Software Testing and Evaluation

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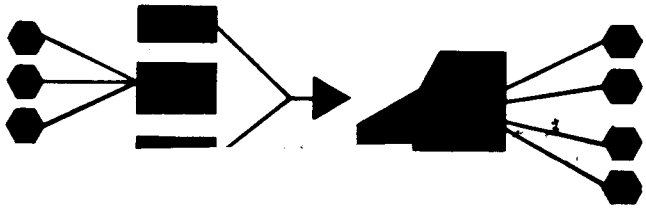

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Preface

This book is an updated and edited version of the report of the Software Test and Evaluation Project to the Office of the Secretary of Defense (Research and Engineering). This report received wide circulation as a Technical Report issued by the Georgia Institute of Technology. While planning for a major revision and eventual publication of the report in book form, we continued to receive many requests for copies of the original document. Bill Riddle -- then Chairman of the ACM Special Interest Group in Software Engineering -- and Alan Apt of Benjamin Cummings were instrumental in persuading us that rapid publication of a slightly revised version would be a service to the community. The present volume is the result.

The Software Test and Evaluation Project (STEP) was initiated in 1981 by the Director Defense Test and Evaluation.† The primary objective of STEP was (and remains) the development of improved policy and guidance for use by the U.S. Department of Defense for the test and evaluation of computer software for so-called "mission-critical" applications. Our group at Georgia Tech was selected to develop and execute a plan for carrying out these improvements. As the project unfolded over the next three years, it became increasingly clear that the results had broad applicability in two directions. First, we were being called upon to develop a methodology for "technology transition" -- the rapid identification, demonstration and introduction to practical use of cutting-edge technologies in environments where they were critically needed. In the area of computer software (for commercial as well as mission-critical applications) it seemed to us that a structured approach to transitioning new technology into practical use might be useful in a variety of applications

† In 1984, special legislation of the U.S. Congress resulted in a reorganization of test and evaluation offices within the Department of Defense. Specifically, a Director of Operational Test and Evaluation was appointed to parallel the Development and Engineering Test and Evaluation carried out by the Office of the Undersecretary of Defense for Research and Engineering (Defense Test and Evaluation). In 1986, the principal office charged with these responsibilities was redesignated Deputy Undersecretary of Defense (Test and Evaluation). It is this latter office that oversees and directs STEP at the present time.

and settings.

Second, the approach which we settled upon -- the development of State-of-the-Art and State-of-Practice overviews -- turned out to be rich with generic technology and technology assessments. These overviews contained brief descriptions of major test methodologies, catalogs of automated tools to support them, essentially exhaustive bibliographies, case studies of good and bad examples of software testing and exegeses of major standards. With the exception of those materials that specifically addressed Military standards and regulations (reflecting the status of these documents in 1983), such overviews can be read and applied to any large-scale software engineering effort in which the test and evaluation of software effectiveness and suitability are major activities.

The context of these results is important. At the time that STEP was initiated, the role of software in escalating the cost and driving down the reliability of systems had become very visible. Virtually, every major Defense system planned or fielded over the previous decade contained at least one subsystem consisting of an embedded computer controlling some mission-critical function. Although hardware and software contributed in equal measure to the successful implementation of system functions, relative imbalances in their treatment during system development had long been observed. In 1974, for example, a Task Force of the Defense Science Board noted: "whereas the hardware development was monitored, tested and regularly evaluated, the software development was not." These findings were repeated in 1979. In 1980 and 1981, the U.S. Secretary of Defense (in his reports to Congress and the Military Services) directed the Armed Forces to "...give priority to development of tools and techniques for testing of embedded computers and software." He further directed that "Testing of software should be sufficient to achieve a balanced risk with the hardware of the same system."

The approach upon which we settled involved constructing two "snapshots". The first of these comprised a view of the sort of testing that could be supported by the state-of-the-art. This was essentially our view of what a technologically ideal world of software testing was capable of supporting. The second snapshot was a picture of current practices. There are methodological difficulties in constructing an overview of practices in a setting as vast as the U.S. Defense industry. Not the least among these are the many programs and organizations to be sampled and the lack of long-term institutional memory. However, by carefully selecting representative programs, organizations, and applications and by religiously adhering to strict data-gathering protocols an assessment of current practices emerged that we believe represents a composite view of how mission-critical software is actually tested. The technology shortfall -- the difference between what the ideal world would support and what was actually available to engineers -- was the gap to be closed.

