CHAPTER

17 SOFTWARE TESTING TECHNIQUES

KEY CONCEPTS

The importance of software testing and its implications with respect to software quality cannot be overemphasized. To quote Deutsch [DEU79],

> The development of software systems involves a series of production activities where opportunities for injection of human fallibilities are enormous. Errors may begin to occur at the very inception of the process where the objectives . . . may be erroneously or imperfectly specified, as well as [in] later design and development stages . . . Because of human inability to perform and communicate with perfection, software development is accompanied by a quality assurance activity.

Software testing is a critical element of software quality assurance and represents the ultimate review of specification, design, and code generation.

The increasing visibility of software as a system element and the attendant "costs" associated with a software failure are motivating forces for well-planned, thorough testing. It is not unusual for a software development organization to expend between 30 and 40 percent of total project effort on testing. In the extreme, testing of human-rated software (e.g., flight control, nuclear reactor monitoring) can cost three to five times as much as all other software engineering steps combined!

QUICK LOOK

What is it? Once source code has been generated, software must be tested to uncover (and correct) as many errors as possible before delivery to your customer. Your goal is to design a series of test cases that have a high likelihood of finding errors—but how? That's where software testing techniques enter the picture. These techniques provide systematic guidance for designing tests that (1) exercise the internal logic of software components, and (2) exercise the input and output domains of the program to uncover errors in program function, behavior. and performance.

Who does it? During early stages of testing, a software engineer performs all tests. However, as the testing process progresses, testing specialists may become involved.

Why is it important? Reviews and other SQA activities can and do uncover errors, but they are not sufficient. Every time the program is executed, the customer tests it! Therefore, you have to execute the program before it gets to the customer with the specific intent of finding and removing all errors. In order to find the highest possible number of errors, tests must be conducted systematically and test cases must be designed using disciplined techniques.

What are the steps? Software is tested from two different perspectives: (1) internal program logic is exercised using "white box" test case design tech- ▶

QUICK LOOK

niques. Software requirements are exercised using "black box" test case design techniques. In both cases, the intent is to find the maximum number of errors with the minimum amount of effort and time.

What is the work product? A set of test cases designed to exercise both internal logic and external requirements is designed and documented, expected results are defined, and actual results are recorded.

How do I ensure that I've done it right? When you begin testing, change your point of view. Try hard to "break" the software! Design test cases in a disciplined fashion and review the test cases you do create for thoroughness.

In this chapter, we discuss software testing fundamentals and techniques for software test case design. Software testing fundamentals define the overriding objectives for software testing. Test case design focuses on a set of techniques for the creation of test cases that meet overall testing objectives. In Chapter 18, testing strategies and software debugging are presented.

17.1 SOFTWARE TESTING FUNDAMENTALS

Quote:

"A working program remains an elusive thing of beauty."

Robert Dunn

Testing presents an interesting anomaly for the software engineer. During earlier software engineering activities, the engineer attempts to build software from an abstract concept to a tangible product. Now comes testing. The engineer creates a series of test cases that are intended to "demolish" the software that has been built. In fact, testing is the one step in the software process that could be viewed (psychologically, at least) as destructive rather than constructive.

Software engineers are by their nature constructive people. Testing requires that the developer discard preconceived notions of the "correctness" of software just developed and overcome a conflict of interest that occurs when errors are uncovered. Beizer [BEI90] describes this situation effectively when he states:

> There's a myth that if we were really good at programming, there would be no bugs to catch. If only we could really concentrate, if only everyone used structured programming, top-down design, decision tables, if programs were written in SQUISH, if we had the right silver bullets, then there would be no bugs. So goes the myth. There are bugs, the myth says, because we are bad at what we do; and if we are bad at it, we should feel guilty about it. Therefore, testing and test case design is an admission of failure, which instills a goodly dose of guilt. And the tedium of testing is just punishment for our errors. Punishment for what? For being human? Guilt for what? For failing to achieve inhuman perfection? For not distinguishing between what another programmer thinks and what he says? For failing to be telepathic? For not solving human communications problems that have been kicked around . . . for forty centuries?

Should testing instill guilt? Is testing really destructive? The answer to these questions is "No!" However, the objectives of testing are somewhat different than we might expect.

17.1.1 Testing Objectives

In an excellent book on software testing, Glen Myers [MYE79] states a number of rules that can serve well as testing objectives:

? What are primary objectives when we test software?

1. Testing is a process of executing a program with the intent of finding an error.
2. A good test case is one that has a high probability of finding an as-yet-undiscovered error.
3. A successful test is one that uncovers an as-yet-undiscovered error.

These objectives imply a dramatic change in viewpoint. They move counter to the commonly held view that a successful test is one in which no errors are found. Our objective is to design tests that systematically uncover different classes of errors and to do so with a minimum amount of time and effort.

Quote:

"Errors are more common, more pervasive, and more troublesome in software than with other technologies."

David Parnas

If testing is conducted successfully (according to the objectives stated previously), it will uncover errors in the software. As a secondary benefit, testing demonstrates that software functions appear to be working according to specification, that behavioral and performance requirements appear to have been met. In addition, data collected as testing is conducted provide a good indication of software reliability and some indication of software quality as a whole. But testing cannot show the absence of errors and defects, it can show only that software errors and defects are present. It is important to keep this (rather gloomy) statement in mind as testing is being conducted.

17.1.2 Testing Principles

Before applying methods to design effective test cases, a software engineer must understand the basic principles that guide software testing. Davis [DAV95] suggests a set[1] of testing principles that have been adapted for use in this book:

- **All tests should be traceable to customer requirements.** As we have seen, the objective of software testing is to uncover errors. It follows that the most severe defects (from the customer's point of view) are those that cause the program to fail to meet its requirements.
- **Tests should be planned long before testing begins.** Test planning (Chapter 18) can begin as soon as the requirements model is complete. Detailed definition of test cases can begin as soon as the design model has

1 Only a small subset of Davis's testing principles are noted here. For more information, see [DAV95].

been solidified. Therefore, all tests can be planned and designed before any code has been generated.

- **The Pareto principle applies to software testing.** Stated simply, the Pareto principle implies that 80 percent of all errors uncovered during testing will likely be traceable to 20 percent of all program components. The problem, of course, is to isolate these suspect components and to thoroughly test them.
- **Testing should begin "in the small" and progress toward testing "in the large."** The first tests planned and executed generally focus on individual components. As testing progresses, focus shifts in an attempt to find errors in integrated clusters of components and ultimately in the entire system (Chapter 18).
- **Exhaustive testing is not possible.** The number of path permutations for even a moderately sized program is exceptionally large (see Section 17.2 for further discussion). For this reason, it is impossible to execute every combination of paths during testing. It is possible, however, to adequately cover program logic and to ensure that all conditions in the component-level design have been exercised.
- **To be most effective, testing should be conducted by an independent third party.** By *most effective,* we mean testing that has the highest probability of finding errors (the primary objective of testing). For reasons that have been introduced earlier in this chapter and are considered in more detail in Chapter 18, the software engineer who created the system is not the best person to conduct all tests for the software.

17.1.3 Testability

In ideal circumstances, a software engineer designs a computer program, a system, or a product with "testability" in mind. This enables the individuals charged with testing to design effective test cases more easily. But what is *testability?* James Bach[2] describes testability in the following manner.

A useful paper entitled "Improving Software Testability" can be found at **www.stlabs.com/newsletters/testnet/docs/testability.htm**

> Software testability is simply how easily [a computer program] can be tested. Since testing is so profoundly difficult, it pays to know what can be done to streamline it. Sometimes programmers are willing to do things that will help the testing process and a checklist of possible design points, features, etc., can be useful in negotiating with them.
>
> There are certainly metrics that could be used to measure testability in most of its aspects. Sometimes, testability is used to mean how adequately a particular set of

2 The paragraphs that follow are copyright 1994 by James Bach and have been adapted from an Internet posting that first appeared in the newsgroup comp.software-eng. This material is used with permission.

tests will cover the product. It's also used by the military to mean how easily a tool can be checked and repaired in the field. Those two meanings are not the same as *software testability.* The checklist that follows provides a set of characteristics that lead to testable software.

"Testability" occurs as a result of good design. Data design, architecture, interfaces, and component-level detail can either facilitate testing or make it difficult.

Operability. "The better it works, the more efficiently it can be tested."

- The system has few bugs (bugs add analysis and reporting overhead to the test process).
- No bugs block the execution of tests.
- The product evolves in functional stages (allows simultaneous development and testing).

Observability. "What you see is what you test."

- Distinct output is generated for each input.
- System states and variables are visible or queriable during execution.
- Past system states and variables are visible or queriable (e.g., transaction logs).
- All factors affecting the output are visible.
- Incorrect output is easily identified.
- Internal errors are automatically detected through self-testing mechanisms.
- Internal errors are automatically reported.
- Source code is accessible.

Controllability. "The better we can control the software, the more the testing can be automated and optimized."

- All possible outputs can be generated through some combination of input.
- All code is executable through some combination of input.
- Software and hardware states and variables can be controlled directly by the test engineer.
- Input and output formats are consistent and structured.
- Tests can be conveniently specified, automated, and reproduced.

Decomposability. "By controlling the scope of testing, we can more quickly isolate problems and perform smarter retesting."

- The software system is built from independent modules.
- Software modules can be tested independently.

Simplicity. "The less there is to test, the more quickly we can test it."

- Functional simplicity (e.g., the feature set is the minimum necessary to meet requirements).

- Structural simplicity (e.g., architecture is modularized to limit the propagation of faults).
- Code simplicity (e.g., a coding standard is adopted for ease of inspection and maintenance).

Stability. "The fewer the changes, the fewer the disruptions to testing."

- Changes to the software are infrequent.
- Changes to the software are controlled.
- Changes to the software do not invalidate existing tests.
- The software recovers well from failures.

Understandability. "The more information we have, the smarter we will test."

- The design is well understood.
- Dependencies between internal, external, and shared components are well understood.
- Changes to the design are communicated.
- Technical documentation is instantly accessible.
- Technical documentation is well organized.
- Technical documentation is specific and detailed.
- Technical documentation is accurate.

The attributes suggested by Bach can be used by a software engineer to develop a software configuration (i.e., programs, data, and documents) that is amenable to testing.

And what about the tests themselves? Kaner, Falk, and Nguyen [KAN93] suggest the following attributes of a "good" test:

? What are the attributes of a "good" test?

1. A good test has a high probability of finding an error. To achieve this goal, the tester must understand the software and attempt to develop a mental picture of how the software might fail. Ideally, the classes of failure are probed. For example, one class of potential failure in a GUI (graphical user interface) is a failure to recognize proper mouse position. A set of tests would be designed to exercise the mouse in an attempt to demonstrate an error in mouse position recognition.
2. A good test is not redundant. Testing time and resources are limited. There is no point in conducting a test that has the same purpose as another test. Every test should have a different purpose (even if it is subtly different). For example, a module of the *SafeHome* software (discussed in earlier chapters) is designed to recognize a user password to activate and deactivate the system. In an effort to uncover an error in password input, the tester designs a series of tests that input a sequence of passwords. Valid and invalid passwords (four numeral sequences) are input as separate tests. However, each

valid/invalid password should probe a different mode of failure. For example, the invalid password 1234 should not be accepted by a system programmed to recognize 8080 as the valid password. If it is accepted, an error is present. Another test input, say 1235, would have the same purpose as 1234 and is therefore redundant. However, the invalid input 8081 or 8180 has a subtle difference, attempting to demonstrate that an error exists for passwords "close to" but not identical with the valid password.

3. A good test should be "best of breed" [KAN93]. In a group of tests that have a similar intent, time and resource limitations may mitigate toward the execution of only a subset of these tests. In such cases, the test that has the highest likelihood of uncovering a whole class of errors should be used.
4. A good test should be neither too simple nor too complex. Although it is sometimes possible to combine a series of tests into one test case, the possible side effects associated with this approach may mask errors. In general, each test should be executed separately.

17.2 TEST CASE DESIGN

Quote:

"There is only one rule in designing test cases: cover all features, but do not make too many test cases."

Tsuneo Yamaura

The design of tests for software and other engineered products can be as challenging as the initial design of the product itself. Yet, for reasons that we have already discussed, software engineers often treat testing as an afterthought, developing test cases that may "feel right" but have little assurance of being complete. Recalling the objectives of testing, we must design tests that have the highest likelihood of finding the most errors with a minimum amount of time and effort.

A rich variety of test case design methods have evolved for software. These methods provide the developer with a systematic approach to testing. More important, methods provide a mechanism that can help to ensure the completeness of tests and provide the highest likelihood for uncovering errors in software.

WebRef

The *Testing Techniques Newsletter* is an excellent source of information on testing methods: **www.testworks.com/News/TTN-Online/**

Any engineered product (and most other things) can be tested in one of two ways: (1) Knowing the specified function that a product has been designed to perform, tests can be conducted that demonstrate each function is fully operational while at the same time searching for errors in each function; (2) knowing the internal workings of a product, tests can be conducted to ensure that "all gears mesh," that is, internal operations are performed according to specifications and all internal components have been adequately exercised. The first test approach is called black-box testing and the second, white-box testing.

When computer software is considered, *black-box testing* alludes to tests that are conducted at the software interface. Although they are designed to uncover errors, black-box tests are used to demonstrate that software functions are operational, that input is properly accepted and output is correctly produced, and that the integrity of

external information (e.g., a database) is maintained. A black-box test examines some fundamental aspect of a system with little regard for the internal logical structure of the software.

KEY POINT

White-box tests can be designed only after a component-level design (or source code) exists. The logical details of the program must be available.

White-box testing of software is predicated on close examination of procedural detail. Logical paths through the software are tested by providing test cases that exercise specific sets of conditions and/or loops. The "status of the program" may be examined at various points to determine if the expected or asserted status corresponds to the actual status.

At first glance it would seem that very thorough white-box testing would lead to "100 percent correct programs." All we need do is define all logical paths, develop test cases to exercise them, and evaluate results, that is, generate test cases to exercise program logic exhaustively. Unfortunately, exhaustive testing presents certain logistical problems. For even small programs, the number of possible logical paths can be very large. For example, consider the 100 line program in the language C. After some basic data declaration, the program contains two nested loops that execute from 1 to 20 times each, depending on conditions specified at input. Inside the interior loop, four if-then-else constructs are required. There are approximately 10^{14} possible paths that may be executed in this program!

To put this number in perspective, we assume that a magic test processor ("magic" because no such processor exists) has been developed for exhaustive testing. The processor can develop a test case, execute it, and evaluate the results in one millisecond. Working 24 hours a day, 365 days a year, the processor would work for 3170 years to test the program. This would, undeniably, cause havoc in most development schedules. Exhaustive testing is impossible for large software systems.

KEY POINT

It is not possible to exhaustively test every program path because the number of paths is simply too large.

White-box testing should not, however, be dismissed as impractical. A limited number of important logical paths can be selected and exercised. Important data structures can be probed for validity. The attributes of both black- and white-box testing can be combined to provide an approach that validates the software interface and selectively ensures that the internal workings of the software are correct.

17.3 WHITE-BOX TESTING

White-box testing, sometimes called *glass-box testing,* is a test case design method that uses the control structure of the procedural design to derive test cases. Using white-box testing methods, the software engineer can derive test cases that (1) guarantee that all independent paths within a module have been exercised at least once, (2) exercise all logical decisions on their true and false sides, (3) execute all loops at their boundaries and within their operational bounds, and (4) exercise internal data structures to ensure their validity.

A reasonable question might be posed at this juncture: "Why spend time and energy worrying about (and testing) logical minutiae when we might better expend effort

ensuring that program requirements have been met?" Stated another way, why don't we spend all of our energy on black-box tests? The answer lies in the nature of software defects (e.g., [JON81]):

- *Logic errors and incorrect assumptions are inversely proportional to the probability that a program path will be executed.* Errors tend to creep into our work when we design and implement function, conditions, or control that are out of the mainstream. Everyday processing tends to be well understood (and well scrutinized), while "special case" processing tends to fall into the cracks.
- *We often believe that a logical path is not likely to be executed when, in fact, it may be executed on a regular basis.* The logical flow of a program is sometimes counterintuitive, meaning that our unconscious assumptions about flow of control and data may lead us to make design errors that are uncovered only once path testing commences.
- *Typographical errors are random.* When a program is translated into programming language source code, it is likely that some typing errors will occur. Many will be uncovered by syntax and type checking mechanisms, but others may go undetected until testing begins. It is as likely that a typo will exist on an obscure logical path as on a mainstream path.

Quote:

"Bugs lurk in corners and congregate at boundaries."

Boris Beizer

Each of these reasons provides an argument for conducting white-box tests. Black-box testing, no matter how thorough, may miss the kinds of errors noted here. White-box testing is far more likely to uncover them.

17.4 BASIS PATH TESTING

Basis path testing is a white-box testing technique first proposed by Tom McCabe [MCC76]. The basis path method enables the test case designer to derive a logical complexity measure of a procedural design and use this measure as a guide for defining a basis set of execution paths. Test cases derived to exercise the basis set are guaranteed to execute every statement in the program at least one time during testing.

17.4.1 Flow Graph Notation

Before the basis path method can be introduced, a simple notation for the representation of control flow, called a *flow graph* (or *program graph*) must be introduced.[3] The flow graph depicts logical control flow using the notation illustrated in Figure 17.1. Each structured construct (Chapter 16) has a corresponding flow graph symbol.

To illustrate the use of a flow graph, we consider the procedural design representation in Figure 17.2A. Here, a flowchart is used to depict program control structure.

3 In actuality, the basis path method can be conducted without the use of flow graphs. However, they serve as a useful tool for understanding control flow and illustrating the approach.

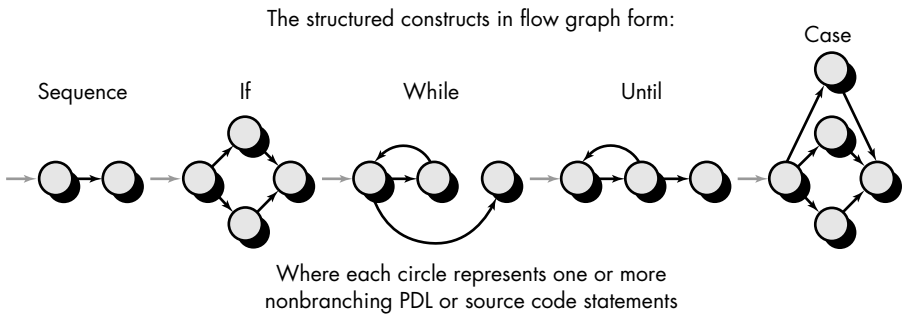


FIGURE 17.1 Flow graph notation

Draw a flow graph when the logical control structure of a module is complex. The flow graph enables you to trace program paths more readily.

Figure 17.2B maps the flowchart into a corresponding flow graph (assuming that no compound conditions are contained in the decision diamonds of the flowchart). Referring to Figure 17.2B, each circle, called a *flow graph node,* represents one or more procedural statements. A sequence of process boxes and a decision diamond can map into a single node. The arrows on the flow graph, called *edges* or *links,* represent flow of control and are analogous to flowchart arrows. An edge must terminate at a node, even if the node does not represent any procedural statements (e.g., see the symbol for the if-then-else construct). Areas bounded by edges and nodes are called *regions.* When counting regions, we include the area outside the graph as a region.[4]

When compound conditions are encountered in a procedural design, the generation of a flow graph becomes slightly more complicated. A compound condition occurs when one or more Boolean operators (logical OR, AND, NAND, NOR) is present in a conditional statement. Referring to Figure 17.3, the PDL segment translates into the flow graph shown. Note that a separate node is created for each of the conditions *a* and *b* in the statement IF *a* OR *b*. Each node that contains a condition is called a *predicate node* and is characterized by two or more edges emanating from it.

17.4.2 Cyclomatic Complexity

Cyclomatic complexity is a software metric that provides a quantitative measure of the logical complexity of a program. When used in the context of the basis path testing method, the value computed for cyclomatic complexity defines the number of independent paths in the basis set of a program and provides us with an upper bound for the number of tests that must be conducted to ensure that all statements have been executed at least once.

An *independent path* is any path through the program that introduces at least one new set of processing statements or a new condition. When stated in terms of a flow

4 A more-detailed discussion of graphs and their use in testing is contained in Section 17.6.1.

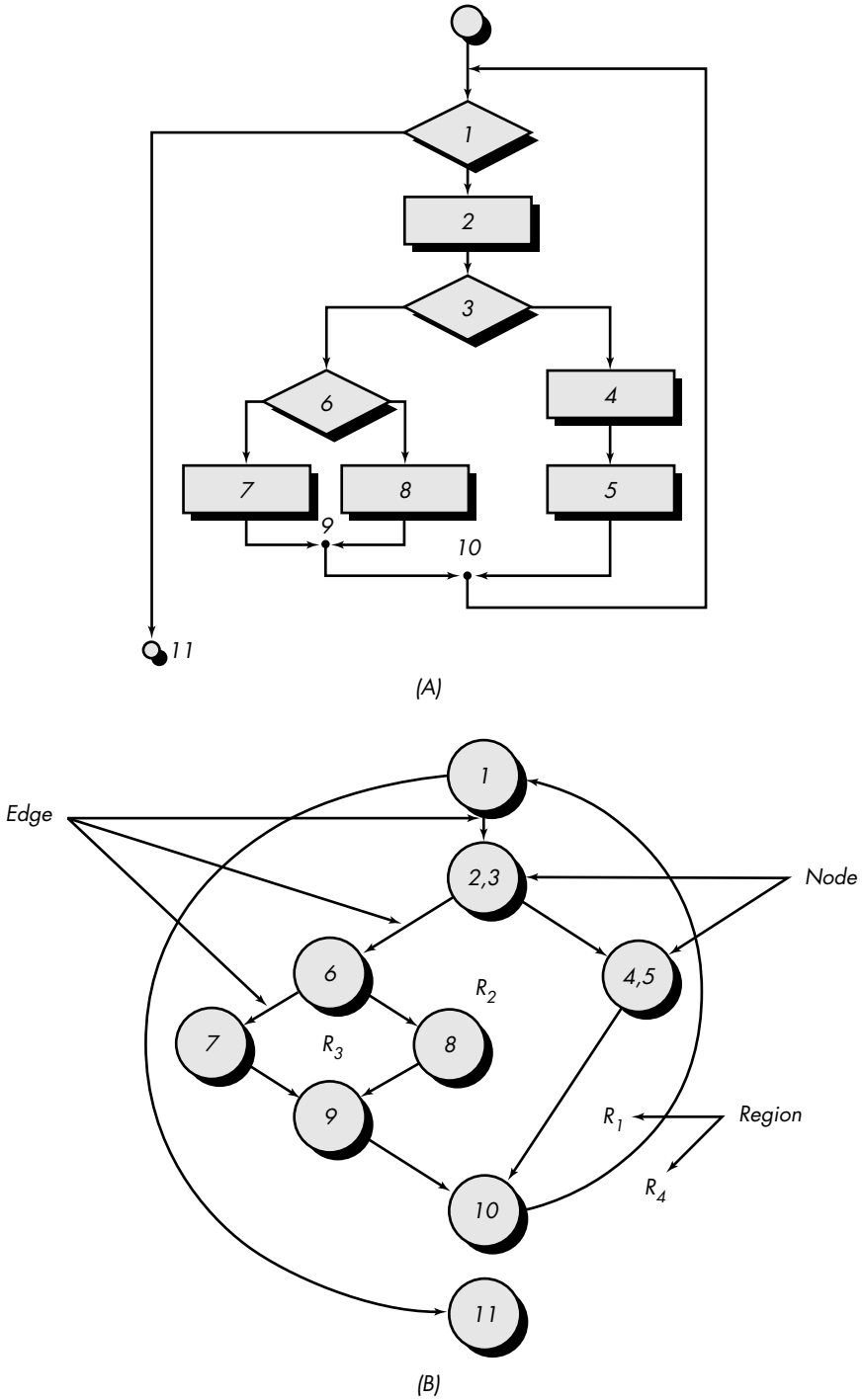


FIGURE 17.2
Flowchart, (A) and flow graph (B)

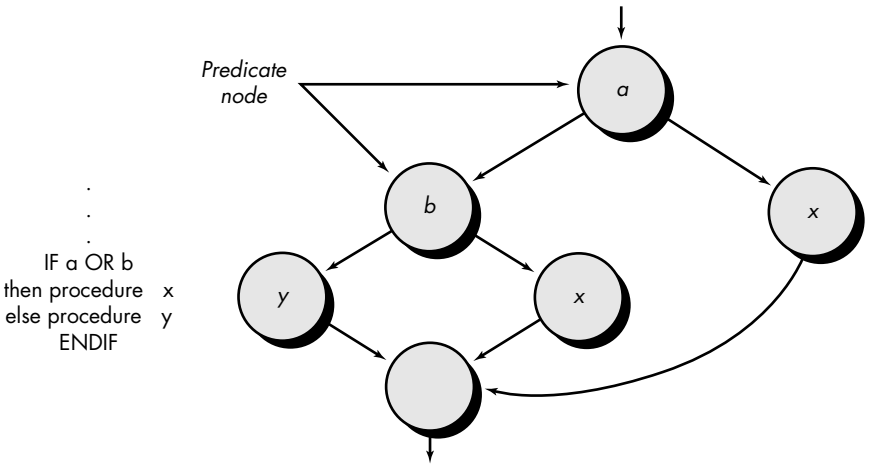


FIGURE 17.3 Compound logic

graph, an independent path must move along at least one edge that has not been traversed before the path is defined. For example, a set of independent paths for the flow graph illustrated in Figure 17.2B is

path 1: 1-11
path 2: 1-2-3-4-5-10-1-11
path 3: 1-2-3-6-8-9-10-1-11
path 4: 1-2-3-6-7-9-10-1-11

ADVICE

Cyclomatic complexity is a useful metric for predicting those modules that are likely to be error prone. It can be used for test planning as well as test case design.

Note that each new path introduces a new edge. The path

1-2-3-4-5-10-1-2-3-6-8-9-10-1-11

is not considered to be an independent path because it is simply a combination of already specified paths and does not traverse any new edges.

Paths 1, 2, 3, and 4 constitute a *basis set* for the flow graph in Figure 17.2B. That is, if tests can be designed to force execution of these paths (a basis set), every statement in the program will have been guaranteed to be executed at least one time and every condition will have been executed on its true and false sides. It should be noted that the basis set is not unique. In fact, a number of different basis sets can be derived for a given procedural design.

