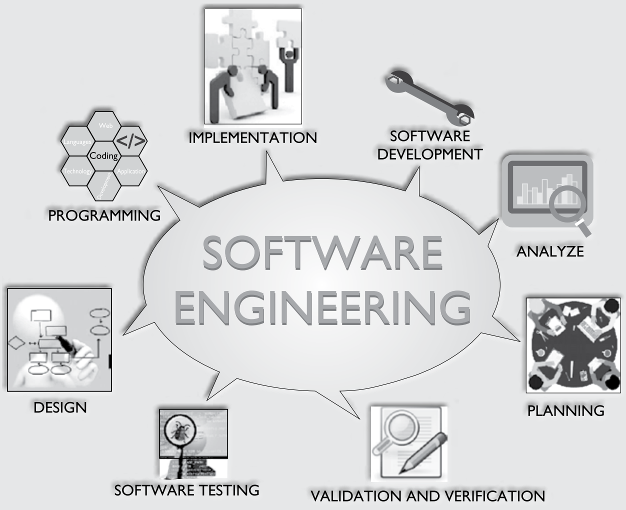
CHAPTER
10

CODING AND TESTING



CHAPTER OUTLINE

Program testing can be used to show the presence of bugs, but never to show their absence!

—Edsger Dijkstra

LEARNING OBJECTIVES

- Coding standards and guidelines
- Code review
- Software documentation
- Basic concepts in software testing
- Unit testing
- Integration testing
- Testing object-oriented programs
- System testing

In this chapter, we will discuss the coding and testing phases of the software life cycle.

In the coding phase, every module specified in the design document is *coded* and *unit tested*. During unit testing, each module is tested in isolation from other modules. That is, a module is tested independently as and when its coding is complete.

Coding is undertaken once the design phase is complete and the design documents have been successfully reviewed.

Integration and testing of modules is carried out according to an *integration plan*. The integration plan, according to which different modules are integrated together, usually envisages integration of modules through a number of steps. During each integration step, a number of modules are added to the partially integrated system and the resultant system is tested. The full product takes shape only after all the modules have been integrated together. System testing is conducted on the full product. During system testing, the product is tested against its requirements as recorded in the SRS document.

After all the modules of a system have been coded and unit tested, the integration and system testing phase is undertaken.

We had already pointed out in Chapter 2 that testing is an important phase in software development and typically requires the maximum effort among all the development phases. Usually, testing of any commercial software is carried out using a large number of test cases. It is usually the case that many of the different test cases can be executed in parallel by different team members. Therefore, to reduce the testing time, during the testing phase the largest manpower (compared to all other life cycle phases) is deployed. In a typical development organisation, at any time, the maximum number of software engineers can be found to be engaged in testing activities. It is not very surprising then that in the software industry there is always a large demand for software test engineers. However, many novice engineers bear the wrong impression that testing is a secondary activity and that it is intellectually not as stimulating as the activities associated with the other development phases.

Over the years, the general perception of testing as monkeys typing in random data and trying to crash the system has changed. Now testers are looked upon as masters of specialised concepts, techniques, and tools.

As we shall soon realize, testing a software product is at least as much challenging as initial development activities such as specifications, design, and coding. Moreover, testing involves a lot of creative thinking.

In this Chapter, we first discuss some important issues associated with the activities undertaken in the coding phase. Subsequently, we focus on various types of program testing techniques that are available for procedural and object-oriented programs.

10.1 CODING

The input to the coding phase is the design document produced at the end of the design phase. Please recollect that the design documents contain not only the high-level design of the software in the form of a structure charts (representing the module call relationships), but also the detailed design. The detailed design is usually documented in the form of module specifications where the data structures and algorithms for each module are specified. During the coding phase, different modules identified in the design document are coded according to their respective module specifications. We can describe the overall objective of the coding phase to be the following.

The objective of the coding phase is to transform the design of a system into code in a high-level language, and then to unit test this code.

Normally, good software development organisations require their programmers to adhere to some well-defined and standard style of coding which is called their *coding standard*. Software development organisations usually formulate their own *coding standards* that suit them the most, and require their developers to follow the standards rigorously because of the significant business advantages it offers. The main advantages of adhering to a standard style of coding are the following:

- A coding standard gives a uniform appearance to the codes written by different engineers.
- It facilitates code understanding and code reuse.
- It promotes good programming practices.

A coding standard lists several rules to be followed during coding, such as the way variables are to be named, the way the code is to be laid out, the error return conventions, etc. Besides the coding standards, several coding guidelines are also prescribed by software companies. But, what is the difference between a coding guideline and a coding standard?

It is mandatory for the programmers to follow the coding standards. Compliance of their code to coding standards is verified during code inspection. Any code that does not conform to the coding standards is rejected during code review and the code is reworked by the concerned programmer. In contrast, coding guidelines provide some general suggestions regarding the coding style to be followed but leave the actual implementation of these guidelines to the discretion of the individual developers.

After a module has been coded, usually code review is carried out to ensure that the coding standards are followed and also to detect as many errors as possible before testing. It is important to detect as many errors as possible during code reviews, because reviews are an efficient way of removing errors from code as compared to defect elimination using testing. We first discuss a few representative coding standards and guidelines. Subsequently, we discuss code review techniques. We then discuss software documentation in Section 10.3.

10.1.1 Coding Standards and Guidelines

Good software development organisations usually develop their own coding standards and guidelines depending on what suits their organisation best and based on the specific types of software they develop. To give an idea about the types of coding standards that are being used, we shall only list some general coding standards and guidelines that are commonly adopted by many software development organisations, rather than trying to provide an exhaustive list.

Representative coding standards

Rules for limiting the use of global: These rules list what types of data can be declared global and what cannot, with a view to limit the data that needs to be defined with global scope.

Standard headers for different modules: The header of different modules should have standard format and information for ease of understanding and maintenance. The following is an example of header format that is being used in some companies:

- Name of the module
- Date on which the module was created
- Author's name
- Modification history
- Synopsis of the module. This is a small write-up about what the module does.
- Different functions supported in the module, along with their input/output parameters
- Global variables accessed/modified by the module

Naming conventions for global variables, local variables, and constant identifiers: A popular naming convention is that variables are named using mixed case lettering. Global variable names would always start with a capital letter (e.g., `GlobalData`) and local variable names start with small letters (e.g., `localData`). Constant names should be formed using capital letters only (e.g., `CONSTDATA`).

Conventions regarding error return values and exception handling mechanisms: The way error conditions are reported by different functions in a program should be standard within an organisation. For example, all functions while encountering an error condition should either return a 0 or 1 consistently, independent of which programmer has written the code. This facilitates reuse and debugging.

Representative coding guidelines: The following are some representative coding guidelines that are recommended by many software development organisations. Wherever necessary, the rationale behind these guidelines is also mentioned.

Do not use a coding style that is too clever or too difficult to understand: Code should be easy to understand. Many inexperienced engineers actually take pride in writing cryptic and incomprehensible code. Clever coding can obscure meaning of the code and reduce code understandability; thereby making maintenance and debugging difficult and expensive.

Avoid obscure side effects: The side effects of a function call include modifications to the parameters passed by reference, modification of global variables, and I/O operations that are not obvious behaviour of the function. An obscure side effect is hard to understand from a casual examination of the code. For example, suppose the value of a global variable is changed or some file I/O is performed, which may be difficult to infer from the function's name and header information.

Do not use an identifier for multiple purposes: Programmers often use the same identifier to denote several temporary entities. For example, some programmers make use of a temporary loop variable for also computing and storing the final result. The rationale that they give for such multiple use of variables is memory efficiency, e.g., three variables use up three memory locations, whereas when the same variable is used for three different purposes, only one memory location is used. However, there are several things wrong with this approach and hence should be avoided. Some of the problems caused by the use of a variable for multiple purposes are as follows:

- Each variable should be given a descriptive name indicating its purpose. This is not possible if an identifier is used for multiple purposes. Use of a variable for multiple purposes can lead to confusion and make it difficult for somebody trying to read and understand the code.
- Use of variables for multiple purposes usually makes future enhancements more difficult. For example, while changing the final computed result from integer to float type, the programmer might subsequently notice that it has also been used as a temporary loop variable that cannot be a float type.

Code should be well-documented: As a rule of thumb, there should be at least one comment line on the average for every three source lines of code.

Length of any function should not exceed 10 source lines: A lengthy function is usually very difficult to understand as it probably has a large number of variables and carries out many different types of computations. For the same reason, lengthy functions are likely to have disproportionately larger number of bugs.

Do not use GO TO statements: Use of GO TO statements makes a program unstructured. This makes the program very difficult to understand, debug, and maintain.

10.2 CODE REVIEW

Code review and testing are both effective defect removal mechanisms. However, review has been acknowledged to be more cost-effective in removing defects as compared to testing. Over the years, review techniques have become extremely popular and have been generalised for use with other work products such as design documents and the SRS document.

Code review for a module (that is, a unit) is undertaken after the module successfully compiles. That is, all the syntax errors have been eliminated from the module. Obviously, code review does not target to detect syntax errors in a program, but is designed to detect logical, algorithmic, and programming errors. Code review has been recognised as an extremely cost-effective strategy for eliminating coding errors and for producing high quality code.

The rationale behind the above statement is explained as follows. Eliminating an error from code involves three main activities: testing (detecting failures), debugging (locating the errors), and then correcting the errors. Testing is carried out to detect if the system fails to work satisfactorily for certain types of inputs and under certain circumstances. Once a failure is detected, debugging is carried out to locate the error that is causing the failure and to remove it. Of the three testing activities, debugging is possibly the most laborious and time consuming activity. In code inspection, errors are directly detected, thereby saving considerable efforts that would have been required to locate the errors.

The reason behind why code review is a much more cost-effective strategy to eliminate errors from code compared to testing is that reviews directly detect errors. On the other hand, testing only helps detect failures and significant effort is needed to locate the error during debugging.

The procedures for conduction and the final objectives of these two review techniques are very different. In the following two subsections, we discuss these two types of code review techniques.

Normally, the following two types of reviews are carried out on the code of a module:

- Code inspection.
- Code walkthrough.

10.2.1 Code Walkthrough

Code walkthrough is an informal code analysis technique. In this technique, a module is taken up for review after the module has been coded, successfully compiled, and all syntax errors have been eliminated. A few members of the development team are given the code a couple of days before the walkthrough meeting. Each member selects some test cases and simulates execution of the code by hand. That is, the reviewer mentally traces the execution through different statements and functions of the code.

The main objective of code walkthrough is to discover the algorithmic and logical errors in the code.

The members note down their findings of their code walkthrough and discuss those in a walkthrough meeting where the coder of the module is present.

Even though code walkthrough is an informal analysis technique, several guidelines have evolved over the years for making this naive but useful analysis technique more effective. These guidelines are based on personal experience, common sense, and several other subjective factors. Therefore, these guidelines should be considered as examples rather than as accepted rules to be applied dogmatically. Some of these guidelines are following:

- The size of the team performing code walkthrough should not be either too large or too small. Ideally, it should consist of between three to seven members.
- Discussions in the walkthrough meeting should focus on discovery of errors and avoid deliberations on how to fix the discovered errors.
- In order to foster co-operation and to avoid the feeling among the engineers that they are being watched and evaluated in the code walkthrough meetings, managers should not attend the walkthrough meetings.

10.2.2 Code Inspection

During code inspection, the code is examined to check for the presence of some common programming errors. This is in contrast to the hand simulation of code execution carried out during code walkthroughs.

The principal aim of code inspection is to check for the presence of some common types of errors that usually creep into code due to programmer mistakes and oversights and to check whether coding standards have been adhered to.

The inspection process has several beneficial side effects, other than finding errors. The programmer usually receives feedback on programming style, choice of algorithm, and programming techniques. The different participants gain by being exposed to another programmer's errors which they can then consciously try to avoid.

As an example of the type of errors detected during code inspection, consider the classic error of writing a procedure that modifies a formal parameter and then calls it with a constant actual parameter. It is more likely that such an error can be discovered by specifically looking for this kinds of mistakes in the code, rather than by simply hand simulating execution of the code. In addition to the commonly made errors, adherence to coding standards is also checked during code inspection.

Good software development companies collect statistics regarding different types of errors that are commonly committed by their engineers and identify the types of errors most frequently committed. Such a list of commonly committed errors can be used as a checklist during code inspection to look out for possible errors.

The following is a checklist of some classical programming errors which can be used during code inspection:

- Use of uninitialised variables
- Jumps into loops
- Non-terminating loops
- Incompatible assignments
- Array indices out of bounds
- Improper storage allocation and deallocation
- Mismatch between actual and formal parameter in procedure calls
- Use of incorrect logical operators or incorrect precedence among operators
- Improper modification of loop variables
- Comparison of equality of floating point values.
- Dangling reference caused when the referenced memory has not been allocated.

10.2.3 Cleanroom Technique

Cleanroom technique was pioneered at IBM. This technique relies heavily on walkthroughs, inspection, and formal verification for bug removal. The programmers are not allowed to test any of their code by executing the code other than doing some syntax testing using a compiler. It is interesting to note that the term *cleanroom* was first coined at IBM by drawing analogy to the semiconductor fabrication units where defects are avoided by manufacturing in an ultra-clean atmosphere.

This technique reportedly produces documentation and code that is more reliable and maintainable than other development methods relying heavily on code execution-based testing. The main problem with this approach is that testing effort is increased as walkthroughs, inspection, and verification are time consuming for detecting simple errors. Also testing-based error detection is efficient for detecting certain errors that escape manual inspection.

10.3 SOFTWARE DOCUMENTATION

When a software is developed, in addition to the executable files and the source code, several kinds of documents such as users' manual, *software requirements specification* (SRS) document, design document, test document, installation manual, etc., are developed as part of the software engineering process. All these documents are considered a vital part of any good software development practice. Good documents are helpful in several ways:

- Good documents help to enhance understandability of a piece of code. Code understanding is an important part of any maintenance activity. Availability of good documents help to reduce the effort and time required for maintenance.
- Documents help the users to understand and effectively use the system.
- Good documents help to effectively tackle the manpower turnover[1] problem. Even when an engineer leaves the organisation, and a new engineer comes in, he can build up the required knowledge easily by referring to the documents.
- Production of good documents helps the manager to effectively track the progress of the project. The project manager would know that some measurable progress has been achieved, if the results of some pieces of work has been documented and the same has been reviewed.

