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Structured Testing: A Testing Methodology Using the Cyclomatic Complexity Metric

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Abstract

The purpose of this document is to describe the structured testing methodology for software testing, also known as basis path testing. Based on the cyclomatic complexity measure of McCabe, structured testing uses the control flow structure of software to establish path coverage criteria. The resultant test sets provide more thorough testing than statement and branch coverage. Extensions of the fundamental structured testing techniques for integration testing and object-oriented systems are also presented. Several related software complexity metrics are described. Summaries of technical papers, case studies, and empirical results are presented in the appendices.

Keywords

Basis path testing, cyclomatic complexity, McCabe, object oriented, software development, software diagnostic, software metrics, software testing, structured testing

Acknowledgments

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Executive Summary

This document describes the structured testing methodology for software testing and related software complexity analysis techniques. The key requirement of structured testing is that all decision outcomes must be exercised independently during testing. The number of tests required for a software module is equal to the cyclomatic complexity of that module. The original structured testing document [NBS99] discusses cyclomatic complexity and the basic testing technique. This document gives an expanded and updated presentation of those topics, describes several new complexity measures and testing strategies, and presents the experience gained through the practical application of these techniques.

The software complexity measures described in this document are: cyclomatic complexity, module design complexity, integration complexity, object integration complexity, actual complexity, realizable complexity, essential complexity, and data complexity. The testing techniques are described for module testing, integration testing, and object-oriented testing.

A significant amount of practical advice is given concerning the application of these techniques. The use of complexity measurement to manage software reliability and maintainability is discussed, along with strategies to control complexity during maintenance. Methods to apply the testing techniques are also covered. Both manual techniques and the use of automated support are described.

Many detailed examples of the techniques are given, as well as summaries of technical papers and case studies. Experimental results are given showing that structured testing is superior to statement and branch coverage testing for detecting errors. The bibliography lists over 50 references to related information.

CONTENTS

1 Introduction

1.1 Software testing

This document describes the structured testing methodology for software testing. Software testing is the process of executing software and comparing the observed behavior to the desired behavior. The major goal of software testing is to discover errors in the software [MYERS2], with a secondary goal of building confidence in the proper operation of the software when testing does not discover errors. The conflict between these two goals is apparent when considering a testing process that did not detect any errors. In the absence of other information, this could mean either that the software is high quality or that the testing process is low quality. There are many approaches to software testing that attempt to control the quality of the testing process to yield useful information about the quality of the software being tested.

Although most testing research is concentrated on finding effective testing techniques, it is also important to make software that can be effectively tested. It is suggested in [VOAS] that software is testable if faults are likely to cause failure, since then those faults are most likely to be detected by failure during testing. Several programming techniques are suggested to raise testability, such as minimizing variable reuse and maximizing output parameters. In [BERTOLINO] it is noted that although having faults cause failure is good during testing, it is bad after delivery. For a more intuitive testability property, it is best to maximize the probability of faults being detected during testing while minimizing the probability of faults causing failure after delivery. Several programming techniques are suggested to raise testability, including assertions that observe the internal state of the software during testing but do not affect the specified output, and multiple version development [BRILLIANT] in which any disagreement between versions can be reported during testing but a majority voting mechanism helps reduce the likelihood of incorrect output after delivery. Since both of those techniques are frequently used to help construct reliable systems in practice, this version of testability may capture a significant factor in software development.

For large systems, many errors are often found at the beginning of the testing process, with the observed error rate decreasing as errors are fixed in the software. When the observed error rate during testing approaches zero, statistical techniques are often used to determine a reasonable point to stop testing [MUSA]. This approach has two significant weaknesses. First, the testing effort cannot be predicted in advance, since it is a function of the intermediate results of the testing effort itself. A related problem is that the testing schedule can expire long before the error rate drops to an acceptable level. Second, and perhaps more importantly, the statistical model only predicts the estimated error rate for the underlying test case distribution being used during the testing process. It may have little or no connection to the likelihood of errors manifesting once the system is delivered or to the total number of errors present in the software.

Another common approach to testing is based on requirements analysis. A requirements specification is converted into test cases, which are then executed so that testing verifies system behavior for at least one test case within the scope of each requirement. Although this approach is an important part of a comprehensive testing effort, it is certainly not a complete solution. Even setting aside the fact that requirements documents are notoriously error-prone, requirements are written at a much higher level of abstraction than code. This means that there is much more detail in the code than the requirement, so a test case developed from a requirement tends to exercise only a small fraction of the software that implements that requirement. Testing only at the requirements level may miss many sources of error in the software itself.

The structured testing methodology falls into another category, the white box (or code-based, or glass box) testing approach. In white box testing, the software implementation itself is used to guide testing. A common white box testing criterion is to execute every executable statement during testing, and verify that the output is correct for all tests. In the more rigorous branch coverage approach, every decision outcome must be executed during testing. Structured testing is still more rigorous, requiring that each decision outcome be tested independently. A fundamental strength that all white box testing strategies share is that the entire software implementation is taken into account during testing, which facilitates error detection even when the software specification is vague or incomplete. A corresponding weakness is that if the software does not implement one or more requirements, white box testing may not detect the resultant errors of omission. Therefore, both white box and requirements-based testing are important to an effective testing process. The rest of this document deals exclusively with white box testing, concentrating on the structured testing methodology.

1.2 Software complexity measurement

Software complexity is one branch of software metrics that is focused on direct measurement of software attributes, as opposed to indirect software measures such as project milestone status and reported system failures. There are hundreds of software complexity measures [ZUSE], ranging from the simple, such as source lines of code, to the esoteric, such as the number of variable definition/usage associations.

An important criterion for metrics selection is uniformity of application, also known as “open reengineering.” The reason “open systems” are so popular for commercial software applications is that the user is guaranteed a certain level of interoperability—the applications work together in a common framework, and applications can be ported across hardware platforms with minimal impact. The open reengineering concept is similar in that the abstract models used to represent software systems should be as independent as possible of implementation characteristics such as source code formatting and programming language. The objective is to be able to set complexity standards and interpret the resultant numbers uniformly across projects and languages. A particular complexity value should mean the same thing whether it was calculated from source code written in Ada, C, FORTRAN, or some other language. The most basic complexity measure, the number of lines of code, does not meet the open reengineering criterion, since it is extremely sensitive to programming language, coding style, and textual formatting of the source code. The cyclomatic complexity measure, which measures the amount of decision logic in a source code function, does meet the open reengineering criterion. It is completely independent of text formatting and is nearly independent of programming language since the same fundamental decision structures are available and uniformly used in all procedural programming languages [MCCABE5].

Ideally, complexity measures should have both descriptive and prescriptive components. Descriptive measures identify software that is error-prone, hard to understand, hard to modify, hard to test, and so on. Prescriptive measures identify operational steps to help control software, for example splitting complex modules into several simpler ones, or indicating the amount of testing that should be performed on given modules.

1.3 Relationship between complexity and testing

There is a strong connection between complexity and testing, and the structured testing methodology makes this connection explicit.

First, complexity is a common source of error in software. This is true in both an abstract and a concrete sense. In the abstract sense, complexity beyond a certain point defeats the human mind's ability to perform accurate symbolic manipulations, and errors result. The same psychological factors that limit people's ability to do mental manipulations of more than the infamous "7 +/- 2" objects simultaneously [MILLER] apply to software. Structured programming techniques can push this barrier further away, but not eliminate it entirely. In the concrete sense, numerous studies and general industry experience have shown that the cyclomatic complexity measure correlates with errors in software modules. Other factors being equal, the more complex a module is, the more likely it is to contain errors. Also, beyond a certain threshold of complexity, the likelihood that a module contains errors increases sharply. Given this information, many organizations limit the cyclomatic complexity of their software modules in an attempt to increase overall reliability. A detailed recommendation for complexity limitation is given in section 2.5.

Second, complexity can be used directly to allocate testing effort by leveraging the connection between complexity and error to concentrate testing effort on the most error-prone software. In the structured testing methodology, this allocation is precise—the number of test paths required for each software module is exactly the cyclomatic complexity. Other common white box testing criteria have the inherent anomaly that they can be satisfied with a small number of tests for arbitrarily complex (by any reasonable sense of "complexity") software as shown in section 5.2.

1.4 Document overview and audience descriptions

- Section 1 gives an overview of this document. It also gives some general information about software testing, software complexity measurement, and the relationship between the two.
- Section 2 describes the cyclomatic complexity measure for software, which provides the foundation for structured testing.
- Section 3 gives some examples of both the applications and the calculation of cyclomatic complexity.
- Section 4 describes several practical shortcuts for calculating cyclomatic complexity.
- Section 5 defines structured testing and gives a detailed example of its application.
- Section 6 describes the Baseline Method, a systematic technique for generating a set of test paths that satisfy structured testing.
- Section 7 describes structured testing at the integration level.
- Section 8 describes structured testing for object-oriented programs.
- Section 9 discusses techniques for identifying and removing unnecessary complexity and the impact on testing.
- Section 10 describes the essential complexity measure for software, which quantifies the extent to which software is poorly structured.
- Section 11 discusses software modification, and how to apply structured testing to programs during maintenance.
- Section 12 summarizes this document by software lifecycle phase, showing where each technique fits into the overall development process.
- Appendix A describes several related case studies.
- Appendix B presents an extended example of structured testing. It also describes an experimental design for comparing structural testing strategies, and applies that design to illustrate the superiority of structured testing over branch coverage.

Figure 1-1 shows the dependencies among the first 11 sections.

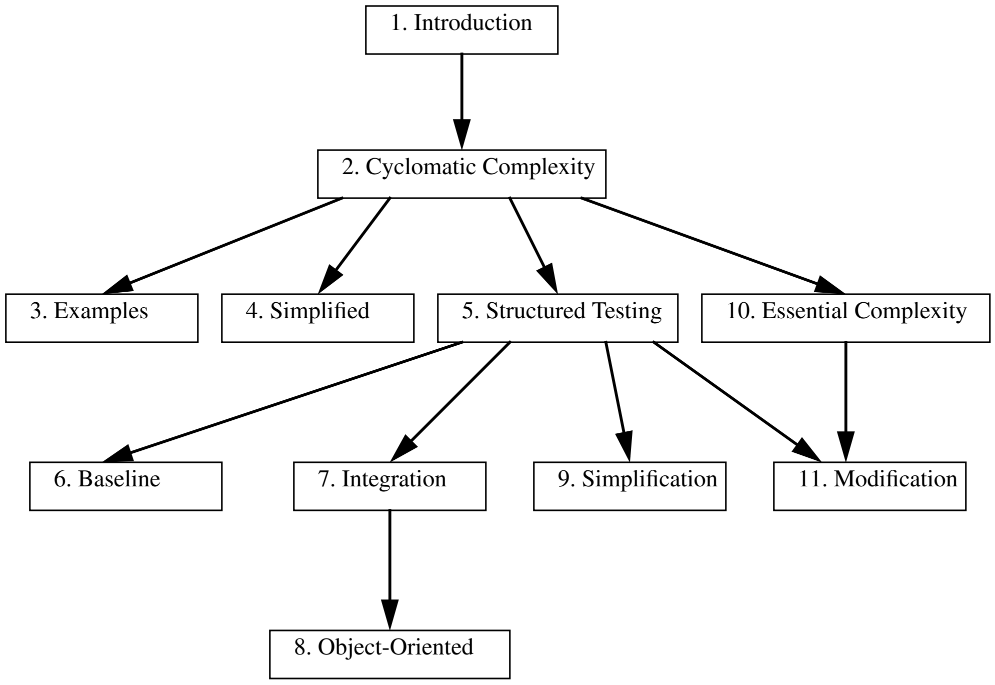


Figure 1-1. Dependencies among sections 1-11.

Readers with different interests may concentrate on specific areas of this document and skip or skim the others. Sections 2, 5, and 7 form the primary material, presenting the core structured testing method. The mathematical content can be skipped on a first reading or by readers primarily interested in practical applications. Sections 4 and 6 concentrate on manual techniques, and are therefore of most interest to readers without access to automated tools. Readers working with object-oriented systems should read section 8. Readers familiar with the original NBS structured testing document [NBS99] should concentrate on the updated material in section 5 and the new material in sections 7 and 8.

Programmers who are not directly involved in testing may concentrate on sections 1-4 and 10. These sections describe how to limit and control complexity, to help produce more testable, reliable, and maintainable software, without going into details about the testing technique.

Testers may concentrate on sections 1, 2, and 5-8. These sections give all the information necessary to apply the structured testing methodology with or without automated tools.

Maintainers who are not directly involved in the testing process may concentrate on sections 1, 2, and 9-11. These sections describe how to keep maintenance changes from degrading the testability, reliability, and maintainability of software, without going into details about the testing technique.

Project Leaders and *Managers* should read through the entire document, but may skim over the details in sections 2 and 5-8.

Quality Assurance, *Methodology*, and *Standards* professionals may skim the material in sections 1, 2, and 5 to get an overview of the method, then read section 12 to see where it fits into the software lifecycle. The Appendices also provide important information about experience with the method and implementation details for specific languages.

2 Cyclomatic Complexity

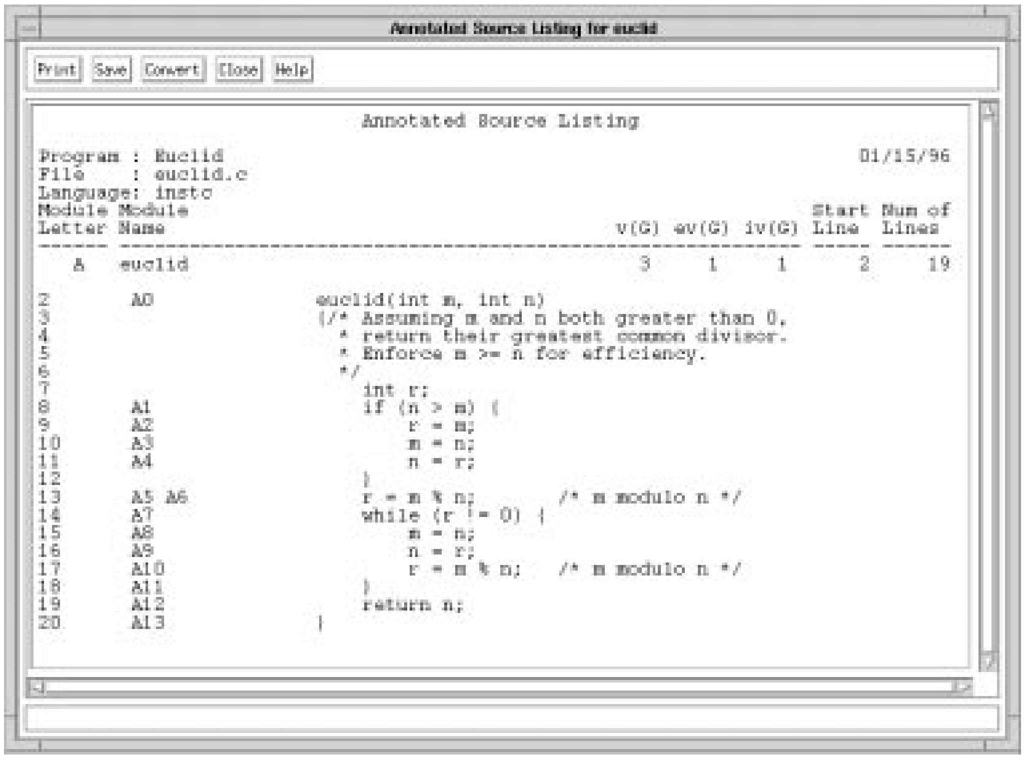
Cyclomatic complexity [MCCABE1] measures the amount of decision logic in a single software module. It is used for two related purposes in the structured testing methodology. First, it gives the number of recommended tests for software. Second, it is used during all phases of the software lifecycle, beginning with design, to keep software reliable, testable, and manageable. Cyclomatic complexity is based entirely on the structure of software's control flow graph.

2.1 Control flow graphs

Control flow graphs describe the logic structure of software modules. A module corresponds to a single function or subroutine in typical languages, has a single entry and exit point, and is able to be used as a design component via a call/return mechanism. This document uses C as the language for examples, and in C a module is a function. Each flow graph consists of nodes and edges. The nodes represent computational statements or expressions, and the edges represent transfer of control between nodes.

Each possible execution path of a software module has a corresponding path from the entry to the exit node of the module's control flow graph. This correspondence is the foundation for the structured testing methodology.

As an example, consider the C function in Figure 2-1, which implements Euclid's algorithm for finding greatest common divisors. The nodes are numbered A0 through A13. The control flow graph is shown in Figure 2-2, in which each node is numbered 0 through 13 and edges are shown by lines connecting the nodes. Node 1 thus represents the decision of the "if" statement with the true outcome at node 2 and the false outcome at the collection node 5. The decision of the "while" loop is represented by node 7, and the upward flow of control to the next iteration is shown by the dashed line from node 10 to node 7. Figure 2-3 shows the path resulting when the module is executed with parameters 4 and 2, as in "euclid(4,2)." Execution begins at node 0, the beginning of the module, and proceeds to node 1, the decision node for the "if" statement. Since the test at node 1 is false, execution transfers directly to node 5, the collection node of the "if" statement, and proceeds to node 6. At node 6, the value of "r" is calculated to be 0, and execution proceeds to node 7, the decision node for the "while" statement. Since the test at node 7 is false, execution transfers out of the loop directly to node 11, then proceeds to node 12, returning the result of 2. The actual return is modeled by execution proceeding to node 13, the module exit node.



```
                          Annotated Source Listing

Program : Euclid                                                  01/15/96
File    : euclid.c
Language: instc
Module Module                                                  Start Num of
Letter Name                                v(G) ev(G) iv(G) Line  Lines
------ ------------------------------------------------------ ----- ------
   A   euclid                                 3     1     1     2     19

2       A0            euclid(int m, int n)
3                     {/* Assuming m and n both greater than 0,
4                       * return their greatest common divisor.
5                       * Enforce m >= n for efficiency.
6                       */
7                         int r;
8       A1                if (n > m) {
9       A2                    r = m;
10      A3                    m = n;
11      A4                    n = r;
12                        }
13      A5 A6             r = m % n;       /* m modulo n */
14      A7                while (r != 0) {
15      A8                    m = n;
16      A9                    n = r;
17      A10                   r = m % n;   /* m modulo n */
18      A11               }
19      A12               return n;
20      A13           }
```

Figure 2-1. Annotated source listing for module "euclid."

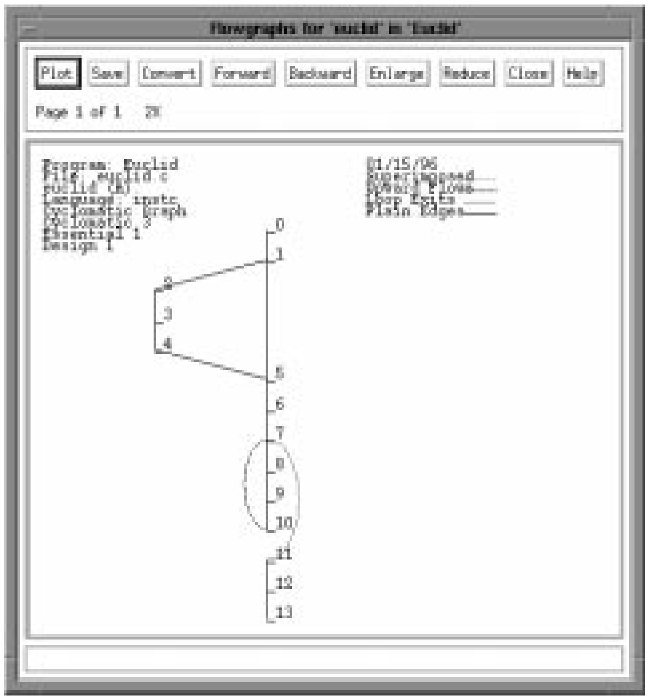
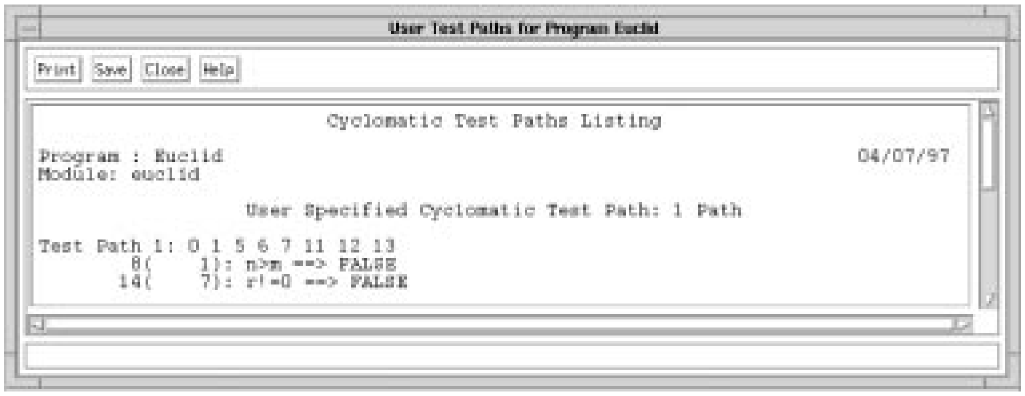


Figure 2-2. **Control flow graph for module "euclid."**



```
                    Cyclomatic Test Paths Listing

Program : Euclid                                             04/07/97
Module: euclid

                User Specified Cyclomatic Test Path: 1 Path

Test Path 1: 0 1 5 6 7 11 12 13
        8(    1): n>m ==> FALSE
       14(    7): r!=0 ==> FALSE
```

Figure 2-3. **A test path through module "euclid."**

2.2 Definition of cyclomatic complexity, v(G)

Cyclomatic complexity is defined for each module to be e - n + 2, where e and n are the number of edges and nodes in the control flow graph, respectively. Thus, for the Euclid's algorithm example in section 2.1, the complexity is 3 (15 edges minus 14 nodes plus 2). Cyclomatic complexity is also known as v(G), where v refers to the cyclomatic number in graph theory and G indicates that the complexity is a function of the graph.

The word "cyclomatic" comes from the number of fundamental (or basic) cycles in connected, undirected graphs [BERGE]. More importantly, it also gives the number of independent paths through strongly connected directed graphs. A strongly connected graph is one in which each node can be reached from any other node by following directed edges in the graph. The cyclomatic number in graph theory is defined as e - n + 1. Program control flow graphs are not strongly connected, but they become strongly connected when a "virtual edge" is added connecting the exit node to the entry node. The cyclomatic complexity definition for program control flow graphs is derived from the cyclomatic number formula by simply adding one to represent the contribution of the virtual edge. This definition makes the cyclomatic complexity equal the number of independent paths through the standard control flow graph model, and avoids explicit mention of the virtual edge.

Figure 2-4 shows the control flow graph of Figure 2-2 with the virtual edge added as a dashed line. This virtual edge is not just a mathematical convenience. Intuitively, it represents the control flow through the rest of the program in which the module is used. It is possible to calculate the amount of (virtual) control flow through the virtual edge by using the conservation of flow equations at the entry and exit nodes, showing it to be the number of times that the module has been executed. For any individual path through the module, this amount of flow is exactly one. Although the virtual edge will not be mentioned again in this document, note that since its flow can be calculated as a linear combination of the flow through the real edges, its presence or absence makes no difference in determining the number of linearly independent paths through the module.

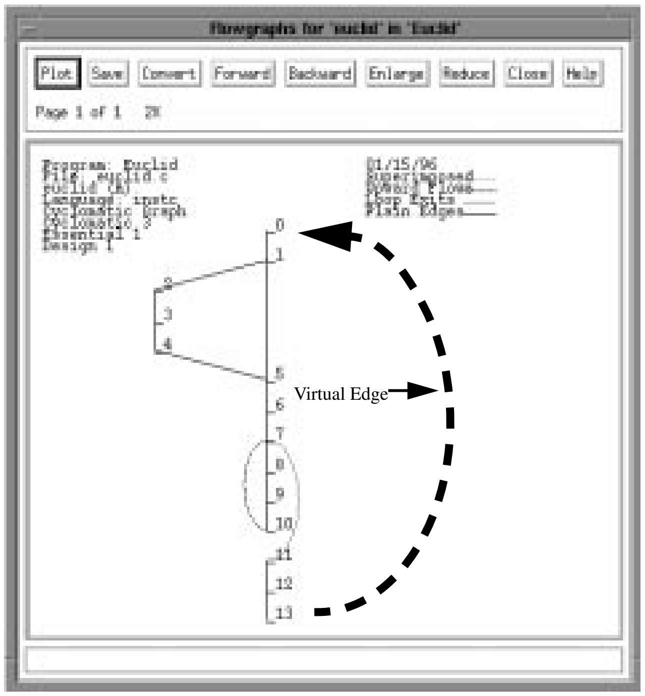


Figure 2-4. **Control flow graph with virtual edge.**

2.3 *Characterization of v(G) using a basis set of control flow paths*

Cyclomatic complexity can be characterized as the number of elements of a basis set of control flow paths through the module. Some familiarity with linear algebra is required to follow the details, but the point is that cyclomatic complexity is precisely the minimum number of paths that can, in (linear) combination, generate all possible paths through the module. To see this, consider the following mathematical model, which gives a vector space corresponding to each flow graph.

Each path has an associated row vector, with the elements corresponding to edges in the flow graph. The value of each element is the number of times the edge is traversed by the path. Consider the path described in Figure 2-3 through the graph in Figure 2-2. Since there are 15 edges in the graph, the vector has 15 elements. Seven of the edges are traversed exactly once as part of the path, so those elements have value 1. The other eight edges were not traversed as part of the path, so they have value 0.

Considering a set of several paths gives a matrix in which the columns correspond to edges and the rows correspond to paths. From linear algebra, it is known that each matrix has a unique rank (number of linearly independent rows) that is less than or equal to the number of columns. This means that no matter how many of the (potentially infinite) number of possible paths are added to the matrix, the rank can never exceed the number of edges in the graph. In fact, the maximum value of this rank is exactly the cyclomatic complexity of the graph. A minimal set of vectors (paths) with maximum rank is known as a basis, and a basis can also be described as a linearly independent set of vectors that generate all vectors in the space by linear combination. This means that the cyclomatic complexity is the number of paths in any independent set of paths that generate all possible paths by linear combination.

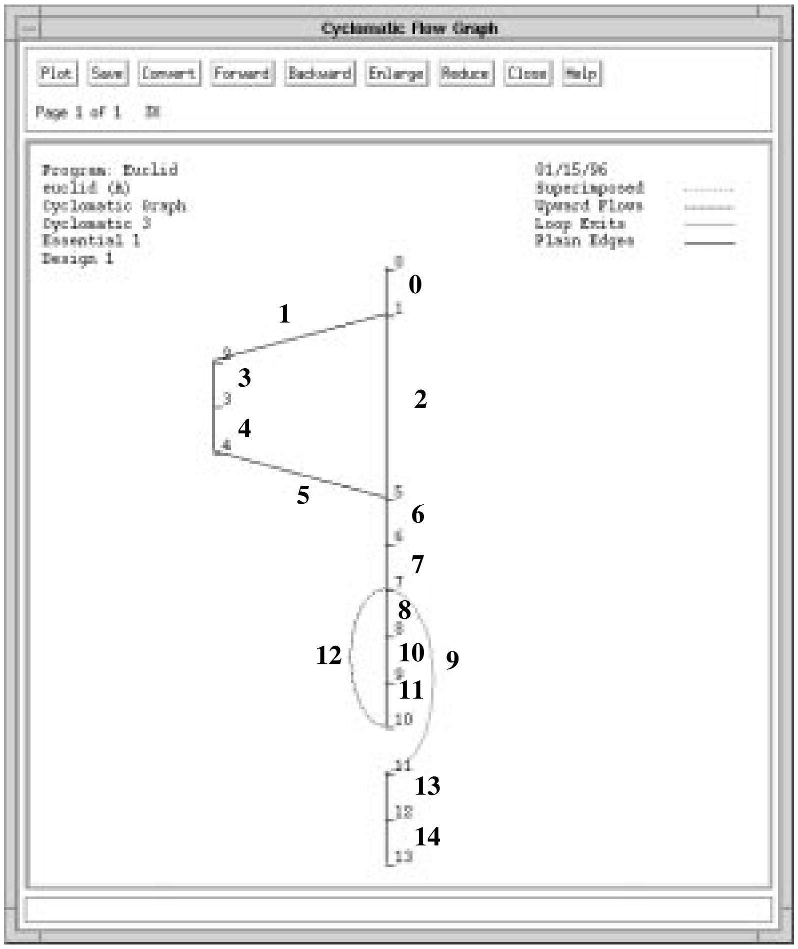
Given any set of paths, it is possible to determine the rank by doing Gaussian Elimination on the associated matrix. The rank is the number of non-zero rows once elimination is complete. If no rows are driven to zero during elimination, the original paths are linearly independent. If the rank equals the cyclomatic complexity, the original set of paths generate all paths by linear combination. If both conditions hold, the original set of paths are a basis for the flow graph.

There are a few important points to note about the linear algebra of control flow paths. First, although every path has a corresponding vector, not every vector has a corresponding path. This is obvious, for example, for a vector that has a zero value for all elements corresponding to edges out of the module entry node but has a nonzero value for any other element cannot correspond to any path. Slightly less obvious, but also true, is that linear combinations of vectors that correspond to actual paths may be vectors that do not correspond to actual paths. This follows from the non-obvious fact (shown in section 6) that it is always possible to construct a basis consisting of vectors that correspond to actual paths, so any vector can be generated from vectors corresponding to actual paths. This means that one can not just find a basis set of vectors by algebraic methods and expect them to correspond to paths—one must use a path-oriented technique such as that of section 6 to get a basis set of paths. Finally, there are a potentially infinite number of basis sets of paths for a given module. Each basis set has the same number of paths in it (the cyclomatic complexity), but there is no limit to the number of different sets of basis paths. For example, it is possible to start with any path and construct a basis that contains it, as shown in section 6.3.

The details of the theory behind cyclomatic complexity are too mathematically complicated to be used directly during software development. However, the good news is that this mathematical insight yields an effective operational testing method in which a concrete basis set of paths is tested: structured testing.