How do we know how many paths to look for? The computation of cyclomatic complexity provides the answer.

Cyclomatic complexity has a foundation in graph theory and provides us with an extremely useful software metric. Complexity is computed in one of three ways:

? How is cyclomatic complexity computed?

1. The number of regions of the flow graph correspond to the cyclomatic complexity.
2. Cyclomatic complexity, $V(G)$, for a flow graph, G, is defined as

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

Cyclomatic complexity provides the upper bound on the number of test cases that must be executed to guarantee that every statement in a component has been executed at least once.

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

3. Cyclomatic complexity, $V(G)$, for a flow graph, G, is also defined as

$$V(G) = P + 1$$

where P is the number of predicate nodes contained in the flow graph G.

Referring once more to the flow graph in Figure 17.2B, the cyclomatic complexity can be computed using each of the algorithms just noted:

1. The flow graph has four regions.
2. $V(G)$ = 11 edges − 9 nodes + 2 = 4.
3. $V(G)$ = 3 predicate nodes + 1 = 4.

Therefore, the cyclomatic complexity of the flow graph in Figure 17.2B is 4.

More important, the value for $V(G)$ provides us with an upper bound for the number of independent paths that form the basis set and, by implication, an upper bound on the number of tests that must be designed and executed to guarantee coverage of all program statements.

17.4.3 Deriving Test Cases

The basis path testing method can be applied to a procedural design or to source code. In this section, we present basis path testing as a series of steps. The procedure *average,* depicted in PDL in Figure 17.4, will be used as an example to illustrate each step in the test case design method. Note that *average,* although an extremely simple algorithm, contains compound conditions and loops. The following steps can be applied to derive the basis set:

"To err is human, to find a bug, devine."
Robert Dunn

1. **Using the design or code as a foundation, draw a corresponding flow graph.** A flow graph is created using the symbols and construction rules presented in Section 16.4.1. Referring to the PDL for average in Figure 17.4, a flow graph is created by numbering those PDL statements that will be mapped into corresponding flow graph nodes. The corresponding flow graph is in Figure 17.5.

2. **Determine the cyclomatic complexity of the resultant flow graph.** The cyclomatic complexity, $V(G)$, is determined by applying the algorithms described in Section 17.5.2. It should be noted that $V(G)$ can be determined without developing a flow graph by counting all conditional statements in the PDL (for the procedure *average,* compound conditions count as two) and adding 1. Referring to Figure 17.5,

   $V(G)$ = 6 regions
   $V(G)$ = 17 edges − 13 nodes + 2 = 6
   $V(G)$ = 5 predicate nodes + 1 = 6

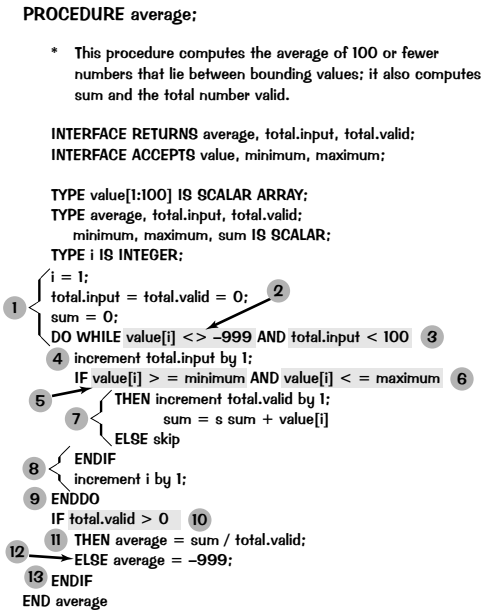


FIGURE 17.4 PDL for test case design with nodes identified

3. **Determine a basis set of linearly independent paths.** The value of $V(G)$ provides the number of linearly independent paths through the program control structure. In the case of procedure *average,* we expect to specify six paths:

   path 1: 1-2-10-11-13

   path 2: 1-2-10-12-13

   path 3: 1-2-3-10-11-13

   path 4: 1-2-3-4-5-8-9-2-. . .

   path 5: 1-2-3-4-5-6-8-9-2-. . .

   path 6: 1-2-3-4-5-6-7-8-9-2-. . .

   The ellipsis (. . .) following paths 4, 5, and 6 indicates that any path through the remainder of the control structure is acceptable. It is often worthwhile to identify predicate nodes as an aid in the derivation of test cases. In this case, nodes 2, 3, 5, 6, and 10 are predicate nodes.

4. **Prepare test cases that will force execution of each path in the basis set.** Data should be chosen so that conditions at the predicate nodes are appropriately set as each path is tested. Test cases that satisfy the basis set just described are

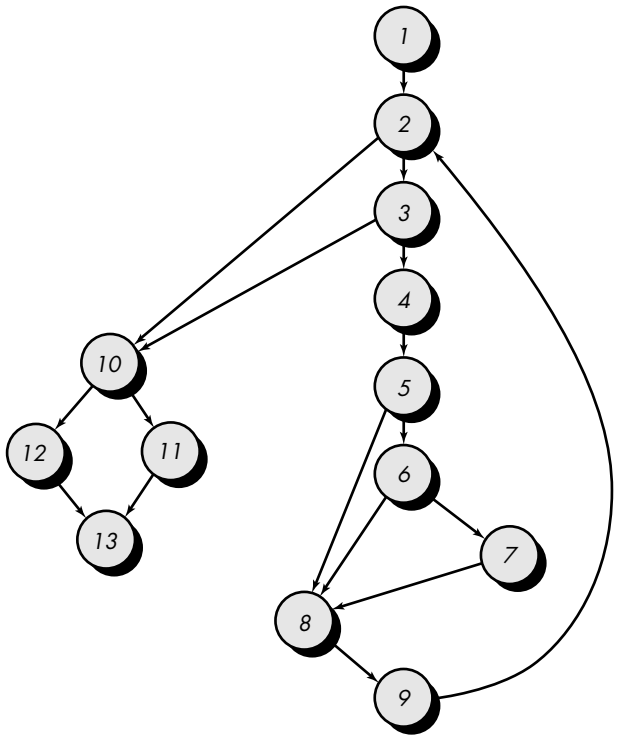


FIGURE 17.5
Flow graph for the procedure **average**

Path 1 test case:
value(k) = valid input, where $k < i$ for $2 \le i \le 100$
value(i) = -999 where $2 \le i \le 100$
Expected results: Correct average based on k values and proper totals.
Note: Path 1 cannot be tested stand-alone but must be tested as part of path 4, 5, and 6 tests.

Path 2 test case:
value(1) = -999
Expected results: Average = -999; other totals at initial values.

Path 3 test case:
Attempt to process 101 or more values.
First 100 values should be valid.
Expected results: Same as test case 1.

Path 4 test case:
value(i) = valid input where i < 100
value(k) < minimum where $k < i$
Expected results: Correct average based on k values and proper totals.

Quote:

"[Software engineers] considerably underestimate the number of tests required to verify a straightforward program."

Martyn Ould and Charles Unwin

Path 5 test case:
value(*i*) = valid input where $i < 100$
value(*k*) > maximum where $k <= i$
Expected results: Correct average based on *n* values and proper totals.

Path 6 test case:
value(*i*) = valid input where $i < 100$
Expected results: Correct average based on *n* values and proper totals.

Each test case is executed and compared to expected results. Once all test cases have been completed, the tester can be sure that all statements in the program have been executed at least once.

It is important to note that some independent paths (e.g., path 1 in our example) cannot be tested in stand-alone fashion. That is, the combination of data required to traverse the path cannot be achieved in the normal flow of the program. In such cases, these paths are tested as part of another path test.

17.4.4 Graph Matrices

The procedure for deriving the flow graph and even determining a set of basis paths is amenable to mechanization. To develop a software tool that assists in basis path testing, a data structure, called a *graph matrix,* can be quite useful.

A *graph matrix* is a square matrix whose size (i.e., number of rows and columns) is equal to the number of nodes on the flow graph. Each row and column corresponds to an identified node, and matrix entries correspond to connections (an edge) between nodes. A simple example of a flow graph and its corresponding graph matrix [BEI90] is shown in Figure 17.6.

Referring to the figure, each node on the flow graph is identified by numbers, while each edge is identified by letters. A letter entry is made in the matrix to correspond to a connection between two nodes. For example, node 3 is connected to node 4 by edge *b*.

? What is a graph matrix and how do we extend it for use in testing?

To this point, the graph matrix is nothing more than a tabular representation of a flow graph. However, by adding a *link weight* to each matrix entry, the graph matrix can become a powerful tool for evaluating program control structure during testing. The link weight provides additional information about control flow. In its simplest form, the link weight is 1 (a connection exists) or 0 (a connection does not exist). But link weights can be assigned other, more interesting properties:

- The probability that a link (edge) will be executed.
- The processing time expended during traversal of a link.
- The memory required during traversal of a link.
- The resources required during traversal of a link.

FIGURE 17.6
Graph matrix

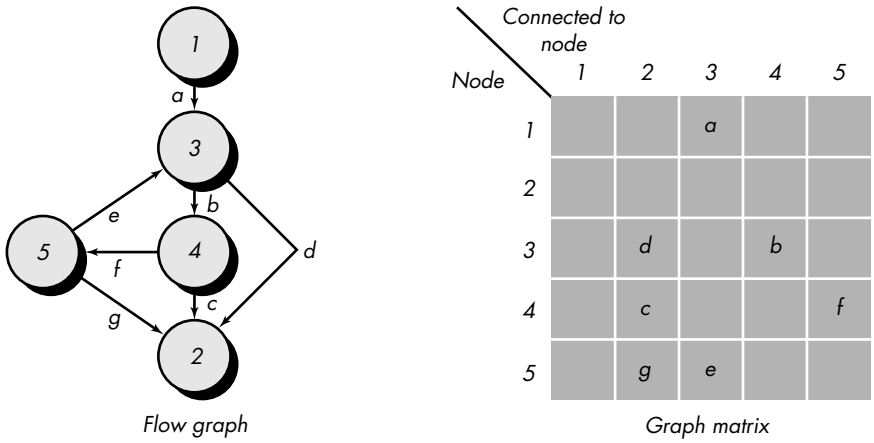
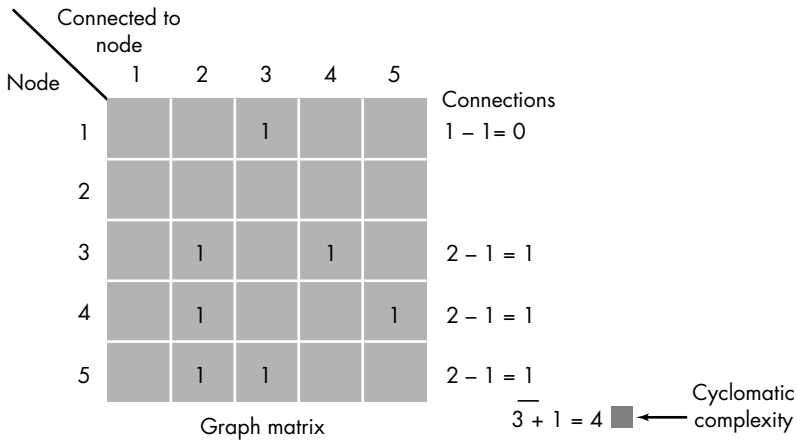


FIGURE 17.7
Connection matrix



To illustrate, we use the simplest weighting to indicate connections (0 or 1). The graph matrix in Figure 17.6 is redrawn as shown in Figure 17.7. Each letter has been replaced with a 1, indicating that a connection exists (zeros have been excluded for clarity). Represented in this form, the graph matrix is called a *connection matrix.*

Referring to Figure 17.7, each row with two or more entries represents a predicate node. Therefore, performing the arithmetic shown to the right of the connection matrix provides us with still another method for determining cyclomatic complexity (Section 17.4.2).

Beizer [BEI90] provides a thorough treatment of additional mathematical algorithms that can be applied to graph matrices. Using these techniques, the analysis required to design test cases can be partially or fully automated.

17.5 CONTROL STRUCTURE TESTING

The basis path testing technique described in Section 17.4 is one of a number of techniques for control structure testing. Although basis path testing is simple and highly effective, it is not sufficient in itself. In this section, other variations on control structure testing are discussed. These broaden testing coverage and improve quality of white-box testing.

17.5.1 Condition Testing[5]

KEY POINT

Errors are much more common in the neighborhood of logical conditions than they are in the locus of sequential processing statements.

Condition testing is a test case design method that exercises the logical conditions contained in a program module. A simple condition is a Boolean variable or a relational expression, possibly preceded with one NOT (¬) operator. A relational expression takes the form

E_1 <relational-operator> E_2

where E_1 and E_2 are arithmetic expressions and <relational-operator> is one of the following: <, ≤, =, ≠ (nonequality), >, or ≥. A *compound condition* is composed of two or more simple conditions, Boolean operators, and parentheses. We assume that Boolean operators allowed in a compound condition include OR (|), AND (&) and NOT (¬). A condition without relational expressions is referred to as a *Boolean expression.*

Therefore, the possible types of elements in a condition include a Boolean operator, a Boolean variable, a pair of Boolean parentheses (surrounding a simple or compound condition), a relational operator, or an arithmetic expression.

If a condition is incorrect, then at least one component of the condition is incorrect. Therefore, types of errors in a condition include the following:

- Boolean operator error (incorrect/missing/extra Boolean operators).
- Boolean variable error.
- Boolean parenthesis error.
- Relational operator error.
- Arithmetic expression error.

The condition testing method focuses on testing each condition in the program. Condition testing strategies (discussed later in this section) generally have two advantages. First, measurement of test coverage of a condition is simple. Second, the test coverage of conditions in a program provides guidance for the generation of additional tests for the program.

The purpose of condition testing is to detect not only errors in the conditions of a program but also other errors in the program. If a test set for a program *P* is effective

5 Section 17.5.1 and 17.5.2 have been adapted from [TAI89] with permission of Professor K. C. Tai.

for detecting errors in the conditions contained in *P,* it is likely that this test set is also effective for detecting other errors in *P.* In addition, if a testing strategy is effective for detecting errors in a condition, then it is likely that this strategy will also be effective for detecting errors in a program.

A number of condition testing strategies have been proposed. *Branch testing* is probably the simplest condition testing strategy. For a compound condition *C,* the true and false branches of *C* and every simple condition in *C* need to be executed at least once [MYE79].

Even if you decide against condition testing, you should spend time evaluating each condition in an effort to uncover errors. This is a primary hiding place for bugs!

Domain testing [WHI80] requires three or four tests to be derived for a relational expression. For a relational expression of the form

E_1 <relational-operator> E_2

three tests are required to make the value of E_1 greater than, equal to, or less than that of E_2 [HOW82]. If <relational-operator> is incorrect and E_1 and E_2 are correct, then these three tests guarantee the detection of the relational operator error. To detect errors in E_1 and E_2, a test that makes the value of E_1 greater or less than that of E_2 should make the difference between these two values as small as possible.

For a Boolean expression with n variables, all of 2^n possible tests are required ($n > 0$). This strategy can detect Boolean operator, variable, and parenthesis errors, but it is practical only if n is small.

Error-sensitive tests for Boolean expressions can also be derived [FOS84, TAI87]. For a singular Boolean expression (a Boolean expression in which each Boolean variable occurs only once) with n Boolean variables ($n > 0$), we can easily generate a test set with less than 2^n tests such that this test set guarantees the detection of multiple Boolean operator errors and is also effective for detecting other errors.

Tai [TAI89] suggests a condition testing strategy that builds on the techniques just outlined. Called *BRO* (branch and relational operator) testing, the technique guarantees the detection of branch and relational operator errors in a condition provided that all Boolean variables and relational operators in the condition occur only once and have no common variables.

The BRO strategy uses condition constraints for a condition *C.* A condition constraint for *C* with n simple conditions is defined as $(D_1, D_2, \ldots, D_n)$, where D_i $(0 < i \leq n)$ is a symbol specifying a constraint on the outcome of the ith simple condition in condition *C.* A condition constraint *D* for condition *C* is said to be covered by an execution of *C* if, during this execution of *C,* the outcome of each simple condition in *C* satisfies the corresponding constraint in *D.*

For a Boolean variable, *B,* we specify a constraint on the outcome of *B* that states that *B* must be either true (t) or false (f). Similarly, for a relational expression, the symbols >, =, < are used to specify constraints on the outcome of the expression.

As an example, consider the condition

$$C_1: \quad B_1 \ \& \ B_2$$

where B_1 and B_2 are Boolean variables. The condition constraint for C_1 is of the form (D_1, D_2), where each of D_1 and D_2 is t or f. The value (t, f) is a condition constraint for C_1 and is covered by the test that makes the value of B_1 to be true and the value of B_2 to be false. The BRO testing strategy requires that the constraint set {(t, t), (f, t), (t, f)} be covered by the executions of C_1. If C_1 is incorrect due to one or more Boolean operator errors, at least one of the constraint set will force C_1 to fail.

As a second example, a condition of the form

$$C_2: \quad B_1 \ \& \ (E_3 = E_4)$$

where B_1 is a Boolean expression and E_3 and E_4 are arithmetic expressions. A condition constraint for C_2 is of the form (D_1, D_2), where each of D_1 is t or f and D_2 is >, =, <. Since C_2 is the same as C_1 except that the second simple condition in C_2 is a relational expression, we can construct a constraint set for C_2 by modifying the constraint set {(t, t), (f, t), (t, f)} defined for C_1. Note that t for $(E_3 = E_4)$ implies = and that f for $(E_3 = E_4)$ implies either < or >. By replacing (t, t) and (f, t) with (t, =) and (f, =), respectively, and by replacing (t, f) with (t, <) and (t, >), the resulting constraint set for C_2 is {(t, =), (f, =), (t, <), (t, >)}. Coverage of the preceding constraint set will guarantee detection of Boolean and relational operator errors in C_2.

As a third example, we consider a condition of the form

$$C_3: \quad (E_1 > E_2) \ \& \ (E_3 = E_4)$$

where E_1, E_2, E_3, and E_4 are arithmetic expressions. A condition constraint for C_3 is of the form (D_1, D_2), where each of D_1 and D_2 is >, =, <. Since C_3 is the same as C_2 except that the first simple condition in C_3 is a relational expression, we can construct a constraint set for C_3 by modifying the constraint set for C_2, obtaining

{(>, =), (=, =), (<, =), (>, >), (>, <)}

Coverage of this constraint set will guarantee detection of relational operator errors in C_3.

17.5.2 Data Flow Testing

The *data flow testing* method selects test paths of a program according to the locations of definitions and uses of variables in the program. A number of data flow testing strategies have been studied and compared (e.g., [FRA88], [NTA88], [FRA93]).

To illustrate the data flow testing approach, assume that each statement in a program is assigned a unique statement number and that each function does not modify its parameters or global variables. For a statement with S as its statement number,

DEF(S) = {X | statement S contains a definition of X}
USE(S) = {X | statement S contains a use of X}

If statement S is an *if* or *loop* statement, its DEF set is empty and its USE set is based on the condition of statement S. The definition of variable X at statement S is said to be *live* at statement S' if there exists a path from statement S to statement S' that contains no other definition of X.

A *definition-use* (DU) *chain* of variable X is of the form [X, S, S'], where S and S' are statement numbers, X is in DEF(S) and USE(S'), and the definition of X in statement S is live at statement S'.

It is unrealistic to assume that data flow testing will be used extensively when testing a large system. However, it can be used in a targeted fashion for areas of the software that are suspect.

One simple data flow testing strategy is to require that every DU chain be covered at least once. We refer to this strategy as the *DU testing strategy.* It has been shown that DU testing does not guarantee the coverage of all branches of a program. However, a branch is not guaranteed to be covered by DU testing only in rare situations such as if-then-else constructs in which the *then part* has no definition of any variable and the *else part* does not exist. In this situation, the else branch of the *if* statement is not necessarily covered by DU testing.

Data flow testing strategies are useful for selecting test paths of a program containing nested *if* and *loop* statements. To illustrate this, consider the application of DU testing to select test paths for the PDL that follows:

```
proc x
   B1;
   do while C1
      if C2
         then
            if C4
               then B4;
               else B5;
            endif;
         else
            if C3
               then B2;
               else B3;
            endif;
         endif;
      enddo;
      B6;
   end proc;
```

To apply the DU testing strategy to select test paths of the control flow diagram, we need to know the definitions and uses of variables in each condition or block in the PDL. Assume that variable X is defined in the last statement of blocks B1, B2, B3, B4, and B5 and is used in the first statement of blocks B2, B3, B4, B5, and B6. The DU testing strategy requires an execution of the shortest path from each of B_i, $0 < i \leq 5$,

to each of B_j, $1 < j \leq 6$. (Such testing also covers any use of variable X in conditions C1, C2, C3, and C4.) Although there are 25 DU chains of variable X, we need only five paths to cover these DU chains. The reason is that five paths are needed to cover the DU chain of X from B_i, $0 < i \leq 5$, to B6 and other DU chains can be covered by making these five paths contain iterations of the loop.

If we apply the branch testing strategy to select test paths of the PDL just noted, we do not need any additional information. To select paths of the diagram for BRO testing, we need to know the structure of each condition or block. (After the selection of a path of a program, we need to determine whether the path is feasible for the program; that is, whether at least one input exists that exercises the path.)

Since the statements in a program are related to each other according to the definitions and uses of variables, the data flow testing approach is effective for error detection. However, the problems of measuring test coverage and selecting test paths for data flow testing are more difficult than the corresponding problems for condition testing.

17.5.3 Loop Testing

Complex loop structures are another hiding place for bugs. It's well worth spending time designing tests that fully exercise loop structures.

Loops are the cornerstone for the vast majority of all algorithms implemented in software. And yet, we often pay them little heed while conducting software tests.

Loop testing is a white-box testing technique that focuses exclusively on the validity of loop constructs. Four different classes of loops [BEI90] can be defined: simple loops, concatenated loops, nested loops, and unstructured loops (Figure 17.8).

Simple loops. The following set of tests can be applied to simple loops, where n is the maximum number of allowable passes through the loop.

1. Skip the loop entirely.
2. Only one pass through the loop.
3. Two passes through the loop.
4. m passes through the loop where $m < n$.
5. $n - 1$, n, $n + 1$ passes through the loop.

Nested loops. If we were to extend the test approach for simple loops to nested loops, the number of possible tests would grow geometrically as the level of nesting increases. This would result in an impractical number of tests. Beizer [BEI90] suggests an approach that will help to reduce the number of tests:

1. Start at the innermost loop. Set all other loops to minimum values.
2. Conduct simple loop tests for the innermost loop while holding the outer loops at their minimum iteration parameter (e.g., loop counter) values. Add other tests for out-of-range or excluded values.

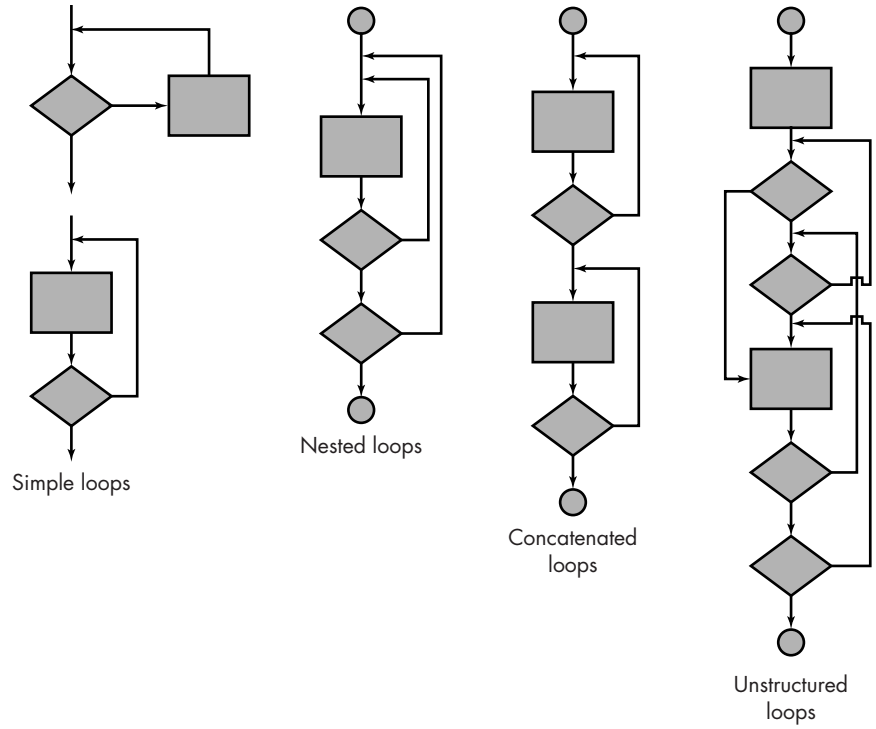


FIGURE 17.8
Classes of loops

3. Work outward, conducting tests for the next loop, but keeping all other outer loops at minimum values and other nested loops to "typical" values.
4. Continue until all loops have been tested.

Concatenated loops. Concatenated loops can be tested using the approach defined for simple loops, if each of the loops is independent of the other. However, if two loops are concatenated and the loop counter for loop 1 is used as the initial value for loop 2, then the loops are not independent. When the loops are not independent, the approach applied to nested loops is recommended.

You can't test unstructured loops effectively. Redesign them.

Unstructured loops. Whenever possible, this class of loops should be redesigned to reflect the use of the structured programming constructs (Chapter 16).

17.6 BLACK-BOX TESTING

Black-box testing, also called *behavioral testing,* focuses on the functional requirements of the software. That is, black-box testing enables the software engineer to derive sets of input conditions that will fully exercise all functional requirements for a program. Black-box testing is not an alternative to white-box techniques. Rather, it is a complementary approach that is likely to uncover a different class of errors than white-box methods.

Black-box testing attempts to find errors in the following categories: (1) incorrect or missing functions, (2) interface errors, (3) errors in data structures or external data base access, (4) behavior or performance errors, and (5) initialization and termination errors.

Unlike white-box testing, which is performed early in the testing process, black-box testing tends to be applied during later stages of testing (see Chapter 18). Because black-box testing purposely disregards control structure, attention is focused on the information domain. Tests are designed to answer the following questions:

- How is functional validity tested?
- How is system behavior and performance tested?
- What classes of input will make good test cases?
- Is the system particularly sensitive to certain input values?
- How are the boundaries of a data class isolated?
- What data rates and data volume can the system tolerate?
- What effect will specific combinations of data have on system operation?

