Software Faults in Evolving a Large, Real-Time System: a Case Study

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Abstract

We report the results of a survey about the software faults encountered during the testing phases in evolving a large real-time system. The survey was done in two parts: the first part surveyed all the faults that were reported and characterized them in terms of general categories of faults; the second part surveyed in depth the faults found in the design and coding phases. For the first part, we describe the general faults found and characterize the requirements, design and coding faults by the testing phases in which they were found and how they were found over time during the testing phases. For the second part, we describe the questionaire used to survey the design and coding faults, report the faults that occurred, how difficult they were to find and to fix, what their underlying causes were (that is, what their corresponding errors were), and what means might have prevented them from occurring; we then characterize the results in terms of interface and implementation faults.

Keywords: Software fault analysis; large-scale, real-time system case study; design and coding faults; interface and implementation faults; effort to find/fix faults; underlying causes of faults; means of fault prevention.

1. Introduction

Far too little attention has been given to the empirical foundations of software engineering. We software engineers, as a group, try the latest techniques and tools with little attention, either before hand or afterwards, to their projected or actual effects. We propose research solutions to the building and evolving of software systems with virtually no empirical basis, with little more than an intuition of what the ''real'' problems are. We build and evolve systems, but spend little time measuring either the process or the product. Or if we do measure the process, we make little use of the resulting information. We make even less use of it as a source of ideas for software engineering research.

It is surprising that so few studies have appeared in the software engineering literature, especially since the monitoring of the mistakes we make is one of the fundamental tools by which we improve our process and product. This is particularly true for the development of large systems. In preceding work [13, 14], Perry and Evangelist reported the prevalence of interface faults as a major factor in the development and evolution of a large real-time system (68% of the faults). One of the main purposes of this software fault study was to indicate the importance of tools (such as the Inscape Environment [16]) that manage interfaces and the dependencies on those interfaces .

Prior to this work, Endress [7], Schneidewind and Hoffman [19], and Glass [8] reported on various fault analyses of software development, but did not delineate interface faults as a specific category. Thayer, Lipow and Nelson [20] and Bowen [5] provide extensive categorization of faults, but with a relatively narrow view of interface faults. Basili and Perricone offer the most comprehensive study of problems encountered in the development phase of a medium-scale system, reporting data on the fault, the number of components affected, the type of the fault, and the effort required to correct the fault. Interface faults were the largest class of faults (39% of the faults).

The purpose of this paper is to three-fold: first, to provide a data point on software (interface and implementation) faults encountered in the evolution (that is, what is often called the maintenance phase, not the initial development phase) of a very large real-time system; second, to provide a deeper understanding of those faults in terms of the effort required to find and fix them, their underlying causes, and their means of prevention; and third, to gain insight into the kinds of tools and techniques that we need to support an evolutionary software process [16].

In section 2, we provide the background for the study, describing the system in general terms, the methodology employed in evolving the system, and the approach we used in conducting the survey. Section 3 reports the overall Modification Request (MR) survey, providing first a summary of the questionnaire, then a summary of the results, and finally some conclusions drawn from this part of the study. Section 4 presents the design and coding fault survey, providing first a summary of the questionnaire, then a discussion of the statistical analysis, and finally a summary relating the results to interface faults. Finally, in section 5, we present our summary, conclusions and recommendations.

2. Background

The system discussed in this paper is a very[1] large scale, distributed, real-time system written in the C

[1] By ''very large'', we mean a system of 1,000,000 lines or more [4]. AT&T has a wide variety of such very large systems.

programming language in a Unix-based, multiple machine, multiple location environment.

The organizational structure is typical with respect to AT&T projects for systems of this size and for the number of people in each organization. Not surprisingly, different organizations are responsible for various parts of the system development: requirements specification; architecture, design, coding and capability testing; system and system stability testing; and alpha testing.

The process of development is also typical with respect to AT&T projects of this size. Systems Engineers prepare informal and structured documents defining the requirements for the changes to be made to the system. Designers prepare informal design documents that are subjected to formal reviews by three to fifteen peers depending on the size of the unit under consideration. The design is then broken into design units for low level design and coding. The products of this phase are subjected both to formal code reviews by three to five reviewers and to low level unit testing. As components are available, integration and system testing is performed until the system is completely integrated.

The release considered here is a ''non-initial'' release — one that can be viewed as an arbitrary point in the evolution of this class of systems. Because of the size of the system, the system evolution process consists of multiple, concurrent releases — that is, while the release dates are sequential, a number of releases proceed concurrently in differing phases. This concurrency accentuates the inter-release dependencies and their associated problems. The magnitude of the changes (approximately 15-20% new code for each release) and the general make-up of the changes (bug-fixes, improvements, and new functionality, etc.) are generally uniform across releases. It is because of these two facts that we consider this study to provide a representative sample in the life of the project. This relative uniformity of releases contrasts with Lehman and Belady [10] where releases alternated between adding new functionality and fixing existing problems.

Faults discovered during testing phases are reported and monitored by a modification request (MR) tracking system (such as for example, CMS [18]). Access to source files for modification is possible only through the tracking system. Thus all change activity is automatically tracked by the system. This activity includes not only repairs but enhancements and new functionality as well. It should be kept in mind, however, that this fault tracking activity occurs only during the testing and released phases of the project, not during the architecture, design and coding phases. Problems encountered during these earlier phases are resolved informally without being tracked by the MR system.

The goal of this study was to gain insight into the current process of system evolution by concentrating on one release of a particular system. The approach we used is that of surveying, by means of a prepared questionnaire, those who ''owned'' the MR at the time it was closed, surveying first the complete set of faults and then concentrating on the largest set of faults in more depth. This survey was the first of its type, although there have been some smaller studies using random selections. The survey data was then used in conjunction with data from the MR tracking system database.

Some caveats should be kept in mind while reviewing our results:

- In both phases, approximately 68% of questionnaires were returned — that is, we have data on about two-thirds of the MRs in both the overall survey and in the design/coding survey. Given the circumstances under which the survey was taken, this level of response exceeded our best expectations. Even so, there is still some room for questions about the representativeness of the responses. We know of no existent factor (such as reporting only the hard or easy problems, receiving reports from only junior or senior programmers, etc.) that would skew the results significantly [1].

- Given the standard development schedule pressures, the survey was mandated to be non-intrusive. The responses were to be voluntary and anonymous and no manual checks were allowed. Because of this management mandate, we were unable to validate the results [3] and are unable to assess the accuracy of the responses. Mitigating the lack of validation are two facts: first, the questionaire was created by the authors working with a group of developers; second, the questionaire was reviewed by an independent group of developers.

- While we tried very hard to provide a neutral questionnaire, we have noticed a few things that we could have done differently. Some of the results may be skewed slightly by the predisposition of the questionnaires (for example, the ordering of the possible faults where a more general fault earlier in the list might subsume a more particular fault later in the list).

- The survey was not an integral part of the evolution cycle, but occurred after the release was completed. Thus, the responses report remembered solutions that may be different from those responses that one would give if the facts were ‘‘fresh’’ — that is, some information may be inadvertently incorrect because the survey occurred anywhere from one to nine months after the MRs were fixed.

- Because the facts may not have been ‘‘fresh’’ in the minds of those taking part in the survey and because there were a limited number of choices, the respondents were, in some cases, forced to make ‘‘judgment calls’’ about their responses — that is, where it was not immediately clear what the correct choice was, the respondent had to choose what he or she considered to be the most appropriate answer.

- The overall proportions of the faults may be affected by the fact that data is only kept during the testing phase of evolution. MRs for the entire process from the receipt of the requirements to the release of the system would, of course, give a much more accurate picture.

- The sample size is large, but due to the proprietary nature of the data we cannot be more specific. However, we have been as precise as is justifiably possible.

It is with this background that we present our surveys, analyses, and results.

3. Overall Survey

There were three specific purposes in the original, overall survey:

- to determine, generally, what kinds of problems were found (which we report here) as well as, specifically, what kinds of application problems arose during the preparation of this release (which we do not report because of their lack of generality);

- to determine how the problem was found (that is, in which testing phase); and

- to determine when the problem was found.

In the discussion that follows, we first present a summary of the questionnaire, summarize our results, and draw some conclusions.

3.1 Summary of Questionnaire

The survey questionnaire had two main components: the determination of the fault reported in the MR and the testing phase in which the fault was found. In determining the fault, two aspects were of importance: first, the development phase in which the fault was introduced, and second, the particular type of the fault. Since the particular type of fault reported at this stage of the survey tended to be application or methodology specific, we have emphasized the phase-origin nature of the fault categorization. The general fault categories are as follows:

- *Previous* — residual problems left over from previous releases;
- *Requirements* — problems originating during the requirements specification phase of development;
- *Design* — problems originating during the architectural and design phases of development;
- *Coding* — problems originating during the coding phases of development;
- *Testing Environment* — problems originating in the construction or provision of the testing environment (for example, faults in the system configuration, static data, etc);
- *Testing* — problems in testing (for example, pilot faults, etc);
- *Duplicates* — problems that have already been reported;
- *No problems* — problems due to misunderstandings about interfaces, functionality, etc., on the part of the user;
- *Other* — various problems that do not fit neatly in the preceding categories such as hardware problems, etc.