2.4 Example of v(G) and basis paths

Figure 2-5 shows the control flow graph for module “euclid” with the fifteen edges numbered 0 to 14 along with the fourteen nodes numbered 0 to 13. Since the cyclomatic complexity is 3 (15 - 14 + 2), there is a basis set of three paths. One such basis set consists of paths B1 through B3, shown in Figure 2-6.



```
Program: Euclid
euclid (A)
Cyclomatic Graph
Cyclomatic 3
Essential 1
Design 1
```

```
01/15/96
Superimposed
Upward Flows
Loop Exits
Plain Edges
```

Figure 2-5. Control flow graph with edges numbered.

```
Module: euclid

                          Basis Test Paths: 3 Paths

Test Path B1: 0 1 5 6 7 11 12 13
        8(    1): n>m ==> FALSE
       14(    7): r!=0 ==> FALSE

Test Path B2: 0 1 2 3 4 5 6 7 11 12 13
        8(    1): n>m ==> TRUE
       14(    7): r!=0 ==> FALSE

Test Path B3: 0 1 5 6 7 8 9 10 7 11 12 13
        8(    1): n>m ==> FALSE
       14(    7): r!=0 ==> TRUE
       14(    7): r!=0 ==> FALSE
```

Figure 2-6. A basis set of paths, B1 through B3.

Any arbitrary path can be expressed as a linear combination of the basis paths B1 through B3. For example, the path P shown in Figure 2-7 is equal to B2 - 2 * B1 + 2 * B3.

```
Module: euclid

                  User Specified Path: 1 Path

Test Path P: 0 1 2 3 4 5 6 7 8 9 10 7 8 9 10 7 11 12 13
        8(    1): n>m ==> TRUE
       14(    7): r!=0 ==> TRUE
       14(    7): r!=0 ==> TRUE
       14(    7): r!=0 ==> FALSE
```

Figure 2-7. Path P.

To see this, examine Figure 2-8, which shows the number of times each edge is executed along each path.

Path/Edge	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
B1	1	0	1	0	0	0	1	1	0	1	0	0	0	1	1
B2	1	1	0	1	1	1	1	1	0	1	0	0	0	1	1
B3	1	0	1	0	0	0	1	1	1	1	1	1	1	1	1
P	1	1	0	1	1	1	1	1	2	1	2	2	2	1	1

Figure 2-8. Matrix of edge incidence for basis paths B1-B3 and other path P.

One interesting property of basis sets is that every edge of a flow graph is traversed by at least one path in every basis set. Put another way, executing a basis set of paths will always cover every control branch in the module. This means that to cover all edges never requires more than the cyclomatic complexity number of paths. However, executing a basis set just to cover all edges is overkill. Covering all edges can usually be accomplished with fewer paths. In this example, paths B2 and B3 cover all edges without path B1. The relationship between basis paths and edge coverage is discussed further in section 5.

Note that apart from forming a basis together, there is nothing special about paths B1 through B3. Path P in combination with any two of the paths B1 through B3 would also form a basis. The fact that there are many sets of basis paths through most programs is important for testing, since it means it is possible to have considerable freedom in selecting a basis set of paths to test.

2.5 Limiting cyclomatic complexity to 10

There are many good reasons to limit cyclomatic complexity. Overly complex modules are more prone to error, are harder to understand, are harder to test, and are harder to modify. Deliberately limiting complexity at all stages of software development, for example as a departmental standard, helps avoid the pitfalls associated with high complexity software. Many organizations have successfully implemented complexity limits as part of their software programs. The precise number to use as a limit, however, remains somewhat controversial. The original limit of 10 as proposed by McCabe has significant supporting evidence, but limits as high as 15 have been used successfully as well. Limits over 10 should be reserved for projects that have several operational advantages over typical projects, for example experienced staff, formal design, a modern programming language, structured programming, code walkthroughs, and a comprehensive test plan. In other words, an organization can pick a complexity limit greater than 10, but only if it is sure it knows what it is doing and is willing to devote the additional testing effort required by more complex modules.

Somewhat more interesting than the exact complexity limit are the exceptions to that limit. For example, McCabe originally recommended exempting modules consisting of single multiway decision (“switch” or “case”) statements from the complexity limit. The multiway decision issue has been interpreted in many ways over the years, sometimes with disastrous results. Some naive developers wondered whether, since multiway decisions qualify for exemption from the complexity limit, the complexity measure should just be altered to ignore them. The result would be that modules containing several multiway decisions would not be identified as overly complex. One developer started reporting a “modified” complexity in which cyclomatic complexity was divided by the number of multiway decision branches. The stated intent of this metric was that multiway decisions would be treated uniformly by having them contribute the average value of each case branch. The actual result was that the developer could take a module with complexity 90 and reduce it to “modified” complexity 10 simply by adding a ten-branch multiway decision statement to it that did nothing.

Consideration of the intent behind complexity limitation can keep standards policy on track. There are two main facets of complexity to consider: the number of tests and everything else (reliability, maintainability, understandability, etc.). Cyclomatic complexity gives the number of tests, which for a multiway decision statement is the number of decision branches. Any attempt to modify the complexity measure to have a smaller value for multiway decisions will result in a number of tests that cannot even exercise each branch, and will hence be inadequate for testing purposes. However, the pure number of tests, while important to measure and control, is not a major factor to consider when limiting complexity. Note that testing effort is much more than just the number of tests, since that is multiplied by the effort to construct each individual test, bringing in the other facet of complexity. It is this correlation of complexity with reliability, maintainability, and understandability that primarily drives the process to limit complexity.

Complexity limitation affects the allocation of code among individual software modules, limiting the amount of code in any one module, and thus tending to create more modules for the same application. Other than complexity limitation, the usual factors to consider when allocating code among modules are the cohesion and coupling principles of structured design: the ideal module performs a single conceptual function, and does so in a self-contained manner without interacting with other modules except to use them as subroutines. Complexity limitation attempts to quantify an "except where doing so would render a module too complex to understand, test, or maintain" clause to the structured design principles. This rationale provides an effective framework for considering exceptions to a given complexity limit.

Rewriting a single multiway decision to cross a module boundary is a clear violation of structured design. Additionally, although a module consisting of a single multiway decision may require many tests, each test should be easy to construct and execute. Each decision branch can be understood and maintained in isolation, so the module is likely to be reliable and maintainable. Therefore, it is reasonable to exempt modules consisting of a single multiway decision statement from a complexity limit. Note that if the branches of the decision statement contain complexity themselves, the rationale and thus the exemption does not automatically apply. However, if all branches have very low complexity code in them, it may well apply. Although constructing "modified" complexity measures is not recommended, considering the *maximum* complexity of each multiway decision branch is likely to be much more useful than the *average*. At this point it should be clear that the multiway decision statement exemption is not a bizarre anomaly in the complexity measure but rather the consequence of a reasoning process that seeks a balance between the complexity limit, the principles of structured design, and the fundamental properties of software that the complexity limit is intended to control. This process should serve as a model for assessing proposed violations of the standard complexity limit. For developers with a solid understanding of both the mechanics and the intent of complexity limitation, the most effective policy is: "For each module, either limit cyclomatic complexity to 10 (as discussed earlier, an organization can substitute a similar number), or provide a written explanation of why the limit was exceeded."

3 Examples of Cyclomatic Complexity

3.1 Independence of complexity and size

There is a big difference between complexity and size. Consider the difference between the cyclomatic complexity measure and the number of lines of code, a common size measure. Just as 10 is a common limit for cyclomatic complexity, 60 is a common limit for the number of lines of code, the somewhat archaic rationale being that each software module should fit on one printed page to be manageable. Although the number of lines of code is often used as a crude complexity measure, there is no consistent relationship between the two. Many modules with no branching of control flow (and hence the minimum cyclomatic complexity of one) consist of far greater than 60 lines of code, and many modules with complexity greater than ten have far fewer than 60 lines of code. For example, Figure 3-1 has complexity 1 and 282 lines of code, while Figure 3-9 has complexity 28 and 30 lines of code. Thus, although the number of lines of code is an important size measure, it is independent of complexity and should not be used for the same purposes.

3.2 Several flow graphs and their complexity

Several actual control flow graphs and their complexity measures are presented in Figures 3-1 through 3-9, to solidify understanding of the measure. The graphs are presented in order of increasing complexity, in order to emphasize the relationship between the complexity numbers and an intuitive notion of the complexity of the graphs.

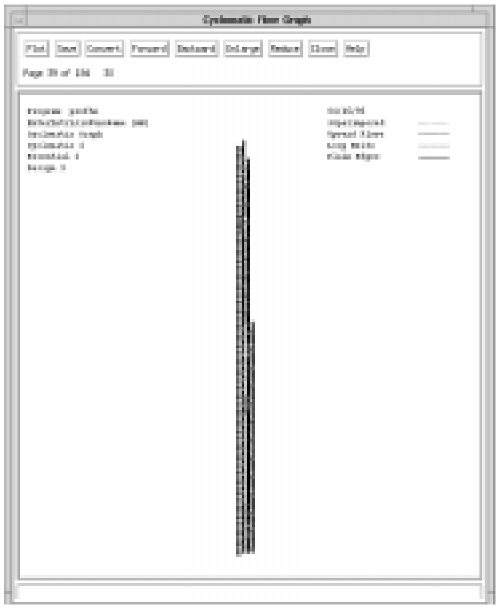


Figure 3-1. **Control flow graph with complexity 1.**

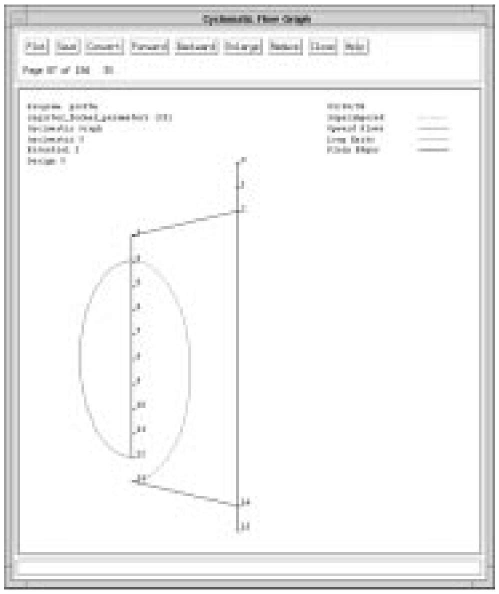


Figure 3-2. **Control flow graph with complexity 3.**

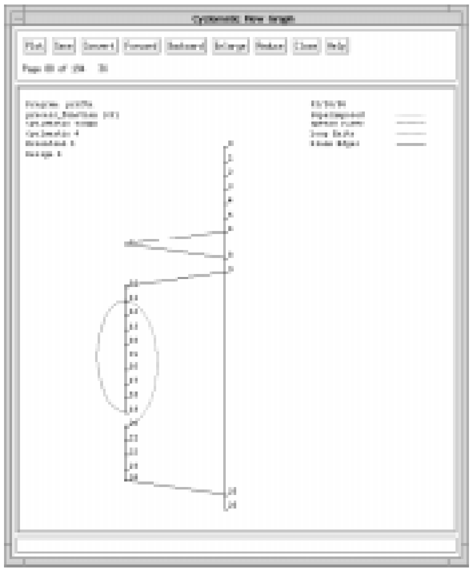


Figure 3-3. **Control flow graph with complexity 4.**

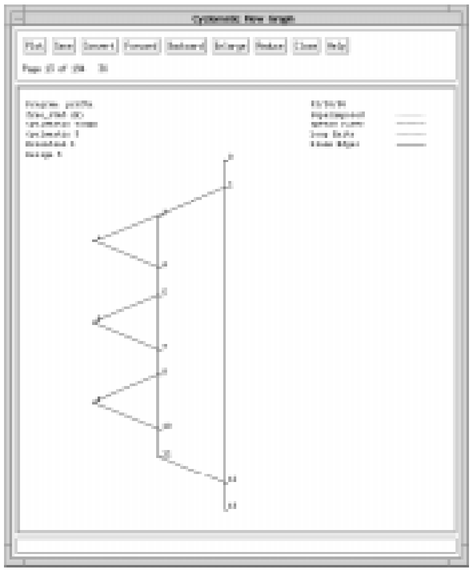


Figure 3-4. **Control flow graph with complexity 5.**

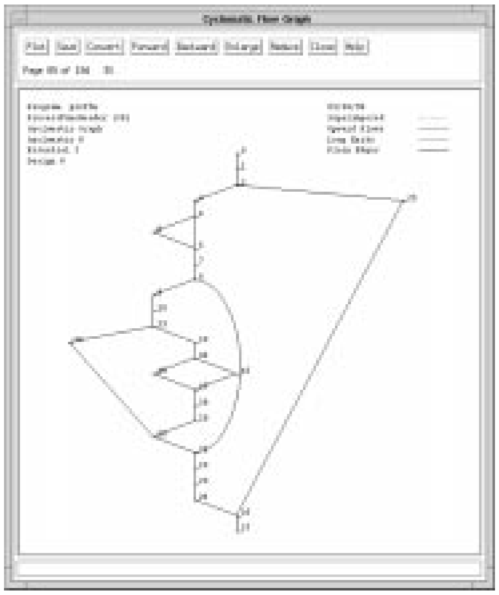


Figure 3-5. Control flow graph with complexity 6.

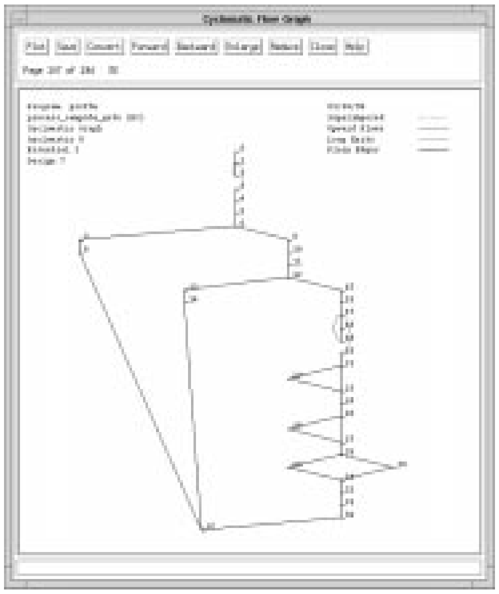


Figure 3-6. Control flow graph with complexity 8.

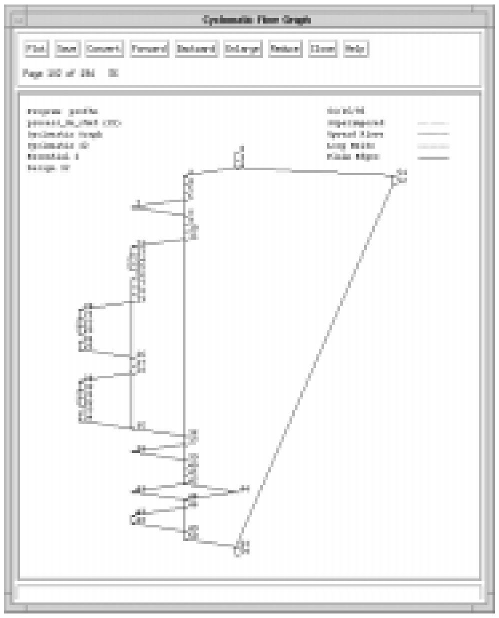


Figure 3-7. **Control flow graph with complexity 12.**

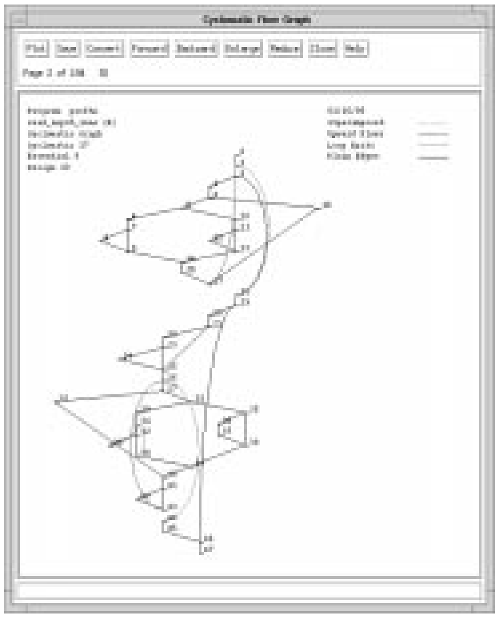


Figure 3-8. **Control flow graph with complexity 17.**

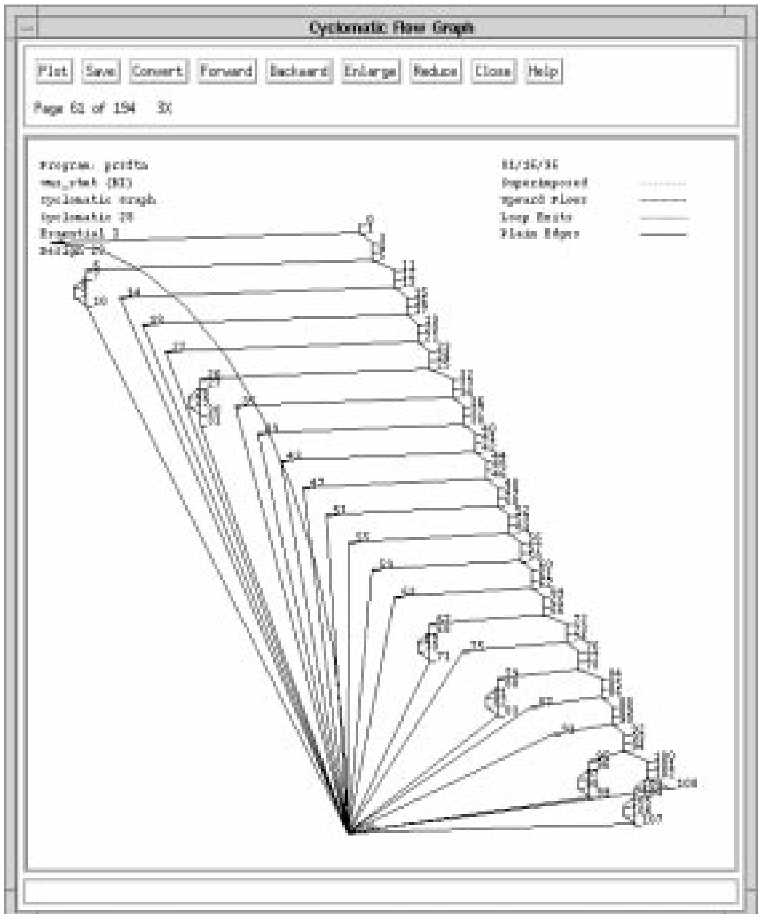


Figure 3-9. **Control flow graph with complexity 28.**

One essential ingredient in any testing methodology is to limit the program logic during development so that the program can be understood, and the amount of testing required to verify the logic is not overwhelming. A developer who, ignorant of the implications of complexity, expects to verify a module such as that of Figure 3-9 with a handful of tests is heading for disaster. The size of the module in Figure 3-9 is only 30 lines of source code. The size of several of the previous graphs exceeded 60 lines, for example the 282-line module in Figure 3-1. In practice, large programs often have low complexity and small programs often have high complexity. Therefore, the common practice of attempting to limit complexity by controlling only how many lines a module will occupy is entirely inadequate. Limiting complexity directly is a better alternative.

4 Simplified Complexity Calculation

Applying the e - n + 2 formula by hand is tedious and error-prone. Fortunately, there are several easier ways to calculate complexity in practice, ranging from counting decision predicates to using an automated tool.

4.1 Counting predicates

If all decisions are binary and there are p binary decision predicates, v(G) = p + 1. A binary decision predicate appears on the control flow graph as a node with exactly two edges flowing out of it. Starting with one and adding the number of such nodes yields the complexity. This formula is a simple consequence of the complexity definition. A straight-line control flow graph, which has exactly one edge flowing out of each node except the module exit node, has complexity one. Each node with two edges out of it adds one to complexity, since the "e" in the e - n + 2 formula is increased by one while the "n" is unchanged. In Figure 4-1, there are three binary decision nodes (1, 2, and 6), so complexity is 4 by direct application of the p + 1 formula. The original e - n + 2 gives the same answer, albeit with a bit more counting, 12 edges - 10 nodes + 2 = 4. Figure 4-2 has two binary decision predicate nodes (1 and 3), so complexity is 3. Since the decisions in Figure 4-2 come from loops, they are represented differently on the control flow graph, but the same counting technique applies.

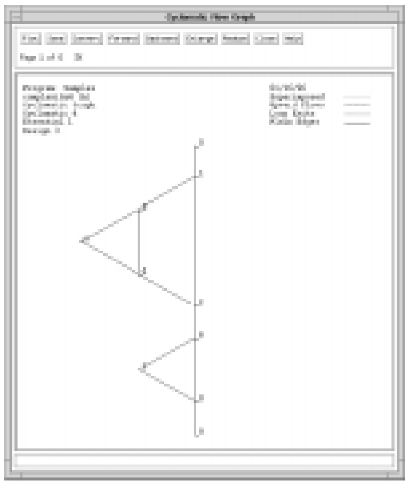


Figure 4-1. Module with complexity four.

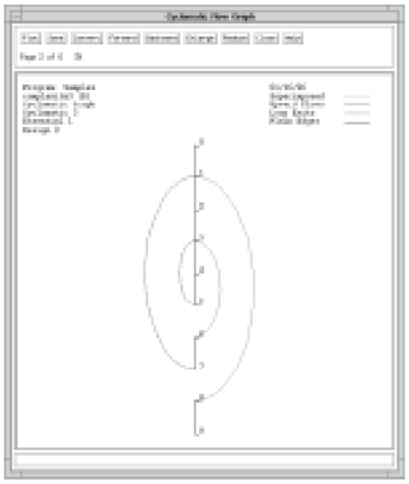


Figure 4-2. **Module with complexity three.**

Multiway decisions can be handled by the same reasoning as binary decisions, although there is not such a neat formula. As in the p + 1 formula for binary predicates, start with a complexity value of one and add something to it for each decision node in the control flow graph. The number added is one less than the number of edges out of the decision node. Note that for binary decisions, this number is one, which is consistent with the p + 1 formula. For a three-way decision, add two, and so on. In Figure 4-3, there is a four-way decision, which adds three to complexity, as well as three binary decisions, each of which adds one. Since the module started with one unit of complexity, the calculated complexity becomes 1 + 3 + 3, for a total of 7.

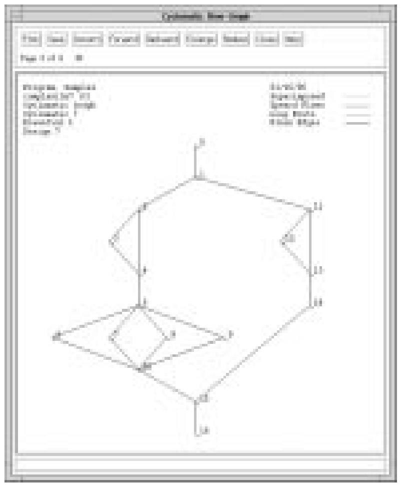
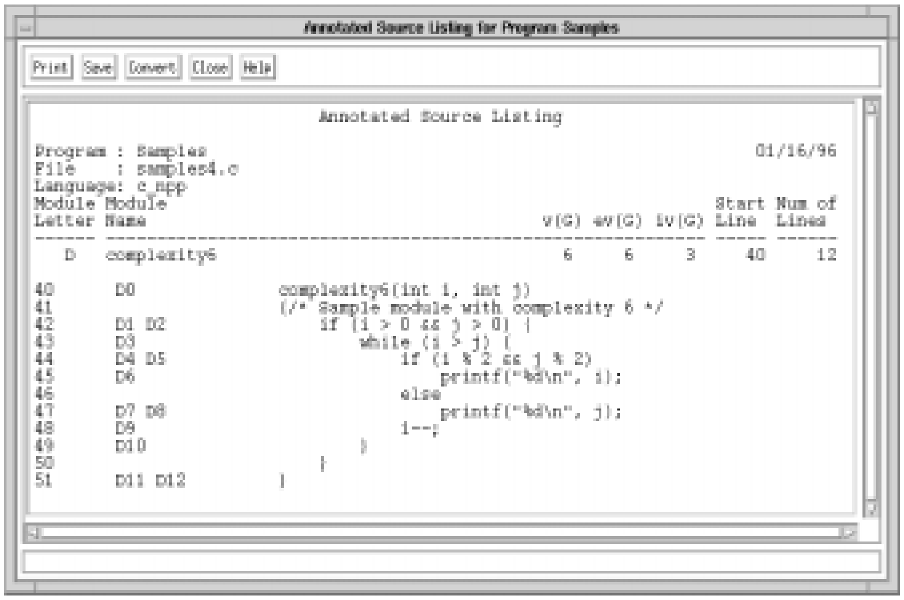


Figure 4-3. **Module with complexity 7.**

In addition to counting predicates from the flow graph, it is possible to count them directly from the source code. This often provides the easiest way to measure and control complexity during development, since complexity can be measured even before the module is complete. For most programming language constructs, the construct has a direct mapping to the control flow graph, and hence contributes a fixed amount to complexity. However, constructs that appear similar in different languages may not have identical control flow semantics, so caution is advised. For most constructs, the impact is easy to assess. An "if" statement, "while" statement, and so on are binary decisions, and therefore add one to complexity. Boolean operators add either one or nothing to complexity, depending on whether they have short-circuit evaluation semantics that can lead to conditional execution of side-effects. For example, the C "&&" operator adds one to complexity, as does the Ada "and then" operator, because both are defined to use short-circuit evaluation. The Ada "and" operator, on the other hand, does not add to complexity, because it is defined to use the full-evaluation strategy, and therefore does not generate a decision node in the control flow graph.

Figure 4-4 shows a C code module with complexity 6. Starting with 1, each of the two "if" statements add 1, the "while" statement adds 1, and each of the two "&&" operators adds 1, for a total of 6. For reference, Figure 4-5 shows the control flow graph corresponding to Figure 4-4.



```
                            Annotated Source Listing

Program : Samples                                                     01/16/96
File    : samples4.c
Language: c_mpp
Module Module                                                    Start  Num of
Letter Name                               v(G) ev(G) iv(G)       Line   Lines
------ ------------------------------------------------------    -----  ------
   D   complexity6                           6     6     3          40      12

40       D0              complexity6(int i, int j)
41                       {/* Sample module with complexity 6 */
42       D1 D2               if (i > 0 && j > 0) {
43       D3                      while (i > j) {
44       D4 D5                       if (i % 2 && j % 2)
45       D6                              printf("%d\n", i);
46                                   else
47       D7 D8                           printf("%d\n", j);
48       D9                          i--;
49       D10                     }
50                           }
51       D11 D12         }
```

Figure 4-4. Code for module with complexity 6.

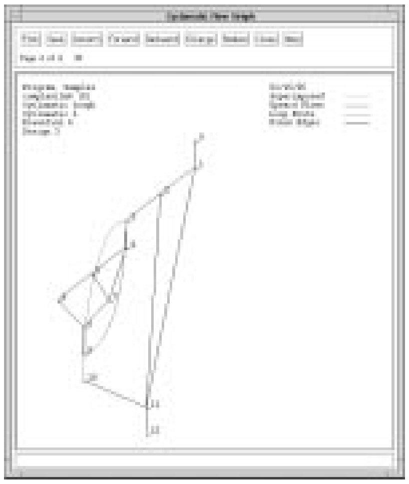
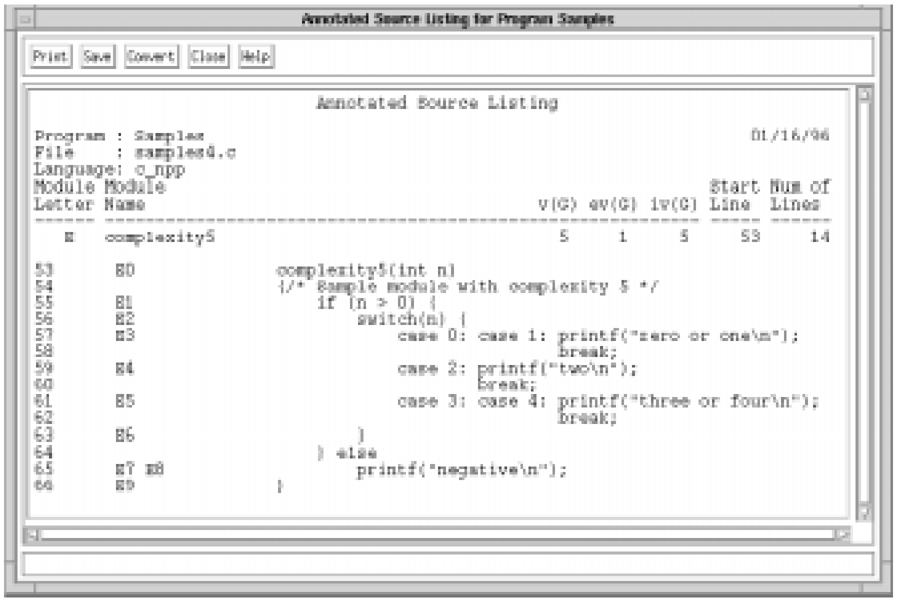


Figure 4-5. **Graph for module with complexity 6.**

It is possible, under special circumstances, to generate control flow graphs that do not model the execution semantics of boolean operators in a language. This is known as "suppressing" short-circuit operators or "expanding" full-evaluating operators. When this is done, it is important to understand the implications on the meaning of the metric. For example, flow graphs based on suppressed boolean operators in C can give a good high-level view of control flow for reverse engineering purposes by hiding the details of the encapsulated and often unstructured expression-level control flow. However, this representation should not be used for testing (unless perhaps it is first verified that the short-circuit boolean expressions do not contain any side effects). In any case, the important thing when calculating complexity from source code is to be consistent with the interpretation of language constructs in the flow graph.

