An Empirical Evaluation of the Impact of Test-Driven Development on Software Quality

By

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Abstract

Test-driven development (TDD) has gained recent attention with the popularity of the Extreme Programming agile software development methodology. Advocates of TDD rely primarily on anecdotal evidence with relatively little empirical evidence of the benefits of the practice. This research is the *first* comprehensive evaluation of how TDD affects software architecture and internal design quality.

Formal controlled experiments were conducted in undergraduate and graduate academic courses, in a professional training course, and with in-house professional development projects in a Fortune 500 company. The experiments involved over 230 student and professional programmers working on almost five hundred software projects ranging in size from one hundred to over 30,000 lines of code. The research also included a case study of fifteen software projects developed over five years in a Fortune 500 corporation.

This research demonstrates that software developers applying a test-first (TDD) approach are likely to improve some software quality aspects at minimal cost over a comparable test-last approach. In particular this research has shown statistically significant differences in the areas of code complexity, size, and testing. These internal quality differences can substantially improve external software quality (defects), software maintainability, software understandability, and software reusability. Further this research has shown that mature programmers who have used both the test-first and test-last development approaches prefer the test-first approach.

In addition, this research contributes a pedagogical approach called test-driven learning (TDL) that integrates TDD instruction at all levels. TDL was partially applied at all academic levels from early programming instruction through professional continuing education. Results indicate some differences between beginning and mature developers including reluctance by early programmers to adopt the TDD approach.

By providing the first substantial empirical evidence on TDD and internal software quality, this research establishes a benchmark and framework for future empirical studies. By focusing on both software design and software testing, this research is already raising awareness of TDD as both a design and testing approach through publications and international awards.

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Chapter 1

Introduction

Test-driven development (TDD) [16] is a novel software development practice that has gained recent attention with the popularity of the Extreme Programming software development methodology. Although TDD may have been applied narrowly and in various forms for several decades, there is evidence that TDD may be at an opportunistic point in its evolution for widespread adoption. The essence of TDD as a design methodology is virtually unstudied, yet scattered early adoption has proceeded based solely on anecdotal evidence.

1.1 Objective

The objective of this research is to study the impact of TDD on the design of software. This research is the first to empirically evaluate the effects of TDD on internal software quality through a series of controlled experiments conducted in academic and industrial contexts.

Early and intermediate results from this work have been widely reported in the literature, and the research has garnered several awards. Most notably, this research was recognized among the three best graduate research projects of 2005 at the ACM Awards Banquet in San Francisco where the A.M. Turing Award was also given.

This chapter summarizes the problem being solved by this research, the solution approach, and the significance of the research contributions. It provides a brief introduction to the test-driven development strategy, summarizes the research conducted, and describes the contents of the remaining chapters.

1.2 State of Software Construction

Software construction is a challenging endeavor. It involves a complex mix of creativity, discipline, communication, and organization. The Standish Group has been studying the state of software projects since 1985 and their research demonstrates

Year	Successful Projects	Challenged Projects	Failed Projects
1995	16.2%	52.7%	31.1%
2004	29%	53%	18%

Table 1.1: Standish Group Comparison of IT Project Success Rates

the difficulty organizations have successfully completing software projects. Table 1.1 compares 1995 statistics [1] with those from the third quarter of 2004 [3]. The 2004 numbers result from over 9,000 software projects from all around the world (58% US, 27% Europe, 15% other) developed by a wide-range of organizations (45% large, 35% mid-range, 20% small) in a variety of domains. Successful projects are those that deliver the requested functionality on-time and within budget. Challenged projects are either late, over budget, and/or deliver less than the required features and functions. Failed projects have been canceled prior to being completed or they were delivered and never used.

As the table demonstrates, the state of software construction has improved considerably since 1994. However, still less than one third of all projects are completed successfully and 18% or nearly one in five projects still failed completely.

Software construction has been compared to constructing buildings, bridges, and automobiles among others. In his 1994 Turing Award lecture, Alan Kay opined that software construction is similar in maturity to building the ancient Egyptian pyramids where thousands of workers toiled for years to build a facade over a rough inner structure. He compared this with the efficiency of constructing the Empire State Building which took just over one year and about seven million man hours to complete. He noted that the process was so efficient that the steel was often still warm from the mills in Pittsburgh when it was being assembled in New York.

While the Empire State Building is a fantastic goal for software construction, there are clearly many differences in the nature of skyscraper construction and software construction. Plus we might note that the Empire State Building set a record for skyscraper construction that still stands today. The point of Kay's discussion is still quite clear and consistent with the Standish numbers: software construction has much room for improvement.

1.3 State of Software Research

Improving the state of software construction is of considerable interest not just in professional software development organizations. Much research has been and continues to be conducted. However, as Brooks points out in his classic 1987 paper [33], most software research focuses on the wrong topics if we want to improve the state of software construction. Brooks classifies software activities as essential

and accidental tasks. Essential tasks focus on conceptual structures and mechanisms for forming abstractions with complex software, while accidental tasks focus more on technologies that facilitate mapping abstractions into actual programs.

In the years since Brooks' paper, there is still much attention on accidental tasks. Web services, modern integrated development environments, and new languages such as Java and C# are just a few examples. Professional training courses are still predominantly focused on new technologies, and undergraduate curriculums continue to emphasize many technical skills while paying relatively little attention to more conceptual and organizational skills such as software design and software development methods.

Attention has been drawn, however, to many essential tasks such as visual modeling, software organization, and development methods. The context for the research proposed in this paper in fact lies in the very iterative and evolutionary types of development models that Brooks was advocating.

Unfortunately few new ideas are thoroughly examined. As Gibbs wrote in 1994, "after 25 years of disappointment with apparent innovations that turned out to be irreproducible or unscalable, many researchers concede that computer science needs an experimental branch to separate the general results from the accidental." [85]

1.3.1 Empirical Software Engineering

Empirical software engineering has emerged as a valuable research discipline that examines ideas in software engineering. While empirical studies will rarely produce absolute repeatable results, such studies can provide evidence of causal relationships, implying results that will most likely occur in given contexts.

Empirical software engineering projects have received significant government and corporate funding. Research centers have been founded such as the "NSF Center for Empirically-Based Software Engineering," the "Software Engineering Institute" at Carnegie Mellon University, and the "Centre for Advanced Software Engineering Research." Many journals such as *IEEE Transactions on Software Engineering* specifically request empirical studies and Springer publishes a dedicated journal titled *Empirical Software Engineering: An International Journal*.

1.4 Summary of Research

This research applies empirical software engineering techniques to examine a newly popularized approach that holds promise to significantly improve the state of software construction. Test-driven development is a relatively new, unstudied development strategy that has caught the attention of a number of prominent computer

scientists. Steve McConnell in his 2004 OOPSLA keynote address included test-driven development as the only yet-to-be-proven development practice among his top ten advances of the last decade.

The next section will briefly introduce test-driven development and the practice will be explored further in chapter 2. The majority of this dissertation then will describe how empirical software engineering practices were applied to examine test-driven development's efficacy or ability to produce desirable results. In particular this research assesses how well test-driven development improves software design quality while also reducing defect density, and whether these improvements come with a cost of increased effort or time.

This research is the first comprehensive evaluation of how TDD affects overall software architecture quality beyond just defect density. The research included eight formal controlled experiments and an extensive case study. The research was conducted in a Fortune 500 company in Kansas and in academic courses at the University of Kansas. The studies involved over two hundred developers writing over fifty thousand lines of code.

Statistically significant results indicate that TDD can improve internal design quality while potentially improving external quality by increasing test coverage. In addition, survey data reveals that developer opinions about the TDD process improve with TDD experience whereas opinions of test-last programming decrease. As usual TDD is not a silver bullet. The approach also appears to increase software coupling, although there is some indication that the coupling may have some beneficial qualities.

1.5 Introduction to Test-Driven Development

Test-driven development is a software development strategy that requires that automated tests be written prior to writing functional code in small, rapid iterations. Although TDD has been applied in various forms for several decades [56] [36], it has gained increased attention in recent years thanks to being identified as one of the twelve core practices in Extreme Programming (XP) [15].

Extreme Programming is a lightweight, evolutionary software development process that involves developing object-oriented software in very short iterations with relatively little up front design. XP is a member of a family of what are termed agile methods [14]. Although not originally given this name, test-driven development was described as an integral practice in XP, necessary for analysis, design, and testing, but also enabling design through refactoring, collective ownership, continuous integration, and programmer courage [15].

In the few years since XP's introduction, test-driven development has received increased individual attention. Besides pair programming [88] and perhaps refactoring [32], it is likely that no other XP practice has received as much individual at-

tention as TDD. Tools have been developed for a range of languages specifically to support TDD. Books have been written explaining how to apply TDD. Research has begun to examine the effects of TDD on defect reduction and quality improvements in both academic and professional practitioner environments. Educators have begun to examine how TDD can be integrated into computer science and software engineering pedagogy. Some of these efforts have been in the context of XP projects, but others are independent.

1.6 Significance of Research Contributions

Advocates claim that TDD is more about design than it is about testing. The fact that it involves both design and testing indicates that if it works, there are many benefits to be gained.

Software development organizations are hard-pressed to select the most effective set of practices that produce the best quality software in the least amount of time. Empirical evidence of a practice's efficacy are rarely available and adopting new practices is time-consuming and risky. Such adoptions often involve a significant conceptual shift and effort in the organization including but not limited to developer training, acquiring and implementing new tools, and collecting and reporting new metrics.

In 2000, Laurie Williams completed her PhD at the University of Utah. Her dissertation presented the results of empirical studies she conducted on pair programming, another XP practice. This new approach has since gained significant popularity, largely based on the empirical evidence. Williams has gone on to publish widely on pair programming and related topics, and she has been very successful in attracting both government and corporate funding for her work.

This research contributes empirical results perhaps even more beneficial than Williams' results on pair programming. While pair programming has been shown to improve defect detection and code understanding, this research demonstrates that TDD does the same with the advantage of also improving software designs. The results from this study will assist professional developers in understanding and choosing whether to adopt test-driven development. For the first time, it reveals the effects on software design quality from applying TDD. It explores many important quality aspects beyond defect density such as understandability, reusability, and maintainability.

In addition, this research makes important pedagogical contributions. The research contributes a new approach to teaching that incorporates teaching with tests called "test-driven learning" (TDL) [50]. The research demonstrates that undergraduate computer science students can learn to apply TDD, and it examines at what point in the curriculum TDD is best introduced.

The early publications, significant conference interest, and prestigious ACM awards

indicate that this research should have a significant impact on the state of software construction because it demonstrates that TDD can significantly improve software quality at minimal cost. The significant results of this research should compel software development organizations to adopt TDD in appropriate situations. In addition the research contributes essential tools for teaching TDD whereby facilitating the crucial inclusion in academia. New textbooks and instructional materials can be written applying the test-driven learning approach. As students learn to take a more disciplined approach to software development associated with TDD, they will carry these skills into professional software organizations and improve the overall state of software construction.

1.7 Summary of Remaining Chapters

Chapter 2 will more thoroughly present the context in which TDD has developed and evolved. Test-driven development will be defined more precisely. Iterative, incremental, and evolutionary development processes will be discussed, along with historical references to various emerging forms of TDD. References to TDD in academia will be noted, and particular attention will be given to the recent context in which TDD has gained popularity.

Chapter 3 will survey the current state of research on TDD, independent of its context. It will not attempt to survey XP research that may provide indirect knowledge of TDD. However some observations on XP practices will be noted, revealing potential reasons why pair programming and TDD can be easily extracted from XP to be studied and applied in a wide variety of process methodologies. It will attempt to provide the necessary definitions and background to fully understand TDD. Then it will attempt to establish the current state of evaluative research on TDD. Finally it will establish the motivation for this research, based on identified shortcomings in previous work.

Chapter 4 presents the methods by which this research was carried out. The chapter begins with an extensive example of how TDD is used in software development and particularly how it can influence design decisions. Experiment design, anticipated risks, and actual experiences are then reported. The chapter identifies tools and metrics that were utilized, and discusses how the results were analyzed and assessed.

Chapters 5 and 6 report and discuss the results of the research conducted in industrial and academic settings respectively. Finally, chapter 7 summarizes the work and discusses its potential to improve the state of software construction and pedagogy. Future work will be identified.

Appendix A describes a new pedagogical approach called test-driven learning (TDL). Although TDL played an important, but relatively small role in the empirical studies, it is recognized as a significant by-product of this research, garnering sig-

nificant attention among computer science educators. Appendix B includes several artifacts developed for teaching TDD using the TDL approach.

Appendix C presents some of the custom-built software tools used in collecting and analyzing the software resulting from the empirical studies. Appendix D gives definitions for the metrics used in analyzing the software in this research. Appendix E compares a number of metrics tools evaluated in the course of conducting this research. Finally appendix F presents the actual survey instruments developed and administered in the empirical studies.

Chapter 2

Test-Driven Development in Context

This chapter presents the context wherein test-driven development is emerging. It surveys a variety of definitions for test-driven development, and provides a new one for the purposes of this research. It discusses historical and recent events that have contributed to the current understanding of test-driven development.

2.1 Definitions of TDD

Although its name would imply that TDD is a testing method, a close examination of the name reveals a more complex picture.

2.1.1 Significance of "Test" in TDD

As the first word implies, test-driven development is concerned with testing. More specifically it is about writing automated unit tests. Unit testing is the process of applying tests to individual units of a program. There is some debate regarding what exactly is a unit in software. Even within the realm of object-oriented programming, both the class and the method have been suggested as the appropriate unit. Generally, however, we will consider a unit to be "the smallest possible testable software component" [20] which currently [17] appears to be the method or procedure.

Test drivers and function stubs are frequently implemented to support the execution of unit tests. Test execution can be either a manual or automated process and may be performed by developers or dedicated testers. *Automated* unit testing involves writing unit tests as code and placing this code in a test harness [20] or a framework such as JUnit [59]. Automated unit testing frameworks can reduce the effort of testing, even for large numbers of tests to a simple button click. In contrast, when test execution is a manual process, developers and/or testers may be required to expend significant effort proportional to the number of tests executed.

Traditionally, unit testing has been applied some time after the unit has been coded. This time interval may be quite small (a few minutes) or quite large (a few months). The unit tests may be written by the same programmer or by a designated tester. With TDD, however, unit tests are prescribed to be written *prior* to writing the code under test. As a result, the unit tests in TDD normally don't exist for very long before they are executed.

2.1.2 Significance of "Driven" in TDD

Some definitions of TDD seem to imply that TDD is primarily a testing strategy. For instance, according to [59] when summarizing Beck [17],

> Test-Driven Development (TDD) is a programming practice that instructs developers to write new code only if an automated test has failed, and to eliminate duplication. The goal of TDD is 'clean code that works.' [51]

However, according to XP and TDD pioneer Ward Cunningham, "Test-first coding is not a testing technique." [16] In fact TDD goes by various names including Test-First Programming, Test-Driven Design, and Test-First Design. The *driven* in test-driven development focuses on how TDD informs and leads analysis, design and programming decisions. TDD assumes that the software design is either incomplete, or at least very pliable and open to evolutionary changes. In the context of XP, TDD even subsumes many analysis decisions. In XP, the customer is supposedly "on-site", and test writing is one of the first steps in deciding what the program should do, which is essentially an analysis step.

Another definition which captures this notion comes from The Agile Alliance [7],

> Test-driven development (TDD) is the craft of producing automated tests for production code, and using that process to drive design and programming. For every tiny bit of functionality in the production code, you first develop a test that specifies and validates what the code will do. You then produce exactly as much code as will enable that test to pass. Then you refactor (simplify and clarify) both the production code and the test code.

As is seen in this definition, promoting testing to an analysis and design step involves the important practice of refactoring [32]. Refactoring is a technique for changing the structure of an existing body of code without changing its external behavior. A test may pass, but the code may be inflexible or overly complex. By refactoring the code, the test should still pass *and* the code will be improved.

Understanding that TDD is more about analysis and design than it is about testing may be one of the most challenging conceptual shifts for new adopters of the practice. As will be discussed later, testing has traditionally assumed the existence

of a program. The idea that a test can be written before the code, and even more, that the test can aid in deciding what code to write and what its interface should look like is a radical concept for most software developers.

2.1.3 Significance of "Development" in TDD

TDD is intended to aid the construction of software. TDD is not in itself a software development methodology or process model. TDD is a practice, or a way of developing software to be used in conjunction with other practices in a particular order and frequency in the context of some process model. As we will see in the next section, TDD has emerged within a particular set of process models. It seems possible that TDD could be applied as a micro-process within the context of many different process models.

We have seen that TDD is concerned with analysis and design. We don't want to ignore the fact that TDD also produces a set of automated unit tests which provide a number of side-effects in the development process. TDD assumes that these automated tests will not be thrown away once a design decision is made. Instead the tests become a vital component of the development process. Among the benefits, the set of automated tests provide quick feedback to any changes to the system. If a change causes a test to fail, the developer should know within minutes of making the change while it is still fresh in his or her mind. Among the drawbacks, the developer now has both the production code and the automated tests which must be maintained.

2.1.4 A New Definition of TDD

TDD definitions proposed to date assume an unspecified design and a commitment to writing automated tests for all non-trivial production code. Despite TDD's promise of delivering "clean code that works", many developers seem to be reluctant to try TDD. This reluctance is perhaps at least partially a result of the choice of overall development process in an organization. Obviously an organization that is applying XP is willing to attempt TDD. However, an organization that is using a more traditional approach is likely unable to see how TDD can fit. This and other factors affecting this choice will be more fully addressed in chapter three.

To expand the utility and applicability of TDD, I propose the following modification of the Agile Alliance definition:

> Test-driven development (TDD) is a software development strategy that requires that automated tests be written prior to writing functional code in small, rapid iterations. For every tiny bit of functionality desired, you first develop a test that specifies and validates what the code will do. You then produce exactly as much code as will enable that test to pass. Then

you refactor (simplify and clarify) both the code under test and the test code. Test-driven development can be used to explore, design, develop, and/or test software.

This definition broadens TDD's sphere of influence by suggesting that TDD can be used to:

- explore a specified or unspecified design
- explore a new or unfamiliar component
- design software
- develop software given a design
- develop tests for software given only its interface

This definition removes the restrictions of working on an unspecified design and working only on production code. It introduces the possibility that TDD could be used as a prototyping mechanism for working out a potential design, without requiring the tests to stick around.

2.2 Survey of Software Development Methodologies

The remainder of this chapter discusses the context that has contributed to the emergence of test-driven development. This section provides a broad survey of software development methodologies to help establish a background for understanding test-driven development.

A software development process or methodology is a framework which defines a particular order, control, and evaluation of the basic tasks involved in creating software. Software process methodologies range in complexity and control from largely informal to highly structured. Methodologies may be classified as being prescriptive [70] or agile [14], and labeled with names such as waterfall [74], spiral [18], incremental [70], and evolutionary [38].

When an organization states that it is using a particular methodology, they are often applying on a project-scale certain combinations of smaller, finer-grained methodologies. For example, an organization may be applying an incremental model of development, building small, cumulative slices of the project's features. In each increment however, they may be applying a waterfall or linear method of determining requirements, designing a solution, coding, testing, and then integrating. Depending on the size of the increments and the time frame of the waterfall, the process may be labeled very differently with possibly very different results regarding quality and developer satisfaction.

If we break a software project into N increments where each increment is represented as I_i, then the entire project could be represented by the equation $\sum_{i=1}^{N} I_i$. If N is reasonably large, then we might label this project as an incremental project. However if $N \leq 2$, then we would likely label this as a waterfall project.

If the increments require the modification of a significant amount of overlapping software, then we might say that our methodology is more iterative in nature. Stated more carefully, for project P consisting of code C and iterations $I = \sum_{i=1}^{N} I_i$, if C_i is the code affected by iteration I_i, then if project P is iterative, $C_i \cap C_{i+1} \neq \emptyset$ for *most* i such that $1 < i < N$. Similarly, with the incremental and waterfall approaches, we might expect a formal artifact (such as a specification document) for documenting the requirements for that increment. If however, the artifact is rather informal (some whiteboard drawings or an incomplete set of UML diagrams), and was generated relatively quickly, then it is likely that we were working in the context of an agile process. Or, the approach and perspective of the architecture and/or design might cause us to label the process as aspect-oriented, component-based, or feature-driven.

Drilling down even further, we might find that individual software developers or smaller teams are applying even finer-grained models such as the Personal Software Process [44] or the Collaborative Software Process [86]. The time, formality, and intersection of the steps in software construction can determine the way in which the process methodology is categorized.

Alternatively, the order in which construction tasks occur influences a project's label, and likely its quality. The traditional ordering is requirements elicitation, analysis, design, code, test, integration, deployment, maintenance. This ordering is very natural and logical, however we may consider some possible re-orderings. Most re-orderings do not make sense. For instance, we would never maintain a system that hasn't been coded. Similarly, we would never code something for which we have no requirements. Note that requirements do not necessarily imply formal requirements, but may be as simple as an idea in a programmer's head. The Prototyping approach [19] has been applied when requirements are fuzzy or incomplete. With this approach, we may do very little analysis and design before coding. The disadvantage is that the prototype is often discarded even though it was a useful tool in determining requirements and evaluating design options.

When we closely examine the phases such as design, code, and test, we see that there are many finer-grained activities. For instance, there are many types of testing: unit testing, integration testing, and regression testing among others. The timing, frequency, and granularity of these tests may vary widely. It may be possible to conduct some testing early, concurrent with other coding activities. Test-driven development, however, attempts to re-order these steps to some advantage. By placing very fine-grained unit tests just prior to just enough code to satisfy that test, TDD has the potential of affecting many aspects of a software development methodology.

2.3 Historical Context of TDD

Test-driven development has emerged in conjunction with the rise of agile process models. Both have roots in the iterative, incremental and evolutionary process models, going back at least as early as the 1950's. In addition, tools have evolved and emerged to play a significant role in support of TDD. Curriculum seems to be lagging in its adoption of TDD, but XP in general has seen some favorable attention in the academic community.

2.3.1 Early Test-Early Examples

Research on testing has generally assumed the existence of a program to be tested [40], implying a test-last approach. Moving tests, however, from the end of coding to the beginning is nothing new. It is common for software and test teams to develop tests early in the software development process, often along with the program logic. Evaluation and Prevention Life Cycle Models [36] integrated testing early into the software development process nearly two decades back. Introduced in the 1980s, the Cleanroom [28] approach to software engineering included formal verification of design elements early in the development process. There are even claims that some form of TDD was applied as early as the 1950's in NASA's Project Mercury [56].

However, prior to the introduction of XP in 1998, very little if anything has been written about the concept of letting small incremental automated unit tests *drive* the software development and particularly the design process. Despite the lack of published documentation, it is very possible that many developers have used a test first approach informally. Kent Beck even claims he

> learned test-first programming as a kid while reading a book on programming. It said that you program by taking the input tape ... and typing in the output tape you expect. Then you program until you get the output tape you expect. [16]

One might argue then that TDD merely gives a name and definition to a practice that has been sporadically and informally applied for some time. It seems, however, that TDD is a bit more than this. As Beck states, XP takes known best practices and "turns the knobs all the way up to ten." In other words, do them in the extreme. Many developers may have been thinking and coding in a test-first manner, but TDD does this in an extreme way, by always writing tests before code, making the tests as small as possible, and never letting the code degrade (test, code, refactor). As we will see next, TDD is a practice that must fit within a process model. The development of incremental, iterative, and evolutionary process models has been vital to the emergence of TDD.

2.3.2 Incremental, Iterative, and Evolutionary Development

Larman and Basili [56] survey a long history of iterative and incremental development models. Iterative development involves repeating a set of development tasks, generally on an expanding set of requirements. Evolutionary approaches as first presented by Gilb [38] involve iterative development which is adaptive and lightweight. Being adaptive generally refers to using feedback from previous iterations to improve and change the software in the current iteration. Being lightweight often refers to the lack of a complete specification at the beginning of development, allowing feedback from previous iterations and from customers to guide future iterations. Lightweight can refer to other aspects such as the level of formality and degree of documentation in a process. The spiral model [18] is an evolutionary approach that incorporates prototyping and the cyclic nature of iterative development along with "risk-driven-iterations" and "anchor point milestones"

According to Pressman [70],

> The incremental model delivers a series of releases, called *increments*, that provide progressively more functionality for the customer as each increment is delivered.

It was within the context of such iterative, incremental, and evolutionary models that TDD developed. In fact, it appears that such iterative, incremental, and/or evolutionary approaches are prerequisite process models which are necessary for TDD to work. As we have stated, TDD is most closely associated with XP which is an iterative, evolutionary model. In fact, Beck claims that in order to implement XP, you must apply all of the incumbent practices. Leaving some out weakens the model and may cause the model to fail [15]. In order for TDD to influence software design, TDD requires that design decisions be delayed and flexible. With each new test, something new may be revealed about the code which requires a refactoring and possible change to the design as determined at that point. Automated tests give the programmer courage to change any code and know quickly if anything has broken, enabling collective ownership.

As originally proposed, TDD requires some form of an evolutionary process model. The converse, however, is clearly not true as many iterative, incremental, and/or evolutionary models have been proposed without the mention of TDD.

2.4 Emergence of Automated Testing Tools

Software tools have become important factors in the development of modern software systems. Tools ranging from compilers, debuggers, and integrated development environments (IDEs) through modeling and computer-aided software engineering (CASE) tools have improved and hence significantly increased developer productivity. Similarly testing tools have matured over the years.

Testing tools vary in purpose and scope, and will not be reviewed here. However, it is important to note the role that tools have played in the emergence of TDD. TDD assumes the existence of an automated unit testing framework. Such a framework simplifies both the creation and execution of software unit tests. Test harnesses are basically automated testing frameworks and have existed for some time. A test harness is a combination of test drivers, stubs, and possibly interfaces to other subsystems [20]. Often such harnesses are custom-built, although commercial tools do exist to assist with test harness preparation [69].

JUnit [34] is an automated unit testing framework for Java developed by Erich Gamma and Kent Beck. JUnit is an essential tool for implementing TDD with Java. In fact, it might be argued that TDD and possibly even XP might not have received such wide popularity if it weren't for JUnit. JUnit-like frameworks have been implemented for a number of different languages, and the family of frameworks is referred to as xUnit [89].

Generally, xUnit allows the programmer to write sets of automated unit tests which initialize, execute, and make assertions about the code under test. Individual tests are independent of each other so that test order does not matter, and total numbers of successes and failures are reported. xUnit tests are written in the same language as the code under test and thus serve as first-class clients of the code. As a result, tests can serve as documentation for the code. On the other hand, because xUnit is implemented in the target language, the tool's simplicity and flexibility are determined somewhat by that language. For instance JUnit is very simple and portable, partly because it takes advantage of Java's portability through the bytecode/virtual machine architecture, it uses Java's ability to load classes dynamically, and it exploits Java's reflection mechanism to automatically discover tests. In addition, it provides a nice, portable graphical user interface that has even been integrated into popular integrated development environments like Eclipse.

A wide range of additional tools have emerged to support automated testing, particularly in Java. Several tools attempt to simplify the creation of mock objects [9] which are essentially stubs which stand-in for needed collaborating objects so that one can only test a particular object. Other tools such as Cactus [10] and Derby [11] can be used in conjunction with JUnit to automate tests which involve J2EE components or databases respectively.

The proliferation of software tools supporting TDD seems to be an indicator that TDD has widespread support and may be on its way to becoming an established approach. A significant factor in the use of TDD particularly in the Java community seems to be the simplicity and elegance of the JUnit tool. Programmers can develop unit-tests easily, and large suites of tests can be executed with a single click of a button, yielding quick results on the state of the system.

2.5 Early Testing in Curriculum

One indicator of the widespread acceptance of a software practice might be the undergraduate curriculum in computer science and software engineering. In some cases, academia has led practice in the field. In others, academia has followed. Software Engineering, iterative development and TDD seem to all fall in with the latter model.

Although much software engineering research has originated in academia, and found its way into common practice, the undergraduate curriculum in computer science and software engineering has tended to reflect and lag behind common practice in industry. Programming Language choice has commonly followed the needs of businesses. Process models have developed in practice and then later been reflected in curriculums.

The 1991 ACM Curriculum Guidelines [6] recommended that a small amount of lecture and lab time be given to iterative development processes (SE2) and verification and validation (SE5) (portions of eight hours each). The 2001 ACM Curriculum Guidelines [2] recommended that a perhaps even smaller amount of time be given to development processes (SE4) and software validation (SE6) (two and three hours respectively).

Undergraduate texts give little attention to comparative process models. Texts have limited coverage of software design and often have minimal coverage of testing techniques. The topics of software design and testing are often relegated to a software engineering course which may not even be required of all students.

There is much debate regarding the place of Extreme Programming in undergraduate education. Some [41] argue strongly in favor of using XP to introduce software engineering to undergraduates. Others [76] argue that XP and agile methods are only beneficial on a very limited basis. Still others [65] report mixed experiences.

Despite the mix of opinions on using XP in the undergraduate curriculum, TDD is receiving some limited exposure at this level. Some educators have called for increased design and testing coverage for some time. Some see TDD as an opportunity to incorporate testing throughout the curriculum, and not relegate it to an individual course [22].

TDD tools have found their way into early programming education. BlueJ [54], a popular environment for learning Java has incorporated JUnit and added helps for building test cases at an early stage in a programmer's learning cycle [67]. JUnit has been advocated for early learning of Java because it abstracts the bootstrapping mechanism of *main()*, allowing the student to concentrate on the use of objects early.

TDD, however, is still far from being widely accepted in academia. Faculty who don't specialize in software engineering are still unlikely to have much familiarity with TDD. Instructional materials on TDD targeted at undergraduate courses are basically non-existent. As we will discuss in section five, several steps need to take

place before TDD finds its place in the undergraduate curriculum.

2.6 Recent Context of TDD

Test-driven development has emerged in the context of agile methods. This section notes the significance of agile methods and considers attempts to measure how many development groups are applying agile methods.

2.6.1 Emergence of Agile Methods

The early years of the twenty-first century have seen significant attention given to what are deemed *agile* methods. Agile methods clearly have roots in the incremental, iterative, and evolutionary methods discussed earlier. Abrahamsson et al. [5] provide an evolutionary map of nine agile methods, and describe such methods as focusing primarily on simplicity and speed, emphasizing people over processes [4].

Extreme Programming (XP) [15] is probably the most well-known agile method, and in fact XP is often used in combination with other agile methods such as Scrum. XP proposes the use of TDD as an integral component of developing high-quality software. There is an interesting conflict between the highly disciplined practice of TDD and the simple, lightweight nature of agile processes. In fact, one of the primary concerns of potential adopters of TDD seems to be the overhead or cost/time of writing and maintaining the unit tests. Although he concedes that automated unit tests are not necessary for absolutely everything (some things are still hard to automatically test), Beck insists that TDD is necessary for XP to work. It seems that TDD may provide the "glue" that holds the process together.

2.6.2 Measuring Adoption of Agile Methods

It is hard to measure the use of a particular software development methodology. Many organizations may be using the methodology, but not talking about it. Others might claim to be using a methodology, when in reality they may be mis-applying the methodology, or worse yet, advertising its use falsely. Surveys might be conducted to gauge a methods use, but often only those who are enthusiastic about the methodology (either in favor or opposed) will respond.

A 2002 survey [73] reported that out of 32 survey respondents across ten industry segments, fourteen firms were using an agile process. Of these, five of the firms were categorized in the E-business industry. Most of the projects using agile processes were small (ten or fewer participants) and lasting one year or less. Another 2003 survey [79] reported 131 respondents claiming they were using an agile method. Of these, 59% claimed to be using XP, implying that they were using TDD.

Both surveys revealed positive results from applying agile methods with increases in productivity and quality, and reduced or minimal changes in costs.

A substantial body of literature regarding XP has accumulated since its inception. Most of this literature admittedly involves promotion of XP or explanations of how to implement XP. Many experience reports present only anecdotal evidence of benefits and drawbacks of XP. However, their existence indicates that XP is being adopted in many organizations. It is not clear yet if these same organizations will continue to use XP over time, or if they have or will move on to other (or old) methods.

We are unaware of any measure of how widespread is the use of TDD. The popularity of XP, however, seems to imply a growing adoption of TDD. It is possible that organizations are adopting XP without adopting all of the practices, or they are applying some practices inconsistently. Rasmusson reports on a project at ThoughtWorks, an early adopter of XP, in which he estimates that one-third of the code was developed using TDD [71]. In the same report, though, he states,

> If I could only recommend one coding practice to software developers, those who use XP or otherwise, it would be to write unit tests.

In this ThoughtWorks project, 16,000 lines of automated unit tests were written for 21,000 lines of production code. It appears that many tests were written in both a test-first and test-last manner.