The other main component of the survey concerned the phase of testing that uncovered the fault. The following are the different testing phases.

- *Capability Test* (CT) — testing isolated portions of the system to ensure proper capabilities of that portion.
- *System Test* (ST) — testing the entire system to ensure proper execution of the system as a whole in the laboratory environment.
- *System Stability Test* (SS) — testing with simulated load conditions in the laboratory environment for extended periods of time.
- *Alpha Test* (AT) — live use of the release in a friendly user environment.
- *Released* (RE) — live use. However, in this study, this data refers not to this release, but the previous release. Our expectation is that this provides a projection of the fault results for this release.

The time interval during which the faults were found (that is, when the MRs were initiated) was retrieved from the MR tracking system database.

Ideally, the testing phases occur sequentially. In practice, however, due to the size and complexity of the system, various phases overlap. The overlap is due to several specific factors. First, various parts of the system are modified in parallel. This means that the various parts of the system are in different states at any one time. Second, the iterative nature of evolution results in recycling back through previous phases for various parts of the system. Third, various testing phases are begun as early as possible, even though it is known that that component may be incomplete. Looked at in one way, testing proceeds in a hierarchical manner: testing is begun with various pieces, then subsystems and finally integrating those parts into the complete system. It is a judgment call as to when different parts of the system move from one phase to the next determined primarily by the percentage of capabilities incorporated and the number of tests executed. Looked at in a slightly different way, testing proceeds by increasing the size and complexity of the system, while at the same time increasing its load and stress.

3.2 Summary of Results

We present the summary of each fault category and discuss some of the main issues that stem from these results. Next we summarize the requirements, design and coding faults first as found by testing phase and then as found by time interval.

3.2.1 Summary of Responses

Table 1 presents the summary of the MRs by category.

TABLE 1. Summary of Faults

MR Categories	Proportion
Previous	4.0%
Requirements	4.9%
Design	10.6%
Coding	18.2%
Testing Environment	19.1%
Testing	5.7%
Duplicates	13.9%
No problems	15.9%
Other	7.8%

‘‘Previous’’ MRs indicate the level of difficulty in finding some of the faults in a large, real-time system. These problems may have been impossible to find in the previous releases and have only now been exposed because of changes in the use of the system.

The MRs representing the earlier part of the development or evolution process (that is, those representing requirements, design and coding) are the most significant, accounting for approximately 33.7% of the MRs. Given that the distinction between a design fault and a coding fault was one of those which required a ‘‘judgment call’’ on the part of the respondent, we decided to merge the results of those two categories into one: design/coding faults account for 28.8% of the MRs. However, in the process structure used in the project, the distinction between requirements and design/coding is much clearer. Requirements specifications are produced by systems engineers while the design and coding are done by developers.

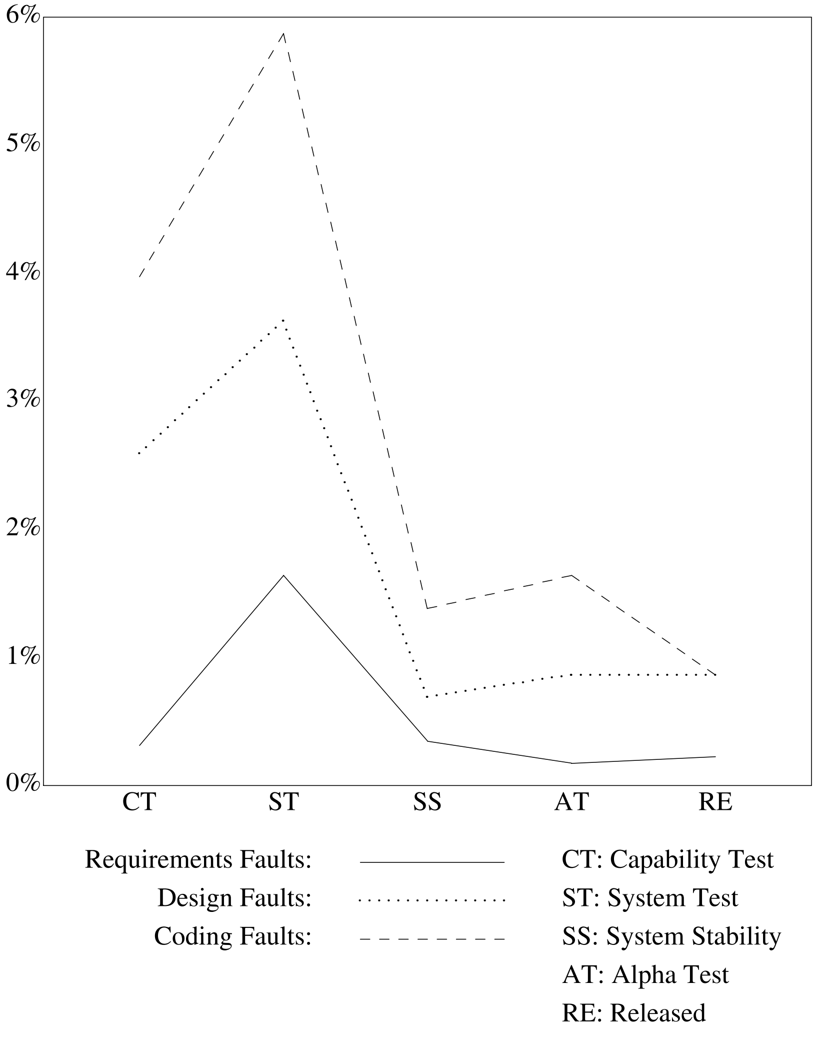
The next most significant subset of MRs were those that concern testing (the testing environment and testing categories) — 24.8% of the MRs. On the one hand, it is not surprising that a significant number of problems are encountered in testing a large and complex real-time system where conditions have to be simulated to represent the ‘‘real-world’’ in a laboratory environment. First, the testing environment itself is a large and complex system that must be tested. Second, as the real-time system evolves, so must the laboratory test environment evolve. On the other hand, this general problem is clearly one that needs to be addressed by further study.

‘‘Duplicate’’ and ‘‘No Problem’’ MRs account for another significant subset of the data — 28.9%. Historically, these have been considered to be part of the overhead. Certainly the ‘‘duplicate’’ MRs are in large part due to the inherent concurrency of activities in a large-scale project and, as such, are difficult to eliminate. The ‘‘no problem’’ MRs, however, are in large part due to the lack of understanding that comes from informal and out-of-date documentation. Obviously, measures taken to reduce these kinds of problems will have beneficial effects on other categories as well. In either case, reduction of administrative overhead will improve the cost effectiveness of the project.

3.2.2 Requirements, Design and Coding MRs by Testing Phase

We have focused on the early part of the software process because that is where the most MRs occurred and, accordingly, where closer attention should yield the most results. For this reason, we present the requirements, design and coding faults distributed by testing phase.