Multiway decision constructs present a couple of issues when calculating complexity from source code. As with boolean operators, consideration of the control flow graph representation of the relevant language constructs is the key to successful complexity measurement of source code. An implicit default or fall-through branch, if specified by the language, must be taken into account when calculating complexity. For example, in C there is an implicit default if no default outcome is specified. In that case, the complexity contribution of the "switch" statement is exactly the number of case-labeled statements, which is one less than the total number of edges out of the multiway decision node in the control flow graph. A less frequently occurring issue that has greater impact on complexity is the distinction between "case-labeled statements" and "case labels." When several case labels apply to the same program statement, this is modeled as a single decision outcome edge in the control flow graph, adding one to complexity. It is certainly possible to make a consistent flow graph model in which each individual case label contributes a different decision outcome edge and hence also adds one to complexity, but that is not the typical usage.

Figure 4-6 shows a C code module with complexity 5. Starting with one unit of complexity, the switch statement has three case-labeled statements (although having five total case labels), which, considering the implicit default fall-through, is a four-way decision that contributes three units of complexity. The “if” statement contributes one unit, for a total complexity of five. For reference, Figure 4-7 shows the control flow graph corresponding to Figure 4-6.



```
                          Annotated Source Listing

Program : Samples                                                  01/16/96
File    : samples4.c
Language: c_npp
Module Module                                               Start Num of
Letter Name                               v(G) ev(G) iv(G) Line  Lines
------ ----------------------------------------------------- ----- ------
   E   complexity5                          5     1     5     53     14

53      E0             complexity5(int n)
54                     {/* Sample module with complexity 5 */
55      E1                 if (n > 0) {
56      E2                     switch(n) {
57      E3                         case 0: case 1: printf("zero or one\n");
58                                                 break;
59      E4                         case 2: printf("two\n");
60                                         break;
61      E5                         case 3: case 4: printf("three or four\n");
62                                                 break;
63      E6                     }
64                         } else
65      E7 E8                  printf("negative\n");
66      E9             }
```

Figure 4-6. **Code for module with complexity 5.**

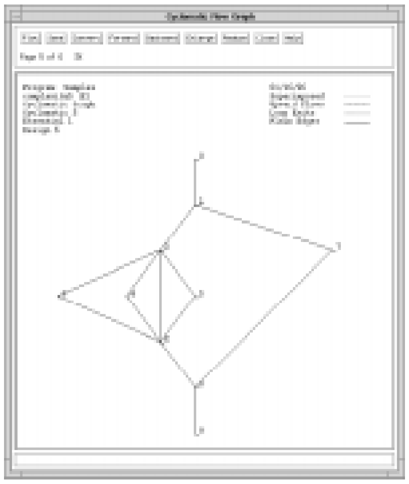
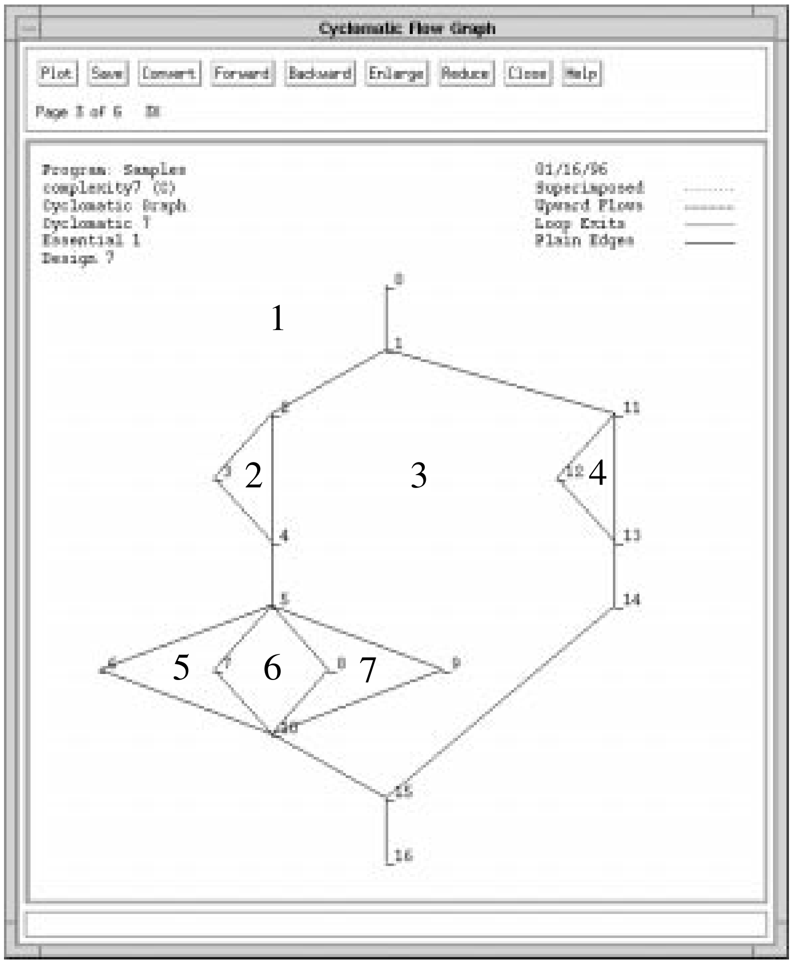


Figure 4-7. **Graph for module with complexity 5.**

4.2 Counting flow graph regions

When the flow graph is planar (no edges cross) and divides the plane into R regions (including the infinite region “outside” the graph), the simplified formula for cyclomatic complexity is just R. This follows from Euler’s formula, which states that for planar graphs n - e + R = 2. Re-arranging the terms, R = e - n + 2, which is the definition of cyclomatic complexity. Thus, for a planar flow graph, counting the regions gives a quick visual method for determining complexity. Figure 4-8 shows a planar flow graph with complexity 7, with the regions numbered from 1 to 7 to illustrate this counting technique. Region number 1 is the infinite region, and otherwise the regions are labeled in no particular order.

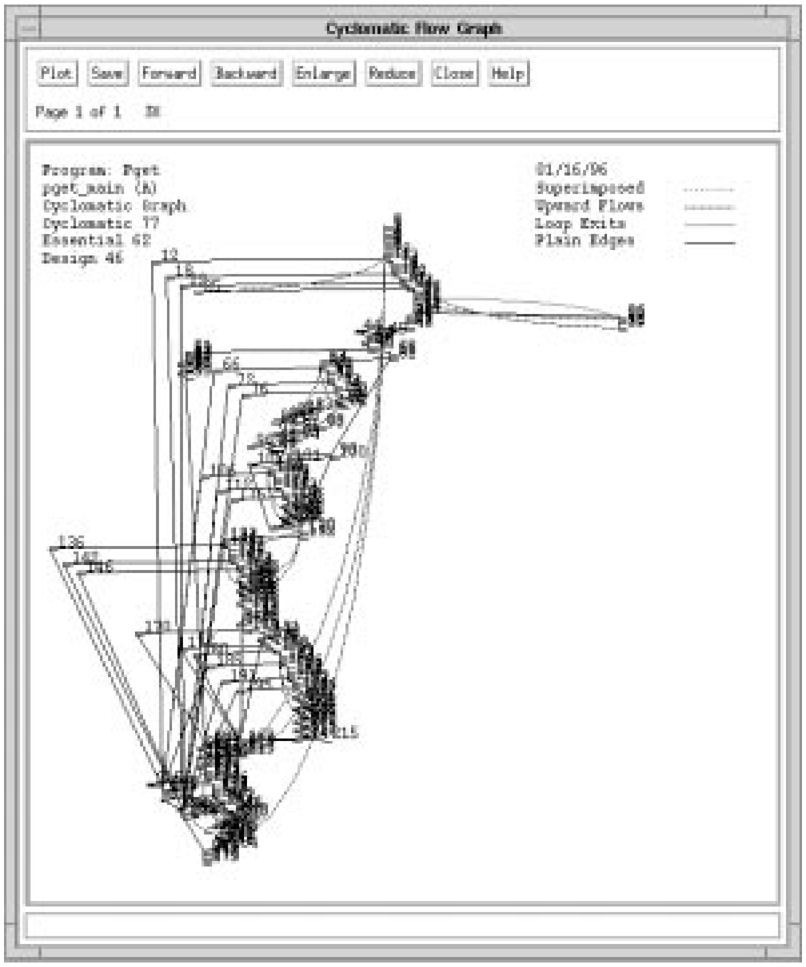


```
Program: Samples                 01/16/96
complexity7 (G)                  Superimposed
Cyclomatic Graph                 Upward Flows
Cyclomatic 7                     Loop Exits
Essential 1                      Plain Edges
Design 7
```

Figure 4-8. **Planar graph with complexity 7, regions numbered.**

4.3 *Use of automated tools*

The most efficient and reliable way to determine complexity is through use of an automated tool. Even calculating by hand the complexity of a single module such as that of Figure 4-9 is a daunting prospect, and such modules often come in large groups. With an automated tool, complexity can be determined for hundreds of modules spanning thousands of lines of code in a matter of minutes. When dealing with existing code, automated complexity calculation and control flow graph generation is an enabling technology. However, automation is not a panacea.



```
Program: Pget                    01/16/96
pget_main (A)                    Superimposed
Cyclomatic Graph                 Upward Flows
Cyclomatic 77                    Loop Exits
Essential 62                     Plain Edges
Design 46
```

Figure 4-9. **Module with complexity 77.**

The feedback from an automated tool may come too late for effective development of new software. Once the code for a software module (or file, or subsystem) is finished and processed by automated tools, reworking it to reduce complexity is more costly and error-prone than developing the module with complexity in mind from the outset. Awareness of manual techniques for complexity analysis helps design and build good software, rather than deferring complexity-related issues to a later phase of the life cycle. Automated tools are an effective way to confirm and control complexity, but they work best where at least rough estimates of complexity are used during development. In some cases, such as Ada development, designs can be represented and analyzed in the target programming language.

5 Structured Testing

Structured testing uses cyclomatic complexity and the mathematical analysis of control flow graphs to guide the testing process. Structured testing is more theoretically rigorous and more effective at detecting errors in practice than other common test coverage criteria such as statement and branch coverage [WATSON5]. Structured testing is therefore suitable when reliability is an important consideration for software. It is not intended as a substitute for requirements-based "black box" testing techniques, but as a supplement to them. Structured testing forms the "white box," or code-based, part of a comprehensive testing program, which when quality is critical will also include requirements-based testing, testing in a simulated production environment, and possibly other techniques such as statistical random testing. Other "white box" techniques may also be used, depending on specific requirements for the software being tested. Structured testing as presented in this section applies to individual software modules, where the most rigorous code-based "unit testing" is typically performed. The integration level Structured testing technique is described in section 7.

5.1 The structured testing criterion

After the mathematical preliminaries of section 2 (especially Sec. 2.3), the structured testing criterion is simply stated: Test a basis set of paths through the control flow graph of each module. This means that any additional path through the module's control flow graph can be expressed as a linear combination of paths that have been tested.

Note that the structured testing criterion measures the quality of testing, providing a way to determine whether testing is complete. It is not a procedure to identify test cases or generate test data inputs. Section 6 gives a technique for generating test cases that satisfy the structured testing criterion.

Sometimes, it is not possible to test a complete basis set of paths through the control flow graph of a module. This happens when some paths through the module can not be exercised by any input data. For example, if the module makes the same exact decision twice in sequence, no input data will cause it to vary the first decision outcome while leaving the second constant or vice versa. This situation is explored in section 9 (especially 9.1), including the possibilities of modifying the software to remove control dependencies or just relaxing the testing criterion to require the maximum attainable matrix rank (known as the actual complexity) whenever this differs from the cyclomatic complexity. All paths are assumed to be exercisable for the initial presentation of the method.

A program with cyclomatic complexity 5 has the property that no set of 4 paths will suffice for testing, even if, for example, there are 39 distinct tests that concentrate on the 4 paths. As discussed in section 2, the cyclomatic complexity gives the number of paths in any basis set. This means that if only 4 paths have been tested for the complexity 5 module, there must be, independent of the programming language or the computational statements of the program, at least one additional test path that can be executed. Also, once a fifth independent path is tested, any further paths are in a fundamental sense redundant, in that a combination of 5 basis paths will generate those further paths.

Notice that most programs with a loop have a potentially infinite number of paths, which are not subject to exhaustive testing even in theory. The structured testing criterion establishes a complexity number, v(G), of test paths that have two critical properties:

1. A test set of v(G) paths can be realized. (Again, see section 9.1 for discussion of the more general case in which actual complexity is substituted for v(G).)
2. Testing beyond v(G) independent paths is redundantly exercising linear combinations of basis paths.

Several studies have shown that the distribution of run time over the statements in the program has a peculiar shape. Typically, 50% of the run time within a program is concentrated within only 4% of the code [KNUTH]. When the test data is derived from only a requirements point of view and is not sensitive to the internal structure of the program, it likewise will spend most of the run time testing a few statements over and over again. The testing criterion in this document establishes a level of testing that is inherently related to the internal complexity of a program's logic. One of the effects of this is to distribute the test data over a larger number of independent paths, which can provide more effective testing with fewer tests. For very simple programs (complexity less than 5), other testing techniques seem likely to exercise a basis set of paths. However, for more realistic complexity levels, other techniques are not likely to exercise a basis set of paths. Explicitly satisfying the structured testing criterion will then yield a more rigorous set of test data.

5.2 Intuition behind structured testing

The solid mathematical foundation of structured testing has many advantages [WATSON2]. First of all, since any basis set of paths covers all edges and nodes of the control flow graph, satisfying the structured testing criterion automatically satisfies the weaker branch and statement testing criteria. Technically, structured testing subsumes branch and statement coverage testing. This means that any benefit in software reliability gained by statement and branch coverage testing is automatically shared by structured testing.

Next, with structured testing, testing is proportional to complexity. Specifically, the minimum number of tests required to satisfy the structured testing criterion is exactly the cyclomatic complexity. Given the correlation between complexity and errors, it makes sense to concentrate testing effort on the most complex and therefore error-prone software. Structured testing makes this notion mathematically precise. Statement and branch coverage testing do not even come close to sharing this property. All statements and branches of an arbitrarily complex module can be covered with just one test, even though another module with the same complexity may require thousands of tests using the same criterion. For example, a loop enclosing arbitrarily complex code can just be iterated as many times as necessary for coverage, whereas complex code with no loops may require separate tests for each decision outcome. With structured testing, any path, no matter how much of the module it covers, can contribute at most one element to the required basis set. Additionally, since the minimum required number of tests is known in advance, structured testing supports objective planning and monitoring of the testing process to a greater extent than other testing strategies.

Another strength of structured testing is that, for the precise mathematical interpretation of "independent" as "linearly independent," structured testing guarantees that all decision outcomes are tested independently. This means that unlike other common testing strategies, structured testing does not allow interactions between decision outcomes during testing to hide errors. As a very simple example, consider the C function of Figure 5-1. Assume that this function is intended to leave the value of variable "a" unchanged under all circumstances, and is thus clearly incorrect. The branch testing criterion can be satisfied with two tests that fail to detect the error: first let both decision outcomes be FALSE, in which case the value of "a" is not affected, and then let both decision outcomes be TRUE, in which case the value of "a" is first incremented and then decremented, ending up with its original value. The statement testing criterion can be satisfied with just the second of those two tests. Structured testing, on the other hand, is guaranteed to detect this error. Since cyclomatic complexity is three, three independent test paths are required, so at least one will set one decision outcome to TRUE and the other to FALSE, leaving "a" either incremented or decremented and therefore detecting the error during testing.

```
void func()
{
   if (condition1)
      a = a + 1;
   if (condition2)
      a = a - 1;
}
```

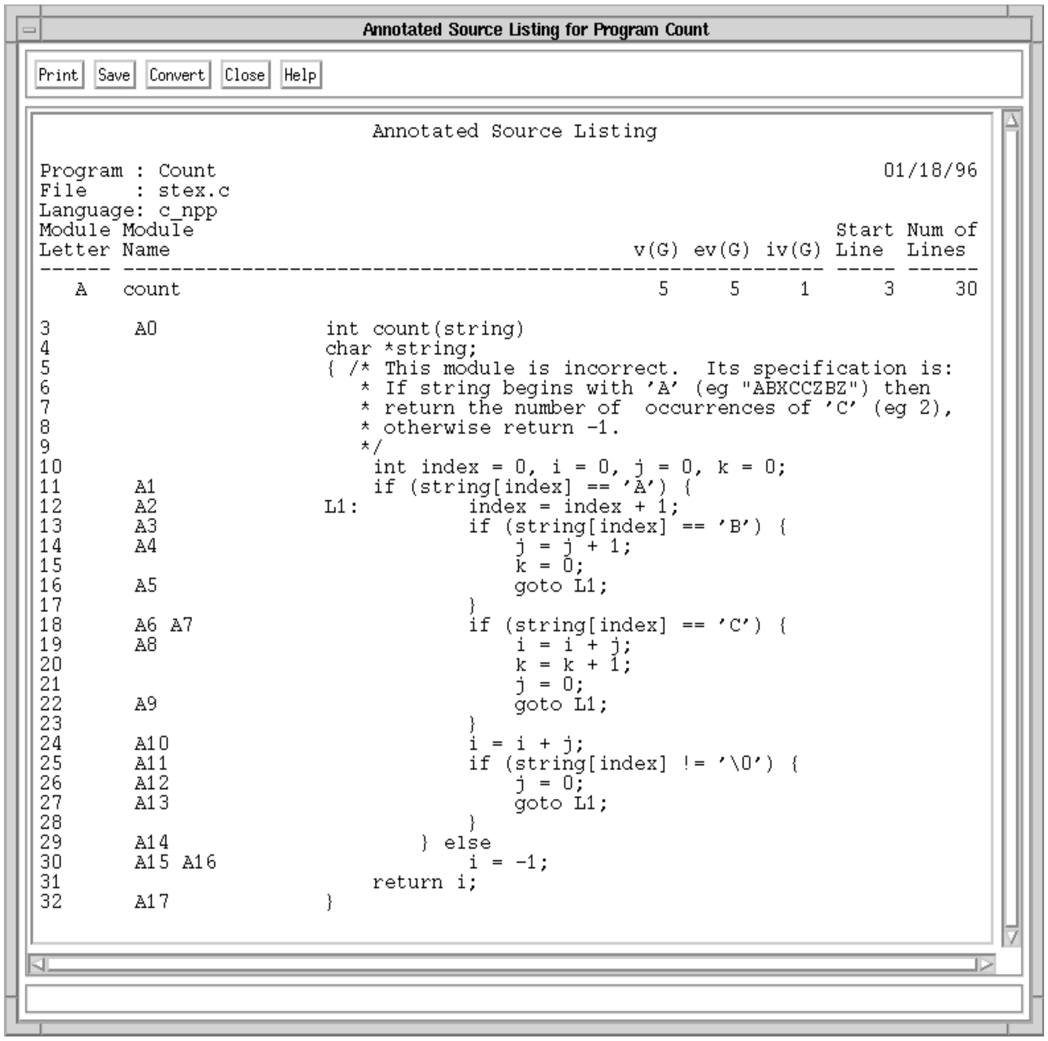
Figure 5-1. Example C function.

5.3 Complexity and reliability

Several of the studies discussed in Appendix A show a correlation between complexity and errors, as well as a connection between complexity and difficulty to understand software. Reliability is a combination of testing and understanding [MCCABE4]. In theory, either perfect testing (verify program behavior for every possible sequence of input) or perfect understanding (build a completely accurate mental model of the program so that any errors would be obvious) are sufficient by themselves to ensure reliability. Given that a piece of software has no known errors, its perceived reliability depends both on how well it has been tested and how well it is understood. In effect, the subjective reliability of software is expressed in statements such as “I understand this program well enough to know that the tests I have executed are adequate to provide my desired level of confidence in the software.” Since complexity makes software both harder to test and harder to understand, complexity is intimately tied to reliability. From one perspective, complexity measures the effort necessary to attain a given level of reliability. Given a fixed level of effort, a typical case in the real world of budgets and schedules, complexity measures reliability itself.

5.4 Structured testing example

As an example of structured testing, consider the C module “count” in Figure 5-2. Given a string, it is intended to return the total number of occurrences of the letter ‘C’ if the string begins with the letter ‘A.’ Otherwise, it is supposed to return -1.



```
                               Annotated Source Listing

Program : Count                                                       01/18/96
File    : stex.c
Language: c_npp
Module Module                                                    Start Num of
Letter Name                                 v(G) ev(G) iv(G) Line  Lines
------ ------------------------------------------------------- ----- ------
   A   count                                    5     5     1      3     30

3       A0              int count(string)
4                       char *string;
5                       { /* This module is incorrect.  Its specification is:
6                          * If string begins with 'A' (eg "ABXCCZBZ") then
7                          * return the number of  occurrences of 'C' (eg 2),
8                          * otherwise return -1.
9                          */
10                          int index = 0, i = 0, j = 0, k = 0;
11      A1                  if (string[index] == 'A') {
12      A2              L1:         index = index + 1;
13      A3                          if (string[index] == 'B') {
14      A4                              j = j + 1;
15                                      k = 0;
16      A5                              goto L1;
17                                  }
18      A6 A7                       if (string[index] == 'C') {
19      A8                              i = i + j;
20                                      k = k + 1;
21                                      j = 0;
22      A9                              goto L1;
23                                  }
24      A10                         i = i + j;
25      A11                         if (string[index] != '\0') {
26      A12                             j = 0;
27      A13                             goto L1;
28                                  }
29      A14                     } else
30      A15 A16                     i = -1;
31                          return i;
32      A17             }
```

Figure 5-2. **Code for module "count."**

The error in the "count" module is that the count is incorrect for strings that begin with the letter 'A' and in which the number of occurrences of 'B' is not equal to the number of occurrences of 'C.' This is because the module is really counting 'B's rather than 'C's. It could be fixed by exchanging the bodies of the "if" statements that recognize 'B' and 'C.' Figure 5-3 shows the control flow graph for module "count."

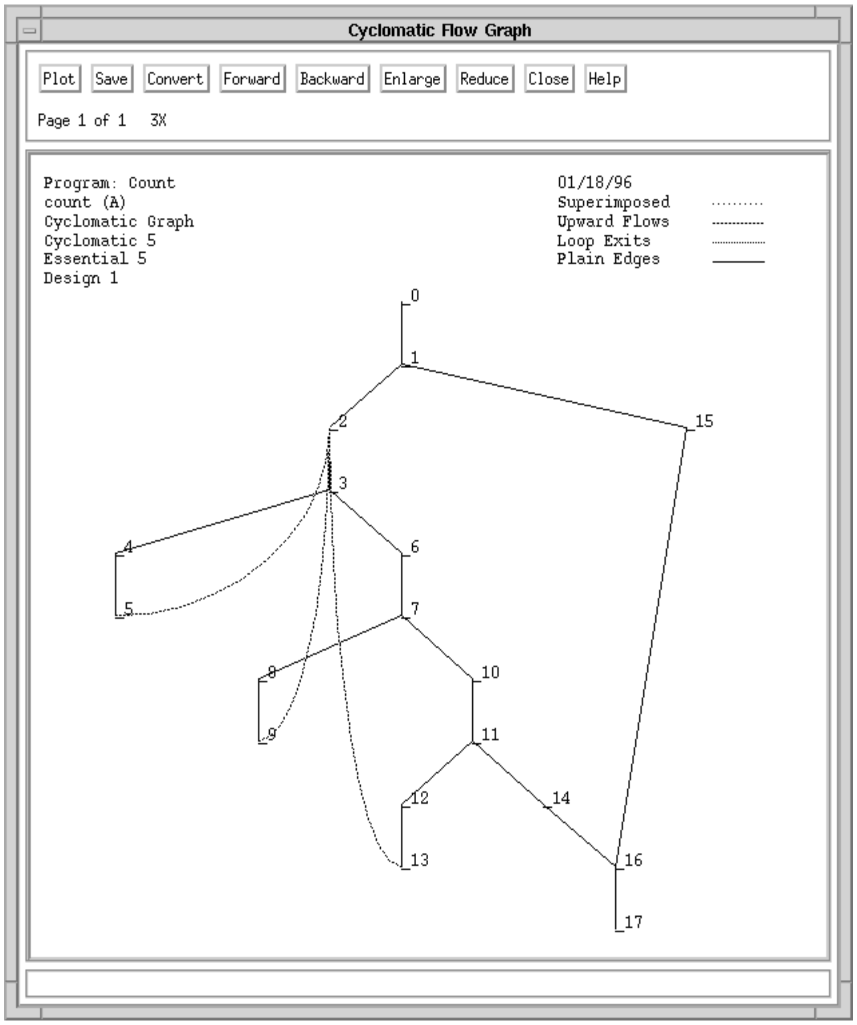


Figure 5-3. **Control flow graph for module "count."**

The "count" module illustrates the effectiveness of structured testing. The commonly used statement and branch coverage testing criteria can both be satisfied with the two tests in Figure 5-4, none of which detect the error. Since the complexity of "count" is five, it is immediately apparent that the tests of Figure 5-4 do not satisfy the structured testing criterion—three additional tests are needed to test each decision independently. Figure 5-5 shows a set of tests that satisfies the structured testing criterion, which consists of the three tests from Figure 5-4 plus two additional tests to form a complete basis.

Input	Output	Correctness
X	-1	Correct
ABCX	1	Correct

Figure 5-4. Tests for "count" that satisfy statement and branch coverage.

Input	Output	Correctness
X	-1	Correct
ABCX	1	Correct
A	0	Correct
AB	1	Incorrect
AC	0	Incorrect

Figure 5-5. Tests for "count" that satisfy the structured testing criterion.

The set of tests in Figure 5-5 detects the error (twice). Input "AB" should produce output "0" but instead produces output "1," and input "AC" should produce output "1" but instead produces output "0." In fact, any set of tests that satisfies the structured testing criterion is guaranteed to detect the error. To see this, note that to test the decisions at nodes 3 and 7 independently requires at least one input with a different number of 'B's than 'C's.

5.5 Weak structured testing

Weak structured testing is, as it appears, a weak variant of structured testing. It can be satisfied by exercising at least v(G) different paths through the control flow graph while simultaneously covering all branches, however the requirement that the paths form a basis is dropped. Structured testing subsumes weak structured testing, but not the reverse. Weak structured testing is much easier to perform manually than structured testing, because there is no need to do linear algebra on path vectors. Thus, weak structured testing was a way to get some of the benefits of structured testing at a significantly lesser cost before automated support for structured testing was available, and is still worth considering for programming languages with no automated structured testing support. In some older literature, no distinction is made between the two criteria.

Of the three properties of structured testing discussed in section 5.2, two are shared by weak structured testing. It subsumes statement and branch coverage, which provides a base level of error detection effectiveness. It also requires testing proportional to complexity, which concentrates testing on the most error-prone software and supports precise test planning and monitoring. However, it does not require all decision outcomes to be tested independently, and thus may not detect errors based on interactions between decisions. Therefore, it should only be used when structured testing itself is impractical.

5.6 Advantages of automation

Although structured testing can be applied manually (see section 6 for a way to generate a basis set of paths without doing linear algebra), use of an automated tool provides several compelling advantages. The relevant features of an automated tool are the ability to instrument software to track the paths being executed during testing, the ability to report the number of independent paths that have been tested, and the ability to calculate a minimal set of test paths that would complete testing after any given set of tests have been run. For complex software, the ability to report dependencies between decision outcomes directly is also helpful, as discussed in section 9.

A typical manual process is to examine each software module being tested, derive the control flow graph, select a basis set of tests to execute (with the technique of section 6), determine input data that will exercise each path, and execute the tests. Although this process can certainly be used effectively, it has several drawbacks when compared with an automated process.

A typical automated process is to leverage the "black box" functional testing in the structured testing effort. First run the functional tests, and use the tool to identify areas of poor coverage. Often, this process can be iterated, as the poor coverage can be associated with areas of functionality, and more functional tests developed for those areas. An important practical note is that it is easier to test statements and branches than paths, and testing a new statement or branch is always guaranteed to improve structured testing coverage. Thus, concentrate first on the untested branch outputs of the tool, and then move on to untested paths. Near the end of the process, use the tool's "untested paths" or "control dependencies" outputs to derive inputs that complete the structured testing process.

By building on a black-box, functional test suite, the automated process bypasses the labor-intensive process of deriving input data for specific paths except for the relatively small number of paths necessary to augment the functional test suite to complete structured testing. This advantage is even larger than it may appear at first, since functional testing is done on a complete executable program, whereas deriving data to execute specific paths (or even statements) is often only practical for individual modules or small subprograms, which leads to the expense of developing stub and driver code. Finally, and perhaps most significantly, an automated tool provides accurate verification that the criterion was successfully met. Manual derivation of test data is an error-prone process, in which the intended paths are often not exercised by a given data set. Hence, if an automated tool is available, using it to verify and complete coverage is very important.

5.7 Critical software

Different types of software require different levels of testing rigor. All code worth developing is worth having basic functional and structural testing, for example exercising all of the major requirements and all of the code. In general, most commercial and government software should be tested more stringently. Each requirement in a detailed functional specification should be tested, the software should be tested in a simulated production environment (and is typically beta tested in a real one), at least all statements and branches should be tested for each module, and structured testing should be used for key or high-risk modules. Where quality is a major objective, structured testing should be applied to all modules. These testing methods form a continuum of functional and structural coverage, from the basic to the intensive. For truly critical software, however, a qualitatively different approach is needed.

Critical software, in which (for example) failure can result in the loss of human life, requires a unique approach to both development and testing. For this kind of software, typically found in medical and military applications, the consequences of failure are appalling [LEVESON]. Even in the telecommunications industry, where failure often means significant economic loss, cost-benefit analysis tends to limit testing to the most rigorous of the functional and structural approaches described above.

Although the specialized techniques for critical software span the entire software lifecycle, this section is focused on adapting structured testing to this area. Although automated tools may be used to verify basis path coverage during testing, the techniques of leveraging functional testing to structured testing are not appropriate. The key modification is to not merely exercise a basis set of paths, but to attempt as much as possible to establish correctness of the software along each path of that basis set. First of all, a basis set of paths facilitates structural code walkthroughs and reviews. It is much easier to find errors in straight-line computation than in a web of complex logic, and each of the basis paths represents a potential single sequence of computational logic, which taken together represent the full structure of the original logic. The next step is to develop and execute several input data sets for each of the paths in the basis. As with the walkthroughs, these tests attempt to establish correctness of the software along each basis path. It is important to give special attention to testing the boundary values of all data, particularly decision predicates, along that path, as well as testing the contribution of that path to implementing each functional requirement.