Despite the possibility of adopting XP without TDD, TDD seems to be a core practice in XP and anecdotal evidence seems to indicate that TDD is commonly included when only a subset of XP is adopted.

Another possible indicator of the use of TDD is the use of the xUnit testing frameworks. JUnit was the first such framework and it has enjoyed widespread popularity. As Martin Fowler stated regarding JUnit,

> Never in the field of software development was so much owed by so many to so few lines of code [34].

No adoption statistics are directly available for JUnit. However, JUnit is included in the core distribution of Eclipse, a popular integrated development environment which is primarily used for Java development. A February, 2004 press release [24] states that the Eclipse platform has recorded more than 18 million download requests since its inception. Although duplicate requests likely occur from the same developer requesting new releases, the figure is still substantial. Certainly not all Eclipse developers are using JUnit, nor are all JUnit adopters using TDD, but it seems likely that the combination of XP, JUnit, and Eclipse popularity implies some degree of TDD adoption.

Chapter 3

Related Work

Since the introduction of XP, many practitioner articles and several books [12,17,59] have been written describing how to apply TDD. Relatively little evaluative research, however has been published on the benefits and effects of TDD.

This chapter will summarize and classify the research discovered to date that specifically evaluates TDD. There are a number of publications on XP and agile methods, many anecdotal and some empirical. The first section will present some observations that validate the notion that TDD can be studied and applied independent of XP. However, this discussion will generally exclude research on XP or agile methods as a whole. Such research on agile methods might prove informative when examining TDD, but it fails to prove any individual merits or shortcomings of TDD.

Research on TDD can be categorized broadly by context. In particular, TDD research will be classified as "Industry" if the study or research was primarily conducted with professional software practitioners. Alternatively, the research will be classified as "Academia" if the software practitioners are primarily students and the work is in the context of a course or some academic setting. Studies in which students work on a project for a company but as the requirements and in the context of some course will be classified with "Academia".

3.1 XP and TDD Observations

As mentioned earlier, TDD has gained significant exposure in recent years due to the popularity of XP. In fact, many would claim that the two are intrinsically linked. XP inventors and advocates claim that XP is not XP without TDD. This research however examines TDD independent of XP. This section presents some observations made by Glenn Vanderburg in the first ever Essay talk at OOPSLA'05 [81]. These observations explain why TDD can be extracted from XP and validate the attempts of this research to do exactly this.

Figure 3.1 illustrates the basic flow of XP. Development is divided into short iterations usually lasting about three or four weeks. Each iteration includes a full pass

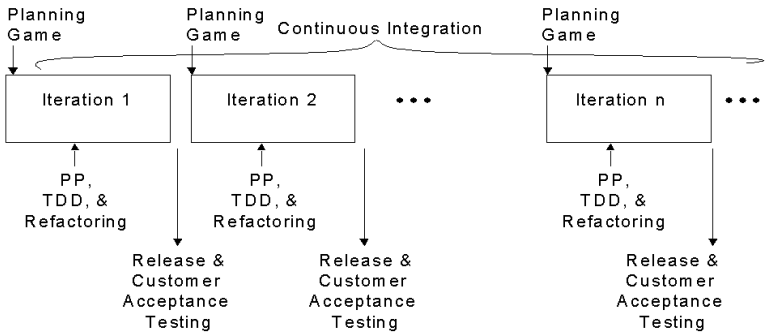

Figure 3.1: Basic Flow of XP

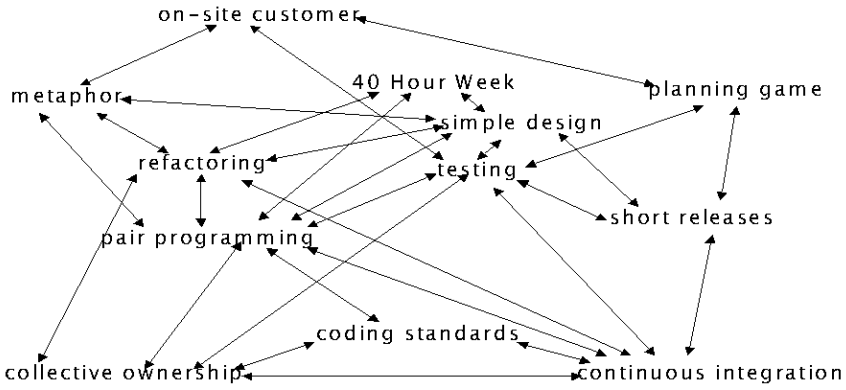

Figure 3.2: XP Practices

through a development process starting with requirements elicitation, estimation, and task assignment (Planning Game). Development proceeds using the practices of pair programming, test-driven development, and refactoring. Software is continuously integrated throughout each iteration, and a deliverable is produced at the end of each iteration.

At its core, XP consists of twelve core practices. The practices are presented in Figure 3.2. This diagram was presented in [15] to illustrate how practices reinforce each other. Vanderburg noticed the high degree of coupling between the practices and attempted to devise a model that organized the practices in a simpler yet meaningful manner. In so doing, he plotted nine of the practices on both a scale-of-focus (see Figure 3.3) and a time-scale (see Figure 3.4) graph. Notice that he separated the testing practice into two practices: test-driven development and acceptance testing. The remaining four practices he identified as noise reduction practices (see Figure 3.5), or practices that improve "the overall quality of the system in ways that allow the other practices to be more effective."

Vanderburg's organization of XP practices identifies pair programming and test-driven development as small-scale and short-scale practices. As practices go up the

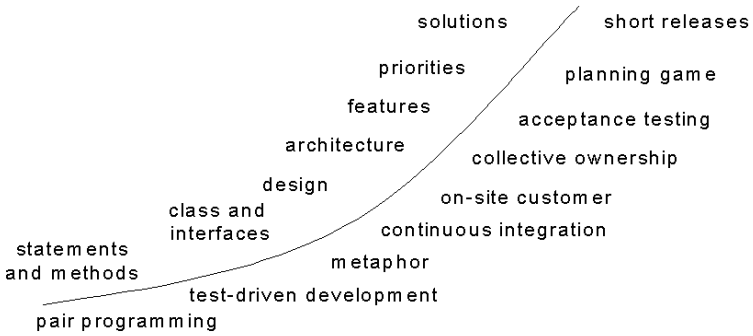

Figure 3.3: XP Scale-Defined Practices

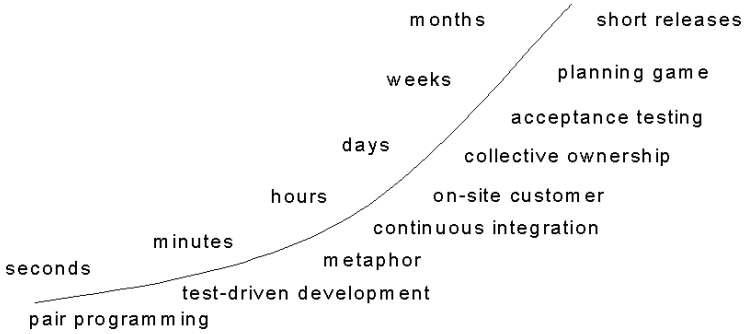

Figure 3.4: XP Time Scale-Defined Practices

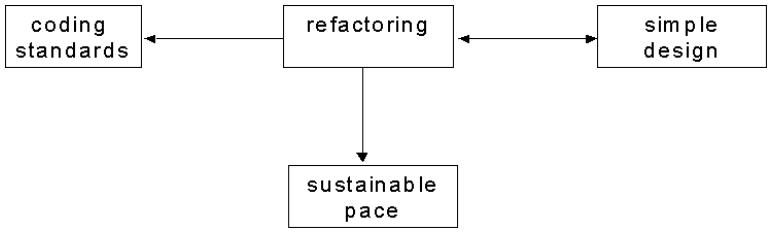

Figure 3.5: XP Noise Reduction Practices

scale, they become more dependent on lower practices. For instance, continuous integration and collective ownership are enabled by the comprehensive automated tests produced by test-driven development and the constant code review resulting from pair programming. In the collective ownership example, developers are more willing to share ownership of code when they know that other developers must keep all tests passing and that no changes will ever occur by an individual developer.

Based on these observations, it should be no surprise that pair programming and now with this research, test-driven development have been the first two practices to be studied independent of XP. As practices focusing on the smallest scales, pair-programming and test-driven development are least dependent on other practices and have the greatest potential of applying in a wider range of development processes.

Chapter 4 will further discuss how this research examines TDD in the context of a more traditional development process. Developers in the empirical studies of this research demonstrate that TDD is an effective practice independent of XP.

3.2 Evaluative Research on TDD in Industry

A very limited number of evaluative research studies have been conducted on TDD with professional practitioners. North Carolina State University (NCSU) seems to be the only source of such studies to date. Researchers at NCSU have performed at least three empirical studies on TDD in industry settings involving fairly small groups in at least four different companies [37, 60, 87]. These studies primarily examined defect density as a measure of software quality, although some survey data indicated that programmers thought TDD promoted simpler designs. In the George study, programmer experience with TDD varied from novice to expert, while the other studies involved programmers new to TDD.

These studies revealed that programmers using TDD produced code which passed between 18% and 50% more external test cases than code produced by the corresponding control groups. The studies also reported less time spent debugging code developed with TDD. Further they reported that applying TDD had from minimal impact to a 16% decrease in programmer productivity. In other words, applying TDD sometimes took longer than not using TDD. In the case of that took 16% more time, it was noted that the control group also wrote far fewer tests than the TDD group.

These studies are summarized in Table 3.1. Each experiment is labeled as either a case study (CS) or a controlled experiment (CE).

Study	Type	No. of Companies	No. of Programmers	Quality Effects	Productivity Effects
George [37]	CE	3	24	TDD passed 18% more tests	TDD took 16% longer
Maximilien [60]	CS	1	9	50% reduction in defect density	minimal impact
Williams [87]	CS	1	9	40% reduction in defect density	no change

Table 3.1: Summary of TDD Research in Industry

3.3 Evaluative Research on TDD in Academia

A number of studies are reported from academic settings. Most of these examine XP as a whole, but a few specifically focus on TDD. Although many of the publications on TDD in academic settings are primarily anecdotal [13, 62], five were discovered which report empirical results. When referring to software quality, all but one [53] of the empirical studies focused on the ability of TDD to detect defects early. Two [26, 53] of the five studies reported significant improvements in software quality and programmer productivity. One [27] reported a correlation between number of tests written and productivity. In this study, students using test-first wrote more tests and were significantly more productive. The remaining two [63, 66] reported no significant improvements in either defect density or productivity. All five studies were relatively small and involved only a single semester or less. In all studies, programmers had little or no previous experience with TDD.

Although not included here, the anecdotal studies are also beneficial to examine. For instance, the Barriocanal study reports that only 10% of the 100 students involved actually wrote unit tests, indicating that motivation is a serious concern.

The empirical studies are summarized in Table 3.2. All studies involved controlled experiments (CE).

3.4 Research Classification

Vessey et al. [39, 83] present a classification system for the computing disciplines. This system provides classification of research by topic, approach, method, reference discipline, and level of analysis. The previously mentioned studies are summarized in Table 3.3. This table applies the Vessey classification system, and the table contents are described in the following sections. This table summarizes all experi-

Study	Type	No. of Programmers	Quality Effects	Productivity Effects
Edwards [26]	CE	59	54% fewer defects	n/a
Kaufmann [53]	CE	8	improved information flow	50% improvement
Muller [63]	CE	19	no change, but better reuse	no change
Pančur [66]	CE	38	no change	no change
Erdogmus [27]	CE	35	no change	improved productivity

Table 3.2: Summary of TDD Research in Academia

mental studies found, plus two anecdotal studies. A number of additional anecdotal studies were discovered. Although some of these do have useful information as mentioned in the previous section, they reveal little concerning classification and thus are not included here.

3.4.1 Definition of "Topic" Attribute

This research concentrates solely on the topic of TDD which fits in category 3.0 Systems/Software Concepts and subcategory 3.4 Methods/techniques.

3.4.2 Definition of "Approach" Attribute

Research approaches may be descriptive, evaluative, or formulative. A number of publications were referenced in previous sections which originally presented and explained TDD. These would be considered formulative and descriptive research. This research focuses primarily on evaluative research of the TDD software method. Such research attempts to evaluate or assess the efficacy of TDD.

Evaluative approaches may be divided into the following four sub-categories: deductive (ED), interpretive (EI), critical (EC), or other (EO). From Table 3.3 one can see all of these studies are classified as evaluative-deductive.

Study	Context	Approach	Method	Reference Discipline	Level of Analysis
George [37]	Industry	ED	LH	SR	GP
Maximilien [60]	Industry	ED	FS	SR	PR
Williams [87]	Industry	ED	FS	SR	PR
Barriocanal [13]	Academia	ED	CS	SR	IN
Mugridge [62]	Academia	ED	CS	SR	GP
Edwards [25]	Academia	ED	LH	SR	IN
Kaufmann [53]	Academia	ED	LH	SR	IN
Muller [63]	Academia	ED	LH	SR	IN
Pančur [66]	Academia	ED	LH	SR	IN
Erdogmus [27]	Academia	ED	LH	SR	IN

Table 3.3: Classification of TDD Research

3.4.3 Definition of "Method" Attribute

Nineteen research methods are proposed ranging from Conceptual Analysis through Simulation. The research under consideration was determined to use either Case Study (CS), Laboratory Experiment - Human Study (LH), or Field Study (FS).

3.4.4 Definition of "Reference Discipline" Attribute

Research bases its theories on other disciplines. In the case of the computing disciplines, computer science and particularly software engineering have been found to overwhelmingly be self-referential. In other words, most computing research is based on other computing research, and it borrows little from other disciplines such as Cognitive Psychology, Science, Management, or Mathematics. This trend is true with TDD as well as all of the research under consideration is considered to be Self-Reference (SR).

3.4.5 Definition of "Level of Analysis" Attribute

The final area of classification deals with the "object on which the research study focused." [39] These objects determine the level of analysis which is almost the granularity of the object. Levels are grouped into technical and behavioral levels. These studies focused on Project (PR), Group/Team (GP), or Individual (IN) which are all behavioral levels. It might be argued that the research also focused on the technical levels of Abstract Concept (AC) because we are looking at software quality, and Computing Element (CE) because we are looking at unit tests.

3.5 Factors in Software Practice Adoption

A variety of factors play into the widespread adoption of a software practice. Motivation for change, economics, availability of tools, training and instructional materials, a sound theoretical basis, empirical and anecdotal evidence of success, time, and even endorsements of the practice by highly regarded individuals or groups can all influence the decision on whether or not to adopt a new practice.

The current state of TDD is mixed regarding this list of factors. With regard to some factors, TDD seems to be poised for growth in adoption. The state of software development practice provides a clear motivation for change. Software development is a complex mix of people, process, technology, and tools which continues to struggle to find consistency and predictability. Projects continue to run over schedule and budget, and practitioners seem eager to find improved methods.

As was noted in earlier sections, tools such as JUnit, MockObjects, and Cactus are mature and widely available. Although much of the tool development has targeted the Java Programming Language, Java is an increasingly popular language both in commercial applications and academia. Further, tool support for TDD is good and improving for most modern languages.

Economic models have considered XP and TDD [64] and note the potential for positive improvements, but recognize that additional research is needed. As was seen in the previous section, empirical and anecdotal evidence is still quite sparse, and limited to fairly small, disparate studies. This research will extend the examination of TDD extensively first by looking at software quality more broadly, and second by looking at a much larger, more diverse population over a longer period of time.

The interplay of acceptance between academics and industry practitioners is a very interesting one. Some reports indicate that it takes five to fifteen years for research developments to make it into commercial practice. The reverse pathway seems to be similar. Some research has shown how TDD can improve programming pedagogy, yet there are few instructional resources available. JUnit incorporation into BlueJ and the corresponding programming textbook indicates that improvements may be on the way in this area.

There are a number of challenges to adopting TDD. Perhaps first and foremost is that TDD requires a good deal of discipline on the part of the programmer. Hence programmers may require compelling reasons before they are willing to give it a try. Secondly, TDD is still widely misunderstood. Perhaps its name is to blame, but many still erroneously think that TDD is only about testing, not design. Third, TDD doesn't appear to fit in every situation. Section three described iterative, incremental, and evolutionary process models which work best with TDD. Developers and managers must then determine when to apply TDD and when to do something else.

It is not clear how widespread TDD will be adopted. Additional research and the availability of training and instructional materials may play an important role.

Chapter 4

Research Methodology

This chapter presents the test-driven development approach and details how this research will examine it. In the first section, TDD will be introduced with a small sample application, giving examples in Java and C++. Particular attention will be given to how TDD informs design decisions.

In the last section, the design of the formal experiment will be detailed.

4.1 TDD Example

This section will present an example of how developing an application with TDD might proceed. The application to be developed is a television channel guide as described by the use cases in Figure 4.1. We will only start the application assuming that there is only one channel and the user can only move left and right. In other words, we will not attempt the use case "Shift Channel Selection Up/Down".

In the Java implementation, the application should provide a graphical user interface that displays a window of maybe three hours worth of shows. It allows the user to select a show and scroll the window of shows to the left and right with the arrow keys.

The C++ implementation will provide a character-based user interface and allow the user to move left and right by entering 4 and 5 respectively. Screen shots of possible Java and C++ implementations are given in Figure 4.2 and Figure 4.3.

4.1.1 Java Example

First we will do a Java example. As discussed in chapter 2, JUnit is the de facto standard testing framework for Java so our example will use JUnit and TDD to develop this application.

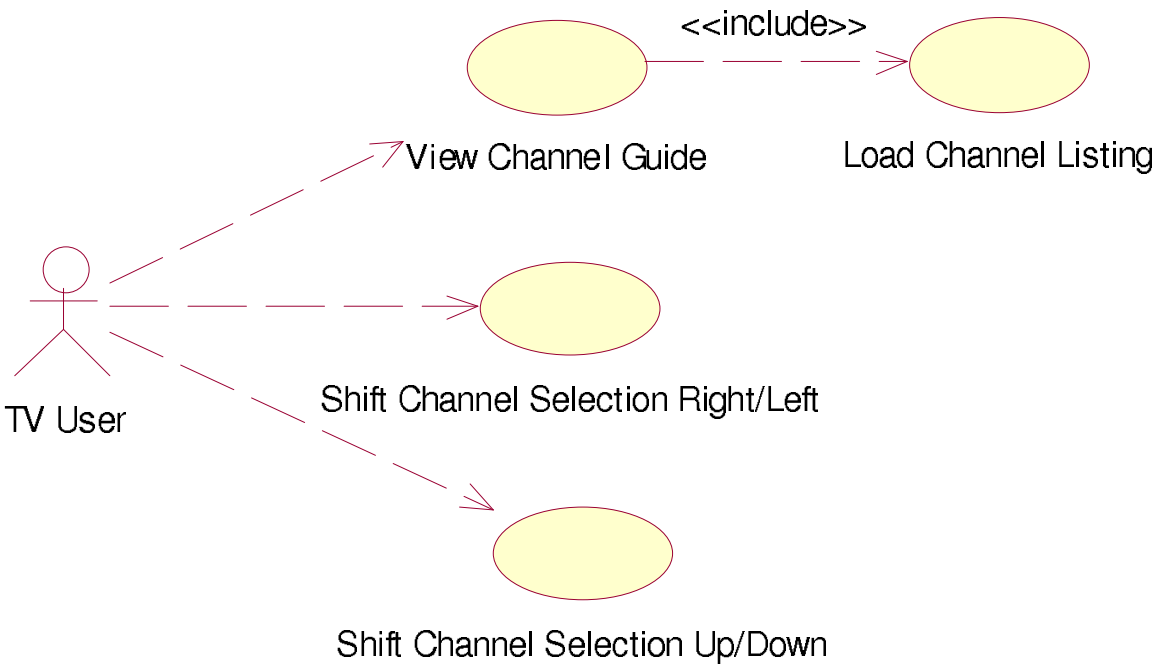

Figure 4.1: Television Channel Guide Use Cases

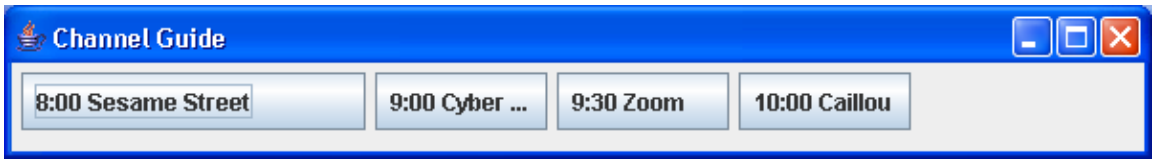

Figure 4.2: Television Channel Guide Java GUI

```
8:00            9:00            10:00   10:30
+==============++==============++======++======+
|Sesame Street ||Cyber Chase   ||Zoom  ||Arthur|
+==============++==============++======++======+
Enter 4 to move left one show, 5 to move right one show, and -1 to quit.
```

Figure 4.3: Television Channel Guide C++ Screen Shot

```
import junit.framework.TestCase;
public class TestShow extends TestCase {
  public void testShowConstructor() {
    Show oneShow = new Show("Sesame␣Street",60,8,0);
    assertEquals(oneShow.getTitle(),"Sesame␣Street");
    assertEquals(oneShow.getDuration(),60);
    assertEquals(oneShow.getStartHr(),8);
    assertEquals(oneShow.getStartMins(),0);
  }
}
```

Figure 4.4: Testing Show in Java

A First Test

To get started, the first test might be to instantiate a television show and access appropriate members. In so doing, we have identified that Show is a likely object and we must specify the interface for inserting and retrieving members. The first test might look something like the code listed in Figure 4.4.

Immediately we see the structure of a JUnit test. We gain access to the JUnit package through the import statement. Then we create a subclass of *TestCase* and write methods that begin with "test". Tests are executed with the *assertEquals()* method. We will see that there are a number of *assertXXX()* methods available to us in JUnit.

At this point, our program will not even compile because the *Show* class has not been written. Because we have only specified very simple methods to this point, we can go ahead and implement the constructors and four accessor methods, then run JUnit to see if they all pass the test. We would not implement multiple methods at once with TDD, except when they are as trivial as these. A screen shot of JUnit after all tests completed successfully is given in Figure 4.5. At this point the code for Show might look like that in Figure 4.6.

Testing Failures

Once the *Show* class has been implemented and the test passes, we might write another test to see how *Show* handles bad input. We might specify in the test that we want *Show* to throw an exception if the duration, start hour, or start minutes is out of range. Exceptional behavior can be difficult to test with integration and functional tests, but JUnit enables simple exception testing. The JUnit approach is as follows:

- Force an exception to be thrown
- Follow with a fail statement to detect if the exception is not thrown

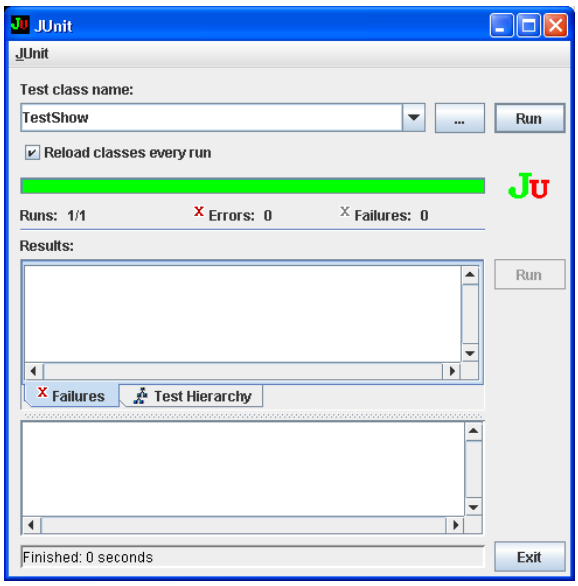

Figure 4.5: JUnit GUI - All Tests Pass

- Catch the exception and assert that it was caught

The test in Figure 4.7 specifies that the constructor should throw the exception. Notice the use of the fail method following the line that is expected to throw the exception. This technique ensures that the exception was thrown and execution did not reach the fail method. In the exception handler, the assertTrue method may be unnecessary, but it provides documentation that execution should reach this point.

Because we have not yet implemented this functionality, this test will fail as shown in Figure 4.8. We would now proceed to implement the desired exception throwing and check to see if we need to refactor to improve either the code or the tests. We would continue to repeatedly write a test, write the code to make the test pass, and refactor until we are satisfied that the *Show* class has the interface and behavior that we desire.

Refactoring to an Improved Design

Next we consider whether the *Show* class was the correct place to start. It was the first thing that came to mind, but maybe we were thinking at too low a level. After reviewing the use cases, we might decide to tackle the “Load Channel Listing” use case. We might start with the test shown in Figure 4.9.

In this test we have defined the file format, identified the *ChannelGuide* class, and specified a constructor that accepts the name of the file containing the television show listings. We might step back and consider how the test drove us to make the filename a parameter to this class. Had we been designing with a UML class diagram, we likely would have included a filename member in this class, but we may

```
public class Show {
  public Show() {}
  public Show(String title, int hr, int min, int duration){
    this.title = title;
    this.duration = duration;
    this.startHr = hr;
    this.startMins = min;
  }
  public String getTitle() {
    return title;
  }
  public int getDuration() {
    return duration;
  }
  public int getStartHr() {
    return startHr;
  }
  public int getStartMins() {
    return startMins;
  }
  private String title;
  private int duration;
  private int startHr;
  private int startMins;
}
```

Figure 4.6: Java Show Class

```
public void testBadMins() {
  try {
    Show oneShow = new Show("Cyber␣Chase",30,7,70);
    fail("Non-default␣constructor␣should␣throw␣an␣Exception␣if␣the\n"
          + "␣minutes␣parameter␣is␣greater␣than␣59␣or␣less␣than␣0");
  }
  catch (Exception expected) {
    assertTrue(true);
  }
}
```

Figure 4.7: Testing Java Exceptions

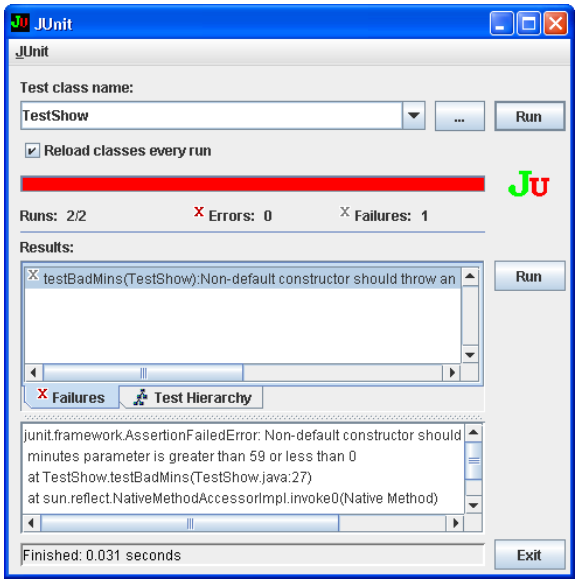

Figure 4.8: JUnit Exception Failure

```
public void testChannelGuideFromFile() {
  try {
    PrintWriter dout = new PrintWriter(
                          new FileWriter("tvlistings.txt"));
    dout.println("Sesame Street:8:0:60");
    dout.println("Cyber Chase:9:0:30");
    dout.println("Zoom:9:30:30");
    dout.println("Caillou:10:0:30");
    dout.println("Mr. Rogers:10:30:30");
    dout.println("Zooboomafoo:11:0:30");
    dout.println("Arthur:11:30:30");
    dout.close();
  } catch(IOException e) { System.out.println(e);}

  ChannelGuide cg = new ChannelGuide("tvlistings.txt");
  assertEquals(cg.numShows(),7);
}
```

Figure 4.9: Channel Guide JUnit Test

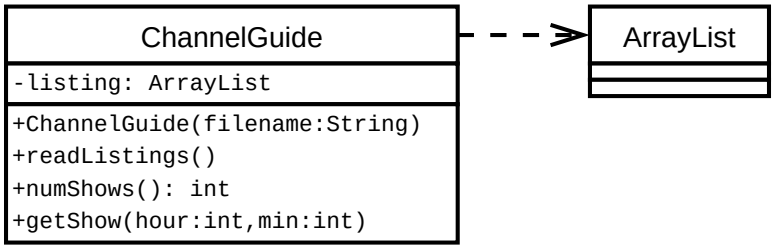

Figure 4.10: Channel Guide UML Class Diagram Prior to Refactoring

```
public void testReadListings() {
   //write shows to tvlistings.txt as in testChannelGuideFromFile()
   List testList = new ArrayList();
   ListingReader lr = new ListingReader("tvlistings.txt",testList);
   assertEquals(testList.size(),7);
 }
```

Figure 4.11: Read Shows from File Test

not have considered passing the name as a constructor parameter. Because we are thinking of how to use and test the class from the beginning, the class is naturally more testable.

Refactoring to the Dependency Injection Design Pattern

In keeping with the TDD cycle of write a test, write code, then refactor, the developer should again examine the test just completed in Figure 4.9 to see if any refactoring needs to occur. Figure 4.10 illustrates the current design with a UML class diagram.

An astute developer will notice that this test is actually testing two things. First it is testing the reading and processing of the input data file. Second it is testing the storing of the shows in some data structure. It would be better if the two functions were separated and tested independently. If the test fails, one would like to know if the failure is caused by a problem with the input file processing or if the failure is caused by a problem with the data structure. In fact by separating the two it should be easier to accommodate new functionality such as retrieving show data from a network service rather than from a file.

The test in Figure 4.11 isolates and tests the functionality of reading show listings from a file. The shows are stored in a simple ArrayList data structure. Note that the ChannelGuide class is not involved in this test at all. Instead a new ListingReader class is introduced whose sole purpose is to read shows into a List. In making this piece of functionality more testable, the two classes ChannelGuide and ListingReader have become more cohesive.

The test in Figure 4.12 isolates and tests the ChannelGuide interface for stor-

```
public void testChannelGuideAlone() {
   List testList = new ArrayList();
   testList.add(new Show("Sesame Street",8,0,60));
   //add other shows
   ChannelGuide cg = new ChannelGuide();
   cg.setListing(testList);
   assertEquals(cg.numShows(),7);
 }
```

Figure 4.12: Show Listing Data Structure Test

```
public void testChannelGuideWithDI() {
   List testList = new ArrayList();
   //testList could be any data structure that implements List
   ListingReader lr = new ListingReader("tvlistings.txt",testList);
   ChannelGuide cg = new ChannelGuide();
   cg.setListing(testList);
   assertEquals(cg.numShows(),7);
 }
```

Figure 4.13: Channel Guide with Dependency Injection Test

ing and retrieving the show listing data structure. The *setListing()* method allows the test to "inject" the data structure into the ChannelGuide class. The ChannelGuide class expects a listing that implements the List interface from the Java API. By taking this approach, the test can inject a simple ArrayList while the production ChannelGuide class can be configured or "wired" with a more advanced data structure. This approach is an example of the Dependency Injection design pattern [31]. Figure 4.13 demonstrates the use of both the show listing and the listing storage functionality in the Channel Guide class. Figure 4.14 illustrates the new design of the Channel Guide with the Dependency Injection pattern. Although this design introduces a new coupling between the ChannelGuide class and the List interface, such a coupling is highly configurable and not hard-coded.

The Dependency Injection pattern has proven to be a very powerful and popular pattern. The pattern was originally given the name Inversion of Control. Several lightweight Java frameworks such as the Spring framework [52] have emerged based primarily on this pattern. Frameworks such as Spring provide "plumbing" code that simplifies the wiring of objects and their dependencies through external configuration files such as XML.

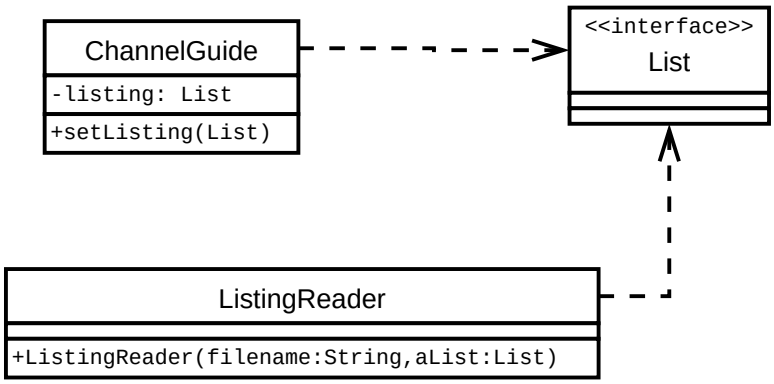

Figure 4.14: Channel Guide UML Class Diagram with Dependency Injection

Testing a Graphical User Interface

As development progresses one might notice the emphasis placed on the underlying model of the application. Because the graphical user interface is difficult to test automatically, TDD encourages placing as much functionality as possible in the model, minimizing what will exist in the GUI. We will conclude this example by looking at some of the event handling code in the GUI.