Different types of software documents can broadly be classified into the following internal documentation and external documentation.

We discuss these two types of documentation in the next section.

Internal documentation: These are provided in the source code itself.

External documentation: These are the supporting documents such as SRS document, installation document, users' manual, design document, and test document.

10.3.1 Internal Documentation

Internal documentation is the code comprehension features provided in the source code itself. Internal documentation can be provided in the code in several forms. The important types of internal documentation are the following:

- Comments embedded in the source code
- Use of meaningful variable names
- Module and function headers
- Code indentation

[1] Manpower turnover is the software industry jargon for denoting the unusually high rate at which personnel attrition occurs (i.e., personnel leave an organisation).

- Code structuring (i.e., code decomposed into modules and functions)
- Use of enumerated types
- Use of constant identifiers
- Use of user-defined data types

Out of these different types of internal documentation, which one is the most valuable for understanding a piece of code?

Careful experiments suggest that out of all types of internal documentation, meaningful variable names is most useful while trying to understand a piece of code.

The above inference, of course, is in contrast to the common expectation that code commenting would be the most useful. The research finding can be far from the truth when comments are written without much thought. For example, the following style of code commenting is not much of a help in understanding the code.

```
a=10; /* a made 10 */
```

A good style of code commenting is to write to clarify certain non-obvious aspects of the working of the code, rather than cluttering the code with trivial comments. Good software development organisations usually ensure good internal documentation by appropriately formulating their coding standards and coding guidelines. Even when a piece of code is carefully commented, meaningful variable names has been found to be the most helpful in understanding a piece of code.

10.3.2 External Documentation

External documentation is provided through various types of supporting documents such as users' manual, software requirements specification document, design document, test document, etc. A systematic software development style ensures that all these documents are of good quality and are produced in an orderly fashion.

An important feature that is required of any good external documentation is consistency with the code. If the different documents are not consistent, a lot of confusion is created for somebody trying to understand the code. In other words, all the documents developed for a product should be up-to-date and every change made to the code should be reflected in the relevant external documents. Even if only a few documents are not up-to-date, they create inconsistency and lead to confusion. Another important feature required for external documents is proper understandability by the category of users for whom the document is designed. For achieving this, Gunning's fog index is very useful. We discuss this next.

Gunning's fog index

Gunning's fog index (developed by Robert Gunning in 1952) is a metric that has been designed to measure the readability of a text document. The computed metric value (fog index) of a document indicates the number of years of formal education that a person should have, in order to be able to comfortably understand that document. That is, if a certain document has a fog index of 12, anyone who has completed his 12th class would not have much difficulty in understanding that document.

The Gunning's fog index of a document D can be computed as follows:

$$\text{fog}(D) = 0.4 \times \left(\frac{\text{Words}}{\text{Sentences}}\right) + \text{Per cent of words having 3 or more syllables}$$

Observe that the fog index is computed as the sum of two different factors. The first factor computes the average number of words per sentence (total number of words in the document divided by the total number of sentences). This factor therefore accounts for the common observation that long sentences are difficult to understand. The second factor measures the percentage of complex words in the document. The complex words are considered to be those with three or more syllabi. Note that a syllable is a group of words that can be independently pronounced. For example, the word "sentence" has three syllables ("sen", "ten", and "ce"). Words having more than three syllables are complex words and presence of many such words hamper readability of a document.

Consider the following sentence: "The Gunning's fog index is based on the premise that use of short sentences and simple words makes a document easy to understand." Calculate its fog index.

Solution: The given sentence has 23 words. Four of the words have three or more syllabi. The fog index of the problem sentence is therefore

$$0.4 \times (23/1) + (4/23) \times 100 = 26.5$$

If a users' manual is to be designed for use by factory workers whose educational qualification is class 8, then the document should be written such that the Gunning's fog index of the document does not exceed 8.

10.4 TESTING

The aim of program testing is to help in identifying all defects in a program. However, in practice, even after satisfactory completion of the testing phase, it is not possible to guarantee that a program is error free. This is because the input data domain of most programs is very large, and it is not practical to test the program exhaustively with respect to each value that the input can assume. Consider a function taking a floating point number as argument. If a tester takes 1 second to type in an integer value, then even a million testers would not be able to exhaustively test it after trying for a million years. Even with this obvious limitation of the testing process, we should not underestimate the importance of testing. We must remember that careful testing can expose a large percentage of the defects existing in a program, and therefore, testing provides a practical way of reducing defects in a system.

10.4.1 Basic Concepts and Terminologies

In this section, we will discuss a few basic concepts in program testing.

How to test a program?

Testing a program involves executing the program with a set of test inputs and observing if the program behaves as expected. If the program fails to behave as expected, then the input data and the conditions under which it fails are noted for later debugging and error correction. A highly simplified view of program testing is schematically shown in Figure 10.1. The tester has been shown as a stick icon, who inputs several test data to the system and observes the outputs produced by it to check if the system fails on some specific inputs. When the system fails, it is necessary to note down the specific input values for which the failure occurs. However, unless the conditions under which a software fails are noted down, it becomes difficult for the developers to reproduce a failure observed by the testers. For example, a software might fail for a test case only when a network connection is enabled. Unless this condition is documented in the failure report, it becomes difficult to reproduce the failure.

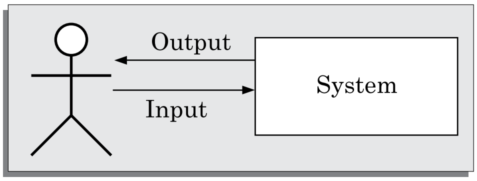


FIGURE 10.1 A simplified view of program testing.

Terminologies

As is true for any specialised domain, the area of software testing has come to be associated with its own set of terminologies. In the following, we discuss a few important terminologies that have been standardised by the IEEE Standard Glossary of Software Engineering Terminology [IEEE, 1990]:

- A **mistake** is essentially any programmer action that later shows up as an incorrect result during program execution. A programmer may commit a mistake in almost any of the development activities. For example, during coding a programmer might commit the mistake of not initializing a certain variable, or might overlook the errors that might arise in some exceptional situations such as division by zero in an arithmetic operation. Both these mistakes can lead to an incorrect result during program execution.
- An **error** is the result of a mistake committed by a developer in any of the development activities. Mistakes can give rise to an extremely large variety of errors. One example error is a call made to a wrong function.

  The terms *error, fault, bug,* and *defect* are used interchangeably by the program testing community. Please note that in the domain of hardware testing, the term *fault* is used with a slightly different connotation [IEEE, 1990] as compared to the terms *error* and *bug*.

The terms *error, fault, bug,* and *defect* are considered to be synonyms in the area of program testing.

Can a designer's mistake give rise to a program error? Give an example of a designer's mistake and the corresponding program error.

Solution: Yes, a designer's mistake can give rise to a program error. For example, a requirement might be overlooked by the designer, which can lead to it being overlooked in the code as well.

- A **failure** of a program essentially denotes an incorrect behaviour exhibited by the program during its execution. An incorrect behaviour is observed either as production of an incorrect result or as an inappropriate activity carried out by the program. Every failure is caused by one or more bugs present in the program. In other words, we can say that every software failure can be traced to one or more bugs present in the code. The number of possible bugs that can cause a program failure is extremely large. Out of the large number of the bugs that can cause program failure, in the following we give three randomly selected examples:

- The result computed by a program is 0, when the correct result is 10.
- A program crashes on an input.
- A robot fails to avoid an obstacle and collides with it.

It may be noted that mere presence of an error in a program code may not necessarily lead to a failure during its execution.

Give an example of a program error that may not cause any failure.

Solution: Consider the following C program segment:

```
int markList[1:10]; /* mark list of 10 students*/
int roll;   /* student roll number*/
       ...
       markList[roll]=mark;
```

In the above code, if the variable *roll* assumes zero or some negative value under some circumstances, then an *array index out of bound* type of error would result. However, it may be the case that for all allowed input values the variable *roll* is always assigned positive values. Then, no failure would occur. Thus, even if an error is present in the code, it does not show up as a failure for normal input values.

Explanation: An *array index out of bound* type of error is said to occur, when the array index variable assumes a value beyond the array bounds.

- A **test case** is a triplet [*I, S, R*], where *I* is the data input to the program under test, *S* is the state of the program at which the data is to be input, and *R* is the result expected to be produced by the program. The state of a program is also called its *execution mode.* As an example, consider the different execution modes of a certain text editor software. The text editor can at any time during its execution assume any of the following execution modes—edit, view, create, and display. In simple words, we can say that a test case is a set of certain test inputs, the mode in which the input is to be applied, and the results that are expected during and after the execution of the test case.

  An example of a test case is—[*input: "abc", state: edit, result: abc is displayed*], which essentially means that the input *abc* needs to be applied in the edit mode, and the expected result is that the string *abc* would be displayed.

- A **test scenario** is an abstract test case in the sense that it only identifies the aspects of the program that are to be tested without identifying the input, state, or output. A test case can be said to be an implementation of a test scenario. For example, a test scenario can be the traversal of a path in the control flow graph of the program. In the test case, the input, output, and the state at which the input would be applied is designed such that the scenario can be executed. An important automatic test case design strategy is to first design test scenarios through an analysis of some program abstraction (model) and then implement the test scenarios as test cases.

- A **test script** is an encoding of a test case as a short program. Test scripts are developed for automated execution of the test cases.
- A test case is said to be a **positive test case** if it is designed to test whether the software correctly performs a required functionality. A test case is said to be **negative test case**, if it is designed to test whether the software carries out something that is not required of the system. As one example each of a positive test case and a negative test case, consider a function to manage user logins. A positive test case can be designed to check if the function correctly validates a legitimate user entering correct user name and password. A negative test case in this case can be a test case that checks whether the login functionality validates and admits a user with wrong or bogus user name or password.
- A **test suite** is the set of all test cases that have been designed by a tester to test a given program.

  Testability of a program indicates the effort needed to validate the program. In other words, the testability of a requirement is the degree of difficulty to adequately test an implementation to determine its conformance to its requirements.

Suppose two programs have been written to implement essentially the same functionality. How can you determine which one of these is more testable?

Solution: A program is more testable, if it can be adequately tested with less number of test cases. Obviously, a less complex program is more testable. The complexity of a program can be measured using several types of metrics such as number of decision statements used in the program. Thus, a more testable program should have a lower structural complexity metric.

- A **failure mode** of a software denotes an observable way in which it can fail. In other words, all failures that have similar observable symptoms, constitute a failure mode. As an example of the failure modes of a software, consider a railway ticket booking software that has three failure modes—failing to book an available seat, incorrect seat booking (e.g., booking an already booked seat), and system crash.
- **Equivalent faults** denote two or more bugs that result in the system failing in the same failure mode. As an example of equivalent faults, consider the following two faults in C language—division by zero and illegal memory access errors. These two are equivalent faults, since each of these leads to a program crash.

Verification *versus* validation

The objectives of both verification and validation techniques are very similar since both these techniques are designed to help remove errors in a software. In spite of the apparent similarity between their objectives, the underlying principles of these two bug detection techniques and their applicability are very different. We summarise the main differences between these two techniques in the following:

- Verification is the process of determining whether the output of one phase of software development conforms to that of its previous phase; whereas validation is the process of determining whether a fully developed software conforms to its requirements specification. Thus, the objective of verification is to check if the work products produced during a phase of development conform to those produced during the preceding phase. For example, a verification step can be to check if the design documents produced after the design step conform to the requirements specification. On the other hand, validation is applied to the fully developed and integrated software to check if it satisfies the customer's requirements.

- The primary techniques used for verification include review, simulation, formal verification, and testing. Review, simulation, and testing are usually considered as informal verification techniques. Formal verification usually involves use of theorem proving techniques or use of automated tools such as a model checker. On the other hand, validation techniques are primarily based on testing. Note that we have categorised testing both under program verification and validation. The reason being that unit and integration testing can be considered as verification steps where it is verified whether the code is as per the module and module interface specifications. On the other hand, system testing can be considered as a validation step where it is determined whether the fully developed code is as per its requirements specification.
- Verification does not require execution of the software, whereas validation requires execution of the software.
- Verification is carried out during the development process to check if the development activities are proceeding alright, whereas validation is carried out to check if the right as required by the customer has been developed.
- Verification techniques can be viewed as an attempt to achieve phase containment of errors. Phase containment of errors has been acknowledged to be a cost-effective way to eliminate program bugs, and is an important software engineering principle. The principle of detecting errors as close to their points of commitment as possible is known as *phase containment of errors*. Phase containment of errors can reduce the effort required for correcting bugs. For example, if a design problem is detected in the design phase itself, then the problem can be taken care of much more easily than if the error is identified, say, at the end of the testing phase. In the later case, it would be necessary not only to rework the design, but also to appropriately redo the relevant coding as well as the system testing activities, thereby incurring higher cost.

We can therefore say that the primary objective of verification is to determine *whether the different steps of product development are being carried out correctly*, whereas validation is carried out towards the end of the development process to determine *whether the right product has been developed.*

While verification is concerned with phase containment of errors, the aim of validation is to check whether the deliverable software is error free.

We can consider the verification and validation techniques to be different types of bug filters. To achieve high product reliability in a cost-effective manner, a development team needs to perform both verification and validation activities. The activities involved in these two types of bug detection techniques together are called the "V and V" activities.

Error detection techniques
= Verification techniques
+ Validation techniques

Based on the above discussions, we can conclude that:

Is it at all possible to develop a highly reliable software, using validation techniques alone? If so, can we say that all verification techniques are redundant?

Solution: It is possible to develop a highly reliable software using validation techniques alone. However, this would cause the development cost to increase drastically. Verification techniques help achieve phase containment of errors and provide a means to cost-effectively remove bugs.