Although no software testing method can ensure correctness, these modifications of the structured testing methodology for critical software provide significantly more power to detect errors in return for the significant extra effort required to apply them. It is important to note that, especially for critical software, structured testing does not preclude the use of other techniques. A notable example is exhaustive path testing: for simple modules without loops, it may be appropriate to test all paths rather than just a basis. Many critical systems may benefit from using several different techniques simultaneously [NIST234].

6 The Baseline Method

The baseline method, described in this section, is a technique for identifying a set of control paths to satisfy the structured testing criterion. The technique results in a basis set of test paths through the module being tested, equal in number to the cyclomatic complexity of the module. As discussed in section 2, the paths in a basis are independent and generate all paths via linear combinations. Note that "the baseline method" is different from "basis path testing." Basis path testing, another name for structured testing, is the requirement that a basis set of paths should be tested. The baseline method is one way to derive a basis set of paths. The word "baseline" comes from the first path, which is typically selected by the tester to represent the "baseline" functionality of the module. The baseline method provides support for structured testing, since it gives a specific technique to identify an adequate test set rather than resorting to trial and error until the criterion is satisfied.

6.1 Generating a basis set of paths

The idea is to start with a baseline path, then vary exactly one decision outcome to generate each successive path until all decision outcomes have been varied, at which time a basis will have been generated. To understand the mathematics behind the technique, a simplified version of the method will be presented and prove that it generates a basis [WATSON5]. Then, the general technique that gives more freedom to the tester when selecting paths will be described. Poole describes and analyzes an independently derived variant in [NIST5737].

6.2 The simplified baseline method

To facilitate the proof of correctness, the method will be described in mathematical terms. Readers not interested in theory may prefer to skip to section 6.3 where a more practical presentation of the technique is given.

In addition to a basis set of paths, which is a basis for the rows of the path/edge matrix if all possible paths were represented, it is possible to also consider a basis set of edges, which is a basis for the columns of the same matrix. Since row rank equals column rank, the cyclomatic complexity is also the number of edges in every edge basis. The overall approach of this section is to first select a basis set of edges, then use that set in the algorithm to generate each successive path, and finally use the resulting path/edge matrix restricted to basis columns to show that the set of generated paths is a basis.

First, for every decision in the module, select an outcome with the shortest (in terms of number of other decisions encountered) path to the module exit. Ties can be broken arbitrarily. Mark these selected decision outcomes non-basic. Call these outcomes non-basic because all other decision outcome edges, along with the module entry edge, form the column basis. The key to the simplified baseline method is to execute exactly one new basis edge with each successive path. This is possible because from any node in the control flow graph, there is a path to the exit node that avoids all basis columns (taking the non-basic outcome of every decision encountered, which also gives a shortest path in terms of decisions encountered to the exit).

The simplified baseline algorithm can now be described. For the initial baseline path, take the non-basic outcome of every decision encountered. Note that this gives a shortest path through the module. For each successive path, first pick any decision that has had the non-basic outcome traversed by an earlier path, but that has a basis outcome that has not been executed by any earlier path. Then, construct the path by following the earlier path up to that decision point, traverse that new basis outcome edge, and then follow only non-basic decision outcomes to the module exit. At each step, exactly one new basis edge is added, so the total number of paths generated is the cyclomatic complexity. It is sufficient to show that they are linearly independent to complete the proof that they are a basis set of paths. To see that, consider the path/edge matrix with the generated set of paths in order as the rows and the basis edges as the columns, with the columns ordered by the index of the path which first traversed each corresponding edge. The matrix is then lower-triangular with all major diagonal entries equal to "1," so all rows are linearly independent. Thus, the simplified baseline algorithm generates a basis.

6.3 The baseline method in practice

Although the simplified baseline method of the previous section has the advantages of theoretical elegance and a concise proof of correctness, its lack of flexibility and its reliance on shortest paths are drawbacks in practice. The general technique allows the tester to choose between various alternatives when generating paths, so that a more robust set of tests can be developed. This is important for two reasons. First, although executing any basis set of paths assures a certain level of testing rigor, a test designer may recognize that some major functional paths are more important to include in the test set than some of the paths given by the simplified technique. Second, it may be impossible to execute some paths due to the specifics of the module's computation, and any added flexibility helps avoid those impossible paths while still developing a robust set of tests.

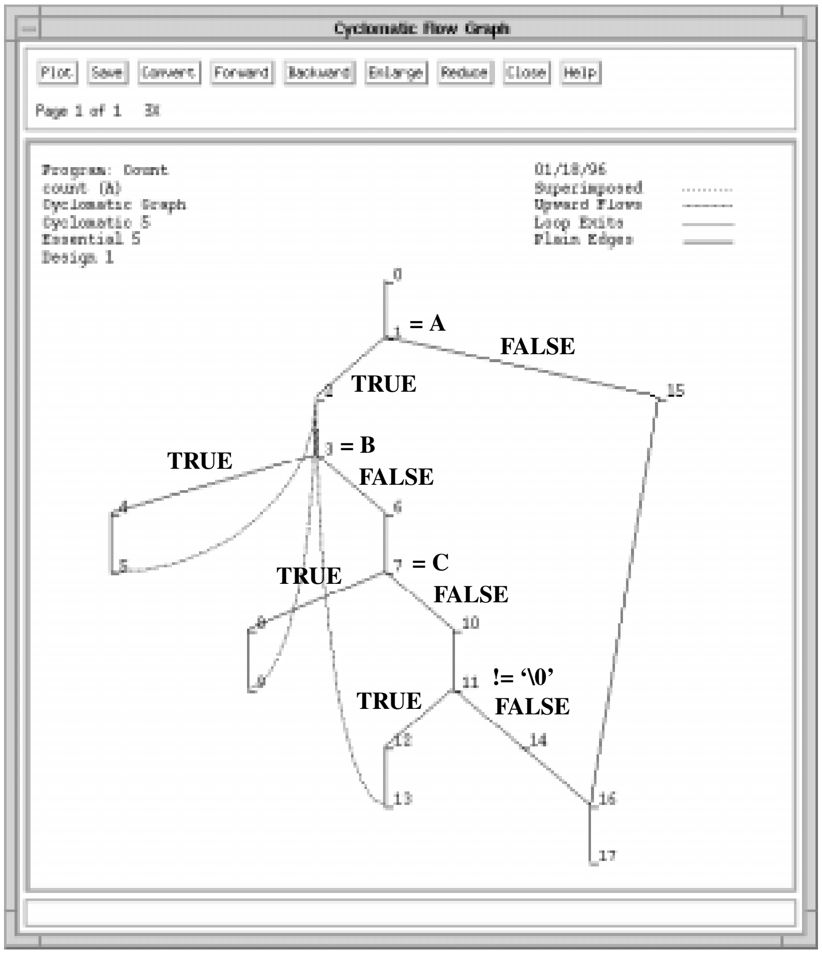
The first step is to pick a functional "baseline" path through the program that represents a legitimate function and not just an error exit. The selection of this baseline path is somewhat arbitrary. The key, however, is to pick a representative function rather than an exceptional condition. The exceptional conditions will of course be tested on some path generated by the method, but since many of the decision outcomes along the baseline path tend to be shared with several other paths it is helpful to make them as "typical" as possible. To summarize, the baseline should be, in the tester's judgement, the most important path to test. It is usually helpful to devote extra effort to the baseline path, exercising all its functional requirements and developing several data sets that might expose errors.

To generate the next path, change the outcome of the first decision along the baseline path while keeping the maximum number of other decision outcomes the same as the baseline path. That is, once the baseline path is "rejoined," it should be followed to the module exit. Any decisions encountered that are not part of the baseline path may be taken arbitrarily, and, as with the baseline path, it is a good idea to follow a robust functional path subject to the constraint of varying just the first baseline decision. To generate the third path, begin again with the baseline but vary the second decision outcome rather than the first. When all of the decisions along the baseline have been flipped, proceed to the second path, flipping its new decisions as if it were the baseline. When every decision in the module has been flipped, the test path set is complete. Multiway decisions must of course be flipped to each of their possible outcomes in turn.

Sometimes a tester wants even more flexibility, relaxing the requirement that once rejoined, the path from which a decision was flipped is followed to the end. Unfortunately, this may result in a linearly dependent set of paths, not satisfying the structured testing criterion (although weak structured testing is still satisfied). For complete freedom in selecting test paths for structured testing, the answer lies with an automated tool. The tester can specify arbitrary paths by their decision outcome sequence, and the tool then determines whether each new path is linearly independent of the previous ones in the same way that it would analyze the execution trace if the paths were actually executed during testing. Similarly, the tool can at any stage produce a minimal set of paths to complete the basis set, which the tester can either accept or change. Even with the standard baseline method, it may be worth having a tool verify that a basis has indeed been generated, since it takes much less effort to correct the test set in the test planning stage than after the tests have already been executed.

6.4 *Example of the baseline method*

The baseline method is now demonstrated using the "count" program from section 5.4. Refer to Figure 5-2 for the source code. Figure 6-1 shows the control flow graph for "count" with the decision outcomes marked.



```
Program: Count
count (A)
Cyclomatic Graph
Cyclomatic 5
Essential 5
Design 1
01/18/96
```

Figure 6-1. **Graph of "count" with decision outcomes marked.**

Figure 6-2 shows the set of test paths constructed by the method. The baseline path corresponds to input "AB", a representative functional input (which happens to expose the module's bug, the goal of every baseline test). It takes "=A" TRUE, "=B" TRUE, "=B" FALSE (note, this does not count as flipping the "=B" decision!), "=C" FALSE, and "!='\0'" FALSE. The second path is generated by flipping the first decision along the baseline, so it takes "=A" FALSE, and there are no other decisions before the module exit. It corresponds to input "X." The third path flips the second decision along the baseline, so it takes "=A" TRUE (following the first decision), "=B" FALSE (flipping the second decision), "=C" FALSE (picking up the baseline again), and “!=‘\0’” FALSE (following the baseline to the end). It corresponds to input “A.” The fourth path flips the third decision along the baseline, so it takes “=A” TRUE (following the first decision), “=B” TRUE (following the second decision), “=B” FALSE (still following the second decision—when a decision is revisited due to looping it is not considered a separate decision for flipping purposes), “=C” TRUE (flipping the third decision), “=B” FALSE (picking up the baseline at the last occurrence of the “=B” decision rather than going through the loop again), “=C” FALSE (continuing to follow the rest of the baseline), “!=‘\0’” FALSE (following the baseline to the end). It corresponds to input “ABC.” The fifth and final path flips the fourth and final decision, so it takes “=A” TRUE (following), “=B” TRUE (following), “=B” FALSE (following), “=C” FALSE (following), “!=‘0’” TRUE (flipping), “=B” FALSE (picking up the baseline again), “=C” FALSE (following), “!=‘\0’” FALSE (following to the end). It corresponds to input “ABX.”

```
Test Path 1 (baseline): 0 1 2 3 4 5 2 3 6 7 10 11 14 16 17
    11(   1): string[index]=='A' ==> TRUE
    13(   3): string[index]=='B' ==> TRUE
    13(   3): string[index]=='B' ==> FALSE
    18(   7): string[index]=='C' ==> FALSE
    25(  11): string[index]!='\0' ==> FALSE

Test Path 2: 0 1 15 16 17
    11(   1): string[index]=='A' ==> FALSE

Test Path 3: 0 1 2 3 6 7 10 11 14 16 17
    11(   1): string[index]=='A' ==> TRUE
    13(   3): string[index]=='B' ==> FALSE
    18(   7): string[index]=='C' ==> FALSE
    25(  11): string[index]!='\0' ==> FALSE

Test Path 4: 0 1 2 3 4 5 2 3 6 7 8 9 2 3 6 7 10 11 14 16 17
    11(   1): string[index]=='A' ==> TRUE
    13(   3): string[index]=='B' ==> TRUE
    13(   3): string[index]=='B' ==> FALSE
    18(   7): string[index]=='C' ==> TRUE
    13(   3): string[index]=='B' ==> FALSE
    18(   7): string[index]=='C' ==> FALSE
    25(  11): string[index]!='\0' ==> FALSE

Test Path 5: 0 1 2 3 4 5 2 3 6 7 10 11 12 13 2 3 6 7 10 11 14 16 17
    11(   1): string[index]=='A' ==> TRUE
    13(   3): string[index]=='B' ==> TRUE
    13(   3): string[index]=='B' ==> FALSE
    18(   7): string[index]=='C' ==> FALSE
    25(  11): string[index]!='\0' ==> TRUE
    13(   3): string[index]=='B' ==> FALSE
    18(   7): string[index]=='C' ==> FALSE
    25(  11): string[index]!='\0' ==> FALSE
```

Figure 6-2. Test paths generated with the baseline method.

Of the tests in Figure 6-2, the baseline and test 5 both detect the error in the module. Although this is a different set of test paths than the ones shown (by input data only) in Figure 5-5, both sets satisfy the structured testing criterion and both sets detect the module's error. One of the strengths of both the structured testing criterion and the baseline method is that testers have a great deal of freedom when developing tests, yet the resultant tests have a guaranteed level of rigor.

6.5 Completing testing with the baseline method

While the baseline method can be used to construct a stand-alone set of tests that satisfy the structured testing criterion, it is usually most cost-effective to first run functional tests and then only construct as many additional test paths as are necessary to have the entire testing process satisfy the structured testing criterion [WATSON5]. Assuming that it is possible to trace paths during testing, specify paths manually, and determine the rank of any set of those paths (for example, using an automated tool), the baseline method can be used to execute the minimum additional tests required.

The technique is to first run the functional test suite and (again, automation is key) fill matrices with the paths that were executed. Next, for those modules that did not have a complete basis set tested, use the baseline method to generate a basis set of paths. Then, for each of the paths resulting from the basis set, determine whether it increases the matrix rank. If it does, execute it; if it does not, discard it. The new independent paths that were not discarded form a minimal set of additional paths to complete testing.

This technique works because, in essence, it extends an independent subset of the functionally-tested paths to form a basis. Regardless of the initial set of paths, adding each independent member of a basis results in a set of tests that generates that basis and therefore also generates all possible paths by linear combination. Additionally, no matter which basis is selected first, each non-discarded member of the basis increases the rank of the matrix by exactly one. The new tests are therefore guaranteed to be a minimal set. In fact, the number of new tests will be the cyclomatic complexity minus the rank of the original set of functional tests.

It may seem that since an automated tool is required to perform the path tracing of the functional test suite and the determination whether each member of the basis generated by the baseline method is independent, it is also possible to use just the minimal set of additional test paths provided by the tool rather than using the baseline method at all. Much of the time this is true. However, just as testers benefit from using the baseline method rather than the simplified baseline method when planning structured testing from scratch, so also the freedom to select candidate completion tests after functional testing is often valuable.

7 Integration Testing

In sections 2 and 5, cyclomatic complexity and the structured testing methodology are discussed at the level of individual modules and unit testing. This section generalizes the approach to the integration level, addressing the complexity and integration testing of design structures that consist of multiple modules.

7.1 Integration strategies

One of the most significant aspects of a software development project is the integration strategy. Integration may be performed all at once, top-down, bottom-up, critical piece first, or by first integrating functional subsystems and then integrating the subsystems in separate phases using any of the basic strategies. In general, the larger the project, the more important the integration strategy.

Very small systems are often assembled and tested in one phase. For most real systems, this is impractical for two major reasons. First, the system would fail in so many places at once that the debugging and retesting effort would be impractical [PRESSMAN]. Second, satisfying any white box testing criterion would be very difficult, because of the vast amount of detail separating the input data from the individual code modules. In fact, most integration testing has been traditionally limited to ‘‘black box’’ techniques [HETZEL]. Large systems may require many integration phases, beginning with assembling modules into low-level subsystems, then assembling subsystems into larger subsystems, and finally assembling the highest level subsystems into the complete system.

To be most effective, an integration testing technique should fit well with the overall integration strategy. In a multi-phase integration, testing at each phase helps detect errors early and keep the system under control. Performing only cursory testing at early integration phases and then applying a more rigorous criterion for the final stage is really just a variant of the high-risk “big bang” approach. However, performing rigorous testing of the entire software involved in each integration phase involves a lot of wasteful duplication of effort across phases. The key is to leverage the overall integration structure to allow rigorous testing at each phase while minimizing duplication of effort.

It is important to understand the relationship between module testing and integration testing. In one view, modules are rigorously tested in isolation using stubs and drivers before any integration is attempted. Then, integration testing concentrates entirely on module interactions, assuming that the details within each module are accurate. At the other extreme, module and integration testing can be combined, verifying the details of each module's implementation in an integration context. Many projects compromise, combining module testing with the lowest level of subsystem integration testing, and then performing pure integration testing at higher levels. Each of these views of integration testing may be appropriate for any given project, so an integration testing method should be flexible enough to accommodate them all. The rest of this section describes the integration-level structured testing techniques, first for some special cases and then in full generality.

7.2 Combining module testing and integration testing

The simplest application of structured testing to integration is to combine module testing with integration testing so that a basis set of paths through each module is executed in an integration context. This means that the techniques of section 5 can be used without modification to measure the level of testing. However, this method is only suitable for a subset of integration strategies.

The most obvious combined strategy is pure "big bang" integration, in which the entire system is assembled and tested in one step without even prior module testing. As discussed earlier, this strategy is not practical for most real systems. However, at least in theory, it makes efficient use of testing resources. First, there is no overhead associated with constructing stubs and drivers to perform module testing or partial integration. Second, no additional integration-specific tests are required beyond the module tests as determined by structured testing. Thus, despite its impracticality, this strategy clarifies the benefits of combining module testing with integration testing to the greatest feasible extent.

It is also possible to combine module and integration testing with the bottom-up integration strategy. In this strategy, using test drivers but not stubs, begin by performing module-level structured testing on the lowest-level modules using test drivers. Then, perform module-level structured testing in a similar fashion at each successive level of the design hierarchy, using test drivers for each new module being tested in integration with all lower-level modules. Figure 7-1 illustrates the technique. First, the lowest-level modules "B" and "C" are tested with drivers. Next, the higher-level module "A" is tested with a driver in integration with modules "B" and "C." Finally, integration could continue until the top-level module of the program is tested (with real input data) in integration with the entire program. As shown in Figure 7-1, the total number of tests required by this technique is the sum of the cyclomatic complexities of all modules being integrated. As expected, this is the same number of tests that would be required to perform structured testing on each module in isolation using stubs and drivers.

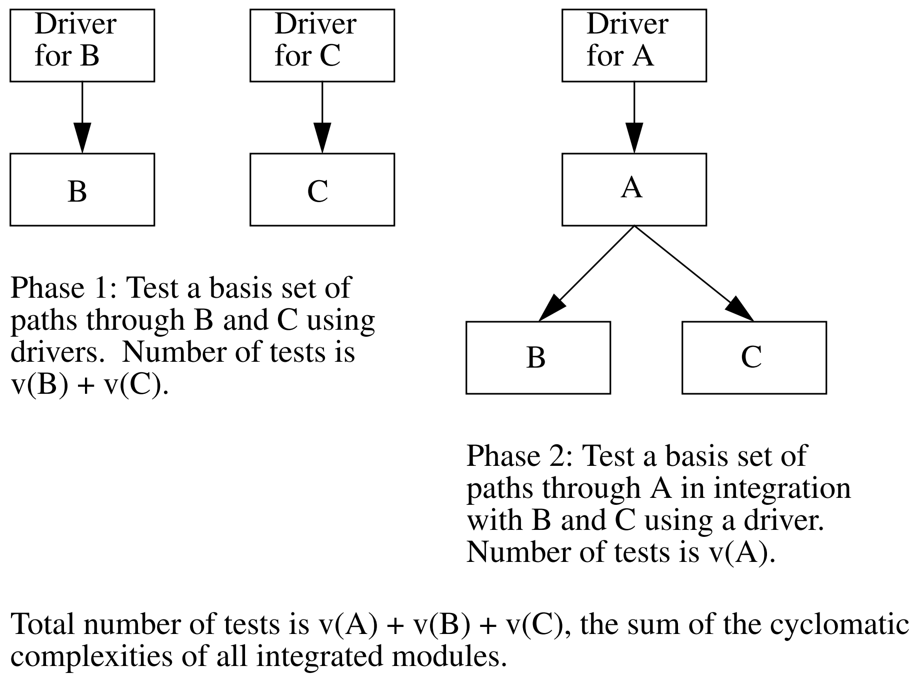

Driver for B
Driver for C
Driver for A
B
C
A
B
C
Phase 1: Test a basis set of paths through B and C using drivers. Number of tests is v(B) + v(C).
Phase 2: Test a basis set of paths through A in integration with B and C using a driver. Number of tests is v(A).
Total number of tests is v(A) + v(B) + v(C), the sum of the cyclomatic complexities of all integrated modules.

Figure 7-1. Combining module testing with bottom-up integration.

7.3 Generalization of module testing criteria

Module testing criteria can often be generalized in several possible ways to support integration testing. As discussed in the previous subsection, the most obvious generalization is to satisfy the module testing criterion in an integration context, in effect using the entire program as a test driver environment for each module. However, this trivial kind of generalization does not take advantage of the differences between module and integration testing. Applying it to each phase of a multi-phase integration strategy, for example, leads to an excessive amount of redundant testing.

More useful generalizations adapt the module testing criterion to focus on interactions between modules rather than attempting to test all of the details of each module's implementation in an integration context. The statement coverage module testing criterion, in which each statement is required to be exercised during module testing, can be generalized to require each module call statement to be exercised during integration testing. Although the specifics of the generalization of structured testing are more detailed, the approach is the same. Since structured testing at the module level requires that all the decision logic in a module's control flow graph be tested independently, the appropriate generalization to the integration level requires that just the decision logic involved with calls to other modules be tested independently. The following subsections explore this approach in detail.

7.4 Module design complexity

Rather than testing all decision outcomes within a module independently, structured testing at the integration level focuses on the decision outcomes that are involved with module calls [MCCABE2]. The *design reduction* technique helps identify those decision outcomes, so that it is possible to exercise them independently during integration testing. The idea behind design reduction is to start with a module control flow graph, remove all control structures that are not involved with module calls, and then use the resultant "reduced" flow graph to drive integration testing. Figure 7-2 shows a systematic set of rules for performing design reduction. Although not strictly a reduction rule, the *call* rule states that function call ("black dot") nodes cannot be reduced. The remaining rules work together to eliminate the parts of the flow graph that are not involved with module calls. The *sequential* rule eliminates sequences of non-call ("white dot") nodes. Since application of this rule removes one node and one edge from the flow graph, it leaves the cyclomatic complexity unchanged. However, it does simplify the graph so that the other rules can be applied. The *repetitive* rule eliminates top-test loops that are not involved with module calls. The *conditional* rule eliminates conditional statements that do not contain calls in their bodies. The *looping* rule eliminates bottom-test loops that are not involved with module calls. It is important to preserve the module's connectivity when using the looping rule, since for poorly-structured code it may be hard to distinguish the ''top'' of the loop from the ''bottom.'' For the rule to apply, there must be a path from the module entry to the top of the loop and a path from the bottom of the loop to the module exit. Since the repetitive, conditional, and looping rules each remove one edge from the flow graph, they each reduce cyclomatic complexity by one.

Rules 1 through 4 are intended to be applied iteratively until none of them can be applied, at which point the design reduction is complete. By this process, even very complex logic can be eliminated as long as it does not involve any module calls.

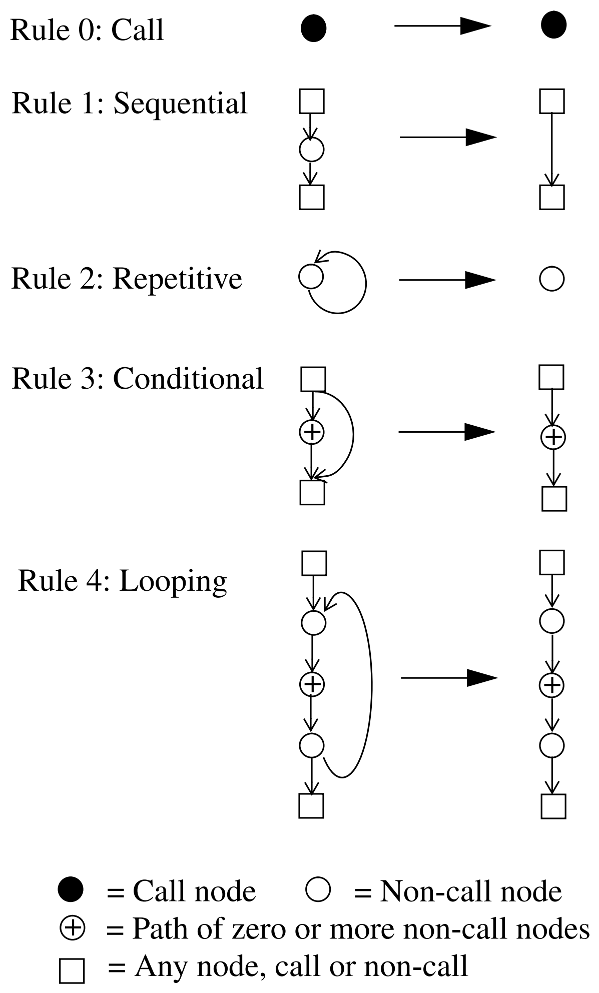


Figure 7-2. Design reduction rules.

Figure 7-3 shows a control flow graph before and after design reduction. Rules 3 and 4 can be applied immediately to the original graph, yielding the intermediate graph. Then rule 1 can be applied three times to the left conditional branch, at which point rule 3 can be applied again, after which five more applications of rule 1 complete the reduction. The second application of rule 3 illustrates that a conditional structure may be eliminated even if its body contains a call node, as long as there is at least one path through its body that does not contain any call nodes.

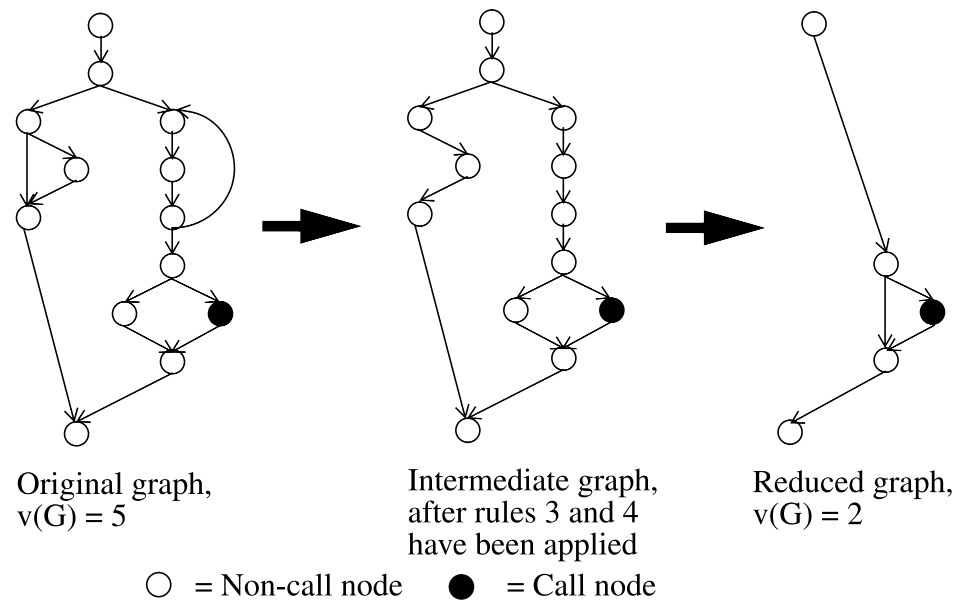
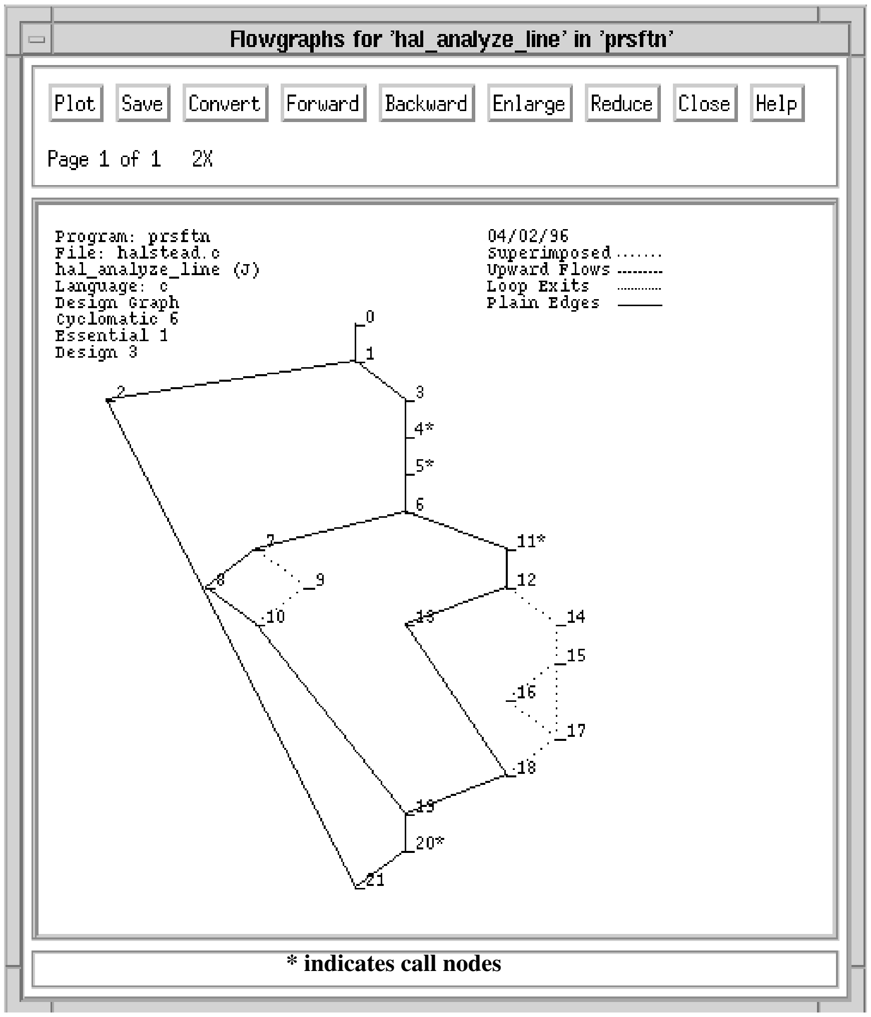


Figure 7-3. Design reduction example.

