
  - Execute every path from entry to exit
    - Path Coverage
    - Also known as Path Testing
  - Execute every statement from entry to exit
    - Statement Coverage
    - Also known as Statement Testing
  - Execute every condition from entry to exit
    - Branch Coverage
    - Also known as Branch Testing
- 100% Path coverage may be impractical
  - Even small routines may have a large number of paths
- Statement and Branch Coverage are more commonly used
  - Insistence based on common sense

Outline of Control Flow Testing

- Inputs to the test generation process
  - Source code
  - Path selection criteria: statement, branch, …
- Generation of control flow graph (CFG)
  - A CFG is a graphical representation of a program unit.
  - Compilers are modified to produce CFGs. (You can draw one by hand.)
- Selection of paths
  - Enough entry/exit paths are selected to satisfy path selection criteria.
- Generation of test input data
  - Two kinds of paths
    - Executable path: There exists input so that the path is executed.
    - Infeasible path: There is no input to execute the path.
  - Solve the path conditions to produce test input for each path.

Control Flow Graph

$$\begin{tikzcd}
1 \arrow[r, "a"] & 3 \arrow[r, "b"] & 4 \arrow[r, "c"] \arrow[d, "h"] & 5 \arrow[r, "d"] & 6 \arrow[r, "e"] \arrow[d, "f"] & 2 \\
 & 10 \arrow[u, "i"] & 9 \arrow[l, "l", "T"'] \arrow[r, "k", "F"'] & 8 \arrow[u, "g"] & 7 \arrow[l, "j", "T"'] \arrow[lll, bend left, "m", "F"'] &
\end{tikzcd}$$

PATHS	DECISIONS				PROCESS LINKS												
	4	6	7	9	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*
abcde	*T*	*T*			*	*	*	*	*								
abhkgde	*F*	*T*		*F*	*	*		*	*		*	*			*		
abhlibcde	*TF*	*T*		*T*	*	*	*	*	*			*	*			*	
abcdfjgde	*T*	*TF*	*T*		*	*	*	*	*	*	*			*			
abcdfmibcde	*T*	*TF*	*F*		*	*	*	*	*	*			*				*

Outline of Control Flow Testing

- Every decision has a True and a False in its column
  - This implies branch coverage
  - Every decision is tested for T and F
- Is every edge executed at least once
  - Edges representing statement (blocks/segments)
  - Implies statement coverage
- Select enough number of paths
  - To get branch coverage
  - To get statement coverage

Path Selection Criteria

- Program paths are selectively executed.
- Question: What paths do I select for testing?
- The concept of *path selection criteria* is used to answer the question.
- Advantages of selecting paths based on defined criteria:
  - Ensure that all program constructs are executed at least once.
  - Repeated selection of the same path is avoided.
  - One can easily identify what features have been tested and what not.
- Path selection criteria
  - Select all paths.
  - Select paths to achieve complete statement coverage.
  - Select paths to achieve complete branch coverage.
  - Select paths to achieve predicate coverage.

Path Selection Criteria

- All-path coverage criterion: Select all the paths in the program unit under consideration.
  - The openfiles() unit has 25+ paths.

Existence of "file1"	Existence of "file2"	Existence of "file3"
No	No	No
No	No	Yes
No	Yes	No
No	Yes	Yes
Yes	No	No
Yes	No	Yes
Yes	Yes	No
Yes	Yes	Yes

Table 4.2: The input domain of openfiles()

  - Selecting all the inputs will exercise all the program paths.

Path Selection Criteria

Input	Path
<No, No, No>	1-2-3(F)-8-9(F)-14-15(F)-19-21
<Yes, No, No>	1-2-3(T)-4(F)-6-8-9(F)-14-15(F)-19-21
<Yes, Yes, Yes>	1-2-3(T)-4(F)-6-8-9(T)-10(T)-11-13(F)-14- 15(T) - 16(T)-18-20-21

Table 4.3 Inputs and paths in openfiles()

Path Selection Criteria

- Statement coverage criterion
  - Statement coverage means executing individual program statements and observing the output.
  - 100% statement coverage means all the statements have been executed at least once.
    - Cover all assignment statements.
    - Cover all conditional statements.
  - Less than 100% statement coverage is unacceptable.

SCPath1	1-2-3(F)-10(F)-11-13
SCPath2	1-2-3(T)-4(T)-5-6(T)-7(T)-8-9-3(F)-10(T)-12-13

Table 4.4: Paths for statement coverage of the CFG of Figure 4.7.