10.4.2 Testing Activities

Testing involves performing the following major activities:

Test suite design: The test suite is designed possibly using several test case design techniques. We discuss a few important test case design techniques later in this Chapter.

Running test cases and checking the results to detect failures: Each test case is run and the results are compared with the expected results. A mismatch between the actual result and expected results indicates a failure. The test cases for which the system fails are noted down for later debugging.

Locate error: In this activity, the failure symptoms are analysed to locate the errors. For each failure observed during the previous activity, the statements that are in error are identified.

Error correction: After the error is located during debugging, the code is appropriately changed to correct the error.

A typical testing process in terms of the activities that are carried out has been shown schematically in Figure 10.2. As can be seen, the test cases are first designed. Subsequently, the test cases are run to detect failures. The bugs causing the failure are identified through debugging, and the identified error is corrected. Of all the above mentioned testing activities, debugging often turns out to be the most time consuming activity.

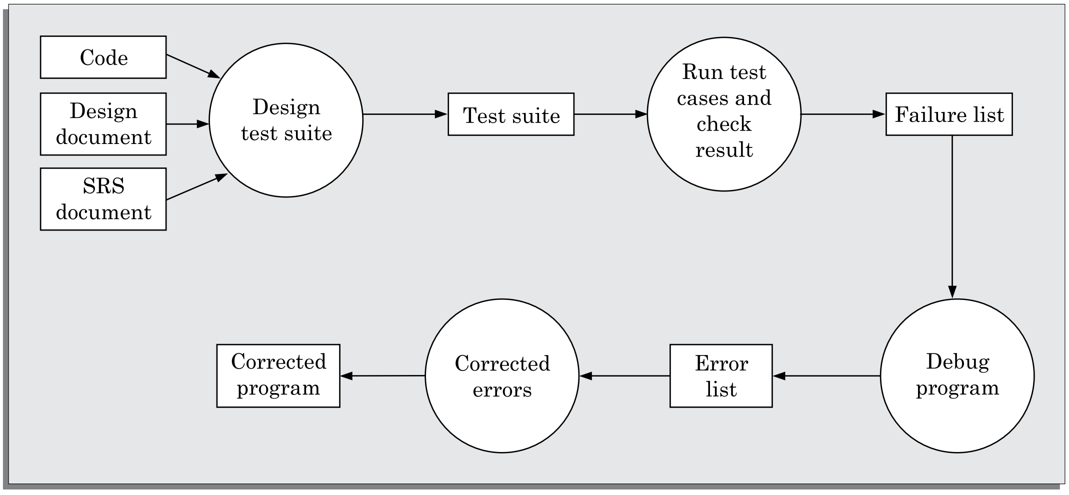


FIGURE 10.2 Testing process.

10.4.3 Why Design Test Cases?

Before discussing the various test case design techniques, we need to convince ourselves on the following question. Would it not be sufficient to test a software using a large number of random input values? Why design test cases? The answer to this question is the following. This would be very ineffective due to the following reasons:

When test cases are designed based on random input data, many of the test cases do not contribute to the *significance* of the test suite, That is, they do not help detect any additional defects not already being detected by other test cases in the suite.

Testing a software using a large collection of randomly selected test cases does not guarantee that all (or even most) of the errors in the system will be uncovered. Let us try to understand why the number of random test cases in a test suite, in general, does not indicate of the effectiveness of testing. Consider the following example code segment which determines the greater of two integer values x and y. This code segment has a simple programming error:

```
if (x>y) max = x;
else max = x; /* should be max = y */
```

For the given code segment, the test suite {(x=3,y=2);(x=2,y=3)} can detect the error, whereas a larger test suite {(x=3,y=2);(x=4,y=3);(x=5,y=1)} does not detect the error. All the test cases in the larger test suite essentially test the same statement, while the other statement remains undetected. So, it would be incorrect to say that a larger test suite would always detect more errors than a smaller one, unless of course the larger test suite has also been carefully designed. This implies that for effective testing, the test suite should be carefully designed rather than picked randomly.

We have already pointed out that exhaustive testing of almost any non-trivial system is impractical due to the fact that the domain of input data values to most practical software systems is extremely large. Therefore, to satisfactorily test a software with minimum cost, we must design a *minimal test suite* that is of reasonable size and can uncover as many existing errors in the system as possible. To reduce testing cost and at the same time to make testing more effective, systematic approaches have been developed to design a small test suite that can detect most, if not all failures.

A minimal test suite is a carefully designed set of test cases such that each test case helps detect different errors. Thus, the wastage of effort due to running multiple tests to detect the same error is avoided.

There are essentially two main approaches to systematically design test cases:

- Black-box approach
- White-box (or glass-box) approach

In the black-box approach, test cases are designed using only the functional specification of the software. That is, test cases are designed solely based on an analysis of the input/out behaviour (that is, functional behaviour) and does not require any knowledge of the internal structure or the code of a program. For this reason, black-box testing is also known as *functional testing*. On the other hand, designing white-box test cases requires a thorough knowledge of the code structure of a program, and therefore white-box testing is also called *structural testing*. Black-box test cases are designed solely based on the input-output behaviour of a program. In contrast, white-box test cases are based on an analysis of the code. These two approaches to test case design are complementary. That is, a program has to be tested using the test cases designed by both the approaches, and one testing using one approach does not substitute testing using the other.

Is it a good idea to thoroughly perform any one of black-box or white-box testing and leave out the other?

Solution: No. Both white-box and black-box tests have to be performed, since some bugs detected by white-box test cases cannot be detected by black-box test cases and vice-versa. For example, a requirement that has not been implemented cannot be detected by any white-box test. On the other hand, some extra functionality that has been implemented by the code cannot be detected by any black-box test case.

10.4.4 Testing in the Large *versus* Testing in the Small

A software product is normally tested in three levels or stages:

- Unit testing
- Integration testing
- System testing

During unit testing, the individual functions (or units) of a program are tested.

Unit testing is referred to as testing in the small, whereas integration and system testing are referred to as *testing in the large*.

After testing all the units individually, the units are incrementally integrated and tested after each step of integration (integration testing). Finally, the fully integrated system is tested (system testing). Integration and system testing are usually referred to as *testing in the large.*

Often beginners ask the question—"Why test each module (unit) in isolation first, then integrate these modules and test, and again test the integrated set of modules—why not just test the integrated set of modules once thoroughly?" The answer to this question is the following—There are two main reasons to it. First while testing a module, other modules with which this module needs to interface may not be ready. Moreover, it is always a good idea to first test the module in isolation before integration because it makes debugging easier. If a failure is detected when an integrated set of modules is being tested, it would be difficult to determine which module exactly has the error, and the code of a large number of modules may have to be examined to localize the error.

In the following sections, we discuss the different levels of testing. It should be borne in mind in all our subsequent discussions that unit testing is carried out in the coding phase itself as soon as coding of a module is complete. On the other hand, integration and system testing are carried out during the testing phase.

10.4.5 Tests as Bug Filters

There exists a large number of black-box and white-box test suite design approaches. Each test suite design approach is essentially based on some heuristics. Commercial software is usually tested using the test suite obtained from several black-box and white-box test suite design approaches. Therefore, a designed test suite though is capable of detecting many errors in the program, it cannot guarantee detection of all errors in a program.

We can think of the test suite designed by using a test case design strategy as a bug filter. When a number of test suite design strategies are used successively to test a program, we can think of the number of bugs in the program successively getting reduced after the application of each bug filter. However, it must be remembered if a program has been adequately tested using some test suite design approaches, then further testing of the program using additional test cases designed using the same approach would yield rapidly diminishing returns. In this context, we discuss an analogy reported in [Beizer, 1990].

Execution of a well-designed test suite can detect many errors in a program, but cannot guarantee complete absence of errors.

Suppose a cotton crop is infested with insects. The farmer may use a pesticide such as DDT, which kills most of the bugs. However, some bugs survive. The surviving bugs develop resistance to DDT. When the farmer grows cotton crop in the next season, the bugs again appear. But, application of DDT does not kill many bugs as the bugs have become resistant to DDT. The farmer would have to use a different insecticide such as Malathion. However, the surviving bugs would have become resistant to both DDT and Malathion, and so on.

Suppose 10 different test case design strategies are successively used to test a program. Each test case design strategy is capable of detecting 30% of the bugs existing at the time of application of the strategy. If 1000 bus existed in the program, determine the number of bugs existing at the end of testing.

Solution: Testing using each test case design strategy, detects 30% of the bugs. So, after testing using a test strategy, 70% of the bugs existing before application of the strategy survive. At the end of application of the 10 strategies, the number of surviving bugs = $1000 \times (0.7)^{10} = 1000 \times 0.028 = 28$.

10.5 UNIT TESTING

Unit testing is undertaken after coding of a module is complete, all syntax errors have been removed, and the code has been reviewed. This activity is typically undertaken by the coder of the module himself in the coding phase. Before carrying out unit testing, the unit test cases have to be designed and the test environment for the unit under test has to be developed. In this section, we first discuss the environment needed to perform unit testing.

Driver and stub modules

In order to test a single module, we need a complete environment to provide all relevant code that is necessary for execution of the module. That is, besides the module under test, the following are needed to test the module:

- The procedures belonging to other modules that the module under test calls.
- Non-local data structures that the module accesses.
- A procedure to call the functions of the module under test with appropriate parameters.

Modules required to provide the necessary environment (which either call, provide the required global data, or are called by the module under test) are usually not available until they too have been unit tested. In this context, *stubs* and *drivers* are designed to provide the complete environment for a module so that testing can be carried out. The role of stub and driver modules is pictorially shown in Figure 10.3. We briefly discuss the stub and driver modules that are required to provide the necessary environment for carrying out unit testing are briefly discussed in the following.

Stub: A stub module consists of several stub procedures that are called by the module under test. A *stub* procedure is a dummy procedure that takes the same parameters as the function called by the unit under test but has a highly simplified behavior. For example, a stub procedure may produce the expected behaviour using a simple table look up mechanism, rather than performing actual computations.

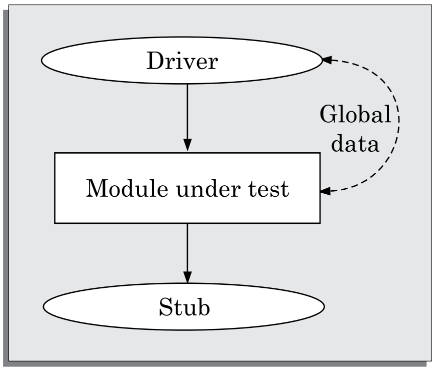


FIGURE 10.3 Unit testing with the help of driver and stub modules.

Driver: A driver module contains the non-local data structures that are accessed by the module under test. Additionally, it should also have the code to call the different functions of the unit under test with appropriate parameter values for testing.

10.6 BLACK-BOX TESTING

In black-box testing, test cases are designed from an examination of the input/output values only and no knowledge of design or code is required. The following are the two main approaches available to design black box test cases:

- Equivalence class partitioning
- Boundary value analysis

In the following subsections, we will elaborate these two test case design techniques.

10.6.1 Equivalence Class Partitioning

In the equivalence class partitioning approach, the domain of input values to the unit under test is partitioned into a set of equivalence classes. The partitioning is done such that for every input data belonging to the same equivalence class, the program behaves similarly.

Equivalence classes for a unit under test can be designed by examining the input data and output data. The following are two general guidelines for designing the equivalence classes:

1. If the input data values to a system can be specified by a range of values, then one valid and two invalid equivalence classes can be defined. For example, if the equivalence class is the set of integers in the range 1 to 10 (i.e., [1,10]), then the two invalid equivalence classes are [−∞,0], [11,+∞], and the valid equivalence class is [1,10].
2. If the input data assumes values from a set of discrete members of some domain, then one equivalence class for the valid input values and another equivalence class for the invalid input values should be defined. For example, if the valid equivalence classes are {A,B,C}, then the invalid equivalence class is ∪-*{*A,B,C*}*, where ∪ is the universe of all possible input values.

The main idea behind defining equivalence classes of input data is that testing the code with any one value belonging to an equivalence class is as good as testing the code with any other value belonging to the same equivalence class.

In the following, we illustrate equivalence class partitioning-based test case generation through three examples.

Consider a program unit that takes an input integer that can assume values in the range of 0 and 5000 and computes its square root. Determine the equivalence classes and the black box test suite for the program unit.

Solution: There are three equivalence classes—The set of negative integers, the set of integers in the range of 0 and 5000, and the set of integers larger than 5000. Therefore, the test cases must include representatives for each of the three equivalence classes. A possible test suite can be: {–5,500,6000}.

Design the equivalence class test cases for a function that reads two integer pairs (m_1, c_1) and (m_2, c_2) defining two straight lines of the form `y=mx+c`. The function computes the intersection point of the two straight lines and displays the point of intersection.

Solution: First, there are two equivalence classes: valid and invalid. The valid class can be divided into the following equivalence classes:

- No point of intersection: Parallel lines ($m_1 = m_2$, c_1 c_2)
- One point of intersection: Intersecting lines (m_1 m_2)
- Infinite points of intersection: Coincident lines ($m_1 = m_2$, $c_1 = c_2$)

Now, selecting one representative value from each equivalence class, we get the required equivalence class test suite {{(a,a)(a,a)}{(2,2)(2,5)},{(5,5)(7,7)}, {(10,10)(10,10)}}. The pair {(a,a)(a,a)} represents the invalid class.

Design equivalence class partitioning test suite for a function that reads a character string of size less than five characters and displays whether it is a palindrome.

Solution: The domain of all input values can be partitioned into two broad equivalence classes: valid values and invalid values. The valid values can be partitioned into palindromes and non-palindromes. The equivalence classes are the leaf level classes shown in Figure 10.4. The equivalence classes are palindromes, non-palindromes, and invalid inputs. Now, selecting one representative value from each equivalence class, we have the required test suite: {abc,aba,abcdef}.