Institutional forces within the Department of Defense and the Defense-related industries have responded encouragingly.

There are several keys to the success of this approach. We were at the outset in full agreement with the project sponsors that this was not to be a study in which sufficient "data" were gathered to support a previously identified conclusion. We were given sufficient resources and access to sufficiently many organizations to derive an objectively supportable assessment of what the true needs were. We were also encouraged to provide "top-down" recommendations to effect improvements. That is, for those instances in which the system development process needed to be modified, we were not discouraged from recommending such modifications.

The need for these improvements has scarcely diminished in the intervening five years. Software has assumed critical (often life-critical) roles in non-military applications ranging from telecommunications to civilian air traffic control. In the Defense sector, command and control, ballistic missile defense, and avionics are but three of the many mission areas in which software is the dominant source of system functionality (and, therefore, risk). The planned and disciplined engineering of software destined for these sorts of applications is, of course, essential. Part of any such engineering process is a technologically sound approach to testing.

Such an approach will incorporate:

- A chain of test plans and procedures that begins at the topmost levels of system development and proceeds through the most detailed levels.
- The use of varied software testing technologies employing automated tools and techniques that are appropriate to the criticality of the application.
- A system of reporting test results and deficiencies that supports objective evaluations of software system status.
- An effective decision-making apparatus, capable of incorporating evaluations of software status into overall assessments of risk associated with the development and eventual fielding of the system.

We intend this volume to be a sourcebook out of which such an approach can be constructed.

Many people have contributed to STEP since its inception. Charles Watt was Deputy Director Defense Test and Evaluation throughout most of the project and provided technical direction and leadership. Donald Greenlee (Deputy Director Operational Test and Evaluation, at this

writing) provided day-to-day oversight and guidance. In addition to their project management roles, both of them contributed technically in substantial ways. Edith Martin helped structure the technology transition methodology in its early stages. Control Data Corporation provided early technical support services, and the National Security Industrial Association (NSIA) provided technical forums for disseminating STEP results. Researchers at Georgia Tech who contributed to the effort include Sinasi Bilsel, Michael Merritt, and E. Pipat. Fred Sayward contributed substantially to the preparation of the STEP reports. Rena Faye Smith aided in the data gathering effort and helped compile much of the material in the overview of current practices. Jackson Dodsworth and Esther Richards entered most of the original manuscript. We gratefully acknowledge the contributions of all of these individuals.

This manuscript was typeset on an Imagen Laser Printer in the School of Information and Computer Science at Georgia Tech using Unix† document preparation tools. Figures and illustrations were developed on a Hewlett-Packard 9845C Graphics system in the Software Engineering Research Center. Ann Richliew and Glenn Barry provided invaluable assistance, for which we are grateful.

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† Unix is trademark of AT&T Bell Laboratories.

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Part I

State-of-the-Art Overview

Chapter 1

Definitions and Theory of Testing

1.1 Program Specification and Correctness

When asked to give a reason for testing a computer program, typical programmers respond, "To see if it works." In practice, the notion of a "working" program is a complex one which takes into account not only the technical requirements of the programming task but also economics, maintainability, ease of interface to other systems and many other less easily quantifiable program characteristics. As these characteristics become more complex, testing to see if a particular piece of software has those characteristics becomes more difficult. The technical literature on program testing tends to deal with "working" in one simplified disguise: *correctness*.

For most of this overview, we will consider the following (simplified) model of the program development cycle (see Figure 1.1).

At the start of the programming task, the programmer is supplied with a *specification* of the program. The specification may be as formal as a document which details the intended behavior of the program in all possible circumstances or it may be as informal as a few instances of what the program is intended to do. In practice, the programmer has available to him several sources of information which comprise the specification. These may include a formal specification document, a working prototype, instances of program behavior, and a priori knowledge about similar software. All of these sources contribute to the programmer's understanding of the task.

Working from this specification, the programmer develops the software. The test -- or, more generally, validation -- of the software lies in the comparison of the software product with the specification of intended behavior.