By applying black-box techniques, we derive a set of test cases that satisfy the following criteria [MYE79]: (1) test cases that reduce, by a count that is greater than one, the number of additional test cases that must be designed to achieve reasonable testing and (2) test cases that tell us something about the presence or absence of classes of errors, rather than an error associated only with the specific test at hand.

17.6.1 Graph-Based Testing Methods

A graph represents the relationships between data objects and program objects, enabling us to derive test cases that search for errors associated with these relationships.

The first step in black-box testing is to understand the objects[6] that are modeled in software and the relationships that connect these objects. Once this has been accomplished, the next step is to define a series of tests that verify "all objects have the expected relationship to one another [BEI95]." Stated in another way, software testing begins by creating a graph of important objects and their relationships and then devising a series of tests that will cover the graph so that each object and relationship is exercised and errors are uncovered.

To accomplish these steps, the software engineer begins by creating a *graph*—a collection of *nodes* that represent objects; *links* that represent the relationships between objects; *node weights* that describe the properties of a node (e.g., a specific data value or state behavior); and *link weights* that describe some characteristic of a link.[7]

---

6 In this context, the term *object* encompasses the data objects that we discussed in Chapters 11 and 12 as well as program objects such as modules or collections of programming language statements.

7 If these concepts seem vaguely familiar, recall that graphs were also used in Section 17.4.1 to create a program graph for the basis path testing method. The nodes of the program graph contained instructions (program objects) characterized as either procedural design representations or source code, and the directed links indicated the control flow between these program objects. Here, the use of graphs is extended to encompass black-box testing as well.

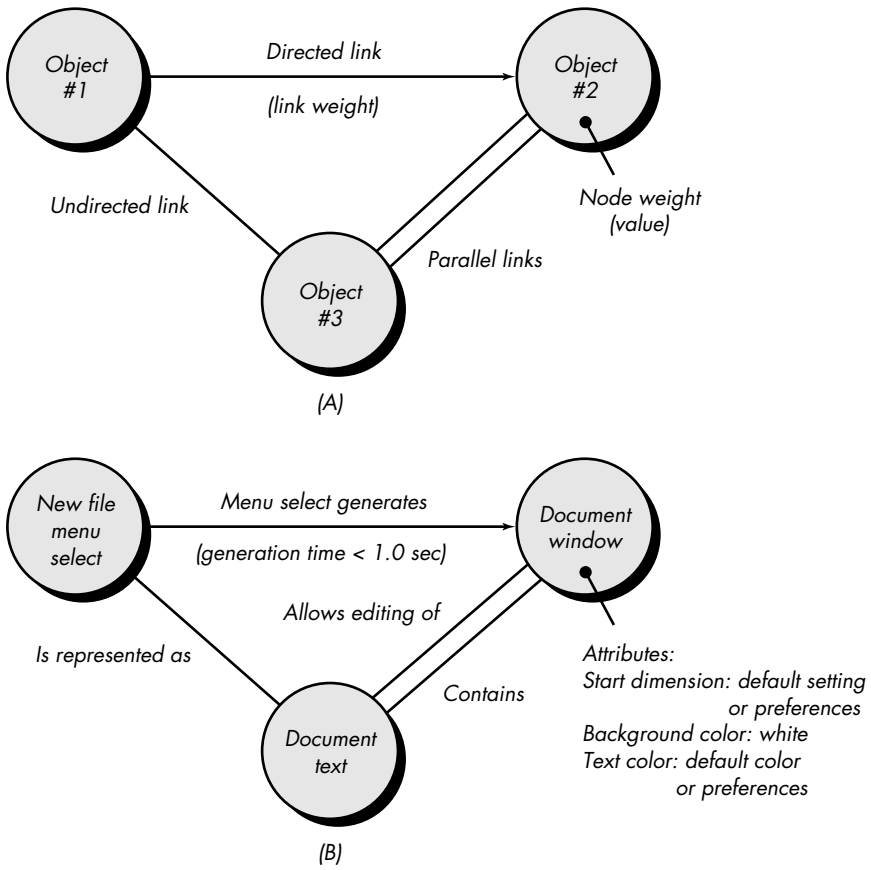


FIGURE 17.9
(A) Graph notation (B) Simple example

The symbolic representation of a graph is shown in Figure 17.9A. Nodes are represented as circles connected by links that take a number of different forms. A *directed link* (represented by an arrow) indicates that a relationship moves in only one direction. A *bidirectional link,* also called a *symmetric link*, implies that the relationship applies in both directions. *Parallel links* are used when a number of different relationships are established between graph nodes.

As a simple example, consider a portion of a graph for a word-processing application (Figure 17.9B) where

Object #1 = **new file menu select**
Object #2 = **document window**
Object #3 = **document text**

Referring to the figure, a menu select on **new file** generates a **document window.** The node weight of **document window** provides a list of the window attributes that are to be expected when the window is generated. The link weight indicates that the window must be generated in less than 1.0 second. An undirected link establishes a

symmetric relationship between the **new file menu select** and **document text,** and parallel links indicate relationships between **document window** and **document text.** In reality, a far more detailed graph would have to be generated as a precursor to test case design. The software engineer then derives test cases by traversing the graph and covering each of the relationships shown. These test cases are designed in an attempt to find errors in any of the relationships.

Beizer [BEI95] describes a number of behavioral testing methods that can make use of graphs:

Transaction flow modeling. The nodes represent steps in some transaction (e.g., the steps required to make an airline reservation using an on-line service), and the links represent the logical connection between steps (e.g., **flight.information.input** is followed by *validation/availability.processing*). The data flow diagram (Chapter 12) can be used to assist in creating graphs of this type.

Finite state modeling. The nodes represent different user observable states of the software (e.g., each of the "screens" that appear as an order entry clerk takes a phone order), and the links represent the transitions that occur to move from state to state (e.g., **order-information** is verified during *inventory-availability look-up* and is followed by **customer-billing-information input**). The state transition diagram (Chapter 12) can be used to assist in creating graphs of this type.

Data flow modeling. The nodes are data objects and the links are the transformations that occur to translate one data object into another. For example, the node **FICA.tax.withheld (FTW)** is computed from **gross.wages (GW)** using the relationship, FTW = 0.62 × GW.

Timing modeling. The nodes are program objects and the links are the sequential connections between those objects. Link weights are used to specify the required execution times as the program executes.

A detailed discussion of each of these graph-based testing methods is beyond the scope of this book. The interested reader should see [BEI95] for a comprehensive discussion. It is worthwhile, however, to provide a generic outline of the graph-based testing approach.

? What generic activities are required during graph-based testing?

Graph-based testing begins with the definition of all nodes and node weights. That is, objects and attributes are identified. The data model (Chapter 12) can be used as a starting point, but it is important to note that many nodes may be program objects (not explicitly represented in the data model). To provide an indication of the start and stop points for the graph, it is useful to define entry and exit nodes.

Once nodes have been identified, links and link weights should be established. In general, links should be named, although links that represent control flow between program objects need not be named.

In many cases, the graph model may have loops (i.e., a path through the graph in which one or more nodes is encountered more than one time). Loop testing (Section 17.5.3) can also be applied at the behavioral (black-box) level. The graph will assist in identifying those loops that need to be tested.

Each relationship is studied separately so that test cases can be derived. The *transitivity* of sequential relationships is studied to determine how the impact of relationships propagates across objects defined in a graph. Transitivity can be illustrated by considering three objects, **X, Y,** and **Z.** Consider the following relationships:

X is required to compute **Y**
Y is required to compute **Z**

Therefore, a transitive relationship has been established between **X** and **Z**:

X is required to compute **Z**

Based on this transitive relationship, tests to find errors in the calculation of **Z** must consider a variety of values for both **X** and **Y.**

The *symmetry* of a relationship (graph link) is also an important guide to the design of test cases. If a link is indeed bidirectional (symmetric), it is important to test this feature. The UNDO feature [BEI95] in many personal computer applications implements limited symmetry. That is, UNDO allows an action to be negated after it has been completed. This should be thoroughly tested and all exceptions (i.e., places where UNDO cannot be used) should be noted. Finally, every node in the graph should have a relationship that leads back to itself; in essence, a "no action" or "null action" loop. These *reflexive* relationships should also be tested.

As test case design begins, the first objective is to achieve *node coverage.* By this we mean that tests should be designed to demonstrate that no nodes have been inadvertently omitted and that node weights (object attributes) are correct.

Next, *link coverage* is addressed. Each relationship is tested based on its properties. For example, a symmetric relationship is tested to demonstrate that it is, in fact, bidirectional. A transitive relationship is tested to demonstrate that transitivity is present. A reflexive relationship is tested to ensure that a null loop is present. When link weights have been specified, tests are devised to demonstrate that these weights are valid. Finally, loop testing is invoked (Section 17.5.3).

17.6.2 Equivalence Partitioning

Equivalence partitioning is a black-box testing method that divides the input domain of a program into classes of data from which test cases can be derived. An ideal test case single-handedly uncovers a class of errors (e.g., incorrect processing of all character data) that might otherwise require many cases to be executed before the general error is observed. Equivalence partitioning strives to define a test case that uncovers classes of errors, thereby reducing the total number of test cases that must be developed.

Input classes are known relatively early in the software process. For this reason, begin thinking about equivalence partitioning as the design is created.

Test case design for equivalence partitioning is based on an evaluation of equivalence classes for an input condition. Using concepts introduced in the preceding section, if a set of objects can be linked by relationships that are symmetric, transitive, and reflexive, an equivalence class is present [BEI95]. An *equivalence class* represents a set of valid or invalid states for input conditions. Typically, an input condition is either a specific numeric value, a range of values, a set of related values, or a Boolean condition. Equivalence classes may be defined according to the following guidelines:

1. If an input condition specifies a *range,* one valid and two invalid equivalence classes are defined.
2. If an input condition requires a specific *value,* one valid and two invalid equivalence classes are defined.
3. If an input condition specifies a member of a *set,* one valid and one invalid equivalence class are defined.
4. If an input condition is *Boolean,* one valid and one invalid class are defined.

As an example, consider data maintained as part of an automated banking application. The user can access the bank using a personal computer, provide a six-digit password, and follow with a series of typed commands that trigger various banking functions. During the log-on sequence, the software supplied for the banking application accepts data in the form

area code—blank or three-digit number
prefix—three-digit number not beginning with 0 or 1
suffix—four-digit number
password—six digit alphanumeric string
commands—check, deposit, bill pay, and the like

The input conditions associated with each data element for the banking application can be specified as

area code: Input condition, *Boolean*—the area code may or may not be present.
Input condition, *range*—values defined between 200 and 999, with specific exceptions.
prefix: Input condition, *range*—specified value >200
Input condition, value—four-digit length
password: Input condition, *Boolean*—a password may or may not be present.
Input condition, *value*—six-character string.
command: Input condition, *set*—containing commands noted previously.

Applying the guidelines for the derivation of equivalence classes, test cases for each input domain data item can be developed and executed. Test cases are selected so that the largest number of attributes of an equivalence class are exercised at once.

17.6.3 Boundary Value Analysis

BVA extends equivalence partitioning by focusing on data at the "edges" of an equivalence class.

For reasons that are not completely clear, a greater number of errors tends to occur at the boundaries of the input domain rather than in the "center." It is for this reason that *boundary value analysis* (BVA) has been developed as a testing technique. Boundary value analysis leads to a selection of test cases that exercise bounding values.

Boundary value analysis is a test case design technique that complements equivalence partitioning. Rather than selecting any element of an equivalence class, BVA leads to the selection of test cases at the "edges" of the class. Rather than focusing solely on input conditions, BVA derives test cases from the output domain as well [MYE79].

Guidelines for BVA are similar in many respects to those provided for equivalence partitioning:

How do I create BVA test cases?

1. If an input condition specifies a range bounded by values *a* and *b,* test cases should be designed with values *a* and *b* and just above and just below *a* and *b*.
2. If an input condition specifies a number of values, test cases should be developed that exercise the minimum and maximum numbers. Values just above and below minimum and maximum are also tested.
3. Apply guidelines 1 and 2 to output conditions. For example, assume that a temperature vs. pressure table is required as output from an engineering analysis program. Test cases should be designed to create an output report that produces the maximum (and minimum) allowable number of table entries.
4. If internal program data structures have prescribed boundaries (e.g., an array has a defined limit of 100 entries), be certain to design a test case to exercise the data structure at its boundary.

Most software engineers intuitively perform BVA to some degree. By applying these guidelines, boundary testing will be more complete, thereby having a higher likelihood for error detection.

16.6.4 Comparison Testing

There are some situations (e.g., aircraft avionics, automobile braking systems) in which the reliability of software is absolutely critical. In such applications redundant hardware and software are often used to minimize the possibility of error. When redundant software is developed, separate software engineering teams develop independent versions of an application using the same specification. In such situations, each version can be tested with the same test data to ensure that all provide identical output. Then all versions are executed in parallel with real-time comparison of results to ensure consistency.

Using lessons learned from redundant systems, researchers (e.g., [BRI87]) have suggested that independent versions of software be developed for critical applications, even when only a single version will be used in the delivered computer-based system. These independent versions form the basis of a black-box testing technique called *comparison testing* or *back-to-back testing* [KNI89].

When multiple implementations of the same specification have been produced, test cases designed using other black-box techniques (e.g., equivalence partitioning) are provided as input to each version of the software. If the output from each version is the same, it is assumed that all implementations are correct. If the output is different, each of the applications is investigated to determine if a defect in one or more versions is responsible for the difference. In most cases, the comparison of outputs can be performed by an automated tool.

Comparison testing is not foolproof. If the specification from which all versions have been developed is in error, all versions will likely reflect the error. In addition, if each of the independent versions produces identical but incorrect results, condition testing will fail to detect the error.

17.6.5 Orthogonal Array Testing

There are many applications in which the input domain is relatively limited. That is, the number of input parameters is small and the values that each of the parameters may take are clearly bounded. When these numbers are very small (e.g., three input parameters taking on three discrete values each), it is possible to consider every input permutation and exhaustively test processing of the input domain. However, as the number of input values grows and the number of discrete values for each data item increases, exhaustive testing become impractical or impossible.

Orthogonal array testing can be applied to problems in which the input domain is relatively small but too large to accommodate exhaustive testing. The orthogonal array testing method is particularly useful in finding errors associated with *region faults*—an error category associated with faulty logic within a software component.

Orthogonal array testing enables you to design test cases that provide maximum test coverage with a reasonable number of test cases.

To illustrate the difference between orthogonal array testing and more conventional "one input item at a time" approaches, consider a system that has three input items, *X, Y,* and *Z.* Each of these input items has three discrete values associated with it. There are $3^3 = 27$ possible test cases. Phadke [PHA97] suggests a geometric view of the possible test cases associated with *X, Y,* and *Z* illustrated in Figure 17.10. Referring to the figure, one input item at a time may be varied in sequence along each input axis. This results in relatively limited coverage of the input domain (represented by the left-hand cube in the figure).

When orthogonal array testing occurs, an *L9 orthogonal array* of test cases is created. The L9 orthogonal array has a "balancing property [PHA97]." That is, test cases (represented by black dots in the figure) are "dispersed uniformly throughout the test

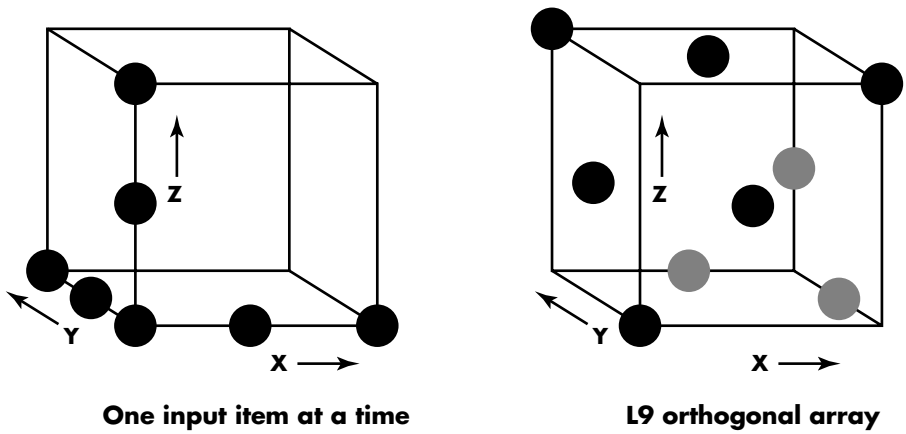


FIGURE 17.10
A geometric view of test cases [PHA97]

domain," as illustrated in the right-hand cube in Figure 17.10. Test coverage across the input domain is more complete.

To illustrate the use of the L9 orthogonal array, consider the *send* function for a fax application. Four parameters, P1, P2, P3, and P4, are passed to the *send* function. Each takes on three discrete values. For example, P1 takes on values:

P1 = 1, send it now
P1 = 2, send it one hour later
P1 = 3, send it after midnight

P2, P3, and P4 would also take on values of 1, 2 and 3, signifying other *send* functions.

If a "one input item at a time" testing strategy were chosen, the following sequence of tests (P1, P2, P3, P4) would be specified: (1, 1, 1, 1), (2, 1, 1, 1), (3, 1, 1, 1), (1, 2, 1, 1), (1, 3, 1, 1), (1, 1, 2, 1), (1, 1, 3, 1), (1, 1, 1, 2), and (1, 1, 1, 3). Phadke [PHA97] assesses these test cases in the following manner:

> Such test cases are useful only when one is certain that these test parameters do not interact. They can detect logic faults where a single parameter value makes the software malfunction. These faults are called *single mode faults*. This method cannot detect logic faults that cause malfunction when two or more parameters simultaneously take certain values; that is, it cannot detect any interactions. Thus its ability to detect faults is limited.

Given the relatively small number of input parameters and discrete values, exhaustive testing is possible. The number of tests required is $3^4 = 81$, large, but manageable. All faults associated with data item permutation would be found, but the effort required is relatively high.

The orthogonal array testing approach enables us to provide good test coverage with far fewer test cases than the exhaustive strategy. An L9 orthogonal array for the fax send function is illustrated in Figure 17.11.

FIGURE 17.11 An L9 orthogonal array

Test case	Test parameters			
	P_1	P_2	P_3	P_4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Phadke [PHA97] assesses the result of tests using the L9 orthogonal array in the following manner:

Detect and isolate all single mode faults. A single mode fault is a consistent problem with any level of any single parameter. For example, if all test cases of factor P1 = 1 cause an error condition, it is a single mode failure. In this example tests 1, 2 and 3 [Figure 17.11] will show errors. By analyzing the information about which tests show errors, one can identify which parameter values cause the fault. In this example, by noting that tests 1, 2, and 3 cause an error, one can isolate [logical processing associated with "send it now" (P1 = 1)] as the source of the error. Such an isolation of fault is important to fix the fault.

Detect all double mode faults. If there exists a consistent problem when specific levels of two parameters occur together, it is called a *double mode fault.* Indeed, a double mode fault is an indication of pairwise incompatibility or harmful interactions between two test parameters.

Multimode faults. Orthogonal arrays [of the type shown] can assure the detection of only single and double mode faults. However, many multi-mode faults are also detected by these tests.

A detailed discussion of orthogonal array testing can be found in [PHA89].

17.7 TESTING FOR SPECIALIZED ENVIRONMENTS, ARCHITECTURES, AND APPLICATIONS

As computer software has become more complex, the need for specialized testing approaches has also grown. The white-box and black-box testing methods discussed in Sections 17.5 and 17.6 are applicable across all environments, architectures, and

applications, but unique guidelines and approaches to testing are sometimes warranted. In this section we consider testing guidelines for specialized environments, architectures, and applications that are commonly encountered by software engineers.

17.7.1 Testing GUIs

XRef

Guidelines for the design of GUIs are presented in Chapter 15.

Graphical user interfaces (GUIs) present interesting challenges for software engineers. Because of reusable components provided as part of GUI development environments, the creation of the user interface has become less time consuming and more precise. But, at the same time, the complexity of GUIs has grown, leading to more difficulty in the design and execution of test cases.

Because many modern GUIs have the same look and feel, a series of standard tests can be derived. Finite state modeling graphs may be used to derive a series of tests that address specific data and program objects that are relevant to the GUI.

Testing GUIs

Due to the large number of permutations associated with GUI operations, testing should be approached using automated tools. A wide array of GUI testing tools has appeared on the market over the past few years. For further discussion, see Chapter 31.

17.7.2 Testing of Client/Server Architectures

Client/server (C/S) architectures represent a significant challenge for software testers. The distributed nature of client/server environments, the performance issues associated with transaction processing, the potential presence of a number of different hardware platforms, the complexities of network communication, the need to service multiple clients from a centralized (or in some cases, distributed) database, and the coordination requirements imposed on the server all combine to make testing of C/S architectures and the software that reside within them considerably more difficult than stand-alone applications. In fact, recent industry studies indicate a significant increase in testing time and cost when C/S environments are developed.

XRef

Client/server software engineering is presented in Chapter 28.

17.7.3 Testing Documentation and Help Facilities

The term *software testing* conjures images of large numbers of test cases prepared to exercise computer programs and the data that they manipulate. Recalling the definition of *software* presented in the first chapter of this book, it is important to note that testing must also extend to the third element of the software configuration—documentation.

Errors in documentation can be as devastating to the acceptance of the program as errors in data or source code. Nothing is more frustrating than following a user guide or an on-line help facility exactly and getting results or behaviors that do not coincide with those predicted by the documentation. It is for this reason that that documentation testing should be a meaningful part of every software test plan.

Documentation testing can be approached in two phases. The first phase, *review and inspection* (Chapter 8), examines the document for editorial clarity. The second phase, *live test,* uses the documentation in conjunction with the use of the actual program.

Surprisingly, a live test for documentation can be approached using techniques that are analogous to many of the black-box testing methods discussed in Section 17.6. Graph-based testing can be used to describe the use of the program; equivalence partitioning and boundary value analysis can be used to define various classes of input and associated interactions. Program usage is then tracked through the documentation. The following questions should be answered during both phases:

? What questions should be addressed as we test documentation?

- Does the documentation accurately describe how to accomplish each mode of use?
- Is the description of each interaction sequence accurate?
- Are examples accurate?
- Are terminology, menu descriptions, and system responses consistent with the actual program?
- Is it relatively easy to locate guidance within the documentation?
- Can troubleshooting be accomplished easily with the documentation?
- Are the document table of contents and index accurate and complete?
- Is the design of the document (layout, typefaces, indentation, graphics) conducive to understanding and quick assimilation of information?
- Are all software error messages displayed for the user described in more detail in the document? Are actions to be taken as a consequence of an error message clearly delineated?
- If hypertext links are used, are they accurate and complete?
- If hypertext is used, is the navigation design appropriate for the information required?

The only viable way to answer these questions is to have an independent third party (e.g., selected users) test the documentation in the context of program usage. All discrepancies are noted and areas of document ambiguity or weakness are defined for potential rewrite.

17.7.4 Testing for Real-Time Systems

The time-dependent, asynchronous nature of many real-time applications adds a new and potentially difficult element to the testing mix—time. Not only does the test case designer have to consider white- and black-box test cases but also event handling (i.e., interrupt processing), the timing of the data, and the parallelism of the tasks (processes) that handle the data. In many situations, test data provided when a real-

time system is in one state will result in proper processing, while the same data provided when the system is in a different state may lead to error.

For example, the real-time software that controls a new photocopier accepts operator interrupts (i.e., the machine operator hits control keys such as RESET or DARKEN) with no error when the machine is making copies (in the "copying" state). These same operator interrupts, if input when the machine is in the "jammed" state, cause a display of the diagnostic code indicating the location of the jam to be lost (an error).

Real-Time Systems

In addition, the intimate relationship that exists between real-time software and its hardware environment can also cause testing problems. Software tests must consider the impact of hardware faults on software processing. Such faults can be extremely difficult to simulate realistically.

Comprehensive test case design methods for real-time systems have yet to evolve. However, an overall four-step strategy can be proposed:

Task testing. The first step in the testing of real-time software is to test each task independently. That is, white-box and black-box tests are designed and executed for each task. Each task is executed independently during these tests. Task testing uncovers errors in logic and function but not timing or behavior.

Behavioral testing. Using system models created with CASE tools, it is possible to simulate the behavior of a real-time system and examine its behavior as a consequence of external events. These analysis activities can serve as the basis for the design of test cases that are conducted when the real-time software has been built. Using a technique that is similar to equivalence partitioning (Section 17.6.1), events (e.g., interrupts, control signals) are categorized for testing. For example, events for the photocopier might be user interrupts (e.g., reset counter), mechanical interrupts (e.g., paper jammed), system interrupts (e.g., toner low), and failure modes (e.g., roller overheated). Each of these events is tested individually and the behavior of the executable system is examined to detect errors that occur as a consequence of processing associated with these events. The behavior of the system model (developed during the analysis activity) and the executable software can be compared for conformance. Once each class of events has been tested, events are presented to the system in random order and with random frequency. The behavior of the software is examined to detect behavior errors.

The *Software Testing Discussion Forum* presents topics of interest to testing professionals: **www.ondaweb.com/HyperNews/get.cgi/forums/sti.html**

Intertask testing. Once errors in individual tasks and in system behavior have been isolated, testing shifts to time-related errors. Asynchronous tasks that are known to communicate with one another are tested with different data rates and processing load to determine if intertask synchronization errors will occur. In addition, tasks that communicate via a message queue or data store are tested to uncover errors in the sizing of these data storage areas.

System testing. Software and hardware are integrated and a full range of system tests (Chapter 18) are conducted in an attempt to uncover errors at the software/hardware interface. Most real-time systems process interrupts. Therefore, testing the handling of these Boolean events is essential. Using the state transition diagram and the control specification (Chapter 12), the tester develops a list of all possible interrupts and the processing that occurs as a consequence of the interrupts. Tests are then designed to assess the following system characteristics:

- Are interrupt priorities properly assigned and properly handled?
- Is processing for each interrupt handled correctly?
- Does the performance (e.g., processing time) of each interrupt-handling procedure conform to requirements?
- Does a high volume of interrupts arriving at critical times create problems in function or performance?

In addition, global data areas that are used to transfer information as part of interrupt processing should be tested to assess the potential for the generation of side effects.