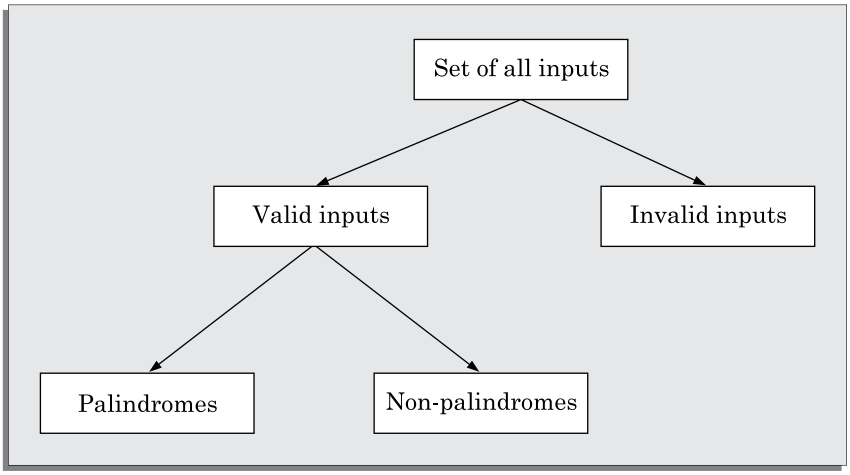


FIGURE 10.4 Equivalence classes for Problem 10.10.

10.6.2 Boundary Value Analysis

A type of programming error that is frequently committed by programmers is missing out on the special consideration that should be given to the values at the boundaries of different equivalence classes of inputs. The reason behind programmers committing such errors might purely be due to psychological factors. Programmers often fail to properly address the special processing required by the input values that lie at the boundary of the different equivalence classes. For example, a programmer may improperly use < instead of <=, or conversely <= for <, etc.

Boundary value analysis-based test suite design involves designing test cases using the values at the boundaries of different equivalence classes.

To design boundary value test cases, it is required to examine the equivalence classes to check if any of the equivalence classes contains a range of values. For those equivalence classes that are not a range of values (i.e., consist of a discrete collection of values) no boundary value test cases can be defined. For an equivalence class that is a range of values, the boundary values need to be included in the test suite. For example, if an equivalence class contains the integers in the range 1 to 10, then the boundary value test suite is {0,1,10,11}.

For a function that computes the square root of the integer values in the range of 0 and 5000, determine the boundary value test suite.

Solution: There are three equivalence classes—The set of negative integers, the set of integers in the range of 0 and 5000, and the set of integers larger than 5000. The boundary value-based test suite is: {0,-1,5000,5001}.

Design boundary value test suite for the function described in Problem 10.8.

Solution: The equivalence classes have been showed in Figure 10.5. There is a boundary between the valid and invalid equivalence classes. Thus, the boundary value test suite is {abcdefg, abcdef}.

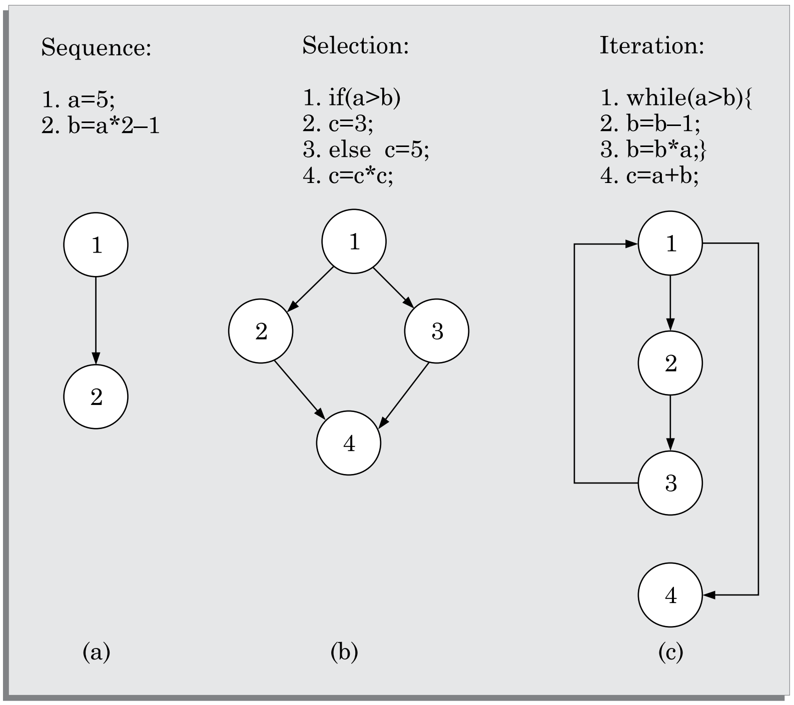


FIGURE 10.5 CFG for (a) sequence, (b) selection, and (c) iteration type of constructs.

10.6.3 Summary of the Black-box Test Suite Design Approach

We now summarise the important steps in the black-box test suite design approach:

- Examine the input and output values of the program.
- Identify the equivalence classes.
- Design equivalence class test cases by picking one representative value from each equivalence class.
- Design the boundary value test cases as follows. Examine if any equivalence class is a range of values. Include the values at the boundaries of such equivalence classes in the test suite.

The strategy for black-box testing is intuitive and simple. For black-box testing, the most important step is the identification of the equivalence classes. Often, the identification of the equivalence classes is not straightforward. However, with little practice one would be able to identify all equivalence classes in the input data domain. Without practice, one may overlook many equivalence classes in the input data set. Once the equivalence classes are identified, the equivalence class and boundary value test cases can be selected almost mechanically.

10.7 WHITE-BOX TESTING

White-box testing is an important type of unit testing. A large number of white-box testing strategies exist. Each testing strategy essentially designs test cases based on analysis of some aspect of source code and is based on some heuristic. We first discuss some basic concepts associated with white-box testing, and follow it up with a discussion on specific testing strategies.

10.7.1 Basic Concepts

A white-box testing strategy can either be coverage-based or fault-based.

Fault-based testing

A fault-based testing strategy targets to detect certain types of faults. An example of a fault-based strategy is mutation testing, which is discussed later in this section.

Coverage-based testing

A coverage-based testing strategy attempts to execute (or cover) certain elements of a program. Popular examples of coverage-based testing strategies are statement coverage, branch coverage, multiple condition coverage, and path coverage-based testing.

Testing criterion for coverage-based testing

A coverage-based testing strategy typically targets to execute (i.e., cover) certain program elements for discovering failures.

For example, if a testing strategy requires all the statements of a program to be executed at least once, then we say that the testing criterion of the strategy is *statement coverage*. We say that a test suite is adequate with respect to a criterion, if it covers all program elements of the domain defined by that criterion.

The set of specific program elements that a testing strategy targets to execute is called the *testing criterion* of the strategy.

Stronger *versus* weaker testing

We have mentioned that a large number of white-box testing strategies have been proposed. It therefore becomes necessary to compare the effectiveness of different testing strategies in detecting faults. We can compare two testing strategies by determining whether one is stronger, weaker, or complementary to the other.

When none of two testing strategies fully covers the program elements exercised by the other, then the two are called *complementary testing strategies*. The concepts of stronger, weaker, and complementary testing are schematically illustrated in Figure 10.6. Observe in Figure 10.6(a) that testing strategy A is stronger than B since B covers only a proper subset of elements covered by B. On the other hand, Figure 10.6(b) shows A and B are complementary testing strategies since some elements of A are not covered by B and *vice versa*.

A white-box testing strategy is said to be stronger than another strategy, if the stronger testing strategy covers all program elements covered by the weaker testing strategy, and the stronger strategy additionally covers at least one program element that is not covered by the weaker strategy.

If a stronger testing has been performed, then a weaker testing need not be carried out.

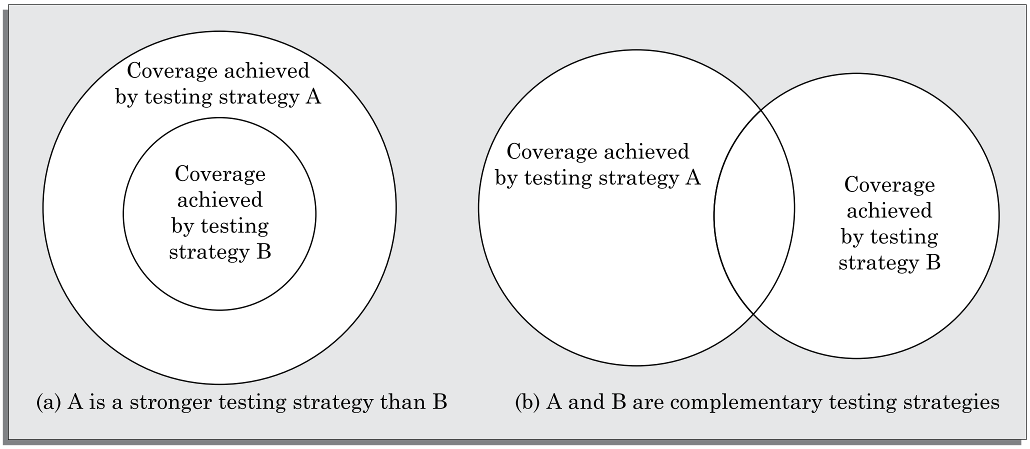

Coverage achieved by testing strategy A
Coverage achieved by testing strategy B
(a) A is a stronger testing strategy than B
Coverage achieved by testing strategy A
Coverage achieved by testing strategy B
(b) A and B are complementary testing strategies

FIGURE 10.6 Illustration of stronger, weaker, and complementary testing strategies.

A test suite should, however, be enriched by using various complementary testing strategies.

10.7.2 Statement Coverage

Statement coverage is a metric to measure the percentage of statements that are executed by a test suite in a program at least once.

It is obvious that without executing a statement, it is difficult to determine whether it causes a failure due to illegal memory access, wrong result computation due to improper arithmetic operation, etc. It must however be pointed out that an important weakness of the statement-coverage strategy is that executing a statement once and observing that it behaves properly for one input value is no guarantee that it will behave correctly for all input values. Never the less, statement coverage is a very intuitive and appealing testing technique. In the following, we illustrate a test suite that achieves statement coverage.

Coverage is frequently used to check the quality of testing achieved by a test suite. It is hard to manually design a test suite to achieve a specific coverage for a non-trivial program.

The principal idea governing the statement coverage strategy is that unless a statement is executed, there is no way to determine whether an error exists in that statement.

Design a statement coverage-based test suite for the following Euclid's GCD computation function:

```
int computeGCD(int x,int y){
 1 while (x != y){
 2 if (x>y) then
 3 x=x-y;
 4 else y=y-x;
 5 }
 6 return x;
 }
```

Solution: To design the test cases for achieving statement coverage, the conditional expression of the `while` statement needs to be made true and the conditional expression of the `if` statement needs to be made both true and false. By choosing the test set {(x = 3, y = 3), (x = 4, y = 3), (x = 3, y = 4)}, all statements of the program would be executed at least once.

10.7.3 Branch Coverage

Branch coverage is also called *decision coverage* (DC). It is also sometimes referred to as *all edge coverage*. A test suite achieves branch coverage, if it makes the decision expression in each branch in the program to assume both true and false values. In other words, for branch coverage each branch in the CFG representation of the program must be taken at least once, when the test suite is executed. Branch testing is also known as all *edge testing*, since in this testing scheme, each edge of a program's control flow graph is required to be traversed at least once.

For the program of Problem 10.13, determine a test suite to achieve branch coverage.

Solution: The test suite {(x = 3, y = 3), (x = 3, y = 2), (x = 4, y = 3), (x = 3, y = 4)} achieves branch coverage.

It is easy to show that branch coverage-based testing is a stronger testing than statement coverage-based testing. We can prove this by showing that branch coverage ensures statement coverage, but not *vice versa*.

Theorem 10.1 Branch coverage-based testing is stronger than statement coverage-based testing.

Proof: We need to show that (a) branch coverage ensures statement coverage, and (b) statement coverage does not ensure branch coverage.

(a) Branch testing would guarantee statement coverage since every statement must belong to some branch (assuming that there is no unreachable code).

(b) To show that statement coverage does not ensure branch coverage, it is sufficient to give an example of a test suite that achieves statement coverage, but does not cover at least one branch. Consider the following code, and the test suite {5}.

```
if(x>2)  x+=1;
```

The test suite would achieve statement coverage. However, it does not achieve branch coverage, since the condition (x > 2) is not made false by any test case in the suite.

10.7.4 Condition Coverage

Condition coverage testing is also known as *basic condition coverage* (BCC) *testing*. A test suite is said to achieve basic condition coverage (BCC), if each basic condition in every conditional expression assumes both true and false values during testing. For example, for the following decision statement: `if(A||B && C) …;` the basic conditions A, B, and C assume both true and false values. However, for the given expression, just two test cases can achieve condition coverage. For example, one test case, may assign A = True, B = True, and C = True and another test case may assign A = False, B = False, and C = False. It is easy to see that basic condition coverage may not achieve branch coverage.

10.7.5 Condition and Decision Coverage

A test suite is said to achieve condition and decision coverage, if it achieves condition coverage as well as decision (that is, branch) coverage. Obviously, condition and decision coverage is stronger than both condition coverage and decision coverage.

10.7.6 Multiple Condition Coverage

Multiple condition coverage (MCC) is achieved, if the test cases make the component conditions of a composite conditional expression to assume all possible combinations of true and false values. For example, consider the composite conditional expression [(c_1 *and* c_2) *or* c_3]. A test suite would achieve MCC, if all the component conditions c_1, c_2, and c_3 are each made to assume all combinations of true and false values. Therefore, at least eight test cases would be required in this case to achieve MCC. It is easy to prove that condition testing is a stronger testing strategy than branch testing. For a composite conditional expression of n components, 2^n test cases are required for multiple condition coverage. Thus, for multiple condition coverage, the number of test cases increases exponentially with the number of component conditions. Therefore, multiple condition coverage-based testing technique is practical only if n (the number of atomic conditions in the decision expression) is small.