Path Selection Criteria

- Branch coverage criterion
  - A branch is an outgoing edge from a node in a CFG.
    - A condition node has two outgoing branches – corresponding to the True and False values of the condition.
  - Covering a branch means executing a path that contains the branch.
  - 100% branch coverage means selecting a set of paths such that each branch is included on some path.

Path Selection Criteria

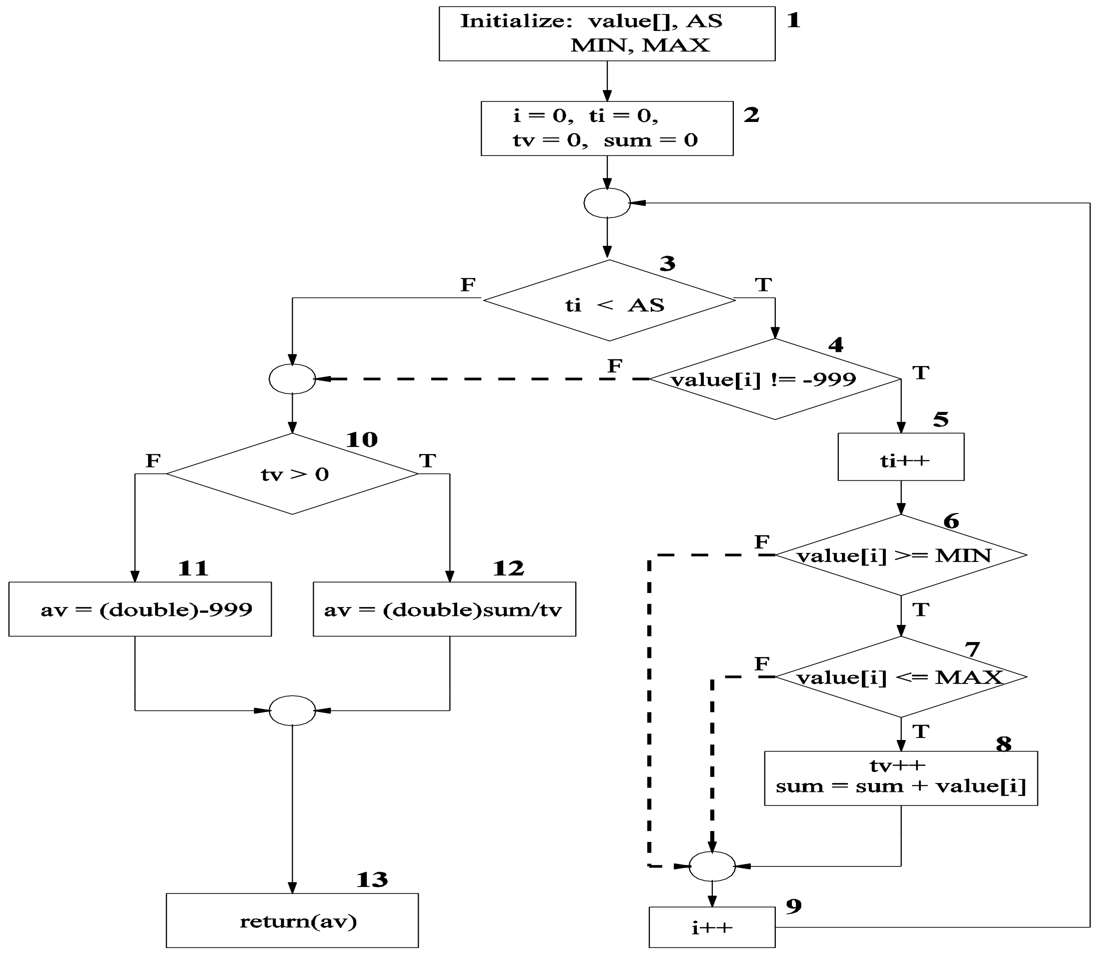


Figure 4.8: The dotted arrows represent the branches not covered by the statement covering in Table 4.4.

Path Selection Criteria

- Branch coverage criterion
  - A branch is an outgoing branch (edge) from a node in a CFG.
    - A condition node has two outgoing branches – corresponding to the True and False values of the condition.
  - Covering a branch means executing a path that contains the branch.
  - 100% branch coverage means selecting a set of paths such that each branch is included on some path.