17.8 SUMMARY

The primary objective for test case design is to derive a set of tests that have the highest likelihood for uncovering errors in the software. To accomplish this objective, two different categories of test case design techniques are used: white-box testing and black-box testing.

White-box tests focus on the program control structure. Test cases are derived to ensure that all statements in the program have been executed at least once during testing and that all logical conditions have been exercised. Basis path testing, a white-box technique, makes use of program graphs (or graph matrices) to derive the set of linearly independent tests that will ensure coverage. Condition and data flow testing further exercise program logic, and loop testing complements other white-box techniques by providing a procedure for exercising loops of varying degrees of complexity.

Hetzel [HET84] describes white-box testing as "testing in the small." His implication is that the white-box tests that we have considered in this chapter are typically applied to small program components (e.g., modules or small groups of modules). Black-box testing, on the other hand, broadens our focus and might be called "testing in the large."

Black-box tests are designed to validate functional requirements without regard to the internal workings of a program. Black-box testing techniques focus on the information domain of the software, deriving test cases by partitioning the input and output domain of a program in a manner that provides thorough test coverage. Equiv-

alence partitioning divides the input domain into classes of data that are likely to exercise specific software function. Boundary value analysis probes the program's ability to handle data at the limits of acceptability. Orthogonal array testing provides an efficient, systematic method for testing systems will small numbers of input parameters.

Specialized testing methods encompass a broad array of software capabilities and application areas. Testing for graphical user interfaces, client/server architectures, documentation and help facilities, and real-time systems each require specialized guidelines and techniques.

Experienced software developers often say, "Testing never ends, it just gets transferred from you [the software engineer] to your customer. Every time your customer uses the program, a test is being conducted." By applying test case design, the software engineer can achieve more complete testing and thereby uncover and correct the highest number of errors before the "customer's tests" begin.

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PROBLEMS AND POINTS TO PONDER

17.1. Myers [MYE79] uses the following program as a self-assessment for your ability to specify adequate testing: A program reads three integer values. The three values are interpreted as representing the lengths of the sides of a triangle. The program prints a message that states whether the triangle is scalene, isosceles, or equilateral. Develop a set of test cases that you feel will adequately test this program.

17.2. Design and implement the program (with error handling where appropriate) specified in Problem 1. Derive a flow graph for the program and apply basis path testing to develop test cases that will guarantee that all statements in the program have been tested. Execute the cases and show your results.

17.3. Can you think of any additional testing objectives that are not discussed in Section 17.1.1?

17.4. Apply the basis path testing technique to any one of the programs that you have implemented in Problems 16.4 through 16.11.

17.5. Specify, design, and implement a software tool that will compute the cyclomatic complexity for the programming language of your choice. Use the graph matrix as the operative data structure in your design.

17.6. Read Beizer [BEI95] and determine how the program you have developed in Problem 17.5 can be extended to accommodate various link weights. Extend your tool to process execution probabilities or link processing times.

17.7. Use the condition testing approach described in Section 17.5.1 to design a set of test cases for the program you created in Problem 17.2.

17.8. Using the data flow testing approach described in Section 17.5.2, make a list of definition-use chains for the program you created in Problem 17.2.

17.9. Design an automated tool that will recognize loops and categorize them as indicated in Section 17.5.3.

17.10. Extend the tool described in Problem 17.9 to generate test cases for each loop category, once encountered. It will be necessary to perform this function interactively with the tester.

17.11. Give at least three examples in which black-box testing might give the impression that "everything's OK," while white-box tests might uncover an error. Give at least three examples in which white-box testing might give the impression that "everything's OK," while black-box tests might uncover an error.

17.12. Will exhaustive testing (even if it is possible for very small programs) guarantee that the program is 100 percent correct?

17.13. Using the equivalence partitioning method, derive a set of test cases for *SafeHome* system described earlier in this book.

17.14. Using boundary value analysis, derive a set of test cases for the PHTRS system described in Problem 12.13.

17.15. Do a bit of outside research and write a brief paper that discusses the mechanics for generating orthogonal arrays for test data.

17.16. Select a specific GUI for a program with which you are familiar and design a series of tests to exercise the GUI.

17.17. Do some research on a client/server system with which you are familiar. Develop a set of user scenarios and then create an operational profile for the system.

17.18. Test a user manual (or help facility) for an application that you use frequently. Find at least one error in the documentation.

FURTHER READINGS AND INFORMATION SOURCES

Software engineering presents both technical and management challenges. Books by Black (*Managing the Testing Process,* Microsoft Press, 1999); Dustin, Rashka, and Paul (*Test Process Improvement: Step-by-Step Guide to Structured Testing,* Addison-Wesley, 1999); Perry (*Surviving the Top Ten Challenges of Software Testing: A People-Oriented Approach,* Dorset House, 1997); and Kit and Finzi (*Software Testing in the Real World: Improving the Process,* Addison-Wesley, 1995) address management and process issues.

A number of excellent books are now available for those readers who desire additional information on software testing technology. Kaner, Nguyen, and Falk (*Testing Computer Software,* Wiley, 1999); Hutcheson (*Software Testing Methods and Metrics: The Most Important Tests,* McGraw-Hill, 1997); Marick (*The Craft of Software Testing: Subsystem Testing Including Object-Based and Object-Oriented Testing,* Prentice-Hall, 1995); Jorgensen (*Software Testing : A Craftsman's Approach,* CRC Press, 1995) present treatments of the subject that consider testing methods and strategies.

Myers [MYE79] remains a classic text, covering black-box techniques in considerable detail. Beizer [BEI90] provides comprehensive coverage of white-box techniques, introducing a level of mathematical rigor that has often been missing in other treatments of testing. His later book [BEI95] presents a concise treatment of important methods. Perry (*Effective Methods for Software Testing,* Wiley-QED, 1995) and Friedman and Voas (*Software Assessment: Reliability, Safety, Testability,* Wiley, 1995) present good introductions to testing strategies and tactics. Mosley (*The Handbook of MIS Application Software Testing,* Prentice-Hall, 1993) discusses testing issues for large information systems, and Marks (*Testing Very Big Systems,* McGraw-Hill, 1992) discusses the special issues that must be considered when testing major programming systems.

Software testing is a resource-intensive activity. It is for this reason that many organizations automate parts of the testing process. Books by Dustin, Rashka, and Poston (*Automated Software Testing: Introduction, Management, and Performance,* Addison-Wesley, 1999) and Poston (*Automating Specification-Based Software Testing,* IEEE Computer Society, 1996) discuss tools, strategies, and methods for automated testing. An excellent source of information on automated tools for software testing is the *Testing Tools Reference Guide* (Software Quality Engineering, Jacksonville, FL, updated yearly). This directory contains descriptions of hundreds of testing tools, categorized by testing activity, hardware platform, and software support.

A number of books consider testing methods and strategies in specialized application areas. Gardiner (*Testing Safety-Related Software: A Practical Handbook,* Springer-Verlag, 1999) has edited a book that addresses testing of safety-critical systems. Mosley (*Client/Server Software Testing on the Desk Top and the Web,* Prentice-Hall, 1999) discusses the test process for clients, servers, and network components. Rubin (*Handbook of Usability Testing,* Wiley, 1994) has written a useful guide for those who must exercise human interfaces.

A wide variety of information sources on software testing and related subjects is available on the Internet. An up-to-date list of World Wide Web references that are relevant to testing concepts, methods, and strategies can be found at the SEPA Web site:

http://www.mhhe.com/engcs/compsci/sepa/resources/test-techniques.mhtml

CHAPTER

18 SOFTWARE TESTING STRATEGIES

KEY CONCEPTS

A strategy for software testing integrates software test case design methods into a well-planned series of steps that result in the successful construction of software. The strategy provides a road map that describes the steps to be conducted as part of testing, when these steps are planned and then undertaken, and how much effort, time, and resources will be required. Therefore, any testing strategy must incorporate test planning, test case design, test execution, and resultant data collection and evaluation.

A software testing strategy should be flexible enough to promote a customized testing approach. At the same time, it must be rigid enough to promote reasonable planning and management tracking as the project progresses. Shooman [SHO83] discusses these issues:

> In many ways, testing is an individualistic process, and the number of different types of tests varies as much as the different development approaches. For many years, our only defense against programming errors was careful design and the native intelligence of the programmer. We are now in an era in which modern design techniques [and formal technical reviews] are helping us to reduce the number of initial errors that are inherent in the code. Similarly, different test methods are beginning to cluster themselves into several distinct approaches and philosophies.

QUICK LOOK

What is it? Designing effective test cases (Chapter 17) is important, but so is the strategy you use to execute them. Should you develop a formal plan for your tests? Should you test the entire program as a whole or run tests only on a small part of it? Should you rerun tests you've already conducted as you add new components to a large system? When should you involve the customer? These and many other questions are answered when you develop a software testing strategy.

Who does it? A strategy for software testing is developed by the project manager, software engineers, and testing specialists.

Why is it important? Testing often accounts for more project effort than any other software engineering activity. If it is conducted haphazardly, time is wasted, unnecessary effort is expended, and even worse, errors sneak through undetected. It would therefore seem reasonable to establish a systematic strategy for testing software.

What are the steps? Testing begins "in the small" and progresses "to the large." By this we mean that early testing focuses on a single component and applies white- and black-box tests to uncover errors in program logic and function. After individual components are tested they must be integrated. Testing continues as the software is constructed. Finally, a series of high-order tests are executed once the full program is operational.

QUICK LOOK

These tests are designed to uncover errors in requirements.

What is the work product? A Test Specification documents the software team's approach to testing by defining a plan that describes an overall strategy and a procedure that defines specific testing steps and the tests that will be conducted.

How do I ensure that I've done it right? By reviewing the Test Specification prior to testing, you can assess the completeness of test cases and testing tasks. An effective test plan and procedure will lead to the orderly construction of the software and the discovery of errors at each stage in the construction process.

These "approaches and philosophies" are what we shall call *strategy*. In Chapter 17, the technology of software testing was presented.[1] In this chapter, we focus our attention on the strategy for software testing.

18.1 A STRATEGIC APPROACH TO SOFTWARE TESTING

Testing is a set of activities that can be planned in advance and conducted systematically. For this reason a template for software testing—a set of steps into which we can place specific test case design techniques and testing methods—should be defined for the software process.

A number of software testing strategies have been proposed in the literature. All provide the software developer with a template for testing and all have the following generic characteristics:

Useful information on software testing strategies is provided by the *Software Testing Newsletter* at **www.ondaweb.com/sti/newsltr.htm**

- Testing begins at the component level[2] and works "outward" toward the integration of the entire computer-based system.
- Different testing techniques are appropriate at different points in time.
- Testing is conducted by the developer of the software and (for large projects) an independent test group.
- Testing and debugging are different activities, but debugging must be accommodated in any testing strategy.

A strategy for software testing must accommodate low-level tests that are necessary to verify that a small source code segment has been correctly implemented as well as high-level tests that validate major system functions against customer requirements. A strategy must provide guidance for the practitioner and a set of milestones for the manager. Because the steps of the test strategy occur at a time when dead-

1 Testing for object-oriented systems is discussed in Chapter 23.

2 For object-oriented systems, testing begins at the class or object level. See Chapter 23 for details.

line pressure begins to rise, progress must be measurable and problems must surface as early as possible.

18.1.1 Verification and Validation

Software testing is one element of a broader topic that is often referred to as *verification and validation* (V&V). *Verification* refers to the set of activities that ensure that software correctly implements a specific function. *Validation* refers to a different set of activities that ensure that the software that has been built is traceable to customer requirements. Boehm [BOE81] states this another way:

Verification: "Are we building the product right?"
Validation: "Are we building the right product?"

XRef
SQA activities are discussed in detail in Chapter 8.

The definition of V&V encompasses many of the activities that we have referred to as *software quality assurance* (SQA).

Verification and validation encompasses a wide array of SQA activities that include formal technical reviews, quality and configuration audits, performance monitoring, simulation, feasibility study, documentation review, database review, algorithm analysis, development testing, qualification testing, and installation testing [WAL89]. Although testing plays an extremely important role in V&V, many other activities are also necessary.

Quote:
"Testing is an unavoidable part of any responsible effort to develop a software system."
William Howden

Testing does provide the last bastion from which quality can be assessed and, more pragmatically, errors can be uncovered. But testing should not be viewed as a safety net. As they say, "You can't test in quality. If it's not there before you begin testing, it won't be there when you're finished testing." Quality is incorporated into software throughout the process of software engineering. Proper application of methods and tools, effective formal technical reviews, and solid management and measurement all lead to quality that is confirmed during testing.

Miller [MIL77] relates software testing to quality assurance by stating that "the underlying motivation of program testing is to affirm software quality with methods that can be economically and effectively applied to both large-scale and small-scale systems."

18.1.2 Organizing for Software Testing

For every software project, there is an inherent conflict of interest that occurs as testing begins. The people who have built the software are now asked to test the software. This seems harmless in itself; after all, who knows the program better than its developers? Unfortunately, these same developers have a vested interest in demonstrating that the program is error free, that it works according to customer requirements, and that it will be completed on schedule and within budget. Each of these interests mitigate against thorough testing.

From a psychological point of view, software analysis and design (along with coding) are *constructive* tasks. The software engineer creates a computer program, its documentation, and related data structures. Like any builder, the software engineer is proud of the edifice that has been built and looks askance at anyone who attempts to tear it down. When testing commences, there is a subtle, yet definite, attempt to "break" the thing that the software engineer has built. From the point of view of the builder, testing can be considered to be (psychologically) *destructive.* So the builder treads lightly, designing and executing tests that will demonstrate that the program works, rather than uncovering errors. Unfortunately, errors will be present. And, if the software engineer doesn't find them, the customer will!

There are often a number of misconceptions that can be erroneously inferred from the preceeding discussion: (1) that the developer of software should do no testing at all, (2) that the software should be "tossed over the wall" to strangers who will test it mercilessly, (3) that testers get involved with the project only when the testing steps are about to begin. Each of these statements is incorrect.

An independent test group does not have the "conflict of interest" that builders of the software have.

The software developer is always responsible for testing the individual units (components) of the program, ensuring that each performs the function for which it was designed. In many cases, the developer also conducts integration testing—a testing step that leads to the construction (and test) of the complete program structure. Only after the software architecture is complete does an independent test group become involved.

If an ITG does not exist within your organization, you'll have to take its point of view. When you test, try to break the software.

The role of an *independent test group* (ITG) is to remove the inherent problems associated with letting the builder test the thing that has been built. Independent testing removes the conflict of interest that may otherwise be present. After all, personnel in the independent group team are paid to find errors.

However, the software engineer doesn't turn the program over to ITG and walk away. The developer and the ITG work closely throughout a software project to ensure that thorough tests will be conducted. While testing is conducted, the developer must be available to correct errors that are uncovered.

The ITG is part of the software development project team in the sense that it becomes involved during the specification activity and stays involved (planning and specifying test procedures) throughout a large project. However, in many cases the ITG reports to the software quality assurance organization, thereby achieving a degree of independence that might not be possible if it were a part of the software engineering organization.

18.1.3 A Software Testing Strategy

The software engineering process may be viewed as the spiral illustrated in Figure 18.1. Initially, system engineering defines the role of software and leads to software requirements analysis, where the information domain, function, behavior, performance, constraints, and validation criteria for software are established. Moving

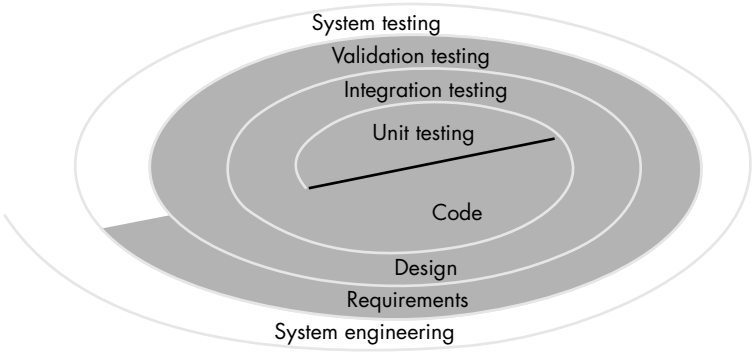

FIGURE 18.1
Testing strategy

inward along the spiral, we come to design and finally to coding. To develop computer software, we spiral inward along streamlines that decrease the level of abstraction on each turn.

? What is the overall strategy for software testing?

A strategy for software testing may also be viewed in the context of the spiral (Figure 18.1). *Unit testing* begins at the vortex of the spiral and concentrates on each unit (i.e., component) of the software as implemented in source code. Testing progresses by moving outward along the spiral to *integration testing,* where the focus is on design and the construction of the software architecture. Taking another turn outward on the spiral, we encounter *validation testing,* where requirements established as part of software requirements analysis are validated against the software that has been constructed. Finally, we arrive at *system testing,* where the software and other system elements are tested as a whole. To test computer software, we spiral out along streamlines that broaden the scope of testing with each turn.

Considering the process from a procedural point of view, testing within the context of software engineering is actually a series of four steps that are implemented sequentially. The steps are shown in Figure 18.2. Initially, tests focus on each component individually, ensuring that it functions properly as a unit. Hence, the name *unit testing*. Unit testing makes heavy use of white-box testing techniques, exercising specific paths in a module's control structure to ensure complete coverage and maximum error detection. Next, components must be assembled or integrated to form the complete software package. Integration testing addresses the issues associated with the dual problems of verification and program construction. Black-box test case design techniques are the most prevalent during integration, although a limited amount of white-box testing may be used to ensure coverage of major control paths. After the software has been integrated (constructed), a set of high-order tests are conducted. Validation criteria (established during requirements analysis) must be tested. Validation testing provides final assurance that software meets all functional, behavioral, and performance requirements. Black-box testing techniques are used exclusively during validation.

XRef
Black-box and white-box testing techniques are discussed in Chapter 17.

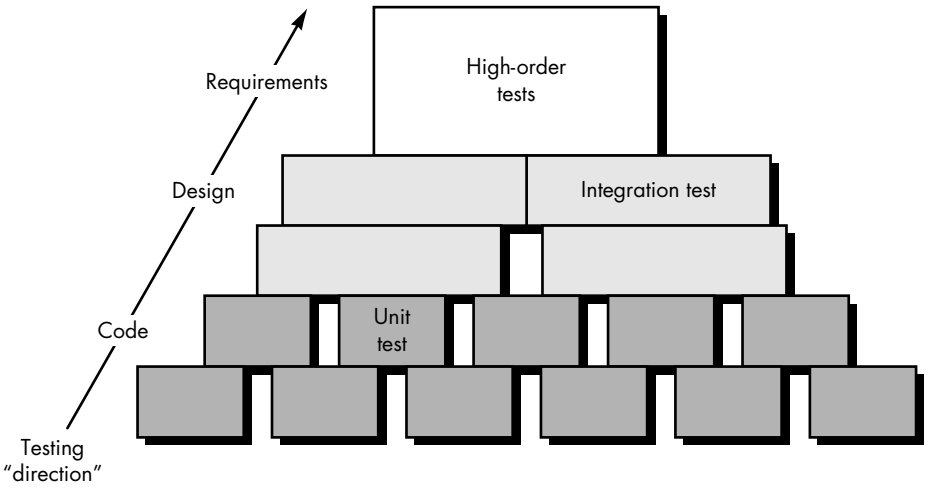

FIGURE 18.2 Software testing steps

The last high-order testing step falls outside the boundary of software engineering and into the broader context of computer system engineering. Software, once validated, must be combined with other system elements (e.g., hardware, people, databases). System testing verifies that all elements mesh properly and that overall system function/performance is achieved.

18.1.4 Criteria for Completion of Testing

A classic question arises every time software testing is discussed: "When are we done testing—how do we know that we've tested enough?" Sadly, there is no definitive answer to this question, but there are a few pragmatic responses and early attempts at empirical guidance.

When are we done testing?

One response to the question is: "You're never done testing, the burden simply shifts from you (the software engineer) to your customer." Every time the customer/user executes a computer program, the program is being tested. This sobering fact underlines the importance of other software quality assurance activities. Another response (somewhat cynical but nonetheless accurate) is: "You're done testing when you run out of time or you run out of money."

Although few practitioners would argue with these responses, a software engineer needs more rigorous criteria for determining when sufficient testing has been conducted. Musa and Ackerman [MUS89] suggest a response that is based on statistical criteria: "No, we cannot be absolutely certain that the software will never fail, but relative to a theoretically sound and experimentally validated statistical model, we have done sufficient testing to say with 95 percent confidence that the probability of 1000 CPU hours of failure free operation in a probabilistically defined environment is at least 0.995."

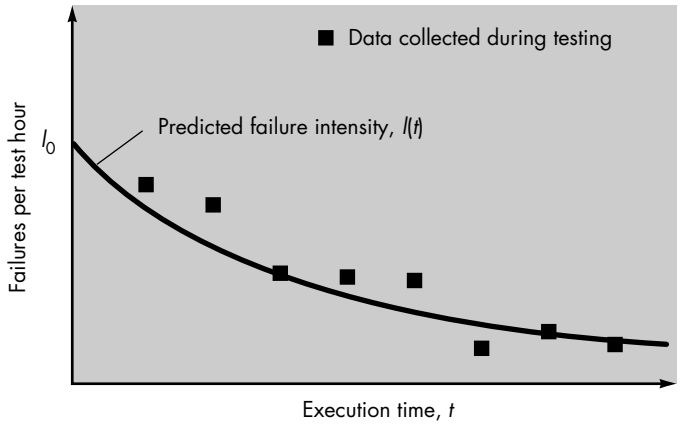

FIGURE 18.3
Failure intensity as a function of execution time

Using statistical modeling and software reliability theory, models of software failures (uncovered during testing) as a function of execution time can be developed [MUS89]. A version of the failure model, called a *logarithmic Poisson execution-time model,* takes the form

$$f(t) = (1/p) \ln [l_0 pt + 1] \quad (18\text{-}1)$$

where $f(t)$ = cumulative number of failures that are expected to occur once the software has been tested for a certain amount of execution time, t,
l_0 = the initial software failure intensity (failures per time unit) at the beginning of testing,
p = the exponential reduction in failure intensity as errors are uncovered and repairs are made.

The instantaneous failure intensity, $l(t)$ can be derived by taking the derivative of $f(t)$

$$l(t) = l_0 / (l_0 pt + 1) \quad (18\text{-}2)$$

Using the relationship noted in Equation (18-2), testers can predict the drop-off of errors as testing progresses. The actual error intensity can be plotted against the predicted curve (Figure 18.3). If the actual data gathered during testing and the logarithmic Poisson execution time model are reasonably close to one another over a number of data points, the model can be used to predict total testing time required to achieve an acceptably low failure intensity.

By collecting metrics during software testing and making use of existing software reliability models, it is possible to develop meaningful guidelines for answering the question: "When are we done testing?" There is little debate that further work remains to be done before quantitative rules for testing can be established, but the empirical approaches that currently exist are considerably better than raw intuition.

18.2 STRATEGIC ISSUES

Later in this chapter, we explore a systematic strategy for software testing. But even the best strategy will fail if a series of overriding issues are not addressed. Tom Gilb [GIL95] argues that the following issues must be addressed if a successful software testing strategy is to be implemented:

? What guidelines lead to a successful testing strategy?

Specify product requirements in a quantifiable manner long before testing commences. Although the overriding objective of testing is to find errors, a good testing strategy also assesses other quality characteristics such as portability, maintainability, and usability (Chapter 19). These should be specified in a way that is measurable so that testing results are unambiguous.

State testing objectives explicitly. The specific objectives of testing should be stated in measurable terms. For example, test effectiveness, test coverage, mean time to failure, the cost to find and fix defects, remaining defect density or frequency of occurrence, and test work-hours per regression test all should be stated within the test plan [GIL95].

XRef

Use-cases describe a scenario for software use and are discussed in Chapter 11.

Understand the users of the software and develop a profile for each user category. Use-cases that describe the interaction scenario for each class of user can reduce overall testing effort by focusing testing on actual use of the product.

Develop a testing plan that emphasizes "rapid cycle testing." Gilb [GIL95] recommends that a software engineering team "learn to test in rapid cycles (2 percent of project effort) of customer-useful, at least field 'trialable,' increments of functionality and/or quality improvement." The feedback generated from these rapid cycle tests can be used to control quality levels and the corresponding test strategies.

Quote:

"Testing only to end-user perceived requirements is like inspecting a building based on the work done by the interior decorator at the expense of the foundations, girders, and plumbing."

Boris Beizer

Build "robust" software that is designed to test itself. Software should be designed in a manner that uses antibugging (Section 18.3.1) techniques. That is, software should be capable of diagnosing certain classes of errors. In addition, the design should accommodate automated testing and regression testing.

Use effective formal technical reviews as a filter prior to testing. Formal technical reviews (Chapter 8) can be as effective as testing in uncovering errors. For this reason, reviews can reduce the amount of testing effort that is required to produce high-quality software.

Conduct formal technical reviews to assess the test strategy and test cases themselves. Formal technical reviews can uncover inconsistencies, omissions, and outright errors in the testing approach. This saves time and also improves product quality.

Develop a continuous improvement approach for the testing process. The test strategy should be measured. The metrics collected during testing should be used as part of a statistical process control approach for software testing.

18.3 UNIT TESTING

Unit testing focuses verification effort on the smallest unit of software design—the software component or module. Using the component-level design description as a guide, important control paths are tested to uncover errors within the boundary of the module. The relative complexity of tests and uncovered errors is limited by the constrained scope established for unit testing. The unit test is white-box oriented, and the step can be conducted in parallel for multiple components.

18.3.1 Unit Test Considerations

Unit Testing

The tests that occur as part of unit tests are illustrated schematically in Figure 18.4. The module interface is tested to ensure that information properly flows into and out of the program unit under test. The local data structure is examined to ensure that data stored temporarily maintains its integrity during all steps in an algorithm's execution. Boundary conditions are tested to ensure that the module operates properly at boundaries established to limit or restrict processing. All independent paths (basis paths) through the control structure are exercised to ensure that all statements in a module have been executed at least once. And finally, all error handling paths are tested.