Give an example of a fault that is detected by multiple condition coverage, but not by branch coverage.

Solution: Consider the following C program segment:

```
if(temperature>150 || temperature>50)
   setWarningLightOn();
```

The program segment has a bug in the second component condition, it should have been `temperature<50`. The test suite {temperature=160, temperature=40} achieves branch coverage. But, it is not able to check that `setWarningLightOn();` should not be called for temperature values within 150 and 50.

10.7.7 Multiple Condition/Decision Coverage (MC/DC)

Multiple condition coverage (MCC) is a strong notion of test coverage. However, MCC is impractical for many programs as the number of test cases required to achieve MCC increases exponentially with the number of basic conditions in a decision expression. Therefore, when a program has decision expressions made up of dozens of atomic conditions, MCC becomes impractical. On the other hand, many embedded control applications incorporate decision statements with several dozens of basic conditions. For the sake of illustration, let us assume that a single conditional expression involves 20 basic conditions. In this case, the number of test cases required to achieve MCC would be 2^{20}, which is almost a million test cases[2]. It is now easy to imagine the number of test cases that

[2] Of course, the number of test cases required to achieve MCC is usually lower, due to the short-circuit expression evaluation deployed by compilers.

would be required to test a function that contains a dozen of such statements. Modified Condition/Decision Coverage (MC/DC) testing was proposed to ensure achievement of almost as much thorough testing as is achieved by MCC, but to keep the number of test cases linear in the number of basic conditions. Due to this reason, MC/DC has become very popular and is mandated by several safety-critical system standards such as the US Federal Aviation Administration (FAA) DO-178C safety-critical standard, and international standards such as IEC 61508, ISO 26262, EN50128.

The name (MC/DC) implies that it ensures decision coverage and modifies (that is relaxes) the MCC. The requirement for MC/DC is usually expressed as the following: *A test suite would achieve MC/DC if during execution of the test suite each condition in a decision expression independently affects the outcome of the decision*. That is, an atomic condition independently affects the outcome of the decision, if the decision outcome changes as a result of changing the truth value of the single atomic condition, while other conditions maintain their truth values. We can express the requirement for MC/DC as three basic requirements. We now state these requirements and for each give an illustrative example.

Requirement 1: Every decision expression in a program must take both true as well as false values.

Recollect that this requirement is the same decision coverage (DC). As an example, consider the following decision statement: `if (( a>10 ) && (( b<50 ) || ( c==0 )))`. In this decision statement, the decision contains three atomic conditions. The decision expression can be made to take true and false values for the following two sets of values: {(a = 5, b = 10, c = 1) (a = 5, b = 10, c = 0)}.

Requirement 2: Every condition in a decision must assume both true and false values.

Recollect that this requirement is the same as BCC. As an example, consider the following decision statement: `if (( a>10 ) && (( b<50 ) || ( c==0 )))`. For this decision expression {(a = 10, b = 10, c = 5)(a = 20, b = 60, c = 0)} will achieve BCC and meet the Requirement 2.

Requirement 3: Each condition in a decision should independently affect the decision's outcome.

Every conditions in the decision independently affect the decision's outcome. As an example, consider the following decision statement: `if (( a>10 ) && (( b<50 ) || ( c==0 )))`. Consider the test suite: {(a = 5, b = 30, c = 1)(a = 15, b = 30, c = 1)}, this achieves toggling of the outcome of the decision with the toggling of the truth value of the first condition, while b and c are maintained at constant values (b = 30, and c = 1). Now, consider the test values {(a = 15, b = 10, c = 1)(a = 15, b = 50, c = 1). This makes the second condition in the decision expression to independently influence the outcome of the decision while the 'a' and 'c' are maintained at the values a = 15 and c = 1. Finally, consider the set of two test cases, {(60,60,0)(60,60,1)}. It can be observed that these two test cases let the condition (c==0) to independently determine the decision outcome.

It is not hard to observe that a set of test cases that satisfies Requirement 3, also satisfies Requirements 2 and 1. We have now explained the requirement for achieving MC/DC. Now, the question arises as to given a decision expression, how do we determine the set of test cases that achieve MC/DC?

Determining the set of test cases to achieve MC/DC

The first step is to draw the truth table involving the basic conditions of the given decision expression. Next by inspection of the truth table, the MC/DC test suite can be determined such that each condition independently affects the outcome of the decision. Typically, we have extra columns in the truth table, which we fill during analysis of the truth table to keep track of which test cases make a condition to independently affect the outcome of the decision. We now illustrate this procedure through the following problems. Though it is harder to prove, for various examples, we can observe that at least $n + 1$ test cases are necessary to achieve MC/DC for decision expressions with n conditions.

Design MC/DC test suite for the following decision statement: `if ( A and B ) then`

Solution: We first draw the truth table (Table 10.1).

TABLE 10.1 Truth table for the decision expression (A and B)

Test case number	*A*	*B*	*Decision*	*Test case pair for A*	*Test case pair for B*
1	T	T	T	3	2
2	T	F	F		1
3	F	T	F	1	
4	F	F	F		

From the truth table in Table 10.1, we can observe that the test cases 1, 2 and 3 together achieve MC/DC for the given expression.

Design a test suite that would achieve MC/DC for the following decision statement: `if( (A && B) || C)`

Solution: We first draw the truth table (Table 10.2).

TABLE 10.2 Truth table for the decision expression ((A&&B)||C)

Test case	*ABC*	*Result*	*A*	*B*	*C*
1	TTT	T	5		
2	TTF	T	6	4	
3	TFT	T	7		4
4	TFF	F		2	3
5	FTT	F	1		
6	FTF	F	2		
7	FFT	F	3		
8	FFF	F			

From the table, we can observe that different sets of test cases achieve MC/DC. The sets are {2,3,4,6}, {2,3,4,7} and {1,2,3,4,5}.

Subsumption hierarchy

We have already pointed out that MCC subsumed the other condition-based test coverage metrics. In fact, it can be proved that we shall have the subsumption hierarchy shown in Figure 10.7 for the various coverage criteria discussed. We leave the proof to be worked out by the reader. Observe that MCC is the strongest, and statement and condition coverage are the weakest. However, statement and condition coverage are not strictly comparable and are complementary.

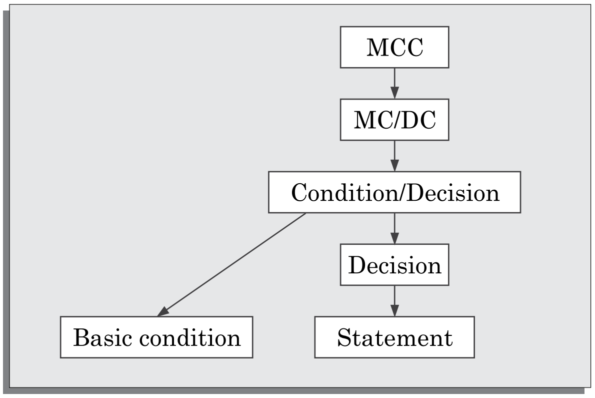


FIGURE 10.7 Subsumption hierarchy of various coverage criteria.

10.7.8 Path Coverage

A test suite achieves path coverage if it exeutes each *linearly independent paths* (or *basis paths*) at least once. A linearly independent path can be defined in terms of the *control flow graph* (CFG) of a program. Therefore, to understand path coverage-based testing strategy, we need to first understand how the CFG of a program can be drawn.

Control flow graph (CFG)

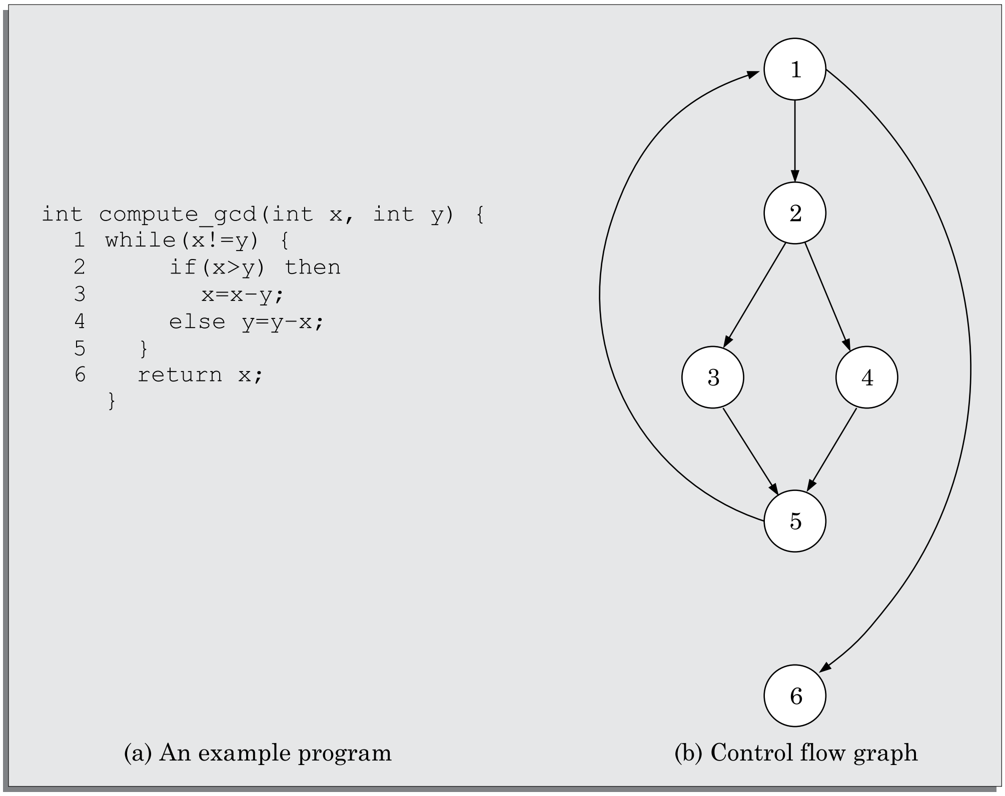
A control flow graph describes how the control flows through the program.

> A control flow graph describes the sequence in which the different instructions of a program get executed.

In order to draw the control flow graph of a program, we need to first number all the statements of a program. The different numbered statements serve as nodes of the control flow graph (see Figure 10.5). There exists an edge from one node to another, if the execution of the statement representing the first node can result in the transfer of control to the other node.

More formally, we can define a CFG as follows. A CFG is a directed graph consisting of a set of nodes and edges (N, E), such that each node $n \in N$ corresponds to a unique program statement and an edge exists between two nodes if control can transfer from one node to the other.

We can easily draw the CFG for any program, if we know how to represent the sequence, selection, and iteration types of statements in the CFG. After all, every program is constructed by using these three types of constructs only. Figure 10.5 summarises how the CFG for these three types of constructs can be drawn. The CFG representation of the sequence and decision types of statements is straight forward. Please note carefully how the CFG for the loop (iteration) construct can be drawn. For iteration type of constructs such as the while construct, the loop condition is tested only at the beginning of the loop and therefore always control flows from the last statement of the loop to the top of the loop. That is, the loop construct terminates from the first statement (after the loop is found to be false) and does not at any time exit the loop at the last statement of the loop. Using these basic ideas, the CFG of the program given in Figure 10.8(a) can be drawn as shown in Figure 10.8(b).



```
int compute_gcd(int x, int y) {
  1 while(x!=y) {
  2     if(x>y) then
  3        x=x-y;
  4     else y=y-x;
  5   }
  6   return x;
    }
```

(a) An example program

(b) Control flow graph

FIGURE 10.8 Control flow diagram of an example program.

Path

A *path* through a program is any node and edge sequence from the *start node* to a *terminal node* of the control flow graph of a program. Please note that a program can have more than one terminal nodes when it contains multiple `exit` or `return` type of statements. Writing test cases to cover all paths of a typical program is impractical since there can be an infinite number of paths through a program in presence of loops. For example, in Figure 10.5(c), there can be an infinite number of paths such as 12314, 12312314, 12312312314, etc. If coverage of all paths is attempted, then the number of test cases required would become infinitely large. Therefore, we can say that *all path* testing is impractical. For this reason, path coverage testing does not try to cover all paths, but only a subset of paths called *linearly independent paths* (or *basis paths*). Let us now discuss what are linearly independent paths and how to determine these in a program.

Linearly independent set of paths (or basis path set)

A set of paths for a given program is called *linearly independent set of paths* (or the *set of basis paths* or simply the basis set), if each path in the set introduces at least one new edge that is not included in any other path in the set. Please note that even if we find that a path has one new node compared to all other linearly independent paths, then this path should also be included in the set of linearly independent paths. This is because, any path having a new node would automatically have a new edge.

If a set of paths is linearly independent of each other, then no path in the set can be obtained through any linear operations (i.e., additions or subtractions) on the other paths in the set.

According to the above definition of a linearly independent set of paths, for any path in the set, its subpath cannot be a member of the set. In fact, any arbitrary path of a program, can be synthesized by carrying out linear operations on the basis paths. Possibly, the name basis set comes from the observation that the paths in the basis set form the "basis" for all the paths of a program. Please note that there may not always exist a unique basis set for a program and several basis sets for the same program can usually be determined.

Even though it is straight forward to identify the linearly independent paths for simple programs, for more complex programs it is not easy to determine the number of independent paths. In this context, McCabe's cyclomatic complexity metric is an important result that lets us compute the number of linearly independent paths for any arbitrary program. McCabe's cyclomatic complexity defines an upper bound for the number of linearly independent paths through a program. Also, the McCabe's cyclomatic complexity is very simple to compute. Though the McCabe's metric does not directly identify the linearly independent paths, but it provides us with a practical way of determining approximately how many paths to look for.

10.7.9 McCabe's Cyclomatic Complexity Metric

McCabe [1976] obtained his results by applying graph-theoretic techniques to the control flow graph of a program. McCabe's cyclomatic complexity metric defines an upper bound on the number of independent paths in a program. We discuss three different ways to compute the cyclomatic complexity. For structured programs, the results computed by all the three methods are guaranteed to agree.