The GUI needs to react to two types of events: pressing the right arrow key should shift the television listing one show to the right, and pressing the left arrow key should shift the listing one show to the left. Prior to even writing the GUI code, we can write tests for the event handlers. The code in Figure 4.15 and Figure 4.16 utilizes the setUp() method to create a test file prior to each test. The first test called *testMoveRight()* creates the GUI with the specified file, then checks to see if the first show is the first one about to be displayed by the GUI ("Sesame Street"). Next the test forces the action of pressing the right arrow key to be performed by extracting the *MoveRightAction* object from the GUI and performing the action. Finally the test checks to see if the new first show is what used to be the second show ("Cyber Chase").

The code under test is given in Figure 4.17 and Figure 4.18 along with the event handling code in Figure 4.19. Notice that no GUI components are tested directly. The *ChannelGuideGUI* object is a *JFrame*, but it is instantiated and tested without actually showing it. We do observe some improvements that could be made. For instance, the *MoveRightAction* and the *MoveLeftAction* classes are so similar that they could probably be combined, perhaps in a common parent that implements the Template Method [35] design pattern. The tests give us courage to refactor to such a pattern. We can make small, incremental changes such as changing a class name, adding a method parameter, or eliminating a class, using the tests to quickly determine if we have broken anything.

```
public class TestChannelGuideGUI extends TestCase {
  public void setUp() {
    try {
      PrintWriter dout = new PrintWriter(
                          new FileWriter("tvlistings.txt"));
      dout.println("Sesame␣Street:8:0:60");
      dout.println("Cyber␣Chase:9:0:30");
      dout.println("Zoom:9:30:30");
      dout.println("Caillou:10:0:30");
      dout.println("Mr.␣Rogers:10:30:30");
      dout.println("Zooboomafoo:11:0:30");
      dout.println("Arthur:11:30:30");
      dout.close();
    } catch(IOException e) { System.out.println(e);}
  }
  public void testMoveRight() {
    ChannelGuideGUI cgui = new ChannelGuideGUI("tvlistings.txt");
    ListIterator it = cgui.cg.currentStartIterator();
    assertEquals(((Show)it.next()).getTitle(),"Sesame␣Street");
               //create move right action
    cgui.showPanel.getActionMap().get("panel.right").
       actionPerformed(new ActionEvent(this, 0, ""));
    it = cgui.cg.currentStartIterator();
               //verify new start
    assertEquals(((Show)it.next()).getTitle(),"Cyber␣Chase");
               //verify button text
    assertEquals(cgui.showButtons[0].getText(),"9:00␣Cyber␣Chase");
  }
  public void testMoveLeft() {
    ChannelGuideGUI cgui = new ChannelGuideGUI("tvlistings.txt");
    ListIterator it = cgui.cg.currentStartIterator();
    assertEquals(((Show)it.next()).getTitle(),"Sesame␣Street");
               //create move left action
    cgui.showPanel.getActionMap().get("panel.left").
       actionPerformed(new ActionEvent(this, 0, ""));
    it = cgui.cg.currentStartIterator();
               //verify start didn't change
    assertEquals(((Show)it.next()).getTitle(),"Sesame␣Street");
               //verify button text
    assertEquals(cgui.showButtons[0].getText(),"8:00␣Sesame␣Street");
  } ...
}
```

Figure 4.15: Testing Events in Java GUI

```
  public void testMoveLeft2() {
    ChannelGuideGUI cgui = new ChannelGuideGUI("tvlistings.txt");
    ListIterator it = cgui.cg.currentStartIterator();
    assertEquals(((Show)it.next()).getTitle(),"Sesame␣Street");
    cgui.showPanel.getActionMap().get("panel.right").
       actionPerformed(new ActionEvent(this, 0, ""));
    it = cgui.cg.currentStartIterator();
    assertEquals(((Show)it.next()).getTitle(),"Cyber␣Chase");
    cgui.showPanel.getActionMap().get("panel.right").
       actionPerformed(new ActionEvent(this, 0, ""));
    it = cgui.cg.currentStartIterator();
    assertEquals(((Show)it.next()).getTitle(),"Zoom");
    cgui.showPanel.getActionMap().get("panel.left").
       actionPerformed(new ActionEvent(this, 0, ""));
    it = cgui.cg.currentStartIterator();
    assertEquals(((Show)it.next()).getTitle(),"Cyber␣Chase");
  }
```

Figure 4.16: Testing Events in Java GUI cont.

4.1.2 C++ Example

A C++ example will be presented next. Unlike with Java, there is no de facto standard unit testing framework for C++. There may be a number of reasons for this [80], not least of which is the lack of reflection capabilities like that in Java.

Of the C++ unit testing frameworks, the CxxTest [84] framework seems to have the simplest interface. In order for it work, CxxTest must be included with the standard libraries. Unfortunately it also requires an installation of perl and an extra step in compilation.

To minimize the intrusion to the learning programmer, the research experiments in CS1 and CS2 used simple assert statements from the standard library cassert. An example is given demonstrating a CS1/CS2 appropriate implementation of the same ChannelGuide application (with a text-based user interface) where students only know about classes, arrays, and assert. The class declarations are shown in Figure 4.20 and the driver, *main()*, is shown in Figure 4.21. Unit tests are relegated to a global function named *run_tests()*. Three tests are shown in Figure 4.22. This approach is described further in Appendix A.

4.2 Experiment Design

This section will outline the details of the formal experiments. It will discuss the hypothesis, independent and dependent variables, the software development pro-

```
public class ChannelGuideGUI extends JFrame {
  public static void main(String [] args) {
    ChannelGuideGUI cgui = new ChannelGuideGUI("tvlistings.txt");
    cgui.setDefaultCloseOperation(JFrame.EXIT_ON_CLOSE);
    cgui.show();
  }
  public ChannelGuideGUI(String fn) {
    cg = new ChannelGuide(fn);
    setTitle("Channel␣Guide");
    setSize(WIDTH, HEIGHT);
    showPanel = new JPanel();
    showPanel.setLayout(new FlowLayout(FlowLayout.LEFT));
    showButtons = new JButton[5];
    for(int a=0;a<5;a++) {
      showButtons[a] = new JButton();
      showPanel.add(showButtons[a]);
    }
    Container contentPane = getContentPane();
    contentPane.add(showPanel);
    addActions();
    displayShows();
  }
  public static final int WIDTH = 600;
  public static final int HEIGHT = 80;
  ChannelGuide cg;
  JPanel showPanel;
  JButton [] showButtons;
```

Figure 4.17: Java GUI

```
  private void addActions() {
    InputMap imap =
      showPanel.getInputMap(JComponent.WHEN_IN_FOCUSED_WINDOW);
    imap.put(KeyStroke.getKeyStroke(KeyEvent.VK_RIGHT,0),
                                    ''panel.right'');
    imap.put(KeyStroke.getKeyStroke(KeyEvent.VK_LEFT,0),
                                    ''panel.left'');
    // associate the names with actions
    ActionMap amap = showPanel.getActionMap();
    amap.put("panel.right", new MoveRightAction(cg,this));
    amap.put("panel.left", new MoveLeftAction(cg,this));
  }

  void displayShows() {
    ListIterator i = cg.currentStartIterator();
    for(int a=0;a<5;a++) {
      showButtons[a].setPreferredSize(new Dimension(0,0));
      showButtons[a].setHorizontalAlignment(SwingConstants.LEFT);
      showButtons[a].setMargin(new Insets(5,5,5,5));
    }
    int duration = 0;
    int c=0;
    while(i.hasNext() && duration < 150) {
      Show s = (Show)i.next();
      int mins = s.getStartMins();
      String t = "" + s.getStartHr() + ":";
      if (mins<10)
        t += "0" + mins;
      else
        t += "" + mins;
      t += "␣" + s.getTitle();
      showButtons[c].setText(t);
      showButtons[c].setPreferredSize(
                          new Dimension(s.getDuration()*3,30));
      c++;
      duration += s.getDuration();
    }
    repaint();
  }
}
```

Figure 4.18: Java GUI cont.

```
class MoveRightAction extends AbstractAction {
  MoveRightAction(ChannelGuide cg, ChannelGuideGUI c) {
    this.cg = cg;
    comp = c;
  }
  public void actionPerformed(ActionEvent a){
    cg.advanceOne();
    comp.displayShows();
  }
  private ChannelGuide cg;
  private ChannelGuideGUI comp;
}

class MoveLeftAction extends AbstractAction {
  MoveLeftAction(ChannelGuide cg, ChannelGuideGUI c) {
    this.cg = cg;
    comp = c;
  }
  public void actionPerformed(ActionEvent a){
    cg.backupOne();
    comp.displayShows();
  }
  private ChannelGuide cg;
  private ChannelGuideGUI comp;
}
```

Figure 4.19: Java GUI Event Handling

```
class Show
{
  public:
    Show() : startHrs(0),startMins(0),duration(0)
       { strcpy(title,""); }
    Show(char[],int,int,int);
    Show(istream&);
    void getTitle(char[]);
    int getStartHours();
    int getStartMins();
    int getDuration();
    void displayTimeHeaders(ostream& out);
    void displayTopBottomLine(ostream& out);
    void displayMiddleLine(ostream& out);
  private:
    char title[21];
    int startHrs;
    int startMins;
    int duration;
};

class Listing
{
  public:
    Listing() {}
    Listing(istream&);
    int getNumShows();
    void setCurrent(int,int);
    Show getCurrent();
    Show getNext();
    Show getPrev();
    bool hasNext();
    bool hasPrev();
  private:
    int getShowIndex(int,int);
    Show shows[20];
    int numShows;
    int current;  // index of current show
};
```

Figure 4.20: C++ Channel Guide

```
class ChannelGuide
{
  public:
    ChannelGuide();
    void display();
    void move(int);
  private:
    Listing listing;
};

int main()
{
  run_tests();
  ChannelGuide cg;
  int input=0;
  do
  {
    cg.display();
    cout << "Enter␣4␣to␣move␣left␣one␣show,␣"
         << "5␣to␣move␣right␣one␣show,␣"
         << "and␣-1␣to␣quit" << endl;
    cin >> input;
    cg.move(input);
  } while(input>=0);
  return 0;
}
```

Figure 4.21: C++ Channel Guide cont.

```
void run_tests()
{
 { //test 1
  Show showOne("Seinfeld",9,0,60);
  char t[20];
  showOne.getTitle(t);
  assert(strcmp(t,"Seinfeld") == 0);
  assert(showOne.getStartHours() == 9);
  assert(showOne.getStartMins() == 0);
  assert(showOne.getDuration() == 60);
 }
 { //tests with input file
  ofstream out;
  out.open("test2.out");
  assert(!out.fail());
  ifstream in;
  in.open("test2.out");
  assert(!in.fail());
  out << "Arthur␣9␣0␣60" << endl
      << "Barney␣10␣0␣30" << endl
      << "Zoom␣10␣30␣30" << endl;
  Listing channelOne(in);
  { //test 2
   assert(channelOne.getNumShows() == 3);
   char t[20];
   channelOne.setCurrent(10,0);
   Show curShow = channelOne.getCurrent();
   curShow.getTitle(t);
   assert(strcmp(t,"Barney") == 0);
   assert(curShow.getStartHours() == 10);
  }
  { //test 3 tests getting a show already in progress
   channelOne.setCurrent(9,30);
   Show curShow = channelOne.getCurrent();
   char t[20];
   curShow.getTitle(t);
   assert(strcmp(t,"Arthur") == 0);
   assert(curShow.getStartHours() == 9);
   assert(curShow.getStartMins() == 0);
  }
 }
}
```

Figure 4.22: C++ Channel Guide Tests

cess context, and the methods of making and analyzing observations. The chapter will end with a discussion of methods used to analyze the experiment data and how the results were assessed and validated. Actual experiment results will be given in chapter 5 and chapter 6.

4.2.1 Hypothesis

The null hypothesis of this experiment is:

> software constructed using the test-driven development approach will have similar quality at higher cost to develop when compared to software constructed with a traditional test-last approach.

The independent variable is the use of test-driven (test-first) versus test-last development. The dependent variables are software quality and software cost (in terms of effort). Additional dependent variables observed included student performance on related assessments and subsequent voluntary usage of TDD. Additional qualitative data was gathered such as programmer attitudes toward testing and TDD.

At the outset the hypothesis was expected to be proven incorrect in the context of larger programming projects. Because small projects such as those developed in early programming courses have relatively little opportunity to vary significantly in design, test-driven development was expected to have little or no effect at these levels. Student discipline, maturity, and ambition were conjectured to be more significant factors than development approach with novice programmers.

4.2.2 Formalized Hypotheses

This section will divide and formalize the overall hypothesis presented in the previous section. A formalization of the hypotheses is presented in Table 4.1. Each of these hypotheses is discussed in turn here.

Some sources [12, 17] claim that test-first programmers consistently write a significant amount of test code. Our first hypothesis **T1** examines whether test-first programmers write more tests than test-last programmers. **T2** augments **T1** by examining whether the tests written by test-first programmers actually exercise more production code (test-coverage) than the tests written by test-last programmers. The rationale for **T2** is that more tests may only be better if the tests actually exercise more lines or branches in the production code.

Hypothesis **P1** considers whether test-first programmers are more productive than test-last programmers. We will examine development time, effort per feature, and effort per lines of code.

Name	Null Hypothesis	Alternative Hypothesis
P1	$Prod_{TF} = Prod_{TL}$	$Prod_{TF} > Prod_{TL}$
T1	$\#Tests_{TF} = \#Tests_{TL}$	$\#Tests_{TF} > \#Tests_{TL}$
T2	$\#TestCov_{TF} = \#TestCov_{TL}$	$\#TestCov_{TF} > \#TestCov_{TL}$
Q1	$IntQlty_{TF} = IntQlty_{TL}$	$IntQlty_{TF} > IntQlty_{TL}$
Q2	$IntQlty\|Tested_{TF} = IntQlty\|NotTested_{TF}$	$IntQlty\|Tested_{TF} > IntQlty\|NotTested_{TF}$
O1	$Op_{TF} = Op_{TL}$	$Op_{TF} > Op_{TL}$
O2	$Op\|TF_{TF} = Op\|TF_{TL}$	$Op\|TF_{TF} > Op\|TF_{TL}$

Table 4.1: Formalized Hypotheses

Hypothesis **Q1** tests if test-first code has higher internal quality than test-last code. Recognizing that not all code may be covered by automated unit-tests, hypothesis **Q2** considers whether code developed in a test-first manner and covered by tests has higher internal quality than code also developed in a test-first manner, but not covered by tests. In an ideal situation, this hypothesis could not be examined because all test-first code would be covered by unit tests. However, the reality is that students first learning to use TDD will rarely achieve such high test-coverage.

Finally hypothesis **O1** and **O2** address programmer opinions of the test-first approach. Hypothesis **O1** examines whether all programmers, whether they have used the test-first approach or not, perceive test-first as a better approach. Hypothesis **O2** more specifically examines whether programmers who have attempted test-first prefer the test-first approach over a test-last approach.

4.2.3 TDD in a Traditional Development Process

As mentioned earlier, attention has focused on TDD recently due to its association with agile methods and particularly XP. This research attempts to examine TDD independent of other process practices. In so doing, TDD was studied in the context of a more traditional development process. The experiments in this research involved relatively short projects (typically three to four months). As a result, it is believed that the process used in this experiment could be repeated as iterations in a larger evolutionary process model, but this is not prescribed.

Figure 4.23 illustrates a traditional test-last flow of development. In such a development process, significant effort is invested in specifying the architecture and design of the system prior to any significant software development. Such an approach does not preclude some programming to explore a prototype or prove a concept, but it assumes that no significant production software is constructed without a detailed design. Unit testing is conducted after a unit is coded. Unit testing may be conducted by the same or a different developer, and the time from unit construction to unit testing may vary from a few seconds to a few months. Writ-

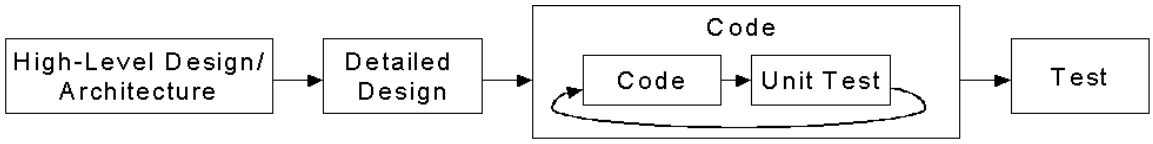

Figure 4.23: Test-Last Flow

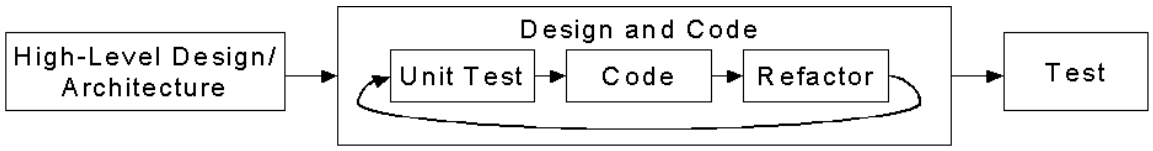

Figure 4.24: Test-First Flow

ing units and tests in short, rapid iterations will be referred to as *iterative test-last programming*, whereas allowing long gaps and additional development before units are tested will be referred to as *linear test-last programming*.

Figure 4.24 illustrates the test-first flow of development. This approach assumes that some high-level architecture is identified, but that design does not proceed to a detailed level. Instead the test-first process of writing unit-tests and constructing the units in short, rapid iterations is used to allow the design to emerge and evolve. Notice that there are no assumptions about other process practices.

4.2.4 Experiment Overview

A total of seven formal experiments and one case study were conducted. An overview of the controlled experiments is given in Figure 4.25.

Five experiments were conducted in academic settings at the University of Kansas. Separate experiments were conducted in courses ranging from beginning programming (CS1) through graduate software engineering. The first experiment was conducted in an undergraduate software engineering course in Summer 2005. In Fall 2005, experiments were conducted in Programming 1 (CS1), Programming 2 (CS2), and the graduate software engineering course. The CS2 experiment was then repeated in Spring 2006. With the exception of this second CS2 experiment, no student participated in multiple experiments.

Two experiments were conducted in a Fortune 500 company with experienced software developers. The larger industrial experiment compared three sets of two projects each, completed with distinct sequences of treatments. This experiment is labeled as "Industry (in-domain)" because the projects were completed by developers in their regular work environment. The projects were prioritized and assigned through the normal business process and the projects were delivered to users for production use. The second, smaller industrial experiment labeled "Industry (in-training)" was conducted in a professional training course developed by

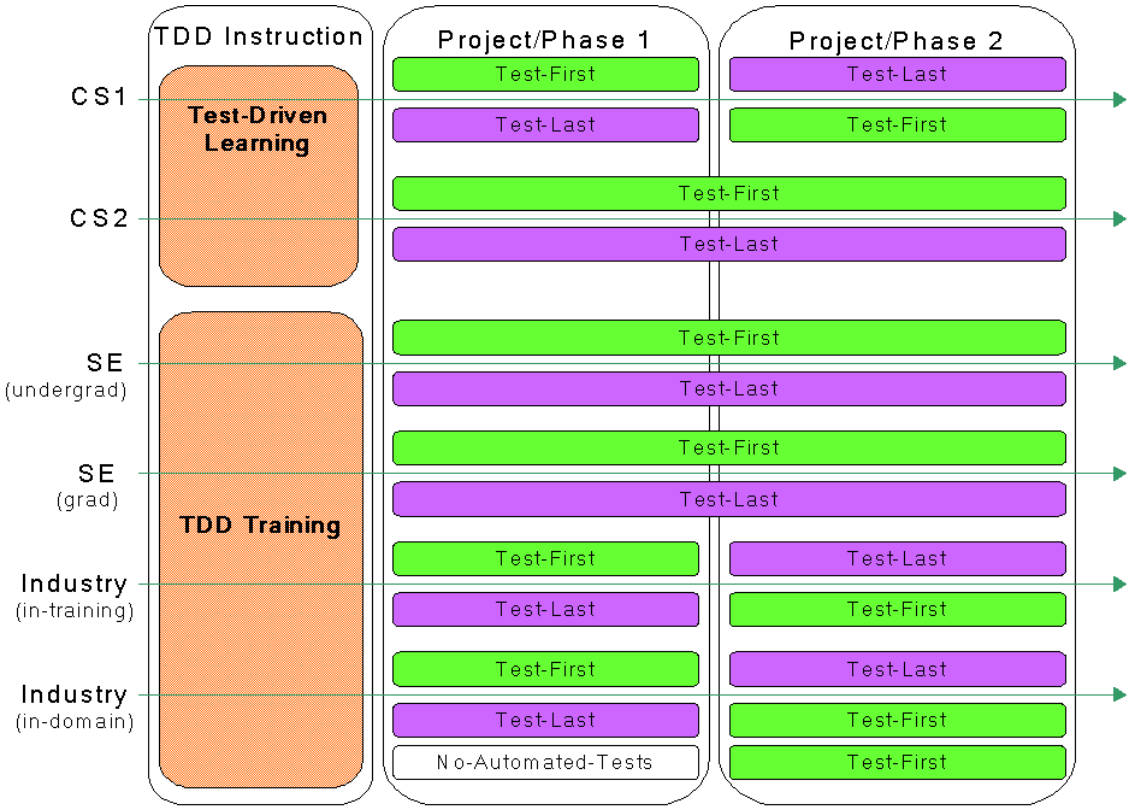

Figure 4.25: Overview of TDD Experiments

the researcher.

TDD Educational Materials

Educational materials were developed and delivered in conjunction with each experiment. The two early programming courses (CS1 and CS2) utilized a condensed form of the test-driven learning approach described in Appendix A. This approach embedded test-driven development training in the context of teaching other course topics. Training materials were also developed and delivered in the two more advanced courses and in the two industry experiments. The software engineering courses involved relatively short (about two hours) training sessions dedicated to the topic of automated unit testing and test-driven development. The industry training consisted of a full-day course on automated unit testing and test-driven development in the context of a larger six-day training course. All materials were developed and delivered by the author and some artifacts are provided in Appendix B.

Team and Treatment Selection

Each experiment involved two phases or projects. The original objective was to determine the amount of software reuse from one phase/project to another. Due to course and industry constraints, this design was not consistent across all experiments although it was consistent within each experiment. In the CS1 experiment, students were randomly assigned to use a test-first or test-last approach on one project. Students were then asked to use the opposite approach on the second project. This design allows one to examine the influence of starting with a particular approach.

In the CS2 experiment, students were allowed to choose which approach they wanted to use. They were then asked to use the same approach on both projects. This design allows one to examine student perceptions of the approaches (willingness to try them) and to look for differences in quality between the two projects as they gain added experience and maturity. In both the CS1 and CS2 experiments, students worked individually and used C++ as the programming language.

In the two software engineering courses, students worked in teams of three or four programmers each. Students self-selected their teammates, but Java experience was established as a blocking variable to ensure that each team had a minimum and balanced skill set. Both experiments involved the same semester-long project. The project was divided into two phases.

Developers worked in pairs in the in-training industry experiment. The experiment consisted of two phases, but developers were only able to complete the first phase in the time allotted. This design allows one to examine programmers' ability to quickly apply test-driven development and compares early quality differences in the test-first and test-last approach.

In the in-domain industry experiment, experienced developers worked in small teams of up to three people. Three sets of two projects were examined. The first set involved a test-last project followed by a test-first project. The second set involved a test-first project followed by a test-last project. The third set involved a test-last project with no automated tests followed by a second phase of the same project completed with a test-first approach. This experiment design allows one to examine quality differences in the approaches on a much larger scale and on practical problems without the confounding factor of inexperienced software developers.

Developer Experience and Perception Surveys

Programmer attitudes towards testing and test-driven development were evaluated through pre- and post- experiment surveys conducted with both the control and the study groups. In the pre-experiment survey, students were asked to report on how they perceive the value of testing, how they currently test their programs, and how open they are to learning to use test-driven development. The pre-experiment survey also asked about programming and academic experience and performance, and requested demographic information so that results can be analyzed for significant differences in women and minority population groups [30]. The pre-experiment surveys were administered after students were given some training on automated unit testing and both the test-first and test-last approaches to software development.

In the post-experiment survey, students were asked to report again on how they perceive the value of testing, whether they feel like they understand test-driven development, whether they used test-driven development in their assignments, and whether they intend to use the test-driven development approach in the future both in course work, or in any professional programming they may do.

The post-experiment survey was administered to all programmers at the end of the semester. The pre- and post-experiment surveys contained many identical questions to determine if student attitudes toward testing and test-driven development changed based on their experiences in the experiment.

Software, Effort, and Grade Artifacts

Developers were required to submit all of the code that they completed on each project. In most cases this code was collected through the normal grading process or extracted from a software configuration management system so no extract effort was required on the part of the subjects. For the semester long projects, code was collected at multiple points in order to see the development progression. The code was then evaluated to determine the code quality and test coverage. In addition, during the coding process, a random sample of students were observed and interviewed regarding their use of test-driven development.

Students were required to track and submit the amount of time they spent on

programming projects. CS1 and CS2 students tracked this data manually or through source code comment entries and reported this data with the final project submissions. SE students were provided a spreadsheet template which they submitted by team each week of the semester. Project time data was not collected or was unreliable in the industry experiments so it was not available for analysis in those contexts.

Student exam and course grades were also collected in order to determine if any correlation exists between test-driven development use and academic performance.

Industry Case Study

In addition a case study was completed in the same industry development group as the aforementioned experiments. The case study examined fifteen software projects completed in one development group over the course of five years. The six projects from the in-domain industry experiment were included in the fifteen projects examined. The projects were generally completed in three to twelve months with less than 10,000 lines of code by development teams with three or fewer primary developers. This development group was selected because the projects were developed with a variety of approaches. Some projects were completed with no automated unit tests. Some projects were completed with automated tests in a test-last manner, and some projects were completed with automated tests in a test-first manner. All projects were completed in Java.

Experiment Context

Figure 4.26 illustrates the context of all the software projects examined (in academia and industry). All projects enjoyed relatively stable requirements. In addition, each project included some degree of new technology. In the academic experiments, developers were generally programming in a language with which they had little familiarity. In the industrial experiments, while developers had experience with the language used, the projects included new frameworks with which developers had no significant previous experience.

The projects, however, included developers with a range of programming experience. While student programmers had generally similar course backgrounds, they reported a mix of programming experience. Similarly the industry project teams included a mix of junior through more senior developers. As will be discussed, the control and experiment groups were balanced to ensure consistency.

The study contexts avoid confounding factors by keeping requirements volatility and technology experience consistent within each experiment. Other confounding factors were avoided by ensuring consistent language use, consistent domain and project assignment, and consistent time frames in each experiment. It would be

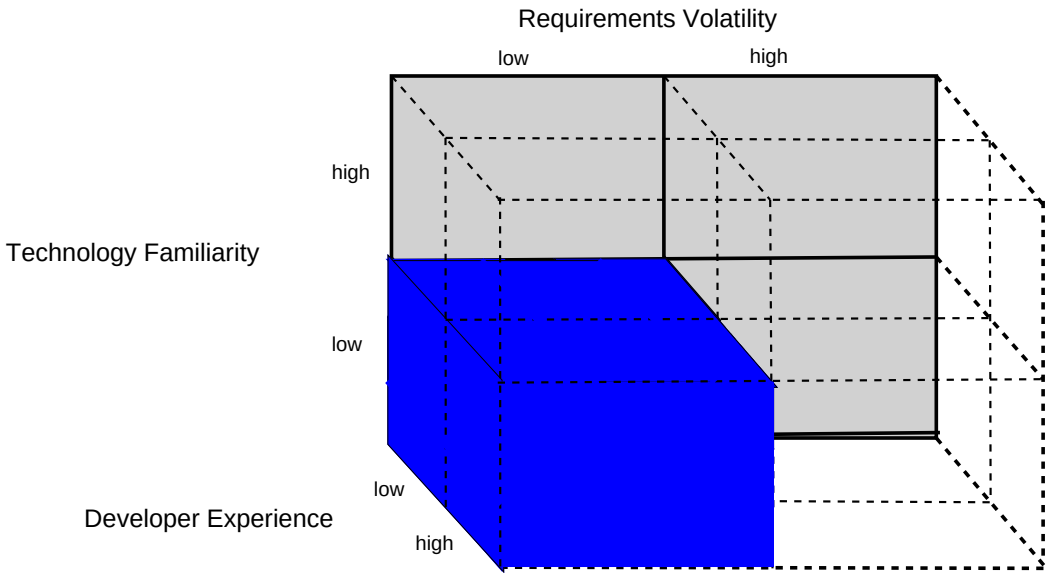

Figure 4.26: Research Study Context Grid

useful, however, to replicate these studies in contexts of high requirements volatility and with only mature developers experienced with all the underlying technologies.

Longitudinal Experiment

A key indicator in whether students agree with the merits of test-driven development is whether they choose to use it. It was anticipated that many students, even if they saw significant value in the test-driven development approach, would choose not to use it on course assignments because they did not foresee having to maintain or reuse these assignments. Although students may see benefits to using test-driven-development in the short-term, in our experience, students will most often take the shortest path to completing an assignment. The shortest path typically involves minimal testing.

A longitudinal experiment was conducted for each of the academic experiments. In each academic experiment, all participating students were contacted by email in the following semester and were asked to complete an on-line survey. The purpose of this survey was to determine the voluntary use of test-driven development in course programming assignments and to see if student perceptions of test-driven development had changed. Generally students from the CS1 experiment were examined while taking CS2. Students from the CS2 experiment were examined while taking the SE course or perhaps an assembly language or programming languages course. Students from the SE courses tended to be in a wider variety of programming and non-programming based subsequent courses.

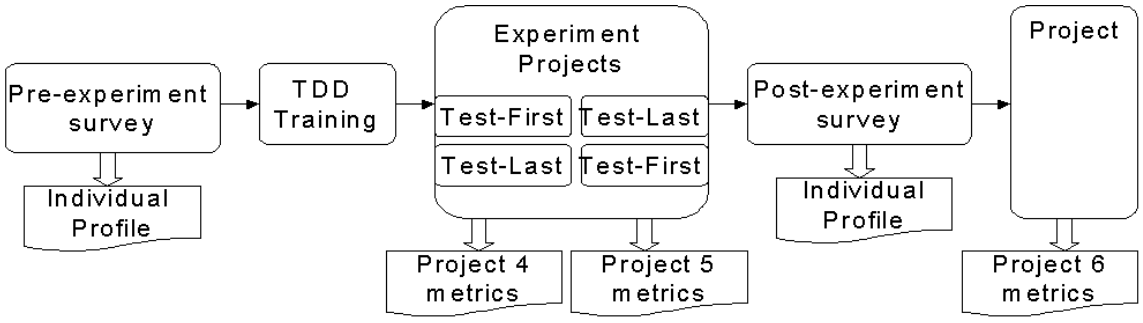

Figure 4.27: CS1 Experiment

4.2.5 Academic Experiments

This section will describe the experiments conducted in academic settings in more detail. The experiment design for each course will be discussed including specific artifacts collected, information on the TDD training provided to subjects, and descriptions of the projects completed by the subjects.

CS1 Experiment

Figure 4.27 illustrates the experiment flow in the CS1 experiment. Because early projects were small and required very little design, this experiment was conducted in the last half of the CS1 course. After students had completed three projects and covered topics such as basic syntax, iteration control structures, elementary functions, and simple data structures such as arrays, the author presented a guest lecture. The lecture was presented with the test-driven learning approach in which automated unit testing using *assert* statements was introduced in the context of a lecture on functions. The pre-experiment survey was administered at the end of the guest lecture.

The lecture was then followed by two labs developed by the author and taught by graduate teaching assistants. The first lab introduced automated unit testing in the context of writing simple functions. The second lab reinforced practice with automated unit tests in the context of writing recursive functions, using reference parameters, and function overloading. The labs introduced the difference between test-first and test-last programming and gave students hands-on experience with both approaches. Although some TDD training occurred in the lecture prior to administering the survey, the figure shows the survey coming before the training since most of the training, particularly the hands-on training, occurred after the survey in the labs.