Figure 1. Fault Categories found by Phase

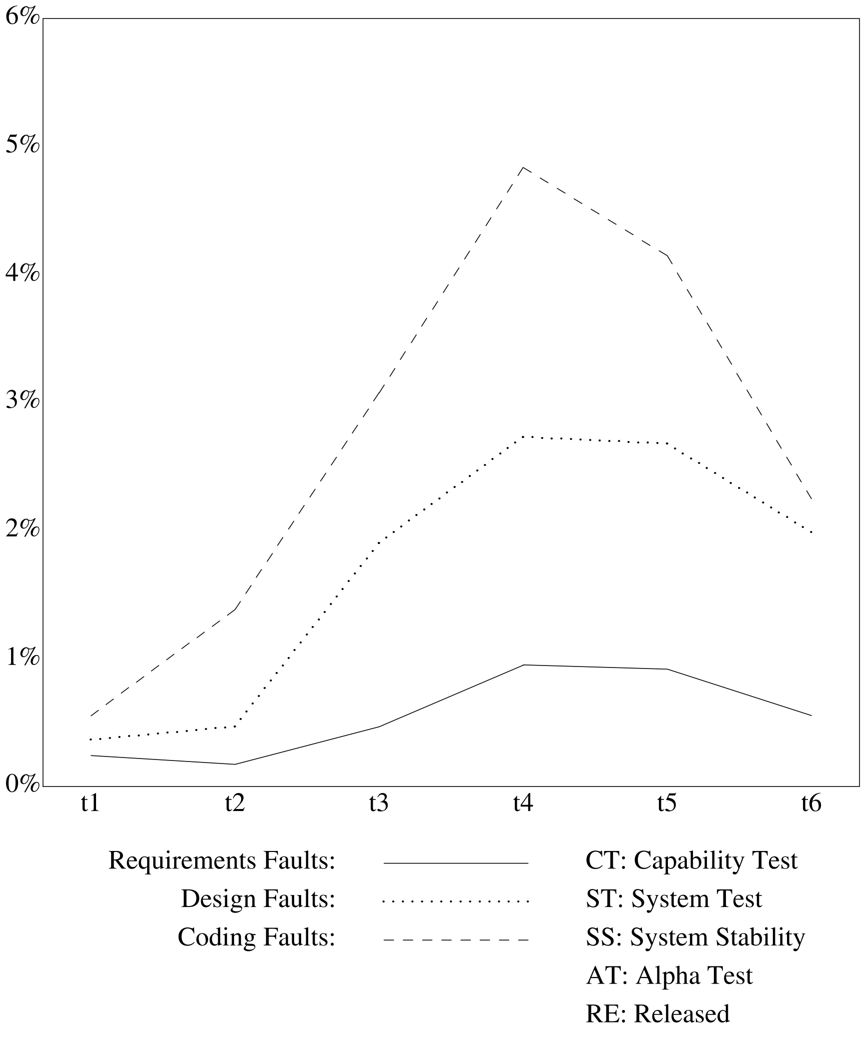


For the requirements, design and coding fault categories, Figure 1 shows the percentage of MRs found during each testing phase. There are two important observations. First, system test (ST) was the source of most of the MRs in each category; capability testing (CT) was the next largest source. This is not particularly surprising, since that is when we were looking the hardest for faults. Second, all testing phases found MRs of each fault category. It is also not surprising that coding faults are found over the entire set of testing phases. One obvious reason for this phenomena is that changes are continually made to correct the faults that are found in the various earlier testing phases. Moreover, while it is disturbing to note that both design and requirements faults continue to be found throughout the entire testing process, we feel that this is due to the lack of precision and completeness in requirements and design documentation and is a general problem in the current state-of-practice rather than a project-specific problem.

3.2.3 Requirements, Design and Coding MRs found over Time

Again, we focus on the early part of the process (requirements, design and coding) in charting the faults found over time as shown in Figure 2. The time values in Figure 2 are fixed intervals. From the shape of the data, it is clear that System Testing overlaps interval t4. It is unfortunate that we have only the calendar data, as a correlation with effort data [11] would be extremely valuable.

Figure 2. Fault Categories found over Time



For the requirements, design and coding fault categories over time, Figure 2 shows that all fault types peaked at time t4, and held through time t5, except for the coding faults which decreased.

3.3 Summary

The following general observations may be drawn from this general survey of the problems encountered in evolving a large-scale, real-time system:

- implementation, testing, and administrative overhead faults occurred in roughly equal proportions;

- requirements problems, while not overwhelmingly numerous, are still significant (especially since the majority were found late in the testing process);
- the most faults were found when the level of testing effort was the highest (that is, at system test); and
- the majority of faults were found late in the testing cycle.

These observations are limited by the fact that the tracking of MRs is primarily a testing activity. It would be extremely useful to observe the kinds and frequencies of faults that exists in the earlier phases of the project. Moreover, it would be beneficial to incorporate ways of detecting requirements and design faults into the existing development process.

4. Design/Code Fault Survey

As a result of the general survey, we decided to survey the design and coding MRs in depth. The following were the goals we wanted to achieve in this part of the study:

- determine the kinds of faults that occurred in design and coding;
- determine the difficulty both in finding or reproducing these faults and in fixing them;
- determine the underlying causes of the faults; and
- determine how the faults might have been prevented.

There were two reasons for choosing this part of the general set of MRs. First, it seemed to be exceedingly difficult to separate the two kinds of faults. Second, catching these kinds of faults earlier in the process would provide a significant reduction in overall fault cost — that is, the cost of finding faults before system integration is significantly less than finding them in the laboratory testing environment. Our internal cost data is consistent with Boehm's [4]. Thus, gaining insight into these problems will yield significant and cost beneficial results.

In the two subsections that follow, we summarize the survey questionnaire, present the results of our statistical analysis, and summarize our findings with regard to interface and implementation faults.

4.1 Summary of Questionnaire and Response

The questionnaire is presented in summary form in the following subsections. The respondents were asked to indicate the difficulty of finding and fixing the problem, determine the actual and underlying causes, indicate the best means of either preventing or avoiding the problem, and give their level of confidence in their responses.

4.1.1 Ease of finding or reproducing the fault

The MR in question is to be ranked according to how difficult it was to reproduce the failure and locate the fault.

1. *Easy* — could produce at will.
2. *Moderate* — happened some of the time (intermittent).
3. *Difficult* — needed theories to figure out how to reproduce the error.
4. *Very Difficult* — exceedingly hard to reproduce.

4.1.2 Ease of fixing the fault

For each MR, how much time was needed to design and code the fix, document and test it.[2]

1. *Easy* — less than one day
2. *Moderate* — 1 to 5 days
3. *Difficult* — 6 to 30 days
4. *Very difficult* — greater than 30 days

4.1.3 Fault Types

For this fault, consider the following 22 possible types and select the one that most closely applies to the cause of this MR.

1. *Language pitfalls* — for example, pointer problems, or the use of ‘‘=’’ instead of ‘‘= =’’.
2. *Protocol* — violated rules about interprocess communication.
3. *Low-level logic* — for example, loop termination problems, pointer initialization, etc.
4. *CMS complexity* — for example, due to software change management system complexity.
5. *Internal functionality* — either inadequate functionality or changes and/or additions were needed to existing functionality within the module or subsystem.
6. *External functionality* — either inadequate functionality or changes and/or additions were needed to existing functionality outside the module or subsystem.
7. *Primitives misused* — the design or code depended on primitives which were not *used* correctly.
8. *Primitives unsupported* — the design or code depended on primitives that were not adequately developed (that is, the primitives do not work correctly).
9. *Change coordination* — either did not know about previous changes or depended on concurrent changes.
10. *Interface complexity* — interfaces were badly structured or incomprehensible.
11. *Design/Code complexity* — the implementation was badly structured or incomprehensible.
12. *Error handling* — incorrect handling of, or recovery from, exceptions.
13. *Race conditions* — incorrect coordination in the sharing of data.
14. *Performance* — for example, real-time constraints, resource access, or response time constraints.
15. *Resource allocation* — incorrect resource allocation and deallocation.

[2] Note that what would be an easy fix in a single programmer system takes considerably more time in a large, multi-person project with a complex laboratory test environment.

16. *Dynamic data design* — incorrect design of dynamic data resources or structures.

17. *Dynamic data use* — incorrect *use* of dynamic data structures (for example, initialization, maintaining constraints, etc.).

18. *Static data design* — incorrect design of static data structures (for example, their location, partitioning, redundancy, etc.).

19. *Unknown Interactions* — unknowingly involved other functionality or parts of the system.

20. *Unexpected dependencies* — unexpected interactions or dependencies on other parts of the system.

21. *Concurrent work* — unexpected dependencies on concurrent work in other releases.

22. *Other* — describe the fault.

4.1.4 Underlying causes

Because the fault may be only a symptom, provide what you regard to be the underlying root cause for each problem.

1. *None given* — no underlying causes given.

2. *Incomplete/omitted requirements* — the source of the fault stemmed from either incomplete or unstated requirements.

3. *Ambiguous requirements* — the requirements were (informally) stated, but they were open to more than one interpretation. The interpretation selected was evidently incorrect.

4. *Incomplete/omitted design* — the source of the fault stemmed from either incomplete or unstated design specifications.

5. *Ambiguous design* — the design was (informally) given, but was open to more than one interpretation. The interpretation selected was evidently incorrect.

6. *Earlier incorrect fix* — the fault was induced by an earlier incorrect fix (that is, the fault was not the result of new development).

7. *Lack of knowledge* — there was something that I needed to know, but did not know that I needed to know it.

8. *Incorrect modification* — I suspected that the solution was incorrect, but could not determine how to correctly solve the problem.

9. *Submitted under duress* — the solution was submitted under duress, knowing that it was incorrect (generally due to schedule pressure, etc).

10. *Other* — describe the underlying cause.

4.1.5 Means of prevention

For this fault, consider possible ways to prevent or avoid it and select the most useful or appropriate choice for preventing or avoiding the fault.

1. *Formal requirements* — use precise, unambiguous requirements (or design) in a formal notation (which may be either graphical or textual).

2. *Requirements/Design templates* — provide more specific requirements (or design) document templates.
3. *Formal interface specifications* — use a formal notation for describing the module interfaces.
4. *Training* — provide discussions, training seminars, and formal courses.
5. *Application walk-throughs* — determine, informally, the interactions among the various application specific processes and data objects.
6. *Expert person/documentation* — provide an ''expert'' person or clear documentation when needed.
7. *Design/code currency* — keep design documents up to date with code changes.
8. *Guideline enforcement* — enforce code inspections guidelines and the use of static analysis tools such as lint.
9. *Better test planning* — provide better test planning and/or execution (for example, automatic regression testing).
10. *Others* — describe the means of prevention.