The *module design complexity*, *iv(G)*, is defined as the cyclomatic complexity of the reduced graph after design reduction has been performed. In Figure 7-3, the module design complexity is 2. The design flow graph in Figure 7-4 displays the logic that contributes to module design complexity superimposed on the entire control flow graph for a module with cyclomatic complexity 6 and module design complexity 3.



```
Program: prsftn                          04/02/96
File: halstead.c                         Superimposed .......
hal_analyze_line (J)                     Upward Flows --------
Language: c                              Loop Exits  ..........
Design Graph                             Plain Edges  ______
Cyclomatic 6
Essential 1
Design 3
```

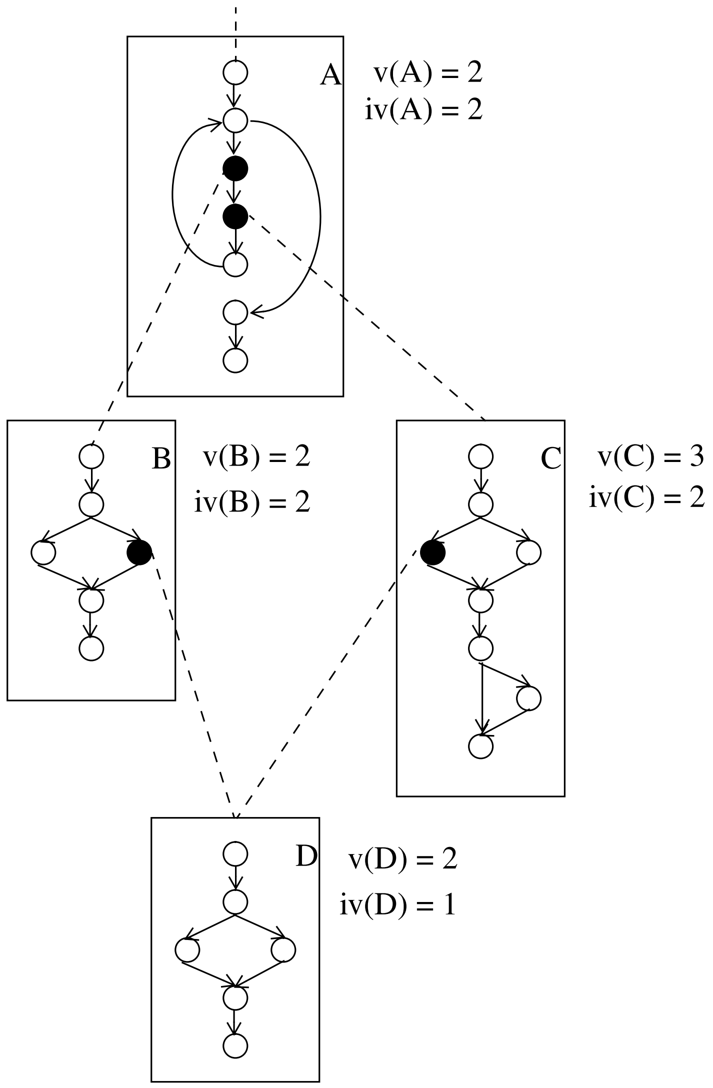
Figure 7-4. **Design graph with v(G) = 6, iv(G) = 3.**

When structured testing has already been performed at the module level, module design complexity can be used to drive integration testing, requiring a basis set of paths through each module's reduced graph to be tested in integration. For the bottom-up integration strategy discussed in section 7-2, the total number of integration tests becomes the sum of the module design complexities of all modules being integrated. Since module design complexity can be significantly less than cyclomatic complexity, this technique reduces the number of integration tests. It also simplifies the process of deriving data for each test path, since there are fewer constraints on paths through the reduced graph than on paths through the full graph.

7.5 Integration complexity

The *integration complexity*, S_1, is defined for a program with n modules (G_1 through G_n) by the formula: $S_1 = (\Sigma\ iv(G_i)) - n + 1$ [MCCABE2]. Integration complexity measures the number of independent integration tests through an entire program's design. To understand the formula, recall the baseline method of section 6 for generating a set of independent tests through an individual module. The analogous integration-level method generates a set of independent tests through the program's design. Begin with a baseline test, which contributes 1 to the S_1 formula and exercises one path through the program's main module. Then, make each successive test exercise exactly one new decision outcome in exactly one module's design-reduced graph. Since the first "mini-baseline" path through each module comes as a result of exercising a path in a higher-level module (except for the main module, which gets its first path from the baseline test), each module contributes a number of new integration tests equal to one less than its module design complexity, for a total contribution of $\Sigma\ (iv(G_i) - 1)$, which (since there are n modules) equals $(\Sigma\ iv(G_i)) - n$. Adding the 1 for the baseline test gives the full S_1 formula. A similar argument shows that substituting v(G) for iv(G) in the S_1 formula gives the number of tests necessary to test every decision outcome in the entire program independently [FEGHALI].

Figure 7-5 shows an example program with integration complexity 4, giving the control structure, cyclomatic complexity, and module design complexity for each module and a set of four independent integration tests.



$S_1 = (2 + 2 + 2 + 1) - 4 + 1 = 4.$

Independent integration tests:
1. A
2. A > B < A > C < A
3. A > B > D < B < A > C < A
4. A > B < A > C > D < C < A

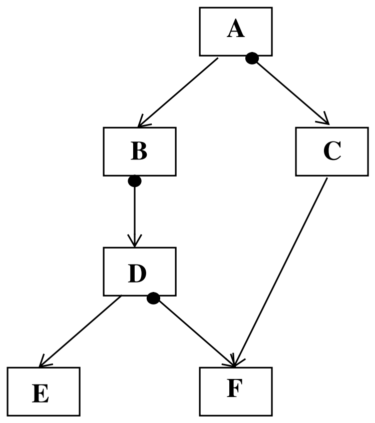
("X > Y < X" means "X calls Y which returns to X.")

○ = non-call node ● = call node

Figure 7-5. **Integration complexity example.**

Although a basis set of paths through each module's design-reduced control flow graph can typically be exercised with fewer than S_1 integration tests, more tests are never required. For the most rigorous level of structured testing, a complete basis set of S_1 integration tests should be performed.

Integration complexity can be approximated from a structured design [YOURDON], allowing integration test effort to be predicted before coding begins. The number of design predicates in a structure chart (conditional and iterative calls) can be used to approximate the eventual integration complexity. Recall the simplified formula for cyclomatic complexity from section 4.1, that for modules with only binary decisions and p decision predicates, $v(G) = p + 1$. The corresponding formula for integration complexity is that for programs with d design predicates, S_1 will be approximately $d + 1$. The reason is that each design predicate (conditional or iterative call) tends to be implemented by a decision predicate in the design-reduced graph of a module in the eventual implemented program. Hence, recalling that iv(G) is the cyclomatic complexity of the design-reduced graph, combine the v(G) and S_1 formulas to calculate the approximation that $S_1 = \Sigma\, iv(G) - n + 1 = \Sigma\, (iv(G) - 1) + 1 = \Sigma\, (v(G_{Reduced}) - 1) + 1 = d + 1$, where d is the total number of decision predicates in the design-reduced graphs of the modules of the implemented program, and approximately equal to the number of design predicates in the original program design. Figure 7-6 shows a structured design representation with three design predicates and therefore an expected integration complexity of four.



● = design predicate (conditional call)

Since there are three design predicates,
The expected integration complexity is four.

Figure 7-6. Predicting integration complexity.

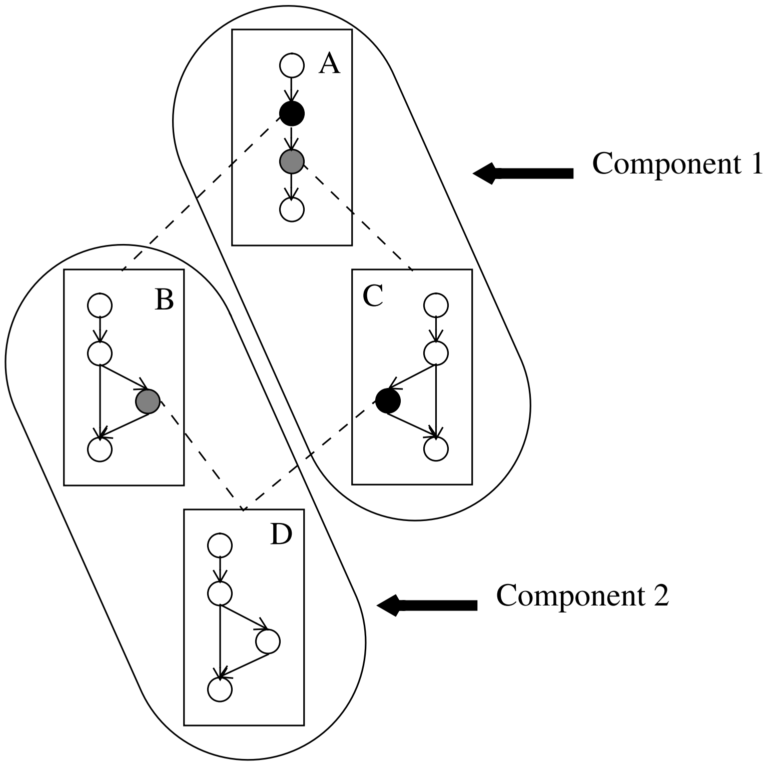
7.6 Incremental integration

Hierarchical system design limits each stage of development to a manageable effort, and it is important to limit the corresponding stages of testing as well [WATSON5]. Hierarchical design is most effective when the coupling among sibling components decreases as the component size increases, which simplifies the derivation of data sets that test interactions among components. The remainder of this section extends the integration testing techniques of structured testing to handle the general case of incremental integration, including support for hierarchical design. The key principle is to test just the interaction among components at each integration stage, avoiding redundant testing of previously integrated sub-components.

As a simple example of the approach, recall the statement coverage module testing criterion and its integration-level variant from section 7.2 that all module call statements should be exercised during integration. Although this criterion is certainly not as rigorous as structured testing, its simplicity makes it easy to extend to support incremental integration. Although the generalization of structured testing is more detailed, the basic approach is the same. To extend statement coverage to support incremental integration, it is required that all module call statements from one component into a different component be exercised at each integration stage. To form a completely flexible “statement testing” criterion, it is required that each statement be executed during the first phase (which may be anything from single modules to the entire program), and that at each integration phase all call statements that cross the boundaries of previously integrated components are tested. Given hierarchical integration stages with good cohesive partitioning properties, this limits the testing effort to a small fraction of the effort to cover each statement of the system at each integration phase.

Structured testing can be extended to cover the fully general case of incremental integration in a similar manner. The key is to perform design reduction at each integration phase using just the module call nodes that cross component boundaries, yielding component-reduced graphs, and exclude from consideration all modules that do not contain any cross-component calls. Integration tests are derived from the reduced graphs using the techniques of sections 7.4 and 7.5. The complete testing method is to test a basis set of paths through each module at the first phase (which can be either single modules, subsystems, or the entire program, depending on the underlying integration strategy), and then test a basis set of paths through each component-reduced graph at each successive integration phase. As discussed in section 7.5, the most rigorous approach is to execute a complete basis set of component integration tests at each stage. However, for incremental integration, the integration complexity formula may not give the precise number of independent tests. The reason is that the modules with cross-component calls may not be connected in the design structure, so it is not necessarily the case that one path through each module is a result of exercising a path in its caller. However, at most one additional test per module is required, so using the S_1 formula still gives a reasonable approximation to the testing effort at each phase.

Figure 7-7 illustrates the structured testing approach to incremental integration. Modules A and C have been previously integrated, as have modules B and D. It would take three tests to integrate this system in a single phase. However, since the design predicate decision to call module D from module B has been tested in a previous phase, only two additional tests are required to complete the integration testing. Modules B and D are removed from consideration because they do not contain cross-component calls, the component module design complexity of module A is 1, and the component module design complexity of module C is 2.



Independent component integration tests:
Test 1: A > B < A > C < A
Test 2: A > B < A > C > D < C < A
("X > Y < X" means "X calls Y which returns to X.")

○ = non-call node
● = cross-component call node
◍ = call node within a component

Figure 7-7. Incremental integration example.

8 Testing Object-Oriented Programs

Object-oriented software differs significantly from traditional procedural software in terms of analysis, design, structure, and development techniques, so specific testing support is also required [FIRESMITH]. The object-oriented language features of encapsulation, polymorphism, and inheritance require special testing support, but also provide opportunities for exploitation by a testing strategy. To adapt structured testing for object-oriented programs, consider both module testing and integration testing. Structured testing at the module level is directly applicable to object-oriented programs, although that fact is not immediately obvious. At the integration level, structured testing does require modification to address the dynamic binding of object-oriented methods. The rest of this section discusses the specific implications of object-oriented programming for structured testing. The majority of this information was previously published in [MCCABE3] and [MCCABE4].

8.1 Benefits and dangers of abstraction

Object-oriented languages and techniques use new and higher levels of abstraction than most traditional languages, particularly via the inheritance mechanism. There are both benefits and dangers to this abstraction. The benefit is that the closer the implementation is to the logical design, the easier it is to understand the intended function of the code. The danger is that the further the implementation is from the machine computation, the harder it is to understand the actual function of the code. Figure 8-1 illustrates this trade-off. The abstraction power of object-oriented languages typically make it easier for programmers to write misleading code. Informally, it is easy to tell what the code was supposed to do, but hard to tell what it actually does. Hence, automated support for analysis and testing is particularly important in an object-oriented environment.

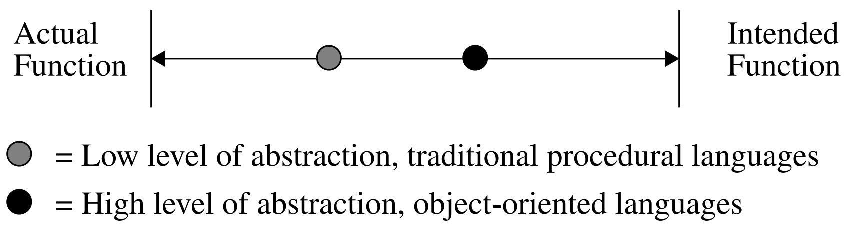

Actual Function
Intended Function
= Low level of abstraction, traditional procedural languages
= High level of abstraction, object-oriented languages

Figure 8-1. Abstraction level trade-off.

When abstraction works well, it hides details that do not need to be tested, so testing becomes easier. When abstraction works poorly, it hides details that need to be tested, so testing becomes harder (or at worst, infeasible). Typically, testing must occur at some compromise level of abstraction, gaining leverage from the abstractions that clarify the software's functionality while penetrating the abstractions that obscure it. Often, a software developer's level of familiarity with object-oriented development techniques is a key factor in determining whether abstraction is used in a positive or negative way, which in turn determines whether testing is helped or hindered by the unique features of object-oriented languages. As discussed in section 8-3, the basic object-oriented structured testing approach can be adapted to unusually positive or negative situations.

Metrics designed specifically for object-oriented software, such as those of [CHIDAMBER], can help assess the effectiveness with which the object-oriented paradigm is used. If class methods are not cohesive and there is substantial coupling between objects, the abstractions of the programming language may have been misused in the software. This in turn suggests that extra caution should be taken during testing.

8.2 Object-oriented module testing

Object-oriented methods are similar in most respects to ordinary functions, so structured testing (as well as other structural testing criteria) applies at the module level without modification. Since methods in object-oriented languages tend to be less complex than the functions of traditional procedural programs, module testing is typically easier for object-oriented programs.

The inheritance and polymorphism features of object-oriented languages may seem to complicate module testing, because of the implicit control flow involved in resolving dynamic method invocations. For example, if an object reference could result in any one of several alternative methods being executed at run time, it is possible to represent the reference as a multi-way decision construct ("case" statement) on the flow graph in which a different possible resolution method for the object reference is called from each branch. Since this representation of implicit control flow would increase the cyclomatic complexity, it would also increase the number of tests required to perform structured testing for the module containing the reference. Figure 8-2 illustrates implicit control flow.

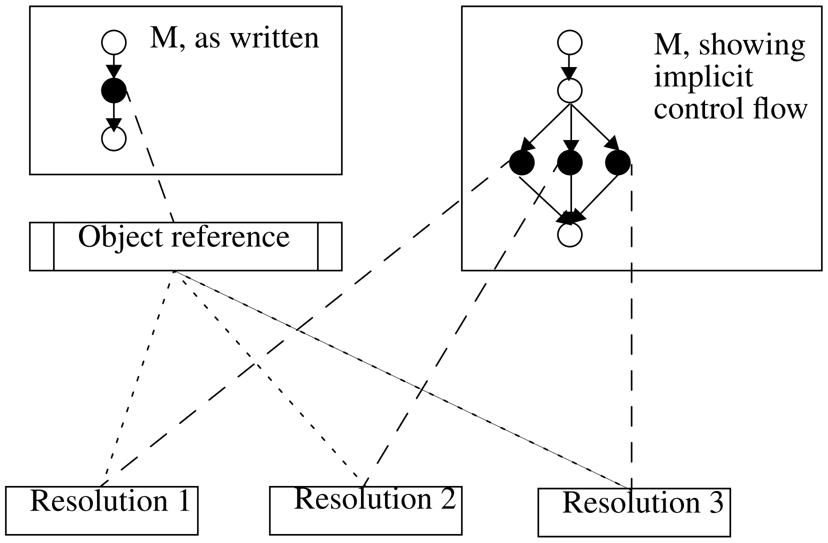


Figure 8-2. Implicit control flow.

Although implicit control flow has significant implications for testing, there are strong reasons to ignore it at the level of module testing. First, the number of possible resolutions of a particular object reference depends on the class hierarchy in which the reference occurs. Hence, if module testing depended on implicit control flow, it would only be possible to perform module testing in the context of a complete class hierarchy, a clearly unrealistic requirement. Also, viewing implicit complexity as a module property rather than a system property defeats one of the major motivations for using an object-oriented language: to develop easily reusable and extensible components. For these reasons, consideration of implicit control flow is deferred until the integration phase when applying structured testing to object-oriented programs.

8.3 Integration testing of object-oriented programs

The most basic application of structured testing to the integration of object-oriented programs is essentially the direct application of the techniques of section 7. It is vitally important, however, to consider the implicit method invocations through object references (not to be confused with the implicit control flow of dynamic binding) when identifying function call nodes to perform design reduction. These method invocations may not be apparent from examination of the source code, so an automated tool is helpful. For example, if variables “a” and “b” are integers, the C++ expression “a+b” is a simple computation. However, if those variables are objects of a class type, the exact same expression can be a call to a method of that class via the operator overloading mechanism of C++, which requires integration testing and hence must be preserved by design reduction.

While the treatment of implicit method calls due to object references is straightforward, the situation with implicit control flow is more complicated. In this case, several possible approaches are worth considering, depending on the extent to which the object-oriented abstraction has a positive or negative impact. This section describes three approaches: optimistic, pessimistic, and balanced. Each approach builds upon the techniques of section 7, requiring that at least a basis set of tests through the design-reduced graph of each module be exercised in an integration context, treating the implicit method invocations due to object references as calls when performing design reduction. The pessimistic and balanced approaches also require additional tests based on implicit control flow. Figure 8-3 shows the structure of a small subset of a program that illustrates each approach. Each of modules "A," "B," and "C" invokes the dynamically bound "Draw" method, which can be resolved at run time to any of "Line::Draw," "Polygon::Draw," and "Ellipse::Draw." For the rest of this section, the methods that may be invoked as a result of a dynamically bound object reference will be referred to as "resolutions."

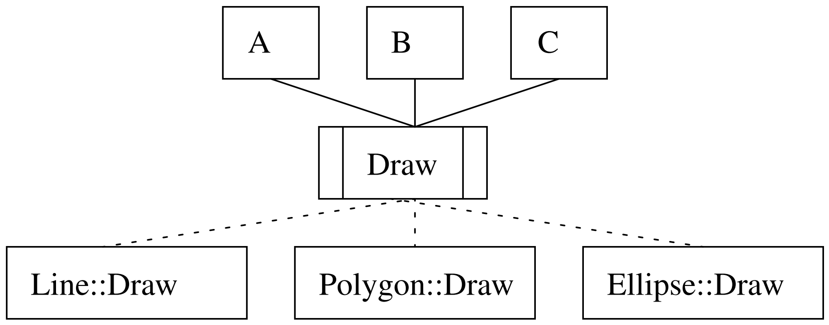


Figure 8-3. Implicit control flow example.

The optimistic approach is the most straightforward integration testing approach. With this approach, it is expected that abstraction will have a positive impact, and therefore testing will be confined to the level of abstraction of the source code. The integration testing techniques of section 7 apply directly. The consequences for implicit control flow are that each call site exercises at least one resolution, and each resolution is exercised by at least one call site. Assuming that no errors are uncovered by testing those interfaces, the object-oriented abstraction is trusted to gain confidence that the other possible interfaces are also correct. Figure 8-4 shows a set of interface tests that are adequate to satisfy the optimistic approach for the example of Figure 8-3.

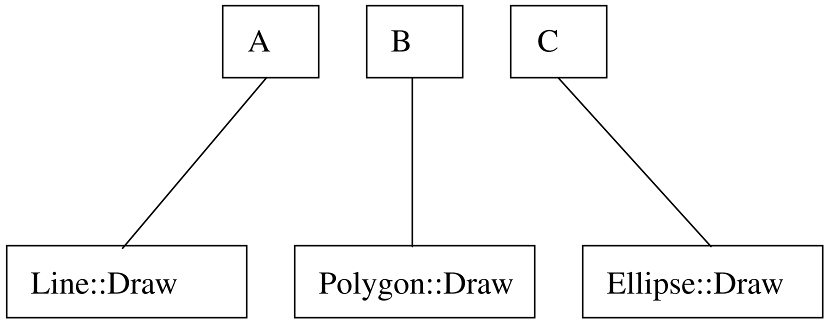


Figure 8-4. The optimistic approach to implicit control flow.

The pessimistic approach is another fairly straightforward approach. With this approach, abstraction is expected to have a negative impact, and therefore testing is required at the level of abstraction of the machine computation underlying the source code. In addition to the integration testing techniques of section 7, implicit control flow is tested by requiring that every resolution be tested from every call site. Thus, each interface is tested directly, and no trust is placed in the object-oriented abstraction. The drawback is that the testing effort can quickly become infeasible as complexity increases. Figure 8-5 shows a set of interface tests that are adequate to satisfy the pessimistic approach for the example of Figure 8-3.

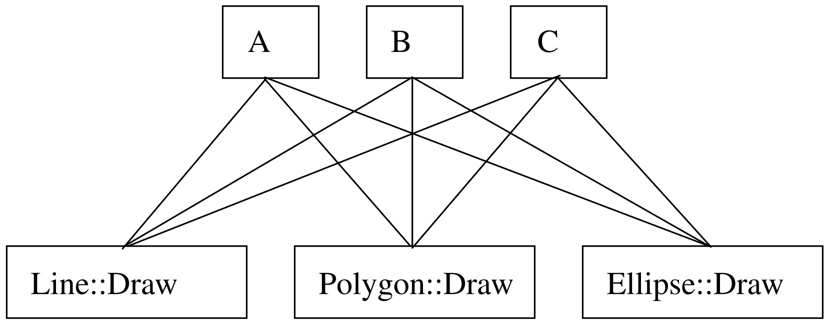


Figure 8-5. The pessimistic approach to implicit control flow.

The balanced approach is a compromise between the optimistic and pessimistic approaches, and is more complicated than either of them. The idea is to test at a level of abstraction between that of the code and that of the underlying mechanics. Abstraction is expected to hide some details that require testing, but also to provide a framework that can be exploited to facilitate testing. In addition to the integration testing techniques of section 7, it is required that some call site exercise the entire set of possible resolutions. The effect of this requirement is to provide evidence that the set of possible resolutions from a given call site form an "equivalence class" in the sense that if exercising one of those resolutions from a new call site works properly than exercising the other possible resolutions are also likely to work properly. This property is assumed by the optimistic approach and exhaustively tested by the pessimistic approach. The balanced approach provides more thorough testing than the optimistic approach without requiring as many tests as the pessimistic approach, and is therefore a good candidate for use in typical situations. Also, the call site used to establish the "equivalence classes" could be a test driver rather than part of the specific application being tested, which provides added flexibility. For example, a test driver program could first be written to test all resolutions of the "Draw" method in the "Shape" class hierarchy, after which the optimistic approach could be used without modification when testing "Draw" method invocations in programs using the "Shape" hierarchy. Figure 8-6 shows a set of interface tests that are adequate to satisfy the balanced approach for the example of Figure 8-3.

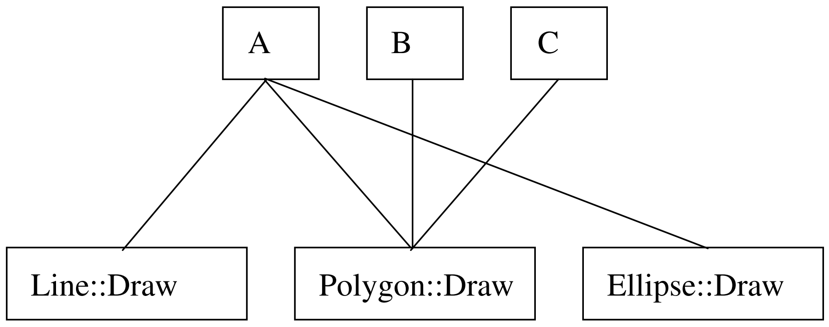


Figure 8-6. The balanced approach to implicit control flow.

Specific resolutions to dynamic control flow are often of interest. For example, the bulk of a drawing application's typical usage may involve polygons, or the polygon functionality may have been recently re-implemented. In that case, it is appropriate to consider a system view in which all shapes are assumed to be polygons, for example connecting all the polymorphic "Draw" calls directly to "Polygon::Draw" and removing alternatives such as "Ellipse::Draw" from consideration. For such a set of resolutions, the *object integration complexity*, OS_1, is defined as the integration complexity (S_1) of the corresponding resolved system. Object integration complexity is very flexible, since its measurement is based on any desired set of resolutions. Those resolutions could be specified either for specific polymorphic methods, or more generally for entire classes.

8.4 Avoiding unnecessary testing

Object-oriented systems are often built from stable components, such as commercial class libraries or re-used classes from previous successful projects. Indeed, component-based reuse is one of the fundamental goals of object-oriented development, so testing techniques must allow for it. Stable, high integrity software can be referred to as "trusted." The concept of trustedness can apply to individual modules, classes, class hierarchies, or a set of potential resolutions for dynamically bound methods, but in each case the meaning is that trusted software is assumed to function correctly and to conform to the relevant object-oriented abstraction. In addition to trusted commercial and reused software, new software becomes trusted after it has been properly tested. In structured testing, the implementation of trusted software is not tested, although its integration with other software is required to be tested. Trusted software is treated as an already-integrated component using the incremental integration techniques of section 7-6.

Trusted software does not have to be tested at the module level at all, and calls internal to a trusted component do not have to be tested at the integration level. The handling of trusted modules, classes, and class hierarchies is straightforward, in that only integration testing need be performed, and even then applying the design reduction technique based on only those calls that cross a boundary of trustedness. For the case of a trusted set of potential resolutions for a dynamically bound method, only one resolution need be tested from each call site even when using the pessimistic approach for testing non-trusted code. When an automated tool is used to display trustedness information, integration tests can be stopped at the trustedness boundary.

9 Complexity Reduction

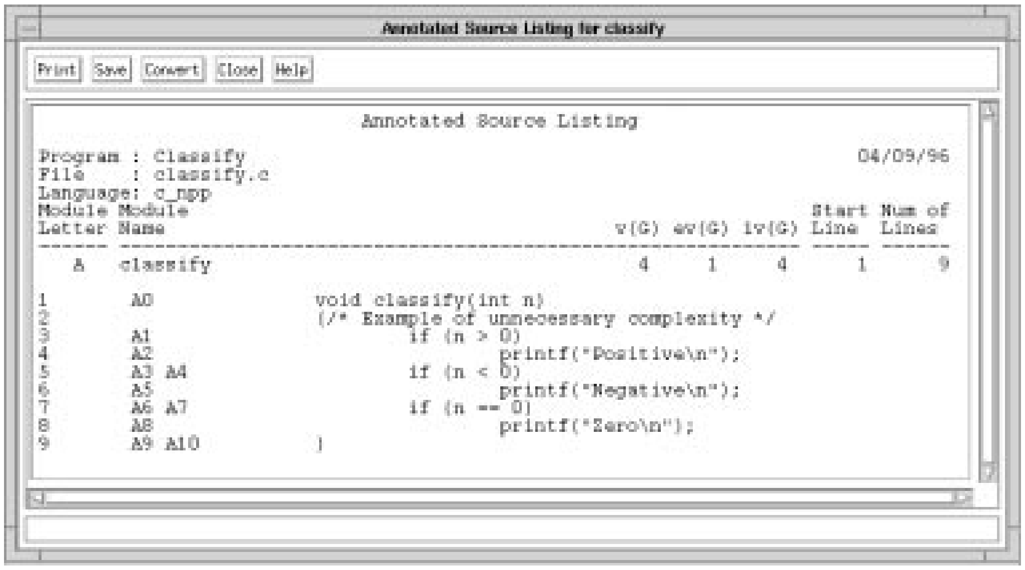
Although the amount of decision logic in a program is to some extent determined by the intended functionality, software is often unnecessarily complex, especially at the level of individual modules. Unnecessary complexity is an impediment to effective testing for three major reasons. First, the extra logic must be tested, which requires extra tests. Second, tests that exercise the unnecessary logic may not appear distinct from other tests in terms of the software's functionality, which requires extra effort to perform each test. Finally, it may be impossible to test the extra logic due to control flow dependencies in the software, which means that unless the risk of not satisfying the testing criterion is accepted, significant effort must be expended to identify the dependencies and show that the criterion is satisfied to the greatest possible extent.