After completing the two labs, students were then asked to complete two programming projects. The first project (Project 4) required students to create a data structure for representing a three-dimensional point and create functions that op-

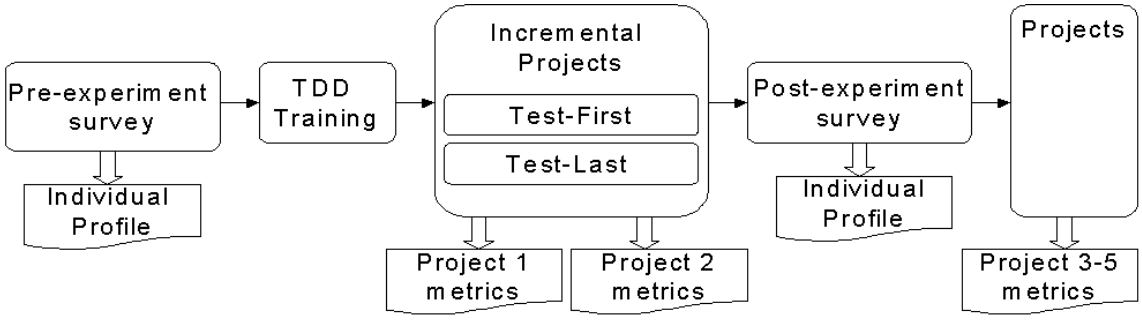

Figure 4.28: CS2 Experiment

erate on such points. Functions included adding, subtracting, multiplying, and dividing points, as well as functions to determine of two points were equal and to calculate the Euclidean distance and dot product of two points. Students had not been introduced to classes so they generally used an array-based data structure and global functions in their solutions.

Students with student IDs ending in an even number were asked to complete the first project with a test-first approach and students with student IDs ending in an odd number were asked to complete the first project with a test-last approach.

The second project (Project 5) required students to create class-based data structures for representing points and polygons. A textual user interface was to allow users to specify a number of points in a polygon and the program was to calculate the perimeter and area of that polygon. Test-first/test-last assignments were switched on the second project so students with student IDs ending in an odd number were asked to complete the second project with a test-first approach and students with student IDs ending in an even number were asked to complete the second project with a test-last approach.

At the beginning of the second project, students were provided with a solution to the first project that included a full set of automated unit tests. The post-experiment survey was then administered in labs following the completion of the second project.

CS2 Experiments

Figure 4.28 illustrates the experiment flow in the two CS2 experiments. Students were given a very brief (five minutes) introduction to test-first and test-last programming on the first day of the course, then given the pre-experiment survey. Students were introduced to automated unit testing using *assert* statements early in the semester in the third week lab. The lab presented examples and required hands-on exercises with automated tests using classes and simple and recursive functions. The lab presented both test-first and test-last approaches.

Students were then required to complete two programming projects. Students were asked to develop the projects with either a test-first or test-last approach. The following statement in the project description prescribes this requirement:

> You should develop this program in a ***test-first*** or a ***test-last*** manner as described in Lab 3. You may choose which approach you use, but use the approach throughout the development of the project. If you don't care which approach you use, choose test-first if your KUID starts with an even number and use test-last if your KUID starts with an odd number.

Each programming project was to be completed in two or three weeks. The first project in Fall 2005 required students to build an application that stored and manipulated a list of drivers with traffic citations. The application had a textual user interface that allowed the user to insert, delete, find, and print driver and citation information. The public interface for the main list data structure class (called DriverTable) was prescribed in the project description. This class was specified to contain a statically allocated array for storing the driver and citation information. Although much of the interface for the one data structure class was specified, students were expected to design at least two other classes. The project description is provided in Appendix B.

The second project extended and modified the first project. The DriverTable class was to be modified internally to use a pointer-based linked list instead of an array-based list. The application was to allow multiple DriverTables and the class interface was modified slightly. Exceptions and some recursive functions were also added to the requirements. At the beginning of the second project, students were provided with a solution to the first project that included a full set of automated unit tests.

Students were asked to use a test-first or test-last approach in the remaining three projects of the semester. Software from these projects was also analyzed, but they were not originally a part of the experiment. At least two of these remaining projects had very procedural solutions (a grammar checker and an experimental profiler of sorting algorithms). Their design was more prescribed than the first two projects that were a part of the formal experiment.

The second CS2 experiment in Spring 2006 was designed to be similar to the first CS2 experiment that was conducted in Fall 2005. The Spring 2006 version required a set of two projects that were very similar to those in Fall 2005 but in a different domain (airline flights instead of traffic citations). In both experiments the post-experiment survey was administered after the completion of the third project.

SE Experiments

Figure 4.29 illustrates the experiment flow in the two experiments conducted in the undergraduate and graduate software engineering courses. The first experiment

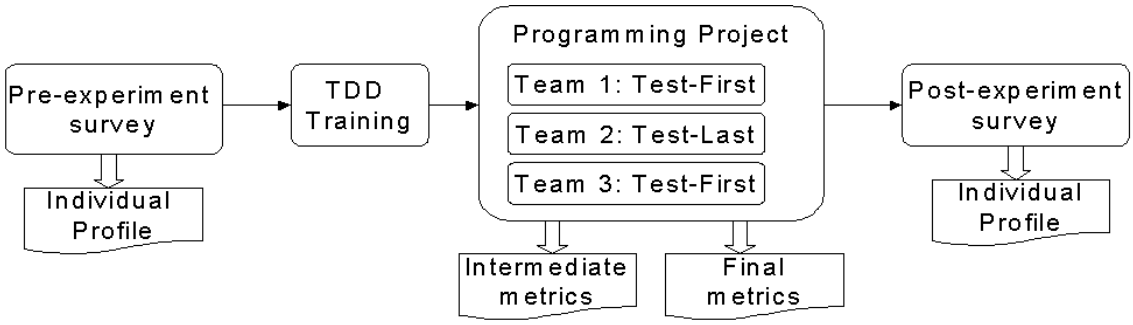

Figure 4.29: Software Engineering and Industry Training Experiments

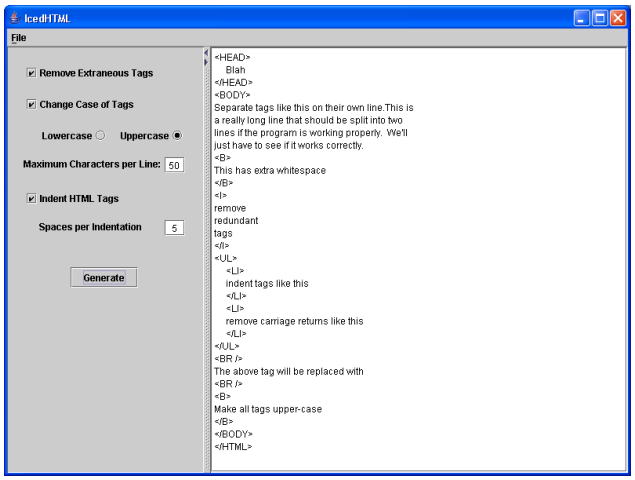

Figure 4.30: Screenshot from HTML Pretty Print application.

was conducted in the context of an undergraduate software engineering course consisting of junior and senior computer science and computer engineering students. This course was taught during summer 2005. Results from this experiment were published and presented at the Conference on Software Engineering Education and Training [49] in Hawaii in April 2006.

Students were asked to design and build an HTML pretty print system. This system was to take an HTML file as input and transform the file into a more human readable format by performing operations such as deleting redundant tags and adding appropriate indentation. A sample application with a graphical user interface is shown in Figure 4.30.

Students were taught and asked to follow a simplified form of the Unified Process including inception, elaboration, construction, and transition stages. The project schedule was divided into two iterations with the first focusing on a text-based user interface and a partial set of features. The second iteration added a graphical user interface and additional features.

Students were asked to complete the pre-experiment survey and then were taught how to write automated unit tests with the JUnit framework. All students were instructed in how to write software in a test-first and test-last manner. The total time spent on JUnit and test-first/test-last programming training was less than one and a half hours. Students were then divided into three groups: two groups were to complete the project with a test-first approach and the third group was to complete the project with a test-last approach. Students were allowed to self-select their teams, but Java programming experience was established as a blocking variable to ensure that each team had at least one member with reasonable previous Java experience. Test-first/test-last team assignments were made after analyzing the pre-experiment questionnaire to ensure the teams were reasonably balanced.

All teams completed a software requirements specification and a high-level architectural design. The test-last teams were asked to complete a detailed design prior to completing any significant coding. The test-first teams on the other hand were asked to use the test-first approach to allow the detailed design to emerge as the software was developed. The test-first teams were asked to document their detailed design after the code was developed.

Student programmers used the Java Programming Language, the JUnit unit testing framework, and the Eclipse integrated development environment. Students submitted electronic time sheets (see Appendix B for a sample) and software on a weekly basis. They presented their projects in the final class period and then completed the post-experiment survey after seeing each others presentations.

The second SE experiment took place in a graduate software engineering course that is the first course in the Masters of Software Engineering program at the University of Kansas. The course is a survey of software engineering and regularly includes a semester-long team-based project. This course met during the Fall 2005 semester and used the exact same semester-long project as the undergraduate course described earlier. The pre-experiment survey, TDD training, development process, weekly time sheet and code submissions, and post-experiment survey also matched the same design and schedule as the undergraduate experiment.

4.2.6 Industry Experiments

This section will describe the experiments conducted with professional programmers in more detail. The experiment design will be discussed including specific artifacts collected, information on the TDD training provided to subjects, and descriptions of the projects completed by the subjects. The industry experiments were all completed in the same Fortune 500 company. The first smaller experiment took place in the context of a training course. The second, significantly larger experiment actually consists of three experiments conducted on production projects in the developers' normal domain.

In-training Experiment

The in-training experiment took place in the context of a six day training course. The experiment followed the same design as the software engineering courses described above and illustrated in Figure 4.29. The primary difference was that the project was significantly smaller. Instead of a semester-long project, this project was intended to be completed in a two-hour block of an eight hour full-day training session.

The course consisted of six full-days of on-site training developed and delivered by the author in Fall 2005. The course included one day of instruction on test-driven development with JUnit and the remaining five days of instruction were split between the Spring and Hibernate frameworks. The Spring [52] framework was described in section 4.1.1 as a lightweight dependency injection framework. Spring also includes a model-view-controller based web application framework as well as a framework for communicating with relational databases. Hibernate [68] is a persistence service providing object/relational mapping functionality. Spring and Hibernate are commonly used together and provide integration support. The course consisted of lecture directed by nearly five hundred presentation slides and hands-on lab exercises. The day on test-driven development was largely a refresher for most developers from a similar course provided two years earlier.

The experiment consisted of an extended exercise near the end of the TDD day. Half of the developers were asked to complete the exercise with a test-first approach and half were asked to complete the exercise with a test-last approach. Subjects were randomly selected for each group. A couple of individuals with limited Java experience requested to work in pairs with more experienced Java developers. This was allowed and both test-first and test-last groups contained one or two such pairs of programmers. All developers were asked to use JUnit in the Eclipse IDE for writing automated unit tests.

The exercise was to build a bowling game scorer. This project was proposed by Robert C. Martin [58] and was used in an industry experiment by Laurie Williams [37] to examine the effects of TDD on external quality. The project involved reading bowling throws from a file, calculating scores, and presenting scores through a text-based user interface. Some sample input/output code was provided to subjects to shorten the development effort. Despite these helps, not all programmers were able to complete the project in the time allotted.

In-domain Experiment

Three experiments were conducted with professional developers in their regular work environment with production projects. The three experiments were designed to examine different sequences of treatments. Each experiment compared two software projects completed in serial. The projects were primarily web applications written in Java.

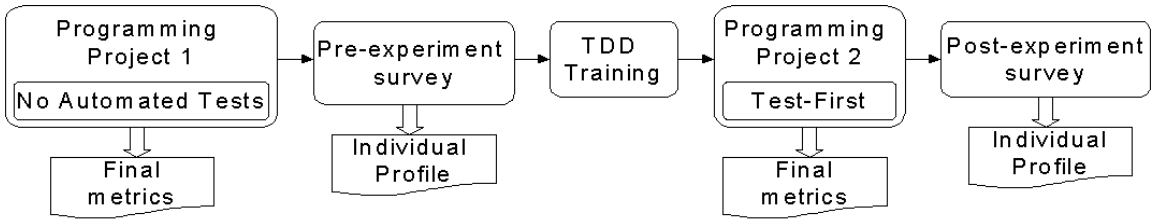

Figure 4.31: Industry Experiment 1

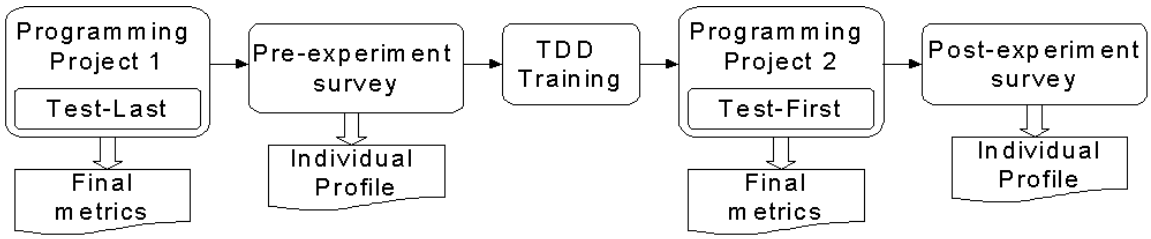

Figure 4.32: Industry Experiment 2

Figure 4.31 illustrates the experiment flow in the first industry experiment. Software from two phases of the same project were collected and compared in this experiment. The first phase was completed in 2001, before any of the developers received any training on TDD or automated unit testing. As a result no automated tests were written and the project was developed in a traditional mode with a large up-front design and manual testing after software was completed. The second phase was implemented in 2005 and 2006 using a test-first approach. In between the two projects, developers completed a pre-experiment survey and participated in the TDD training described earlier.

Figure 4.32 illustrates the experiment flow in the second industry experiment. The first project was developed with a traditional test-last approach. Developers learned to use JUnit and wrote automated unit tests without formal training. This project is then compared with the same second project from the first industry experiment. Although these projects were distinct (not continuation phases as in the first experiment), there was significant developer overlap on the two projects and they had many similarities. As described above developers completed a pre-experiment survey and participated in a TDD training class prior to completing the second project with a test-first approach.

Figure 4.33 illustrates the experiment flow in the third industry experiment. Programmers were presented with TDD training in Summer 2004. They then completed a project with a test-first approach. These two steps occurred before formal approval for the research study was received. Programmers then participated in the TDD/Spring/Hibernate training course described above. At the beginning of this training they completed the pre-experiment survey. Two-thirds of the devel-

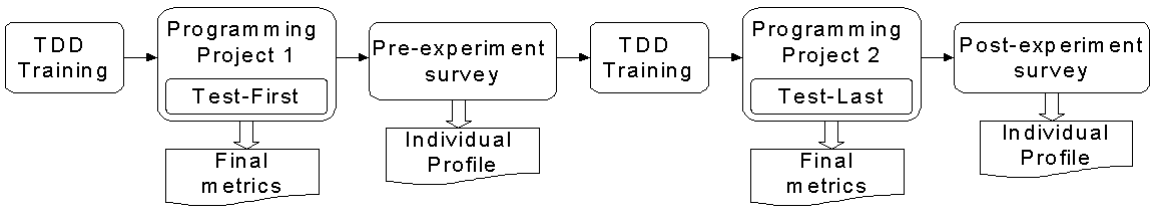

Figure 4.33: Industry Experiment 3

opers from the test-first project then completed a second project using a test-last approach. Both projects used the Struts web application framework. The second project also used the Spring and Hibernate frameworks for dependency injection support and simplified object/relational database mapping respectively. All the developers then completed the post-experiment survey.

4.2.7 Software Metrics and Analysis

The goal of this research is to examine the internal quality of software. This research takes the approach of Reeves [72] to recognize the software as the design. In order to measure internal quality, software from all of the academic and industry experiments was collected and product metrics were generated and analyzed statistically. Fenton's [29] taxonomy of software metrics identifies three classes: Process, Product, and Resource. Table 4.2 expands on these three classes [55].

This section will describe the metrics collected, the tools used to generate them, and the analysis process. Desirable attributes of high quality software will be examined first, followed by a discussion of static code-based metrics and dynamic test-coverage metrics.

Desirable Attributes of Quality Software

Desirable attributes of high quality software were identified as:

- Understandability
  - low complexity, high cohesion, simplicity
- Maintainability
  - low complexity, high cohesion, low coupling
- Reusability
  - low complexity, high cohesion, low coupling, inheritance
- Testability
  - high cohesion, low coupling, high test coverage

Process	• Maturity Metrics • Management Metrics • Life Cycle Metrics
Product	• Size Metrics • Architecture Metrics • Structure Metrics • Quality Metrics • Complexity Metrics
Resource	• Personnel Metrics • Software Metrics • Hardware Metrics

Table 4.2: Fenton's Taxonomy of Software Metrics

One will note that complexity, coupling, and cohesion are cross-cutting measures affecting many desirable attributes. Although it is difficult to relegate these measures to a single attribute, a broad look at many metrics can indicate high or low internal quality. Table 4.3 and Table 4.4 identify many of the objective metrics considered for these categories.

Static Code Analysis

An extensive search produced twelve static code analysis metrics tools that were then acquired and evaluated for the purposes of this research. The search focused on tools that generate metrics from C++ and Java code. These static analysis tools come from a variety of sources. Some are free and open-source. Others are commercial products. In the case of the latter, fully functional trial versions were acquired.

The tools produce a total of 116 unique traditional and object-oriented metrics. Appendix E identifies all 116 metrics and gives a very brief description of each metric. The appendix also identifies what languages are supported by each tool and which tools generate each metric. In some cases, multiple tools generate the same metric, sometimes with different names which is noted in the table. Appendix D provides brief definitions and some examples for many of the metrics collected.

An automated metrics collection framework and some custom metrics collection scripts were developed by the author. The framework was an Ant-based script

Attribute	Metrics
Complexity	• McCabe's Cyclomatic Complexity • Halstead Complexity • LOC/method • Weighted Methods per Class (WMC) • Number of Parameters • Depth of Inheritance Tree • #Children (bigger can be bad) • Specialization Index • #Overridden Methods • Nested Block Depth • Cyclic Dependencies • Limited Size Principle • Response for Class
Coupling	• Coupling between Objects • Fan-in, Fan-out (Afferent/Efferent Coupling) • Information Flow • Instability • #Interfaces • Cyclic Dependencies • Direct Cyclic Dependencies • Dependency Inversion Principle • Encapsulation Principle
Cohesion	• Lack of Cohesion of Methods • Weighted Methods per Class • LOC/Method

Table 4.3: Sample Metrics by Attribute 1

Attribute	Metrics
Size	• LOC (source and test) • #Modules • #Classes • #Methods • #Interfaces • Weighted Methods per Class • LOC/Module • LOC/Method • LOC/Class • #Attributes • #Static Attributes • #Packages
Reusability	• Depth of Inheritance Tree • #Children (bigger is good) • Fan-in • Specialization Index • Distance from Main • Abstractness • Instability • #Overridden Methods • #Interfaces
Testability	• #Asserts • #Tests • Line Coverage • Branch Coverage • Method Coverage • Total Coverage • Response for Class • Depth of Inheritance Tree • #Children • #Overridden Methods

Table 4.4: Sample Metrics by Attribute 2

coupled with several Java programs that would invoke metrics tools, parse xml output files, and consolidate desired metrics in comma separated spreadsheet files by experiment. Additionally some Java programs were written to count assert testing statements in the CS1 and CS2 C++ programs. Unfortunately not all metrics collection was able to be automated. Some metrics tools such as JStyle and RefactorIT required invocation through a graphical user interface. Collecting metrics with these tools was manually intensive involving many steps for each of the Java projects evaluated. Also, not all xml parsing was automated. Although this again involved many manual steps of extracting xml data through an editor or parsing it in a spreadsheet with many custom spreadsheet formulas, it was deemed to be faster than writing the code for all metrics desired.

Project metrics were produced from CCCC [57] (C++ and Java), custom scripts to count asserts (C++), Eclipse Metrics [75] (Java), JStyle [78] (Java), and Krakatau Professional Metrics (C++) [77]. Class, file, and method metrics were primarily produced using JStyle (Java), Eclipse Metrics (Java), and Krakatau Professional Metrics (C++).

Dynamic Test Coverage Analysis

All software produced was expected to have associated automated unit tests. Code from the CS1 and CS2 experiments contained *assert()* statements embedded in the source code, but separated in a global *run_tests()* function. Code from all other experiments utilized the JUnit framework so the test code was separate from the source/production code.

Code coverage tools were employed to determine line, branch, and overall test coverage. Cobertura [23] and Clover [21] were used to generate test coverage metrics for all Java projects. Generally all tests should pass. In the rare instances where a project contained tests that did not pass, the failing test was omitted in order to generate test coverage metrics. Although defect density turned out to be a difficult measure to capture, a detailed analysis did examine this measure in the undergraduate software engineering projects.

Code coverage tools also exist for C++ [82], but test coverage metrics were not produced for the CS1 and CS2 projects. A couple of factors weighed in on the decision not to collect CS1/CS2 test coverage metrics. First, a not-insignificant percentage of these projects failed to compile and execute correctly. Second, even when automated tests were written, they were generally commented out before final submission for grading purposes. As a result it was unreasonable to manually examine every CS1/CS2 project to determine what tests were working. Instead a script was written to count the number of asserts written in each CS1/CS2 project. Although this is a very suspicious metric, it gives an indication of testing effort and when combined with the graded score on each project, provides a reasonable measure of testing.

4.2.8 Assessment and Validity

Data collected from the experiments were analyzed statistically. The next two chapters will report results of this analysis. Statistical tests such as the Analysis of Variance (ANOVA) and the two-sample *t*-test were employed to determine if differences between the control and experimental groups are statistically significant.

For privacy reasons, student performance results are only reported in aggregate. In fact, training and approval for the experiments was obtained from the University of Kansas Human Subjects Committee - Lawrence Campus (HSCL) prior to conducting the studies.

The experiment design and corresponding results between experiments should establish internal validity of the experiments. As mentioned earlier, care was taken to ensure that the control and experimental groups are homogeneous and random. Both groups were presented with the same instructional material to ensure that no bias was introduced.

External validity of the experiments is established through peer reviewed publications, consistent results across seven studies in diverse environments, and through external recognition of the research merits. This research resulted in a peer reviewed publication in *IEEE Computer*, and conference publications and presentations at the Technical Symposium of the Special Interest Group on Computer Science Education (SIGCSE'06) in Houston, Texas, and the 19th Conference on Software Engineering Education and Training (CSEE&T'06) in North Shore, Oahu. External recognition includes third place in the ACM Student Research Competition Grand Finals, third place in the OOPSLA ACM Student Research Competition, a SIGCSE Special Projects Award, and acceptance to the OOPSLA'05 Doctoral Symposium. The final results are being prepared for submission to *IEEE Transactions on Software Engineering* and additional publications are expected.

Chapter 5

Experiments in Industry

This chapter summarizes research conducted with professional programmers in Fortune 500 companies. Four semi-controlled experiments were conducted. The first three experiments compare three sets of two projects. The first set involved a test-last project with no automated tests followed by a second phase of the same project completed with a test-first approach. The second set involved a test-first project followed by a test-last project. The third set involved a test-last project followed by a test-first project.

The fourth experiment was conducted in a training course and is significantly smaller than the other studies. A case study was also conducted with fifteen projects completed by a software development group in a single company over a span of five years. Results from the case study are reported in the last section.

The chapter begins with a description of the metrics collected and the corresponding analysis performed.

5.1 Metrics Collection and Analysis

For each experiment and the case study, a large number of metrics will be reported and analyzed. This section describes the metrics collected and their source. It also describes the statistical analysis conducted. This research focuses on metrics that pertain to internal design and code quality. These metrics will be categorized as method-level, class-level, interface-level, and project-level. Test metrics are also evaluated due to the key role of automated unit testing in the experiments. No productivity or defect data was available for the industry projects. An external design review was conducted on the third controlled experiment. Subjective and evaluative measures from this experiment were collected and are discussed.

For each set of metrics, a one-way analysis of variance (ANOVA) with unbalanced data and a two-sample two-tailed unequal variance t-test were performed to determine differences between two populations of metrics values. Statistical significance is determined with $p<.05$. The mean and standard deviation for the test-first and

Metric	Expanded Name
NOS	Number of Statements
NOE	Number of Exceptions thrown
V(G)	Cyclomatic Complexity
PL	Program Length
AHL	Actual Halstead Length
VOC	ProgramŠs Vocabulary
VOL	Program Volume
LVL	Program Level
PD	Program Difficulty
EFF	Development Effort
BUG	Bugs Predicted
MLOC	Method Lines of Code
NBD	Nested Block Depth
PAR	Number of Parameters

Table 5.1: Method-level Metrics

test-last groups are reported, and the %difference is calculated as the test-first mean minus the test-last mean divided by the test-last mean ((TF-TL)/TL). When the test-last mean is 0 and the test-first mean is non-zero, a 100% difference is recorded. When both means are zero, a 0% difference is recorded.

5.1.1 Method-Level Metrics

The method-level metrics calculated are expanded in Table 5.1 and defined in Appendix D. The first eleven metrics were produced by JStyle [78] and the remaining three were produced by Eclipse Metrics [75].

5.1.2 Class-Level Metrics

The class-level metrics calculated are expanded in Table 5.2 and defined in Appendix D. The first twenty-six metrics were produced by JStyle [78]. Eclipse Metrics [75] was used to generate MLOC, NOF, NORM, NBD, PAR, SIX, and VG. The metrics TL, CL, BL, SL, and CD were collected by JStyle at the file level but are considered here as class metrics as Java files are typically one class per file. Total and average values by class were aggregated by class from the method level metrics NOS, NOE, V(G), PL, AHL, VOC, VOL, LVL, PD, EFF, and BUG.

Although the metrics tools calculate class and Java interface metrics together, the two were separated prior to conducting this analysis. Several of the metrics only pertain to classes or interfaces, but not both. In addition, leaving the two combined could skew some metrics. For instance, when counting the number of instance

methods (NIM) or weighted method complexity per class (WMC), interfaces would always have zero values. Including interfaces might unfairly penalize or reward a project that had an unusually high number of interfaces. The next section will report the interface only metrics and analysis.

5.1.3 Interface-Level Metrics

As mentioned in the previous section, Java Interfaces were isolated from classes. This section reports metrics only for interfaces. The pertinent interface-level metrics are expanded in Table 5.3 and defined in Appendix D.

5.1.4 Project-Level Metrics

Project-level metrics include some new metrics that were collected only at the project level as well as some method, class, and interface level metrics that were aggregated at the project level. A total of one hundred and forty-six project-level metrics were calculated for each project. Table 5.4 lists the subset of these metrics that will be reported. For many of the metrics maximum, average, and standard deviation values were calculated for visible (public), internal (private), and total (public + private) entities. In most cases only the average total metric values will be reported. The first six were generated or calculated by CCCC [57]. The next sixteen were generated by Eclipse Metrics [75]. The final three were generated by JStyle [78].

Because the project-level metrics result in a single value per project, a statistical analysis is not meaningful when comparing the project-level metrics from two projects. Hence only the case study metrics will be analyzed statistically at this level. Project-level metrics from individual experiments will still be reported and discussed.

In the project-level metrics, a module is generally the same as a class. Some metrics tools [57] identified basic data types such as *int* and *double* as modules so these were excluded. Some projects, namely the CS1 and CS2 C++ projects in the next chapter, included a mix of global functions and class member functions. In such projects all global functions were grouped into a single “anonymous” module.

5.1.5 Test Metrics

The degree and quality of testing will be compared between the test-first and test-last projects. Because the tests are automated in the same programming languages as the source code, coverage and volume metrics can be collected and analyzed.

Test coverage metrics will include both line coverage and branch (or condition) coverage. Test volume will be measured with several metrics. The number of lines of test code (TestLOC) will be compared to the number of lines of source code (SLOC). The two will be divided to give a ratio of test to source lines of code (T/S

Metric	Expanded Name
DIT	Depth of Inheritance Tree
NII	Number of Interfaces Implemented
NIV	Number of Instance Variables
NSV	Number of Static Variables
NOV	Number of Variables
NIM	Number of Instance Methods
NSM	Number of Static Methods
NPM	Number of Primitive Methods
NNP	Number of NonPrimitive Methods
NOM	Number of Methods
WMC	Weighted Methods Complexity
RFC	Response For Class
LCOM_CK	Lack of Cohesion of Methods (Chidamber-Kemerer)
LCOM_LH	Lack of Cohesion of Methods (Li-Henry)
LCOM_HS	Lack of Cohesion of Methods (Henderson-Sellers)
NIC	Number of Inner Classes
NIS	Number of Inner Static Classes
NLC	Number of Local Classes
NAC	Number of Anonymous Classes
NOC	Number of Children
FI	Fan-in
FO	Fan-out
PFI	Intra-Package Fan-in
PFO	Intra-Package Fan-out
IFI	Inter-package Fan-in
IFO	Inter-package Fan-out
MLOC	Average Method Lines of Code
NOF	Number of Fields
NORM	Number of Overridden Methods
NBD	Average Nested Block Depth
PAR	Average Number of Parameters
SIX	Specialization Index
VG	Cyclomatic Complexity (class)
V(G)	Cyclomatic Complexity (avg of methods in class)
TL	Total Lines
CL	Comment Lines
BL	Blank Lines
SL	Source Lines
CD	Comment Density

Table 5.2: Class-level Metrics

Metric	Expanded Name
DIT	Depth of Inheritance Tree
NCI	Number of classes implementing interface
NSV	Number of Static Variables
NIM	Number of Instance Methods
NPM	Number of Primitive Methods
NOM	Number of Methods
RFC	Response For Class
NIC	Number of Inner Classes

Table 5.3: Interface-level Metrics

Metric	Expanded Name
LOC/Mod	Lines of Code per Module
CBO(Avg)	Average Coupling Between Objects
DIT(Avg)	Average Depth of Inheritance Tree
NOC(Avg)	Average Number of Children
FO(Avg)	Average Fan-out
FI(Avg)	Average Fan-in
IF(Avg)	Average Information Flow
CA(Avg)	Average Afferent Coupling
CE(Avg)	Average Efferent Coupling
V(G)/Mod	Cyclomatic Complexity per Module
V(G)/Mod(Max)	Maximum Complexity per Module
RMD(Avg)	Average Normalized Distance from Mean
SIX(Avg)	Average Specialization Index
RMI(Avg)	Average Instability
RMA(Avg)	Average Abstractness
NOF(Avg)	Average Number of Attributes
NSF(Avg)	Average Number of Static Attributes
NBD(Avg)	Average Nested Block Depth
NOM(Avg)	Average Number of Methods
MLOC(Avg)	Average Method Lines of Code
LCOM(Avg)	Average Lack of Cohesion of Methods
PAR(Avg)	Average Number of Parameters
NOI(Avg)	Average Number of Interfaces
NOA(Avg)	Average Number of Abstract Classes
REU	Reuse Ratio
SPC	Specialization Ratio

Table 5.4: Project-level Metrics

Ratio). This value can indicate the effort extended in writing the automated tests. In addition, the number of assert statements will be measured in aggregate (#Asserts), per lines of source code (#Asserts/LOC), per class (#Asserts/Class), and per method (#Asserts/Method). An assert statement is an individual claim that some condition is true. A single test might consist of multiple asserts, but must contain at least one assert. By measuring the volume of asserts and comparing it to test coverage, one can see the efficiency of the tests. Tests that use many lines of code and asserts yet achieve low test coverage would be inefficient tests. Whereas tests that use fewer lines of code and asserts yet achieve high test coverage would be highly efficient tests.

5.1.6 Subjective and Evaluative Metrics

A formal design review was conducted on one of the controlled experiments. The review was completed independently by three reviewers in the same company where the experiments were conducted. None of the reviewers worked on any of the projects under examination. However, all three had expertise and experience with the languages, technologies, and domain of the projects.

The reviewers were asked to review the two projects of experiment three. The first project was completed with a test-last approach and the second project was completed with a test-first approach. The projects are described further in section 5.4. Each reviewer was given a brief overview of the two projects that included instructions on how to obtain the source code for the projects. The reviewers were asked to not spend more than two hours completing the review of each project. They were given a short survey (see Appendix F) to complete at the end of the review. The survey asked the reviewers to rate the projects using a Likert scale in five areas: Understandability, Maintainability, Reusability, Testability, and Overall Design Quality. The results will be presented and discussed in section 5.4.

Additional subjective and evaluative metrics will be reported and discussed regarding the experiment in the training class and the overall case study. These metrics come from three surveys conducted. A pre- and post-experiment survey were administered in the training course. The intent of the surveys was twofold. First the surveys were used to ensure that the experiment and control groups were balanced with programmers of similar academic and professional experience. Second the surveys were used to measure programmer opinions regarding the test-first and test-last approaches. In addition, a longitudinal survey was administered over the web after development completed on all of the experiment projects. The intent of the longitudinal survey was to measure if programmer opinions persisted or changed over time.