4.1.6 Confidence levels

Confidence levels requested of the respondents were: *very high, high, moderate, low* and *very low*. We discarded the small number of responses that had a confidence level of either low or very low.

4.2 Statistical Analysis

68% of the questionnaires were returned. Of those, we dropped the responses that were either low or very low in confidence (6%). The remainder were then subjected to analysis.

TABLE 2. Chi-Square Analysis Summary

Variables	Degrees of Freedom	Total Chi-Square	p
Find, Fix	6	51.489	.0001
Fault, Find	63	174.269	.0001
Fault, Fix	63	204.252	.0001
Cause, Find	27	94.493	.0001
Cause, Fix	27	55.232	.0011
Fault, Cause	189	403.136	.0001
Prevention, Find	27	41.021	.041
Prevention, Fix	27	97.886	.0001
Fault, Prevention	189	492.826	.0001
Cause, Prevention	81	641.417	.0001

The results of the survey were cross tabulated and then subjected to chi-square analysis. Table 2 provides a summary of the chi-square analysis. Note that that in all cases the relationships are clearly statistically significant, with the relationship between the means of prevention and the ease of finding the fault coming closest to being independent and the relationship between the means of prevention and the underlying causes being the most significantly interdependent.

We first consider the difficulty of finding and fixing the faults. We then discuss the faults and weight them by the cost of finding and fixing them. Next we consider the underlying causes and the means of prevention, correlate the faults with underlying causes and means of prevention, and correlate underlying causes and means of prevention. Finally, we divide the faults into interface and implementation categories and compare them in terms of difficulty to find and fix, their underlying causes and their means of prevention.

4.2.1 Finding and Fixing Faults

Table 3 provides a cross-tabulation of the difficulty in finding and fixing the design and coding faults.

TABLE 3. Find versus Fix Comparison

find/fix	< 1	1 - 5	6 - 30	> 30
easy	23.7%	32.1%	10.0%	1.7%
moderate	4.2%	12.5%	5.6%	1.1%
difficult	1.7%	3.4%	2.1%	.5%
very difficult	.5%	.3%	.3%	.3%

78% took less than 5 days to fix. In general, the easier to find faults were easier to fix; the more difficult to find faults were more difficult to fix as well. There were more faults that were easy to find and took less than one day to fix than were expected by the chi-square analysis. Interestingly, there were fewer than expected easy to find faults that took 6 to 30 days to fix.

While the coordinates of the effort to find and fix the faults are non-comparable, we note that the following relationship is suggestive. Collapsing the above table yields an interesting insight in table 4 that seems counter to the common wisdom that says ‘‘once you have found the problem, it is easy to fix it’’. There is a significant number of ‘‘easy/moderate to find’’ faults that require a relatively long time to fix.

TABLE 4. Summary of Find/Fix

Find/Fix effort	≤ 5 days	≥ 6 days
easy/moderate	72.5%	18.4%
difficult/very difficult	5.9%	3.2%

4.2.2 Faults

Table 5 below shows the fault types of the MRs as ordered by their frequency in the survey independent of any other factors.

The first 5 fault categories account for 60% of the faults. That ‘‘internal functionality’’ is the leading fault by such a large margin is somewhat surprising; that ‘‘interface complexity’’ is such a significant problem is not surprising at all. However, that the first five faults are leading faults is consistent with the nature of the evolution of the system. Adding significant amounts of new functionality to a system easily accounts for problems with ‘‘internal functionality’’, ‘‘low-level logic’’ and ‘‘external functionality’’.

The fact that the system is a very large, complicated real-time system easily accounts for the fact that there are problems with ‘‘interface complexity’’, ‘‘unexpected dependencies’’ and design/code complexity’’, ‘‘change coordination’’ and ‘‘concurrent work’’.

C has well-know ‘‘language pitfalls’’ that account for the rank of that fault in the middle of the set. Similarly, ‘‘race conditions’’ are a reasonably significant problem because of the lack of suitable language

TABLE 5. Faults ordered by Frequency

cause	observed %	description
5	25.0%	internal functionality
10	11.4%	interface complexity
20	8.0%	unexpected dependencies
3	7.9%	low-level logic
11	7.7%	design/code complexity
22	5.8%	other
9	4.9%	change coordination
21	4.4%	concurrent work
13	4.3%	race conditions
6	3.6%	external functionality
1	3.5%	language pitfalls
12	3.3%	error handling
7	2.4%	primitive's misuse
17	2.1%	dynamic data use
15	1.5%	resource allocation
18	1.0%	static data design
14	.9%	performance
19	.7%	unknown interactions
8	.6%	primitives unsupported
2	.4%	protocol
4	.3%	CMS complexity
16	.3%	dynamic data design

facilities in C.

That ‘‘performance’’ faults are a relatively insignificant is due probably to the fact that this is not an early release of the system.

4.2.3 Finding and Fixing Faults

There are two interesting relationships to consider in the ordering of the various faults: the affect that the difficulty in finding the faults have on the ordering and the affect that the difficulty of fixing the faults has on the ordering.

The following table (table 6) captures the weighted difficulty of finding the various faults. The weighting is done multiplying the proportion of observed values for each fault with multiplicative weights of 1, 2, 3 and 4[3] for each find category, respectively, and summing the results. For example, if a fault was easy to find in 66% of the cases, moderate in 23%, difficult in 11%, and very difficult in 0%, the weight is 145 = (66 * 1) + (23 * 2) + (11 * 3) + (0 * 4). The following are the faults weighted by difficulty to find from easiest to

[3] Obviously it would have been better to have had some duration assigned to the effort to find faults and the correlated the weighting with those durations as we do subsequently in weighting by effort to fix faults. The weights used are intended to be suggestive, not definitive.

TABLE 6. Determining the Find weighting

fault	find proportion e/m/d/vd	weight	change description
4	100/0/0/0	100	CMS complexity
18	100/0/0/0	100	static data design
7	88/8/4/0	120	primitive's misuse
2	75/25/0/0	125	protocol
20	78/16/5/1	129	unexpected dependencies
21	70/23/2/4	130	concurrent work
3	73/22/5/0	132	low-level logic
22	82/12/2/5	132	other
5	74/19/6/1	134	internal functionality
6	67/31/3/0	139	external functionality
1	68/26/2/2	141	language pitfalls
10	66/23/11/0	145	interface complexity
9	65/20/12/2	149	change coordination
8	67/17/17/0	152	primitives unsupported
19	88/8/4/0	157	unknown interactions
16	67/0/33/0	157	dynamic data design
17	52/38/10/0	158	dynamic data use
15	47/47/7/0	162	resource allocation
12	55/30/12/3	163	error handling
11	55/29/16/1	165	code complexity
14	56/11/11/22	199	performance
13	12/67/21/0	209	race conditions

most difficult.

We do not find the ordering here to conflict with our intuition of how difficult these faults might be to find. Typically, performance faults and race conditions are very difficult to isolate and reproduce. We would expect that ''code complexity'' and ''error handling'' faults would also be difficult to find and reproduce.

In the chi-square analysis, ''internal functionality'', ''unexpected dependencies'' and ''other'' tended to be easier to find than expected. ''Code complexity'' and ''performance'' tended to be harder to find than expected. There tended to be more significant deviations where the population was larger.

If we weight the proportions by multiplying the number of occurrences of each fault by its weight from Table 5 and dividing by the total weighted number of occurrences, we get only a slight change in the ordering of the faults, with ''internal functionality'', ''code complexity'', and ''race conditions'' (faults 5, 11, and 13) changing slightly more than the rest of the faults.

The following table (table 7) represents the results of weighting the difficulty of fixing the various faults by factoring in the actual time needed to fix the faults. The multiplicative scheme uses the values 1, 3, 15, and 30 for the four average times in fixing a fault. The calculations are performed as in the example of weighting the difficulty of finding the faults.