Method 1: Given a control flow graph G of a program, the cyclomatic complexity $V(G)$ can be computed as:

$$V(G) = E - N + 2$$

where, N is the number of nodes of the control flow graph and E is the number of edges in the control flow graph.

For the CFG of the example program shown in Figure 10.8, $E = 7$ and $N = 6$. Therefore, the value of the Cyclomatic complexity $= 7 - 6 + 2 = 3$.

Method 2: An alternate way of computing the cyclomatic complexity of a program is based on a visual inspection of the control flow graph is as follows—In this method, the cyclomatic complexity $V(G)$ for a graph G is given by the following expression:

```
V(G) = Total number of non-overlapping bounded areas + 1
```

In the program's control flow graph G, any region enclosed by nodes and edges can be called as a *bounded area*. This is an easy way to determine the McCabe's cyclomatic complexity. But, what if the graph G is not planar (i.e., however you draw the graph, two or more edges intersect). Actually, it can be shown that control flow representation of structured programs always yields planar graphs. But, presence of GOTO's can easily add intersecting edges and make the CFG non-planar. Therefore, for non-structured programs, this way of computing the McCabe's cyclomatic complexity does not apply.

The number of bounded areas in a CFG increases with the number of decision statements and loops. Therefore, the McCabe's metric provides a quantitative measure of the testing difficulty of a program and its ultimate reliability after testing. Consider the CFG example shown in Figure 10.8. From a visual examination of the CFG the number of bounded areas is 2. Therefore, the cyclomatic complexity, computed with this method is also 2+1=3. This method provides a very easy way of computing the cyclomatic complexity of CFGs, just from a visual examination of the CFG. On the other hand, the method for computing CFGs can easily be automated. That is, the McCabe's metric computations methods 1 and 3 can be easily coded into a tool that can be used to automatically determine the cyclomatic complexities of arbitrary programs.

Method 3: The cyclomatic complexity of a program can also be easily computed by computing the number of decision and loop statements of the program. If N is the number of decision and loop statements of a program, then the McCabe's metric is equal to $N + 1$.

How is path testing carried out by using computed McCabe's cyclomatic metric value?

Knowing the number of basis paths in a program does not make it any easier to design test cases for path coverage, only it gives an indication of the minimum number of test cases required for path coverage. For the CFG of a moderately complex program segment of say 20 nodes and 25 edges, you may need several days of effort to identify all the linearly independent paths in it and to design the test cases. It is therefore impractical to require the test designers to identify all the linearly independent paths in a code, and then design the test cases to force execution along each of the identified paths. In practice, for path testing, usually the tester keeps on forming test cases with random data and executes those until the required coverage is achieved. A testing tool such as a dynamic program analyser (see Section 10.8.2) is used to determine the percentage of linearly independent paths covered by the test cases that have been executed so far. If the percentage of linearly independent paths covered is below 90 per cent, more test cases (with random inputs) are added to increase the path coverage. Normally, it is not practical to target achievement of 100 per cent path coverage. The first reason is the presence of infeasible paths. Though the percentage of infeasible programs varies across programs, it is often in the range of 1–10%. An example of an infeasible path is the following:

```
 if(x==1) {…}
if (x==2) {…}
```

In the above code segment, it is not possible to have both the conditional expressions as true. Also, McCabe's metric is only an upper bound and does not give the exact number of paths.

Steps to carry out path coverage-based testing

The following is the sequence of steps that need to be undertaken for deriving the path coverage-based test cases for a program:

1. Draw control flow graph for the program.
2. Determine the McCabe's metric $V(G)$.
3. Determine the cyclomatic complexity. This gives the minimum number of test cases required to achieve path coverage.
4. *repeat*

   Test using a randomly designed set of test cases.
   Perform dynamic analysis to check the path coverage achieved.
   until at least 90 per cent path coverage is achieved.

Uses of McCabe's cyclomatic complexity metric

Beside its use in path testing, cyclomatic complexity of programs has many other interesting applications such as the following:

Estimation of structural complexity of code: McCabe's cyclomatic complexity is a measure of the *structural complexity* of a program. The reason for this is that it is computed based on the code structure (number of decision and iteration constructs used). Intuitively, the McCabe's complexity metric correlates with the difficulty level of understanding a program, since one understands a program by understanding the computations carried out along all independent paths of the program.

In view of the above result, from the maintenance perspective, it makes good sense to limit the cyclomatic complexity of all functions to some reasonable value. Good software development organisations usually restrict the cyclomatic complexity of different functions to a maximum value of ten or so. This is in contrast to the computational complexity that is based on the execution of the program statements.

Cyclomatic complexity of a program is a measure of the psychological complexity or the level of difficulty in understanding the program.

Estimation of testing effort: Cyclomatic complexity is a measure of the maximum number of basis paths. Thus, it indicates the minimum number of test cases required to achieve path coverage. Therefore, the testing effort and the time required to test a piece of code satisfactorily is proportional to the cyclomatic complexity of the code. To reduce testing effort, it is considered necessary to restrict the cyclomatic complexity of every function to seven or so.

Estimation of program reliability: Experimental studies indicate there exists a clear relationship between the McCabe's metric and the number of errors latent in the code after testing. This relationship exists possibly due to the correlation of cyclomatic complexity with the structural complexity of code. Usually the larger is the structural complexity, the more difficult it is to test and debug the code.

10.7.10 Data Flow-based Testing

Data flow based testing method selects test paths of a program according to the definitions and uses of different variables in a program.

Consider a program P . For a statement numbered S of P, let

DEF(S) = {X/statement S contains a definition of X} and

USES(S)= {X/statement S contains a use of X}

For the statement `S: a=b+c;`, DEF(S)={a}, USES(S)={b, c}. The definition of variable X at statement S is said to be live at statement S_1, if there exists a path from statement S to statement S_1 which does not contain any definition of X. Based on these notions, it is possible to define several test coverage criteria.

All definitions criterion is a test coverage criterion that requires that test suite should cover at least one use of all definition occurrences. All use criterion requires that all uses of a definition should be covered. Clearly, all-uses criterion is stronger than all-definitions criterion. An even stronger criterion is all definition-use-paths criterion, which requires the coverage of all possible definition-use paths that either are cycle-free or have only simple cycles. A simple cycle is a path in which only the end node and the start node are the same.

A stronger coverage is the DU chain coverage. A DU chain is a sequence of DU pairs. A *definition-use pair* (or DU pair) of a variable X is of the form [X,S,S_1], where S and S_1 are statement numbers, such that X DEF(S) and X USES(S_1), and the definition of X in the statement S is live at statement S_1. One simple data flow testing strategy is to require that every DU chain be covered at least once.

10.7.11 Mutation Testing

All white-box testing strategies that we have discussed so far, are coverage-based testing techniques. In contrast, mutation testing is a fault-based testing technique in the sense that mutation test cases are designed to help detect specific types of faults in a program. In mutation testing, a program is first tested by using an initial test suite designed by using various white box testing strategies that we have discussed. After the initial testing is complete, mutation testing can be taken up.

The idea behind mutation testing is to make a few arbitrary changes to a program at a time. These changes correspond to simple programming errors such as using an inappropriate operator in an arithmetic expression. Each time the program is changed, it is called a *mutated program* and the specific change effected is called a *mutant*. An underlying assumption behind mutation testing is that all programming errors can be expressed as a combination of several simple errors.

Mutation testing is started by first defining a set of mutation operators. A mutation operator defines a specific type of change to a program. For example, one mutation operator may be defined to randomly delete a program statement. A few other examples of mutation operators are changing an addition operator in an arithmetic operation by a subtraction operator or changing a logical and by a logical or in a conditional expression. A mutant may or may not cause an error in the program. As an example of a mutant that does not cause an error, consider an arithmetic expression involving addition with a variable having value zero and the mutation operator is to flip the addition operator to a subtraction operator. If a mutant does not introduce any error in the program, then the original program and the mutated program are called *equivalent programs.*

It is clear that a large number of mutants can be generated for a program. Each time a mutated program is created by application of a mutation operator, it is tested by using the original test suite of the program. If at least one test case in the test suite yields an incorrect result, then the mutant is said to be dead, since the error introduced by the mutation operator has successfully been detected by the test suite. If a mutant remains alive even after all the test cases have been exhausted, it indicates inadequacy of the test suite and the test suite is enhanced to kill the mutant. However, it is not this straightforward. Remember that there is a possibility of a mutated program to be an *equivalent program*. When this is the case, it is futile to try to design a test case that would identify the error. An equivalent mutant has to be recognized, and needs to be ignored rather than trying to add a test case that can kill the equivalent mutant.

An important advantage of mutation testing is that it can be automated to a great extent. The process of generation of mutants can be automated by predefining a set of primitive changes that can be applied to the program. These primitive changes can be simple program alterations such as—deleting a statement, deleting a variable definition, changing the type of an arithmetic operator (e.g., `+` to `-`), changing a logical operator (`and` to `or`) changing the value of a constant, changing the data type of a variable, etc. A major pitfall of the mutation-based testing approach is that it is computationally very expensive, since a large number of possible mutants can be generated.

Mutation testing involves generating a large number of mutants. Also each mutant needs to be tested with the full test suite. Obviously therefore, mutation testing is not suitable for manual testing. Mutation testing is most suitable to be used in conjunction of some testing tool that should automatically generate the mutants and run the test suite automatically on each mutant. At present, several test tools are available that automatically generate mutants for a given program.

10.8 DEBUGGING

After a failure has been detected, it is necessary to first identify the program statement(*s*) that are in error and are responsible for the failure, the error can then be fixed. In this section, we shall summarise the important approaches that are available to identify the error locations. Each of these approaches has its own advantages and disadvantages and therefore each will be useful in appropriate circumstances. We also provide some guidelines for effective debugging.

10.8.1 Debugging Approaches

The following are some of the approaches that are popularly adopted by the programmers for debugging:

Brute force method

This is the most common method of debugging but is the least efficient method. In this approach, print statements are inserted throughout the program to print the intermediate values with the hope that some of the printed values will help to identify the statement in error. This approach becomes more systematic with the use of a symbolic debugger (also called a *source code debugger*), because values of different variables can be easily checked and break points and watch points can be easily set to test the values of variables effortlessly. Single stepping using a symbolic debugger is another form of this approach, where the developer mentally computes the expected result after every source instruction and checks whether the same is actually computed by a statement by single stepping through the program.

Backtracking

This is also a fairly common approach. In this approach, starting from the statement at which an error symptom has been observed, the source code is traced backwards until the error is discovered. Unfortunately, in the presence of decision statements and loops, this approach becomes cumbersome as the number of source lines to be traced back increases, the number of potential backward paths increases and may become unmanageably large for complex programs, limiting the use of this approach.

Cause elimination method

In this approach, once a failure is observed, the symptoms of the failure (i.e., certain variable is having a negative value though it should be positive, etc.) are noted. Based on the failure symptoms, the causes which could possibly have contributed to the symptom is identified and tests are conducted to eliminate each. A related technique of identification of the error from the error symptom is the *software fault tree analysis*.

Program slicing

This technique is similar to back tracking. In the backtracking approach, one often has to examine a large number of statements. However, the search space is reduced by defining slices. A slice of a program for a particular variable and at a particular statement is the set of source lines preceding this statement that can influence the value of that variable [Mund, Mall and Sarkar, 2002]. Program slicing makes use of the fact that an error in the value of a variable can be caused by the statements on which it is data dependent.

10.8.2 Debugging Guidelines

Debugging is often carried out by programmers based on their ingenuity and experience. The following are some general guidelines for effective debugging:

- Many times debugging requires a thorough understanding of the program design. Trying to debug based on a partial understanding of the program design may require an inordinate amount of effort to be put into debugging even for simple problems.
- Debugging may sometimes even require full redesign of the system. In such cases, a common mistakes that novice programmers often make is attempting not to fix the error but its symptoms.
- One must be beware of the possibility that an error correction may introduce new errors. Therefore after every round of error-fixing, regression testing (see Section 10.13) must be carried out.

10.9 PROGRAM ANALYSIS TOOLS

A program analysis tool usually is an automated tool that takes either the source code or the executable code of a program as input and produces reports regarding several important characteristics of the program, such as its size, complexity, adequacy of commenting, adherence to programming standards, adequacy of testing, etc. We can classify various program analysis tools into the following two broad categories:

- Static analysis tools
- Dynamic analysis tools

These two categories of program analysis tools are discussed in the following subsection.

10.9.1 Static Analysis Tools

Static program analysis tools assess and compute various characteristics of a program without executing it. Typically, static analysis tools analyse the source code to compute certain metrics characterising the source code (such as size, cyclomatic complexity, etc.) and also report certain analytical conclusions. These also check the conformance of the code with the prescribed coding standards. In this context, it displays the following analysis results:

- To what extent the coding standards have been adhered to?
- Whether certain programming errors such as uninitialised variables, mismatch between actual and formal parameters, variables that are declared but never used, etc., exist? A list of all such errors is displayed.

Code review techniques such as code walkthrough and code inspection discussed in Sections 10.2.1 and 10.2.2 can be considered as static analysis methods since those target to detect errors based on analysing the source code. However, strictly speaking, this is not true since we are using the term *static program analysis* to denote *automated* analysis tools. On the other hand, a compiler can be considered to be a type of a static program analysis tool.

A major practical limitation of the static analysis tools lies in their inability to analyse run-time information such as dynamic memory references using pointer variables and pointer arithmetic, etc. In a high level programming languages, pointer variables and dynamic memory allocation provide the capability for dynamic memory references. However, dynamic memory referencing is a major source of programming errors in a program.

Static analysis tools often summarise the results of analysis of every function in a polar chart known as *Kiviat Chart*. A Kiviat Chart typically shows the analysed values for cyclomatic complexity, number of source lines, percentage of comment lines, Halstead's metrics, etc.