5.2 Formal Industry Experiment #1: No-Tests - Test-First

This section reports results from the first of three controlled experiments. The experiment design and context are reviewed, followed by the results of an analysis of the experiment.

5.2.1 Experiment Design and Context

This section describes the experiment design and context of an experiment conducted in a large, Fortune 500 corporation. Two phases of the same project were developed by the same group of programmers. The first phase was completed in 2001, before any of the developers received formal training on TDD or automated unit testing. As a result no automated tests were written and the project was developed in a traditional mode with a large up-front design and manual testing after the software was implemented. This project will be labeled as test-last (TL). The second phase was implemented in 2005 and 2006 using a test-first approach with automated unit tests. This project will be labeled as test-first (TF). In between the two projects, developers completed a pre-experiment survey and participated in the TDD training described earlier.

The majority of the development effort in this project was completed by a single programmer. This programmer reported having 6 to 10 years of experience and earned an undergraduate degree in a computing discipline. They reported having extensive and recent previous Java and web experience.

The first phase was named “Part Number Advanced Search” and was completed in 2001 and contained 1,562 lines of source code. The project was a web application that provided an interface to a database for searching for engineering part information. This project utilized Java Servlets and JavaServer Pages and used a Java beans approach for centralizing database access.

The second phase was named “Part Number Advanced Search, Part II” and fully replaced the first with no reuse from phase 1. Phase 2 was completed in 2006 containing 842 lines of source code. This phase refactored the first phase to use the Spring framework for wiring dependent objects together and the Spring web application model-view-controller framework for managing the application flow. The second phase implemented the data access object (DAO) design pattern for centralizing database access. The second phase added several features such as data searching and sorting, and it satisfied a number of maintenance requests.

A couple of threats to external validity of this experiment are identified. The small team size causes one to question whether the same results found here should be expected in general. In addition the extended time frame between the two project phases allows for possible developer maturation that could have affected the re-

Metric	NOS	NOE	V(G)	PL	AHL	VOC	VOL
	Analysis of Variance (ANOVA) Results						
F-ratio	16.0108	2.0948	16.7466	9.2832	14.7237	9.3636	13.5218
p-value	0.0001	0.1496	0.0001	0.0027	0.0002	0.0026	0.0003
Significant?	Yes	No	Yes	Yes	Yes	Yes	Yes
	Two-sample t-test						
p-value	0.0056	0.2427	0.0043	0.0220	0.0076	0.0177	0.0109
df	180	180	180	180	180	180	180
Significant?	Yes	No	Yes	Yes	Yes	Yes	Yes
Higher Method	TL	TL	TL	TL	TL	TL	TL
TF Mean	3.36	0.06	1.50	37.69	23.17	11.09	109.01
Std Dev	5.55	0.23	1.21	78.75	41.25	14.54	244.81
TL Mean	15.58	0.13	3.80	103.63	105.37	21.82	648.47
Std Dev	0.00	0.00	0.00	7.60	3.54	2.83	12.52
%difference	-78%	-57%	-60%	-64%	-78%	-49%	-83%

Table 5.5: Analysis of Method Metrics for Industry Experiment 1, Part 1

sults. However the results are valuable even if only anecdotal, and these results may enlighten conclusions when examining all the experiments and the case study in aggregate.

5.2.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level.

Method-Level Metrics

Table 5.5 and Table 5.6 present the results of the statistical analysis of the method-level metrics comparing the phase 1 (test-last/no-automated-tests) and phase 2 (test-first) methods.

This analysis demonstrates statistically significant differences with twelve of the fourteen metrics. Figure 5.1 illustrates the differences in a radar chart. Each of the metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the degree and consistency by which the means of the test-last and test-first metrics varied.

This data implies and the radar chart illustrates that software developed with a test-last approach is significantly larger (NOS, PL, AHL, VOC, VOL, and MLOC), is

Metric	LVL	PD	EFF	BUG	MLOC	NBD	PAR
	Analysis of Variance (ANOVA) Results						
F-ratio	0.0010	7.0236	10.3928	13.5237	16.6473	8.6491	8.1909
p-value	0.9746	0.0088	0.0015	0.0003	0.0001	0.0037	0.0047
Significant?	No	Yes	Yes	Yes	Yes	Yes	Yes
	Two-sample t-test						
p-value	0.9754	0.0493	0.0270	0.0108	0.0045	0.0155	0.0026
df	180	180	180	180	179	179	179
Significant?	No	Yes	Yes	Yes	Yes	Yes	Yes
Higher Method	TF	TL	TL	TL	TL	TL	TF
TF Mean	0.47	4.14	1.07	0.04	4.21	1.32	0.87
Std Dev	0.37	3.88	3.18	0.08	7.77	0.74	0.86
TL Mean	0.46	7.26	19.36	0.22	20.60	1.77	0.50
Std Dev	0.44	1.18	0.04	0.00	0.00	0.00	0.00
%difference	0%	-43%	-94%	-83%	-80%	-25%	73%

Table 5.6: Analysis of Method Metrics for Industry Experiment 1, Part 2

significantly more complex (V(G), PD, NBD), and is less maintainable (PD, EFF, BUG) than software developed with a test-first approach. In contrast, this also implies that software developed with a test-first approach has higher coupling (PAR) than software developed with a test-last approach.

Class-Level Metrics

Table 5.7 and Table 5.8 present the results of the statistical analysis of the class-level metrics comparing the phase 1 (test-last/no-automated-tests) and phase 2 (test-first) classes. To save space, only the two-sample t-test p-values are reported. Although the ANOVA results strengthen the confidence, the t-test should be sufficient here to indicate significant differences between the two samples. The test-last project contained five classes and the test-first project contained nine classes.

Like the method-level metrics, a number of large differences exist between the two projects. However, unlike the method-level metrics, the differences on only a couple of metrics (NII and NSV) are statistically significant. Still the data indicates notable differences. Table 5.9 presents the same data from Table 5.7 and Table 5.8, but in sorted order by %difference with the middle metrics eliminated for space. This view illustrates more clearly that the phase 1 (test-last/no-automated-tests) classes were longer and more complex while the phase 2 (test-first) classes tended to be more abstract (NII) with higher cohesion (LCOM), higher reuse (SIX, FI), and higher coupling (PAR). An exception to these generalizations would be the higher nested block depth (NBD) in the test-first classes indicating some complexity.

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	0.1493	No	TL	0.89	0.33	2.20	1.64	-60%
NII	0.0039	Yes	TF	0.67	0.50	0.00	0.00	100%
NIV	0.6523	No	TL	4.89	8.24	8.20	14.29	-40%
NSV	0.0467	Yes	TL	0.00	0.00	16.60	13.05	-100%
NOV	0.1488	No	TL	4.89	8.24	24.80	24.83	-80%
NIM	0.8669	No	TF	13.44	16.08	11.80	17.53	14%
NSM	0.1778	No	TL	0.00	0.00	1.20	1.64	-100%
NPM	0.8951	No	TF	10.11	16.89	8.80	17.48	15%
NNP	0.6736	No	TF	3.11	3.06	2.60	1.34	20%
NOM	0.9636	No	TF	13.44	16.08	13.00	17.33	3%
WMC	0.5057	No	TL	20.22	19.31	46.80	80.58	-57%
RFC	0.5613	No	TL	23.44	22.93	35.40	39.75	-34%
LCOM_CK	0.7372	No	TF	184.67	341.05	126.80	275.74	46%
LCOM_LH	0.1135	No	TF	7.78	7.58	3.00	2.55	159%
LCOM_HS	0.7243	No	TF	0.42	0.44	0.33	0.46	28%
NIC	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NIS	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NLC	0.3466	No	TF	0.22	0.67	0.00	0.00	100%
NAC	0.3466	No	TF	0.22	0.67	0.00	0.00	100%
NOC	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
FI	0.2198	No	TF	1.11	0.93	0.60	0.55	85%
FO	0.4913	No	TL	7.56	5.22	10.40	7.77	-27%
PFI	0.8864	No	TL	0.56	0.53	0.60	0.55	-7%
PFO	0.9420	No	TL	0.56	1.33	0.60	0.89	-7%
IFI	0.1786	No	TF	0.56	1.13	0.00	0.00	100%
IFO	0.4483	No	TL	7.00	4.06	9.80	7.05	-29%

Table 5.7: Analysis of Class Metrics for Industry Experiment 1, Part 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
MLOC	0.3877	No	TL	69.29	69.12	255.40	427.61	-73%
NOF	0.7560	No	TL	6.29	8.96	8.60	14.03	-27%
WMC	0.4801	No	TL	28.14	18.99	60.80	93.02	-54%
NORM	0.7676	No	TL	0.57	1.51	0.80	1.10	-29%
NBD	0.4489	No	TF	1.58	0.52	1.37	0.40	15%
PAR	0.0782	No	TF	1.30	0.68	0.65	0.46	98%
SIX	0.5119	No	TF	0.65	1.73	0.19	0.35	247%
VG	0.4493	No	TL	2.09	0.76	3.11	2.68	-33%
NOS	0.3410	No	TL	45.22	44.46	198.60	316.78	-77%
NOE	0.5914	No	TL	0.78	1.30	1.60	3.05	-51%
V(G)	0.4436	No	TL	20.22	19.31	50.40	78.68	-60%
PL	0.4139	No	TL	506.77	676.32	1346.51	2025.77	-62%
AHL	0.3507	No	TL	311.56	348.85	1332.40	2154.84	-77%
VOC	0.4603	No	TL	149.11	149.71	301.20	407.41	-50%
VOL	0.3329	No	TL	1465.64	1967.40	8031.76	13305.30	-82%
LVL	0.8761	No	TL	6.27	10.08	7.06	8.12	-11%
PD	0.5438	No	TL	55.64	49.65	100.02	146.69	-44%
EFF	0.2904	No	TL	14.43	21.13	233.40	402.14	-94%
BUG	0.3329	No	TL	0.49	0.66	2.68	4.44	-82%
NOSAvg	0.3030	No	TL	4.31	2.87	10.19	11.05	-58%
NOEAvg	0.9882	No	TL	0.23	0.35	0.24	0.52	-2%
V(G)Avg	0.3792	No	TL	1.65	0.67	2.46	1.79	-33%
PLAvg	0.5716	No	TL	51.33	42.82	73.21	74.84	-30%
AHLAvg	0.3692	No	TL	32.68	23.15	67.92	76.93	-52%
VOCAvg	0.7032	No	TL	14.69	8.59	17.04	11.51	-14%
VOLAvg	0.3346	No	TL	152.28	128.88	413.27	528.20	-63%
LVLAvg	0.2278	No	TL	0.33	0.19	0.43	0.11	-23%
PDAvg	0.9973	No	TL	5.02	2.09	5.03	3.30	0%
EFFAvg	0.2431	No	TL	1.42	1.47	11.98	17.26	-88%
BUGAvg	0.3346	No	TL	0.05	0.04	0.14	0.18	-63%
MLOCAvg	0.8377	No	TL	6.36	5.29	7.49	11.08	-15%
NBDAvg	0.1827	No	TF	1.72	0.69	1.31	0.39	31%
PARAvg	0.0635	No	TF	1.24	0.57	0.61	0.51	102%
TL	0.3415	No	TL	196.29	116.96	517.60	662.62	-62%
CL	0.1416	No	TL	54.43	33.40	145.60	111.08	-63%
BL	0.4732	No	TL	21.57	16.71	39.80	50.30	-46%
SL	0.4029	No	TL	120.29	87.43	335.00	510.81	-64%
CD	0.2407	No	TL	0.30	0.16	0.44	0.20	-31%

Table 5.8: Analysis of Class Metrics for Industry Experiment 1, Part 2

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NSV	0.0467	Yes	TL	0.00	0.00	16.60	13.05	-100%
NSM	0.1778	No	TL	0.00	0.00	1.20	1.64	-100%
EFF	0.2904	No	TL	14.43	21.13	233.40	402.14	-94%
EFFAvg	0.2431	No	TL	1.42	1.47	11.98	17.26	-88%
BUG	0.3329	No	TL	0.49	0.66	2.68	4.44	-82%
VOL	0.3329	No	TL	1465.64	1967.40	8031.76	13305.30	-82%
NOV	0.1488	No	TL	4.89	8.24	24.80	24.83	-80%
NOS	0.3410	No	TL	45.22	44.46	198.60	316.78	-77%
AHL	0.3507	No	TL	311.56	348.85	1332.40	2154.84	-77%
MLOC	0.3877	No	TL	69.29	69.12	255.40	427.61	-73%
SL	0.4029	No	TL	120.29	87.43	335.00	510.81	-64%
VOLAvg	0.3346	No	TL	152.28	128.88	413.27	528.20	-63%
BUGAvg	0.3346	No	TL	0.05	0.04	0.14	0.18	-63%
NIM	0.8669	No	TF	13.44	16.08	11.80	17.53	14%
NPM	0.8951	No	TF	10.11	16.89	8.80	17.48	15%
NBD	0.4489	No	TF	1.58	0.52	1.37	0.40	15%
NNP	0.6736	No	TF	3.11	3.06	2.60	1.34	20%
LCOM_HS	0.7243	No	TF	0.42	0.44	0.33	0.46	28%
NBDAvg	0.1827	No	TF	1.72	0.69	1.31	0.39	31%
LCOM_CK	0.7372	No	TF	184.67	341.05	126.80	275.74	46%
FI	0.2198	No	TF	1.11	0.93	0.60	0.55	85%
PAR	0.0782	No	TF	1.30	0.68	0.65	0.46	98%
NII	0.0039	Yes	TF	0.67	0.50	0.00	0.00	100%
PARAvg	0.0635	No	TF	1.24	0.57	0.61	0.51	102%
LCOM_LH	0.1135	No	TF	7.78	7.58	3.00	2.55	159%
SIX	0.5119	No	TF	0.65	1.73	0.19	0.35	247%

Table 5.9: Sorted Class Metrics for Industry Experiment 1

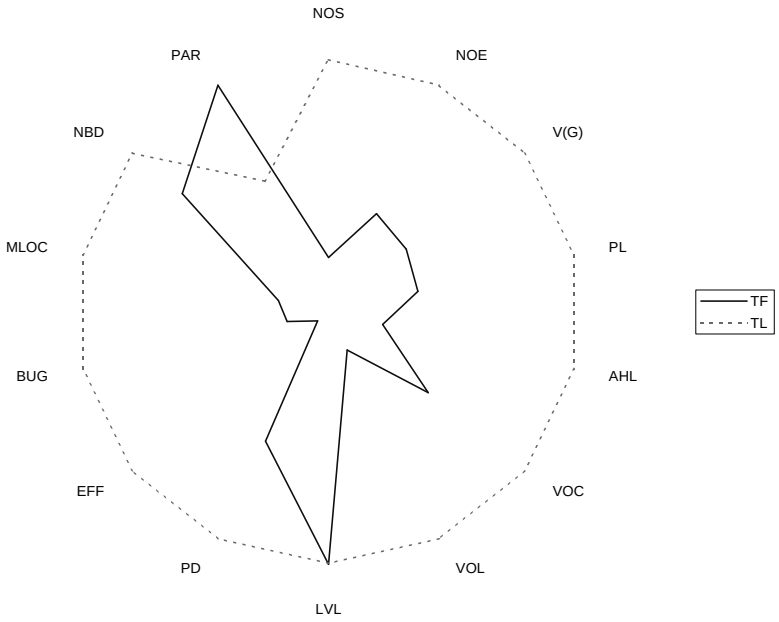

Figure 5.1: Industry Experiment 1 Method Metrics Radar Chart

Interface-Level Metrics

The test-last project did not include any interfaces and the test-first project had one interface. This raises a slight concern for both projects regarding the possible lack of abstractness and tightness of coupling.

Project-Level Metrics

The project-level metrics are reported in Table 5.10. The data is reported in sorted order by %difference. This view allows one to see trends in the metrics. In line with the method and class level metrics, we see that the phase 1 (test-last/no automated tests) project tended to be larger and more complex while the phase 2 (test-first) project tended to be more reusable, have higher cohesion, but also have higher coupling.

5.2.3 Test Results

Table 5.11 presents the test metrics for the first experiment. No technical comparison can be made between the two projects because the first phase did not contain any automated unit tests. However it is important to note the very high test coverage values in the test-first project.

Metric	TF Value	TL Value	Higher Method	%diff
NSFavg	0.00	20.00	TL	-100%
MLOCavg	4.08	20.22	TL	-80%
VGmax	9.00	44.00	TL	-80%
LOC/module	25.52	78.10	TL	-67%
VGavg	1.66	4.62	TL	-64%
RMIavg	0.47	1.00	TL	-53%
NOFavg	6.29	10.25	TL	-39%
NBDavg	1.32	1.75	TL	-25%
DITavg	0.14	0.17	TL	-14%
NOAavg	0.00	0.00	N/A	0%
REU	0.00	0.00	N/A	0%
SPC	0.00	0.00	N/A	0%
FIavg	1.54	1.33	TF	15%
CBOavg	2.71	2.33	TF	16%
FOavg	1.18	1.00	TF	18%
NOMavg	17.00	13.50	TF	26%
CEavg	4.00	3.00	TF	33%
LCOMavg	0.39	0.27	TF	44%
NOCavg	0.18	0.11	TF	61%
PARavg	0.87	0.48	TF	79%
RMAavg	0.17	0.00	TF	100%
RMDavg	0.36	0.00	TF	100%
NOIavg	0.50	0.00	TF	100%
CAavg	6.00	0.00	TF	100%
SIXavg	0.65	0.24	TF	178%
IFavg	4.86	0.22	TF	2086%

Table 5.10: Analysis of Project Metrics for Industry Experiment 1

Metric	TF	TL
T/S Ratio	1.33	N/A
#Asserts/LOC	0.24	N/A
#Asserts/Class	9.46	N/A
#Asserts/Method	2.60	N/A
Line Coverage	98%	N/A
Cond Coverage	100%	N/A

Table 5.11: Test Metrics for Industry Experiment 1

5.3 Formal Industry Experiment #2: Test-Last - Test-First

This section reports results from the second of three controlled experiments. The experiment design and context are reviewed, followed by the results of an analysis of the experiment.

5.3.1 Experiment Design and Context

This section describes the experiment design and context of an experiment conducted in a large, Fortune 500 corporation. Two different projects were developed by overlapping teams of developers. The first project was completed in 2003. The developers employed a test-last approach including automated unit-tests written in JUnit. The project was developed in a traditional mode with a large up-front design and automated and manual testing after the software was implemented. This project will be labeled as test-last (TL). The second project is the same second project compared in the previous experiment. This project was implemented in 2005 and 2006 using a test-first approach with automated unit tests. This project will be labeled as test-first (TF). In between the two projects, developers completed a pre-experiment survey and participated in the TDD training described earlier.

The majority of the development effort in the first test-last project was completed by two programmers. Both programmers reported having 6 to 10 years of experience and earned an undergraduate or graduate degree in a computing discipline. They reported having extensive and recent previous Java and web experience. The second test-first project staff was described in the previous section and was led by one of the lead developers on the first test-last project.

The first project was named “Workflow” and was completed in 2003. It contained 811 lines of source code. The project was a utility project that used XML for storing a workflow (paths and steps). Jakarta Common Digester was used for processing the XML.

The second project was named “Part Number Advanced Search, Part II” and was completed in 2006 containing 842 lines of source code. This phase refactored an earlier phase to use the Spring framework for wiring dependent objects together and the Spring web application model-view-controller framework for managing the application flow. This second phase implemented the data access object (DAO) design pattern for centralizing database access. This second phase added several features such as data searching and sorting, and it satisfied a number of maintenance requests.

Metric	NOS	NOE	V(G)	PL	AHL	VOC	VOL
	Analysis of Variance (ANOVA) Results						
F-ratio	0.0001	8.0412	0.0720	3.4710	0.9483	4.5632	0.8070
p-value	0.9933	0.0049	0.7886	0.0636	0.3311	0.0336	0.3699
Significant?	No	Yes	No	No	No	Yes	No
	Two-sample t-test						
p-value	0.9932	0.0076	0.7843	0.0690	0.3295	0.0364	0.3689
df	252	252	252	252	252	252	
Significant?	No	Yes	No	No	No	Yes	No
Higher Method	TL	TF	TF	TF	TF	TF	TF
TF Mean	3.36	0.06	1.50	37.69	23.17	11.09	109.01
Std Dev	5.55	0.23	1.21	78.75	41.25	14.54	244.81
TL Mean	3.37	0.00	1.45	22.39	17.90	7.73	80.64
Std Dev	8.37	0.00	2.04	49.83	44.57	10.31	256.45
%difference	0%	0%	4%	68%	29%	44%	35%

Table 5.12: Analysis of Method Metrics for Industry Experiment 2, Part 1

5.3.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level.

For each set of metrics, a one-way analysis of variance (ANOVA) with unbalanced data and a two-sample two-tailed unequal variance t-test were performed to determine differences between two populations of metrics values. Statistical significance is determined with $p<.05$. The mean and standard deviation for the test-first and test-last groups are reported, and the %difference is calculated as the test-first mean minus the test-last mean divided by the test-last mean ((TF-TL)/TL).

Method-Level Metrics

Table 5.12 and Table 5.13 present the results of the statistical analysis of the method-level metrics comparing the test-last and test-first methods. The method-level metrics calculated are expanded in Table 5.1 and defined in Appendix D. The first eleven metrics were produced by JStyle [78] and the remaining three were produced by Eclipse Metrics [75].

This analysis demonstrates statistically significant differences with four of the fourteen metrics. Figure 5.2 illustrates the differences in a radar chart. Each of the metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the

Metric	LVL	PD	EFF	BUG	MLOC	NBD	PAR
	Analysis of Variance (ANOVA) Results						
F-ratio	1.2625	7.4288	0.0220	0.8053	0.4407	0.5084	24.8605
p-value	0.2623	0.0069	0.8822	0.3704	0.5074	0.4765	0.0000
Significant?	No	Yes	No	No	No	No	Yes
	Two-sample t-test						
p-value	0.2623	0.0070	0.8797	0.3694	0.5071	0.4757	0.0000
df	252	252	252	252	241	241	241
Significant?	No	Yes	No	No	No	No	Yes
Higher Method	TF	TF	TF	TF	TF	TF	TF
TF Mean	0.47	4.14	1.07	0.04	4.21	1.32	0.87
Std Dev	0.37	3.88	3.18	0.08	7.77	0.74	0.86
TL Mean	0.41	2.83	0.99	0.03	3.52	1.24	0.42
Std Dev	0.37	3.76	5.47	0.09	8.42	0.96	0.50
%difference	13%	46%	9%	35%	20%	6%	107%

Table 5.13: Analysis of Method Metrics for Industry Experiment 2, Part 2

degree and consistency by which the means of the test-last and test-first metrics varied.

This data implies and the radar chart illustrates relatively few significant differences between methods developed with a test-last approach and methods developed with a test-first approach. Notice that unlike the previous experiment, test-last methods tend to have (insignificantly) lower mean metric values than the test-first methods. The data indicates that software developed with a test-first approach is significantly larger in only two of the size and complexity measures (VOC and PD), has significantly more exceptions (NOE), and again has higher coupling (PAR) than software developed with a test-last approach.

Class-Level Metrics

Table 5.14 and Table 5.15 present the results of the statistical analysis of the class-level metrics comparing the test-last and test-first classes. To save space, only the two-sample t-test p-values are reported. Although the ANOVA results strengthen the confidence, the t-test should be sufficient here to indicate significant differences between the two samples. The test-last project contained eleven classes and the test-first project contained nine classes.

Table 5.16 presents the same data from Table 5.14 and Table 5.15, but in sorted order by %difference with the middle metrics eliminated for space. This view illustrates some slight trends but also some contradictions. It appears that the Workflow (test-last) project has a bit more reuse (DIT, NOC) but also perhaps more coupling. The phase 2 (test-first) project may be a bit longer and more complex (MLOC, VOC,

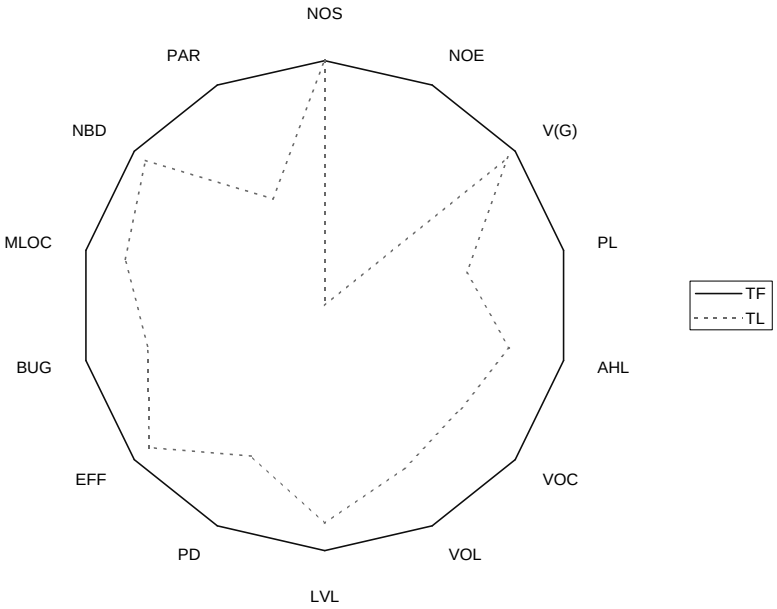

Figure 5.2: Industry Experiment 2 Method Metrics Radar Chart

VOL), but also may be more abstract and have higher internal reuse (NII, SIX, NORM). Again the test-first project has a higher number of parameters, but the fan-in and fan-out metrics cause one to question which project has the higher coupling. Finally, the three calculations of LCOM present inconsistencies regarding cohesion.

Interface-Level Metrics

As mentioned in the first section, Java Interfaces were isolated from classes. This section reports metrics only for interfaces. The pertinent interface-level metrics are expanded in Table 5.3 and defined in Appendix D.

The test-first project did not include any interfaces. The test-last project did include two interfaces. This raises a slight concern for both projects regarding the possible lack of abstractness and tightness of coupling. Table 5.17 presents the results of the statistical analysis of the interface-level metrics for the test-last project.

Project-Level Metrics

The project-level metrics are reported in Table 5.18. The data is reported in sorted order by %difference. This view allows one to see trends in the metrics. Similar to the method and class level metrics, few clear trends seem to exist in the differences between the two projects of experiment two. The Workflow (test-last) project seems to have higher coupling (CBO, IF) and perhaps better reuse (REU, SPC, NOI, DIT) although neither of these trends are completely clear (PAR, SIX).

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	0.1647	No	TL	0.89	0.33	1.27	0.79	-30%
NII	0.0891	No	TF	0.67	0.50	0.27	0.47	144%
NIV	0.5704	No	TF	4.89	8.24	3.18	3.19	54%
NSV	0.1337	No	TL	0.00	0.00	0.82	1.66	-100%
NOV	0.7645	No	TF	4.89	8.24	4.00	2.93	22%
NIM	0.7005	No	TF	13.44	16.08	11.00	10.46	22%
NSM	0.3409	No	TL	0.00	0.00	0.09	0.30	-100%
NPM	0.2723	No	TF	10.11	16.89	3.36	4.01	201%
NNP	0.3332	No	TF	3.11	3.06	1.73	3.13	80%
NOM	0.7109	No	TF	13.44	16.08	11.09	10.44	21%
WMC	0.7381	No	TF	20.22	19.31	17.36	17.93	16%
RFC	0.8519	No	TF	23.44	22.93	21.64	18.84	8%
LCOM_CK	0.3111	No	TF	184.67	341.05	59.18	89.64	212%
LCOM_LH	0.3860	No	TF	7.78	7.58	5.18	4.67	50%
LCOM_HS	0.7753	No	TL	0.42	0.44	0.48	0.46	-12%
NIC	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NIS	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NLC	0.3466	No	TF	0.22	0.67	0.00	0.00	100%
NAC	0.3466	No	TF	0.22	0.67	0.00	0.00	100%
NOC	0.0816	No	TL	0.00	0.00	0.55	0.93	-100%
FI	0.0182	Yes	TL	1.11	0.93	2.45	1.37	-55%
FO	0.6199	No	TL	7.56	5.22	8.73	5.08	-13%
PFI	0.0009	Yes	TL	0.56	0.53	2.45	1.37	-77%
PFO	0.0189	Yes	TL	0.56	1.33	2.91	2.59	-81%
IFI	0.1786	No	TF	0.56	1.13	0.00	0.00	100%
IFO	0.4967	No	TF	7.00	4.06	5.82	3.40	20%

Table 5.14: Analysis of Class Metrics for Industry Experiment 2, Part 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
MLOC	0.3230	No	TF	69.29	69.12	39.00	41.08	78%
NOF	0.4072	No	TF	6.29	8.96	3.18	3.19	98%
WMC	0.3678	No	TF	28.14	18.99	19.45	19.72	45%
NORM	0.5277	No	TF	0.57	1.51	0.18	0.40	214%
NBD	0.1151	No	TF	1.58	0.52	1.20	0.24	31%
PAR	0.0178	Yes	TF	1.30	0.68	0.47	0.21	175%
SIX	0.4624	No	TF	0.65	1.73	0.14	0.32	379%
VG	0.2289	No	TF	2.09	0.76	1.67	0.52	25%
NOS	0.8090	No	TF	45.22	44.46	40.45	41.61	12%
NOE	0.1108	No	TF	0.78	1.30	0.00	0.00	100%
V(G)	0.7381	No	TF	20.22	19.31	17.36	17.93	16%
PL	0.3467	No	TF	506.77	676.32	268.66	287.70	89%
AHL	0.4828	No	TF	311.56	348.85	213.91	229.10	46%
VOC	0.3376	No	TF	149.11	149.71	91.82	95.08	62%
VOL	0.5096	No	TF	1465.64	1967.40	967.71	1081.37	51%
LVL	0.7273	No	TF	6.27	10.08	4.97	4.51	26%
PD	0.2907	No	TF	55.64	49.65	33.95	35.85	64%
EFF	0.7798	No	TF	14.43	21.13	11.86	18.68	22%
BUG	0.5100	No	TF	0.49	0.66	0.32	0.36	51%
NOSAvg	0.4082	No	TF	4.31	2.87	3.36	1.85	28%
NOEAvg	0.0806	No	TF	0.23	0.35	0.00	0.00	100%
V(G)Avg	0.5113	No	TF	1.65	0.67	1.47	0.45	12%
PLAvg	0.0863	No	TF	51.33	42.82	22.88	13.32	124%
AHLAvg	0.0959	No	TF	32.68	23.15	17.54	9.81	86%
VOCAvg	0.0524	No	TF	14.69	8.59	8.03	3.23	83%
VOLAvg	0.1359	No	TF	152.28	128.88	77.70	56.10	96%
LVLAvg	0.1210	No	TL	0.33	0.19	0.45	0.12	-26%
PDAvg	0.0157	Yes	TF	5.02	2.09	2.86	0.96	76%
EFFAvg	0.2837	No	TF	1.42	1.47	0.80	0.83	77%
BUGAvg	0.1360	No	TF	0.05	0.04	0.03	0.02	96%
MLOCAvg	0.7134	No	TF	6.36	5.29	5.40	6.16	18%
NBDAvg	0.7279	No	TF	1.72	0.69	1.59	1.03	9%
PARAvg	0.0060	Yes	TF	1.24	0.57	0.54	0.25	129%
TL	0.7841	No	TF	196.29	116.96	179.09	142.42	10%
CL	0.1836	No	TL	54.43	33.40	88.64	69.85	-39%
BL	0.4728	No	TL	21.57	16.71	27.55	16.70	-22%
SL	0.2249	No	TF	120.29	87.43	70.91	63.41	70%
CD	0.0141	Yes	TL	0.30	0.16	0.50	0.04	-40%

Table 5.15: Analysis of Class Metrics for Industry Experiment 2, Part 2

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NSV	0.1337	No	TL	0.00	0.00	0.82	1.66	-100%
NSM	0.3409	No	TL	0.00	0.00	0.09	0.30	-100%
NOC	0.0816	No	TL	0.00	0.00	0.55	0.93	-100%
PFO	0.0189	Yes	TL	0.56	1.33	2.91	2.59	-81%
PFI	0.0009	Yes	TL	0.56	0.53	2.45	1.37	-77%
FI	0.0182	Yes	TL	1.11	0.93	2.45	1.37	-55%
CD	0.0141	Yes	TL	0.30	0.16	0.50	0.04	-40%
CL	0.1836	No	TL	54.43	33.40	88.64	69.85	-39%
DIT	0.1647	No	TL	0.89	0.33	1.27	0.79	-30%
LVLAvg	0.1210	No	TL	0.33	0.19	0.45	0.12	-26%
BL	0.4728	No	TL	21.57	16.71	27.55	16.70	-22%
FO	0.6199	No	TL	7.56	5.22	8.73	5.08	-13%
LCOM_HS	0.7753	No	TL	0.42	0.44	0.48	0.46	-12%
LCOM_LH	0.3860	No	TF	7.78	7.58	5.18	4.67	50%
BUG	0.5100	No	TF	0.49	0.66	0.32	0.36	51%
VOL	0.5096	No	TF	1465.64	1967.40	967.71	1081.37	51%
NIV	0.5704	No	TF	4.89	8.24	3.18	3.19	54%
VOC	0.3376	No	TF	149.11	149.71	91.82	95.08	62%
PD	0.2907	No	TF	55.64	49.65	33.95	35.85	64%
SL	0.2249	No	TF	120.29	87.43	70.91	63.41	70%
PDAvg	0.0157	Yes	TF	5.02	2.09	2.86	0.96	76%
EFFAvg	0.2837	No	TF	1.42	1.47	0.80	0.83	77%
MLOC	0.3230	No	TF	69.29	69.12	39.00	41.08	78%
NNP	0.3332	No	TF	3.11	3.06	1.73	3.13	80%
VOCAvg	0.0524	No	TF	14.69	8.59	8.03	3.23	83%
AHLAvg	0.0959	No	TF	32.68	23.15	17.54	9.81	86%
PL	0.3467	No	TF	506.77	676.32	268.66	287.70	89%
BUGAvg	0.1360	No	TF	0.05	0.04	0.03	0.02	96%
VOLAvg	0.1359	No	TF	152.28	128.88	77.70	56.10	96%
NOF	0.4072	No	TF	6.29	8.96	3.18	3.19	98%
PLAvg	0.0863	No	TF	51.33	42.82	22.88	13.32	124%
PARAvg	0.0060	Yes	TF	1.24	0.57	0.54	0.25	129%
NII	0.0891	No	TF	0.67	0.50	0.27	0.47	144%
PAR	0.0178	Yes	TF	1.30	0.68	0.47	0.21	175%
NPM	0.2723	No	TF	10.11	16.89	3.36	4.01	201%
LCOM_CK	0.3111	No	TF	184.67	341.05	59.18	89.64	212%
NORM	0.5277	No	TF	0.57	1.51	0.18	0.40	214%
SIX	0.4624	No	TF	0.65	1.73	0.14	0.32	379%

Table 5.16: Sorted Class Metrics for Industry Experiment 2

Metric	TL Mean	TL SDev
DIT	0.50	0.71
NCI	4.00	2.83
NSV	0.00	0.00
NIM	5.00	5.66
NPM	5.00	5.66
NOM	5.00	5.66
RFC	5.00	5.66
NIC	0.00	0.00

Table 5.17: Analysis of Interface Metrics for Experiment 2

Metric	TF Value	TL Value	Higher Method	%diff
NSFavg	0.00	0.82	TL	-100%
NOAavg	0.00	2.00	TL	-100%
REU	0.00	0.27	TL	-100%
SPC	0.00	2.33	TL	-100%
IFavg	4.86	48.14	TL	-90%
NOIavg	0.50	2.00	TL	-75%
DITavg	0.14	0.43	TL	-67%
VGmax	9.00	21.00	TL	-57%
CEavg	4.00	9.00	TL	-56%
NOCavg	0.18	0.33	TL	-46%
RMAavg	0.17	0.31	TL	-46%
CAavg	6.00	11.00	TL	-45%
FOavg	1.18	1.95	TL	-40%
CBOavg	2.71	4.43	TL	-39%
FIavg	1.54	2.48	TL	-38%
LOC/Mod	25.52	36.86	TL	-31%
LCOMavg	0.39	0.47	TL	-18%
VGavg	1.66	1.75	TL	-6%
RMIavg	0.47	0.45	TF	5%
NBDavg	1.32	1.24	TF	7%
MLOCavg	4.08	3.52	TF	16%
RMDavg	0.36	0.24	TF	49%
NOMavg	17.00	11.00	TF	55%
NOFavg	6.29	3.18	TF	98%
PARavg	0.87	0.42	TF	107%
SIXavg	0.65	0.14	TF	380%

Table 5.18: Analysis of Project Metrics for Industry Experiment 2

Metric	TL	TF	Higher Method	%diff
T/S Ratio	1.33	0.87	TF	52%
#Asserts/LOC	0.24	0.16	TF	45%
#Asserts/Class	9.46	5.04	TF	88%
#Asserts/Method	2.60	1.45	TF	79%
Line Coverage	98%	31%	TF	216%
Cond Coverage	100%	24%	TF	317%

Table 5.19: Test Metrics for Industry Experiment 2

5.3.3 Test Results

Table 5.19 presents the testing metrics for the second experiment. The test-first project has significantly more testing including 216% and 317% higher test coverage (line and condition coverage respectively). This data perhaps highlights the emphasis that the test-first approach places on writing automated tests.