The weighting according to the difficulty in fixing the fault causes some interesting shifts in the ordering of the faults. ''Language pitfalls'', ''low-level logic'', and ''internal functionality'' (faults 1, 3, and 5) drop

TABLE 7. Determining the Fix weighting

fault	proportion e/m/d/vd	weight	brief description
16	67/33/0/0	166	dynamic data design
4	67/33/0/0	166	CMS complexity
8	50/50/0/0	200	primitive's unsupported
18	50/50/0/0	200	static data design
1	63/31/6/0	244	language pitfalls
3	59/37/3/1	245	low-level logic
2	25/75/0/0	250	protocol
17	38/48/14/0	392	dynamic data use
9	37/49/14/0	394	change coordination
5	27/59/14/0	414	internal functionality
22	40/43/12/5	496	other
7	46/37/8/8	497	primitive's misuse
10	17/57/26/1	608	interface complexity
21	25/43/30/2	661	concurrent work
6	22/50/22/6	682	external functionality
13	16/56/21/7	709	race conditions
12	21/52/18/9	717	error handling
19	29/43/14/14	785	unknown interactions
20	24/39/33/5	786	unexpected dependencies
11	22/39/27/12	904	design/code complexity
14	11/22/44/22	1397	performance
15	0/47/27/27	1356	resource allocation

significantly in their relative importance. This coincides with one's intuition about these kinds of faults. ‘‘Design/code complexity’’, ‘‘resource allocation’’, and ‘‘unexpected dependencies’’ (faults 11, 15, and 20) rise significantly in their relative importance; ‘‘interface complexity’’, ‘‘race conditions’’, and ‘‘performance’’ (faults 10, 13, 14) rise but not significantly so.

Table 8 shows the top weighted faults. According to our weighting scheme, these four faults account for 55.2% of the effort expended to fix all the faultss and 51% of the effort to find them, but represent 52.1% of the faults by frequency count. Collectively, they are somewhat harder to fix than rest of the faults and slightly easier to find. We again note that while the two scales are not strictly comparable, the comparison is an interesting one none-the-less.

TABLE 8. Faults weighted by Fix difficulty

fault	weighted %	description
5	18.7%	internal functionality
10	12.6%	interface complexity
11	12.6%	code complexity
20	11.3%	unexpected dependencies

In the chi-square analysis, ''language pitfalls'', and ''low-level logic'' took fewer days to fix than expected. ''Interface complexity'' and ''internal functionality'' took 1 to 30 days more often than expected, while ''design/code complexity'' and ''unexpected dependencies'' took longer to fix (that is, 6 to over 30 days) than expected. These deviations reenforce our weighted assessment of the effort to fix the faults.

4.2.4 Underlying Causes

The table below (table 9) shows the underlying causes of the MRs as ordered by their frequency in the survey independent of any other factors.

TABLE 9. Underlying causes of Faults

fault	observed %	change
4	25.2%	incomplete/omitted design
1	20.5%	none given
7	17.8%	lack of knowledge
5	9.8%	ambiguous design
6	7.3%	earlier incorrect fix
9	6.8%	submitted under duress
2	5.4%	incomplete/omitted requirements
10	4.1%	other
3	2.0%	ambiguous requirements
8	1.1%	incorrect modification

Weighting the underlying causes by the effort to find or reproduce the faults for which these are the underlying causes produces almost no change in either the ordering or in the relative proportion of the underlying causes.

TABLE 10. Weighting of the Underlying Causes by Find Effort

underlying causes	proportion	weight	brief description
8	91/9/0/0	109	incorrect modification
7	74/18/7/1	135	lack of knowledge
3	60/40/0/0	140	ambiguous requirements
5	66/27/7/0	141	ambiguous design
2	70/17/13/0	143	incomplete/omitted requirements
4	68/25/7/1	143	incomplete/omitted design
6	73/12/10/5	147	earlier incorrect fix
10	76/12/0/12	148	other
1	63/25/11/1	150	none given
9	50/46/4/0	158	submitted under duress

Table 10 above shows the relative difficulty in finding the faults associated with the underlying causes. The resulting ordering is particularly non-intuitive: the MRs with no underlying cause are the second most difficult to find; those submitted under duress are the most difficult to find.

In the chi-square analysis of finding underlying causes, faults caused by ''lack of knowledge'' tended to be easier to find than expected while faults caused by ''submitted under duress'' tended to be moderately hard to find more often than expected.

Weighting the underlying causes by the effort to fix the faults (table 11) represented by the underlying causes yields a few shifts in the proportion of effort: ‘‘incomplete/omitted design’’ increased significantly, ‘‘unclear requirements’’ and ‘‘incomplete/omitted requirements’’ increased less significantly; ‘‘none’’ decreased significantly, ‘‘unclear design’’ and ‘‘other’’ decreased less significantly. However, the relative ordering of the various underlying causes is unchanged.

TABLE 11. Weighting of the Underlying Causes by Fix Effort

underlying causes	proportion	weight	brief description
10	37/42/12/10	340	other
1	43/43/12/2	412	none given
5	29/55/14/2	464	ambiguous design
7	30/50/17/3	525	lack of knowledge
6	34/45/17/4	544	earlier incorrect fix
9	18/57/25/0	564	submitted under duress
8	18/55/27/0	588	incorrect modification
4	23/50/22/5	653	incomplete/omitted design
2	26/44/24/6	698	incomplete/omitted requirements
3	25/30/24/6	940	ambiguous requirements

The relative weighting of the effort to fix these kinds of underlying causes seems to coincide with one’s intuition very nicely.

In the chi-square analysis of fixing underlying causes, faults caused by ‘‘none given’’ tended to take less time to fix than expected, while faults caused by ‘‘incomplete/omitted design’’ and ‘‘submitted under duress’’ tended to take more time to fix than expected.

In table 12, we present the cross-tabulation of faults and their underlying causes. Faults are represented by the rows, underlying causes by the columns. The numbers in the matrix are the percentages of the total population of faults. Thus, 1.5% of the total faults were fault 1 with the underlying cause 1. The expected number of faults for fault 1 and underlying cause 1 can be computed by multiplying the total faults for each of those categories: 20.5% * 3.5% = .7%. In this example, the actual number of faults was higher than expected.

For the sake of brevity, we consider only the most frequently occurring faults and their major underlying causes. ‘‘Incomplete/omitted design’’ (cause 4) is the primary underlying cause in all of these major faults. ‘‘Ambiguous design’’ (cause 5), ‘‘lack of knowledge’’ (cause 7), and ‘‘none given’’ (cause 1) were also significant contributors to the presense of these faults.

- *internal functionality* (fault 5) — ‘‘incomplete/omitted design’’ (cause 4) was felt to have been the cause of 31% (that is, 7.7% / 25%) of the occurrences of this fault, a percentage higher than expected; ‘‘lack of knowledge’’ (cause 7) was thought to have caused 21% of the occurrences of this fault, higher than expected; and ‘‘none given’’ was listed as the third underlying cause representing 13% of the occurrences.

- *interface complexity* (fault 10) — again, ‘‘incomplete/omitted design’’ was seen to be the primary cause in the occurrence of this fault (36%), higher than expected; ‘‘lack of knowledge’’ and ‘‘ambiguous design’’ were seen as the second and third primary causes of this fault (13% and 12% respectively).

TABLE 12. Cross Tabulating Underlying Causes and Faults

		1	2	3	4	5	6	7	8	9	10
		none	i/o	ambiguous	i/o	ambiguous	earlier	lack of	incorrect	sub'd	other
		given	reqs	reqs	design	design	incorrect	knowledge	mod	under	
							fix			duress	
		20.5%	5.4%	2.0%	25.2%	9.8%	7.3%	17.8%	1.1%	6.8%	4.1%
1 language pitfalls	3.5%	1.5	.0	.0	.2	.1	.2	.8	.1	.5	.1
2 protocol	.4%	.0	.0	.1	.2	.0	.0	.1	.0	.0	.0
3 low-level logic	7.9%	3.7	.3	.1	.6	.3	1.2	.7	.0	.6	.4
4 CMS complexity	.3%	.1	.0	.0	.0	.0	.1	.1	.0	.0	.0
5 internal functionality	25.0%	3.3	1.3	.6	7.7	2.8	2.0	5.2	.3	1.2	.6
6 external functionality	3.6%	.7	.3	.1	.4	.5	.6	.7	.0	.3	.0
7 primitives misused	2.4%	.4	.0	.0	.5	.0	.1	.8	.0	.0	.6
8 primitives unsupported	.6%	.0	.2	.0	.1	.0	.1	.1	.0	.1	.0
9 change coordination	4.9%	1.1	.0	.0	.8	1.0	.6	.8	.1	.3	.2
10 interface complexity	11.4%	2.1	.6	.2	4.1	1.4	1.1	1.4	.2	.0	.3
11 design/code complexity	7.7%	1.3	.0	.3	3.0	1.6	.2	1.0	.0	.0	.3
12 error handling	3.3%	.9	.3	.0	.8	.0	.1	.7	.0	.4	.1
13 race conditions	4.3%	1.4	.2	.0	1.3	.5	.1	.3	.0	.4	.1
14 performance	.9%	.2	.0	.1	.2	.0	.0	.3	.0	.0	.1
15 resource allocation	1.5%	.5	.0	.0	.3	.1	.0	.4	.1	.0	.1
16 dynamic data design	.3%	.0	.0	.0	.1	.0	.0	.1	.0	.1	.0
17 dynamic data use	2.1%	.7	.1	.0	.2	.1	.0	.6	.0	.4	.0
18 static data design	1.0%	.3	.1	.1	.2	.1	.0	.1	.0	.1	.0
19 unknown interactions	.7%	.0	.1	.1	.0	.2	.0	.2	.0	.1	.0
20 unexpected dependencies	8.0%	.5	.8	.3	2.7	.5	.1	1.4	.0	1.7	.0
21 concurrent work	4.4%	.6	.3	.0	1.2	.2	.4	.9	.2	.4	.2
22 other	5.8%	1.2	.8	.0	.6	.4	.4	1.1	.1	.2	1.0

- *unexpected dependencies* (fault 20) — not surprisingly, ‘‘incomplete/omitted design’’ was felt to have been the primary cause of this fault (in 34% of the cases); ‘‘submitted under duress’’ (cause 9) contributed to 21% of the occurrences, a percentage higher than expected; ‘‘lack of knowledge’’ was the tertiary cause of this fault, representing 18% of the occurrences.
- *design/code complexity* (fault 11) — again, ‘‘incomplete/omitted design’’ was felt to have been the primary cause in 39% of the occurrences of this fault, a percentage higher than expected; ‘‘ambiguous design’’ was the second most frequent underlying cause of this fault, causing 21% of the faults (also a higher percentage than expected); ‘‘none given’’ was listed as the third underlying cause representing 17% of the occurrences.