Unnecessary complexity also complicates maintenance, since the extra logic is misleading unless its unnecessary nature is clearly identified. Even worse, unnecessary complexity may indicate that the original developer did not understand the software, which is symptomatic of both maintenance difficulty and outright errors. This section quantifies unnecessary complexity, and discusses techniques for removing and testing it.

9.1 Actual complexity and realizable complexity

The most innocuous kind of unnecessary complexity merely requires extra testing. It may increase testing effort and obscure the software's functionality, so it is often appropriate to remove it by reengineering the software. However, when the structured testing methodology can be used to verify proper behavior for a basis set of tests, adequate testing is simply a matter of resources.

A more problematic kind of unnecessary complexity prevents structured testing as described in section 5 from being fully satisfied by any amount of testing. The problem is that data-driven dependencies between the control structures of a software module can prevent a basis set of paths through the module's control flow graph from being exercised. The "classify" module in Figure 9-1 and its control flow graph in Figure 9-2 illustrate this phenomenon. Although the cyclomatic complexity is 4, only 3 paths can possibly be executed, because the "TRUE" outcome of exactly one of the three decisions must be exercised on any path. Another way to view this is that the outcome of the first decision may determine the outcome of the second, and the outcomes of the first two decisions always determine the outcome of the third. Figures 9-3 and 9-4 show “classify2,” a reengineered version with no unnecessary complexity.



```
                          Annotated Source Listing

Program : Classify                                                     04/09/96
File    : classify.c
Language: c_npp
Module Module                                                     Start  Num of
Letter Name                                      v(G) ev(G) iv(G) Line   Lines
------ ------------------------------------------------------------ ----- ------
   A   classify                                     4     1     4     1      9

1       A0              void classify(int n)
2                       (/* Example of unnecessary complexity */
3       A1                     if (n > 0)
4       A2                            printf("Positive\n");
5       A3 A4                  if (n < 0)
6       A5                            printf("Negative\n");
7       A6  A7                 if (n == 0)
8       A8                            printf("Zero\n");
9       A9 A10          }
```

Figure 9-1. **Code for module with unnecessary complexity.**

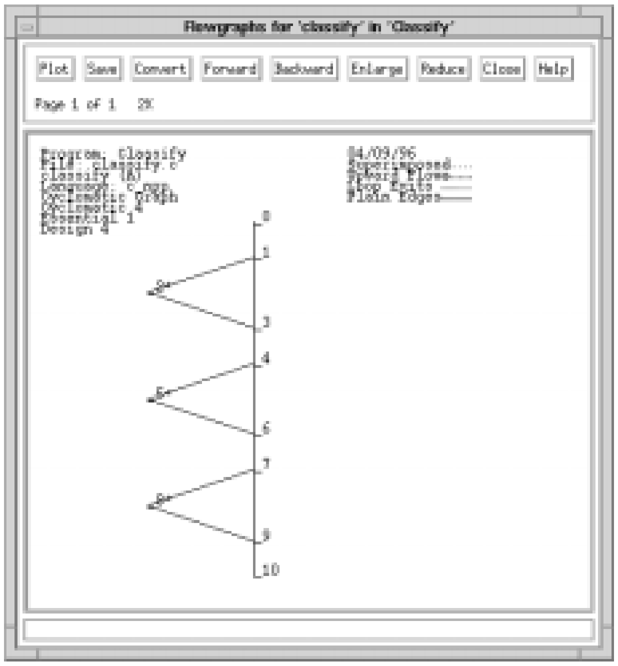
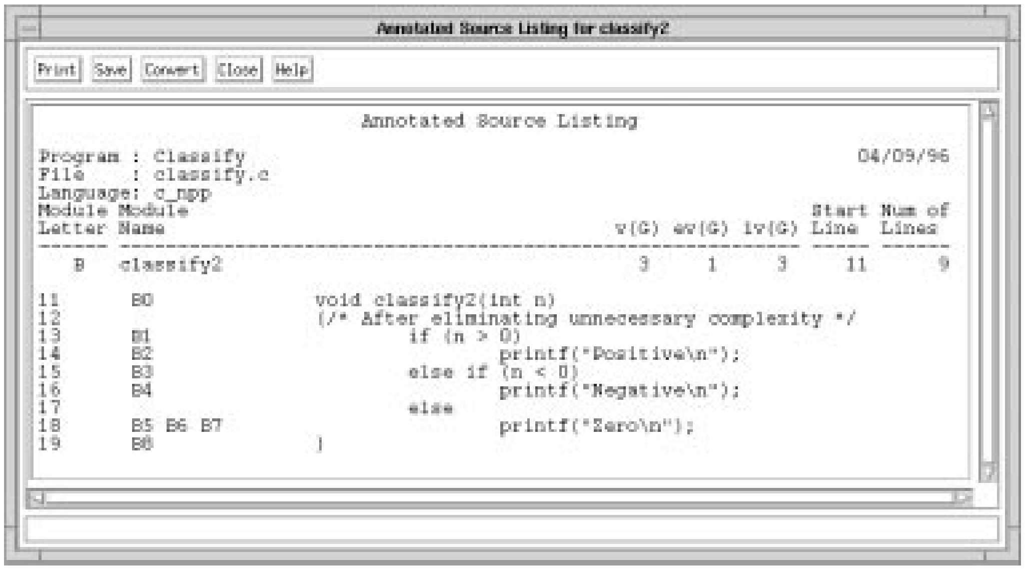


Figure 9-2. **Graph for module with unnecessary complexity.**



```
                         Annotated Source Listing

Program : Classify                                                  04/09/96
File    : classify.c
Language: c_npp
Module Module                                                   Start  Num of
Letter Name                               v(G) ev(G) iv(G) Line   Lines
------ ------------------------------------------------------ -----  ------
   B   classify2                            3     1     3     11      9

11       B0              void classify2(int n)
12                       (/* After eliminating unnecessary complexity */
13       B1                      if (n > 0)
14       B2                              printf("Positive\n");
15       B3                      else if (n < 0)
16       B4                              printf("Negative\n");
17                               else
18       B5 B6 B7                        printf("Zero\n");
19       B8              }
```

Figure 9-3. **Code after removing unnecessary complexity.**

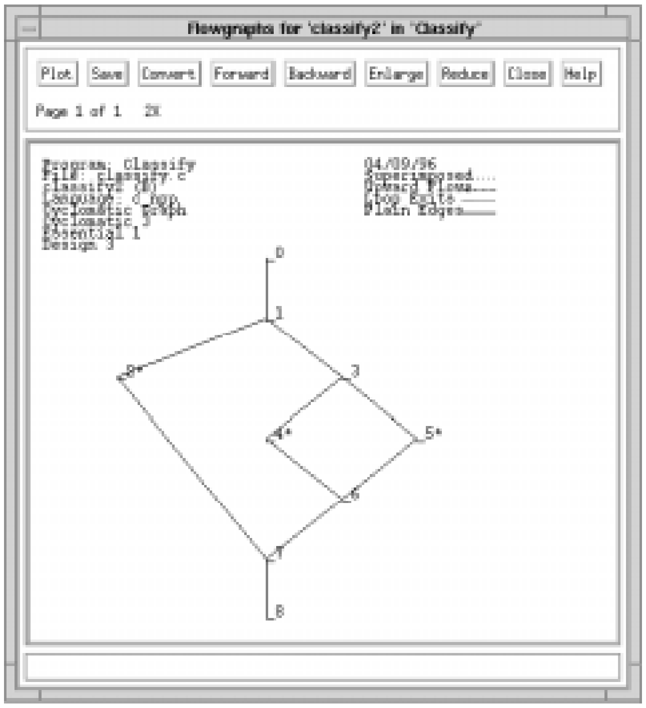


Figure 9-4. **Graph after removing unnecessary complexity.**

The *actual complexity, ac,* of a module is defined as the number of linearly independent paths that have been executed during testing, or more formally as the rank of the set of paths that have been executed during testing. The structured testing criterion requires that the actual complexity equal the cyclomatic complexity after testing. Note that the actual complexity is a property of both the module and the testing. For example, each new independent test increases the actual complexity.

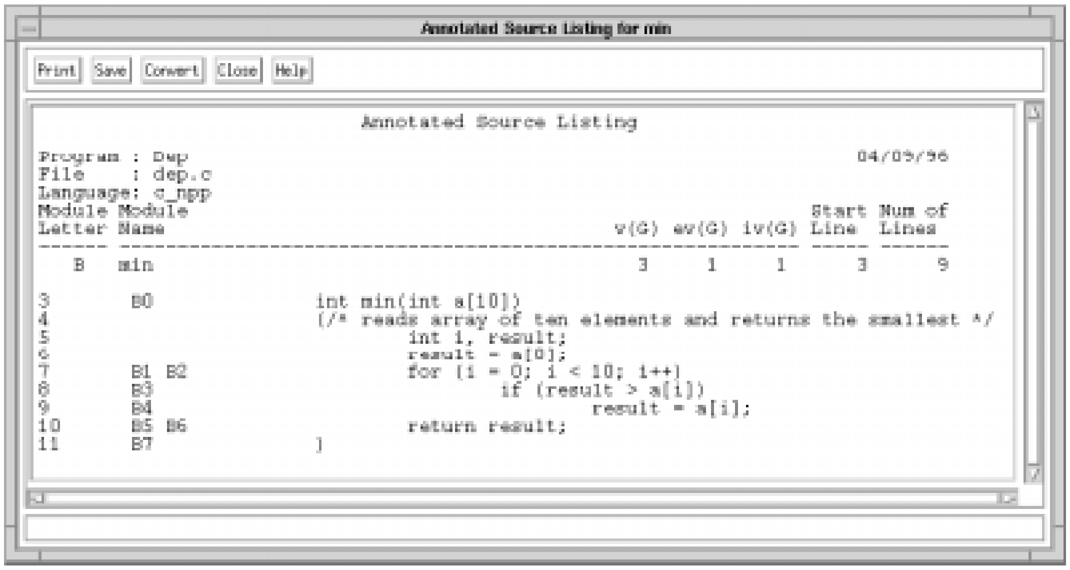
The *realizable complexity, rc,* is the maximum possible actual complexity, i.e., the rank of the set of the paths induced by all possible tests. This is similar to the characterization of cyclomatic complexity as the rank of the set of all possible paths, except that some paths may not be induced by any test. In the "classify" example, rc is 3 whereas v(G) is 4. Although rc is an objective and well-defined metric, it may be hard to calculate. In fact, calculating rc is theoretically undecidable [HOPCROFT], since, if it were possible to calculate rc, it would also be possible to determine whether rc is at least 1, which would indicate whether at least one complete path could be executed, which is equivalent to the module halting on some input.

One obvious property of rc is that after any amount of testing has been performed on a module, ac <= rc <= v(G). Satisfying the structured testing criterion therefore suffices to prove that rc = v(G). However, when ac < v(G), one of two situations can hold:

1. At least one additional independent test can be executed.
2. ac = rc, and hence rc < v(G).

In the first case, the solution is simply to continue testing until either ac = v(G) or case 2 is reached. In the second case, the software can typically be reengineered to remove unnecessary complexity, yielding a module in which rc = v(G). This was performed in the "classify" example. As an alternative to reengineering the software, the structured testing criterion can be modified to require testing until ac = rc. However, due to the undecidability of rc, some manual work is required to set the target value when using an automated tool to measure ac. A tool can help by reporting the current set of control dependencies, at which point the user can review the observed dependencies and decide whether or not additional tests could increase ac. If additional tests can increase ac, dependency information can also help construct those tests. One special case is "infinite loop" modules, which have rc = 0 because no complete path can be executed. This does *not* mean that these modules should not be tested at all! Infinite loops in real software are typically not really infinite, they are just waiting for some external event to interrupt them in a way that is not explicitly specified in their source code. Such modules should be as small as possible, so that they can be adequately tested just by executing them once. Any complex processing should be performed by subordinate modules that do not contain infinite loops, and hence have basis paths to test.

There are many situations in which it is easy to see that rc < v(G). One example is a loop with a constant number of iterations, such as the “min” module in Figure 9-5. The “TRUE” out-



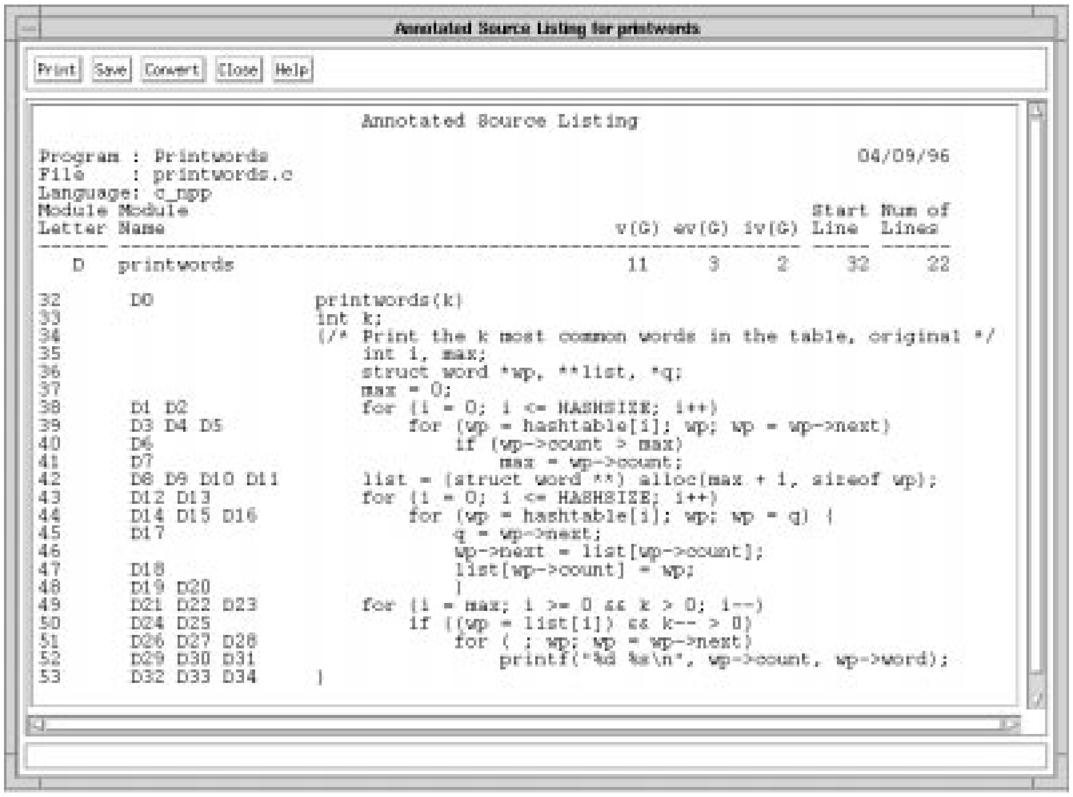
```
                              Annotated Source Listing

Program : Dep                                                          04/09/96
File    : dep.c
Language: c_npp
Module Module                                                        Start  Num of
Letter Name                                      v(G)  ev(G)  iv(G)  Line   Lines
------ ---------------------------------------------------------------- -----  ------
   B   min                                          3      1      1      3       9

3       B0             int min(int a[10])
4                      {/* reads array of ten elements and returns the smallest */
5                              int i, result;
6                              result = a[0];
7       B1  B2                 for (i = 0; i < 10; i++)
8       B3                             if (result > a[i])
9       B4                                     result = a[i];
10      B5  B6                 return result;
11      B7             }
```

Figure 9-5. **Loop with constant number of iterations.**

come of the loop is always executed ten times as frequently as the “ENTRY” branch along any executable path, which is a linear control dependency and thus reduces rc by one. Loops with a constant number of iterations are fairly common in software. When the constant might change during maintenance (for example, a hash table size), it is worth running a test with a different constant value. When the constant will not change (for example, the number of axes in graphics rendering code), the dependency can simply be taken into account during testing.

9.2 Removing control dependencies

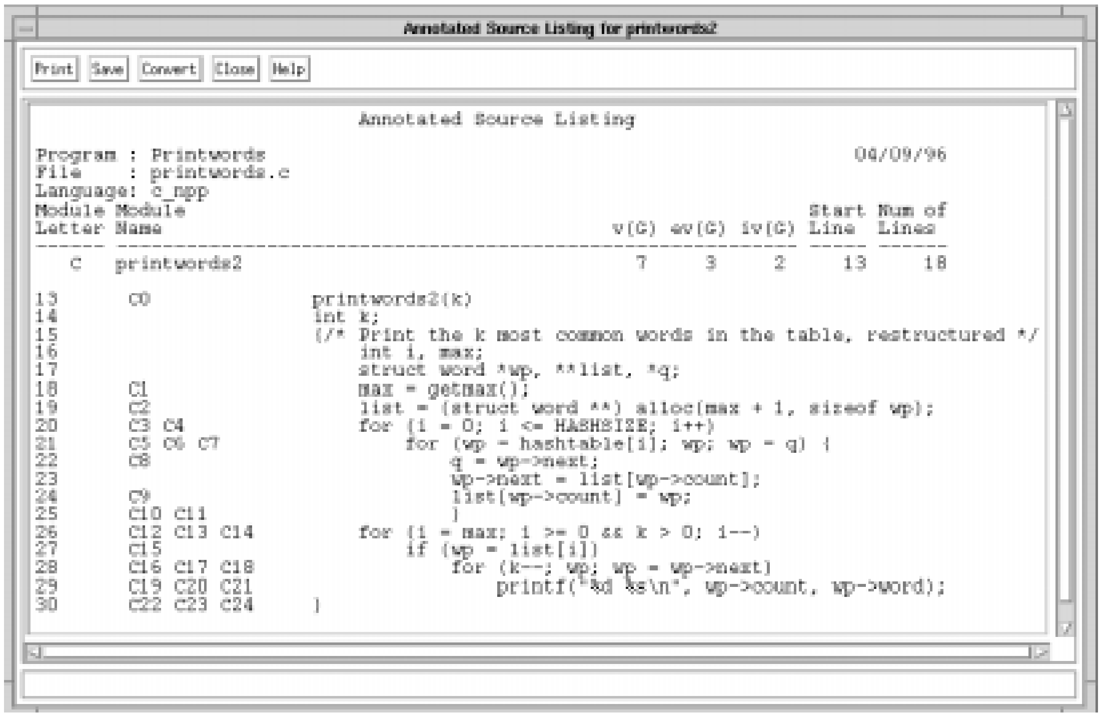
Removing control dependencies often improves code, since the resulting modules tend to be less complex and have straightforward decision logic. When all dependencies are removed, testing is facilitated by allowing the cyclomatic complexity to be used as a target for actual complexity. Two important reduction techniques are direct logic simplification and modularization. The following complex example [WATSON5] illustrates both techniques. Figure 9-6 shows the code for module “printwords,” [HANSON] which contains three control dependencies (for this example, HASHSIZE is not constant). One dependency is the “&& k-- > 0”



```
                          Annotated Source Listing

Program : Printwords                                                04/09/96
File    : printwords.c
Language: c_npp
Module Module                                                    Start Num of
Letter Name                               v(G) ev(G) iv(G) Line  Lines
------ ---------------------------------------------------- ----- ------
   D   printwords                           11     3     2    32     22

32       D0             printwords(k)
33                      int k;
34                      (/* Print the k most common words in the table, original */
35                          int i, max;
36                          struct word *wp, **list, *q;
37                          max = 0;
38       D1 D2              for (i = 0; i <= HASHSIZE; i++)
39       D3 D4 D5               for (wp = hashtable[i]; wp; wp = wp->next)
40       D6                         if (wp->count > max)
41       D7                             max = wp->count;
42       D8 D9 D10 D11      list = (struct word **) alloc(max + 1, sizeof wp);
43       D12 D13            for (i = 0; i <= HASHSIZE; i++)
44       D14 D15 D16            for (wp = hashtable[i]; wp; wp = q) {
45       D17                        q = wp->next;
46                                  wp->next = list[wp->count];
47       D18                        list[wp->count] = wp;
48       D19 D20                    }
49       D21 D22 D23        for (i = max; i >= 0 && k > 0; i--)
50       D24 D25                if ((wp = list[i]) && k-- > 0)
51       D26 D27 D28                for ( ; wp; wp = wp->next)
52       D29 D30 D31                    printf("%d %s\n", wp->count, wp->word);
53       D32 D33 D34    }
```

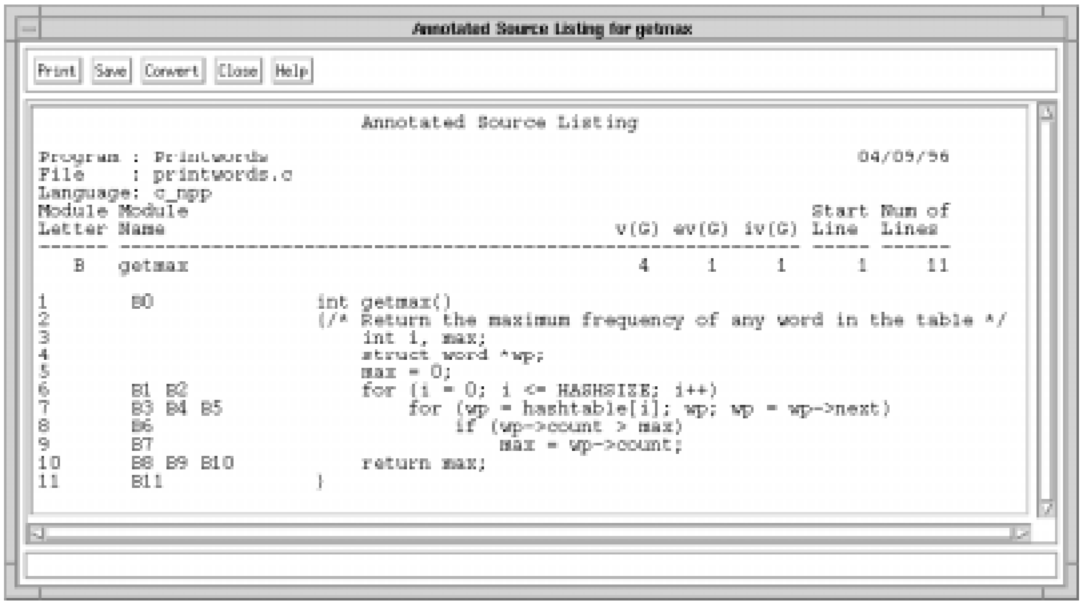
Figure 9-6. **Module with three dependencies.**

condition at line 50. This condition is always true, since it can only be reached when “k > 0” is true at line 49, and the value of k is not changed in the interim. The condition can therefore be eliminated, moving the “k--” to the initialization part of the loop on line 51 to preserve functionality. The other two dependencies are due to the hash table being traversed twice, once to get the value of “max” for the list allocation, then again to fill the list. These dependencies can be eliminated by modularization of the “max” calculation. Figures 9-7 and 9-8 show the reengineered functions “printwords2” and “getmax,” for which rc = v(G) and the maximum v(G) has been reduced from 11 to 7.



```
                         Annotated Source Listing

Program : Printwords                                                  04/09/96
File    : printwords.c
Language: c_npp
Module Module                                                         Start Num of
Letter Name                                       v(G) ev(G) iv(G) Line  Lines
------ ------------------------------------------------------------- ----- ------
   C   printwords2                                   7     3     2    13     18

13      C0               printwords2(k)
14                       int k;
15                       {/* Print the k most common words in the table, restructured */
16                           int i, max;
17                           struct word *wp, **list, *q;
18      C1                   max = getmax();
19      C2                   list = (struct word **) alloc(max + 1, sizeof wp);
20      C3 C4                for (i = 0; i <= HASHSIZE; i++)
21      C5 C6 C7                 for (wp = hashtable[i]; wp; wp = q) {
22      C8                           q = wp->next;
23                                   wp->next = list[wp->count];
24      C9                           list[wp->count] = wp;
25      C10 C11                      }
26      C12 C13 C14          for (i = max; i >= 0 && k > 0; i--)
27      C15                      if (wp = list[i])
28      C16 C17 C18                  for (k--; wp; wp = wp->next)
29      C19 C20 C21                      printf("%d %s\n", wp->count, wp->word);
30      C22 C23 C24      }
```

Figure 9-7. **First reengineered module.**

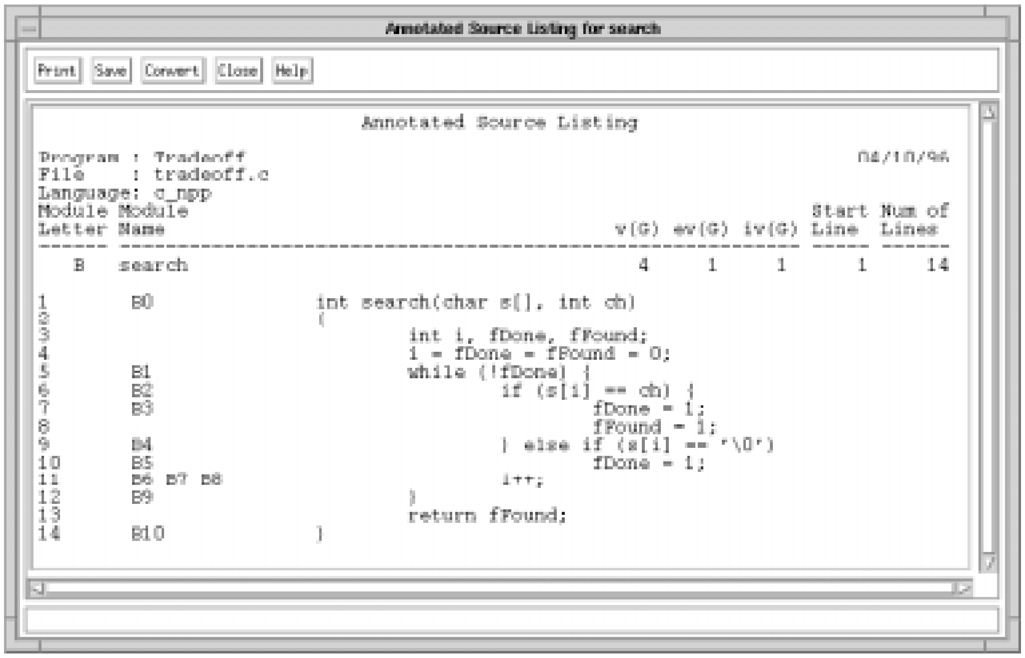


```
                         Annotated Source Listing

Program : Printwords                                                  04/09/96
File    : printwords.c
Language: c_npp
Module Module                                                         Start Num of
Letter Name                                       v(G) ev(G) iv(G) Line  Lines
------ ------------------------------------------------------------- ----- ------
   B   getmax                                        4     1     1     1     11

1       B0               int getmax()
2                        {/* Return the maximum frequency of any word in the table */
3                            int i, max;
4                            struct word *wp;
5                            max = 0;
6       B1 B2                for (i = 0; i <= HASHSIZE; i++)
7       B3 B4 B5                 for (wp = hashtable[i]; wp; wp = wp->next)
8       B6                           if (wp->count > max)
9       B7                               max = wp->count;
10      B8 B9 B10            return max;
11      B11              }
```

Figure 9-8. **Second reengineered module.**

9.3 Trade-offs when reducing complexity

Removing control dependencies, although typically beneficial, can sometimes have a negative impact on software. The most common pitfall when reducing complexity is to introduce unstructured logic. The essential complexity metric, described in section 10, can help resolve this problem by quantifying unstructured logic. However, structural degradation is often obvious directly from the code and flow graph. Figures 9-9 and 9-10 show the code and graph for "search," a well-structured module with v(G) = 4 and rc = 3. This type of code is often seen in Pascal programs, using a single Boolean to control a loop and assigning it a value based on multiple termination conditions.



```
                        Annotated Source Listing

Program : Tradeoff                                                  04/10/96
File    : tradeoff.c
Language: c_npp
Module Module                                                    Start Num of
Letter Name                                   v(G) ev(G) iv(G) Line  Lines
------ -------------------------------------------------------- ----- ------
   B   search                                    4     1     1     1     14

1        B0              int search(char s[], int ch)
2                        {
3                                int i, fDone, fFound;
4                                i = fDone = fFound = 0;
5        B1                      while (!fDone) {
6        B2                              if (s[i] == ch) {
7        B3                                      fDone = 1;
8                                                fFound = 1;
9        B4                              } else if (s[i] == '\0')
10       B5                                      fDone = 1;
11       B6 B7 B8                        i++;
12       B9                      }
13                               return fFound;
14       B10             }
```

Figure 9-9. **Code for structured module, rc < v(G).**

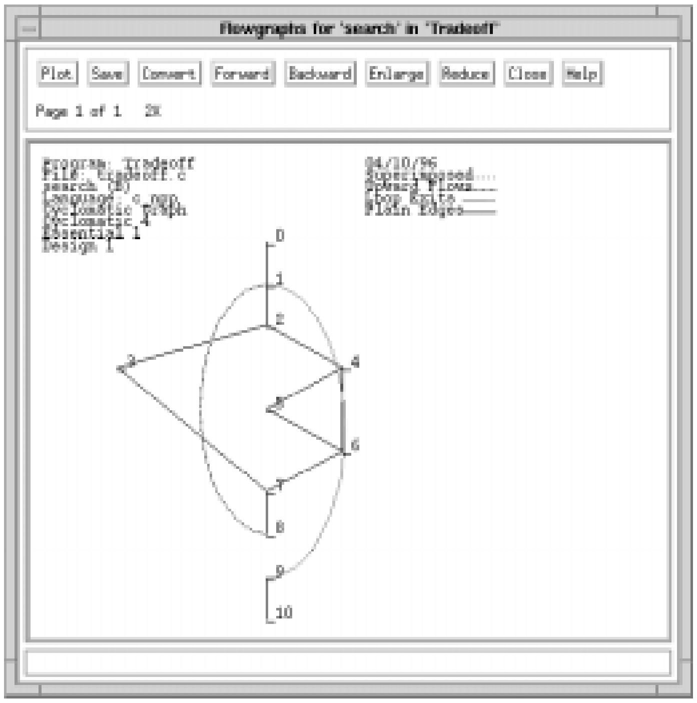
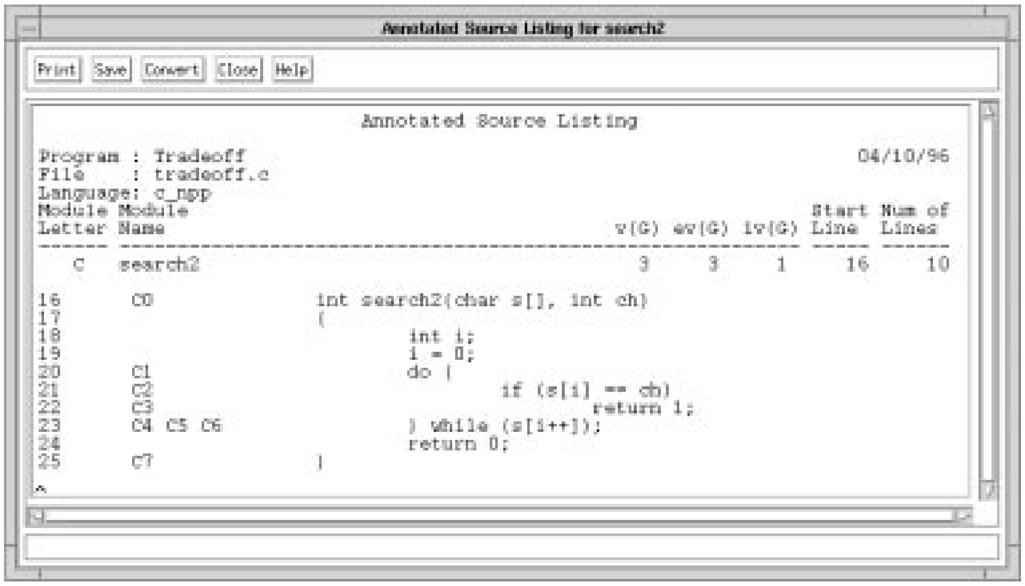


Figure 9-10. **Graph for structured module, rc < v(G).**

Figures 9-11 and 9-12 show the code and graph for a reengineered version of the same module, with rc and v(G) both equal to 3. Although in principle this is an improvement, the new version is not well-structured. The loop has two exit points, the bottom test and the conditional return in the middle. Even so, most programmers would agree that the reengineered version is better in this simple example. However, for more complex programs the structural degradation from complexity reduction can be much more severe, in which case the original version would be preferred. There is also a "middle ground" of programs for which reasonable programmers can disagree about the desirability of reengineering, depending on their experience and stylistic preferences. In such cases, it is less important to worry about making the “right” choice, and more important to document the reasons for the trade-off.



```
                              Annotated Source Listing

Program : Tradeoff                                                    04/10/96
File    : tradeoff.c
Language: c_npp
Module Module                                                     Start  Num of
Letter Name                                  v(G) ev(G) iv(G)  Line   Lines
------ -------------------------------------------------------- -----  ------
   C   search2                                  3     3     1     16      10

16      C0              int search2(char s[], int ch)
17                      {
18                              int i;
19                              i = 0;
20      C1                      do {
21      C2                              if (s[i] == ch)
22      C3                                      return 1;
23      C4  C5  C6              } while (s[i++]);
24                              return 0;
25      C7              }
^
```

Figure 9-11.Reengineered code, rc = v(G) but not well-structured.