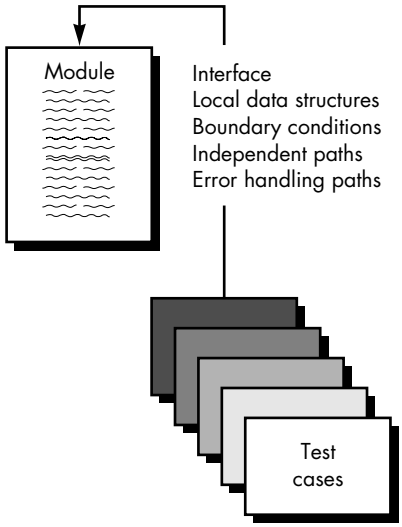

FIGURE 18.4
Unit test

Tests of data flow across a module interface are required before any other test is initiated. If data do not enter and exit properly, all other tests are moot. In addition, local data structures should be exercised and the local impact on global data should be ascertained (if possible) during unit testing.

Selective testing of execution paths is an essential task during the unit test. Test cases should be designed to uncover errors due to erroneous computations, incorrect comparisons, or improper control flow. Basis path and loop testing are effective techniques for uncovering a broad array of path errors.

? What errors are commonly found during unit testing?

Among the more common errors in computation are (1) misunderstood or incorrect arithmetic precedence, (2) mixed mode operations, (3) incorrect initialization, (4) precision inaccuracy, (5) incorrect symbolic representation of an expression. Comparison and control flow are closely coupled to one another (i.e., change of flow frequently occurs after a comparison). Test cases should uncover errors such as (1) comparison of different data types, (2) incorrect logical operators or precedence, (3) expectation of equality when precision error makes equality unlikely, (4) incorrect comparison of variables, (5) improper or nonexistent loop termination, (6) failure to exit when divergent iteration is encountered, and (7) improperly modified loop variables.

Good design dictates that error conditions be anticipated and error-handling paths set up to reroute or cleanly terminate processing when an error does occur. Yourdon [YOU75] calls this approach *antibugging*. Unfortunately, there is a tendency to incorporate error handling into software and then never test it. A true story may serve to illustrate:

> A major interactive design system was developed under contract. In one transaction processing module, a practical joker placed the following error handling message after a series of conditional tests that invoked various control flow branches: ERROR! THERE IS NO WAY YOU CAN GET HERE. This "error message" was uncovered by a customer during user training!

Be sure that you design tests to execute every error-handling path. If you don't, the path may fail when it is invoked, exacerbating an already dicey situation.

Among the potential errors that should be tested when error handling is evaluated are

1. Error description is unintelligible.
2. Error noted does not correspond to error encountered.
3. Error condition causes system intervention prior to error handling.
4. Exception-condition processing is incorrect.
5. Error description does not provide enough information to assist in the location of the cause of the error.

Boundary testing is the last (and probably most important) task of the unit test step. Software often fails at its boundaries. That is, errors often occur when the *n*th element of an *n*-dimensional array is processed, when the *i*th repetition of a loop with

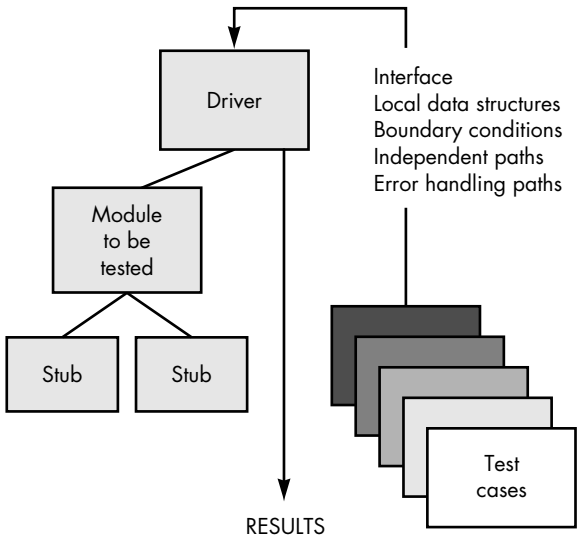

FIGURE 18.5
Unit test environment

i passes is invoked, when the maximum or minimum allowable value is encountered. Test cases that exercise data structure, control flow, and data values just below, at, and just above maxima and minima are very likely to uncover errors.

18.3.2 Unit Test Procedures

There are some situations in which you will not have the resources to do comprehensive unit testing. Select critical modules and those with high cyclomatic complexity and unit test only them.

Unit testing is normally considered as an adjunct to the coding step. After source level code has been developed, reviewed, and verified for correspondence to component-level design, unit test case design begins. A review of design information provides guidance for establishing test cases that are likely to uncover errors in each of the categories discussed earlier. Each test case should be coupled with a set of expected results.

Because a component is not a stand-alone program, driver and/or stub software must be developed for each unit test. The unit test environment is illustrated in Figure 18.5. In most applications a *driver* is nothing more than a "main program" that accepts test case data, passes such data to the component (to be tested), and prints relevant results. *Stubs* serve to replace modules that are subordinate (called by) the component to be tested. A stub or "dummy subprogram" uses the subordinate module's interface, may do minimal data manipulation, prints verification of entry, and returns control to the module undergoing testing.

Drivers and stubs represent overhead. That is, both are software that must be written (formal design is not commonly applied) but that is not delivered with the final software product. If drivers and stubs are kept simple, actual overhead is relatively low. Unfortunately, many components cannot be adequately unit tested with "simple" overhead software. In such cases, complete testing can be postponed until the integration test step (where drivers or stubs are also used).

Unit testing is simplified when a component with high cohesion is designed. When only one function is addressed by a component, the number of test cases is reduced and errors can be more easily predicted and uncovered.

18.4 INTEGRATION TESTING[3]

A neophyte in the software world might ask a seemingly legitimate question once all modules have been unit tested: "If they all work individually, why do you doubt that they'll work when we put them together?" The problem, of course, is "putting them together"—interfacing. Data can be lost across an interface; one module can have an inadvertent, adverse affect on another; subfunctions, when combined, may not produce the desired major function; individually acceptable imprecision may be magnified to unacceptable levels; global data structures can present problems. Sadly, the list goes on and on.

Integration testing is a systematic technique for constructing the program structure while at the same time conducting tests to uncover errors associated with interfacing. The objective is to take unit tested components and build a program structure that has been dictated by design.

Taking the big bang approach to integration is a lazy strategy that is doomed to failure. Integration testing should be conducted incrementally.

There is often a tendency to attempt nonincremental integration; that is, to construct the program using a "big bang" approach. All components are combined in advance. The entire program is tested as a whole. And chaos usually results! A set of errors is encountered. Correction is difficult because isolation of causes is complicated by the vast expanse of the entire program. Once these errors are corrected, new ones appear and the process continues in a seemingly endless loop.

Incremental integration is the antithesis of the big bang approach. The program is constructed and tested in small increments, where errors are easier to isolate and correct; interfaces are more likely to be tested completely; and a systematic test approach may be applied. In the sections that follow, a number of different incremental integration strategies are discussed.

18.4.1 Top-down Integration

When you develop a detailed project schedule you have to consider the manner in which integration will occur so that components will be available when needed.

Top-down integration testing is an incremental approach to construction of program structure. Modules are integrated by moving downward through the control hierarchy, beginning with the main control module (main program). Modules subordinate (and ultimately subordinate) to the main control module are incorporated into the structure in either a depth-first or breadth-first manner.

Referring to Figure 18.6, *depth-first integration* would integrate all components on a major control path of the structure. Selection of a major path is somewhat arbitrary and depends on application-specific characteristics. For example, selecting the left-hand path, components M_1, M_2 , M_5 would be integrated first. Next, M_8 or (if neces-

3 Integration strategies for object-oriented systems are discussed in Chapter 23.

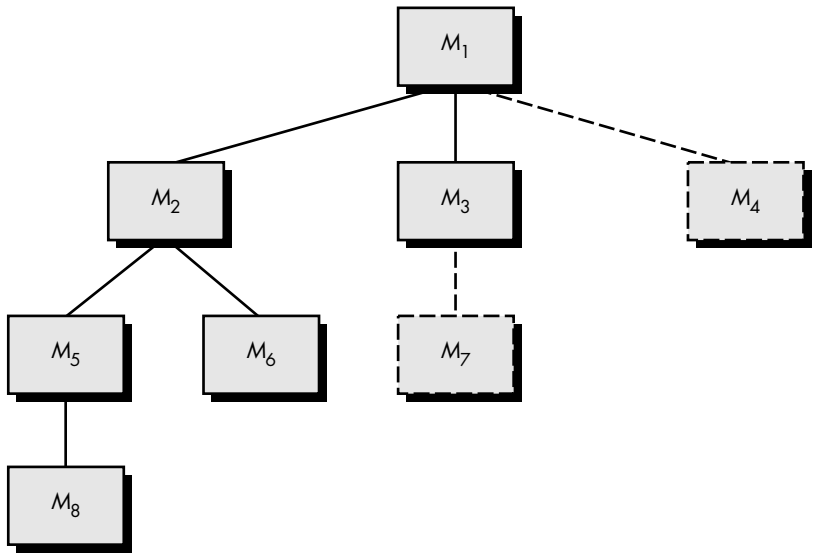

FIGURE 18.6
Top-down integration

sary for proper functioning of M_2) M_6 would be integrated. Then, the central and right-hand control paths are built. *Breadth-first integration* incorporates all components directly subordinate at each level, moving across the structure horizontally. From the figure, components M_2, M_3, and M_4 (a replacement for stub S_4) would be integrated first. The next control level, M_5, M_6, and so on, follows.

The integration process is performed in a series of five steps:

? What are the steps for top-down integration?

1. The main control module is used as a test driver and stubs are substituted for all components directly subordinate to the main control module.
2. Depending on the integration approach selected (i.e., depth or breadth first), subordinate stubs are replaced one at a time with actual components.
3. Tests are conducted as each component is integrated.
4. On completion of each set of tests, another stub is replaced with the real component.
5. Regression testing (Section 18.4.3) may be conducted to ensure that new errors have not been introduced.

The process continues from step 2 until the entire program structure is built.

XRef
Factoring is important for certain architectural styles. See Chapter 14 for additional details.

The top-down integration strategy verifies major control or decision points early in the test process. In a well-factored program structure, decision making occurs at upper levels in the hierarchy and is therefore encountered first. If major control problems do exist, early recognition is essential. If depth-first integration is selected, a complete function of the software may be implemented and demonstrated. For example, consider a classic transaction structure (Chapter 14) in which a complex series of interactive inputs is requested, acquired, and validated via an incoming path. The

incoming path may be integrated in a top-down manner. All input processing (for subsequent transaction dispatching) may be demonstrated before other elements of the structure have been integrated. Early demonstration of functional capability is a confidence builder for both the developer and the customer.

? What problems may be encountered when the top-down integration strategy is chosen?

Top-down strategy sounds relatively uncomplicated, but in practice, logistical problems can arise. The most common of these problems occurs when processing at low levels in the hierarchy is required to adequately test upper levels. Stubs replace low-level modules at the beginning of top-down testing; therefore, no significant data can flow upward in the program structure. The tester is left with three choices: (1) delay many tests until stubs are replaced with actual modules, (2) develop stubs that perform limited functions that simulate the actual module, or (3) integrate the software from the bottom of the hierarchy upward.

The first approach (delay tests until stubs are replaced by actual modules) causes us to loose some control over correspondence between specific tests and incorporation of specific modules. This can lead to difficulty in determining the cause of errors and tends to violate the highly constrained nature of the top-down approach. The second approach is workable but can lead to significant overhead, as stubs become more and more complex. The third approach, called *bottom-up testing*, is discussed in the next section.

18.4.2 Bottom-up Integration

Bottom-up integration testing, as its name implies, begins construction and testing with *atomic modules* (i.e., components at the lowest levels in the program structure). Because components are integrated from the bottom up, processing required for components subordinate to a given level is always available and the need for stubs is eliminated.

A bottom-up integration strategy may be implemented with the following steps:

? What are the steps for bottom-up integration?

1. Low-level components are combined into clusters (sometimes called *builds*) that perform a specific software subfunction.
2. A driver (a control program for testing) is written to coordinate test case input and output.
3. The cluster is tested.
4. Drivers are removed and clusters are combined moving upward in the program structure.

KEY POINT

Bottom-up integration eliminates the need for complex stubs.

Integration follows the pattern illustrated in Figure 18.7. Components are combined to form clusters 1, 2, and 3. Each of the clusters is tested using a driver (shown as a dashed block). Components in clusters 1 and 2 are subordinate to M_a. Drivers D_1 and D_2 are removed and the clusters are interfaced directly to M_a. Similarly, driver D_3 for cluster 3 is removed prior to integration with module M_b. Both M_a and M_b will ultimately be integrated with component M_c, and so forth.

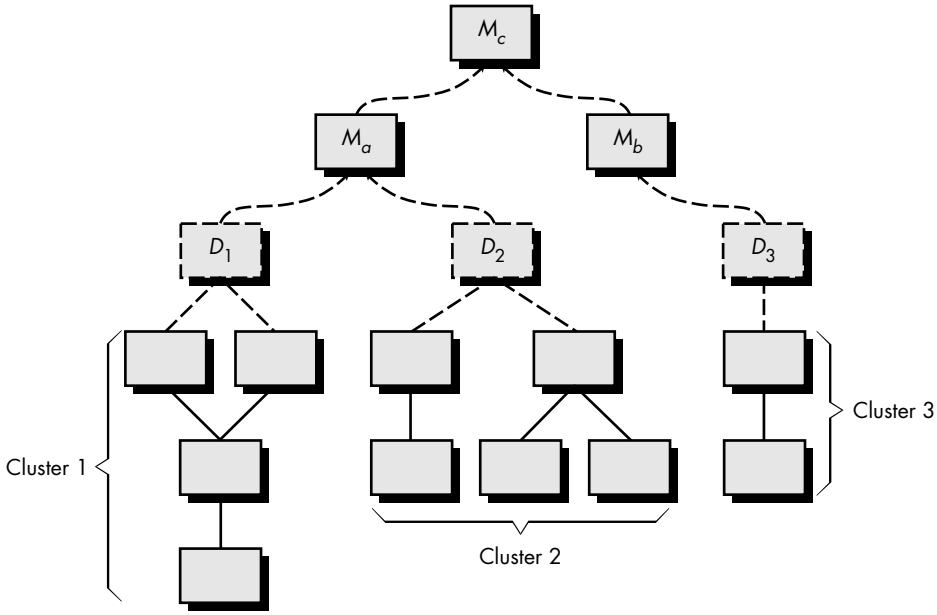

FIGURE 18.7
Bottom-up integration

As integration moves upward, the need for separate test drivers lessens. In fact, if the top two levels of program structure are integrated top down, the number of drivers can be reduced substantially and integration of clusters is greatly simplified.

18.4.3 Regression Testing

Each time a new module is added as part of integration testing, the software changes. New data flow paths are established, new I/O may occur, and new control logic is invoked. These changes may cause problems with functions that previously worked flawlessly. In the context of an integration test strategy, *regression testing* is the re-execution of some subset of tests that have already been conducted to ensure that changes have not propagated unintended side effects.

Regression testing is an important strategy for reducing "side effects." Run regression tests every time a major change is made to the software (including the integration of new modules).

In a broader context, successful tests (of any kind) result in the discovery of errors, and errors must be corrected. Whenever software is corrected, some aspect of the software configuration (the program, its documentation, or the data that support it) is changed. Regression testing is the activity that helps to ensure that changes (due to testing or for other reasons) do not introduce unintended behavior or additional errors.

Regression testing may be conducted manually, by re-executing a subset of all test cases or using automated *capture/playback tools.* Capture/playback tools enable the software engineer to capture test cases and results for subsequent playback and comparison.

The regression test suite (the subset of tests to be executed) contains three different classes of test cases:

- A representative sample of tests that will exercise all software functions.
- Additional tests that focus on software functions that are likely to be affected by the change.
- Tests that focus on the software components that have been changed.

As integration testing proceeds, the number of regression tests can grow quite large. Therefore, the regression test suite should be designed to include only those tests that address one or more classes of errors in each of the major program functions. It is impractical and inefficient to re-execute every test for every program function once a change has occurred.

18.4.4 Smoke Testing

Smoke testing is an integration testing approach that is commonly used when "shrink-wrapped" software products are being developed. It is designed as a pacing mechanism for time-critical projects, allowing the software team to assess its project on a frequent basis. In essence, the smoke testing approach encompasses the following activities:

Smoke testing might be characterized as a rolling integration strategy. The software is rebuilt (with new components added) and exercised every day.

1. Software components that have been translated into code are integrated into a "build." A build includes all data files, libraries, reusable modules, and engineered components that are required to implement one or more product functions.
2. A series of tests is designed to expose errors that will keep the build from properly performing its function. The intent should be to uncover "show stopper" errors that have the highest likelihood of throwing the software project behind schedule.
3. The build is integrated with other builds and the entire product (in its current form) is smoke tested daily. The integration approach may be top down or bottom up.

The daily frequency of testing the entire product may surprise some readers. However, frequent tests give both managers and practitioners a realistic assessment of integration testing progress. McConnell [MCO96] describes the smoke test in the following manner:

> The smoke test should exercise the entire system from end to end. It does not have to be exhaustive, but it should be capable of exposing major problems. The smoke test should be thorough enough that if the build passes, you can assume that it is stable enough to be tested more thoroughly.

Smoke testing provides a number of benefits when it is applied on complex, time-critical software engineering projects:

- *Integration risk is minimized.* Because smoke tests are conducted daily, incompatibilities and other show-stopper errors are uncovered early, thereby reducing the likelihood of serious schedule impact when errors are uncovered.
- *The quality of the end-product is improved.* Because the approach is construction (integration) oriented, smoke testing is likely to uncover both functional errors and architectural and component-level design defects. If these defects are corrected early, better product quality will result.
- *Error diagnosis and correction are simplified.* Like all integration testing approaches, errors uncovered during smoke testing are likely to be associated with "new software increments"—that is, the software that has just been added to the build(s) is a probable cause of a newly discovered error.
- *Progress is easier to assess.* With each passing day, more of the software has been integrated and more has been demonstrated to work. This improves team morale and gives managers a good indication that progress is being made.

Quote:

"Treat the daily build as the heartbeat of the project. If there's no heartbeat, the project is dead."

Jim McCarthy

18.4.5 Comments on Integration Testing

There has been much discussion (e.g., [BEI84]) of the relative advantages and disadvantages of top-down versus bottom-up integration testing. In general, the advantages of one strategy tend to result in disadvantages for the other strategy. The major disadvantage of the top-down approach is the need for stubs and the attendant testing difficulties that can be associated with them. Problems associated with stubs may be offset by the advantage of testing major control functions early. The major disadvantage of bottom-up integration is that "the program as an entity does not exist until the last module is added" [MYE79]. This drawback is tempered by easier test case design and a lack of stubs.

Selection of an integration strategy depends upon software characteristics and, sometimes, project schedule. In general, a combined approach (sometimes called *sandwich testing*) that uses top-down tests for upper levels of the program structure, coupled with bottom-up tests for subordinate levels may be the best compromise.

? What is a critical module and why should we identify it?

As integration testing is conducted, the tester should identify *critical modules.* A critical module has one or more of the following characteristics: (1) addresses several software requirements, (2) has a high level of control (resides relatively high in the program structure), (3) is complex or error prone (cyclomatic complexity may be used as an indicator), or (4) has definite performance requirements. Critical modules should be tested as early as is possible. In addition, regression tests should focus on critical module function.

18.4.6 Integration Test Documentation

Test Specification

An overall plan for integration of the software and a description of specific tests are documented in a *Test Specification.* This document contains a test plan, and a test procedure, is a work product of the software process, and becomes part of the software configuration.

The test plan describes the overall strategy for integration. Testing is divided into phases and builds that address specific functional and behavioral characteristics of the software. For example, integration testing for a CAD system might be divided into the following test phases:

- User interaction (command selection, drawing creation, display representation, error processing and representation).
- Data manipulation and analysis (symbol creation, dimensioning; rotation, computation of physical properties).
- Display processing and generation (two-dimensional displays, three-dimensional displays, graphs and charts).
- Database management (access, update, integrity, performance).

Each of these phases and subphases (denoted in parentheses) delineates a broad functional category within the software and can generally be related to a specific domain of the program structure. Therefore, program builds (groups of modules) are created to correspond to each phase. The following criteria and corresponding tests are applied for all test phases:

> **Interface integrity.** Internal and external interfaces are tested as each module (or cluster) is incorporated into the structure.
>
> **Functional validity.** Tests designed to uncover functional errors are conducted.
>
> **Information content.** Tests designed to uncover errors associated with local or global data structures are conducted.
>
> **Performance.** Tests designed to verify performance bounds established during software design are conducted.

A schedule for integration, the development of overhead software, and related topics is also discussed as part of the test plan. Start and end dates for each phase are established and "availability windows" for unit tested modules are defined. A brief description of overhead software (stubs and drivers) concentrates on characteristics that might require special effort. Finally, test environment and resources are described. Unusual hardware configurations, exotic simulators, and special test tools or techniques are a few of many topics that may also be discussed.

The detailed testing procedure that is required to accomplish the test plan is described next. The order of integration and corresponding tests at each integration

step are described. A listing of all test cases (annotated for subsequent reference) and expected results is also included.

A history of actual test results, problems, or peculiarities is recorded in the *Test Specification.* Information contained in this section can be vital during software maintenance. Appropriate references and appendixes are also presented.

Like all other elements of a software configuration, the test specification format may be tailored to the local needs of a software engineering organization. It is important to note, however, that an integration strategy (contained in a test plan) and testing details (described in a test procedure) are essential ingredients and must appear.

18.5 VALIDATION TESTING

At the culmination of integration testing, software is completely assembled as a package, interfacing errors have been uncovered and corrected, and a final series of software tests—*validation testing*—may begin. Validation can be defined in many ways, but a simple (albeit harsh) definition is that validation succeeds when software functions in a manner that can be reasonably expected by the customer. At this point a battle-hardened software developer might protest: "Who or what is the arbiter of reasonable expectations?"

KEY POINT

Like all other testing steps, validation tries to uncover errors, but the focus is at the requirements level—on things that will be immediately apparent to the end-user.

Reasonable expectations are defined in the *Software Requirements Specification*—a document (Chapter 11) that describes all user-visible attributes of the software. The specification contains a section called *Validation Criteria.* Information contained in that section forms the basis for a validation testing approach.

18.5.1 Validation Test Criteria

Software validation is achieved through a series of black-box tests that demonstrate conformity with requirements. A test plan outlines the classes of tests to be conducted and a test procedure defines specific test cases that will be used to demonstrate conformity with requirements. Both the plan and procedure are designed to ensure that all functional requirements are satisfied, all behavioral characteristics are achieved, all performance requirements are attained, documentation is correct, and human-engineered and other requirements are met (e.g., transportability, compatibility, error recovery, maintainability).

After each validation test case has been conducted, one of two possible conditions exist: (1) The function or performance characteristics conform to specification and are accepted or (2) a deviation from specification is uncovered and a *deficiency list* is created. Deviation or error discovered at this stage in a project can rarely be corrected prior to scheduled delivery. It is often necessary to negotiate with the customer to establish a method for resolving deficiencies.

18.5.2 Configuration Review

An important element of the validation process is a *configuration review.* The intent of the review is to ensure that all elements of the software configuration have been properly developed, are cataloged, and have the necessary detail to bolster the support phase of the software life cycle. The configuration review, sometimes called an *audit,* has been discussed in more detail in Chapter 9.

18.5.3 Alpha and Beta Testing

It is virtually impossible for a software developer to foresee how the customer will really use a program. Instructions for use may be misinterpreted; strange combinations of data may be regularly used; output that seemed clear to the tester may be unintelligible to a user in the field.

When custom software is built for one customer, a series of *acceptance tests* are conducted to enable the customer to validate all requirements. Conducted by the end-user rather than software engineers, an acceptance test can range from an informal "test drive" to a planned and systematically executed series of tests. In fact, acceptance testing can be conducted over a period of weeks or months, thereby uncovering cumulative errors that might degrade the system over time.

If software is developed as a product to be used by many customers, it is impractical to perform formal acceptance tests with each one. Most software product builders use a process called alpha and beta testing to uncover errors that only the end-user seems able to find.

The *alpha test* is conducted at the developer's site by a customer. The software is used in a natural setting with the developer "looking over the shoulder" of the user and recording errors and usage problems. Alpha tests are conducted in a controlled environment.

The *beta test* is conducted at one or more customer sites by the end-user of the software. Unlike alpha testing, the developer is generally not present. Therefore, the beta test is a "live" application of the software in an environment that cannot be controlled by the developer. The customer records all problems (real or imagined) that are encountered during beta testing and reports these to the developer at regular intervals. As a result of problems reported during beta tests, software engineers make modifications and then prepare for release of the software product to the entire customer base.

18.6 SYSTEM TESTING

At the beginning of this book, we stressed the fact that software is only one element of a larger computer-based system. Ultimately, software is incorporated with other system elements (e.g., hardware, people, information), and a series of system integration and validation tests are conducted. These tests fall outside the scope of the

software process and are not conducted solely by software engineers. However, steps taken during software design and testing can greatly improve the probability of successful software integration in the larger system.

A classic system testing problem is "finger-pointing." This occurs when an error is uncovered, and each system element developer blames the other for the problem. Rather than indulging in such nonsense, the software engineer should anticipate potential interfacing problems and (1) design error-handling paths that test all information coming from other elements of the system, (2) conduct a series of tests that simulate bad data or other potential errors at the software interface, (3) record the results of tests to use as "evidence" if finger-pointing does occur, and (4) participate in planning and design of system tests to ensure that software is adequately tested.

Quote:

"Like death and taxes, testing is both unpleasant and inevitable."

Ed Yourdon

System testing is actually a series of different tests whose primary purpose is to fully exercise the computer-based system. Although each test has a different purpose, all work to verify that system elements have been properly integrated and perform allocated functions. In the sections that follow, we discuss the types of system tests [BEI84] that are worthwhile for software-based systems.

18.6.1 Recovery Testing

Many computer based systems must recover from faults and resume processing within a prespecified time. In some cases, a system must be fault tolerant; that is, processing faults must not cause overall system function to cease. In other cases, a system failure must be corrected within a specified period of time or severe economic damage will occur.

WebRef

Extensive information on software testing and related quality issues can be obtained at **www.stqe.net**

Recovery testing is a system test that forces the software to fail in a variety of ways and verifies that recovery is properly performed. If recovery is automatic (performed by the system itself), reinitialization, checkpointing mechanisms, data recovery, and restart are evaluated for correctness. If recovery requires human intervention, the mean-time-to-repair (MTTR) is evaluated to determine whether it is within acceptable limits.