10.9.2 Dynamic Analysis Tools

Dynamic program analysis tools can be used to evaluate several program characteristics based on an analysis of the run time behaviour of a program. These tools usually record and analyse the actual behaviour of a program while it is being executed. A dynamic program analysis tool (also called a *dynamic analyser*) usually collects execution trace information by instrumenting the code. Code instrumentation is usually achieved by inserting additional statements to print the values of certain variables into a file to collect the execution trace of the program. The instrumented code when executed, records the behaviour of the software for different test cases.

After a software has been tested with its full test suite and its behaviour recorded, the dynamic analysis tool carries out a post execution analysis and produces reports which describe the coverage that has been achieved by the complete test suite for the program. For example, the dynamic analysis tool can report the statement, branch, and path coverage achieved by a test suite. If the coverage achieved is not satisfactory more test cases can be designed, added to the test suite, and run. Further, dynamic analysis results can help eliminate redundant test cases from a test suite.

An important characteristic of a test suite that is computed by a dynamic analysis tool is the extent of coverage achieved by the test suite.

Normally the dynamic analysis results are reported in the form of a histogram or pie chart to describe the structural coverage achieved for different modules of the program. The output of a dynamic analysis tool can be stored and printed easily to provide evidence that thorough testing has been carried out.

10.10 INTEGRATION TESTING

Integration testing is carried out after all (or at least some of) the modules have been unit tested. Successful completion of unit testing, to a large extent, ensures that the unit (or module) as a whole works satisfactorily. In this context, the objective of integration testing is to detect the errors at the module interfaces (call parameters). For example, it is checked that no parameter mismatch occurs when one module invokes the functionality of another module. Thus, the primary objective of integration testing is to test the module interfaces, i.e., there are no errors in parameter passing, when one module invokes the functionality of another module.

The objective of integration testing is to check whether the different modules of a program interface with each other properly.

During integration testing, different modules of a system are integrated in a planned manner using an *integration plan*. The integration plan specifies the steps and the order in which modules are combined to realise the full system. After each integration step, the partially integrated system is tested.

An important factor that guides the integration plan is the module dependency graph. We have already discussed in Chapter 6 that a structure chart (or module dependency graph) specifies the order in which different modules call each other. Thus, by examining the structure chart, the integration plan can be developed. Any one (or a mixture) of the following approaches can be used to develop the test plan:

- Big-bang approach to integration testing
- Top-down approach to integration testing
- Bottom-up approach to integration testing
- Mixed (also called *sandwiched*) approach to integration testing

In the following subsections, we provide an overview of these approaches to integration testing.

Big-bang approach to integration testing

Big-bang testing is the most obvious approach to integration testing. In this approach, all the modules making up a system are integrated in a single step. In simple words, all the unit tested modules of the system are simply linked together and tested. However, this technique can meaningfully be used only for very small systems. The main problem with this approach is that once a failure has been detected during integration testing, it is very difficult to localise the error as the error may potentially exist in any of the modules. Therefore, debugging errors reported during big-bang integration testing are very expensive to fix. As a result, big-bang integration testing is almost never used for large programs.

Bottom-up approach to integration testing

Large software products are often made up of several subsystems. A subsystem might consist of many modules which communicate among each other through well-defined interfaces. In bottom-up integration testing, first the modules for the each subsystem are integrated. Thus, the subsystems can be integrated separately and independently.

The primary purpose of carrying out the integration testing a subsystem is to test whether the interfaces among various modules making up the subsystem work satisfactorily. The test cases must be carefully chosen to exercise the interfaces in all possible manners.

In a pure bottom-up testing no stubs are required, and only test-drivers are required. Large software systems normally require several levels of subsystem testing, lower-level subsystems are successively combined to form higher-level subsystems. The principal advantage of bottom-up integration testing is that several disjoint subsystems can be tested simultaneously. Another advantage of bottom-up testing is that the low-level modules get tested thoroughly, since they are exercised in each integration step. Since the low-level modules do I/O and other critical functions, testing the low-level modules thoroughly increases the reliability of the system. A disadvantage of bottom-up testing is the complexity that occurs when the system is made up of a large number of small subsystems that are at the same level. This extreme case corresponds to the big-bang approach.

Top-down approach to integration testing

Top-down integration testing starts with the root module in the structure chart and one or two subordinate modules of the root module. After the top-level 'skeleton' has been tested, the modules that are at the immediately lower layer of the 'skeleton' are combined with it and tested. Top-down integration testing approach requires the use of program stubs to simulate the effect of lower-level routines that are called by the routines under test. A pure top-down integration does not require any driver routines. An advantage of top-down integration testing is that it requires writing only stubs, and stubs are simpler to write compared to drivers. A disadvantage of the top-down integration testing approach is that in the absence of lower-level routines, it becomes difficult to exercise the top-level routines in the desired manner since the lower level routines usually perform input/output (I/O) operations.

Mixed approach to integration testing

The mixed (also called *sandwiched*) integration testing follows a combination of top-down and bottom-up testing approaches. In top-down approach, testing can start only after the top-level modules have been coded and unit tested. Similarly, bottom-up testing can start only after the bottom level modules are ready. The mixed approach overcomes this shortcoming of the top-down and bottom-up approaches. In the mixed testing approach, testing can start as and when modules become available after unit testing. Therefore, this is one of the most commonly used integration testing approaches. In this approach, both stubs and drivers are required to be designed.

10.10.1 Phased *versus* Incremental Integration Testing

Big-bang integration testing usually implies single step integration. In contrast, in the other strategies, integration is carried out over a number of steps. In multi-step integration strategies, modules are integrated either in a phased or incremental manner. A comparison of these two strategies is as follows:

- In incremental integration testing, only one new module is added to the partially integrated system in each step of integration.
- In phased integration, a group of related modules are added to the partial system in each step of integration.

Obviously, phased integration requires less number of integration steps compared to the incremental integration approach. However, when failures are detected, it is easier to debug the system while using the incremental testing approach since the errors can easily be traced to the interface of the recently integrated module. Please observe that a degenerate case of the phased integration testing approach is big-bang testing.

10.11 TESTING OBJECT-ORIENTED PROGRAMS

During the initial years of object-oriented programming, it was believed that object-orientation would, to a great extent, reduce the cost and effort incurred on testing. This thinking was based on the observation that object-orientation incorporates several good programming features such as encapsulation, abstraction, reuse through inheritance, polymorphism, etc., thereby chances of errors in the code is minimised. However, it was soon realised that satisfactory testing object-oriented programs is much more difficult and requires much more cost and effort as compared to testing similar procedural programs. The main reason behind this situation is that various object-oriented features introduce additional complications and scope of new types of bugs that are present in procedural programs. Therefore additional test cases are needed to be designed to detect these. We examine these issues as well as some other basic issues in testing object-oriented programs in the following subsections.

10.11.1 What is a Suitable Unit for Testing Object-oriented Programs?

For procedural programs, we had seen that procedures are the *basic units of testing*. That is, first all the procedures are unit tested. Then various tested procedures are integrated together and tested. Thus, as far as procedural programs are concerned, procedures are the basic units of testing. Since methods in an object-oriented program are analogous to procedures in a procedural program, can we then consider the methods of object-oriented programs as the basic unit of testing? Weyuker studied this issue and postulated his *anticomposition* axiom as follows:

The main intuitive justification for the anticomposition axiom is the following. A method operates in the scope of the data and other methods of its object. That is, all the methods share the data of the class. Therefore, it is necessary to test a method in the context of these. Moreover, objects can have significant number of states. The behaviour of a method can be different based on the state of the corresponding object. Therefore, it is not enough to test all the methods and check whether they can be integrated satisfactorily. A method has to be tested with all the other methods and data of the corresponding object. Moreover, a method needs to be tested at all the states that the object can assume. As a result, it is improper to consider a method as the basic unit of testing an object-oriented program.

Adequate testing of individual methods does not ensure that a class has been satisfactorily tested.

Thus, in an object oriented program, unit testing would mean testing each object in isolation. During integration testing (called *cluster testing* in the object-oriented testing literature) various unit tested objects are integrated and tested. Finally, system-level testing is carried out.

An object is the basic unit of testing of object-oriented programs.

10.11.2 Do Various Object-orientation Features Make Testing Easy?

In this section, we discuss the implications of different object-orientation features in testing.

Encapsulation: We had discussed in Chapter 7 that the encapsulation feature helps in data abstraction, error isolation, and error prevention. However, as far as testing is concerned, encapsulation is not an obstacle to testing, but leads to difficulty during debugging. Encapsulation prevents the tester from accessing the data internal to an object. Of course, it is possible that one can require classes to support state reporting methods to print out all the data internal to an object. Thus, the encapsulation feature though makes testing difficult, the difficulty can be overcome to some extent through use of appropriate state reporting methods.

Inheritance: The inheritance feature helps in code reuse and was expected to simplify testing. It was expected that if a class is tested thoroughly, then the classes that are derived from this class would need only incremental testing of the added features. However, this is not the case.

The reason for this is that the inherited methods would work in a new context (new data and method definitions). As a result, correct behaviour of a method at an upper level, does not guarantee correct behaviour at a lower level. Therefore, retesting of inherited methods needs to be followed as a rule, rather as an exception.

Even if the base class has been thoroughly tested, the methods inherited from the base class need to be tested again in the derived class.

Dynamic binding: Dynamic binding was introduced to make the code compact, elegant, and easily extensible. However, as far as testing is concerned all possible bindings of a method call have to be identified and tested. This is not easy since the bindings take place at run-time.

Object states: In contrast to the procedures in a procedural program, objects store data permanently. As a result, objects do have significant states. The behaviour of an object is usually different in different states. That is, some methods may not be active in some of its states. Also, a method may act differently in different states. For example, when a book has been issued out in a library information system, the book reaches the `issuedOut` state. In this state, if the issue method is invoked, then it may not exhibit its normal behaviour.

In view of the discussions above, testing an object in only one of its states is not enough. The object has to be tested at all its possible states. Also, whether all the transitions between states (as specified in the object model) function properly or not should be tested. Additionally, it needs to be tested that no extra (sneak) transitions exist, neither are there extra states present other than those defined in the state model. For state-based testing, it is therefore beneficial to have the state model of the objects, so that the conformance of the object to its state model can be tested.

10.11.3 Why are Traditional Techniques Considered Not Satisfactory for Testing Object-oriented Programs?

We have already seen that in traditional procedural programs, procedures are the basic unit of testing. In contrast, objects are the basic unit of testing for object-oriented programs. Besides this, there are many other significant differences as well between testing procedural and object-oriented programs. For example, statement coverage-based testing which is popular for testing procedural programs is not satisfactory for object-oriented programs. The reason is that inherited methods have to be retested in the derived class.

Various object-oriented features (inheritance, polymorphism, dynamic binding, state-based behaviour, etc.) require special test cases to be designed compared to the traditional testing as discussed in Section 10.11.4. The various object-orientation features are explicit in the design models, and it is usually difficult to extract from and analysis of the source code. As a result, the design model is a valuable artifact for designing test cases for object-oriented programs. Therefore, this approach is considered to be intermediate between a fully white-box and a fully black-box approach, and is called a *grey-box* approach. Please note that grey-box testing is considered important for object-oriented programs. This is in contrast to testing procedural programs.

10.11.4 Grey-Box Testing of Object-oriented Programs

As we have already mentioned, model-based testing is important for object-oriented programs, as these test cases help detect bugs that are specific to the object-orientation constructs.

For object-oriented programs, several types of test cases can be designed based on the design models of object-oriented programs. These are called the grey-box test cases.

The following are some important types of grey-box testing that can be carried on based on UML models:

State model-based testing

State coverage: Each method of an object are tested at each state of the object.

State transition coverage: It is tested whether all transitions depicted in the state model work satisfactorily.

State transition path coverage: All transition paths in the state model are tested.

Use case-based testing

Scenario coverage: Each use case typically consists of a mainline scenario and several alternate scenarios. For each use case, the mainline and all alternate sequences are tested to check if any errors show up.

Class diagram-based testing

Testing derived classes: All derived classes of a base class have to be instantiated and tested. In addition to testing the new methods defined in the derived class, the inherited methods must be retested.

Association testing: All association relations are tested.

Aggregation testing: Various aggregate objects are created and tested.

Sequence diagram-based testing

Method coverage: All methods depicted in the sequence diagrams are covered.

Message path coverage: All message paths that can be constructed from the sequence diagrams are covered. Each sequence diagram represents the message passing among objects that occurs for each use case. Each use case consists of a set of scenarios, and a message path represents the message exchanges that occur among concerned objects during execution of a scenario

10.11.5 Integration Testing of Object-oriented Programs

In a procedural program, the module structure is typically represented using a structure chart, which is a rooted tree. Therefore, top-down, bottom-up, and mixed integration strategies are applicable and have been discussed in Section 10.10. However, in case of object-oriented programs, the class structure is an arbitrary graph and is not restricted to a tree structure. Therefore, the integration testing strategies for procedural programs are difficult to apply for object-oriented programs. Two approaches to integration testing of object-oriented programs have become popular:

- Thread-based
- Use based

Thread-based approach: In this approach, all classes that need to collaborate to realise the behaviour of a single use case are integrated and tested. After all the required classes for a use case are integrated and tested, another use case is taken up and other classes (if any) necessary for execution of the second use case to run are integrated and tested. This is continued till all use cases have been considered.

Use-based approach: Use-based integration begins by testing classes that either do not need any service from other classes or need services from at most a few other classes. After these classes have been integrated and tested, classes that use the services from the already integrated classes are integrated and tested. This is continued till all the classes have been integrated and tested.

10.12 SYSTEM TESTING

After all the units of a program have been integrated together and tested, system testing is taken up.

System tests are designed to validate a fully developed system to assure that it meets its requirements. The test cases are therefore designed solely based on the SRS document.

The system testing procedures are the same for both object-oriented and procedural programs, since system test cases are designed solely based on the SRS document and the actual implementation (procedural or object-oriented) is immaterial.

There are three main kinds of system testing. These are essentially similar tests, but differ in who carries out the testing:

1. **Alpha Testing:** Alpha testing refers to the system testing carried out by the test team within the developing organisation.
2. **Beta Testing:** Beta testing is the system testing performed by a select group of friendly customers.
3. **Acceptance Testing:** Acceptance testing is the system testing performed by the customer to determine whether to accept the delivery of the system.