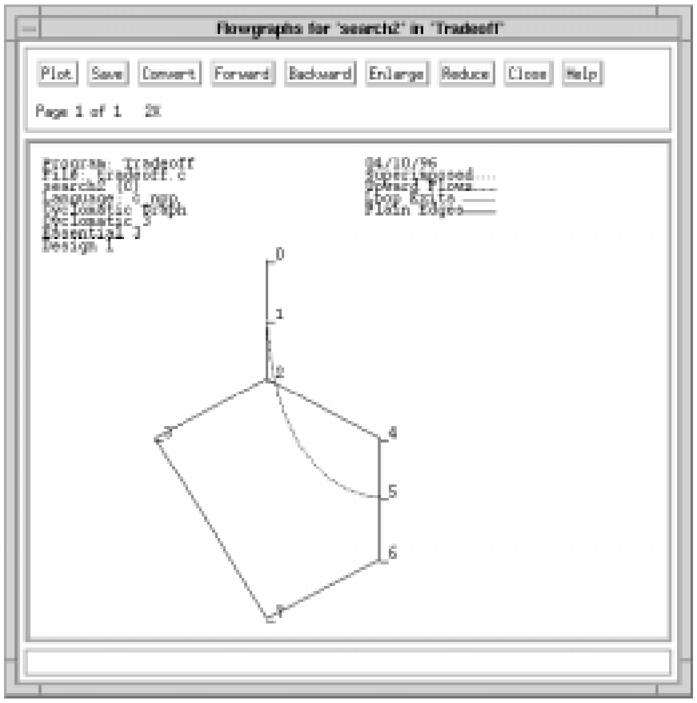


Figure 9-12.Reengineered graph, v(G) = rc but not well-structured.

In addition to the trade-off between direct complexity reduction and structural quality, there is also a trade-off between modularization and design quality [PARNAS]. When splitting a control dependency across a module boundary, there is the risk of introducing control coupling between the modules and limiting the cohesion of each module. As when considering splitting up a module to satisfy a complexity threshold, the most important consideration is whether each new module performs a single cohesive function. If it does, then the modularization is consistent with design quality. Otherwise, the design quality degradation must be weighed against the benefits of the reduced complexity. In the “printwords” example, the new “getmax” function performed a single cohesive function, so the complexity reduction was justified. If, on the other hand, the module was split in such a way as to require passing local variables by reference and the only name that could be thought of for the new module was “more_printwords,” the modularization would not have been justified. As with structural quality, having a clearly documented reasoning process is vital when the trade-off seems fairly balanced.

10 Essential Complexity

In addition to the quantity of decision logic as measured by cyclomatic complexity, the quality of that logic is also a significant factor in software development [PRESSMAN]. Structured programming [DAHL] avoids unmaintainable "spaghetti code" by restricting the usage of control structures to those that are easily analyzed and decomposed. Most programming languages allow unstructured logic, and few real programs consist entirely of perfectly structured code. The essential complexity metric described in this section quantifies the extent to which software is unstructured, providing a continuous range of structural quality assessments applicable to all software rather than the "all or nothing" approach of pure structured programming.

10.1 Structured programming and maintainability

The primitive operations of structured programming, shown in Figure 10-1, are sequence, selection, and iteration.

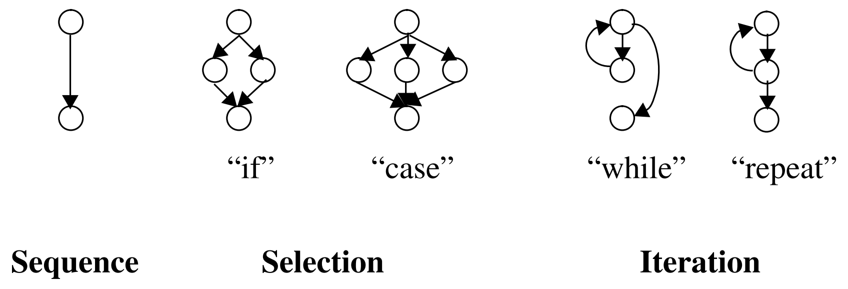


Figure 10-1.Structured programming primitives.

The fundamental strength of structured programming is that the primitive operations give a natural decomposition of arbitrarily complex structures. This decomposition facilitates modularization of software because each primitive construct appears as a component with one entry point and one exit point. The decomposition also allows a "divide and conquer" strategy to be used to understand and maintain complex software even when the software is not physically decomposed. Unstructured code must typically be understood and maintained as a single unit, which can be impractical even for programs of moderate cyclomatic complexity.

Since poor module structure makes software harder to understand, it also impedes testing. First, as discussed in section 5.3, poorly understood software requires extra testing to gain confidence. Second, it requires more effort to construct each specific test case for poorly understood code, since the connection between input data and the details of the implementation tends to be unclear. Finally, poorly understood code is both error-prone and hard to debug, so an iterative process of testing and error correction may be required.

10.2 Definition of essential complexity, ev(G)

The *essential complexity, ev(G)* [MCCABE1], of a module is calculated by first removing structured programming primitives from the module's control flow graph until the graph cannot be reduced any further, and then calculating the cyclomatic complexity of the reduced graph. An immediate consequence is that 1 <= ev(G) <= v(G). A somewhat less obvious consequence, which can help when evaluating complexity analysis tools, is that ev(G) can never be equal to 2. This is because after all sequential nodes have been eliminated, the only graphs with v(G) equal to 2 are structured programming primitives, which can then be removed to get an ev(G) of 1. The reduction proceeds from the deepest level of nesting outward, which means that a primitive construct can be removed only when no other constructs are nested within it.

It is important to note that the structured programming primitives used in the calculation of essential complexity are based on the control flow graph rather than the source code text. This allows the essential complexity metric to measure structural quality independently of the syntax of any particular programming language. For example, a bottom-test loop is a structured primitive whether it is written using a high-level looping construct or an assembly language conditional branch. Programming language constructs such as the "goto" statement only increase essential complexity when they are actually used to implement poorly structured logic, not just because they could be used that way. Of course, any program that is written entirely with high-level "structured programming" language constructs will have a perfectly structured control flow graph and therefore have an essential complexity of 1.

The essential complexity calculation process is similar to the calculation of module design complexity as described in section 7.4 (and in fact was developed first), but there are two key differences. First, primitive constructs can be removed whether or not they involve module calls when calculating essential complexity. Second, only entire primitive constructs can be removed when calculating essential complexity. The module design complexity reduction rules allow removing partial decision constructs when there are no module calls involved, which can eliminate unstructured code. Thus, despite the similarity between the two calculation methods, there is no mathematical relationship between the two metrics.

10.3 Examples of essential complexity

Figure 10-2 illustrates the calculation of essential complexity from a control flow graph. The original graph has a cyclomatic complexity of 8. First the innermost primitive constructs are removed (a bottom-test loop and two decisions). Then, the new innermost primitive construct is removed (a top-test loop), after which no further reductions are possible. The cyclomatic complexity of the final reduced graph is 4, so the essential complexity of the original graph is also 4.

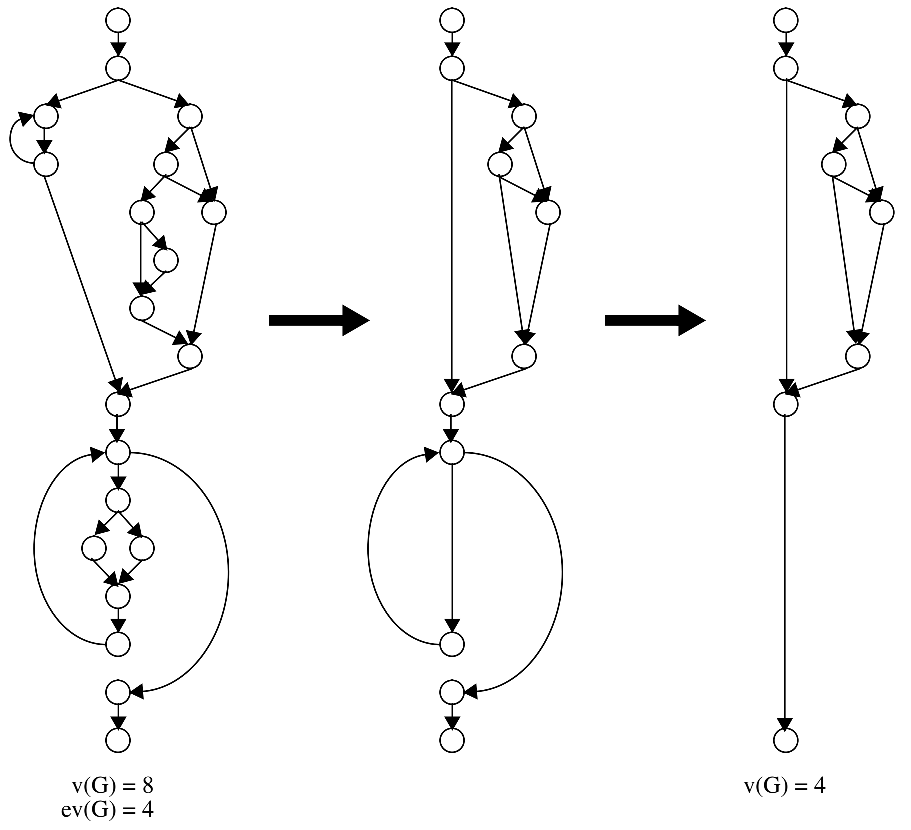
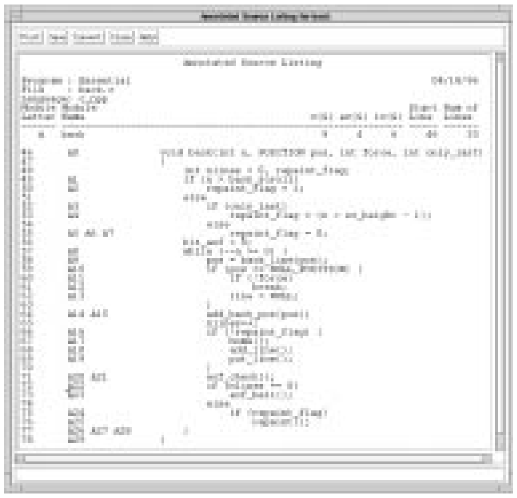


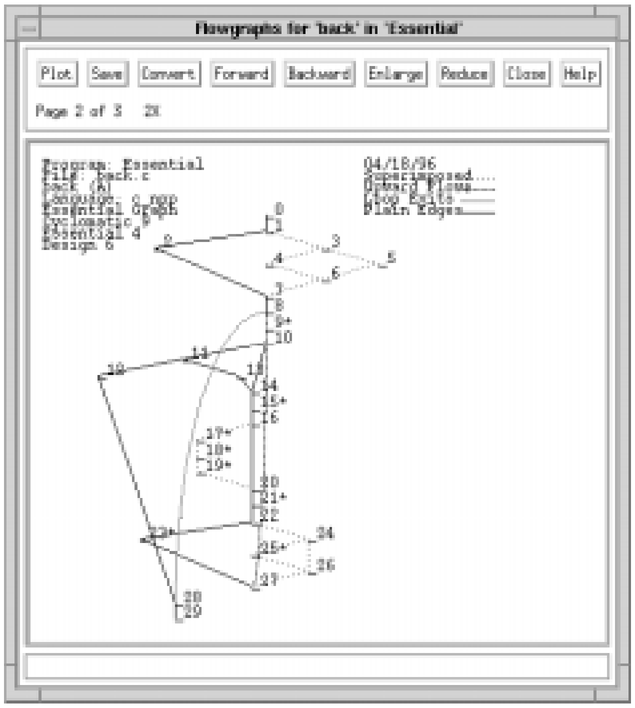
Figure 10-2. Essential complexity calculation example.

Figure 10-3 shows the source code for a module with cyclomatic complexity 9 and essential complexity 4. The essential complexity is caused by the conditional break out of the loop. Figure 10-4 shows the essential control flow graph for the same module, in which the unstructured logic is superimposed on the entire flow graph structure. This representation identifies the control structures that contribute to essential complexity.



[illegible]

Figure 10-3.Source code for module with v(G) = 9 and ev(G) = 4.



```
Program: Essential                04/18/96
File: back.c                      Superimposed
back (A)                          Upward Flows
Language: c_npp                   Loop Exits
Essential Graph                   Plain Edges
Cyclomatic 9
Essential 4
Design 6
```

Figure 10-4.Essential graph for module with v(G) = 9 and ev(G) = 4.

11 Maintenance

Maintenance is the most expensive phase of the software lifecycle, with typical estimates ranging from 60% to 80% of total cost [PRESSMAN]. Consequently, maintenance methodology has a major impact on software cost. “Bad fixes,” in which errors are introduced while fixing reported problems, are a significant source of error [JONES]. Complexity analysis can guide maintenance activity to preserve (or improve) system quality, and specialized testing techniques help guard against the introduction of errors while avoiding redundant testing.

11.1 Effects of changes on complexity

Complexity tends to increase during maintenance, for the simple reason that both error correction and functional enhancement are much more frequently accomplished by adding code than by deleting it. Not only does overall system complexity increase, but the complexity of individual modules increases as well, because it is usually easier to “patch” the logic in an existing module rather than introducing a new module into the system design.

11.1.1 Effect of changes on cyclomatic complexity

Cyclomatic complexity usually increases gradually during maintenance, since the increase in complexity is proportional to the complexity of the new code. For example, adding four decisions to a module increases its complexity by exactly four. Thus, although complexity can become excessive if not controlled, the effects of any particular modification on complexity are predictable.

11.1.2 Effect of changes on essential complexity

Essential complexity can increase suddenly during maintenance, since adding a single statement can raise essential complexity from 1 to the cyclomatic complexity, making a perfectly structured module completely unstructured. Figure 11-1 illustrates this phenomenon. The first flow graph is perfectly structured, with an essential complexity of 1. The second flow graph, derived from the first by replacing a functional statement with a single “goto” statement, is completely unstructured, with an essential complexity of 12. The impact on essential complexity may not be obvious from inspection of the source code, or even to the developer making the change. It is therefore very important to measure essential complexity before accepting each modification, to guard against such catastrophic structural degradation.

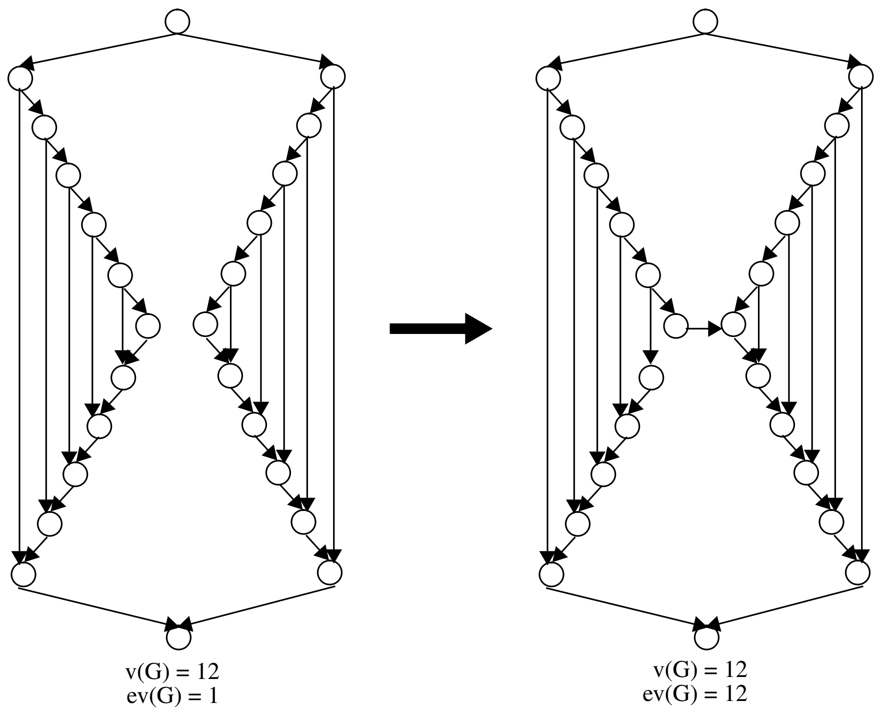


Figure 11-1.Catastrophic structural degradation.

11.1.3 Incremental reengineering

An incremental reengineering strategy [WATSON1] provides greater benefits than merely monitoring the effects of individual modifications on complexity. A major problem with software is that it gets out of control. Generally, the level of reengineering effort increases from simple maintenance patches through targeted reverse engineering to complete redevelopment as software size increases and quality decreases, but only up to a point. There is a boundary beyond which quality is too poor for effective reverse engineering, size is too large for effective redevelopment, and so the only approach left is to make the system worse by performing localized maintenance patches. Once that boundary is crossed, the system is out of control and becomes an ever-increasing liability. The incremental reengineering technique helps keep systems away from the boundary by improving software quality in the vicinity of routine maintenance modifications. The strategy is to improve the quality of poor software that interacts with software that must be modified during maintenance. The result is that software quality improves during maintenance rather than deteriorating.

11.2 Retesting at the path level

Although most well-organized testing is repeatable as discussed in section 11.4, it is sometimes expensive to perform complete regression testing. When a change to a module is localized, it may be possible to avoid testing the changed module from scratch. Any path that had been tested in the previous version and does not execute any of the changed software may be considered tested in the new version. After testing information for those preserved paths has been carried forward as if it had been executed through the new system, the standard structured testing techniques can be used to complete the basis. This technique is most effective when the change is to a rarely executed area of the module, so that most of the tested paths through the previous version can be preserved. The technique is not applicable when the changed software is always executed, for example the module's initialization code, since in that case all paths must be retested.

11.3 Data complexity

The *specified data complexity*, *sdv*, of a module and a set of data elements is defined as the cyclomatic complexity of the reduced graph after applying the module design complexity reduction rules from section 7.4, except that the "black dot" nodes correspond to references to data elements in the specified set rather than module calls. As a special case, the sdv of a module with no references to data in the specified set is defined to be 0. Specified data complexity is really an infinite class of metrics rather than a single metric, since any set of data elements may be specified. Examples include a single element, all elements of a particular type, or all global elements [WATSON3].

The data-reduced graph contains all control structures that interact with references to specified data, and changes to that data may be tested by executing a basis set of paths through the reduced graph. Specified data complexity can therefore be used to predict the impact of changes to the specified data.

One particularly interesting data set consists of all references to dates [MCCABE6]. The "Year 2000 Problem" refers to the fact that a vast amount of software only stores the last two digits of the year field of date data. When this field changes from 99 to 00 in the year 2000, computations involving date comparison will fail. Correcting this problem is already (in 1996) becoming a major focus of software maintenance activity. Calculating the "date complexity" (specified data complexity with respect to date references) helps determine the scope of the problem, and the corresponding "date-reduced" flow graphs can be used to generate test cases when the corrections are implemented.

11.4 Reuse of testing information

Although the technique described in section 11.2 can occasionally be used to reduce the regression testing effort, it is best to rerun all of the old tests after making modifications to software. The outputs should be examined to make sure that correct functionality was preserved and that modified functionality conforms to the intended behavior. Then, the basis path coverage of the new system induced by those old tests should be examined and augmented as necessary. Although this may seem like a tremendous effort, it is mostly a matter of good organization and proper tool selection.

Graphical regression testing tools and embedded system simulators facilitate test execution and functional comparison in the most difficult environments. Most non-interactive applications software can be tested effectively at the integration level with simple regression suites and a text comparison utility for outputs, tied together with system command scripts. At the module level, stub and driver code should certainly not be discarded after one use -- minimal extra effort is required to store it for automated regression purposes, although it must be kept current as the software itself is modified.

An automated coverage tool can determine the level of basis path coverage at each regression run, and indicate what further tests need to be added to reflect the changes to the software. The resulting new tests should of course be added to the automated regression suite rather than executed once and discarded. Some discipline is required to maintain regression suites in the face of limited schedules and budgets, but the payoff is well worth the effort.

When full regression testing is really impractical, there are various shortcuts that still give a reasonable level of testing. First is to keep "minimized" regression suites, in which only key functional tests and tests that increased basis path coverage on the original system are executed. This technique preserves most but not all of the error detection ability of the complete set of original tests, as discussed in Appendix B, and may result in a regression suite of manageable size. A possible drawback is that some of the original tests that were eliminated due to not increasing coverage of the original system might have increased coverage of the new system, so extra test cases may be needed. Another technique is to save the old coverage information for modules that have not changed, and fully test only those modules that have changed. At the integration level, calls to changed modules from unchanged modules can be tested using the incremental integration method described in section 7-6.

One final point about regression testing is that it is only as effective as the underlying behavior verification oracle. Too many otherwise comprehensive regression suites use unexamined (and therefore probably incorrect) output from the time when the suite was constructed as the standard for comparison. Although it may not be feasible to verify correctness for every test case in a large regression suite, it is often appropriate to have an ongoing project that gradually increases the percentage of verified regression outputs.

12 Summary by Lifecycle Process

This section gives a brief summary of the structured testing techniques during each process in a simplified software lifecycle.

12.1 Design process

Consider the expected cyclomatic complexity when partitioning functionality into modules, with a view towards limiting the complexity of each module to 10. Limiting the explicit complexity of modules in the design to 7 is usually sufficient. Estimate unit testing effort. Estimate the eventual integration complexity from the design. Plan high-level integration tests.

12.2 Coding process

Limit the cyclomatic complexity of modules to 10 wherever possible without violating other good design principles, and document any exceptions. Examine the control flow graphs of modules with essential complexity greater than 1 and improve the quality of their logic structure where feasible. Plan unit tests.

12.3 Unit testing process

Test a basis set of paths through each module. This can be done either by first running functional tests and then executing only the additional paths to complete basis path coverage, or by planning and executing a complete basis set of paths using the baseline method independently of functional testing. For modules for which a complete basis cannot be executed due to control flow dependencies, analyze those dependencies and either eliminate or document them. Build a unit level regression suite so that all tests are repeatable.

12.4 Integration testing process

Test a basis set of paths through the design-reduced control flow graph of each module, either by first running functional tests and then executing only the additional paths to complete coverage, or by using integration complexity to plan and execute a complete basis set of integration subtrees. Apply the incremental integration testing techniques at each stage of the overall integration strategy. For object-oriented systems, select a strategy for testing polymorphic call resolutions based on complexity analysis and subjective risk assessment, and apply the safety analysis technique to avoid unnecessary testing. Build an integration level regression suite so that all tests are repeatable. Take care to verify initial system behavior to the greatest feasible extent so that the error detection power of the regression suite is not wasted.

12.5 Maintenance process

Prevent sudden degradation of control structure quality by rejecting modifications that significantly increase essential complexity. Avoid increasing the cyclomatic complexity of modules beyond 10 whenever feasible. Use the incremental reengineering technique to improve overall system quality during routine modifications. Use data complexity analysis to assess the impact of potential data structure changes and guide testing of data changes. Perform full regression testing where feasible, otherwise select a shortcut technique to test the specific changed software.

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Appendix A. Related Case Studies

The structured testing methodology, including the testing techniques and related complexity metrics described in this document, is above all a *practical* tool to support effective software engineering. The vast majority of this document describes structured testing by using mathematics, examples, intuition, and theoretical analysis. This appendix provides empirical evidence by presenting several case studies from the software engineering literature.

Lloyd K. Mosemann III, while serving as Deputy Assistant Secretary of the Air Force (Communications, Computers, and Logistics), wrote:

> For many years, most of us have been guilty of throwing verbal rocks at those developing software metrics. We have denigrated their work on the basis that their products did not "fully" or "completely" measure such quantities as software size, structure, performance, and productivity. While we have been waiting for the perfect metrics we demand, however, we have been measuring almost nothing... I believe the time has come for us to cease our admiration of the metrics problem and to start implementing some metrics. [MOSEMANN]

Fortunately, complexity measurement has become a standard part of software engineering practice, and the metrics described in this document have gained wide acceptance. Cyclomatic complexity in particular is calculated in some form by nearly every commercial software complexity analysis product. The papers in this section are listed chronologically, from the earliest work in 1977 to the most recent in 1996. Most examine various uses of cyclomatic complexity in software development.

A.1 Myers

Myers [MYERS1] calculated cyclomatic complexity for the programs contained in the classic text by Kernighan and Plauger [KERNIGHAN]. For every case in which an improved program was suggested, this improvement resulted in a lower value of v(G). Myers describes one interesting case in which Kernighan and Plauger suggested two simplified versions of a program that has v(G) equal to 16. Myers found that both improvements resulted in a complexity value of 10.

A.2 Schneidewind and Hoffman

Schneidewind and Hoffman [SCHNEIDEWIND1] performed an experiment that related complexity to various error characteristics of software. They wrote:

The propensity to make programming errors and the rates of error detection and correction are dependent on program complexity. Knowledge of these relationships can be used to avoid error-prone structures in software design and to devise a testing strategy which is based on anticipated difficulty of error detection and correction. An experiment in software error data collection and analysis was conducted in order to study these relationships under conditions where the error data could be carefully defined and collected. Several complexity measures which can be defined in terms of the directed graph representation of a program, such as cyclomatic number, were analyzed with respect to the following error characteristics: errors found, time between error detections, and error correction time. Significant relationships were found between complexity measures and error characteristics. The meaning of directed graph structural properties in terms of the complexity of the programming and testing tasks was examined.

Based on this experiment we conclude that, for similar programming environments and assuming a stable programming personnel situation, structure would have a significant effect on the number of errors made and labor time required to find and correct the errors ... complexity measures serve to partition structures into high or low error occurrence according to whether the complexity measure values are high or low, respectively.

A.3 Walsh

Walsh [WALSH] collected data on the number of software errors detected during the development phase of the AEGIS Naval Weapon System. The system contained a total of 276 modules, approximately half of which had a v(G) less than 10 and half with v(G) of 10 or greater. The average error rate for modules with complexity less than 10 was 4.6 per 100 source statements, while the corresponding error rate for the more complex modules was 5.6. As Walsh pointed out, one would expect a similar pattern for undetected errors as well, so that less complex modules will have a lower error rate after delivery as well.

A.4 Henry, Kafura, and Harris

Henry, Kafura, and Harris [HENRY] reported empirical error data collected on the UNIX operating system. The authors obtained a list of errors from the UNIX Users Group and performed correlations with three metrics. The cyclomatic complexity was the most closely related to errors of the three—the correlation between v(G) and number of errors was .96.

A.5 Sheppard and Kruesi

Sheppard and Kruesi [SHEPPARD] examined the performance of programmers in constructing programs from various specification formats. An automated data collection system recorded the complete sequence of events involved in constructing and debugging the program. An analysis of the error data revealed that the major source of difficulty was related to the control flow and not to such factors as the number of statements or variables. The most difficult program had the most complex decision structure, while a considerably easier program performed extremely complex arithmetic calculations but had a simpler decision structure. Thus, v(G) can be used to measure a difficult aspect of programming.