18.6.2 Security Testing

Any computer-based system that manages sensitive information or causes actions that can improperly harm (or benefit) individuals is a target for improper or illegal penetration. Penetration spans a broad range of activities: hackers who attempt to penetrate systems for sport; disgruntled employees who attempt to penetrate for revenge; dishonest individuals who attempt to penetrate for illicit personal gain.

Security testing attempts to verify that protection mechanisms built into a system will, in fact, protect it from improper penetration. To quote Beizer [BEI84]: "The system's security must, of course, be tested for invulnerability from frontal attack—but must also be tested for invulnerability from flank or rear attack."

During security testing, the tester plays the role(s) of the individual who desires to penetrate the system. Anything goes! The tester may attempt to acquire passwords

through external clerical means; may attack the system with custom software designed to breakdown any defenses that have been constructed; may overwhelm the system, thereby denying service to others; may purposely cause system errors, hoping to penetrate during recovery; may browse through insecure data, hoping to find the key to system entry.

Given enough time and resources, good security testing will ultimately penetrate a system. The role of the system designer is to make penetration cost more than the value of the information that will be obtained.

18.6.3 Stress Testing

During earlier software testing steps, white-box and black-box techniques resulted in thorough evaluation of normal program functions and performance. Stress tests are designed to confront programs with abnormal situations. In essence, the tester who performs stress testing asks: "How high can we crank this up before it fails?"

Quote:

"If you're trying to find true system bugs and have never subjected your software to a real stress test, then it is high time you started."

Boris Beizer

Stress testing executes a system in a manner that demands resources in abnormal quantity, frequency, or volume. For example, (1) special tests may be designed that generate ten interrupts per second, when one or two is the average rate, (2) input data rates may be increased by an order of magnitude to determine how input functions will respond, (3) test cases that require maximum memory or other resources are executed, (4) test cases that may cause thrashing in a virtual operating system are designed, (5) test cases that may cause excessive hunting for disk-resident data are created. Essentially, the tester attempts to break the program.

A variation of stress testing is a technique called *sensitivity testing*. In some situations (the most common occur in mathematical algorithms), a very small range of data contained within the bounds of valid data for a program may cause extreme and even erroneous processing or profound performance degradation. Sensitivity testing attempts to uncover data combinations within valid input classes that may cause instability or improper processing.

18.6.4 Performance Testing

For real-time and embedded systems, software that provides required function but does not conform to performance requirements is unacceptable. *Performance testing* is designed to test the run-time performance of software within the context of an integrated system. Performance testing occurs throughout all steps in the testing process. Even at the unit level, the performance of an individual module may be assessed as white-box tests are conducted. However, it is not until all system elements are fully integrated that the true performance of a system can be ascertained.

Performance tests are often coupled with stress testing and usually require both hardware and software instrumentation. That is, it is often necessary to measure resource utilization (e.g., processor cycles) in an exacting fashion. External instru-

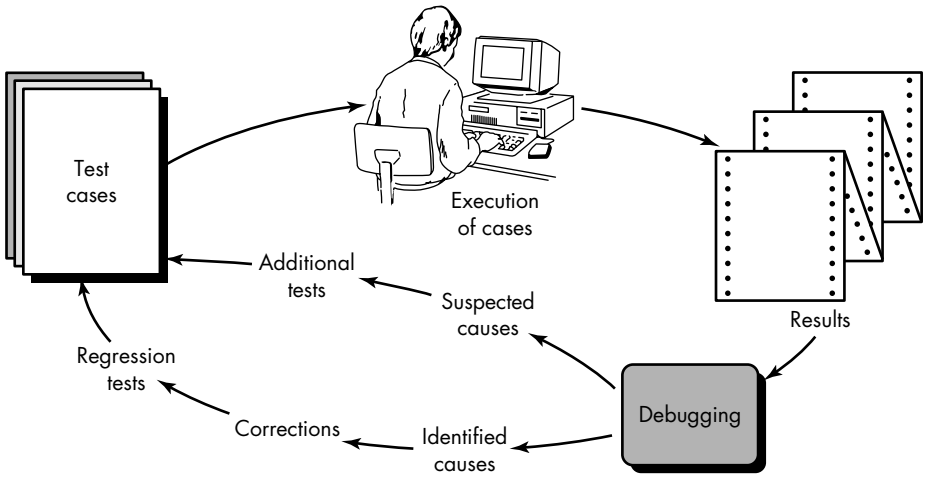

FIGURE 18.8
The debugging process

mentation can monitor execution intervals, log events (e.g., interrupts) as they occur, and sample machine states on a regular basis. By instrumenting a system, the tester can uncover situations that lead to degradation and possible system failure.

18.7 THE ART OF DEBUGGING

Software testing is a process that can be systematically planned and specified. Test case design can be conducted, a strategy can be defined, and results can be evaluated against prescribed expectations.

WebRef

BugNet tracks security problems and bugs in PC-based software and provides useful information on debugging topics:
www.bugnet.com

Debugging occurs as a consequence of successful testing. That is, when a test case uncovers an error, debugging is the process that results in the removal of the error. Although debugging can and should be an orderly process, it is still very much an art. A software engineer, evaluating the results of a test, is often confronted with a "symptomatic" indication of a software problem. That is, the external manifestation of the error and the internal cause of the error may have no obvious relationship to one another. The poorly understood mental process that connects a symptom to a cause is debugging.

18.7.1 The Debugging Process

Debugging is not testing but always occurs as a consequence of testing.[4] Referring to Figure 18.8, the debugging process begins with the execution of a test case. Results are assessed and a lack of correspondence between expected and actual performance is encountered. In many cases, the noncorresponding data are a symptom

4 In making this statement, we take the broadest possible view of testing. Not only does the developer test software prior to release, but the customer/user tests software every time it is used!

of an underlying cause as yet hidden. The debugging process attempts to match symptom with cause, thereby leading to error correction.

The debugging process will always have one of two outcomes: (1) the cause will be found and corrected, or (2) the cause will not be found. In the latter case, the person performing debugging may suspect a cause, design a test case to help validate that suspicion, and work toward error correction in an iterative fashion.

Why is debugging so difficult? In all likelihood, human psychology (see the next section) has more to do with an answer than software technology. However, a few characteristics of bugs provide some clues:

1. The symptom and the cause may be geographically remote. That is, the symptom may appear in one part of a program, while the cause may actually be located at a site that is far removed. Highly coupled program structures (Chapter 13) exacerbate this situation.

2. The symptom may disappear (temporarily) when another error is corrected.

3. The symptom may actually be caused by nonerrors (e.g., round-off inaccuracies).

4. The symptom may be caused by human error that is not easily traced.

5. The symptom may be a result of timing problems, rather than processing problems.

6. It may be difficult to accurately reproduce input conditions (e.g., a real-time application in which input ordering is indeterminate).

7. The symptom may be intermittent. This is particularly common in embedded systems that couple hardware and software inextricably.

8. The symptom may be due to causes that are distributed across a number of tasks running on different processors [CHE90].

Quote:

"The variety within all computer programs that must be diagnosed [for debugging] is probably greater than the variety within all other examples of systems that are regularly diagnosed."

John Gould

During debugging, we encounter errors that range from mildly annoying (e.g., an incorrect output format) to catastrophic (e.g. the system fails, causing serious economic or physical damage). As the consequences of an error increase, the amount of pressure to find the cause also increases. Often, pressure sometimes forces a software developer to fix one error and at the same time introduce two more.

18.7.2 Psychological Considerations

Unfortunately, there appears to be some evidence that debugging prowess is an innate human trait. Some people are good at it and others aren't. Although experimental evidence on debugging is open to many interpretations, large variances in debugging ability have been reported for programmers with the same education and experience.

Commenting on the human aspects of debugging, Shneiderman [SHN80] states:

> Debugging is one of the more frustrating parts of programming. It has elements of problem solving or brain teasers, coupled with the annoying recognition that you have made a mistake. Heightened anxiety and the unwillingness to accept the possibility of errors increases the task difficulty. Fortunately, there is a great sigh of relief and a lessening of tension when the bug is ultimately . . . corrected.

Although it may be difficult to "learn" debugging, a number of approaches to the problem can be proposed. We examine these in the next section.

18.7.3 Debugging Approaches

Regardless of the approach that is taken, debugging has one overriding objective: to find and correct the cause of a software error. The objective is realized by a combination of systematic evaluation, intuition, and luck. Bradley [BRA85] describes the debugging approach in this way:

> Debugging is a straightforward application of the scientific method that has been developed over 2,500 years. The basis of debugging is to locate the problem's source [the cause] by binary partitioning, through working hypotheses that predict new values to be examined.
>
> Take a simple non-software example: A lamp in my house does not work. If nothing in the house works, the cause must be in the main circuit breaker or outside; I look around to see whether the neighborhood is blacked out. I plug the suspect lamp into a working socket and a working appliance into the suspect circuit. So goes the alternation of hypothesis and test.

In general, three categories for debugging approaches may be proposed [MYE79]: (1) brute force, (2) backtracking, and (3) cause elimination.

Set a time limit, say two hours, on the amount of time you spend trying to debug a problem on your own. After that, get help!

The *brute force* category of debugging is probably the most common and least efficient method for isolating the cause of a software error. We apply brute force debugging methods when all else fails. Using a "let the computer find the error" philosophy, memory dumps are taken, run-time traces are invoked, and the program is loaded with WRITE statements. We hope that somewhere in the morass of information that is produced we will find a clue that can lead us to the cause of an error. Although the mass of information produced may ultimately lead to success, it more frequently leads to wasted effort and time. Thought must be expended first!

Backtracking is a fairly common debugging approach that can be used successfully in small programs. Beginning at the site where a symptom has been uncovered, the source code is traced backward (manually) until the site of the cause is found. Unfortunately, as the number of source lines increases, the number of potential backward paths may become unmanageably large.

The third approach to debugging—*cause elimination*—is manifested by induction or deduction and introduces the concept of binary partitioning. Data related to the error occurrence are organized to isolate potential causes. A "cause hypothesis" is

devised and the aforementioned data are used to prove or disprove the hypothesis. Alternatively, a list of all possible causes is developed and tests are conducted to eliminate each. If initial tests indicate that a particular cause hypothesis shows promise, data are refined in an attempt to isolate the bug.

CASE Tools
Testing and Debugging

Each of these debugging approaches can be supplemented with debugging tools. We can apply a wide variety of debugging compilers, dynamic debugging aids ("tracers"), automatic test case generators, memory dumps, and cross-reference maps. However, tools are not a substitute for careful evaluation based on a complete software design document and clear source code.

Any discussion of debugging approaches and tools is incomplete without mention of a powerful ally—other people! Each of us can recall puzzling for hours or days over a persistent bug. A colleague wanders by and in desperation we explain the problem and throw open the listing. Instantaneously (it seems), the cause of the error is uncovered. Smiling smugly, our colleague wanders off. A fresh viewpoint, unclouded by hours of frustration, can do wonders. A final maxim for debugging might be: "When all else fails, get help!"

Once a bug has been found, it must be corrected. But, as we have already noted, the correction of a bug can introduce other errors and therefore do more harm than good. Van Vleck [VAN89] suggests three simple questions that every software engineer should ask before making the "correction" that removes the cause of a bug:

? When I correct an error, what questions should I ask myself?

1. **Is the cause of the bug reproduced in another part of the program?** In many situations, a program defect is caused by an erroneous pattern of logic that may be reproduced elsewhere. Explicit consideration of the logical pattern may result in the discovery of other errors.
2. **What "next bug" might be introduced by the fix I'm about to make?** Before the correction is made, the source code (or, better, the design) should be evaluated to assess coupling of logic and data structures. If the correction is to be made in a highly coupled section of the program, special care must be taken when any change is made.
3. **What could we have done to prevent this bug in the first place?** This question is the first step toward establishing a statistical software quality assurance approach (Chapter 8). If we correct the process as well as the product, the bug will be removed from the current program and may be eliminated from all future programs.

18.8 SUMMARY

Software testing accounts for the largest percentage of technical effort in the software process. Yet we are only beginning to understand the subtleties of systematic test planning, execution, and control.

The objective of software testing is to uncover errors. To fulfill this objective, a series of test steps—unit, integration, validation, and system tests—are planned and executed. Unit and integration tests concentrate on functional verification of a component and incorporation of components into a program structure. Validation testing demonstrates traceability to software requirements, and system testing validates software once it has been incorporated into a larger system.

Each test step is accomplished through a series of systematic test techniques that assist in the design of test cases. With each testing step, the level of abstraction with which software is considered is broadened.

Unlike testing (a systematic, planned activity), debugging must be viewed as an art. Beginning with a symptomatic indication of a problem, the debugging activity must track down the cause of an error. Of the many resources available during debugging, the most valuable is the counsel of other members of the software engineering staff.

The requirement for higher-quality software demands a more systematic approach to testing. To quote Dunn and Ullman [DUN82],

> What is required is an overall strategy, spanning the strategic test space, quite as deliberate in its methodology as was the systematic development on which analysis, design and code were based.

In this chapter, we have examined the strategic test space, considering the steps that have the highest likelihood of meeting the overriding test objective: to find and remove errors in an orderly and effective manner.

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PROBLEMS AND POINTS TO PONDER

18.1. Using your own words, describe the difference between verification and validation. Do both make use of test case design methods and testing strategies?

18.2. List some problems that might be associated with the creation of an independent test group. Are an ITG and an SQA group made up of the same people?

18.3. Is it always possible to develop a strategy for testing software that uses the sequence of testing steps described in Section 18.1.3? What possible complications might arise for embedded systems?

18.4. If you could select only three test case design methods to apply during unit testing, what would they be and why?

18.5. Why is a highly coupled module difficult to unit test?

18.6. The concept of "antibugging" (Section 18.2.1) is an extremely effective way to provide built-in debugging assistance when an error is uncovered:

a. Develop a set of guidelines for antibugging.
b. Discuss advantages of using the technique.
c. Discuss disadvantages.

18.7. Develop an integration testing strategy for the any one of the systems implemented in Problems 16.4 through 16.11. Define test phases, note the order of integration, specify additional test software, and justify your order of integration. Assume that all modules (or classes) have been unit tested and are available. Note: it may be necessary to do a bit of design work first.

18.8. How can project scheduling affect integration testing?

18.9. Is unit testing possible or even desirable in all circumstances? Provide examples to justify your answer.

18.10. Who should perform the validation test—the software developer or the software user? Justify your answer.

18.11. Develop a complete test strategy for the *SafeHome* system discussed earlier in this book. Document it in a *Test Specification.*

18.12. As a class project, develop a *Debugging Guide* for your installation. The guide should provide language and system-oriented hints that have been learned through the school of hard knocks! Begin with an outline of topics that will be reviewed by the class and your instructor. Publish the guide for others in your local environment.

FURTHER READINGS AND INFORMATION RESOURCES

Books by Black (*Managing the Testing Process,* Microsoft Press, 1999); Dustin, Rashka, and Paul (*Test Process Improvement: Step-by-Step Guide to Structured Testing,* Addison-Wesley, 1999); Perry (*Surviving the Top Ten Challenges of Software Testing: A People-Oriented Approach,* Dorset House, 1997); and Kit and Finzi (*Software Testing in the Real World: Improving the Process,* Addison-Wesley, 1995) address software testing strategies.

Kaner, Nguyen, and Falk (*Testing Computer Software,* Wiley, 1999); Hutcheson (*Software Testing Methods and Metrics: The Most Important Tests* McGraw-Hill, 1997); Marick (*The Craft of Software Testing: Subsystem Testing Including Object-Based and Object-Oriented Testing,* Prentice-Hall, 1995); Jorgensen (*Software Testing: A Craftsman's Approach,* CRC Press, 1995) present treatments of the subject that consider testing methods and strategies.

In addition, older books by Evans *(Productive Software Test Management,* Wiley-Interscience, 1984), Hetzel (*The Complete Guide to Software Testing,* QED Information Sciences, 1984), Beizer [BEI84], Ould and Unwin (*Testing in Software Development,* Cambridge University Press, 1986), Marks (*Testing Very Big Systems,* McGraw-Hill, 1992, and Kaner et al. (*Testing Computer Software,* 2nd ed., Van Nostrand-Reinhold, 1993), delineate the steps of an effective testing strategy, provide a set of techniques and guidelines, and suggest procedures for controlling and tracking the testing process. Hutcheson (*Software Testing Methods and Metrics,* McGraw-Hill, 1996) presents testing methods and strategies but also provides a detailed discussion of how measurement can be used to achieve efficient testing.

Guidelines for debugging are contained in a book by Dunn (*Software Defect Removal,* McGraw-Hill, 1984). Beizer [BEI84] presents an interesting "taxonomy of bugs" that can lead to effective methods for test planning. McConnell (*Code Complete,* Microsoft Press, 1993) presents pragmatic advice on unit and integration testing as well as debugging.

A wide variety of information sources on software testing and related subjects is available on the Internet. An up-to-date list of World Wide Web references that are relevant to testing concepts, methods, and strategies can be found at the SEPA Website: **http://www.mhhe.com/engcs/compsci/pressman/resources/test-strategy.mhtml**

CHAPTER

19 TECHNICAL METRICS FOR SOFTWARE

KEY CONCEPTS

A key element of any engineering process is measurement. We use measures to better understand the attributes of the models that we create and to assess the quality of the engineered products or systems that we build. But unlike other engineering disciplines, software engineering is not grounded in the basic quantitative laws of physics. Absolute measures, such as voltage, mass, velocity, or temperature, are uncommon in the software world. Instead, we attempt to derive a set of indirect measures that lead to metrics that provide an indication of the quality of some representation of software. Because software measures and metrics are not absolute, they are open to debate. Fenton [FEN91] addresses this issue when he states:

> Measurement is the process by which numbers or symbols are assigned to the attributes of entities in the real world in such a way as to define them according to clearly defined rules. . . . In the physical sciences, medicine, economics, and more recently the social sciences, we are now able to measure attributes that we previously thought to be unmeasurable. . . . Of course, such measurements are not as refined as many measurements in the physical sciences . . ., but they exist [and important decisions are made based on them]. We feel that the obligation to attempt to "measure the unmeasurable" in order to improve our understanding of particular entities is as powerful in software engineering as in any discipline.

QUICK LOOK

What is it? By its nature, engineering is a quantitative discipline. Engineers use numbers to help them design and assess the product to be built. Until recently, software engineers had little quantitative guidance in their work—but that's changing. Technical metrics help software engineers gain insight into the design and construction of the products they build.

Who does it? Software engineers use technical metrics to help them build higher-quality software.

Why is it important? There will always be a qualitative element to the creation of computer software. The problem is that qualitative assessment may not be enough. A software engineer needs objective criteria to help guide the design of data, architecture, interfaces, and components. The tester needs quantitative guidance that will help in the selection of test cases and their targets. Technical metrics provide a basis from which analysis, design, coding, and testing can be conducted more objectively and assessed more quantitatively.

What are the steps? The first step in the measurement process is to derive the software measures and metrics that are appropriate for the representation of software that is being considered. Next, data required to derive the formulated metrics are collected. Once computed, appropriate metrics are analyzed based on pre-established ▶

QUICK LOOK

guidelines and past data. The results of the analysis are interpreted to gain insight into the quality of the software, and the results of the interpretation lead to modification of work products arising out of analysis, design, code, or test.

What is the work product? Software metrics that are computed from data collected from the analysis and design models, source code, and test cases.

How do I ensure that I've done it right? You should establish the objectives of measurement before data collection begins, defining each technical metric in an unambiguous manner. Define only a few metrics and then use them to gain insight into the quality of a software engineering work product.

But some members of the software community continue to argue that software is unmeasurable or that attempts at measurement should be postponed until we better understand software and the attributes that should be used to describe it. This is a mistake.

Although technical metrics for computer software are not absolute, they provide us with a systematic way to assess quality based on a set of clearly defined rules. They also provide the software engineer with on-the-spot, rather than after-the-fact insight. This enables the engineer to discover and correct potential problems before they become catastrophic defects.

In Chapter 4, we discussed software metrics as they are applied at the process and project level. In this chapter, our focus shifts to measures that can be used to assess the quality of the product as it is being engineered. These measures of internal product attributes provide the software engineer with a real-time indication of the efficacy of the analysis, design, and code models; the effectiveness of test cases; and the overall quality of the software to be built.

19.1 SOFTWARE QUALITY

Quote:

"Every program does something right, it just may not be the thing that we want it to do."

author unknown

Even the most jaded software developers will agree that high-quality software is an important goal. But how do we define *quality?* In Chapter 8, we proposed a number of different ways to look at software quality and introduced a definition that stressed conformance to explicitly stated functional and performance requirements, explicitly documented development standards, and implicit characteristics that are expected of all professionally developed software.

There is little question that the preceding definition could be modified or extended and debated endlessly. For the purposes of this book, the definition serves to emphasize three important points:

1. Software requirements are the foundation from which quality is measured. Lack of conformance to requirements is lack of quality.[1]

1 It is important to note that quality extends to the technical attributes of the analysis, design, and code models. Models that exhibit high quality (in the technical sense) will lead to software that exhibits high quality from the customer's point of view.

2. Specified standards define a set of development criteria that guide the manner in which software is engineered. If the criteria are not followed, lack of quality will almost surely result.
3. There is a set of implicit requirements that often goes unmentioned (e.g., the desire for ease of use). If software conforms to its explicit requirements but fails to meet implicit requirements, software quality is suspect.

Software quality is a complex mix of factors that will vary across different applications and the customers who request them. In the sections that follow, software quality factors are identified and the human activities required to achieve them are described.

19.1.1 McCall's Quality Factors

KEY POINT

It's interesting to note that McCall's quality factors are as valid today as they were when they were first proposed in the 1970s. Therefore, it's reasonable to assert that the factors that affect software quality do not change.

The factors that affect software quality can be categorized in two broad groups: (1) factors that can be directly measured (e.g., defects per function-point) and (2) factors that can be measured only indirectly (e.g., usability or maintainability). In each case measurement must occur. We must compare the software (documents, programs, data) to some datum and arrive at an indication of quality.

McCall, Richards, and Walters [MCC77] propose a useful categorization of factors that affect software quality. These software quality factors, shown in Figure 19.1, focus on three important aspects of a software product: its operational characteristics, its ability to undergo change, and its adaptability to new environments.

Referring to the factors noted in Figure 19.1, McCall and his colleagues provide the following descriptions:

Correctness. The extent to which a program satisfies its specification and fulfills the customer's mission objectives.

Reliability. The extent to which a program can be expected to perform its intended function with required precision. [It should be noted that other, more complete definitions of reliability have been proposed (see Chapter 8).]

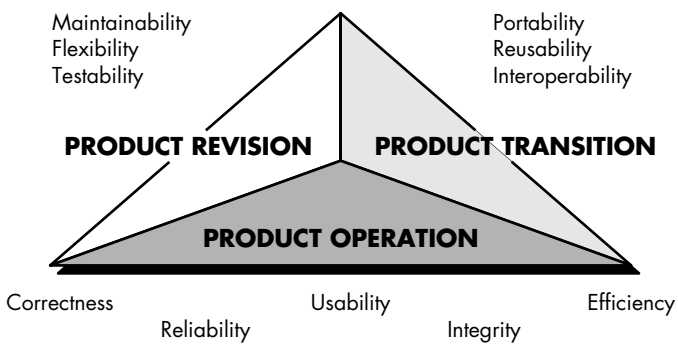

FIGURE 19.1 McCall's software quality factors

Efficiency. The amount of computing resources and code required by a program to perform its function.

Integrity. Extent to which access to software or data by unauthorized persons can be controlled.

Quote:
"A product's quality is a function of how much it changes the world for the better."
Tom DeMarco

Usability. Effort required to learn, operate, prepare input, and interpret output of a program.

Maintainability. Effort required to locate and fix an error in a program. [This is a very limited definition.]

Flexibility. Effort required to modify an operational program.

Testability. Effort required to test a program to ensure that it performs its intended function.

Portability. Effort required to transfer the program from one hardware and/or software system environment to another.

Reusability. Extent to which a program [or parts of a program] can be reused in other applications—related to the packaging and scope of the functions that the program performs.

Interoperability. Effort required to couple one system to another.

It is difficult, and in some cases impossible, to develop direct measures of these quality factors. Therefore, a set of metrics are defined and used to develop expressions for each of the factors according to the following relationship:

$$F_q = c_1 \times m_1 + c_2 \times m_2 + \ldots + c_n \times m_n$$

where F_q is a software quality factor, c_n are regression coefficients, m_n are the metrics that affect the quality factor. Unfortunately, many of the metrics defined by McCall et al. can be measured only subjectively. The metrics may be in the form of a checklist that is used to "grade" specific attributes of the software [CAV78]. The grading scheme proposed by McCall et al. is a 0 (low) to 10 (high) scale. The following metrics are used in the grading scheme:

Auditability. The ease with which conformance to standards can be checked.

Accuracy. The precision of computations and control.

Communication commonality. The degree to which standard interfaces, protocols, and bandwidth are used.

XRef
The metrics noted can be assessed during formal technical reviews discussed in Chapter 8.

Completeness. The degree to which full implementation of required function has been achieved.

Conciseness. The compactness of the program in terms of lines of code.

Consistency. The use of uniform design and documentation techniques throughout the software development project.

Data commonality. The use of standard data structures and types throughout the program.

Error tolerance. The damage that occurs when the program encounters an error.

Execution efficiency. The run-time performance of a program.

Expandability. The degree to which architectural, data, or procedural design can be extended.

Generality. The breadth of potential application of program components.

Hardware independence. The degree to which the software is decoupled from the hardware on which it operates.

Instrumentation. The degree to which the program monitors its own operation and identifies errors that do occur.

Quality Factors

Modularity. The functional independence (Chapter 13) of program components.

Operability. The ease of operation of a program.

Security. The availability of mechanisms that control or protect programs and data.

Self-documentation. The degree to which the source code provides meaningful documentation.

Simplicity. The degree to which a program can be understood without difficulty.

Software system independence. The degree to which the program is independent of nonstandard programming language features, operating system characteristics, and other environmental constraints.

Traceability. The ability to trace a design representation or actual program component back to requirements.

Training. The degree to which the software assists in enabling new users to apply the system.

The relationship between software quality factors and these metrics is shown in Figure 19.2. It should be noted that the weight given to each metric is dependent on local products and concerns.