Again, for the sake of brevity, we consider only the most frequently occurring underlying causes and the faults they were most applicable to. Since ‘‘internal functionality’’ is the most frequently occurring fault, one is not surprised that it is one of the faults to which these major underlying causes are applicable,

- *incomplete/omitted design* (cause 4) — as we noted in the preceding paragraph, ‘‘internal functionality’’, ‘‘interface complexity’’, ‘‘code/design complexity’’, and ‘‘unexpected dependencies’’ were the major applicable faults (31%, 12%, 12% and 11% respectively) with the first three occurring with higher than expected frequency.
- *none given* (cause 1) — ‘‘low-level logic’’ (fault 3) was the leading fault, representing 18% of the occurrences (a percentage higher than expected); ‘‘internal functionality’’ (fault 5) was the second major fault, representing 16% of the occurrences (a percentage lower than expected); ‘‘interface complexity’’ (fault 10) was the third leading fault, representing 10% of the occurrences; and ‘‘language pitfalls’’ was the fourth leading fault, representing 8% of the occurrences (a percentage higher than expected).
- *lack of knowledge* (cause 7) — ‘‘internal functionality’’ was the leading fault, representing 29% of the occurrences (a percentage higher than expected); ‘‘interface complexity’’ was next with 8% of the occurrences (a percentage lower than expected); ‘‘unexpected dependencies’’ was third with 8% of the occurrences; and ‘‘other’’ (fault 22) was the fourth with 6%.
- *ambiguous design* (cause 5) — ‘‘internal functionality’’ represented 29% of the occurrences; ‘‘code/design complexity’’ (fault 11) was second fault, representing 16% of the occurrences (a percentage higher than expected); ‘‘interface complexity’’ was third with 14%; and ‘‘change coordination’’ (fault 9) was fourth, representing 10% of the occurrences (a percentage higher than expected).

The high proportion of ‘‘none given’’ as an underlying cause requires some explanation. One of the reasons for this is that faults such as ‘‘language pitfalls’’, ‘‘low-level logic’’, ‘‘race conditions’’ and ‘‘change coordination’’ tend to be both the fault and the underlying cause (7.8% — or 33% of the in the ‘‘none given’’ underlying cause category). In addition, one could easily imagine that some of the faults such as ‘‘interface complexity’’ and ‘‘design/code complexity’’ could also be considered both the fault and the underlying cause (3.3% — or 16% of the faults in the ‘‘none given’’ underlying cause category). On the other hand, we were surprised that no cause was given for a substantial part of the ‘‘internal functionality’’ faults (3.7% — or 18% of the faults in the ‘‘none given’’ category). One would expect there to be some underlying cause for that particular fault.

4.2.5 *Means of Prevention*

The table below (table 13) shows the means of prevention of the MRs as ordered by their occurrence independent of any other factors. We note that the various means of prevention are by no means independent or non-overlapping. Moreover, the means selected may well reflect a particular approach of the responder in selecting one means over another (for example, see the discussion below about formal versus informal means of prevention).

TABLE 13. Means of Error Prevention

causes	observed %	brief description
5	24.5%	application walk-throughs
6	15.7%	expert person/documentation
8	13.3%	guideline enforcement
2	10.0%	requirements/design templates
9	9.9%	better test planning
1	8.8%	formal requirements
3	7.2%	formal interface specifications
10	6.9%	other
4	2.2%	training
7	1.5%	design/code currency

It is interesting to note that the application-specific means of prevention (‘‘application walk-throughs’’) is considered the most effective means of prevention. This selection of application walk-throughs as the most useful means of error prevention appears to confirm the observation of Curtis, Krasner and Iscoe [6] that a thin spread of application knowledge is the most significant problem in building large systems.

Further it is worth noting that informal means of prevention rank higher than formal ones. On the one hand, this may reflect the general bias in the United States against formal methods. On the other hand, the informal means are a non-technical solution to providing the information that may be supplied by the formal representations (and which provide a more technical solution with perhaps higher attendant adoption costs).

The level of effort to find the faults for which these are the means of prevention does not change the order found in the table above, with the exception of ‘‘requirements/design templates’’ which seems to apply to the easier to find faults and ‘‘guideline enforcement’’ which seems to apply more to the harder to find faults.

In the chi-square analysis, the relationship between finding faults and preventing them is the most independent of the relationships reported here with p=.041. ‘‘Application walk-throughs’’ applied to faults that were marginally easier to find than expected, while ‘‘guideline enforcement’’ applied to faults that were less easy to find than expected.

The table below is the means of prevention weighted by the effort to fix the associated faultss.

TABLE 14. Means of Prevention Weighted by Fix Effort

prevention	proportion	weight	brief description
8	38/52/7/3	389	guideline enforcement
9	35/52/12/1	401	better test planning
7	40/40/20/0	460	design/code currency
5	33/50/17/1	468	application walk-throughs
10	49/36/6/9	517	other
2	10/52/30/1	654	requirements/design templates
3	26/43/26/4	675	formal interface specifications
6	22/48/24/6	706	expert person/documentation
1	20/50/22/8	740	formal requirements
4	23/36/23/18	1016	training

It is interesting to note that the faults considered to be prevented by training are the hardest to fix. The formal methods also apply to classes of faults that take a long time to fix.

Weighting the means of prevention by effort to fix their corresponding faults yields a few shifts in proportion: ‘‘application walk-throughs’’, ‘‘better test planning’’, and ‘‘guideline enforcement’’ decreased in proportion; ‘‘expert person/documentation’’ and ‘‘formal requirements’’ increased in proportion, ‘‘formal interface specifications’’ and ‘‘other’’ less so. As a result, the ordering changes slightly to 5, 6, 2, 1, 8, 10, 3, 9, 4, 7: ‘‘expert person/documentation’’ and ‘‘ formal requirements’’ (numbers 6 and 1) are weighted significantly higher; ‘‘requirements/design templates’’, ‘‘formal interface specifications’’, ‘‘training’’, and ‘‘other’’ (numbers 2, 3, 4, and 10) are less significantly higher; ‘‘guideline enforcement’’ and ‘‘better test planning’’ (numbers 8 and 9) are significantly lower.

In the chi-square analysis, faults prevented by ‘‘application walk-throughs’’, ‘‘guideline enforcement’’, and ‘‘other’’ tended to take fewer days to fix than expected, while faults prevented by ‘‘formal requirements’’, requirements/design templates’’ and ‘‘expert person/documentation’’ took longer to fix than expected.

In the table below (table 15), we present the cross-tabulation of faults and their means of prevention. Again, the faults are represented by the rows, and the means of prevention are represented by the columns. The data is analogous to the preceding cross tabulation of faults and underlying causes.

For the sake of brevity, we consider only the most frequently occurring faults and their major means of prevention. ‘‘Application walk-throughs’’ were felt to be an effective means of preventing these most significant faults. ‘‘Expert person/documentation’’, ‘‘formal requirements’’ and ‘‘formal interface specifications’’ were also significant means of preventing these faults.

- *internal functionality* (fault 5) — ‘‘application walk-throughs’’ (prevention 5) were thought to be the most effective means of prevention, applicable to 27% of the occurrences of this fault; ‘‘expert person/documentation’’ (prevention 6) was felt to be the second most effective means, applicable to 18% of the fault occurrences; and ‘‘requirements/design templates’’ were thought to applicable to 14% of the fault occurrences, a percentage higher than expected.