5.4 Formal Industry Experiment #3: Test-First - Test-Last

This section reports results from the second of three controlled experiments. The experiment design and context are reviewed, followed by the results of an analysis of the experiment.

5.4.1 Experiment Design and Context

This section describes the experiment design and context of a third experiment conducted in a large, Fortune 500 corporation. In contrast to the previous two experiments, in this experiment the first project was developed with a test-first approach and the second project was developed with a test-last approach. Both projects involved aggressive automated unit testing. The two different projects were developed by overlapping teams of developers. The first project was completed in 2005. The developers employed a test-first approach including automated unit-tests written in JUnit. This project will be labeled as test-first (TF). The second project was implemented in 2005 and 2006 using a test-last approach with automated unit tests. This project will be labeled as test-last (TL). The project was developed in a traditional mode with an up-front design and automated testing after the software was implemented. Automated tests were written shortly after code in an iterative test-last fashion. In between the two projects, developers completed a pre-experiment survey and participated in the TDD training described earlier.

The majority of the development effort in the first test-first project was completed by three programmers. Two of the three programmers reported having 6 to 10 years of experience and earned an undergraduate or graduate degree in a computing discipline. They reported having extensive and recent previous Java and web experience. The second test-last project staff consisted primarily of two of the lead developers from the first test-first project.

The first project was named "Inventory Scanners" and was completed in 2005 and contained 1559 lines of source code. The project was a web application that was run via a web browser in a hand-held bar-code scanner running Windows for Pocket PC. This project was created to improve inventory tracking and reduce data entry errors. The scanners allow attendants to check-in, check-out, stow, and move parts by selecting the desired function from the web interface menu and then scanning the data from the part barcode or other source. This project utilized Java Servlets and JavaServer Pages, the Struts model-view-controller architecture, and the Spring framework for wiring dependent objects together. This project implemented the data access object (DAO) design pattern for centralizing database access.

The second project was named "Conformity Request Tracking" and was completed in 2006 containing 2071 lines of source code. This project also was a web application that was created to improve tracking of conformity requests needed for external certification on new development projects. This project also used Struts and Spring like the first project. In addition it used Hibernate and the data access object (DAO) design pattern for centralizing database access.

5.4.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level.

For each set of metrics, a one-way analysis of variance (ANOVA) with unbalanced data and a two-sample two-tailed unequal variance t-test were performed to determine differences between two populations of metrics values. Statistical significance is determined with $p<.05$. The mean and standard deviation for the test-first and test-last groups are reported, and the %difference is calculated as the test-first mean minus the test-last mean divided by the test-last mean ((TF-TL)/TL).

Method-Level Metrics

Table 5.20 and Table 5.21 present the results of the statistical analysis of the method-level metrics comparing the test-last and test-first methods. The method-level metrics calculated are expanded in Table 5.1 and defined in Appendix D. The first eleven metrics were produced by JStyle [78] and the remaining three were produced by Eclipse Metrics [75].

Metric	NOS	NOE	V(G)	PL	AHL	VOC	VOL
	Analysis of Variance (ANOVA) Results						
F-ratio	51.003	322.360	16.766	49.008	30.528	59.437	26.754
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Two-sample t-test						
p-value	0.0000	0.0000	0.0041	0.0000	0.0000	0.0000	0.0001
df	562	562	562	562	562	562	562
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Higher Method	TF	TF	TF	TF	TF	TF	TF
TF Mean	5.21	0.61	1.28	51.26	31.52	14.06	155.91
Std Dev	7.90	0.55	1.04	78.75	51.70	15.26	306.54
TL Mean	1.71	0.04	1.03	15.30	11.70	6.28	47.80
Std Dev	3.69	0.20	0.41	41.68	31.32	8.33	179.11
%difference	205%	1550%	24%	235%	169%	124%	226%

Table 5.20: Analysis of Method Metrics for Industry Experiment 3, Part 1

Metric	LVL	PD	EFF	BUG	MLOC	NBD	PAR
	Analysis of Variance (ANOVA) Results						
F-ratio	87.734	16.454	10.022	26.773	38.423	40.466	40.527
p-value	0.000	0.000	0.002	0.000	0.000	0.000	0.000
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Two-sample t-test						
p-value	0.0000	0.0007	0.0071	0.0001	0.0000	0.0000	0.0000
df	562	562	562	562	561	561	561
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Higher Method	TL	TF	TF	TF	TF	TF	TF
TF Mean	0.23	3.78	1.40	0.05	5.34	1.33	1.32
Std Dev	0.25	3.68	4.01	0.10	7.41	0.50	1.32
TL Mean	0.54	2.66	0.44	0.02	2.21	1.08	0.69
Std Dev	0.38	2.55	2.82	0.06	4.29	0.39	0.95
%difference	-57%	42%	214%	226%	141%	24%	93%

Table 5.21: Analysis of Method Metrics for Industry Experiment 3, Part 2

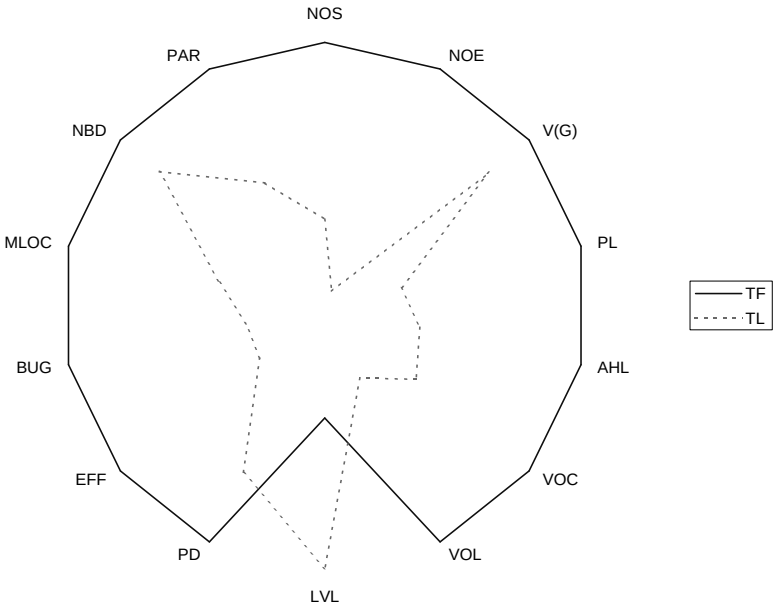

Figure 5.3: Industry Experiment 3 Method Metrics Radar Chart

This analysis demonstrates statistically significant differences with all fourteen of the method-level metrics. Figure 5.3 illustrates the differences in a radar chart. Each of the metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the degree and consistency by which the means of the test-last and test-first metrics varied.

This data implies and the radar chart illustrates very interesting and significant differences between methods developed with a test-last approach and methods developed with a test-first approach. Unlike the other experiments, in this experiment the test-last methods tend to have significantly lower mean metric values than the test-first methods. This data indicates that software developed with a test-last approach is significantly better in all categories (size, complexity, effort).

Class-Level Metrics

Table 5.22 and Table 5.23 present the results of the statistical analysis of the class-level metrics comparing the test-last and test-first classes. To save space, only the two-sample t-test p-values are reported. Although the ANOVA results strengthen the confidence, the t-test should be sufficient here to indicate significant differences between the two samples. The test-last project contained thirty-three classes and the test-first project contained thirty-six classes.

Table 5.24 presents the same data from Table 5.22 and Table 5.23, but in sorted

order by %difference with the middle metrics eliminated for space. This view illustrates a number of perhaps surprising trends. Unlike the previous experiment, the two projects of this experiment demonstrate a large number (thirty-seven) of class-level metrics with significant differences. Again the test-first project has a higher number of parameters (PAR) and exceptions (NOE). The methods in the test-first project tended to be larger and more complex (MLOCAvg, VOL, VOC, VG, NBD), but the test-last classes were more complex (WMC, V(G)) and larger in some ways (NIV). The test-first classes may have had a higher amount of reuse (NORM, IFI). The test-last project used more interfaces (NII) and appeared to be more cohesive (LCOM).

Interface-Level Metrics

As mentioned in the first section, Java Interfaces were isolated from classes. This section reports metrics only for interfaces. The pertinent interface-level metrics are expanded in Table 5.3 and defined in Appendix D.

Table 5.25 presents the results of the statistical analysis of the interface-level metrics for the test-last project. The test-first project included five interfaces and the test-last project included three interfaces. The interface metrics were similar between the two projects and none of the differences were statistically significant.

Project-Level Metrics

The project-level metrics are reported in Table 5.26. The data is reported in sorted order by %difference. This view allows one to see trends in the metrics. The differences are relatively inconsistent and inconclusive. Although the test-first project seems to be more complex, the coupling (CBO, IF, PAR) and size (LOC/Mod, MLOCAvg) measures are mixed.

5.4.3 Test Results

Table 5.27 presents the testing metrics for the third experiment. Despite the most impressive testing numbers of all the test-last projects analyzed, the test-first project still has the highest saturation of tests including a significantly higher conditional coverage at 94%. Conditional coverage is widely viewed as the more important of the two coverage metrics reported.

5.4.4 Subjective and Evaluative Results

An external design review was conducted on the two projects in this experiment. Three professional developers within the same company but who had not worked on either of the projects were asked to conduct a design review of both projects and complete a quality review scorecard with their impressions. The scorecard is

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	0.2382	No	TF	1.25	0.84	1.06	0.43	18%
NII	0.0200	Yes	TL	0.17	0.38	0.42	0.50	-61%
NIV	0.0010	Yes	TL	0.22	0.48	4.73	7.17	-95%
NSV	0.0904	No	TL	0.42	0.94	0.79	0.86	-47%
NOV	0.0007	Yes	TL	0.64	1.15	5.52	7.45	-88%
NIM	0.0033	Yes	TL	3.14	4.02	11.97	15.63	-74%
NSM	0.0798	No	TF	0.42	1.27	0.03	0.17	1275%
NPM	0.0038	Yes	TL	1.53	3.14	9.73	14.86	-84%
NNP	0.1493	No	TL	1.08	0.94	1.52	1.44	-29%
NOM	0.0047	Yes	TL	3.56	4.03	12.00	15.61	-70%
WMC	0.0172	Yes	TL	5.50	4.97	12.70	15.89	-57%
RFC	0.0168	Yes	TL	8.97	5.55	18.39	20.93	-51%
LCOM_CK	0.0392	Yes	TL	8.56	34.91	157.55	396.82	-95%
LCOM_LH	0.0276	Yes	TL	2.14	3.63	5.52	7.77	-61%
LCOM_HS	0.0049	Yes	TL	0.14	0.31	0.41	0.44	-66%
NIC	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NIS	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NLC	0.6914	No	TF	0.06	0.33	0.03	0.17	83%
NAC	0.6914	No	TF	0.06	0.33	0.03	0.17	83%
NOC	0.9334	No	TF	0.94	5.67	0.85	3.71	11%
FI	0.9091	No	TL	1.53	3.22	1.61	2.42	-5%
FO	0.0758	No	TF	6.67	3.50	5.15	3.47	29%
PFI	0.5075	No	TL	0.75	2.84	1.15	2.14	-35%
PFO	0.2445	No	TL	0.86	0.68	1.27	1.89	-32%
IFI	0.3486	No	TF	0.78	1.61	0.45	1.23	71%
IFO	0.0074	Yes	TF	5.81	3.35	3.88	2.39	50%

Table 5.22: Analysis of Class Metrics for Industry Experiment 3, Part 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
MLOC	0.9368	No	TL	2.59	22.79	23.34	18.36	-89%
NOF	0.0010	Yes	TL	2.52	0.49	4.88	7.23	-48%
WMC	0.0444	Yes	TL	2.66	7.83	13.97	15.97	-81%
NORM	0.0000	Yes	TF	2.60	0.51	1.72	1.37	52%
NBD	0.0469	Yes	TF	2.62	0.46	1.27	0.49	106%
PAR	0.0108	Yes	TF	2.70	1.56	1.48	1.49	82%
SIX	0.3757	No	TF	2.74	1.50	1.16	1.62	137%
VG	0.0001	Yes	TF	2.83	1.58	1.47	0.68	92%
NOS	0.7305	No	TF	22.42	23.18	20.64	19.53	9%
NOE	0.0041	Yes	TF	1.81	3.08	0.21	0.48	751%
V(G)	0.0255	Yes	TL	5.50	4.97	12.27	16.04	-55%
PL	0.4303	No	TF	220.68	213.15	185.58	151.23	19%
AHL	0.8342	No	TL	134.97	120.17	141.00	118.03	-4%
VOC	0.3285	No	TL	59.78	61.23	75.30	69.04	-21%
VOL	0.5267	No	TF	671.28	610.99	580.64	571.99	16%
LVL	0.0037	Yes	TL	0.99	1.22	6.44	9.95	-85%
PD	0.0350	Yes	TL	16.26	18.74	31.84	37.11	-49%
EFF	0.7797	No	TF	6.02	7.31	5.45	9.38	10%
BUG	0.5251	No	TF	0.22	0.20	0.19	0.19	16%
NOSAvg	0.0065	Yes	TF	11.94	12.18	5.32	6.71	124%
NOEAvg	0.0069	Yes	TF	0.52	0.43	0.21	0.48	146%
V(G)Avg	0.0004	Yes	TF	2.07	1.22	1.21	0.55	71%
PLAvg	0.0155	Yes	TF	122.25	119.49	62.13	78.46	97%
AHLAvg	0.0457	Yes	TF	78.08	82.37	43.49	57.30	80%
VOCAvg	0.0108	Yes	TF	27.50	21.12	15.96	15.05	72%
VOLAvg	0.0460	Yes	TF	429.97	506.03	222.60	327.41	93%
LVLAvg	0.0056	Yes	TL	0.23	0.14	0.36	0.21	-36%
PDAvg	0.0373	Yes	TF	6.34	4.38	4.40	3.13	44%
EFFAvg	0.1029	No	TF	4.56	7.31	2.23	4.03	105%
BUGAvg	0.0460	Yes	TF	0.14	0.17	0.07	0.11	93%
MLOCAvg	0.0038	Yes	TF	11.75	11.78	5.01	5.99	135%
NBDAvg	0.0063	Yes	TF	1.52	0.47	1.21	0.45	26%
PARAvg	0.0092	Yes	TF	2.51	1.61	1.53	1.42	64%
TL	0.6505	No	TL	85.76	55.91	92.91	70.21	-8%
CL	0.0023	Yes	TF	31.09	19.41	18.44	12.10	69%
BL	0.6159	No	TL	12.12	6.22	13.44	13.49	-10%
SL	0.1083	No	TL	42.59	34.62	61.06	54.44	-30%
CD	0.0001	Yes	TF	0.39	0.14	0.24	0.14	63%

Table 5.23: Analysis of Class Metrics for Industry Experiment 3, Part 2

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NIV	0.0010	Yes	TL	0.22	0.48	4.73	7.17	-95%
LCOM_CK	0.0392	Yes	TL	8.56	34.91	157.55	396.82	-95%
MLOC	0.9368	No	TL	2.59	22.79	23.34	18.36	-89%
NOV	0.0007	Yes	TL	0.64	1.15	5.52	7.45	-88%
LVL	0.0037	Yes	TL	0.99	1.22	6.44	9.95	-85%
NPM	0.0038	Yes	TL	1.53	3.14	9.73	14.86	-84%
WMC	0.0444	Yes	TL	2.66	7.83	13.97	15.97	-81%
NIM	0.0033	Yes	TL	3.14	4.02	11.97	15.63	-74%
NOM	0.0047	Yes	TL	3.56	4.03	12.00	15.61	-70%
LCOM_HS	0.0049	Yes	TL	0.14	0.31	0.41	0.44	-66%
LCOM_LH	0.0276	Yes	TL	2.14	3.63	5.52	7.77	-61%
NII	0.0200	Yes	TL	0.17	0.38	0.42	0.50	-61%
V(G)	0.0255	Yes	TL	5.50	4.97	12.27	16.04	-55%
RFC	0.0168	Yes	TL	8.97	5.55	18.39	20.93	-51%
NORM	0.0000	Yes	TF	2.60	0.51	1.72	1.37	52%
CD	0.0001	Yes	TF	0.39	0.14	0.24	0.14	63%
PARAvg	0.0092	Yes	TF	2.51	1.61	1.53	1.42	64%
CL	0.0023	Yes	TF	31.09	19.41	18.44	12.10	69%
V(G)Avg	0.0004	Yes	TF	2.07	1.22	1.21	0.55	71%
IFI	0.3486	No	TF	0.78	1.61	0.45	1.23	71%
VOCAvg	0.0108	Yes	TF	27.50	21.12	15.96	15.05	72%
AHLAvg	0.0457	Yes	TF	78.08	82.37	43.49	57.30	80%
PAR	0.0108	Yes	TF	2.70	1.56	1.48	1.49	82%
NLC	0.6914	No	TF	0.06	0.33	0.03	0.17	83%
NAC	0.6914	No	TF	0.06	0.33	0.03	0.17	83%
VG	0.0001	Yes	TF	2.83	1.58	1.47	0.68	92%
VOLAvg	0.0460	Yes	TF	429.97	506.03	222.60	327.41	93%
BUGAvg	0.0460	Yes	TF	0.14	0.17	0.07	0.11	93%
PLAvg	0.0155	Yes	TF	122.25	119.49	62.13	78.46	97%
EFFAvg	0.1029	No	TF	4.56	7.31	2.23	4.03	105%
NBD	0.0469	Yes	TF	2.62	0.46	1.27	0.49	106%
NOSAvg	0.0065	Yes	TF	11.94	12.18	5.32	6.71	124%
MLOCAvg	0.0038	Yes	TF	11.75	11.78	5.01	5.99	135%
SIX	0.3757	No	TF	2.74	1.50	1.16	1.62	137%
NOEAvg	0.0069	Yes	TF	0.52	0.43	0.21	0.48	146%
NOE	0.0041	Yes	TF	1.81	3.08	0.21	0.48	751%
NSM	0.0798	No	TF	0.42	1.27	0.03	0.17	1275%

Table 5.24: Sorted Class Metrics for Industry Experiment 3

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NCI	0.4226	No	TL	2.00	0.00	2.67	1.15	-25%
NSV	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%
NIM	0.6911	No	TF	5.40	6.02	4.00	3.46	35%
NPM	0.6911	No	TF	5.40	6.02	4.00	3.46	35%
NOM	0.6911	No	TF	5.40	6.02	4.00	3.46	35%
RFC	0.6911	No	TF	5.40	6.02	4.00	3.46	35%
NIC	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0%

Table 5.25: Analysis of Interface Metrics for Experiment 3

Metric	TF Value	TL Value	Higher Method	%diff
NOFavg	0.24	4.88	TL	-95%
LCOMavg	0.02	0.40	TL	-94%
NOMavg	3.27	12.31	TL	-73%
REU	0.03	0.06	TL	-54%
NOAavg	1.00	2.00	TL	-50%
NSFavg	0.44	0.81	TL	-46%
LOC/Mod	21.65	33.95	TL	-36%
NOCavg	0.43	0.53	TL	-17%
RMDavg	0.23	0.28	TL	-17%
FIavg	2.70	3.05	TL	-12%
CBOavg	5.03	5.56	TL	-10%
FOavg	2.33	2.51	TL	-7%
DITavg	0.68	0.72	TL	-5%
RMIavg	0.64	0.65	TL	-2%
VGmax	6.00	6.00	TL	0%
CAavg	5.00	4.75	TF	5%
SIXavg	1.46	1.16	TF	26%
NBDavg	1.39	1.06	TF	31%
NOIavg	1.25	0.75	TF	67%
RMAavg	0.21	0.12	TF	79%
VGavg	2.04	1.13	TF	80%
CEavg	8.75	4.75	TF	84%
SPC	34.00	15.00	TF	127%
PARavg	1.43	0.60	TF	137%
MLOCavg	6.10	1.89	TF	222%
IFavg	341.93	44.81	TF	663%

Table 5.26: Analysis of Project Metrics for Industry Experiment 3

Metric	TF	TL	Higher Method	%diff
T/S Ratio	1.08	0.61	TF	78%
#Asserts/LOC	0.10	0.09	TF	12%
#Asserts/Class	4.38	3.00	TF	46%
#Asserts/Method	1.12	1.06	TF	6%
Line Coverage	72%	84%	TL	-14%
Cond Coverage	94%	74%	TF	27%

Table 5.27: Test Metrics for Industry Experiment 3

Metric	TF Mean	TF SDev	TL Mean	TL SDev	%diff	Higher Method
Understandability	3.67	1.15	3.33	0.58	10%	TF
Maintainability	3.00	1.00	3.67	0.58	-18%	TL
Reusability	3.33	0.58	3.00	0.00	11%	TF
Testability	3.33	1.15	3.33	0.58	0%	N/A
Design Quality	3.67	0.58	3.67	0.58	0%	N/A

Table 5.28: Design Review Results for Industry Experiment 3

presented in Appendix F. The reviewers were asked to spend less than two hours reviewing each of the projects. Reviewers were given a brief overview of the project which included a very short description of the project architecture.

The three reviewers were selected based on development experience qualifications. Two reviewers reported having six to ten years development experience and having completed a graduate degree in a computing-related major. The third reviewer reported a bachelor's degree in a non-computing-related major, but reported having over twenty years development experience. All reviewers had experience developing Java web applications similar to those being reviewed.

The reviewers were requested to rate each project on a scale of 1 to 5 (1 being the worst and 5 being the best rating) in terms of understandability, maintainability, reusability, testability, and overall design quality. Table 5.28 presents the results of the reviewer ratings. The reviewer ratings were very similar for the two projects with the test-first project being slightly better for understandability and reusability, but slightly worse for maintainability.

The reviewers were also given the opportunity to make general comments about the two projects. Several comments regarded the lack of programmer documentation in both projects. One reviewer stated that "Tests are complex and do not cover all of the classes" in regards to the test-last project.

The design reviews provide additional validity to the objective metric analysis. Although many metrics had statistically significant differences, the class, interface, and project-level metrics provided many inconsistent and inconclusive results. Plus

the similar testing metrics lead one to think that the internal quality of these two projects is fairly similar.

5.4.5 Possible Explanations of Results

This section has noted improved metrics on the test-last project compared to the test-last projects in the other experiments, particularly in the area of testing. A number of possible explanations could account for the similar results between the two projects. Because the test-last developers recently finished a test-first project, they may have adjusted their development style to focus more heavily on automated unit testing.

Another possibility could be the Hawthorne effect. In the first two experiments, testing improved in the test-first projects which were the projects where developers knew they were participating in this study. In this third experiment, developers in the test-last project knew they were participating in this study. Perhaps this knowledge caused an awareness of testing strategy that resulted in improved numbers. Even if this was the case, as discussed earlier the test-last testing metrics still were not as good as those from the earlier test-first project.

5.5 Industry Experiment in Training Course

This section describes a short experiment conducted in a professional training course. The context of the course and experiment is reviewed, followed by a few comments regarding the results. The results of pre and post training surveys will be presented and discussed.

5.5.1 Experiment Design and Context

The description of the experiment from Section 4.2.6 will be repeated and expanded here. Sixteen developers participated in a six-day on-site professional training course developed and presented by the author in Fall 2005. The developers were from several development groups in the same company as the other experiments.

The course included one day of instruction on test-driven development with JUnit and the remaining five days of instruction were split between the Spring and Hibernate frameworks. The Spring [52] framework was described in section 4.1.1 as a lightweight dependency injection framework. Spring also includes a model-view-controller based web application framework as well as a framework for communicating with relational databases. Hibernate [68] is a persistence service providing object/relational mapping functionality. Spring and Hibernate are commonly used together and provide integration support. The course consisted of lecture directed by nearly five hundred presentation slides and hands-on lab exercises. The day on

test-driven development was largely a refresher for most developers from a similar course provided two years earlier.

At the beginning of the course, students completed the pre-experiment survey. The experiment then consisted of an extended exercise near the end of the TDD day. Half of the developers were asked to complete the exercise with a test-first approach and half were asked to complete the exercise with a test-last approach. Subjects were randomly selected for each group. A couple of individuals with limited Java experience requested to work in pairs with more experienced Java developers. This was allowed and both test-first and test-last groups contained one or two such pairs of programmers. All developers were asked to use JUnit in the Eclipse IDE for writing automated unit tests.

The exercise was to build a bowling game scorer as described in Appendix B.2.2. This project was proposed by Robert C. Martin [58] and was used in an industry experiment by Laurie Williams [37] to examine the effects of TDD on external quality. The project involved reading bowling throws from a file, calculating scores, and presenting scores through a text-based user interface. Some sample input/output code was provided to subjects to shorten the development effort. Despite these helps, not all programmers were able to complete the project in the time allotted.

Students completed a post-experiment survey on the second day of the training course after completing the Bowling experiment.

5.5.2 Internal Quality Results

Source and test code from six projects were submitted from students in the course. Three were completed with a test-first approach and three were completed with a test-last approach. The six projects submitted were completed primarily by developers with previous JUnit experience. The other developers who did not complete and did not submit their projects reported running out of time because they spent most of their time gaining familiarity with JUnit and the test-first/test-last approach.

No statistically significant differences existed between the software developed with a test-first and a test-last approach. Perhaps this is due to the small size of the project completed. All projects were completed with two or three classes and an average of eighty lines of code (Std Dev of 19.2). Or perhaps this stems from the fact that one of the three test-last projects submitted were from developers with previous test-first experience (see experiment #3 discussion).

5.5.3 Test Results

Table 5.29 reports the test coverage metrics from the training experiment. Although there are no significant differences, it is interesting to note that the test-first metrics are more consistent than the test-last metrics. Plus the highest coverage metrics

Prev TF Experience	Approach	Line Coverage	Cond Coverage
No	TF	50%	19%
No	TF	58%	55%
No	TF	49%	30%
No	TL	68%	63%
Yes	TL	73%	80%
No	TL	6%	0%
Two-sample t-test			
p-value		0.8916	0.6658
Significant?		No	No
TF Mean		0.52	0.35
Std Dev		0.05	0.18
TL Mean		0.49	0.48
Std Dev		0.37	0.42
Higher Method		TF	TL
%difference		7%	-27%

Table 5.29: Test Metrics for Industry Training Experiment

were achieved by the one project where the developers had previous test-first experience. This is consistent with the results from experiment #3.

5.5.4 Subjective and Evaluative Results

Pre and post experiment surveys were conducted before and after the bowling assignment in the training course. The surveys are presented in Appendix F. No statistically significant differences existed between the test-first and test-last groups in terms of academic background, work experience, or specific programming experience.

In the post-experiment survey, the industry programmers overwhelmingly preferred the test-first approach. Ninety to one hundred percent of the programmers chose the test-first approach in all of the queries including:

- which approach they would choose in the future (Choice)
- which approach was the best for the project(s) they completed (BestApproach)
- which approach would cause them to more thoroughly test a program (ThoroughTesting)
- which approach produces a correct solution in less time (Correct)
- which approach produces code that is simpler, more reusable, and more maintainable (Simpler)

- which approach produces code with fewer defects (FewerDefects)

Programmer responses on six questions were analyzed for changes from the pre to the post experiment survey. Table 5.30 presents the results of this analysis. The first section gives results from the programmers who used a test-first approach in the experiment. The second section gives the results from the programmers who used a test-last approach in the experiment. The third section gives the results from all programmers including five programmers who took the surveys but did not participate in the programming portion of the experiment. The questions rated programmer attitudes toward the following factors:

- importance of unit testing (Testing Attitude)
- timing of writing unit tests (Test Timing)
- importance of software design prior to coding (Design Attitude)
- efficacy of test-first programming (TF Attitude)
- efficacy of test-last programming (TL Attitude)
- choice of test-first or test-last programming (Choice)

A paired, two-tailed t-test was applied to both the test-first and test-last groups to determine if the differences from the pre to post experiment survey were significant. The only difference that was significant was on the first question regarding the importance of unit testing. Both the test-first and test-last groups improved their attitudes toward the importance of unit testing after participating in the bowling experiment.