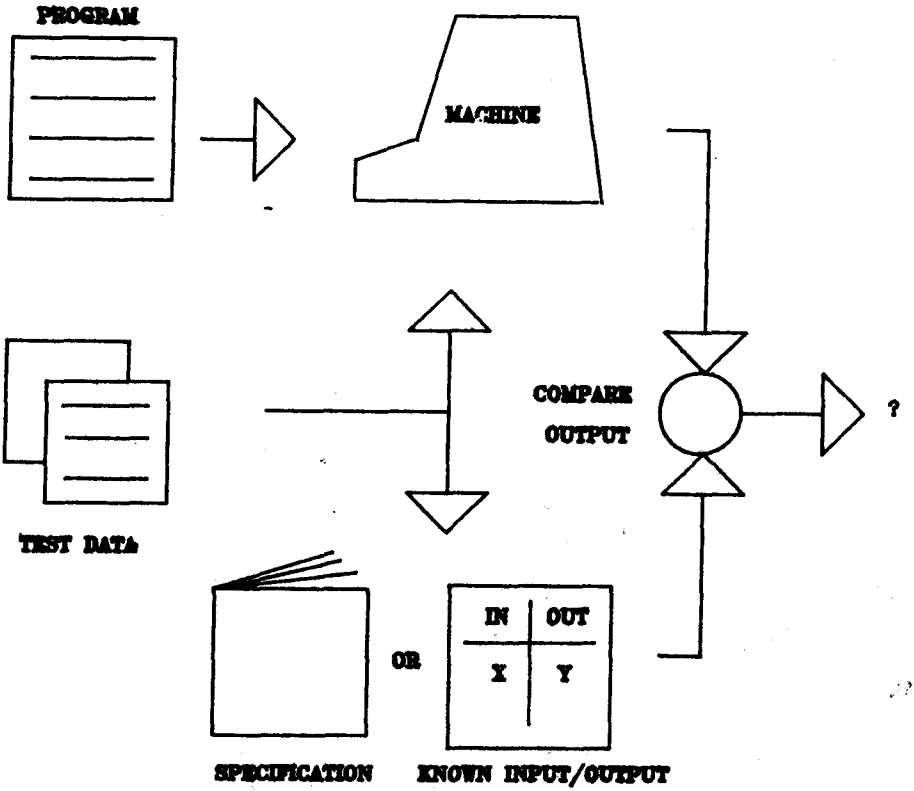

Figure 1.1. Testing for Correctness

For most of this overview, we will not be concerned with the exact nature of specifications. The examples we give will be small and understandable. For instance, the specification of a sorting program might be the following:

INPUT: up to 10,000 input records in the format (KEY1, KEY2, VALUE).

OUTPUT: a reordering of the input records with the following properties:

(1) the primary (KEY1) keys should appear in ascending order,

(2) if two records $R1$ and $R2$ have equal primary keys and if $R1$ precedes $R2$ in the input sequence, then $R1$ precedes $R2$ in the output.

Additional information could have been added to this specification. It could be required, for example, that the sorting program satisfy some performance criteria or that some standard interface conventions be followed.

Practical situations hardly ever give rise to such "clean" specifications. Much research has been devoted to the problem of specifying large and complex software systems [see references 1,3,6,8,12,15]. For our discussion of software testing research, we will not need to be more precise about the nature of program specification.

A specification provides a description of the input data for the program. This input data is called the *domain* of the program and is usually represented by D. The specification also provides a description of the intended behavior of the program on D. We will represent the intended behavior on input data d by $f(d)$. In practice, $f(d)$ may be quite complex.

Similarly, a program P represents some computational actions which will take place when the program is supplied with input data. Even though these actions may be quite complex, we will simplify things considerably by representing the behavior of program P by P^*. Thus, $P^*(d)$ is a mathematical idealization of the behavior of program P on data item d.

The shorthand notation $f(D)$ and $P^*(D)$ is used to represent the intended behavior on all input data and the behavior of P on all input data, respectively.

The program P is said to be *correct* with respect to a specification f if $f(D) = P^*(D)$, that is, if P's behavior matches the intended behavior on all input data.

A problem arises in practical applications of the mathematical theory. How is it possible to determine whether or not $f(d) = P^*(d)$ for some particular datum d in the domain? If the specification document is completely formal, then it should also answer this question. However, specification documents are hardly ever completely formalized (even when they are, determining $f(d)$ may be infeasible). When the specification is not formalized, $f(d)$ may be obtained by hand calculation, textbook requirements or by the application of estimates obtained from