TABLE 16. Cross Tabulating Means of Prevention and Faults

		1	2	3	4	5	6	7	8	9	10
		formal	req/des	formal	training	appl	expert	design	guide-	better	others
		reqs	forms	i'face		walk-	person	code	line	test	
				specs		thrus	doc'n	currency	enf'mt	plans	
		8.8%	10.0%	7.2%	2.2%	24.5%	15.7%	1.5%	13.3%	9.9%	6.9%
1 language pitfalls	3.5%	.0	.1	.1	.0	1.0	.3	.1	1.3	.4	.2
2 protocol	.4%	.1	.2	.0	.0	.1	.0	.0	.0	.0	.0
3 low-level logic	7.9%	.1	.0	.1	.2	2.3	.3	.2	3.2	.8	.7
4 CMS complexity	.3%	.0	.0	.0	.0	.0	.1	.0	.1	.1	.0
5 internal functionality	25.0%	1.9	3.5	1.5	.4	6.6	4.4	.2	3.3	3.1	.1
6 external functionality	3.6%	.6	.3	.4	.0	.1	.7	.0	.5	.9	.1
7 primitives misused	2.4%	.1	.1	.2	.0	.8	.3	.0	.1	.2	.6
8 primitives unsupported	.6%	.1	.0	.0	.0	.3	.0	.0	.0	.1	.1
9 change coordination	4.9%	.4	.9	.3	.4	.8	.3	.3	.3	.7	.5
10 interface complexity	11.4%	2.1	.3	2.1	.0	3.0	1.7	.1	1.2	.7	.2
11 design/code complexity	7.7%	.8	.5	.1	.4	2.2	2.4	.2	.3	.4	.4
12 error handling	3.3%	.2	.2	.3	.1	.6	.6	.0	.4	.5	.4
13 race conditions	4.3%	.8	.0	.4	.0	1.2	.4	.2	.4	.2	.7
14 performance	.9%	.0	.0	.0	.2	.2	.3	.0	.0	.0	.2
15 resource allocation	1.5%	.1	.1	.1	.0	.3	.3	.0	.3	.3	.0
16 dynamic data design	.3%	.0	.0	.0	.0	.1	.0	.0	.1	.0	.1
17 dynamic data use	2.1%	.0	.0	.2	.0	.8	.5	.0	.5	.0	.1
18 static data design	1.0%	.1	.1	.0	.0	.2	.2	.0	.0	.3	.1
19 unknown interactions	.7%	.1	.0	.2	.0	.0	.2	.0	.0	.2	.0
20 unexpected dependencies	8.0%	.6	2.2	1.1	.1	2.3	.6	.0	.4	.6	.1
21 concurrent work	4.4%	.4	.7	.0	.2	1.2	1.1	.1	.3	.0	.4
22 other	5.8%	.3	.8	.1	.2	.4	1.0	.1	.6	.4	1.9

- *interface complexity* (fault 10) — again, ‘‘application walk-throughs’’ were considered to be the most effective applicable to 26% of the cases; ‘‘formal requirements’’ (prevention 1) and ‘‘formal interface specifications’’ were felt to be equally effective with each preventing 18% of the fault occurrences (in both cases, a percentage higher than expected).

- *unexpected dependencies* (fault 20) — ‘‘application walk-throughs’’ were felt to be the most effective means of preventing this fault, applicable to 29% of the occurrences; ‘‘requirements/design templates’’ were considered the second most effective and applicable to 28% of the fault occurrences (a percentage higher than expected); and ‘‘formal interface specifications’’ were considered applicable to 14% of the fault occurrences, a percentage higher than expected.

- *design/code complexity* (fault 11) — ‘‘expert person/documentation’’ was felt to be the most effective means of preventing this fault, applicable to 31% of the cases (higher than expected); ‘‘application walk-throughs’’ were the second most effective means, applicable to 29% of the occurrences; and ‘‘formal requirements’’ was third, applicable to 10% of the fault occurrences.

Again, for the sake of brevity, we consider only the most frequently occurring means of prevention and the faults they were most applicable to. Not surprisingly, these means were most applicable to ‘‘internal functionality’’, and ‘‘interface complexity’’ the most prevalent faults. Counter-intuitively, they are also strongly recommended as applicable to ‘‘low level logic’’.

- *application walk-throughs* (prevention 5) — ‘‘internal functionality’’ (fault 5) was considered as the primary target in 27% of the uses of this means of prevention; ‘‘interface complexity’’ (fault 10) was felt to be the secondary target, representing 12% of the uses of this means; and ‘‘low-level logic’’ (fault 3) and ‘‘unexpected dependencies’’ (fault 20) were next with 9% each.

- *expert person/documentation* (prevention 6) — again, ‘‘internal functionality’’ is the dominant target for this means, representing 29% of the possible applications; ‘‘design/code complexity’’ is the second most applicable target, representing 15% of the possible applications (a percentage higher than expected); and ‘‘interface complexity’’ represented 11% of the uses (higher than expected).

- *guideline enforcement* (prevention 8) — ‘‘internal functionality’’ and ‘‘low-level logic’’ were the dominant targets for this means of prevention, representing 25% and 24% respectively (the latter being higher than expected); ‘‘language pitfalls (fault 1) was seens as the third most relevant fault representing 10% of the possible applications (higher than expected); and ‘‘interface complexity’’ was the fourth with 9% of the possible applications of this means of prevention.

4.2.6 Underlying Causes and Means of Prevention

In this section on the data, we summarize the relationships between underlying causes and means of prevention. The underlying causes are listed across the top of the table and represent the columns, and the means of prevention are listed down the left side and represent the rows of the table.

It is interesting to note (in table 16 below) that in the chi-square analysis there are lots of deviations (that is, there is a wider variance between the actual values and the expected values in correlating underlying causes and means of prevention) and that there does not appear to be much statistical structure. This indicates that there are strong dependencies between the underlying causes and their means of prevention. Intuitively, this type of relationship is just what we would expect.

TABLE 16. Cross Tabulating Underlying Causes and Means of Prevention

		1	2	3	4	5	6	7	8	9	10
		none	i/o	ambiguous	i/o	ambiguous	earlier	lack of	incorrect	sub’d	other
		given	reqs	reqs	design	design	incorrect	knowledge	mod	under	
							fix			duress	
		20.5%	5.4%	2.0%	25.2%	9.8%	7.3%	17.8%	1.1%	6.8%	4.1%
1 formal requirements	8.8%	.4	2.3	.9	3.5	.8	.3	.5	.1	.0	.0
2 reqs/design templates	10.0%	.4	1.7	.1	3.7	1.9	.1	.8	.0	1.3	.0
3 formal interface specs	7.2%	.8	.3	.1	2.7	.8	.3	2.0	.0	.2	.0
4 training	2.2%	.4	.0	.1	.7	.1	.3	.6	.0	.0	.0
5 application walk-thrus	24.5%	7.5	.2	.3	7.3	3.1	1.8	3.1	.0	.5	.7
6 expert person/doc	15.7%	1.5	.4	.4	3.5	1.8	1.0	5.8	.6	.3	.4
7 design/code currency	1.5%	.4	.0	.0	.6	.2	.1	.2	.0	.0	.0
8 guideline enforcement	13.3%	4.0	.1	.0	.6	.2	1.6	2.5	.0	3.7	.6
9 better test planning	9.90%	2.8	.2	.0	1.7	.8	1.6	1.9	.3	.2	.4
10 others	6.9%	2.3	.2	.1	.9	.1	.2	.4	.1	.6	2.0

We first summarize the means of prevention associated with the major underlying causes. ‘‘Application walk-throughs’’, ‘‘expert person/documentation’’, and ‘‘guideline enforcement’’ were considered important in addressing these major underlying causes.

- *incomplete/omitted design* (cause 4) — ‘‘application walk-throughs’’ (prevention 5) was thought to be applicable to 28% of the faults with this underlying cause (a percentage higher than expected); ‘‘requirements/design templates’’ (prevention 2) and ‘‘expert person/documentation’’ (prevention 6) were next in importance with 14% each (the first being higher than expected); and ‘‘formal requirements’’ (prevention 1) was felt to be applicable to 12% of the faults with this underlying cause (a percentage higher than expected)

- *none given* (cause 1) — again, ‘‘application walk-throughs’’ was thought to be applicable to 37% of the faults with these underlying causes; ‘‘guideline enforcement’’ (prevention 8), ‘‘better test planning’’ (prevention 9), and ‘‘other’’ (prevention 10) were felt to be applicable to 19%, 14%, and 10% of the faults, respectively. In all four of these cases, the percentages were higher than expected.

- *lack of knowledge* (cause 7) — ‘‘expert person/documentation’’ was thought to be applicable to 32% of the faults with this underlying cause, a percentage higher than expected; ‘‘application walk-throughs’’, ‘‘guideline enforcement’’, and ‘‘formal interface specifications’’ were felt to be applicable to 17%, 14% and 11% of the faults with this underlying cause, respectively, though ‘‘application walk-throughs’’ had a lower percentage than expected, while ‘‘formal interface specifications’’ had a higher percentage than expected.