BCPath 1	1-2-3(F)-10(F)-11-13
BCPath 2	1-2-3(T)-4(T)-5-6(T)-7(T)-8-9-3(F)-10(T)-12-13
BCPath 3	1-2-3(T)-4(F)-10(F)-11-13
BCPath 4	1-2-3(T)-4(T)-5-6(F)-9-3(F)-10(F)-11-13
BCPath 5	1-2-3(T)-4(T)-5-6(T)-7(F)-9-3(F)-10(F)-11-13

Table 4.5: Paths for branch coverage of the flow graph of Figure 4.7.

Path Selection Criteria

- Predicate coverage criterion
  - If all possible combinations of truth values of the conditions affecting a path have been explored under some tests, then we say that predicate coverage has been achieved.

Path Selection Criteria

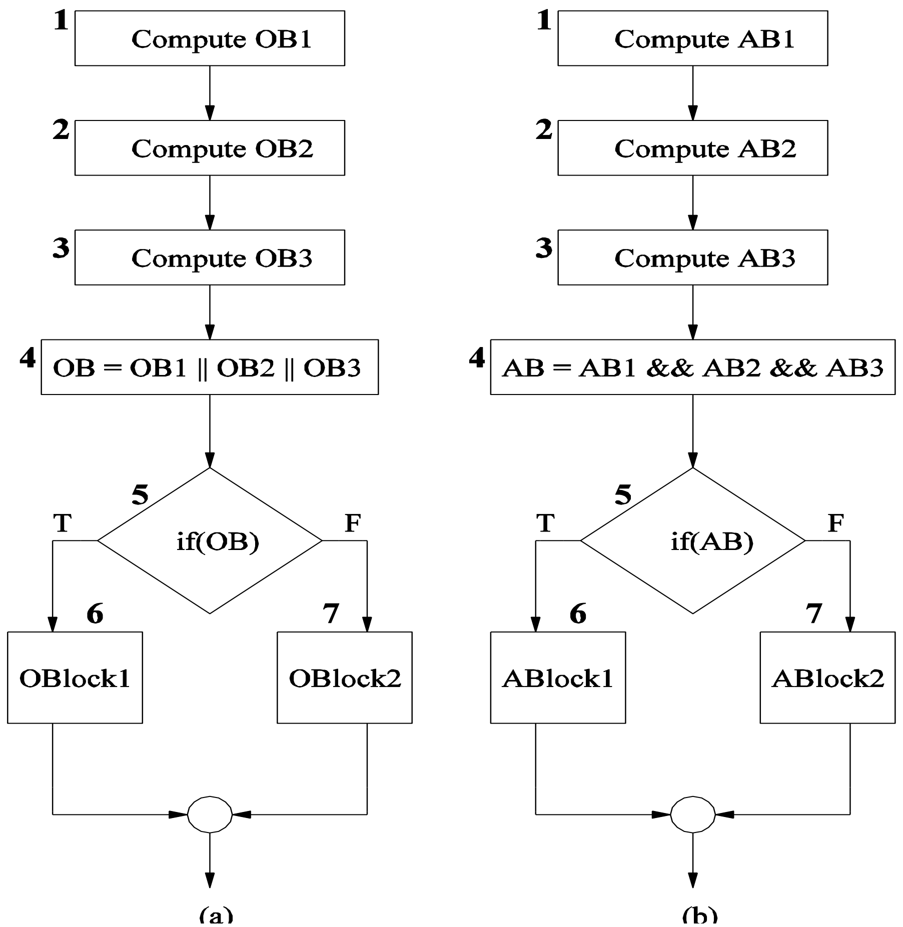


Figure 4.9: Partial control flow graph with (a) OR operation and (b) AND operation.

Generating Test Input

- Having identified a path, a key question is how to make the path execute, if possible.
  - Generate input data that satisfy all the conditions on the path.
- Key concepts in generating test input data
  - Input vector
  - Predicate
  - Path condition
  - Predicate interpretation
  - Path predicate expression
  - Generating test input from path predicate expression

Generating Test Input

- Input vector
  - An input vector is a collection of all data entities read by the routine whose values must be fixed prior to entering the routine.
  - Members of an input vector can be as follows.
    - Input arguments to the routine
    - Global variables and constants
    - Files
    - Contents of registers (in Assembly language programming)
    - Network connections
    - Timers
  - Example: An input vector for openfiles() consists of individual presence or absence of the files "files1," "file2," and "file3."
  - Example: The input vector of ReturnAverega() shown in Figure 4.6 is <value[], AS, MIN, MAX>.