Similarly, a paired, two-tailed t-test was applied to all participants in the class (regardless of whether they used a test-first or test-last approach on the bowling project). This revealed a statistically significant improvement in both the importance of unit testing and a shift in test timing. The average response on the test timing question changed from "after I think a small portion of the program is complete (such as a single function)" to "before I have written a new important portion of the program (such as a class), but after I have tested other code that is finished)."

Also, programmer opinion of the test-first approach improved on the whole by 10% (not statistically significant). However, programmer opinion of the test-last approach decreased 38%, a statistically significant amount. The average test-first opinion was "I think it might be a good approach on projects where programmers understand the domain well" and the average test-last opinion in the post experiment was between "I think it might be a good approach on small projects" and "I think it might be a good approach on projects where programmers have a lot of programming experience."

Metric	Testing Attitude	Test Timing	Design Attitude	TF Attitude	TL Attitude	Choice
test-first programmers						
paired t-test p-value	0.0250	0.0643	0.1747	1.0000	0.3632	0.3632
Significant	Yes	No	No	No	No	No
Higher Method	Post	Post	Post	Post	Pre	Pre
Pre Mean	2.83	3.00	2.83	3.67	1.83	0.33
Pre Std Dev	0.98	2.28	0.41	0.52	1.17	0.52
Post Mean	3.50	5.50	3.17	3.67	1.67	0.17
Post Std Dev	0.55	1.22	0.41	0.82	1.21	0.41
%difference	-19%	-45%	-11%	0%	10%	100%
test-last programmers						
paired t-test p-value	0.0422	0.2080	1.0000	0.0791	0.1801	0.3632
Significant	Yes	No	No	No	No	No
Higher Method	Post	Post	Post	Post	Pre	Pre
Pre Mean	2.83	3.40	3.00	3.08	2.42	0.33
Pre Std Dev	0.75	1.67	0.63	1.02	1.02	0.52
Post Mean	3.67	4.50	3.00	4.00	1.83	0.17
Post Std Dev	0.52	1.22	0.89	0.00	1.17	0.41
%difference	-23%	-24%	0%	-23%	32%	100%
all programmers						
paired t-test p-value	0.0019	0.0295	0.3370	0.2301	0.0475	0.1661
Significant	Yes	Yes	No	No	Yes	No
Higher Method	Post	Post	Post	Post	Pre	Pre
Pre Mean	3.06	3.13	2.88	3.38	2.34	0.33
Pre Std Dev	0.85	2.03	0.50	0.90	1.25	0.49
Post Mean	3.62	5.00	3.08	3.77	1.69	0.17
Post Std Dev	0.51	1.22	0.64	0.60	1.11	0.39
%difference	-15%	-37%	-7%	-10%	38%	100%

Table 5.30: Programmer Attitude Changes in Industry Training Experiment

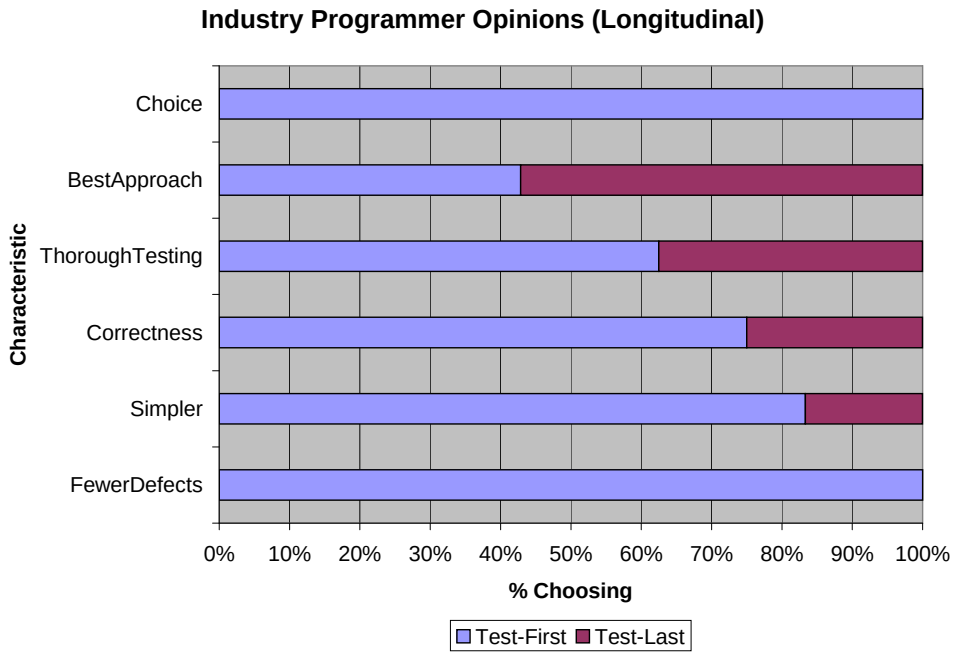

Figure 5.4: Longitudinal Industry Programmer Opinions

Finally in the pre-experiment survey, 67% of the programmers indicated they would choose the test-first approach over test-last. In the post-experiment survey, this number increased to 83%. These numbers reveal a possible pre-disposition to the test-first approach within the development group. Still the improvement was substantial and equivalent between the test-first and test-last groups.

A longitudinal survey was administered with all of the participants from the training course and the industry experiments. The survey was administered over the web approximately seven months after the training course and eight of the twelve developers responded. This time period ensured that all of the industry experiment projects were complete and that programmers had the opportunity to voluntarily choose to use the test-first or test-last approach on subsequent projects. Figure 5.4 presents the results from the longitudinal survey. Although results declined slightly on a few questions from the post-experiment survey, programmers still unanimously would choose the test-first approach.

Other survey responses indicated that 62% of the programmers had used the test-first approach on subsequent projects when they had the choice. Interestingly, 75% indicated that they had also used the test-last approach on some projects. One comment from the surveys is presented here and may shed light on this result.

> I have found that both test first and test last have their place in programming. For some issues, it is necessary to write the code first because the idea needs further development. In database applications, or file based applications, I have found that the test can become extremely compli-

Project	Approach	JUnit	Team	SLOC	Date
Component Tracking	TL	Yes	ABC	32065	'01,'03,'04
Common	TL	Yes	many	7807	on-going
Project Engineer	TL	No	AB	2787	'02
Part # Adv. Search	TL	No	C	1562	'01
Workflow	TL	Yes	BC	811	'03
Common Parameter	TL	Yes	C	678	'03
Authentication	TL	No	BC	476	'01
PDD	TL	Yes	D	427	on-going
Exp. Common Classes	TL	No	E	399	'02
Exp. Data Connection	TL	No	E	133	'02
Exp. Access	TL	No	E	114	'02
Conformity Request Tracking	TL	Yes	AB	2071	'06
Exp. Inv. Scanners	TF	Yes	ABC	1559	'05
Part # Adv. Search II	TF	Yes	C	842	'06
Common Pagination	TF	Yes	C	349	'06

Table 5.31: Project Summary

cated and difficult to change when refactoring. In these cases a test last using stubs seems to work better than test first. Even in these situations, the test first method is used for pieces of the code where the database or file can be separated from the code.

5.6 Industry Case Study

This section reports results from a case study conducted on fifteen software projects developed by a single development group in a Fortune 500 company. The context of the projects is reviewed, followed by the results of an analysis of the projects.

5.6.1 Context and Overview

Table 5.31 summarizes the projects included in the case study. Each project is labeled with the approach used (test-first TF or test-last TL) and whether automated tests were written. All projects are written in Java with automated tests written with JUnit. Lead developers are labeled with A, B, C, D, and E to enable fair comparisons. Years are given for project or major milestone completion.

The data presented in this case study represents recent test-first and test-last software projects written with automated unit tests as well as some test-last projects that were only manually tested. The projects were produced over a span of approximately five years. The study includes the five projects reported in earlier sections,

but does not include the projects from the small training experiment of the previous section. All projects were identified and prioritized through normal business processes and were developed for production use.

The projects were primarily web applications written in Java using the Java Servlet and JavaServer Pages technology. Some projects also utilized additional frameworks and libraries including Struts, Spring, Hibernate, and Tiles.

The development group was organized into small teams of usually three or fewer developers per project. Developers worked directly with internal users and customers to elicit requirements. Some projects included an external client base, but most supported internal corporate functions. Projects were typically completed in three to six months.

The lead developers A, B, C, and D all participated in a JUnit training course in Summer 2003 and in the Fall 2005 training course described earlier. A survey was conducted in the Fall 2005 training course. At this time, all of the developers working on these projects had completed at least a bachelors degree, and all but developer D had completed a degree in a computing related discipline. Developers A, B, and C reported having six to ten years of experience in a computing-related job and developer D reported eleven to twenty years of experience. They all reported recent (within previous three months) Java and web programming experience.

5.6.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level.

Method-Level Metrics

Table 5.32 and 5.33 summarizes results of method-level metrics performed on approximately 5,173 methods representing over 30,000 lines of code in fifteen primarily web-based Java software projects.

This analysis demonstrates statistically significant differences with ten of the fourteen method-level metrics. Figure 5.5 illustrates the differences in a radar chart. Each of the metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates that degree and consistency by which the means of the test-last and test-first metrics varied.

This data implies and the radar chart illustrates that software developed in a test-first manner is likely to be smaller (NOS and MLOC), have more exceptions (NOE), and have a lower computational complexity (V(G)). Test-first code is also likely to be simpler as measured with Halstead's length and level metrics (AHL and

Metric	NOS	NOE	V(G)	PL	AHL	VOC	VOL
	Analysis of Variance (ANOVA) Results						
F-ratio	4.3113	91.5485	11.3979	1.3274	5.6427	1.2471	4.9479
p-value	0.0379	0.0000	0.0007	0.2493	0.0176	0.2642	0.0262
Significant?	Yes	Yes	Yes	No	Yes	No	Yes
	Two-sample t-test						
p-value	0.0001	0.0000	0.0000	0.0975	0.0000	0.1593	0.0000
df	5172	5172	5172	5172	5172	5172	5172
Significant?	Yes	Yes	Yes	No	Yes	No	Yes
Higher Method	TL	TF	TL	TL	TL	TL	TL
TF Mean	3.90	0.29	1.29	39.57	24.58	11.54	117.02
Std Dev	6.53	0.49	1.08	72.44	43.82	13.97	257.74
TL Mean	5.48	0.09	1.76	46.52	37.93	12.66	202.19
Std Dev	14.12	0.37	2.61	111.29	104.61	18.33	713.89
%difference	-29%	230%	-27%	-15%	-35%	-9%	-42%

Table 5.32: Analysis of Method Metrics on Industry Data, Part 1

Metric	LVL	PD	EFF	BUG	MLOC	NBD	PAR
	Analysis of Variance (ANOVA) Results						
F-ration	45.2856	1.5559	3.0696	4.9505	5.0386	1.0060	100.1750
p-value	0.0000	0.2123	0.0798	0.0261	0.0248	0.3159	0.0000
Significant?	Yes	No	No	Yes	Yes	No	Yes
	Two-sample t-test						
p-value	0.0000	0.0855	0.0000	0.0000	0.0000	0.2283	0.0000
df	5172	5172	5172	5172	4598	4598	4598
Significant?	Yes	No	Yes	Yes	Yes	No	Yes
Higher Method	TL	TL	TL	TL	TL	TF	TF
TF Mean	0.33	3.71	1.08	0.04	4.50	1.31	1.03
Std Dev	0.33	3.71	3.32	0.09	7.14	0.61	1.10
TL Mean	0.47	4.07	3.57	0.07	6.71	1.27	0.57
Std Dev	0.37	5.42	26.66	0.24	17.75	0.76	0.78
%difference	-29%	-9%	-70%	-42%	-33%	3%	81%

Table 5.33: Analysis of Method Metrics on Industry Data, Part 2

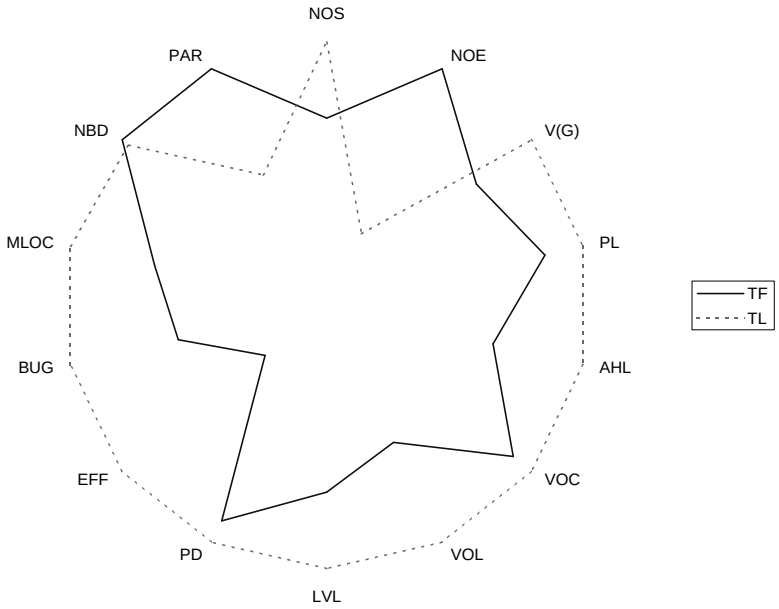

Figure 5.5: Industry Case Study Method Metrics Radar Chart

LVL), have fewer expected defects (BUG), and possibly take less effort (EFF) (note ANOVA results are not quite statistically significant). Finally, test-first methods are likely to have more parameters (PAR).

Class-Level Metrics

Table 5.34 and Table 5.35 present the results of the statistical analysis of the class-level metrics comparing the test-last and test-first classes. To save space, only the two-sample t-test p-values are reported. Although the ANOVA results strengthen the confidence, the t-test should be sufficient here to indicate significant differences between the two samples. Thirty-nine metrics demonstrated statistically significant differences.

Table 5.36 presents the same data from Table 5.34 and Table 5.35, but in sorted order by %difference with the middle metrics eliminated for space. This view illustrates a number of trends. For instance, test-last projects tended to have larger and more complex methods and classes. Test-last projects may demonstrate more reuse (Fan-in). Test-first projects have methods with more parameters and throw more exceptions.

There were a total of 51 classes in the three test-first projects and 515 classes in the twelve test-last project. Table 5.37 reports the ratio of interfaces to classes. Test-first projects made significantly more use of interfaces, indicating a higher level of abstraction and looser coupling.

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	0.8375	No	TL	1.18	0.74	1.20	1.09	-2%
NII	0.1136	No	TF	0.33	0.48	0.22	0.46	51%
NIV	0.0314	Yes	TL	1.33	3.85	2.61	5.01	-49%
NSV	0.0000	Yes	TL	0.29	0.81	3.21	9.86	-91%
NOV	0.0000	Yes	TL	1.63	3.87	5.83	11.89	-72%
NIM	0.0388	Yes	TL	5.69	8.74	8.53	12.94	-33%
NSM	0.0265	Yes	TL	0.29	1.08	0.71	2.38	-59%
NPM	0.1472	No	TL	3.75	8.30	5.63	12.46	-33%
NNP	0.0758	No	TL	1.51	1.86	2.01	2.30	-25%
NOM	0.0182	Yes	TL	5.98	8.65	9.23	13.43	-35%
WMC	0.0001	Yes	TL	8.88	10.99	16.52	24.07	-46%
RFC	0.0000	Yes	TL	12.75	12.66	25.34	30.14	-50%
LCOM_CK	0.2712	No	TL	42.12	155.82	80.38	612.34	-48%
LCOM_LH	0.3304	No	TL	3.29	4.92	4.00	4.31	-18%
LCOM_HS	0.0005	Yes	TL	0.23	0.37	0.43	0.43	-47%
NIC	0.0252	Yes	TL	0.00	0.00	0.02	0.20	-100%
NIS	0.0026	Yes	TL	0.00	0.00	0.02	0.13	-100%
NLC	0.1335	No	TF	0.10	0.41	0.01	0.10	910%
NAC	0.1335	No	TF	0.10	0.41	0.01	0.10	910%
NOC	0.9766	No	TL	0.71	4.76	0.73	3.95	-3%
FI	0.0064	Yes	TL	1.33	2.75	2.75	7.65	-51%
FO	0.0031	Yes	TL	7.10	3.85	9.01	7.23	-21%
PFI	0.0454	Yes	TL	0.69	2.40	1.44	3.69	-52%
PFO	0.0019	Yes	TL	0.96	0.96	1.51	2.49	-36%
IFI	0.0364	Yes	TL	0.65	1.44	1.30	5.39	-50%
IFO	0.0160	Yes	TL	6.14	3.42	7.50	6.28	-18%

Table 5.34: Analysis of Class Metrics for Industry Case Study, Part 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
MLOC	0.0000	Yes	TL	30.13	35.81	60.42	97.96	-50%
NOF	0.0587	No	TL	1.50	3.97	2.68	5.08	-44%
NORM	0.9282	No	TL	0.48	0.71	0.49	0.98	-2%
NBD	0.0962	No	TF	1.50	0.45	1.38	0.52	8%
PAR	0.0000	Yes	TF	2.07	1.50	0.62	0.64	236%
SIX	0.0000	Yes	TF	1.20	1.51	0.22	0.62	455%
VG	0.6682	No	TF	2.51	1.45	2.41	2.09	4%
NOS	0.0000	Yes	TL	22.06	27.55	49.26	78.90	-55%
NOE	0.0416	Yes	TF	1.65	3.17	0.79	1.95	108%
V(G)	0.0000	Yes	TL	7.31	10.52	15.87	23.81	-54%
PL	0.0002	Yes	TL	224.00	330.57	418.48	658.01	-46%
AHL	0.0000	Yes	TL	139.15	181.45	341.21	561.25	-59%
VOC	0.0002	Yes	TL	65.35	85.01	113.89	158.35	-43%
VOL	0.0000	Yes	TL	662.50	955.24	1818.96	3453.72	-64%
LVL	0.0004	Yes	TL	1.89	4.44	4.24	7.24	-55%
PD	0.0006	Yes	TL	20.99	29.78	36.66	52.25	-43%
EFF	0.0000	Yes	TL	6.09	10.39	32.13	102.62	-81%
BUG	0.0000	Yes	TL	0.22	0.32	0.61	1.15	-64%
NOSAvg	0.5683	No	TF	7.87	10.56	7.06	9.37	11%
NOEAvg	0.0005	Yes	TF	0.43	0.46	0.20	0.47	112%
V(G)Avg	0.0857	No	TL	1.57	1.23	1.86	1.40	-16%
PLAvg	0.1891	No	TF	81.12	105.13	62.82	80.21	29%
AHLAvg	0.8385	No	TF	52.06	70.77	50.12	68.89	4%
VOCAvg	0.1640	No	TF	19.23	19.47	15.65	13.59	23%
VOLAvg	0.9466	No	TF	279.28	428.02	275.39	464.06	1%
LVLAvg	0.0000	Yes	TL	0.23	0.18	0.38	0.20	-40%
PDAvg	0.6687	No	TF	4.80	4.19	4.57	3.57	5%
EFFAvg	0.0668	No	TL	2.92	5.91	4.65	13.02	-37%
BUGAvg	0.9467	No	TF	0.09	0.14	0.09	0.15	1%
MLOCAvg	0.3009	No	TF	9.16	10.30	7.67	9.07	19%
NBDAvg	0.0334	Yes	TF	1.50	0.49	1.35	0.50	11%
PARAvg	0.0000	Yes	TF	1.93	1.54	0.69	0.58	181%
TL	0.0000	Yes	TL	96.39	76.23	168.86	207.84	-43%
CL	0.0000	Yes	TL	35.32	28.62	56.27	68.65	-37%
BL	0.0143	Yes	TL	12.86	9.17	16.60	20.14	-23%
SL	0.0000	Yes	TL	48.23	50.41	96.82	134.60	-50%
CD	0.1730	No	TF	0.41	0.17	0.38	0.15	9%

Table 5.35: Analysis of Class Metrics for Industry Case Study, Part 2

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NIC	0.0252	Yes	TL	0.00	0.00	0.02	0.20	-100%
NIS	0.0026	Yes	TL	0.00	0.00	0.02	0.13	-100%
NSV	0.0000	Yes	TL	0.29	0.81	3.21	9.86	-91%
EFF	0.0000	Yes	TL	6.09	10.39	32.13	102.62	-81%
NOV	0.0000	Yes	TL	1.63	3.87	5.83	11.89	-72%
BUG	0.0000	Yes	TL	0.22	0.32	0.61	1.15	-64%
VOL	0.0000	Yes	TL	662.50	955.24	1818.96	3453.72	-64%
AHL	0.0000	Yes	TL	139.15	181.45	341.21	561.25	-59%
NSM	0.0265	Yes	TL	0.29	1.08	0.71	2.38	-59%
LVL	0.0004	Yes	TL	1.89	4.44	4.24	7.24	-55%
NOS	0.0000	Yes	TL	22.06	27.55	49.26	78.90	-55%
MLOC	0.0000	Yes	TL	23.89	31.49	53.24	102.65	-55%
V(G)	0.0000	Yes	TL	7.31	10.52	15.87	23.81	-54%
PFI	0.0454	Yes	TL	0.69	2.40	1.44	3.69	-52%
FI	0.0064	Yes	TL	1.33	2.75	2.75	7.65	-51%
IFI	0.0364	Yes	TL	0.65	1.44	1.30	5.39	-50%
SL	0.0000	Yes	TL	48.23	50.41	96.82	134.60	-50%
RFC	0.0000	Yes	TL	12.75	12.66	25.34	30.14	-50%
NIV	0.0314	Yes	TL	1.33	3.85	2.61	5.01	-49%
LCOM_CK	0.2712	No	TL	42.12	155.82	80.38	612.34	-48%
LCOM_HS	0.0005	Yes	TL	0.23	0.37	0.43	0.43	-47%
PL	0.0002	Yes	TL	224.00	330.57	418.48	658.01	-46%
WMC	0.0001	Yes	TL	8.88	10.99	16.52	24.07	-46%
NOF	0.0587	No	TL	1.50	3.97	2.68	5.08	-44%
TL	0.0000	Yes	TL	96.39	76.23	168.86	207.84	-43%
PD	0.0006	Yes	TL	20.99	29.78	36.66	52.25	-43%
VOC	0.0002	Yes	TL	65.35	85.01	113.89	158.35	-43%
NII	0.1136	No	TF	0.33	0.48	0.22	0.46	51%
NOE	0.0416	Yes	TF	1.65	3.17	0.79	1.95	108%
NOEAvg	0.0005	Yes	TF	0.43	0.46	0.20	0.47	112%
PARAvg	0.0000	Yes	TF	1.93	1.54	0.69	0.58	181%
PAR	0.0000	Yes	TF	2.07	1.50	0.62	0.64	236%
SIX	0.0000	Yes	TF	1.20	1.51	0.22	0.62	455%
NLC	0.1335	No	TF	0.10	0.41	0.01	0.10	910%
NAC	0.1335	No	TF	0.10	0.41	0.01	0.10	910%

Table 5.36: Sorted Class Metrics for Industry Case Study

Method	# Projects	# Classes	# Interfaces	Ratio
TF	3	51	11	0.21
TL	12	515	21	0.04

Table 5.37: Industry Case Study Class/Interface Ratio

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	0.2719	No	TF	0.27	0.47	0.10	0.30	186%
NCI	0.0789	No	TL	1.82	1.08	2.86	2.15	-36%
NSV	0.0829	No	TL	0.00	0.00	0.14	0.36	-100%
NIM	0.4808	No	TF	4.18	4.40	3.14	2.48	33%
NPM	0.4808	No	TF	4.18	4.40	3.14	2.48	33%
NOM	0.4808	No	TF	4.18	4.40	3.14	2.48	33%
RFC	0.4808	No	TF	4.18	4.40	3.14	2.48	33%
NIC	0.3293	No	TL	0.00	0.00	0.05	0.22	-100%

Table 5.38: Analysis of Interface Metrics for Industry Case Study

Interface-Level Metrics

As mentioned in the first section, Java Interfaces were isolated from classes. This section reports metrics only for interfaces. The pertinent interface-level metrics are expanded in Table 5.3 and defined in Appendix D.

Table 5.38 presents the results of the statistical analysis of the interface-level metrics comparing test-last and test-first interfaces.

Project-Level Metrics

The project-level metrics are reported in Table 5.39. The data is reported in sorted order by %difference. From this view one notices that the test-last projects tend to be larger and more complex (LOC, MLOC, VG) and the test-first projects tend to be more abstract (RMA, NOI) and have higher coupling (IF, FO, CBO). Only two metrics, both size metrics, are statistically significant at the project level.

5.6.3 Test Results

Table 5.40 presents the results of the statistical analysis of the test coverage metrics comparing test-last and test-first projects that contained automated tests. The first two columns of data compare three test-last and three test-first projects. The last two columns of data include a fourth test-last project (named “Common”). This fourth test-last project was significantly larger than the other six projects considered, and it had significantly lower test-coverage measures. The table illustrates

Metric	p-value	Sig?	TF Mean	TF StdDev	TL Mean	TL StdDev	Higher Method	%diff
Two-sample t-test								
NSFavg	0.0235	Yes	0.15	0.25	5.56	7.13	TL	-97%
NOAavg	0.0564	No	0.33	0.58	2.58	3.53	TL	-87%
VGmax	0.0926	No	7.00	1.73	26.08	35.79	TL	-73%
LOC/Mod	0.0373	Yes	21.26	4.46	37.84	23.08	TL	-44%
CAavg	0.2544	No	4.58	1.66	7.45	7.64	TL	-39%
RMDavg	0.3765	No	0.22	0.15	0.33	0.26	TL	-34%
MLOCavg	0.4871	No	4.27	1.74	5.53	4.97	TL	-23%
CEavg	0.7899	No	4.67	3.79	5.44	5.77	TL	-14%
REU	0.8645	No	0.06	0.09	0.08	0.09	TL	-14%
VGavg	0.4255	No	1.70	0.32	1.97	0.91	TL	-14%
RMIavg	0.4357	No	0.52	0.11	0.59	0.25	TL	-13%
LCOMavg	0.9403	No	0.34	0.30	0.35	0.15	TL	-4%
NOCavg	0.9311	No	0.34	0.14	0.34	0.21	TF	3%
NOFavg	0.9322	No	3.28	3.03	3.11	2.51	TF	6%
NBDavg	0.3142	No	1.31	0.08	1.24	0.19	TF	6%
FIavg	0.7333	No	2.06	0.59	1.91	0.80	TF	8%
DITavg	0.7759	No	0.49	0.30	0.42	0.33	TF	14%
NOMavg	0.7711	No	10.09	6.87	8.75	3.50	TF	15%
CBOavg	0.5225	No	3.84	1.16	3.29	1.47	TF	17%
FOavg	0.3602	No	1.78	0.58	1.38	0.67	TF	30%
IFavg	0.7429	No	122.80	189.95	79.09	180.64	TF	55%
PARavg	0.2826	No	0.97	0.42	0.61	0.27	TF	58%
RMAavg	0.2175	No	0.29	0.18	0.11	0.11	TF	165%
SPC	0.5179	No	13.00	18.36	4.73	5.50	TF	175%
NOIavg	0.1155	No	1.08	0.52	0.36	0.60	TF	201%
SIXavg	0.3258	No	0.74	0.68	0.24	0.32	TF	212%

Table 5.39: Analysis of Project Metrics for Industry Case Study

	Line	Branch	Line w/Common	Branch w/Common
	Two-sample t-test			
p-value	0.0123	0.0003	0.0000	0.0000
Significant?	Yes	Yes	Yes	Yes
Higher Method	TF	TF	TF	TF
TF Mean	0.76	0.88	0.76	0.88
Std Dev	0.30	0.32	0.30	0.32
TL Mean	0.59	0.50	0.23	0.20
Std Dev	0.39	0.49	0.36	0.39
%difference	30%	78%	233%	344%

Table 5.40: Analysis of Test Coverage Metrics for Industry Projects with Automated Tests

Project	Approach	Line	Branch
Scanners	TF	72%	94%
Part Number Advanced Search, Part II	TF	98%	100%
Pagination	TF	79%	100%
Common	TL	7%	8%
Common Paramater	TL	34%	39%
Workflow	TL	31%	24%
Conformity Request Tracking	TL	84%	74%

Table 5.41: Test Coverage Metrics for Industry Projects with Automated Tests

that even excluding this project, the test-first projects had significantly higher test-coverage both for line and branch coverage.

Table 5.41 presents the actual test coverage results for the seven projects with automated unit tests. Table 5.42 presents additional test metrics for eight projects with automated unit tests. The extra project PDD was not included earlier because coverage metrics were unable to be obtained. This data reveals that in the test-first projects, developers wrote significantly more testing code. This is demonstrated in the test to source ratio. However, it is interesting to note that the test-first projects did not contain a significantly higher number of assert statements per LOC, class, or method. Combining this fact with the significantly higher test coverage of the test-first projects and one might conclude that the test-first tests are of a higher quality (higher coverage), and they are more efficient (higher coverage with the same number of asserts), but that they may have required more effort (higher test LOC).

Project	Approach	SLOC	TestLOC	T/S Ratio
Scanners	TF	1559	1683	1.08
Part # Adv Search, Part II	TF	842	1118	1.33
Pagination	TF	349	511	1.46
Common	TL	7807	473	0.06
Common Parameter	TL	678	150	0.22
PDD	TL	427	91	0.21
Workflow	TL	811	708	0.87
Conformity Req Tracking	TL	2071	1253	0.61
	Two-sample t-test			
p-value		0.3660	0.2347	0.0031
Significant?		No	No	Yes
Higher Method		TL	TF	TF
TF Mean		916.67	1104.00	1.29
Std Dev		608.45	586.13	0.20
TL Mean		2358.80	535.00	0.39
Std Dev		3111.20	472.93	0.33
%difference		-61%	106%	227%

Table 5.42: Test/Source Ratio Metrics for Industry Projects with Automated Tests

Project	#Asserts	#Asserts/ LOC	#Asserts/ Class	#Asserts/ Method
Scanners	162	0.10	4.38	1.12
Part # Adv Search, Part II	265	0.24	9.46	2.60
Pagination	57	0.11	2.28	1.54
Common	74	0.16	2.96	1.10
Common Parameter	37	0.25	4.11	3.70
PDD	7	0.08	1.75	0.70
Workflow	116	0.16	5.04	1.45
Conformity Req Tracking	108	0.09	3.00	1.06
	Two-sample t-test			
p-value	0.2572	0.9687	0.4496	0.8372
Significant?	No	No	No	No
Higher Method	TF	TF	TF	TF
TF Mean	161.33	0.15	5.37	1.75
Std Dev	104.00	0.08	3.69	0.76
TL Mean	68.40	0.15	3.37	1.60
Std Dev	46.43	0.07	1.25	1.20
%difference	136%	2%	59%	9%

Table 5.43: Test Saturation Metrics for Industry Projects with Automated Tests

Chapter 6

Experiments in Academia

This chapter summarizes research conducted with student programmers in five courses at the University of Kansas. The five controlled experiments will be presented starting with the software engineering experiments. In order to increase sample size and corresponding confidence in the results, data from the undergraduate and graduate software engineering experiments will be combined and again analyzed in section 6.4. The Programming 1 and 2 experiments will be presented last. Section 6.6 will present the results from two experiments conducted in the Programming 2 course in Fall 2005 and Spring 2006.

The chapter begins with a description of the metrics collected and the corresponding analysis performed. Each experiment and corresponding results are then described in turn.

6.1 Metrics Collection and Analysis

The projects in the Undergraduate and Graduate Software Engineering courses are comparable to those in Chapter 5 in that they used the Java Programming Language, the Eclipse IDE, and JUnit. In addition, the projects were semester-long team projects. As a result the metrics generated and analysis conducted will closely follow that of Chapter 5. In addition, productivity, student grade data, and individual pre and post experiment survey data will be analyzed for each experiment.

Unlike the software engineering courses, the Programming 1 and Programming 2 projects were completed in the C++ programming language using a non-integrated development environment and simple assert statements for automated unit testing as described in Chapter 4. Students worked alone on two to three week projects in these classes. As a result, different metrics tools were used. In particular, CCCC [57] was used to generate some project-level metrics. The same tool was used with the Java projects. Krakatau Professional [77] was used to generate method, class, and additional project level metrics. These metrics are expanded in Table 6.1 and Table 6.2, and are described in Appendix D. Although many metrics overlap with

Metric	Equivalent	Expanded Name
V(G)	V(G)	Cyclomatic Complexity
V'(G)		Enhanced Cyclomatic Complexity
eV(G)		Essential Complexity
OC		Operational Complexity
B	BUG	Halstead Bug Prediction
D	PD	Halstead Difficulty
E	EFF	Halstead Effort
EXEC	NOS	Number of Executable Statements
LOC		Lines of Code
N	AHL	Halstead Program Length
N1		Total Number of Operators
N2		Total Number of Operands
n	VOC	Halstead Program Vocabulary
n1		Number of Unique Operators
n2		Number of Unique Operands
V	VOL	Halstead Program Volume
NEST	NBD	Maximum Number of Levels
NION		Number of Input/Output Nodes
NP	PAR	Number of Parameters
BRANCH		Number of Branching Nodes
CDENS		Control Density
CONTROL		Number of control statements
NSC		Number of Semicolons
NSTAT		Number of Statements
RLOC		Relative Lines of Code
SLOC		Source Lines of Code

Table 6.1: C++ Method-level Metrics

the Java-based experiments, a few are different. The "Equivalent" column gives the equivalent metric abbreviation from the Java-based experiments as described in Table 5.1, Table 5.2, and Table 5.4.