The system test cases can be classified into functionality and performance test cases.

As can be observed from the above discussions, in the different types of system tests, the test cases can be the same, but the difference is with respect to who designs test cases and carries out testing.

Before a fully integrated system is accepted for system testing, *smoke testing* is performed. Smoke testing is done to check whether at least the main functionalities of the software are working properly. Unless the software is stable and at least the main functionalities are working satisfactorily, system testing is not undertaken.

The functionality tests are designed to check whether the software satisfies the functional requirements as documented in the SRS document. The performance tests, on the other hand, test the conformance of the system with the non-functional requirements of the system. We have already discussed how to design the functionality test cases by using a black-box approach (in Section 10.5 in the context of unit testing). So, in the following subsection we discuss only smoke and performance testing.

10.12.1 Smoke Testing

Smoke testing is carried out before initiating system testing to ensure that system testing would be meaningful, or whether many parts of the software would fail. The idea behind smoke testing is that if the integrated program cannot pass even the basic tests, it is not ready for a vigorous testing. For smoke testing, a few test cases are designed to check whether the basic functionalities are working. For example, for a library automation system, the smoke tests may check whether books can be created and deleted, whether member records can be created and deleted, and whether books can be loaned and returned.

10.12.2 Performance Testing

Performance testing is carried out to check whether the system meets its non-functional requirements identified in the SRS document.

Performance testing is an important type of system testing.

There are several types of performance testing corresponding to various types of non-functional requirements. For a specific system, the types of performance testing to be carried out on a system depends on the different non-functional requirements of the system documented in its SRS document. All performance tests can be considered as black-box tests.

Stress testing

Stress testing is also known as *endurance testing*. Stress testing evaluates system performance when it is stressed for short periods of time. Stress tests are black-box tests which are designed to impose a range of abnormal and even illegal input conditions so as to stress the capabilities of the software. Input data volume, input data rate, processing time, utilisation of memory, etc., are tested beyond the designed capacity. For example, suppose an operating system is supposed to support fifteen concurrent transactions, then the system is stressed by attempting to initiate fifteen or more transactions simultaneously. A real-time system might be tested to determine the effect of simultaneous arrival of several high-priority interrupts.

Stress testing is especially important for systems that under normal circumstances operate below their maximum capacity but may be severely stressed at some peak demand hours. For example, if the corresponding non-functional requirement states that the response time should not be more than twenty secs per transaction when sixty concurrent users are working, then during stress testing the response time is checked with exactly sixty users working simultaneously.

Volume testing

Volume testing checks whether the data structures (buffers, arrays, queues, stacks, etc.) have been designed to successfully handle extraordinary situations. For example, the volume testing for a compiler might be to check whether the symbol table overflows when a very large program is compiled.

Configuration testing

Configuration testing is used to test system behaviour in various hardware and software configurations specified in the requirements. Sometimes systems are built to work in different configurations for different users. For instance, a minimal system might be required to serve a single user, and other extended configurations may be required to serve additional users. During configuration testing, the system is configured in each of the required configurations and it is checked if the system behaves correctly in all required configurations.

Compatibility testing

This type of testing is required when the system interfaces with external systems (e.g., databases, servers, etc.). Compatibility aims to check whether the interfaces with the external systems are performing as required. For instance, if the system needs to communicate with a large database system to retrieve information, compatibility testing is required to test the speed and accuracy of data retrieval.

Regression testing

This type of testing is required when a software is maintained to fix some bugs or enhance functionality, performance, etc. Regression testing is discussed in some detail in Section 10.13.

Recovery testing

Recovery testing tests the response of the system to the presence of faults, or loss of power, devices, services, data, etc. The system is subjected to the loss of the mentioned resources (as discussed in the SRS document) and it is checked if the system recovers satisfactorily. For example, the printer can be disconnected to check if the system hangs. Or, the power may be shut down to check the extent of data loss and corruption.

Maintenance testing

This addresses testing the diagnostic programs, and other procedures that are required to help maintenance of the system. It is verified that the artifacts exist and they perform properly.

Documentation testing

It is checked whether the required user manual, maintenance manuals, and technical manuals exist and are consistent. If the requirements specify the types of audience for which a specific manual should be designed, then the manual is checked for compliance of this requirement.

Usability testing

Usability testing concerns checking the user interface to see if it meets all user requirements concerning the user interface. During usability testing, the display screens, messages, report formats, and other aspects relating to the user interface requirements are tested. A GUI being just being functionally correct is not enough. Therefore, the GUI has to be checked against the checklist we discussed in Section 9.5.6.

Security testing

Security testing is essential for software that handle or process confidential data that is to be guarded against pilfering. It needs to be tested whether the system is fool-proof from security attacks such as intrusion by hackers. Over the last few years, a large number of security testing techniques have been proposed, and these include password cracking, penetration testing, and attacks on specific ports, etc.

10.12.3 Error Seeding

Sometimes customers specify the maximum number of residual errors that can be present in the delivered software. These requirements are often expressed in terms of maximum number of allowable errors per line of source code. The error seeding technique can be used to estimate the number of residual errors in a software.

Error seeding, as the name implies, it involves seeding the code with some known errors. In other words, some artificial errors are introduced (seeded) into the program. The number of these seeded errors that are detected in the course of standard testing is determined. These values in conjunction with the number of unseeded errors detected during testing can be used to predict the following aspects of a program:

- The number of errors remaining in the product.
- The effectiveness of the testing strategy.

Let N be the total number of defects in the system, and let n of these defects be found by testing.

Let S be the total number of seeded defects, and let s of these defects be found during testing. Therefore, we get:

$$\frac{n}{N} = \frac{s}{S}$$

or

$$N = S \times \frac{n}{s}$$

Defects still remaining in the program after testing can be given by:

$$N - n = n \times \frac{(S - 1)}{s}$$

Error seeding works satisfactorily only if the kind seeded errors and their frequency of occurrence matches closely with the kind of defects that actually exist. However, it is difficult to predict the types of errors that exist in a software. To some extent, the different categories of errors that are latent and their frequency of occurrence can be estimated by analyzing historical data collected from similar projects. That is, the data collected is regarding the types and the frequency of latent errors for all earlier related projects. This gives an indication of the types (and the frequency) of errors that are likely to have been committed in the program under consideration. Based on these data, the different types of errors with the required frequency of occurrence can be seeded.

10.13 SOME GENERAL ISSUES ASSOCIATED WITH TESTING

In this section, we shall discuss two general issues associated with testing. These are—how to document the results of testing and how to perform regression testing.

Test documentation

A piece of documentation that is produced towards the end of testing is the *test summary report*. This report normally covers each subsystem and represents a summary of tests which have been applied to the subsystem and their outcome. It normally specifies the following:

- What is the total number of tests that were applied to a subsystem?
- Out of the total number of tests how many tests were successful?
- How many were unsuccessful, and the degree to which they were unsuccessful, e.g., whether a test was an outright failure or whether some of the expected results of the test were actually observed?

Regression testing

Regression testing spans unit, integration, and system testing. Therefore, it is difficult to classify it into any of these three levels of testing. Instead, it can be considered to be a separate dimension to these three forms of testing. After a piece of code has been successfully tested, changes to it later or may be needed for various reasons. Regression testing is the practice of running an old test suite after each change to the system or after each bug fix to ensure that no new bug has been introduced due to the change or the bug fix. However, if only a few statements are changed, then the entire test suite need not be run—only those test cases that test the functions and are likely to be affected by the change need to be run.

While resolution testing checks whether the defect has been fixed, regression testing checks whether the unmodified functionalities still continue to work correctly. Thus, whenever a defect is corrected and the change is incorporated in the program code, a danger is that a change introduced to correct an error could actually introduce errors in functionalities that were previously working correctly. As a result, after a bug-fixing session, both the resolution and regression test cases need to be run. This is where the additional effort required to create automated test scripts can pay off. As shown in Figure 10.9, some test cases may no more be valid after the change. These have been shown as invalid test case. The rest are redundant test cases, which check those parts of the program code that are not at all affected by the change.

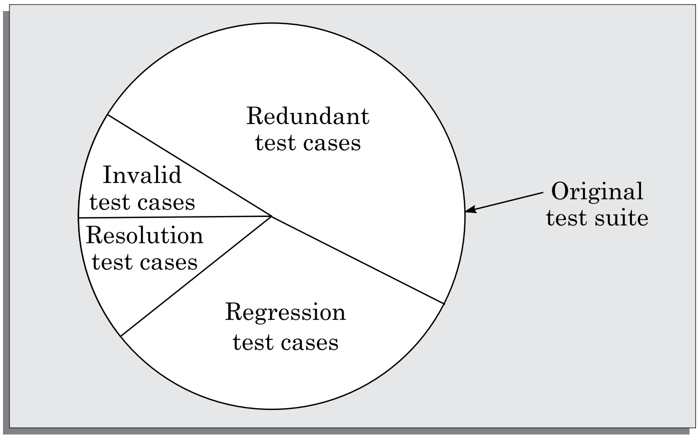


FIGURE 10.9 Types of test cases in the original test suite after a change.

Test automation

Testing is usually the most time consuming and laborious of all software development activities. This is especially true for large and complex software products that are being developed nowadays. In fact, at present testing cost often exceeds all other development life cycle costs. With the growing size of programs and the increased importance being given to product quality, test automation is drawing considerable attention from both industry circles and academia. Test automation is a generic term for automating one or some activities of the test process.

Other than reducing human effort and time, test automation also significantly improves the thoroughness of testing, because more testing can be carried out using a large number of test cases within a short period of time without any significant cost overhead.

The effectiveness of testing, to a large extent, depends on the exact test case design strategy used. Considering the large overheads that sophisticated testing techniques incur, in many industrial projects, often testing is carried out using randomly selected test values. With automation, more sophisticated test case design techniques can be deployed. Without the use of proper tools, testing large and complex software products can especially be extremely time consuming and laborious. A further advantage of using testing tools is that automated test results are much more reliable and eliminate human errors during testing. Regression testing after ever change or error correction requires running of several old test cases. In this situation, test automation simplifies running of the test cases again and again. Testing tools hold out the promise of substantial cost and time reduction even in the testing and maintenance phases.

Every software product undergoes significant changes overtime. Each time the code changes, it needs to be tested whether the changes induce any failures in the unchanged features. Thus, the originally designed test suite needs to be run repeatedly each time code changes, of course additional tests have to be designed and carried out on the enhanced features. Repeated running of the same set of test cases over and over after every change is monotonous, boring, and error-prone. Automated testing tools can be of considerable use in repeatedly running the same set of test cases. Testing tools can entirely or at least substantially eliminate the drudgery of running same test cases and also significantly reduce testing costs. A large number of tools are at present available both in the public domain as well as from commercial sources. It is possible to classify the tools into the following types based on the specific methodology on which they are based.

Capture and playback: In this type of tools, the test cases are executed manually only once. During the manual execution, the sequence and values of various inputs as well as the outputs produced are recorded. On any subsequent occasion, the test can be automatically replayed and the results checked against the recorded output. An important advantage of the capture playback tools is that once test data are captured and the results verified, the tests can be rerun easily and cheaply a large number of times. Thus, these tools are very useful for regression testing. However, capture and playback tools have a few disadvantages as well. Test maintenance can be costly when the unit under test changes since some of the captured tests may become invalid. It would require considerable effort to determine and remove the invalid test cases or modify the test input and output data. Also new test cases would have to be added for the altered code.

Test script: Test scripts are used to drive an automated test tool. The scripts provide input to the unit under test and record the output. The testers employ a variety of languages to express test scripts. An important advantage of test script-based tools is that once the test script is debugged and verified, it can be rerun easily and cheaply a large number of times. However, debugging the test script to ensure its accuracy requires significant effort. Also, every subsequent change to the unit under test entails effort to identity impacted test scripts, modify them, rerun and reconfirm them.

Random input test: In this type of automatic testing tool, test values are randomly generated cover the input space of the unit under test. The outputs are ignored because analyzing them would be extremely expensive. The goal is usually to crash the unit under test and not to check if the produced results are correct. An advantage of random input testing tools is that it is relatively easy. This approach however can be the most cost-effective for finding some types of defects. However, random input testing is a very limited form of testing. It finds only the defects that crash the unit under test and not the majority of defects that do not crash the system, but simply produce incorrect results.

Model-based test: A model is a simplified representation of program. There can be several types of models of a program. These models can be either structural models or behavioral models. Examples of behavioral models are state models and activity models. A state model-based testing generates tests that adequately covers the state space described by the model.

SUMMARY

- In this chapter we discussed the coding and testing phases of the software life cycle.
- Most software development organisations formulate their own coding standards and expect their engineers to adhere to them. On the other hand, coding guidelines serve as general suggestions to programmers regarding good programming styles, but the implementation of the guidelines is left to the discretion to the individual engineers.
- Code review is an efficient way of removing errors as compared to testing, because code review identifies errors whereas testing identifies failures. Therefore, after identifying failures, additional efforts (debugging) must be done to locate and fix the errors.
- Exhaustive testing of almost any non-trivial system is impractical. Also, random selection of test cases is inefficient since many test cases become redundant as they detect the same type of errors. Therefore, we need to design a minimal test suite that would expose as many errors as possible.
- There are two well-known approaches to testing—black-box testing and white-box testing. Black box testing is also known as functional testing. Designing test cases for black box testing does not require any knowledge about how the functions have been designed and implemented. On the other hand, white-box testing requires knowledge about internals of the software.
- Object-oriented features complicate the testing process as test cases have to be designed to detect bugs that are associated with these new types of features that are specific to object-orientation programs.
- We discussed some important issues in integration and system testing. We observed that the system test suite is designed based on the SRS document. The two major types of system testing are functionality testing and performance testing. The functionality test cases are designed based on the functional requirements and the performance test cases are designed to test the compliance of the system to the non-functional requirements documented in the SRS document.