Generating Test Input

- Predicate
  - A predicate is a logical function evaluated at a decision point.
  - Example: ti < AS is a predicate in node 3 of Figure 4.7.
  - Example: The construct OB is a predicate in node 5 in Figure 4.9.
- Path predicate
  - A path predicate is the set of predicates associated with a path.
  - **Figure 4.10:** An example path from Fig. 4.7:
    - 1-2-3(T)-4(T)-5-6(T)-7(T)-8-9-3(F)-10(T)-12-13.
  - **Figure 4.11:** The path predicate for the path shown in Figure 4.10.

ti < AS	≡ True
value[i] != -999	≡ True
value[i] >= MIN	≡ True
value[i] <= MAX	≡ True
ti < AS	≡ False
tv > 0	≡ True

Generating Test Input

- Predicate interpretation
  - A path predicate may contain local variables.
  - Example: <i, ti, tv> in Figure 4.11 are local variables.
  - Local variables play no role in selecting inputs that force a path to execute.
  - Local variables can be eliminated by a process called **symbolic execution**.
  - Predicate interpretation is defined as the process of
    - symbolically substituting operations along a path in order to express the predicate solely in terms of the input vector and a constant vector.
  - A predicate may have different interpretations depending on how control reaches the predicate.

Generating Test Input

- Path predicate expression
  - An interpreted path predicate is called a path predicate expression.
  - A path predicate expression has the following attributes.
    - It is void of local variables.
    - It is a set of constraints in terms of the input vector, and, maybe, constants.
    - Path forcing inputs can be generated by solving the constraints.
    - If a path predicate expression has no solution, the path is infeasible.
  - **Figure 4.13:** Path predicate expression for the path shown in Figure 4.10.

0 < AS	≡ True	…… (1)
value[0] != -999	≡ True	…… (2)
value[0] >= MIN	≡ True	…… (3)
value[0] <= MAX	≡ True	…… (4)
1 < AS	≡ False	…… (5)
1 > 0	≡ True	…… (6)

Generating Test Input

- Path predicate expression
  - An example of infeasible path
  - **Figure 4.14:** Another example of path from Figure 4.7.
    - 1-2-3(T)-4(F)-10(T)-12-13
  - **Figure 4.15:** Path predicate expression for the path shown in Figure 4.14.

$0 < AS$	$\equiv$ True	…… (1)
value[0] != -999	$\equiv$ True	…… (2)
$0 > 0$	$\equiv$ True	…… (3)

Generating Test Input

- Generating input data from a path predicate expression
  - Consider the path predicate expression of Figure 4.13 (reproduced below.)

$0 < AS$	≡ True	……	(1)
$value[0] != -999$	≡ True	……	(2)
$value[0] >= MIN$	≡ True	……	(3)
$value[0] <= MAX$	≡ True	……	(4)
$1 < AS$	≡ False	……	(5)
$1 > 0$	≡ True	……	(6)

  - One can solve the above equations to obtain the following test input data

AS	= 1
MIN	= 25
MAX	= 35
Value[0]	= 30

  - Note: The above set is not unique.

Containing Infeasible Paths

- A program unit may contain a large number of paths.
  - Path selection becomes a problem. Some selected paths may be infeasible.
  - Apply a path selection strategy:
    - Select as many short paths as possible.
    - Choose longer paths.
  - There are efforts to write code with fewer/no infeasible paths.

Outline of Control Flow Testing

- Effectiveness
  - Control flow testing is effective in unstructured programs
  - Unit testing is dominated by control flow testing
  - Evidence shows
    - Control flow testing catches 50% of all bugs caught in unit testing
    - That is about 33% of all bugs
- Control Flow Testing is dominated by
  - Statement Testing/Coverage
  - Branch Testing/Coverage

Outline of Control Flow Testing

- Limitations
  - Not all interface errors are not caught
  - Not all initialization mistakes are not caught
  - Not all specification errors are not caught
- That is because Control Flow Testing assumptions
  - We have correct specifications
  - Definitions of data are correct
  - Data can be accessed correctly
  - All known bugs have been resolved
    - Except for the one that affect control flow

Summary

- Control flow is a fundamental concept in program execution.
- A program path is an instance of execution of a program unit.
- Select a set of paths by considering path **selection criteria**.
  - Statement coverage
  - Branch coverage
  - Predicate coverage
  - All paths
- From source code, derive a CFG (compilers are modified for this.)
- Select paths from a CFG based on path selection criteria.
- Extract path predicates from each path.
- Solve the path predicate expression to generate test input data.
- There are two kinds of paths.
  - feasible
  - infeasible