19.1.2 FURPS

The quality factors described by McCall and his colleagues [MCC77] represent one of a number of suggested "checklists" for software quality. Hewlett-Packard [GRA87] developed a set of software quality factors that has been given the acronym FURPS—

FIGURE 19.2 Quality factors and metrics

Quality factor \ Software quality metric	Correctness	Reliability	Efficiency	Integrity	Maintainability	Flexibility	Testability	Portability	Reusability	Interoperability	Usability
Auditability				x			x				
Accuracy		x									
Communication commonality										x	
Completeness	x										
Complexity		x				x	x				
Concision			x		x	x					
Consistency	x	x			x	x					
Data commonality										x	
Error tolerance		x									
Execution efficiency			x								
Expandability						x					
Generality						x		x	x	x	
Hardware Indep.								x	x		
Instrumentation				x	x		x				
Modularity		x			x	x	x	x	x	x	
Operability			x								x
Security				x							
Self-documentation					x	x	x	x	x		
Simplicity		x			x	x	x				
System Indep.								x	x		
Traceability	x										
Training											x

(Adapted from Arthur, L. A., *Measuring Programmer Productivity and Software Quality,* Wiley-Interscience, 1985.)

functionality, usability, reliability, performance, and supportability. The FURPS quality factors draw liberally from earlier work, defining the following attributes for each of the five major factors:

- *Functionality* is assessed by evaluating the feature set and capabilities of the program, the generality of the functions that are delivered, and the security of the overall system.
- *Usability* is assessed by considering human factors (Chapter 15), overall aesthetics, consistency, and documentation.
- *Reliability* is evaluated by measuring the frequency and severity of failure, the accuracy of output results, the mean-time-to-failure (MTTF), the ability to recover from failure, and the predictability of the program.
- *Performance* is measured by processing speed, response time, resource consumption, throughput, and efficiency.

- *Supportability* combines the ability to extend the program (extensibility), adaptability, serviceability—these three attributes represent a more common term, maintainability—in addition, testability, compatibility, configurability (the ability to organize and control elements of the software configuration, Chapter 9), the ease with which a system can be installed, and the ease with which problems can be localized.

The FURPS quality factors and attributes just described can be used to establish quality metrics for each step in the software engineering process.

19.1.3 ISO 9126 Quality Factors

The ISO 9126 standard was developed in an attempt to identify the key quality attributes for computer software. The standard identifies six key quality attributes:

Functionality. The degree to which the software satisfies stated needs as indicated by the following subattributes: suitability, accuracy, interoperability, compliance, and security.

Reliability. The amount of time that the software is available for use as indicated by the following subattributes: maturity, fault tolerance, recoverability.

Usability. The degree to which the software is easy to use as indicated by the following subattributes: understandability, learnability, operability.

Efficiency. The degree to which the software makes optimal use of system resources as indicated by the following subattributes: time behavior, resource behavior.

Maintainability. The ease with which repair may be made to the software as indicated by the following subattributes: analyzability, changeability, stability, testability.

Portability. The ease with which the software can be transposed from one environment to another as indicated by the following subattributes: adaptability, installability, conformance, replaceability.

Quote:

"Any activity becomes creative when the doer cares about doing it right, or better."

John Updike

Like other software quality factors discussed in Sections 19.1.1 and 19.1.2, the ISO 9126 factors do not necessarily lend themselves to direct measurement. However, they do provide a worthwhile basis for indirect measures and an excellent checklist for assessing the quality of a system.

19.1.4 The Transition to a Quantitative View

In the preceding sections, a set of qualitative factors for the "measurement" of software quality was discussed. We strive to develop precise measures for software quality and are sometimes frustrated by the subjective nature of the activity. Cavano and McCall [CAV78] discuss this situation:

The determination of quality is a key factor in every day events—wine tasting contests, sporting events [e.g., gymnastics], talent contests, etc. In these situations, quality is judged in the most fundamental and direct manner: side by side comparison of objects under identical conditions and with predetermined concepts. The wine may be judged according to clarity, color, bouquet, taste, etc. However, this type of judgement is very subjective; to have any value at all, it must be made by an expert.

Subjectivity and specialization also apply to determining software quality. To help solve this problem, a more precise definition of software quality is needed as well as a way to derive quantitative measurements of software quality for objective analysis . . . Since there is no such thing as absolute knowledge, one should not expect to measure software quality exactly, for every measurement is partially imperfect. Jacob Bronkowski described this paradox of knowledge in this way: "Year by year we devise more precise instruments with which to observe nature with more fineness. And when we look at the observations we are discomfited to see that they are still fuzzy, and we feel that they are as uncertain as ever."

In the sections that follow, we examine a set of software metrics that can be applied to the quantitative assessment of software quality. In all cases, the metrics represent indirect measures; that is, we never really measure quality but rather some manifestation of quality. The complicating factor is the precise relationship between the variable that is measured and the quality of software.

19.2 A FRAMEWORK FOR TECHNICAL SOFTWARE METRICS

As we noted in the introduction to this chapter, measurement assigns numbers or symbols to attributes of entities in the real word. To accomplish this, a measurement model encompassing a consistent set of rules is required. Although the theory of measurement (e.g., [KYB84]) and its application to computer software (e.g., [DEM81], [BRI96], [ZUS97]) are topics that are beyond the scope of this book, it is worthwhile to establish a fundamental framework and a set of basic principles for the measurement of technical metrics for software.

Quote:

"Just as temperature measurement began with an index finger . . . and grew to sophisticated scales, tools and techniques, so too is software measurement maturing . . ."

Shari Pfleeger

19.2.1 The Challenge of Technical Metrics

Over the past three decades, many researchers have attempted to develop a single metric that provides a comprehensive measure of software complexity. Fenton [FEN94] characterizes this research as a search for "the impossible holy grail." Although dozens of complexity measures have been proposed [ZUS90], each takes a somewhat different view of what complexity is and what attributes of a system lead to complexity. By analogy, consider a metric for evaluating an attractive car. Some observers might emphasize body design, others might consider mechanical characteristics, still others might tout cost, or performance, or fuel economy, or the ability to recycle when the car is junked. Since any one of these characteristics may be at odds with others, it is difficult to derive a single value for "attractiveness." The same problem occurs with computer software.

WebRef

Voluminous information on technical metrics has been compiled by Horst Zuse: **irb.cs.tu-berlin.de/~zuse/**

Yet there is a need to measure and control software complexity. And if a single value of this quality metric is difficult to derive, it should be possible to develop measures of different internal program attributes (e.g., effective modularity, functional independence, and other attributes discussed in Chapters 13 through 16). These measures and the metrics derived from them can be used as independent indicators of the quality of analysis and design models. But here again, problems arise. Fenton [FEN94] notes this when he states:

> The danger of attempting to find measures which characterize so many different attributes is that inevitably the measures have to satisfy conflicting aims. This is counter to the representational theory of measurement.

Although Fenton's statement is correct, many people argue that technical measurement conducted during the early stages of the software process provides software engineers with a consistent and objective mechanism for assessing quality.

It is fair to ask, however, just how valid technical metrics are. That is, how closely aligned are technical metrics to the long-term reliability and quality of a computer-based system? Fenton [FEN91] addresses this question in the following way:

> In spite of the intuitive connections between the internal structure of software products [technical metrics] and its external product and process attributes, there have actually been very few scientific attempts to establish specific relationships. There are a number of reasons why this is so; the most commonly cited is the impracticality of conducting relevant experiments.

Each of the "challenges" noted here is a cause for caution, but it is no reason to dismiss technical metrics.[2] Measurement is essential if quality is to be achieved.

19.2.2 Measurement Principles

Before we introduce a series of technical metrics that (1) assist in the evaluation of the analysis and design models, (2) provide an indication of the complexity of procedural designs and source code, and (3) facilitate the design of more effective testing, it is important to understand basic measurement principles. Roche [ROC94] suggests a measurement process that can be characterized by five activities:

? What are the steps of an effective measurement process?

- *Formulation*. The derivation of software measures and metrics that are appropriate for the representation of the software that is being considered.
- *Collection*. The mechanism used to accumulate data required to derive the formulated metrics.
- *Analysis*. The computation of metrics and the application of mathematical tools.

---

2 A vast literature on software metrics (e.g., see [FEN94], [ROC94], [ZUS97] for extensive bibliographies) has been spawned, and criticism of specific metrics (including some of those presented in this chapter) is common. However, many of the critiques focus on esoteric issues and miss the primary objective of measurement in the real world: to help the engineer establish a systematic and objective way to gain insight into his or her work and to improve product quality as a result.

- *Interpretation*. The evaluation of metrics results in an effort to gain insight into the quality of the representation.
- *Feedback*. Recommendations derived from the interpretation of technical metrics transmitted to the software team.

The principles that can be associated with the formulation of technical metrics are [ROC94]

? What rules should we observe when we establish technical measures?

- The objectives of measurement should be established before data collection begins.
- Each technical metric should be defined in an unambiguous manner.
- Metrics should be derived based on a theory that is valid for the domain of application (e.g., metrics for design should draw upon basic design concepts and principles and attempt to provide an indication of the presence of an attribute that is deemed desirable).
- Metrics should be tailored to best accommodate specific products and processes [BAS84].

Although formulation is a critical starting point, collection and analysis are the activities that drive the measurement process. Roche [ROC94] suggests the following principles for these activities:

Above all, keep your early attempts at technical measurement simple. Don't obsess over the "perfect" metric because it doesn't exist.

- Whenever possible, data collection and analysis should be automated.
- Valid statistical techniques should be applied to establish relationships between internal product attributes and external quality characteristics (e.g., is the level of architectural complexity correlated with the number of defects reported in production use?).
- Interpretative guidelines and recommendations should be established for each metric.

In addition to these principles, the success of a metrics activity is tied to management support. Funding, training, and promotion must all be considered if a technical measurement program is to be established and sustained.

19.2.3 The Attributes of Effective Software Metrics

Hundreds of metrics have been proposed for computer software, but not all provide practical support to the software engineer. Some demand measurement that is too complex, others are so esoteric that few real world professionals have any hope of understanding them, and others violate the basic intuitive notions of what high-quality software really is.

Ejiogu [EJI91] defines a set of attributes that should be encompassed by effective software metrics. The derived metric and the measures that lead to it should be

How should we assess the quality of a proposed software metric?

- *Simple and computable.* It should be relatively easy to learn how to derive the metric, and its computation should not demand inordinate effort or time.
- *Empirically and intuitively persuasive.* The metric should satisfy the engineer's intuitive notions about the product attribute under consideration (e.g., a metric that measures module cohesion should increase in value as the level of cohesion increases).
- *Consistent and objective.* The metric should always yield results that are unambiguous. An independent third party should be able to derive the same metric value using the same information about the software.

Experience indicates that a technical metric will be used only if it is intuitive and easy to compute. If dozens of "counts" have to be made and complex computations are required, it's unlikely that the metric will be widely applied.

- *Consistent in its use of units and dimensions.* The mathematical computation of the metric should use measures that do not lead to bizarre combinations of units. For example, multiplying people on the project teams by programming language variables in the program results in a suspicious mix of units that are not intuitively persuasive.
- *Programming language independent.* Metrics should be based on the analysis model, the design model, or the structure of the program itself. They should not be dependent on the vagaries of programming language syntax or semantics.
- *An effective mechanism for high-quality feedback.* That is, the metric should provide a software engineer with information that can lead to a higher-quality end product.

Although most software metrics satisfy these attributes, some commonly used metrics may fail to satisfy one or two of them. An example is the function point (discussed in Chapter 4 and again in this chapter). It can be argued[3] that the consistent and objective attribute fails because an independent third party may not be able to derive the same function point value as a colleague using the same information about the software. Should we therefore reject the FP measure? The answer is: "Of course not!" FP provides useful insight and therefore provides distinct value, even if it fails to satisfy one attribute perfectly.

19.3 METRICS FOR THE ANALYSIS MODEL

XRef

Data, functional, and behavioral models are discussed in Chapters 11 and 12.

Technical work in software engineering begins with the creation of the analysis model. It is at this stage that requirements are derived and that a foundation for design is established. Therefore, technical metrics that provide insight into the quality of the analysis model are desirable.

3 Please note that an equally vigorous counterargument can be made. Such is the nature of software metrics.

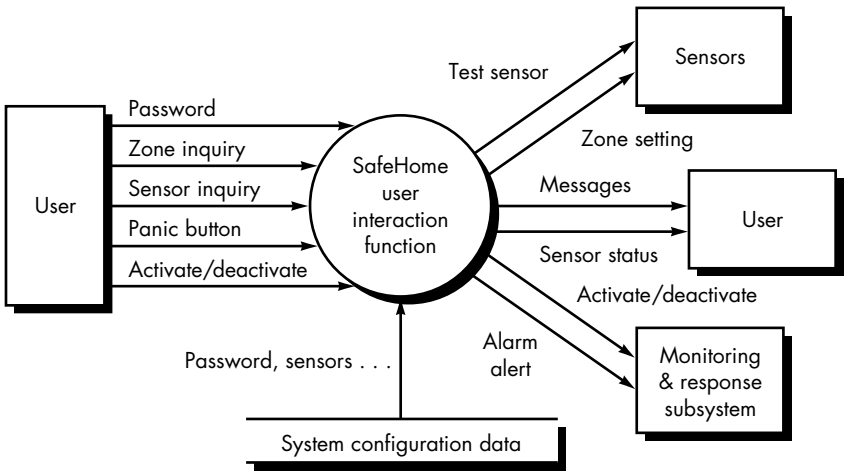

FIGURE 19.3
Part of the analysis model for SafeHome software

Although relatively few analysis and specification metrics have appeared in the literature, it is possible to adapt metrics derived for project application (Chapter 4) for use in this context. These metrics examine the analysis model with the intent of predicting the "size" of the resultant system. It is likely that size and design complexity will be directly correlated.

19.3.1 Function-Based Metrics

To be useful for technical work, measures that will assist technical decision making (e.g., errors found during unit testing) must be collected and then normalized using the FP metric.

The function point metric (Chapter 4) can be used effectively as a means for predicting the size of a system that will be derived from the analysis model. To illustrate the use of the FP metric in this context, we consider a simple analysis model representation, illustrated in Figure 19.3. Referring to the figure, a data flow diagram (Chapter 12) for a function within the *SafeHome* software[4] is represented. The function manages user interaction, accepting a user password to activate or deactivate the system, and allows inquiries on the status of security zones and various security sensors. The function displays a series of prompting messages and sends appropriate control signals to various components of the security system.

The data flow diagram is evaluated to determine the key measures required for computation of the function point metric (Chapter 4):

- number of user inputs
- number of user outputs
- number of user inquiries
- number of files
- number of external interfaces

4 *SafeHome* is a home security system that has been used as an example application in earlier chapters.

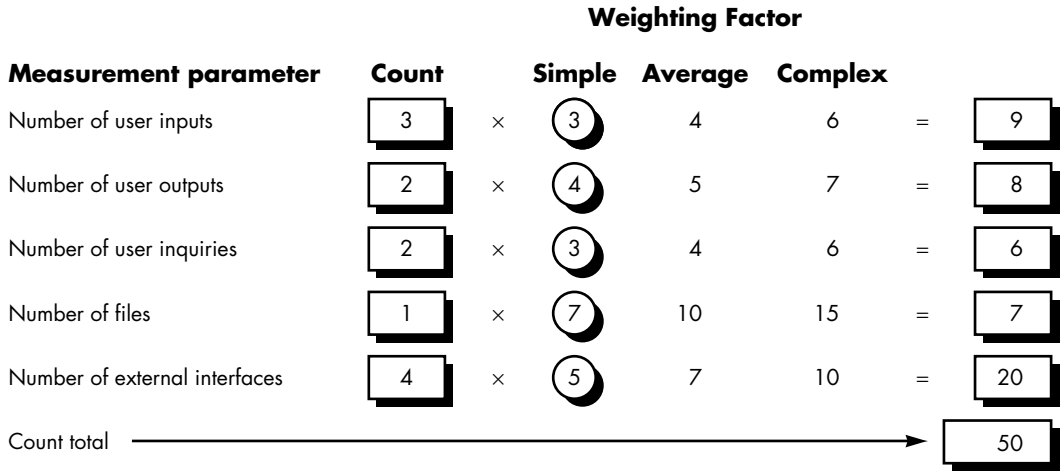

FIGURE 19.4 Computing function points for a SafeHome function

Three user inputs—**password, panic button,** and **activate/deactivate**—are shown in the figure along with two inquires—**zone inquiry** and **sensor inquiry.** One file (**system configuration file**) is shown. Two user outputs (**messages** and **sensor status**) and four external interfaces (**test sensor, zone setting, activate/deactivate,** and **alarm alert**) are also present. These data, along with the appropriate complexity, are shown in Figure 19.4.

The *count total* shown in Figure 19.4 must be adjusted using Equation (4-1):

$$\text{FP} = \text{count total} \times [0.65 + 0.01 \times \Sigma (F_i)]$$

where count total is the sum of all FP entries obtained from Figure 19.3 and F_i (i = 1 to 14) are "complexity adjustment values." For the purposes of this example, we assume that $\Sigma (F_i)$ is 46 (a moderately complex product). Therefore,

$$\text{FP} = 50 \times [0.65 + (0.01 \times 46)] = 56$$

Based on the projected FP value derived from the analysis model, the project team can estimate the overall implemented size of the *SafeHome* user interaction function. Assume that past data indicates that one FP translates into 60 lines of code (an object-oriented language is to be used) and that 12 FPs are produced for each person-month of effort. These historical data provide the project manager with important planning information that is based on the analysis model rather than preliminary estimates. Assume further that past projects have found an average of three errors per function point during analysis and design reviews and four errors per function point during unit and integration testing. These data can help software engineers assess the completeness of their review and testing activities.

A useful introduction on FP has been prepared by Capers Jones and may be obtained at **www.spr.com/library/0funcmet.htm**

19.3.2 The Bang Metric

Like the function point metric, the *bang metric* can be used to develop an indication of the size of the software to be implemented as a consequence of the analysis model. Developed by DeMarco [DEM82], the bang metric is "an implementation independent indication of system size." To compute the bang metric, the software engineer must first evaluate a set of *primitives*—elements of the analysis model that are not further subdivided at the analysis level. Primitives [DEM82] are determined by evaluating the analysis model and developing counts for the following forms:[5]

Quote:

"Rather than just musing on what 'new metric' might apply . . . we should also be asking ourselves the more basic question, 'What will we do with metrics.'"

Michael Mah and Larry Putnam

Functional primitives (FuP). The number of transformations (bubbles) that appear at the lowest level of a data flow diagram (Chapter 12).

Data elements (DE). The number of attributes of a data object, data elements are not composite data and appear within the data dictionary.

Objects (OB). The number of data objects as described in Chapter 12.

Relationships (RE). The number of connections between data objects as described in Chapter 12.

States (ST). The number of user observable states in the state transition diagram (Chapter 12).

Transitions (TR). The number of state transitions in the state transition diagram (Chapter 12).

In addition to these six primitives, additional counts are determined for

Modified manual function primitives (FuPM). Functions that lie outside the system boundary but must be modified to accommodate the new system.

Input data elements (DEI). Those data elements that are input to the system.

Output data elements. (DEO). Those data elements that are output from the system.

Retained data elements. (DER). Those data elements that are retained (stored) by the system.

Data tokens (TC_i). The data tokens (data items that are not subdivided within a functional primitive) that exist at the boundary of the *i*th functional primitive (evaluated for each primitive).

Relationship connections (RE_i). The relationships that connect the *i*th object in the data model to other objects.

DeMarco [DEM82] suggests that most software can be allocated to one of two domains: *function strong* or *data strong,* depending upon the ratio RE/FuP. Function-strong

5 The acronym noted in parentheses following the primitive is used to denote the count of the particular primitive, e,g., FuP indicates the number of functional primitives present in an analysis model.

applications (often encountered in engineering and scientific applications) emphasize the transformation of data and do not generally have complex data structures. Data-strong applications (often encountered in information systems applications) tend to have complex data models.

RE/FuP < 0.7 implies a function-strong application.
0.8 < RE/FuP < 1.4 implies a hybrid application.
RE/FuP > 1.5 implies a data-strong application.

Because different analysis models will partition the model to greater or lessor degrees of refinement, DeMarco suggests that an average token count per primitive is

$$TC_{avg} = \Sigma TC_i / FuP$$

be used to control uniformity of partitioning across many different models within an application domain.

To compute the bang metric for function-strong applications, the following algorithm is used:

```
set initial value of bang = 0;
do while functional primitives remain to be evaluated
    Compute token-count around the boundary of primitive i
    Compute corrected FuP increment (CFuPI)
    Allocate primitive to class
    Assess class and note assessed weight
    Multiply CFuPI  by the assessed weight
    bang = bang + weighted CFuPI
enddo
```

The token-count is computed by determining how many separate tokens are "visible" [DEM82] within the primitive. It is possible that the number of tokens and the number of data elements will differ, if data elements can be moved from input to output without any internal transformation. The corrected CFuPI is determined from a table published by DeMarco. A much abbreviated version follows:

TC_i	CFuPI
2	1.0
5	5.8
10	16.6
15	29.3
20	43.2

The assessed weight noted in the algorithm is determined from 16 different classes of functional primitives defined by DeMarco. A weight ranging from 0.6 (simple data routing) to 2.5 (data management functions) is assigned, depending on the class of the primitive.

For data-strong applications, the bang metric is computed using the following algorithm:

```
set initial value of bang = 0;
do while objects remain to be evaluated in the data model
    compute count of relationships for object i
    compute corrected OB increment (COBI)
    bang = bang + COBI
enddo
```

The COBI is determined from a table published by DeMarco. An abbreviated version follows:

RE_i	COBI
1	1.0
3	4.0
6	9.0

Once the bang metric has been computed, past history can be used to associate it with size and effort. DeMarco suggests that an organization build its own versions of the CFuPI and COBI tables using calibration information from completed software projects.

19.3.3 Metrics for Specification Quality

By measuring characteristics of the specification, it is possible to gain quantitative insight into specificity and completeness.

Davis and his colleagues [DAV93] propose a list of characteristics that can be used to assess the quality of the analysis model and the corresponding requirements specification: *specificity* (lack of ambiguity), *completeness, correctness, understandability, verifiability, internal and external consistency, achievability, concision, traceability, modifiability, precision,* and *reusability.* In addition, the authors note that high-quality specifications are electronically stored, executable or at least interpretable, annotated by relative importance and stable, versioned, organized, cross-referenced, and specified at the right level of detail.

Although many of these characteristics appear to be qualitative in nature, Davis et al. [DAV93] suggest that each can be represented using one or more metrics.[6] For example, we assume that there are n_r requirements in a specification, such that

$$n_r = n_f + n_{nf}$$

where n_f is the number of functional requirements and n_{nf} is the number of nonfunctional (e.g., performance) requirements.

To determine the *specificity* (lack of ambiguity) of requirements, Davis et al. suggest a metric that is based on the consistency of the reviewers' interpretation of each requirement:

$$Q_1 = n_{ui}/n_r$$

6 A complete discussion of specification quality metrics is beyond the scope of this chapter. See [DAV93] for more details.

where n_{ui} is the number of requirements for which all reviewers had identical interpretations. The closer the value of Q to 1, the lower is the ambiguity of the specification.

The *completeness* of functional requirements can be determined by computing the ratio

$$Q_2 = n_u/[n_i \times n_s]$$

where n_u is the number of unique function requirements, n_i is the number of inputs (stimuli) defined or implied by the specification, and n_s is the number of states specified. The Q_2 ratio measures the percentage of necessary functions that have been specified for a system. However, it does not address nonfunctional requirements. To incorporate these into an overall metric for completeness, we must consider the degree to which requirements have been validated:

$$Q_3 = n_c/[n_c + n_{nv}]$$

where n_c is the number of requirements that have been validated as correct and n_{nv} is the number of requirements that have not yet been validated.

19.4 METRICS FOR THE DESIGN MODEL

Quote:

"Measure what is measurable, and what is not measurable, make measurable."

Galileo

It is inconceivable that the design of a new aircraft, a new computer chip, or a new office building would be conducted without defining design measures, determining metrics for various aspects of design quality, and using them to guide the manner in which the design evolves. And yet, the design of complex software-based systems often proceeds with virtually no measurement. The irony of this is that design metrics for software are available, but the vast majority of software engineers continue to be unaware of their existence.

Design metrics for computer software, like all other software metrics, are not perfect. Debate continues over their efficacy and the manner in which they should be applied. Many experts argue that further experimentation is required before design measures can be used. And yet, design without measurement is an unacceptable alternative.

In the sections that follow, we examine some of the more common design metrics for computer software. Each can provide the designer with improved insight and all can help the design to evolve to a higher level of quality.

19.4.1 Architectural Design Metrics

Architectural design metrics focus on characteristics of the program architecture (Chapter 14) with an emphasis on the architectural structure and the effectiveness of modules. These metrics are black box in the sense that they do not require any knowledge of the inner workings of a particular software component.

Card and Glass [CAR90] define three software design complexity measures: structural complexity, data complexity, and system complexity.

Structural complexity of a module *i* is defined in the following manner:

$$S(i) = f^2_{out}(i) \tag{19-1}$$

KEY POINT

Metrics can provide insight into structural, data and system complexity associated with the architectural design.

where $f_{out}(i)$ is the fan-out[7] of module *i*.

Data complexity provides an indication of the complexity in the internal interface for a module *i* and is defined as

$$D(i) = v(i)/[f_{out}(i) + 1] \tag{19-2}$$

where *v(i)* is the number of input and output variables that are passed to and from module *i*.

Finally, *system complexity* is defined as the sum of structural and data complexity, specified as

$$C(i) = S(i) + D(i) \tag{19-3}$$

As each of these complexity values increases, the overall architectural complexity of the system also increases. This leads to a greater likelihood that integration and testing effort will also increase.

? Is there a way to assess the complexity of certain architectural models?

An earlier high-level architectural design metric proposed by Henry and Kafura [HEN81] also makes use of the fan-in and fan-out. The authors define a complexity metric (applicable to call and return architectures) of the form

$$\text{HKM} = \text{length}(i) \times [f_{in}(i) + f_{out}(i)]^2 \tag{19-4}$$

where length*(i)* is the number of programming language statements in a module *i* and $f_{in}(i)$ is the fan-in of a module *i*. Henry and Kafura extend the definitions of *fan-in* and *fan-out* presented in this book to include not only the number of module control connections (module calls) but also the number of data structures from which a module *i* retrieves (fan-in) or updates (fan-out) data. To compute HKM during design, the procedural design may be used to estimate the number of programming language statements for module *i*. Like the Card and Glass metrics noted previously, an increase in the Henry-Kafura metric leads to a greater likelihood that integration and testing effort will also increase for a module.