The following summarizes the major underlying causes addressed by the most frequently considered means of prevention. ‘‘Lack of knowledge’’, ‘‘none given’’, ‘‘incomplete/omitted design’’, and ‘‘ambiguous design’’ were the major underlying causes for which these means of prevention were considered important. It is somewhat non-intuitive that the ‘‘none given’’ underlying cause category is so prominent as an appropriate target for these primary means of prevention.

- *application walk-throughs* (prevention 5) — ‘‘none given’’ (cause 1) and ‘‘incomplete/omitted design’’ (cause 4) were thought to be the appropriate for this means of prevention for 31% and 30% of the cases (higher than expected); ‘‘ambiguous design’’ (cause 5) and ‘‘lack of knowledge’’ (cause 7) were both felt to apply to 13% of the cases each (though the first was higher than expected and the second lower).

- *expert person/documentation* (prevention 6) — ‘‘lack of knowledge’’ was considered the major target for this means of prevention, accounting for 37% of the cases (a higher than expected value); ‘‘incomplete/omitted design’’ and ‘‘ambiguous design’’ were thought to be appropriate in 23% and 11% of the cases, respectively; and ‘‘none given’’ was thought appropriate in 10% of the cases (lower than expected).

- *guideline enforcement* (prevention 8) — ‘‘none given’’ and ‘‘incorrect modification’’ were felt to be the most appropriate for this means of prevention for 30% and 28% of the cases, respectively (both higher than expected); ‘‘lack of knowledge’’ and ‘‘incorrect earlier fix’’ were appropriate in 19% and 12% of the cases, respectively (the latter was higher than expected).

4.3 Interface Faults versus Implementation Faults

The definition of an interface fault that we use here is that of Basili and Perricone [2] and Perry and Evangelist [13, 14]: interface faults are ‘‘those that are associated with structures existing outside the module’s local environment but which the module used’’. Using this definition, we roughly characterize ‘‘language pitfalls’’ (1), ‘‘low-level logic’’ (3), ‘‘internal functionality’’ (5), ‘‘design/code complexity’’ (11), ‘‘performance’’ (14), and ‘‘other’’ (22) as implementation faults. The remainder are considered interface faults. We say ‘‘roughly’’ because there are some cases where the implementation categories may contain some interface problems — remember that some of the ‘‘design/code complexity’’ faults were considered preventable by formal interface specifications.

TABLE 17. Interface/Implementation Fault Comparison

	Interface	Implementation
frequency	49%	51%
find weighted	50%	50%
fix weighted	56%	44%

Interface faults occur with slightly less frequency than implementation faults, but require about the same effort to find them and more effort to fix them.

The table below compares interface and implementation faults with respect to their underlying causes. Underlying causes ‘‘other’’, ‘‘ambiguous requirements’’, ‘‘none given’’, ‘‘earlier incorrect fix’’ and ‘‘ambiguous design’’ tended to be the underlying causes more for implementation faults than for interface faults. Underlying causes ‘‘incomplete/omitted requirements’’, ‘‘incorrect modification’’ and ‘‘submitted under duress’’ tended to be the causes more for interface faults than for implementation faults.

Note that underlying causes that involved ambiguity tended to result more in implementation faults than in interface faults, while underlying causes involving incompleteness or omission of information tended to result more in interface faults than in implementation faults.

TABLE 18. Interface/Implementation Faults and Underlying Causes

		Interface 49%	Implementation 51%
1	none given	45.2%	54.8%
2	incomplete/omitted requirements	79.6%	20.4%
3	ambiguous requirements	44.5%	55.5%
4	incomplete/omitted design	50.8%	49.2%
5	ambiguous design	47.0%	53.0%
6	earlier incorrect fix	45.1%	54.9%
7	lack of knowledge	49.2%	50.8%
8	incorrect modification	54.5%	45.5%
9	submitted under duress	63.1%	36.9%
10	other	39.1%	60.1%

The table below compares interface and implementation faults with respect to the means of prevention. Not surprisingly means 1 and 3 were more applicable to interface faults than to implementation faults. Means of prevention 8, 4, and 6 were considered more applicable to implementation faults than to interface faults.

TABLE 18. Interface/Implementation Faults and Means of Prevention

		Interface 49%	Implementation 51%
1	formal requirements	64.8%	35.2%
2	requirements/design templates	51.5%	48.5%
3	formal interface specifications	73.6%	26.4%
4	training	36.4%	63.6%
5	application walk-troughs	48.0%	52.0%
6	expert person/documentation	44.3%	55.7%
7	design/code currency	46.7%	53.3%
8	guideline enforcement	33.1%	66.9%
9	better test planning	48.0%	52.0%
10	others	49.3%	50.7%

5. Summary and Conclusions

We have presented the results of a two-part survey concerning the software faults encountered in evolving a large-scale, real-time system. We first presented the general results, reporting the phases where the faults occurred and the testing phases in which they were uncovered. We then discussed in depth the design and coding faults survey, reporting the frequency of fault occurrence, the effort to find and fix them, their underlying causes and means of prevention. Finally, we characterized these faults as interface and implementation faults, the effort to find and fix them, their contributing underlying causes and applicable means of prevention.

The results of the two studies are summarized as follows:

- Problems with requirements, design and coding accounted for 34% of the total MRs. Requirements account for about 5% of the total MRs and, while not extremely numerous, are particularly important because they have been found so late in the development process where they are particularly expensive to fix.

- Testing large, complex real-time systems often requires elaborate test laboratories that are themselves large, complex, real-time systems. In the development of this release, testing MRs accounted for 25% of the total MRs.

- The fact that 16% of the total MRs are ‘‘no problems’’ and the presence of a significant set of design and coding faults such as ‘‘unexpected dependencies’’, ‘‘interface and design/code complexity’’ indicate that *lack of system knowledge* is a significant problem in the development of this release.

- 78% of the design and coding faults took five days or less to fix; 22% took 6 or more days to fix. We note that there is a certain overhead factor that is imposed on the fixing of each fault that includes getting consensus, building the relevant pieces of the system and using the system test laboratory to validate the repairs. Unfortunately, we do not have data on those overhead factors.

- Five fault categories account for 60% of the design and coding faults: internal functionality, interface complexity, unexpected dependencies, low-level logic, and design/code complexity. With the exception of ‘‘low-level logic’’, this set of faults is what we would expect to be significant in evolving a large, complex real-time system.

- Weighting the fault categories by the effort to find and to fix them yielded results that coincide with our intuition of which faults are easy and hard to find and fix.
- ``Incomplete/omitted design'', ``lack of knowledge'', and ``none given'' (which we conjecture means that the surface fault is also the underlying cause) account for the underlying causes for 64% of design and coding faults. The weighting of the effort to fix these underlying causes coincides very nicely with our intuition: faults caused by requirements problems require the most effort to fix, while faults cause by ambiguous design and lack of knowledge required among the least effort to fix.
- ``Application walk-throughs'', ``expert person/documentation'', ``guideline enforcement'', and ``requirements/design templates'' represent 64% of the suggested means of preventing design and coding faults. As application walk-throughs accounted for 25% of the suggested means of prevention, we believe that this supports Curtis, Krasner and Iscoe's claim that lack of application knowledge is a significant problem.
- While informal means of prevention were preferred over formal means, it was the case that informal means of prevention tended to be suggested for faults that required less effort to fix and formal means tended to be suggested for faults that required more effort to fix.
- In Perry and Evangelist [13, 14], interface faults were seen to be a significant portion of the entire set of faults (68%). However, there was no weighting of these faults versus implementation faults. We found in this study that interface faults were roughly (see the discussion above) 49% of the entire set of design and coding faults and that they were harder to fix than the implementation faults. Not surprisingly, formal requirements and formal interface specifications were suggested as significant means of preventing interface faults.

The system reported here was developed and evolved using the current ``best practice'' techniques and tools with well-qualified practitioners. Because of this fact, we feel that the data point is generalizable to other large-scale, real-time systems. With this in mind, we offer the following recommendations to improve the current ``best practice''.

- Obtain fault data throughout the entire development/evolution cycle (not just in the testing cycle) and use it monitor the progress of the process.
- Incorporate the non-technological, people-intensive means of prevention into the current process. As our survey has shown, this will yield benefits for the majority of the faults reported here.
- Introduce tools to increase the precision and completeness of requirements, architecture and design documents. This will yield benefits for those faults that were generally harder to fix and will help to detect the requirements, architecture and design problems earlier in the life-cycle.

We are currently incorporating the non-technological solutions into our development process. As we noted in the introduction, empirical data provides us with insight into the kinds of tools and techniques needed to support the software engineering of large systems. The data reported here shows clearly the efficacy of research on requirements specifications (as exemplified by such projects as Watson [9] and Kaleidoscope [21]), and architectural and design specifications (as exemplified by Perry and Wolf [17] and the Inscape Environment [15]).

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