A.6 Carver

Carver [CARVER] collected data on approximately 14,000 lines of code in order to study the change in complexity metrics from code initiation to code completion. Structured programming practices were followed and code reviews used in the generation of the code. The cyclomatic complexity values ranged from 8 to 78 for this code, with changes to v(G) averaging 35% with a median value of 25%, indicating that "approximately 1/3 of the control flow logic was added after code initiation. ...A percentage of 35% increase suggests that either the original designs were incomplete or the programmers implemented the designs in an unsatisfactory manner." The complexity metric variance investigation benefits include: "First, it is valuable for anticipating complexity increases during design so that proper module sizing can be addressed. Secondly, it provides input for measuring the completeness of the original design specification." The study concludes that complexity increases in the ranges noted indicate that designers must not only plan for growth, but also modularize the code to allow for controlled growth, otherwise modules will be implemented with unacceptable complexity levels.

A.7 Kafura and Reddy

A study was performed by Kafura and Reddy [KAFURA] that related cyclomatic complexity as well as six other software complexity metrics to the experience of various maintenance activities performed on a database management system consisting of 16,000 lines of FORTRAN code. The authors used a subjective evaluation technique, relating the quantitative measures obtained from the metrics to assessments by informed experts who are very familiar with the systems being studied. This was done to determine if the information obtained from the metrics would be consistent with expert experience and could be used as a guide to avoid poor maintenance work.

Changes in system level complexity for each of three versions were analyzed. After an analysis of the results of the metrics, the authors concluded that the "change in complexities over time agrees with what one would expect." Also noted was that the complexity growth curves "seemed to support the view that maintenance activities - either enhancements or repairs - impact many different aspects of the system simultaneously."

An observation made is that changes in procedure complexity can be monitored to question large changes in complexity that are not planned. The authors also note that developers tend to avoid changing very complex procedures during maintenance, even if the alternative changes lead to a degradation in overall design quality, and suggest that managers monitor the implementation of those changes.

A.8 Gibson and Senn

Gibson and Senn [GIBSON] conducted an experiment using COBOL code to investigate the relationship between system structure and maintainability, with the purpose of determining whether a set of six objective complexity metrics might offer potential as project management tools. They studied the effects when an old, badly structured system is “improved” and how the improvements impact maintainability. The objectives were to determine whether improvements in the system structure result in measurable improvements in programmer performance, whether programmers can discern system differences, and whether these system differences can be measured by existing, automated metrics.

While all six metrics appeared to be related to performance, the metrics were grouped into two sets of three metrics each. The cyclomatic complexity metric was in the set which provided “relative rankings consistent with relative time and the frequency of serious ripple effect errors”, while the other set was related more to the frequency of primary errors introduced with modifications. To address the first issue of the study, the average maintenance time did decrease when the system structure was improved, measured in terms of the effect of structure on time, accuracy, and confidence.

With respect to their second objective, the study revealed that structural differences were not discernible to programmers since programmers in the study could not separate out the complexity of the system from the complexity of the task being undertaken. The authors stated that this result “offers important evidence on the efficacy of subjectively based complexity metrics... The inspector's perceptions may not conform to those of the maintenance programmers, which may affect the predictive ability of subjective metrics over the life of the system.” It should be noted that cyclomatic complexity is not subjective.

The third objective dealt with the effect of system structure and metrics, and when the system structure was improved, cyclomatic complexity did indeed decrease. The authors conclude that “objectively based metrics might provide more reliable information for managers than subjectively based measures.”

A.9 Ward

Ward [WARD] studied two large-scale firmware projects at HP's Waltham Division that had a very low postrelease defect density. He found that approximately 60% of post-release defects had been introduced during the implementation phase, indicating that implementation improvements such as limiting complexity had the largest potential for quality improvement. Upon further investigation, he found that cyclomatic complexity had a .8 correlation with error density for the projects, and concluded that limiting complexity was a significant factor in software quality. He also reported successful usage of the baseline method to generate module test cases.

A.10 Caldiera and Basili

Caldiera and Basili [CALDIERA] conducted experiments by using software metrics to identify and "qualify" reusable software components from existing systems in order to reduce the amount of code that experts must analyze. The data consisted of 187,000 lines of ANSI C code, spanning 9 existing systems which represented a variety of applications. They used four metrics in their study, one of which was cyclomatic complexity. The reason for using cyclomatic complexity in their study was that, "The component complexity affects reuse cost and quality, taking into account the characteristics of the component's control flow. As with volume, reuse of a component with very low complexity may not repay the cost, whereas high component complexity may indicate poor quality - low readability, poor testability, and a higher possibility of errors. On the other hand, high complexity with high regularity of implementation suggests high functional usefulness. Therefore, for this measure we need both an upper and a lower bound in the basic model."

By using the metrics, the authors were able to identify candidates for code reuse. They determined that they could obtain satisfactory results using values that they calculated as extremes for the ranges of acceptable values. In this study, the upper bound for v(G) was 15.00 with a lower bound of 5.00. The authors concluded that "these case studies show that reusable components have measurable properties that can be synthesized in a simple quantitative model."

A.11 Gill and Kemerer

Gill and Kemerer [GILL] presented research that studied "the relationship between McCabe's cyclomatic complexity and software maintenance productivity, given that a metric which measures complexity should prove to be a useful predictor of maintenance costs." They conducted this study to specifically validate the cyclomatic complexity metric for use in software testing and maintenance. The project analyzed approximately 150,000 lines of code from 19 software systems, comprising 834 modules of which 771 were written in Pascal and 63 in FORTRAN. The authors wrote:

> Knowledge of the impact of cyclomatic complexity on maintenance productivity is potentially more valuable than that of NCSLOC [noncomment source lines of code], because managers typically do not have a great deal of control over the size of a program since it is intimately connected to the size of the application. However, by measuring and adopting complexity standards and/or by using CASE restructuring tools, they can manage unnecessary cyclomatic complexity.

The data from this study supported previous research regarding the high correlation between cyclomatic complexity and NCSLOC. The authors extended the idea of cyclomatic complexity to “cyclomatic density”, which is the ratio of the module's cyclomatic complexity to its length in NCSLOC. The intent is to factor out the size component of complexity. It has the effect of normalizing the complexity of a module, and therefore its maintenance difficulty. The density ratio was tested in this research and “shown to be a statistically significant single-value predictor of maintenance productivity.”

A.12 Schneidewind

Schneidewind performed a validation study [SCHNEIDEWIND2], the purpose being to determine whether cyclomatic complexity and size metrics could be used to control factor reliability (represented as a factor error count), either singly or in combination. A factor is a quality factor, “an attribute that contributes to its quality, where software quality is defined as the degree to which software possesses a desired combination of attributes.” The data used in the study was collected from actual software projects consisting of 112 total procedures, of which 31 were known to have errors, and 81 with no errors. The Pascal language was used for the 1,600 source code statements that were included in the study.

One of the statistical procedures used was a chi-square test, to determine whether cyclomatic complexity could discriminate between those procedures with errors (as in low-quality software) versus those without errors (a high-quality software). The misclassifications that were studied were divided into two groups: Type 1 misclassifications included procedures with errors that were classified as not having errors. The type 2 category was just the opposite: those modules without errors were classified as having errors. The study found that as cyclomatic complexity increases, Type 1 misclassifications increased because an increasing number of high complexity procedures, of which many had errors, were incorrectly classified as having no errors. However, as cyclomatic complexity decreased, Type 2 misclassifications increased, because an increasing number of low complexity procedures, many having no errors, were incorrectly classified as having errors.

The most significant v(G) threshold for error prediction in this study was at v(G) <= 3, meaning that 3 would be used as a critical value of cyclomatic complexity to discriminate between components containing errors and those that do not. (This value was supported by plotting points, as well as by the chi-square test.) Correctly classified were 75 of the 81 procedures containing no errors, and 21 of the 31 procedures known to have errors. A similar analysis was performed on source code size for these procedures, with an optimal value of 15 being found. The author concludes that size and cyclomatic complexity are valid with respect to the "Discriminative Power" criterion, and either could be used to distinguish between acceptable and unacceptable quality for the application studied and similar applications. Although the author's focus was more on the validation technique than the specific validation study, it is interesting that the thresholds for both complexity and size were found to be much less than those in common usage.

The author notes that quality control "is to allow software managers to identify software that has unacceptable quality sufficiently early in the development process to take corrective action." Quality could be controlled throughout a component's life cycle, so that if v(G) increased from 3 to 8 due to a design change, it could indicate a possible degradation in quality.

A.13 Case study at Stratus Computer

Cyclomatic and essential complexity were measured for a tape driver subsystem before and after a reengineering project. The new version was significantly less complex than the original. Twelve months after release, a follow-up study showed that fewer than five serious or critical errors had been discovered in the new software, a dramatic increase in reliability over the original system. Based on this result, complexity analysis was recommended as part of the design process. [GEORGE]

A.14 Case study at Digital Equipment Corporation

The relationship between defect corrections in production software and both cyclomatic complexity and the number of lines of code was studied. Defect corrections were used since they map defects to individual source modules in an objectively measurable way. Defect corrections were more strongly correlated with cyclomatic complexity than with the number of lines of code.

The correlation between complexity and defect corrections was also investigated when modules with complexity greater than 12 and modules with complexity less than 12 were considered separately. In the high-complexity subset, complexity had a definite correlation with defect corrections. However, there was little or no correlation in the low-complexity subset.

The suggested explanation is that other factors outweigh complexity as a source of error when complexity is low, but that the impact of complexity on defect occurrence is greater when complexity is high. [HEIMANN]

A.15 Case study at U.S. Army Missile Command

Automated analysis of cyclomatic complexity was used as part of several Independent Validation and Verification projects, and found to be more accurate and comprehensive than the manual methods for identifying overly complex software that had been previously used. Automated complexity analysis also yielded a significant reduction in cost. Based on the success of these projects, the same techniques were applied to other projects in various languages, including Ultra, Ada, C, C++, PL/M, and FORTRAN. [ROBERTS]

A.16 Coleman et al

A recent study was performed by Coleman, Ash, Lowther, and Oman [COLEMAN] to demonstrate how automating the analysis of software maintainability can be used to guide software-related decision making. The authors developed a four-metric polynomial, known as HPMAS (HP Multidimensional Assessment Model), in which cyclomatic complexity was one of the four metrics used. The data used to test and validate their model utilized actual systems provided by Hewlett-Packard and the Department of Defense which encompassed eleven software systems written in C for a Unix platform. They used their model to study three aspects of system maintenance: To study pre/postanalysis of maintenance changes (over 1,200 lines of code); to rank-order module maintainability (236,000 lines of code); and, to compare software systems (one system consisted of 236,275 lines of code and the other 243,273 lines). In each case, the model proved extremely useful.

The authors write that in each case,

> the results from our analysis corresponded to the maintenance engineers' "intuition" about the maintainability of the (sub)system components. But, in every case, the automated analysis provided additional data that was useful in supporting or providing credence for the experts' opinions. Our analyses have assisted in buy-versus-build decisions, targeting subcomponents for perfective maintenance, controlling software quality and entropy over several versions of the same software, identifying change-prone subcomponents, and assessing the effects of reengineering efforts.

A.17 Case study at the AT&T Advanced Software Construction Center

Various aspects of the structured testing methodology have been integrated into the overall development process, concentrating on code inspections and unit testing. The techniques helped control complexity of code, select code for inspection, and measure basis path coverage during unit testing. The development team also used complexity analysis to re-design overly complex modules, which reduced the unit testing effort. [BORGER]

A.18 Case study at Sterling Software

The cyclomatic, design, and essential complexity metrics as well as test coverage were applied to a successful large-scale prototyping effort. The project was part of the Air Force Geographical Information Handling System (AFGIHS), a 3 year, $3.5 million effort to produce an advanced prototype for transition to a full scale development to support Air Force requirements for geospatial display and analysis. Complexity analysis was used to monitor software quality, reduce risk, and optimize testing resources. [BOYD]

A.19 Case Study at GTE Government Systems

Cyclomatic and design complexity were included in a large-scale software metrics collection effort spanning many projects over an eight-year time period. Projects with similar cyclomatic and design complexity profiles were found to follow similar schedules, with respect to the amount of time spent on each development phase. Much of the development work involves the reengineering of legacy systems. Comparison of the cumulative complexity distribution of a legacy program with known programs in the metrics database is used to anticipate the development phases required to reengineer the legacy program. [SCHULTZ-JONES]

A.20 Case study at Elsag Bailey Process Automation

The cyclomatic and essential complexity metrics were used on a successful project that involved the development of application and communications interface software using a client/server architecture to provide bi-directional communications to digital systems. Complexity analysis helped identify potentially defective modules by pinpointing highly complex and unstructured code, based on pre-defined company and industry standards. Acquisition of this information early in the product release cycle helped minimize post-release maintenance costs. These techniques allowed the product verification efforts to be quantified and monitored. [VENTRESS]

A.21 Koshgoftaar et al

Koshgoftaar, Allen, Kalaichelvan, and Goel [KOSHGOFTAAR] performed a case study using a large telecommunications system that consisted of 1.3 million lines of code that was written in a language similar to Pascal. The authors applied discriminant analysis to identify fault-prone areas in a system prior to testing. They developed a model that incorporated cyclomatic complexity as one of the design product metrics. To evaluate the model's ability to predict fault-prone modules, they compared the quality of the predictions based on test data to the actual quality. The results were successful. The authors found that “design product metrics based on call graphs and control-flow graphs can be useful indicators of fault-prone modules... The study provided empirical evidence that in a software-maintenance context, a large system's quality can be predicted from measurements of early development products and reuse indicators.”

Appendix B. Extended Example

This appendix illustrates the structured testing technique of Chapter 5 for a module of significant complexity. The example is a C translation of the FORTRAN blackjack game program used in [NBS99] for the same purpose. No attempt has been made to improve the structural quality of the original version, and the error has been preserved. Section B.2 describes an experimental framework for comparison of test coverage criteria. Although structured testing does not guarantee detection of the error in the blackjack program, experimental results show that it is much more effective than branch coverage.

B.1 Testing the blackjack program

Since there are many variants on the blackjack rules, the following specification describes the rules being used for this example. The mechanics of the application of structured testing can be understood without reference to the details of the specification, but the specification is required to detect incorrect program behavior. The details of the "hand" module follow, as does the description of the testing process.

B.1.1 The specification

The program, as the dealer, deals two cards to itself and two cards to the player. The player's two cards are shown face up, while only one of the dealer's cards is shown. Both the dealer and the player may draw additional cards, which is known as being "hit." The player's goal is to reach 21 or less, but be closer to 21 than the dealer's hand—in which case the player wins. Ties go to the dealer. If the player's or the dealer's hand totals greater than 21, the hand is "busted" (a loss). The King, Queen, and Jack all count as 10 points. All other cards, except the Ace, count according to their face values. The Ace counts as 11 unless this causes the hand to be over 21, in which case it counts as 1.

If both the dealer and the player get Blackjack, which is a two-card hand totaling 21, it is a "push" (neither wins). Blackjack beats all other hands—if the player has Blackjack, he wins "automatically" before the dealer has a chance to take a hit. The player can also win automatically by having five cards without being busted. The player may take any number of hits, as long as the hand is not busted. The dealer must take a hit while the hand is less than or equal to 16, and must "stand" at 17.

B.1.2 The module

Figure B-1 shows the code for module “hand” from the blackjack program, which will be used to illustrate structured testing.

```
A0              int hand()
                {/* return win */
                    int d = 0, pace, dace;
                    int fHit;    /* 1 for hit, zero for not hit */
A1 A2 A3 A4 A5      p = 0; d = 0; pace = 0; dace = 0; win = 0;
                /* win will be 0 if dealer wins, 1 if player wins, 2 if a push */
A6 A7 A8 A9         hit(&p, &pace); hit(&d, &dace);
A10 A11 A12 A13     hit(&p, &pace); hit(&d, &dace);
A14                 count = 0;
A15 A16             printf("DEALER SHOWS ---  %d\n", cards[i-1]);
A17                 dshow = cards[i-1];
A18 A19             printf("PLAYER = %d, NO OF ACES - %d\n", p, pace);
A20                 if (p == 21) {
A21 A22                 printf("PLAYER HAS BLACKJACK\n");
A23                     win = 1;
                    } else {
A24                     count = 2;
                L11:
A25 A26                 check_for_hit(&fHit, p, count);
A27                     if (fHit == 1) {
A28 A29                     hit(&p,&pace);
A30                         count += 1;
A31 A32                     printf("PLAYER = %d, NO OF ACES - %d\n", p, pace);
A33                         if (p > 21) {
A34 A35                         printf("PLAYER BUSTS - DEALER WINS\n");
A36                             goto L13;
                            }
A37 A38                     goto L11;
                        }
A39 A40             }
                /* Handle blackjack situations, case when dealer has blackjack */
A41                 if (d == 21) {
A42 A43                 printf("DEALER HAS BJ\n");
A44                     if (win == 1) {
A45 A46                     printf("------ PUSH\n");
A47                         win = 2;
A48                         goto L13;
                        } else {
A49 A50                     printf("DEALER AUTOMATICALLY WINS\n");
A51                         goto L13;
A52                     }
                    } else {
                /* case where dealer doesn't have blackjack:
                 * check for player blackjack or five card hand
                 */
A53 A54                 if (p == 21 || count >= 5) {
A55 A56                     printf("PLAYER AUTOMATICALLY WINS\n");
A57                         win = 1;
A58                         goto L13;
                        }
A59 A60             }
A61 A62             printf("DEALER HAS %d\n", d);
                L12:
A63                 if (d <= 16) {
A64 A65                 hit(&d,&dace);
A66                     if (d > 21) {
A67 A68                     printf("DEALER BUSTS - PLAYER WINS\n");
A69                         win = 1;
A70                         goto L13;
                        }
A71 A72                 goto L12;
                    }
A73 A74 A75         printf(" PLAYER = %d  DEALER = %d\n", p, d);
A76                 if (p > d) {
A77 A78                 printf("PLAYER WINS\n");
A79                     win = 1;
                    } else
A80 A81 A82             printf("DEALER WINS\n");
                L13:
A83                 return win;
A84             }
```

Figure B-1. Code for example blackjack module “hand.”

Figure B-2 shows the graph for module "hand," which has cyclomatic complexity 11 and essential complexity 9. The high essential complexity makes the control structure difficult to follow. In such cases, the baseline method can be performed using the source listing as a guide, with paths represented by ordered lists of decision outcomes. Decisions are "flipped" exactly as in the graphical version of the method.

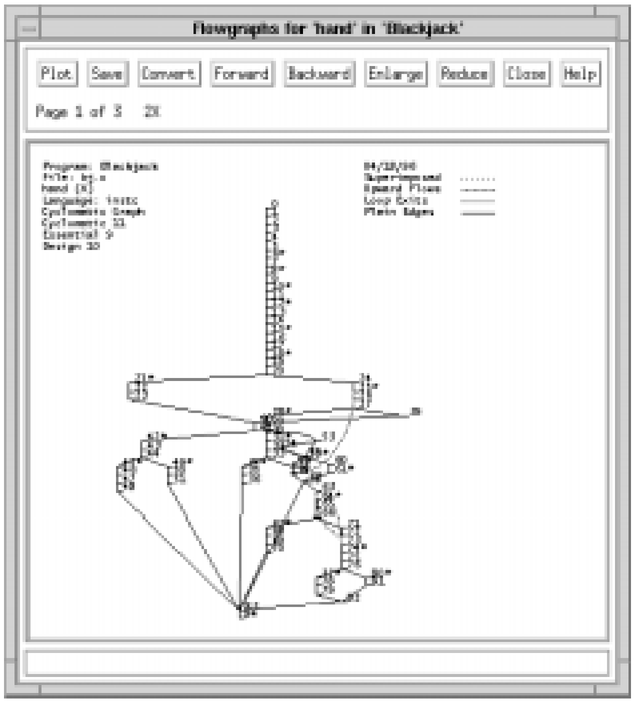

Figure B-2. Graph for module "hand."

The original blackjack testing example [NBS99] demonstrated the manual application of the baseline method in full detail, which will not be duplicated here. Instead, we follow the modern tool-assisted testing process, in which basis path coverage is built on a foundation of functional testing. We show that unrealizable test paths do not necessarily imply that rc < v(G) or that testing should cease, and we also demonstrate control dependency analysis as a test case derivation technique.

B.1.3 Tests through the module

Replacing the "hit" routine with a version that allows user input of the next card is sufficient to allow individual paths to be exercised. We now follow a typical structured testing process, beginning with functional tests while using an automated tool to measure ac. Input data derivation is simplified by first determining the meaning of all program variables used in decision expressions. The variable "p" holds the total value of the player's hand, and "d" holds the dealer's hand value. Those two variables are updated by the "hit" routine. The "fHit" and "win" variables are commented with their usage. When "fHit" is 1, the player or dealer has elected to hit, and a value of 0 means stand. A value of 0 for "win" means the dealer wins, 1 means the player wins, and 2 means there was a push. This is the value returned by the module. Finally, the variable "count" stores the total number of cards in the player's hand.

The first functional test is a "push," which can be exercised by having the replacement "hit" module first set p to 11 and pace to 1, then set d to 11 and dace to 1, then set p to 21 and leave pace at 1, then set d to 21 and leave dace at 1. We could also have exercised the same path by having "hit" set the contents of its first argument unconditionally to 21. However, it is best to make stub and driver modules conform to the specified behavior of the real modules that they replace, and in fact behave as realistically as possible. Since the input data derivation is straightforward, we omit it for the rest of the paths. Execution of this test does in fact show a push, the correct behavior. When discussing control flow paths, we use the notation "18(20): p==21 ==> TRUE" to indicate that the test on line 18 at node 20 with decision predicate "p==21" takes on the value "TRUE." The path executed by the first functional test is:

```
18(   20): p==21 ==> TRUE
37(   41): d==21 ==> TRUE
39(   44): win==1 ==> TRUE
```

The second functional test is blackjack for the player, in which the original deal leaves the player with 21 and leaves the dealer with an inferior hand. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> TRUE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> TRUE
```

The third functional test is blackjack for the dealer, in which the original deal leaves the player with less then 21, the player does not get hit, and the dealer has 21. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> TRUE
39(   44): win==1 ==> FALSE
```

The fourth functional test is a five-card win, in which the player accumulates five cards without going over 21 and the dealer was not dealt blackjack. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> TRUE
29(   33): p>21 ==> FALSE
25(   27): fHit==1 ==> TRUE
29(   33): p>21 ==> FALSE
25(   27): fHit==1 ==> TRUE
29(   33): p>21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> FALSE
51(   54): count>=5 ==> TRUE
```

The fifth functional test is a win for the player in which neither the player nor the dealer takes a hit, and neither has blackjack. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> FALSE
51(   54): count>=5 ==> FALSE
59(   63): d<=16 ==> FALSE
69(   76): p>d ==> TRUE
```

The sixth functional test is a win for the dealer in which neither the player nor the dealer takes a hit, and neither has blackjack. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> FALSE
51(   54): count>=5 ==> FALSE
59(   63): d<=16 ==> FALSE
69(   76): p>d ==> FALSE
```

The seventh functional test is a win for the dealer in which the player is busted. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> TRUE
29(   33): p>21 ==> TRUE
```

The eighth functional test is a win for the player in which the dealer is busted. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> FALSE
51(   54): count>=5 ==> FALSE
59(   63): d<=16 ==> TRUE
61(   66): d>21 ==> TRUE
```

The ninth functional test is a win for the dealer in which the player is hit to reach 21 and the dealer has blackjack. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> TRUE
29(   33): p>21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> TRUE
39(   44): win==1 ==> FALSE
```

This concludes our initial set of functional tests. No error has been detected yet, and each test increased ac by 1, so ac is now 9. The coverage analysis tool reports that one branch has not yet been executed, "61(66): d>21 ==> FALSE." This corresponds to the dealer taking a hit without being busted. Since branches are usually easier to test than paths, and testing a previously unexecuted branch must increase ac, we construct a new test for this branch immediately. The test makes the dealer win the hand by hitting once and then standing. Execution shows correct behavior. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> FALSE
51(   54): count>=5 ==> FALSE
59(   63): d<=16 ==> TRUE
61(   66): d>21 ==> FALSE
59(   63): d<=16 ==> FALSE
69(   76): p>d ==> FALSE
```

All branches have now been covered. No error has been detected yet, and ac is now 10. The coverage analysis tool reports that executing the following path would be sufficient to complete basis path coverage:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> TRUE
```

Unfortunately, this particular path is unrealizable, since the value of p is not altered between the mutually exclusive "30(13): p==21 ==> FALSE" and "62(44): p==21 ==> TRUE" decision outcomes. If the basis completion path had been realizable, we could have just derived the corresponding data, executed the test, and completed the testing process. For modules as poorly structured as "hand," however, unrealizable paths are fairly common, so it is important to be prepared for them. As discussed in section 9, the existence of unrealizable paths does not necessarily mean that rc < v(G). To help determine whether a realizable alternative path can complete basis path testing, we use the dependency analysis technique. The dependency analysis tool indicates that for every tested path, the total number of times branches "39(44): win==1 ==> TRUE" and "51(53): p==21 ==> TRUE" were executed is equal to the number of times branch "18(20): p==21 ==> TRUE" was executed. Note that for any single path, none of those three decision outcomes can be executed more than once and at most one of the first two can be executed. We may therefore rephrase the dependency equation in terms of the module's functionality: The player has blackjack if and only if either the result is a push or the player automatically wins with 21. Any test that does not satisfy this dependency relationship will be independent of the current set of tests and increase ac, in this case completing testing by making ac equal to v(G). On the other hand, if we can prove that the dependency must hold for every feasible test, then we have shown that rc < v(G). Fortunately, we can simplify the dependency even further, showing that rc = v(G) and giving a concise characterization of all feasible basis completion paths. Note that if the player has blackjack, the result must be either a push or an automatic win with 21 for the player. Also, there is no way to reach a push result without the player having blackjack. Thus, a test breaks the dependency relationship if and only if the player gets an automatic win with 21 without having blackjack. This is clearly possible for the module as written, for example by having the player reach exactly 21 after taking one hit. Execution of this test shows incorrect behavior—the module declares an automatic win for the player without giving the dealer a chance to take hits and win by also reaching 21. The specification states that the player can only win "automatically" with either Blackjack or a five-card hand. As expected, this test completes the basis set. The associated path is:

```
18(   20): p==21 ==> FALSE
25(   27): fHit==1 ==> TRUE
29(   33): p>21 ==> FALSE
25(   27): fHit==1 ==> FALSE
37(   41): d==21 ==> FALSE
51(   53): p==21 ==> TRUE
```

Note that in addition to providing a test that detected the error, dependency analysis clarified the nature of the error and gave a straightforward repair technique: replace the automatic win test "51(53): p==21" with "51(53): win==1," since at that point win==1 is precisely equivalent to the player having blackjack. If the error is repaired in this manner, there will be no way to break the dependency with a feasible path, and rc will therefore be reduced to 10.

Note also that structured testing is not guaranteed to detect the error, as can be seen from dependency analysis. If the player reaches exactly 21 after taking at least three hits, the error will not result in incorrect module output even though a dependency-breaking "incorrect" control flow path is executed. The reason is that there is no difference in specified behavior between an automatic win due to blackjack and an automatic win due to a five-card hand. Hence, the five-card hand masks the error. This is the only situation in which structured testing can fail to detect the error in the blackjack program, and as shown in section B-2 it is an extremely rare situation during actual play of the game.

B.2 Experimental comparison of structured testing and branch coverage

The "hand" module from section B-1 is one of several modules used in [WATSON4] to compare the error detection effectiveness of structured testing with branch coverage. The rest of this appendix discusses that work. Although neither testing technique is guaranteed to detect the error, structured testing performed dramatically better than branch coverage in the experiment, which used random test data generation to simulate actual play.

B.2.1 Experimental design

The overall experimental design was to package the test module with a driver program that accepts a random number seed as input, generates random test data from a realistic distribution, executes the test module with that data, analyzes the module's behavior, and returns an exit code indicating whether an error was detected. A higher-level driver invokes the module test driver with a sequence of seed values, uses an automated tool to measure the test coverage level according to each criterion being compared, and tracks both the error detection and the coverage results.

For both structured testing and branch coverage, 100 experimental trials were performed, in each of which random test cases were generated iteratively until the current testing criterion was satisfied. Four kinds of data were collected during each trial for the two testing criteria:

- Tests, the total number of tests executed until the criterion was satisfied
- Testsinc, the number of tests that increased coverage with respect to the criterion
- Detect, whether an error was detected during the trial
- Detectinc, whether an error was detected by a test that increased coverage

> There is an important distinction between considering all tests and just considering the ones that increased coverage. Considering all tests is essentially doing random testing while using the coverage criterion as a stopping rule. This may be appropriate when detecting incorrect program behavior is cheap, so that program behavior can be examined for each test. However, the criteria comparison information from such an experiment tends to be diluted by the effectiveness of the underlying random test data distribution. A criterion that requires more random tests is likely to detect more errors, regardless of the value of the specific test cases that contribute to satisfying the criterion. Therefore, we also consider just the tests that increase coverage. In that case, we factor out most of the influence of the underlying random test data distribution by in effect considering random minimal test data sets that satisfy each criterion. In addition to giving a more objective comparison, this more accurately models test effectiveness when detecting incorrect program behavior is expensive, so that program behavior can only be examined for tests that contribute to satisfaction of the test coverage criterion. [WATSON4]

B.2.2 Comparative frequency of error detection

Figure B-3 shows the data collected for the “hand” module during the experiment. Data about number of tests is averaged over the 100 trials. Data about error detection is added for the 100 trials, giving a convenient interpretation as a percentage of trials in which errors were detected by the criteria.

	Structured Testing	Branch Coverage
Tests	45	36
Testsinc	11	8
Detect	97	85
Detectinc	96	53

Figure B-3. Experimental data.

B.2.3 Interpretation of experimental data

Structured testing decisively outperformed branch coverage at detecting the error while requiring only 25% more total tests and 38% more tests that increase coverage. The most notable feature of the data is the robustness of structured testing with respect to test set minimization. Only 1% of the error detection effectiveness of structured testing was lost when considering only tests that increased coverage, whereas the number of tests required was reduced by 75%. For branch coverage, 38% of error detection effectiveness was lost, and the number of tests required was reduced by 78%. This indicates that the effectiveness of structured testing is due to the criterion itself rather than just the number of tests required to satisfy it. For the complete set of test programs used in [WATSON4], structured testing preserved 94% of its error detection effectiveness when restricted to the 24% of test cases that increased coverage.