Fenton [FEN91] suggests a number of simple *morphology* (i.e., shape) metrics that enable different program architectures to be compared using a set of straightforward dimensions. Referring to Figure 19.5, the following metrics can be defined:

$$\text{size} = n + a$$

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7 Recalling the discussion presented in Chapter 13, fan-out indicates the number of modules immediately subordinate to module *i;* that is, the number of modules that are directly invoked by module *i*.

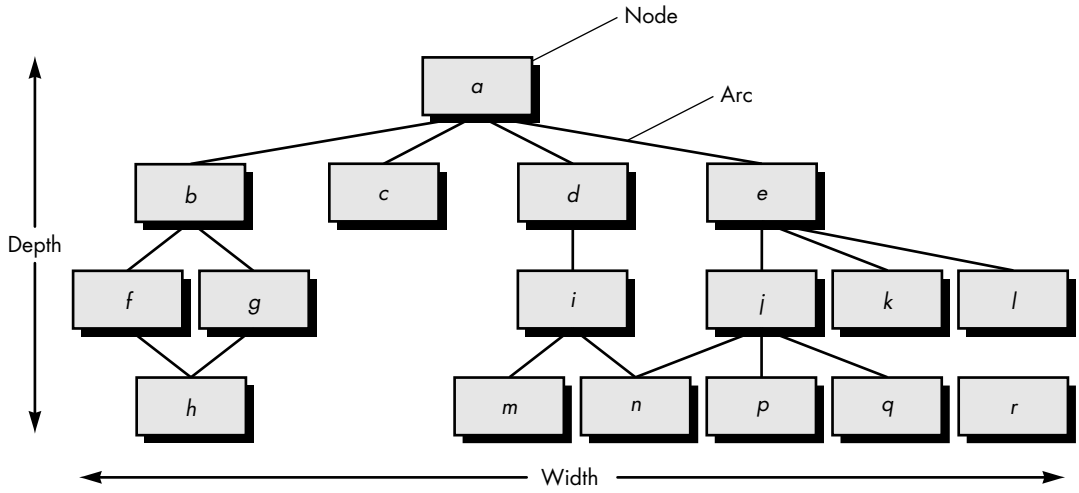

FIGURE 19.5 Morphology metrics

where n is the number of nodes and a is the number of arcs. For the architecture shown in Figure 19.5,

size = 17 + 18 = 35

depth = the longest path from the root (top) node to a leaf node. For the architecture shown in Figure 19.5, depth = 4.

width = maximum number of nodes at any one level of the architecture. For the architecture shown in Figure 19.5, width = 6.

arc-to-node ratio, $r = a/n$,

which measures the connectivity density of the architecture and may provide a simple indication of the coupling of the architecture. For the architecture shown in Figure 19.5, r = 18/17 = 1.06.

The U.S. Air Force Systems Command [USA87] has developed a number of software quality indicators that are based on measurable design characteristics of a computer program. Using concepts similar to those proposed in IEEE Std. 982.1-1988 [IEE94], the Air Force uses information obtained from data and architectural design to derive a *design structure quality index* (DSQI) that ranges from 0 to 1. The following values must be ascertained to compute the DSQI [CHA89]:

S_1 = the total number of modules defined in the program architecture.

S_2 = the number of modules whose correct function depends on the source of data input or that produce data to be used elsewhere (in general, control modules, among others, would not be counted as part of S_2).

S_3 = the number of modules whose correct function depends on prior processing.

S_4 = the number of database items (includes data objects and all attributes that define objects).

S_5 = the total number of unique database items.

S_6 = the number of database segments (different records or individual objects).

S_7 = the number of modules with a single entry and exit (exception processing is not considered to be a multiple exit).

Quote:

"Measurement can be seen as a detour. This detour is necessary because humans mostly are not able to make clear and objective decisions [without quantitative support]."

Horst Zuse

Once values S_1 through S_7 are determined for a computer program, the following intermediate values can be computed:

Program structure: D_1, where D_1 is defined as follows: If the architectural design was developed using a distinct method (e.g., data flow-oriented design or object-oriented design), then $D_1 = 1$, otherwise $D_1 = 0$.

Module independence: $D_2 = 1 - (S_2/S_1)$

Modules not dependent on prior processing: $D_3 = 1 - (S_3/S_1)$

Database size: $D_4 = 1 - (S_5/S_4)$

Database compartmentalization: $D_5 = 1 - (S_6/S_4)$

Module entrance/exit characteristic: $D_6 = 1 - (S_7/S_1)$

With these intermediate values determined, the DSQI is computed in the following manner:

$$\text{DSQI} = \Sigma\, w_i D_i \tag{19-5}$$

where $i = 1$ to 6, w_i is the relative weighting of the importance of each of the intermediate values, and $\Sigma\, w_i = 1$ (if all D_i are weighted equally, then $w_i = 0.167$).

The value of DSQI for past designs can be determined and compared to a design that is currently under development. If the DSQI is significantly lower than average, further design work and review are indicated. Similarly, if major changes are to be made to an existing design, the effect of those changes on DSQI can be calculated.

19.4.2 Component-Level Design Metrics

Component-level design metrics focus on internal characteristics of a software component and include measures of the "three Cs"—module cohesion, coupling, and complexity. These measures can help a software engineer to judge the quality of a component-level design.

The metrics presented in this section are glass box in the sense that they require knowledge of the inner working of the module under consideration. Component-level

design metrics may be applied once a procedural design has been developed. Alternatively, they may be delayed until source code is available.

It is possible to compute measures of the functional independence—coupling and cohesion—of a component and to use these to assess the quality of the design.

Cohesion metrics. Bieman and Ott [BIE94] define a collection of metrics that provide an indication of the cohesiveness (Chapter 13) of a module. The metrics are defined in terms of five concepts and measures:

Data slice. Stated simply, a data slice is a backward walk through a module that looks for data values that affect the module location at which the walk began. It should be noted that both program slices (which focus on statements and conditions) and data slices can be defined.

Data tokens. The variables defined for a module can be defined as data tokens for the module.

Glue tokens. This set of data tokens lies on one or more data slice.

Superglue tokens. These data tokens are common to every data slice in a module.

Stickiness. The relative stickiness of a glue token is directly proportional to the number of data slices that it binds.

Bieman and Ott develop metrics for *strong functional cohesion* (SFC), *weak functional cohesion* (WFC), and *adhesiveness* (the relative degree to which glue tokens bind data slices together). These metrics can be interpreted in the following manner [BIE94]:

> All of these cohesion metrics range in value between 0 and 1. They have a value of 0 when a procedure has more than one output and exhibits none of the cohesion attribute indicated by a particular metric. A procedure with no superglue tokens, no tokens that are common to all data slices, has zero strong functional cohesion—there are no data tokens that contribute to all outputs. A procedure with no glue tokens, that is no tokens common to more than one data slice (in procedures with more than one data slice), exhibits zero weak functional cohesion and zero adhesiveness—there are no data tokens that contribute to more than one output.

Strong functional cohesion and adhesiveness are encountered when the Bieman and Ott metrics take on a maximum value of 1.

A detailed discussion of the Bieman and Ott metrics is best left to the authors [BIE94]. However, to illustrate the character of these metrics, consider the metric for strong functional cohesion:

$$SFC(i) = SG\ [SA(i))/(tokens(i)] \tag{19-6}$$

where SG[SA(*i*)] denotes superglue tokens—the set of data tokens that lie on all data slices for a module *i*. As the ratio of superglue tokens to the total number of tokens in a module *i* increases toward a maximum value of 1, the functional cohesiveness of the module also increases.

Coupling metrics. Module coupling provides an indication of the "connectedness" of a module to other modules, global data, and the outside environment. In Chapter 13, coupling was discussed in qualitative terms.

Dhama [DHA95] has proposed a metric for module coupling that encompasses data and control flow coupling, global coupling, and environmental coupling. The measures required to compute module coupling are defined in terms of each of the three coupling types noted previously.

WebRef

A paper, "A Software Metric System for Module Coupling," can be downloaded from **www.isse.gmu.edu/faculty/ofut/rsrch/abstracts/mj-coupling.html**

For data and control flow coupling,

d_i = number of input data parameters
c_i = number of input control parameters
d_o = number of output data parameters
c_o = number of output control parameters

For global coupling,

g_d = number of global variables used as data
g_c = number of global variables used as control

For environmental coupling,

w = number of modules called (fan-out)
r = number of modules calling the module under consideration (fan-in)

Using these measures, a module coupling indicator, m_c, is defined in the following way:

$$m_c = k/M$$

where k = 1, a proportionality constant[8] and

$$M = d_i + (a \times c_i) + d_o + (b \times c_o) + g_d + (c \times g_c) + w + r$$

where $a = b = c = 2$.

The higher the value of m_c, the lower is the overall module coupling. For example, if a module has single input and output data parameters, accesses no global data, and is called by a single module,

$$m_c = 1/(1 + 0 + 1 + 0 + 0 + + 0 + 1 + 0) = 1/3 = 0.33$$

We would expect that such a module exhibits low coupling. Hence, a value of m_c = 0.33 implies low coupling. Alternatively, if a module has five input and five output data parameters, an equal number of control parameters, accesses ten items of global data, has a fan-in of 3 and a fan-out of 4,

$$m_c = 1/[5 + (2 \times 5) + 5 + (2 \times 5) + 10 + 0 + 3 + 4] = 0.02$$

and the implied coupling would be high.

8 The author [DHA95] notes that the values of k and a, b, and c (discussed in the next equation) may be adjusted as more experimental verification occurs.

In order to have the coupling metric move upward as the degree of coupling increases (an important attribute discussed in Section 18.2.3), a revised coupling metric may be defined as

$$C = 1 - m_C$$

where the degree of coupling increases nonlinearly between a minimum value in the range 0.66 to a maximum value that approaches 1.0.

Complexity metrics. A variety of software metrics can be computed to determine the complexity of program control flow. Many of these are based on the flow graph. As we discussed in Chapter 17, a graph is a representation composed of nodes and links (also called *edges*). When the links (edges) are *directed,* the flow graph is a directed graph.

McCabe and Watson [MCC94] identify a number of important uses for complexity metrics:

> Complexity metrics can be used to predict critical information about reliability and maintainability of software systems from automatic analysis of source code [or procedural design information]. Complexity metrics also provide feedback during the software project to help control the [design activity]. During testing and maintenance, they provide detailed information about software modules to help pinpoint areas of potential instability.

Cyclomatic complexity is only one of a large number of complexity metrics.

The most widely used (and debated) complexity metric for computer software is cyclomatic complexity, originally developed by Thomas McCabe [MCC76], [MCC89] and discussed in detail in Section 17.4.2.

The McCabe metric provides a quantitative measure of testing difficulty and an indication of ultimate reliability. Experimental studies indicate distinct relationships between the McCabe metric and the number of errors existing in source code, as well as time required to find and correct such errors.

McCabe also contends that cyclomatic complexity may be used to provide a quantitative indication of maximum module size. Collecting data from a number of actual programming projects, he has found that cyclomatic complexity = 10 appears to be a practical upper limit for module size. When the cyclomatic complexity of modules exceeded this number, it became extremely difficult to adequately test a module. See Chapter 17 for a discussion of cyclomatic complexity as a guide for the design of white-box test cases.

Zuse ([ZUS90], [ZUS97]) presents an encyclopedic discussion of no fewer that 18 different categories of software complexity metrics. The author presents the basic definitions for metrics in each category (e.g., there are a number of variations on the cyclomatic complexity metric) and then analyzes and critiques each. Zuse's work is the most comprehensive published to date.

19.4.3 Interface Design Metrics

Although there is significant literature on the design of human/computer interfaces (see Chapter 15), relatively little information has been published on metrics that would provide insight into the quality and usability of the interface.

Sears [SEA93] suggests that *layout appropriateness* (LA) is a worthwhile design metric for human/computer interfaces. A typical GUI uses *layout entities*—graphic icons, text, menus, windows, and the like—to assist the user in completing tasks. To accomplish a given task using a GUI, the user must move from one layout entity to the next. The absolute and relative position of each layout entity, the frequency with which it is used, and the "cost" of the transition from one layout entity to the next all contribute to the appropriateness of the interface.

Quote:

"Beauty—the adjustment of all parts proportionately so that one cannot add or subtract or change without impairing the harmony of the whole."

Leon Alberti (1404–1472)

For a specific layout (i.e., a specific GUI design), cost can be assigned to each sequence of actions according to the following relationship:

$$\text{cost} = \Sigma\ [\text{frequency of transition}(k) \times \text{cost of transition}(k)] \tag{19-7}$$

where k is a specific transition from one layout entity to the next as a specific task is accomplished. The summation occurs across all transitions for a particular task or set of tasks required to accomplish some application function. Cost may be characterized in terms of time, processing delay, or any other reasonable value, such as the distance that a mouse must travel between layout entities. Layout appropriateness is defined as

$$\text{LA} = 100 \times [(\text{cost of LA} - \text{optimal layout})/(\text{cost of proposed layout})] \tag{19-8}$$

where LA = 100 for an optimal layout.

To compute the optimal layout for a GUI, interface real estate (the area of the screen) is divided into a grid. Each square of the grid represents a possible position for a layout entity. For a grid with N possible positions and K different layout entities to place, the number of possible layouts is represented in the following manner [SEA93]:

$$\text{number of possible layouts} = [N!/(K! \times (N - K)!] \times K! \tag{19-9}$$

ADVICE

Interface design metrics are fine, but above all else, be absolutely sure that your end-users like the interface and are comfortable with the interactions required.

As the number of layout positions increases, the number of possible layouts grows very large. To find the optimal (lowest cost) layout, Sears [SEA93] proposes a tree searching algorithm.

LA is used to assess different proposed GUI layouts and the sensitivity of a particular layout to changes in task descriptions (i.e., changes in the sequence and/or frequency of transitions). The interface designer can use the change in layout appropriateness, ΔLA, as a guide in choosing the best GUI layout for a particular application.

It is important to note that the selection of a GUI design can be guided with metrics such as LA, but the final arbiter should be user input based on GUI prototypes. Nielsen and Levy [NIE94] report that "one has a reasonably large chance of suc-

cess if one chooses between interface [designs] based solely on users' opinions. Users' average task performance and their subjective satisfaction with a GUI are highly correlated."

19.5 METRICS FOR SOURCE CODE

Quote:

"The Human Brain follows a more rigid set of rules [in developing algorithms] than it has been aware of."

Maurice Halstead

Halstead's theory of software science [HAL77] is one of "the best known and most thoroughly studied . . . composite measures of (software) complexity" [CUR80]. Software science proposed the first analytical "laws" for computer software.[9]

Software science assigns quantitative laws to the development of computer software, using a set of primitive measures that may be derived after code is generated or estimated once design is complete. These follow:

n_1 = the number of distinct operators that appear in a program.
n_2 = the number of distinct operands that appear in a program.
N_1 = the total number of operator occurrences.
N_2 = the total number of operand occurrences.

Halstead uses these primitive measures to develop expressions for the overall *program length, potential minimum volume* for an algorithm, the *actual volume* (number of bits required to specify a program), the *program level* (a measure of software complexity), the *language level* (a constant for a given language), and other features such as development effort, development time, and even the projected number of faults in the software.

ADVICE

Operators include all flow of control constructs, conditionals, and math operations. Operands encompass all program variables and constants.

Halstead shows that length N can be estimated

$$N = n_1 \log_2 n_1 + n_2 \log_2 n_2 \tag{19-10}$$

and program volume may be defined

$$V = N \log_2 (n_1 + n_2) \tag{19-11}$$

It should be noted that V will vary with programming language and represents the volume of information (in bits) required to specify a program.

Theoretically, a minimum volume must exist for a particular algorithm. Halstead defines a volume ratio L as the ratio of volume of the most compact form of a program to the volume of the actual program. In actuality, L must always be less than 1. In terms of primitive measures, the volume ratio may be expressed as

$$L = 2/n_1 \times n_2/N_2 \tag{19-12}$$

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9 It should be noted that Halstead's "laws" have generated substantial controversy and that not everyone agrees that the underlying theory is correct. However, experimental verification of Halstead's findings have been made for a number of programming languages (e.g., [FEL89]).

Halstead's work is amenable to experimental verification and a large body of research has been conducted to investigate software science. A discussion of this work is beyond the scope of this text, but it can be said that good agreement has been found between analytically predicted and experimental results. For further information, see [ZUS90], [FEN91], and [ZUS97].

19.6 METRICS FOR TESTING

Although much has been written on software metrics for testing (e.g., [HET93]), the majority of metrics proposed focus on the process of testing, not the technical characteristics of the tests themselves. In general, testers must rely on analysis, design, and code metrics to guide them in the design and execution of test cases.

Testing metrics fall into two broad categories: (1) metrics that attempt to predict the likely number of tests required at various testing levels and (2) metrics that focus on test coverage for a given component.

Function-based metrics (Section 19.3.1) can be used as a predictor for overall testing effort. Various project-level characteristics (e.g., testing effort and time, errors uncovered, number of test cases produced) for past projects can be collected and correlated with the number of FP produced by a project team. The team can then project "expected values" of these characteristics for the current project.

The bang metric can provide an indication of the number of test cases required by examining the primitive measures discussed in Section 19.3.2. The number of functional primitives (FuP), data elements (DE), objects (OB), relationships (RE), states (ST), and transitions (TR) can be used to project the number and types of black-box and white-box tests for the software. For example, the number of tests associated with the human/computer interface can be estimated by (1) examining the number of transitions (TR) contained in the state transition representation of the HCI and evaluating the tests required to exercise each transition; (2) examining the number of data objects (OB) that move across the interface, and (3) the number of data elements that are input or output.

Architectural design metrics provide information on the ease or difficulty associated with integration testing (Chapter 18) and the need for specialized testing software (e.g., stubs and drivers). Cyclomatic complexity (a component-level design metric) lies at the core of basis path testing, a test case design method presented in Chapter 17. In addition, cyclomatic complexity can be used to target modules as candidates for extensive unit testing (Chapter 18). Modules with high cyclomatic complexity are more likely to be error prone than modules whose cyclomatic complexity is lower. For this reason, the tester should expend above average effort to uncover errors in such modules before they are integrated in a system. Testing effort can also be estimated using metrics derived from Halstead measures (Section 19.5). Using the definitions for program volume, V, and program level, PL, software science effort, e, can be computed as

$$\text{PL} = 1/[(n_1/2)\bullet(N_2/n_2)] \tag{19-13a}$$

$$e = V/\text{PL} \tag{19-13b}$$

The percentage of overall testing effort to be allocated to a module k can be estimated using the following relationship:

$$\text{percentage of testing effort } (k) = e(k) / \Sigma\, e(i) \tag{19-14}$$

where $e(k)$ is computed for module k using Equations (19-13) and the summation in the denominator of Equation (19-14) is the sum of software science effort across all modules of the system.

As tests are conducted, three different measures provide an indication of testing completeness. A measure of the breath of testing provides an indication of how many requirements (of the total number of requirements) have been tested. This provides an indication of the completeness of the test plan. Depth of testing is a measure of the percentage of independent basis paths covered by testing versus the total number of basis paths in the program. A reasonably accurate estimate of the number of basis paths can be computed by adding the cyclomatic complexity of all program modules. Finally, as tests are conducted and error data are collected, fault profiles may be used to rank and categorize errors uncovered. Priority indicates the severity of the problem. Fault categories provide a description of an error so that statistical error analysis can be conducted.

19.7 METRICS FOR MAINTENANCE

All of the software metrics introduced in this chapter can be used for the development of new software and the maintenance of existing software. However, metrics designed explicitly for maintenance activities have been proposed.

IEEE Std. 982.1-1988 [IEE94] suggests a *software maturity index* (SMI) that provides an indication of the stability of a software product (based on changes that occur for each release of the product). The following information is determined:

M_T = the number of modules in the current release
F_c = the number of modules in the current release that have been changed
F_a = the number of modules in the current release that have been added
F_d = the number of modules from the preceding release that were deleted in the current release

The software maturity index is computed in the following manner:

$$\text{SMI} = [M_T - (F_a + F_c + F_d)] / M_T \tag{19-15}$$

As SMI approaches 1.0, the product begins to stabilize. SMI may also be used as metric for planning software maintenance activities. The mean time to produce a release of a software product can be correlated with SMI and empirical models for maintenance effort can be developed.

19.8 SUMMARY

Software metrics provide a quantitative way to assess the quality of internal product attributes, thereby enabling the software engineer to assess quality before the product is built. Metrics provide the insight necessary to create effective analysis and design models, solid code, and thorough tests.

To be useful in a real world context, a software metric must be simple and computable, persuasive, consistent, and objective. It should be programming language independent and provide effective feedback to the software engineer.

Metrics for the analysis model focus on function, data, and behavior—the three components of the analysis model. The function point and the bang metric each provide a quantitative means for evaluating the analysis model. Metrics for design consider architecture, component-level design, and interface design issues. Architectural design metrics consider the structural aspects of the design model. Component-level design metrics provide an indication of module quality by establishing indirect measures for cohesion, coupling, and complexity. Interface design metrics provide an indication of layout appropriateness for a GUI.

Software science provides an intriguing set of metrics at the source code level. Using the number of operators and operands present in the code, software science provides a variety of metrics that can be used to assess program quality.

Few technical metrics have been proposed for direct use in software testing and maintenance. However, many other technical metrics can be used to guide the testing process and as a mechanism for assessing the maintainability of a computer program.

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PROBLEMS AND POINTS TO PONDER

19.1. Measurement theory is an advanced topic that has a strong bearing on software metrics. Using [ZUS97], [FEN91], [ZUS90], [KYB84] or some other source, write a brief paper that outlines the main tenets of measurement theory. Individual project: Develop a presentation on the subject and present it to your class.

19.2. McCall's quality factors were developed during the 1970s. Almost every aspect of computing has changed dramatically since the time that they were developed, and yet, McCall's factors continue to apply to modern software. Can you draw any conclusions based on this fact?

19.3. Why is it that a single, all-encompassing metric cannot be developed for program complexity or program quality?

19.4. Review the analysis model you developed as part of Problem 12.13. Using the guidelines presented in Section 19.3.1, develop an estimate for the number of function points associated with PHTRS.

19.5. Review the analysis model you developed as part of Problem 12.13. Using the guidelines presented in Section 19.3.2, develop primitive counts for the bang metric. Is the PHTRS system function strong or data strong?

19.6. Compute the value of the bang metric using the measures you developed in Problem 19.5.

19.7. Create a complete design model for a system that is proposed by your instructor. Compute structural and data complexity using the metrics described in Section 19.4.1. Also compute the Henry-Kafura and morphology metrics for the design model.

19.8. A major information system has 1140 modules. There are 96 modules that perform control and coordination functions and 490 modules whose function depends on prior processing. The system processes approximately 220 data objects that each have an average of three attributes. There are 140 unique data base items and 90 different database segments. Finally, 600 modules have single entry and exit points. Compute the DSQI for this system.

19.9. Research Bieman and Ott's [BIE94] paper and develop a complete example that illustrates the computation of their cohesion metric. Be sure to indicate how data slices, data tokens, glue, and superglue tokens are determined.

19.10. Select five modules in an existing computer program. Using Dhama's metric described in Section 19.4.2, compute the coupling value for each module.

19.11. Develop a software tool that will compute cyclomatic complexity for a programming language module. You may choose the language.

19.12. Develop a software tool that will compute layout appropriateness for a GUI. The tool should enable you to assign the transition cost between layout entities. (Note: Recognize that the size of the potential population of layout alternatives grows very large as the number of possible grid positions grows.)

19.13. Develop a small software tool that will perform a Halstead analysis on programming language source code of your choosing.

19.14. Research the literature and write a paper on the relationship of Halstead's metric and McCabe's metric on software quality (as measured by error count). Are the data compelling? Recommend guidelines for the application of these metrics.

19.15. Research the literature for any recent papers on metrics specifically developed to assist in test case design. Present your findings to the class.

19.16. A legacy system has 940 modules. The latest release required that 90 of these modules be changed. In addition, 40 new modules were added and 12 old modules were removed. Compute the software maturity index for the system.

FURTHER READING AND INFORMATION SOURCES

There are a surprisingly large number of books that are dedicated to software metrics, although the majority focus on process and project metrics to the exclusion of technical metrics. Zuse [ZUS97] has written the most thorough treatment of technical metrics published to date.

Books by Card and Glass [CAR90], Zuse [ZUS90], Fenton {FEN91], Ejiogu [EJI91], Moeller and Paulish *(Software Metrics,* Chapman and Hall, 1993), and Hetzel [HET93] all address technical metrics in some detail. Oman and Pfleeger (*Applying Software Metrics,* IEEE Computer Society Press, 1997) have edited an anthology of important papers on software metrics. In addition, the following books are worth examining:

Conte, S.D., H.E. Dunsmore, and V.Y. Shen. *Software Engineering Metrics and Models,* Benjamin/Cummings, 1984.

Fenton, N.E. and S.L. Pfleeger, *Software Metrics: A Rigorous and Practical Approach,* 2nd ed., PWS Publishing Co., 1998.

Grady, R.B. *Practical Software Metrics for Project Management and Process Improvement,* Prentice-Hall, 1992.

Perlis, A., et al., *Software Metrics: An Analysis and Evaluation,* MIT Press, 1981.

Sheppard, M., *Software Engineering Metrics,* McGraw-Hill, 1992.

The theory of software measurement is presented by Denvir, Herman, and Whitty in an edited collection of papers (*Proceedings of the International BCS-FACS Workshop: Formal Aspects of Measurement,* Springer-Verlag, 1992). Shepperd (*Foundations of Software Measurement,* Prentice-Hall, 1996) also addresses measurement theory in some detail.

A comprehensive summary of dozens of useful software metrics is presented in [IEE94]. In general, a discussion of each metric has been distilled to the essential "primitives" (measures) required to compute the metric and the appropriate relationships to effect the computation. An appendix provides discussion and many references.

A wide variety of information sources on technical metrics and related subjects is available on the Internet. An up-to-date list of World Wide Web references that are relevant to technical metrics can be found at the SEPA Web site:
http://www.mhhe.com/engcs/compsci/pressman/resources/tech-metrics.mhtml