Productivity, student grade data, and individual pre and post experiment survey data will be analyzed for each experiment. In addition, a longitudinal survey will be analyzed. This survey was administered over the web in the subsequent semester with all students except the Programming 2 Spring 2006 students.

Test volume metrics will be evaluated for all experiments, but test coverage will not be presented for the Programming 1 and 2 experiments as discussed in section 4.2.7. The analysis techniques will be the same as those used in Chapter 5.

Metric	Equivalent	Expanded Name
DIT	DIT	Depth of Inheritance Tree
CBO	CBO	Coupling Between Objects
CSA	NIV+NSV	Class Size (Attributes)
CSAO		Class Size (Attributes & Operations)
CSI		Class Specialization Index
CSO	NOM	Class Size (Operations)
LCOM	LCOM	Lack of Cohesion of Methods
LOC		Lines of Code
NAAC		Number of Attributes Added
NAIC		Number of Attributes Inherited
NOAC		Number of Operations Added
NOIC		Number of Operations Inherited
NOOC	NORM	Number of Operations Overridden
NPavgC	PARAvg	Average Number of Method Parameters
OSavg	MLOC	Average Operation Size
PA		Private Attribute Usage
PPPC		Percentage Public/Protected Members
RFC	RFC	Response for Class
SLOC	SL	Source Lines of Code
TLOC	TL	Total Lines of Code
WMC	WMC	Weighted Methods in Class

Table 6.2: C++ Class-level Metrics

6.2 Undergraduate Software Engineering Experiment

This section presents results from the first academic study conducted in Summer 2005 with undergraduate students in an upper-level software engineering course at the University of Kansas. Results from this experiment were presented in April 2006 at the Conference on Software Engineering Education and Training [49] at Turtle Bay, Hawaii.

6.2.1 Experiment Design and Context

This section will repeat and expand the experiment design and context presented in section 4.2.5.

Students were asked to design and build an HTML pretty print system as described in Appendix B.1.6. This system was to take an HTML file as input and transform the file into a more human readable format by performing operations such as deleting redundant tags and adding appropriate indentation. A sample application with a graphical user interface is shown in Figure 4.30.

Students were taught and asked to follow a simplified form of the Unified Process including inception, elaboration, construction, and transition stages. The project schedule was divided into two iterations with the first focusing on a text-based user interface and a partial set of features. The second iteration added a graphical user interface and additional features.

Students were asked to complete the pre-experiment survey and then were taught how to write automated unit tests with the JUnit framework. All students were instructed in how to write software in a test-first and test-last manner. The total time spent on JUnit and test-first/test-last programming training was less than one and a half hours. Students were then divided into three groups: two groups were to complete the project with a test-first approach and the third group was to complete the project with a test-last approach. Students were allowed to self-select their teams, but Java programming experience was established as a blocking variable to ensure that each team had at least one member with reasonable previous Java experience. Test-first/test-last team assignments were made after analyzing the pre-experiment questionnaire to ensure the teams were reasonably balanced.

In actuality, only one team of three students applied test-first programming. A second "test-first" team of four students actually applied test-last programming. Despite being instructed to write automated unit tests, the final test-last team of three students reported that they "ran out of time" and performed only manual testing. This team will be labeled the "No-Tests" team.

All teams completed a software requirements specification and a high-level architectural design. The test-last teams were asked to complete a detailed design prior to completing any significant coding. The test-first teams on the other hand were asked to use the test-first approach to allow the detailed design to emerge

Metric	NOS	NOE	V(G)	PL	AHL	VOC	VOL
	Analysis of Variance (ANOVA) Results						
	NOS	NOE	V(G)	PL	AHL	VOC	VOL
F-ratio	5.9081	10.175	5.2868	4.9133	8.2043	4.6326	7.9815
p-value	0.0161	0.0017	0.0227	0.028	0.0047	0.0328	0.0053
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Two-sample t-test						
p-value	0.0200	0.0033	0.0299	0.0323	0.0075	0.0368	0.0084
df	132	99	115	140	108	145	107
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Higher Method	TL	TL	TL	TL	TL	TL	TL
TF Mean	7.43	0.02	2.02	63.18	43.77	17.40	212.36
Std Dev	10.12	0.15	1.87	69.66	56.27	13.70	327.45
TL Mean	12.15	0.15	2.97	91.11	82.51	22.57	438.82
Std Dev	15.19	0.36	3.45	95.17	115.27	17.78	686.80
%difference	-39%	-86%	-32%	-31%	-47%	-23%	-52%

Table 6.3: Analysis of Method Metrics for Undergraduate SE Experiment, Part 1

as the software was developed. The test-first teams were asked to document their detailed design after the code was developed.

Student programmers used the Java Programming Language, the JUnit unit testing framework, and the Eclipse integrated development environment. Students submitted electronic time sheets (see Appendix B for a sample) and software on a weekly basis. They presented their projects in the final class period and then completed the post-experiment survey after seeing each others presentations.

6.2.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level. An additional micro-evaluation of the one test-first project examines differences between code covered by tests and untested code.

Method-Level Metrics

Table 6.3 and Table 6.4 present the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods. A total of ninety-eight test-first methods were compared to seventy-nine test-last methods.

This analysis demonstrates statistically significant differences with ten of the fourteen metrics. Figure 6.1 illustrates the differences in a radar chart. Each of the

Metric	LVL	PD	EFF	BUG	MLOC	NBD	PAR
	Analysis of Variance (ANOVA) Results						
F-ratio	1.1375	7.6426	8.0947	7.981	3.1153	0.0048515	1.0382
p-value	0.2877	0.0063	0.005	0.0053	0.0795	0.9446	0.3098
Significant?	No	Yes	Yes	Yes	No	No	No
	Two-sample t-test						
p-value	0.2866	0.0103	0.0098	0.0084	0.0824	0.9447	0.3093
df	166	102	85	107	141	153	156
Significant?	No	Yes	Yes	Yes	No	No	No
Higher Method	TF	TL	TL	TL	TL	TL	TL
TF Mean	0.37	5.79	2.41	0.07	9.48	2.02	0.62
Std Dev	0.32	5.11	6.52	0.11	12.93	1.26	0.99
TL Mean	0.31	9.54	10.89	0.15	13.71	2.04	0.78
Std Dev	0.31	11.86	27.89	0.23	17.17	1.38	0.95
%difference	16%	-39%	-78%	-52%	-31%	-1%	-20%

Table 6.4: Analysis of Method Metrics for Undergraduate SE Experiment, Part 2

metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the degree and consistency by which the means of the test-last and test-first metrics varied.

This data implies and the radar chart illustrates that software developed with a test-last approach is significantly larger (NOS, PL, AHL, VOC, and VOL), is significantly more complex (V(G), PD, NBD), and is less maintainable (PD, EFF, BUG) than software developed with a test-first approach.

Class-Level Metrics

Table 6.5 presents the results of the statistical analysis of the class-level metrics comparing the test-last and test-first classes in sorted order by %difference with the middle metrics eliminated for space. To save space, only the two-sample t-test p-values are reported. Although the ANOVA results strengthen the confidence, the t-test should be sufficient here to indicate significant differences between the two samples.

Only five of the metrics demonstrated statistically significant differences. However, this view illustrates some trends. The test-last classes tend to be larger and more complex (NOS, V(G), WMC, VOL, BUG) and the test-first classes possibly tend to have better reuse (NII, FI) and perhaps be less cohesive (LCOM) and have higher coupling (FO, FI).

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NSV	0.2889	No	TL	0.00	0.00	0.73	2.58	-100%
NOEAvg	0.0197	Yes	TL	0.01	0.05	0.30	0.43	-97%
NOE	0.0526	No	TL	0.09	0.43	0.80	1.26	-89%
EFF	0.1046	No	TL	10.17	17.11	57.37	104.63	-82%
NSM	0.2523	No	TL	0.23	0.53	1.27	3.35	-82%
EFFAvg	0.1011	No	TL	3.18	9.07	17.14	30.13	-81%
VOLAvg	0.0745	No	TL	223.17	427.58	620.51	738.73	-64%
BUGAvg	0.0745	No	TL	0.07	0.14	0.21	0.25	-64%
AHLAvg	0.0653	No	TL	43.84	68.08	113.08	125.32	-61%
VOL	0.1246	No	TL	897.71	1571.24	2311.10	3147.90	-61%
BUG	0.1245	No	TL	0.30	0.52	0.77	1.05	-61%
PDAvg	0.0636	No	TL	4.84	4.65	11.86	13.12	-59%
AHL	0.1383	No	TL	185.05	327.41	434.53	565.09	-57%
PLAvg	0.0558	No	TL	55.34	82.53	115.16	93.93	-52%
PD	0.2099	No	TL	24.48	44.03	50.25	68.19	-51%
NOS	0.1626	No	TL	31.41	49.79	64.00	77.08	-51%
NOSAvg	0.1268	No	TL	8.05	12.92	15.95	16.19	-50%
WMC	0.2644	No	TL	8.55	12.63	15.67	21.65	-45%
V(G)	0.2644	No	TL	8.55	12.63	15.67	21.65	-45%
PL	0.2404	No	TL	267.07	535.37	479.83	527.54	-44%
VOCAvg	0.0380	Yes	TL	15.10	14.37	26.86	17.15	-44%
VOC	0.3158	No	TL	73.55	143.84	118.87	124.84	-38%
NPM	0.5753	No	TL	1.68	5.65	2.67	4.86	-37%
BL	0.1835	No	TL	16.00	9.91	25.15	21.26	-36%
V(G)Avg	0.2426	No	TL	2.16	2.13	3.37	3.50	-36%
CL	0.2914	No	TF	61.36	45.04	42.31	40.32	45%
CD	0.0060	Yes	TF	0.40	0.09	0.27	0.12	47%
FI	0.2198	No	TF	2.05	2.21	1.33	1.23	53%
PFI	0.2198	No	TF	2.05	2.21	1.33	1.23	53%
PFO	0.3184	No	TF	2.09	3.07	1.33	1.40	57%
NIV	0.5126	No	TF	2.32	5.35	1.47	2.29	58%
LVLAvg	0.0045	Yes	TF	0.46	0.20	0.27	0.18	72%
LCOM_LH	0.2815	No	TF	2.45	4.33	1.40	0.99	75%
NOF	0.2051	No	TF	4.64	6.95	1.69	2.39	174%
NLC	0.4854	No	TF	0.50	2.35	0.13	0.52	275%
NAC	0.4854	No	TF	0.50	2.35	0.13	0.52	275%
NII	0.0063	Yes	TF	0.55	0.51	0.13	0.35	309%
LCOM_CK	0.3006	No	TF	19.68	76.71	2.27	5.42	768%

Table 6.5: Sorted Class Metrics for Undergraduate SE Experiment

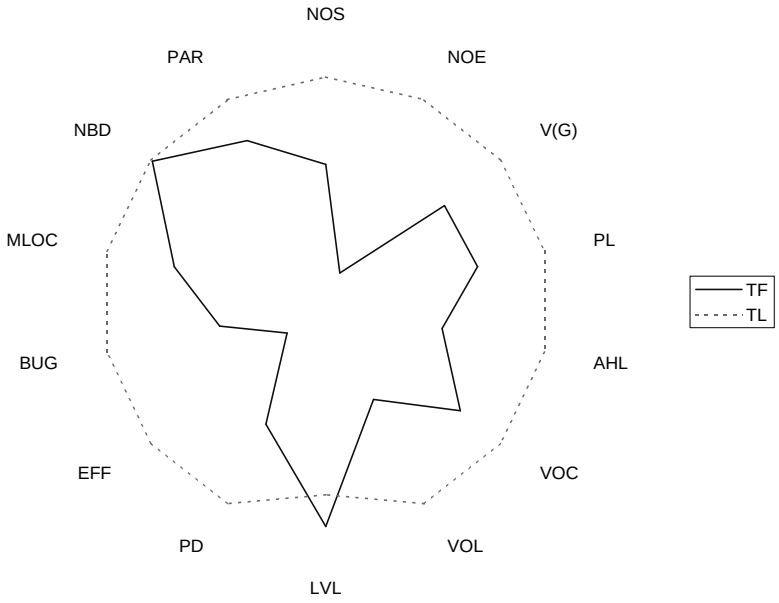

Figure 6.1: Undergraduate SE Experiment Method Metrics Radar Chart

Project-Level Metrics

The project-level metrics are reported in Table 6.6. The data is reported in sorted order by %difference. From this view one notices that the test-last projects tend to be larger and more complex (LOC, MLOC, VG) and the test-first projects tend to have higher coupling (IF, FO, CBO) and better cohesion (LCOM).

Analysis of Tested Code

An additional micro-evaluation was performed on the test-first code. Code that was covered by automated unit tests was separated from code not covered by any tests. Table 6.7 reports differences with Weighted Methods per Class (WMC), Coupling Between Objects (CBO), Nested Block Depth (NBD), Computational Complexity, and Number of Parameters. All values for the 28% of methods that were tested directly are within normal acceptable levels, but values for NBD, Complexity, and # Parameters are flagged with warnings in the untested code. The tested methods had a complexity average 43% lower than their untested counterparts. This difference is approaching statistical significance at p=.08. In addition, tested classes had 104% lower coupling measures than untested classes.

6.2.3 Productivity

Table 6.8 summarizes the functionality implemented by the three teams. The test-first team implemented about twice as many features (12) as the no-tests and test-

Metric	TF Mean	TL Mean	TL StdDev	Higher Method	%diff
NSFavg	0.00	0.79	1.11	TL	-100%
VGavg	2.44	3.96	3.63	TL	-38%
LOC/Mod	32.91	52.68	13.45	TL	-38%
MLOCavg	9.79	14.24	11.45	TL	-31%
PARavg	0.63	0.80	0.40	TL	-21%
VGmax	13.00	15.50	16.26	TL	-16%
NBDavg	2.06	2.10	1.28	TL	-2%
RMIavg	1.00	1.00	0.00	N/A	0%
CAavg	0.00	0.00	0.00	N/A	0%
CEavg	0.00	0.00	0.00	N/A	0%
NOAavg	0.00	0.00	0.00	N/A	0%
REU	0.00	0.00	0.00	N/A	0%
SPC	0.00	0.00	0.00	N/A	0%
FIavg	1.61	1.32	0.10	TF	22%
NOMavg	6.75	4.62	2.90	TF	46%
LCOMavg	0.38	0.25	0.25	TF	53%
CBOavg	2.75	1.59	0.48	TF	73%
SIXavg	0.01	0.00	0.00	TF	100%
DITavg	0.04	0.00	0.00	TF	100%
NOCavg	0.07	0.00	0.00	TF	100%
RMDavg	0.08	0.00	0.00	TF	100%
RMAavg	0.08	0.00	0.00	TF	100%
NOIavg	1.00	0.00	0.00	TF	100%
IFavg	2.93	0.00	0.00	TF	100%
NOFavg	4.50	1.77	1.50	TF	154%
FOavg	1.14	0.27	0.38	TF	324%

Table 6.6: Analysis of Project Metrics for Undergraduate SE Experiment

	WMC		CBO		NBD		Complexity		#Parameters	
Code	mean	max	mean	max	mean	max	mean	max	mean	max
Tested	7.80	21	2.2	3	1.50	3	1.77	5	1.00	3
Untested	13.55	53	**4.5**	**20**	**2.20**	**6**	**2.53**	**13**	**0.48**	**6**

Table 6.7: Metrics on Tested and Untested code of Test-First Project

Feature	Test-First	No-Tests	Test-Last
remove xml data	Yes w/defects	No	No
split long lines	Yes	Yes	Yes
indent tags	Yes	Yes w/defects	Yes
remove redundant tags	Yes	No	No
remove carriage returns	Yes	Yes	Yes
tags on individual lines	Yes	No	Yes w/defects
remove extra whitespace	Yes	Yes	Yes
simplify empty tags	Yes	No	No
make tag case consistent	Yes	No	No
text ui	Yes	Yes	Yes
graphical ui	Yes	No	No
user can modify parameters	Yes	No	No
#Features Provided	12	5	6
#Features Provided w/no defects	11	4	5

Table 6.8: Features Implemented

Team	Total Effort	Dev Effort	Dev Effort/LOC	Dev Effort/Feature
Test-First	6504	2239	2.13	186.58
No-Tests	11385	7340	7.38	1468.00
Test-Last	4450	2575	9.94	429.17

Table 6.9: Undergraduate SE Effort in Minutes

last teams (5 and 6), with similar numbers of defects. In addition, the test-first team was the only one to complete the graphical user interface. Despite implementing more features, the test-first team did not invest the most time of all the teams.

Table 6.9 reports the amount of time each team spent on the project. Total effort includes time spent on all project activities including general meetings and research. Dev(elopment) Effort includes only time spent directly on the project including analysis, design, code, test, fix, and review.

The test-first team spent less effort per line-of-code and they spent 88% less effort per feature than the no-tests team, and 57% less effort per feature than the test-last team. This data supports the rejection of the **P1** null hypothesis, making it likely that test-first programmers are more productive than test-last programmers. Individual productivity is known to vary widely among programmers so it is certainly possible that the test-first team was blessed with one or more highly productive programmers. However, the pre-experiment questionnaire indicates that there was no statistically significant difference in the academic or practical background of the teams.

Student-reported major and overall GPA's were all above 2.5 and GPA differences

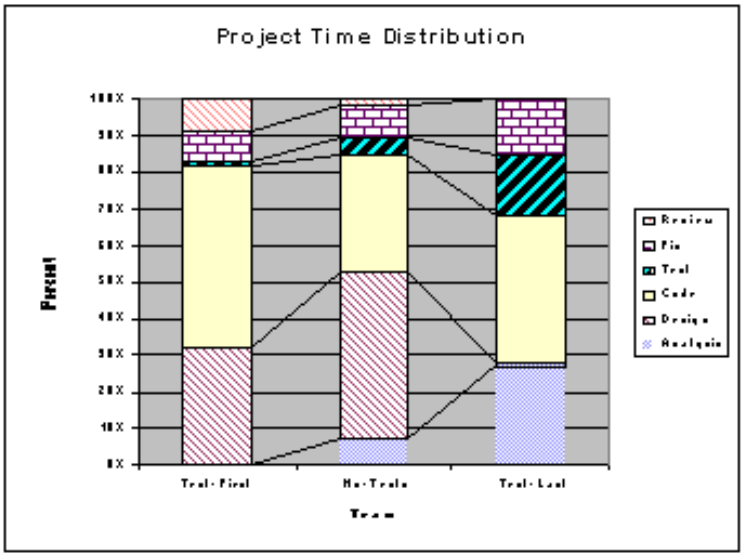

Figure 6.2: Undergraduate SE Time Distribution by Team

between the three teams was not statistically significant (all $p>0.55$). Students had almost identical backgrounds in C++ and a similar mix of experiences with other non-Java programming languages. While the test-first team did report slightly more Java programming experience, an analysis of variance did not indicate a significant difference (ANOVA p=.247). Furthermore a two-sample *t*-test between each set of teams showed no significant difference between the test-first and no-tests (p=0.62) and the test-first and test-last (p=0.16) teams.

Figure 6.2 displays how the teams spent their time on various phases of project development. The chart displays times by phase as percentages of each team's total time. Interestingly, while the test-first team wrote more tests (see next section), they reported less time testing. Most likely they were unable to distinguish testing from coding because of the constant intermixing of the two.

Because the test-first team reported almost no time on analysis, we might assume that they performed analysis in what they call design. We note the significant analysis and design investment of the no-tests team. Because the test-last team was originally instructed to use a test-first approach, it is no surprise that the test-first and test-last teams had similar proportions of time spent in analysis and design.

Because the project was time-bound by the class, teams were required to turn in their applications whether they thought they were complete or not. The author observed the teams on the final day prior to the project presentations. The test-last team was removing all code related to their graphical user interface because it was not working. The no-tests team was still debugging code, dreary-eyed from a lack of sleep. The test-first team was polishing their presentation for the next day. It is likely that the number of features and the portion of test and fix time would

Team	# of classes	LOC	Test LOC	LOC/method	LOC/feature
Test-First	13	1053	168	12.10	87.75
Test-First(less GUI)	11	670	168	11.75	55.83
No-Tests	7	995	0	27.64	199.00
Test-Last	4	259	38	7.40	43.17

Table 6.10: Undergraduate SE Code Size Metrics

have increased for the no-tests and the test-last team had students been allowed to finish late. Students observed each other's experiences and, while anecdotal, this observation complements the presented data and may account for differences in programmer perceptions discussed later.

Table 6.10 reports the size of the code implemented in terms of number of classes and lines of code. For comparison, we also give the code size of the Test-First application with only the text user interface. While the Test-First application implemented more additional features besides the graphical user interface, the GUI was a significant feature and this allows a more consistent comparison with the two teams that only implemented a text user interface.

The test-first team implemented more code than the other two teams. We note that both the test-first and test-last teams have a reasonable average method size and lines-of-code per feature, but the no-tests team apparently wrote long methods and implemented an excessive amount of code for the provided functionality.

6.2.4 Test Results

This section presents the test density and coverage measurements for the undergraduate software engineering experiment. Table 6.11 presents the testing metrics for the test-first and test-last projects. Recall that the third team wrote no automated tests so they are not included here. Table 6.12 presents the testing metrics comparing the test-first project without the GUI with the test-last project. As mentioned in the previous section, the test-first team was the only one to implement both the textual and graphical user interface. Given that GUI's are traditionally difficult to implement, and that students were not taught techniques for testing GUI's, it is not surprising that test coverage was poor on the GUI code.

The test-first metrics are better in all measures except asserts per lines of code and asserts per class. When the GUI code is excluded, the test-first metrics are substantially better with conditional coverage almost doubling the test-last numbers. Unfortunately the coverage metrics are still quite low with none of the values exceeding 50%. Considering this was the student's first exposure to automated unit testing, perhaps this is acceptable. As the graduate software engineering and the industry experiments demonstrate, good coverage is attained with maturity.

Metric	TF	TL	Higher Method	%diff
T/S Ratio	0.16	0.15	TF	9%
#Asserts/LOC	0.03	0.03	TL	-2%
#Asserts/Class	1	1.75	TL	-43%
#Asserts/Method	0.32	0.2	TF	61%
Line Coverage	28%	25%	TF	13%
Cond Coverage	20%	15%	TF	31%

Table 6.11: Test Metrics for Undergraduate SE Experiment

Metric	TF	TL	Higher Method	%diff
T/S Ratio	0.25	0.15	TF	71%
#Asserts/LOC	0.17	0.03	TF	517%
#Asserts/Class	2.55	1.75	TF	45%
#Asserts/Method	1.56	0.2	TF	678%
Line Coverage	44%	25%	TF	77%
Cond Coverage	31%	15%	TF	99%

Table 6.12: Test Metrics for Undergraduate SE Experiment (Text UI only)

6.2.5 Programmer Perceptions

Pre and post-experiment surveys were administered to all programmers. Comparisons between the two surveys in Table 6.13 revealed that all three teams perceived the test-first approach more positively after the experiment (up to 39% more) and inversely perceived the test-last approach more negatively (up to 30% more). Table 6.14 reports results from the statistical analysis of the changes from the pre to post experiment survey for all responses. This data indicates that the improved perception of the test-first approach was statistically significant as was an overall shift towards a test-first design approach.

Additionally, 89% of programmers thought test-first produced simpler designs, 70% thought test-first produced code with fewer defects, and 75% thought test-first was the best approach for this project as illustrated in Figure 6.3.

In the post-experiment survey, all programmers who tried test-first indicated

	Test-First			Test-Last		
Team	Pre	Post	% Change	Pre	Post	% Change
Test-First	3.67	4	9%	3.33	2.33	-30%
No-Tests	1.5	2	33%	3.67	3.33	-9%
Test-Last	2.33	3.25	39%	4	3.25	-19%

Table 6.13: Programmer Perceptions of Test-First and Test-Last (0 to 4 scale)

Metric	Testing Attitude	Test Timing	Design Attitude	TF Attitude	TL Attitude	Choice
paired t-test p-value	1.0000	0.7509	0.0224	0.0222	0.0886	1.0000
Significant	No	No	Yes	Yes	No	No
Higher Method	Post	Pre	Pre	Pre	Post	Post
Pre Mean	3.70	3.70	2.40	2.44	3.70	0.50
Pre Std Dev	0.48	1.83	1.17	1.51	0.67	0.53
Post Mean	3.70	3.90	3.20	3.10	3.00	0.50
Post Std Dev	0.48	1.29	0.79	1.10	1.41	0.53
%difference	0%	5%	33%	27%	-19%	0%

Table 6.14: Undergraduate SE Programmer Opinion Changes

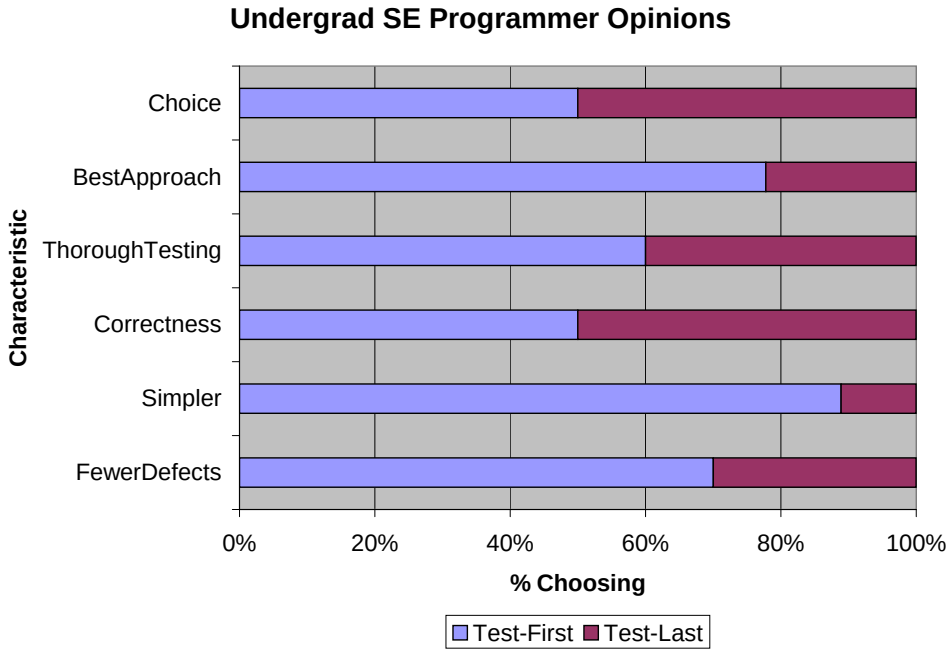

Figure 6.3: Undergraduate SE Programmer Opinions

they would use it again, supporting the rejection of the **O2** null hypothesis. All programmers from the no-tests team indicated they would prefer to use test-last, causing us to keep the **O1** null hypothesis. Comments on their surveys indicated that the no-tests programmers are more comfortable with an approach that they already know. Programmers from the test-last team were split with half preferring to use test-first on future projects and half choosing test-last.

Programmers were also asked in the post-experiment survey to evaluate their confidence in the software they developed. Although most responses were similar, the test-first team did report higher confidence in the ability to make future changes to their software. This difference with the test-last team was nearly statistically significant (p=.059).

6.2.6 Longitudinal Results

This section describes the results from the longitudinal survey. This survey was administered via an email request and a web survey late in the Fall 2005 semester. One of the primary goals of the longitudinal survey was to measure voluntary usage of the test-first or test-last approach after having participated in the experiment.

Five of the ten students completed the longitudinal survey. Four of the five programmers reported using the test-first approach on subsequent projects in which they had the choice. Similarly, four of the five programmers indicated that they would choose to use the test-first approach on future projects given the choice.

6.3 Graduate Software Engineering Experiment

This section presents results from the academic experiment conducted in Fall 2005 with graduate students in the first course of the Masters in Software Engineering program at the University of Kansas.

6.3.1 Experiment Design and Context

This section will repeat and expand the experiment design and context presented in section 4.2.5.

This experiment took place in a graduate software engineering course that is the first course in the Masters of Software Engineering program at the University of Kansas. The course is a survey of software engineering and regularly includes a semester-long team-based project. This course met during the Fall 2005 semester and used the exact same semester-long project as the undergraduate course described in section 4.2.5 and Appendix B.1.6. The pre-experiment survey, TDD training, development process, weekly time sheet and code submissions, and

post-experiment survey also matched the same design and schedule as the undergraduate experiment.

The two primary differences from the undergraduate study were the academic and professional experience of the students and the meeting times of the course. All students in the course had completed at least a bachelors degree in a computing related field. All but one of the students reported at least one year of experience in a computing related job and 44% of the students reported at least six years of experience in a computing related job. The course met one evening a week for a sixteen week semester. The undergraduate course met three days per week for two hours per day in an eight-week summer session.

Students were divided into three teams of three students each. Java programming experience was again used as a blocking variable to ensure equitable technical skills. Two teams were asked to use a test-first approach and one team was asked to use a test-last approach.

Similar to the undergraduate experiment, the test-last team did not accomplish writing any automated unit tests. Unlike the undergraduate experiment though, both test-first teams were successful in writing automated unit tests. The author provided a three-hour guest lecture early in the semester. Because the Java Programming Language was new for a number of students, the lecture covered some Java fundamentals as well as training on JUnit and test-first and test-last programming.

In both the undergraduate and graduate experiments the author offered additional assistance for any students struggling with JUnit and the test-first or test-last approach. A few students in both experiments requested minor help through email. One of the test-first teams in the graduate course requested a short (about one hour) hands-on tutorial to get started with JUnit.

Like in the undergraduate experiment, all teams completed a software requirements specification and a high-level architectural design. The test-last team was asked to complete a detailed design prior to completing any significant coding. The test-first teams on the other hand were asked to use the test-first approach to allow the detailed design to emerge as the software was developed. The test-first teams were asked to document their detailed design after the code was developed.

Student programmers used the Java Programming Language, the JUnit unit testing framework, and the Eclipse integrated development environment. Students submitted electronic time sheets (see Appendix B for a sample) and software on a weekly basis. They presented their projects in the final class period and then completed the post-experiment survey after seeing each others presentations.

6.3.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level.

Metric	NOS	NOE	V(G)	PL	AHL	VOC	VOL
	Analysis of Variance (ANOVA) Results						
	NOS	NOE	V(G)	PL	AHL	VOC	VOL
F-ratio	3.629	6.9498	1.0305	1.342	0.44549	2.1411	0.23171
p-value	0.0608	0.0103	0.3134	0.2505	0.5066	0.1478	0.6317
Significant?	No	Yes	No	No	No	No	No
	Two-sample t-test						
p-value	0.0673	0.0830	0.2483	0.1883	0.4290	0.1075	0.5593
df	43	23	64	64	68	60	70
Significant?	No	No	No	No	No	No	No
Higher Method	TL	TL	TL	TL	TL	TL	TL
TF Mean	20.12	0.00	5.28	136.03	141.00	30.96	812.10
Std Dev	23.02	0.00	5.88	153.77	214.08	24.13	1417.37
TL Mean	31.17	0.13	6.63	176.15	172.54	39.04	961.10
Std Dev	24.04	0.34	3.92	102.43	125.43	17.54	763.97
%difference	-35%	-100%	-20%	-23%	-18%	-21%	-16%

Table 6.15: Analysis of Method Metrics for Graduate SE Experiment, Part 1

Method-Level Metrics

Table 6.15 and Table 6.16 present the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods. A total of fifty test-first methods were compared to twenty-four test-last methods.

This analysis demonstrates statistically significant differences with only two of the fourteen metrics. Figure 6.4 illustrates the differences in a radar chart. Each of the metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the degree and consistency by which the means of the test-last and test-first metrics varied.

Although few of the differences are significant, this data implies and the radar chart illustrates that software developed with a test-last approach is larger (NOS, PL, AHL, VOC, and VOL), more complex (V(G), PD, NBD), and possibly less maintainable (PD, BUG) than software developed with a test-first approach.

Class-Level Metrics

Table 6.17 presents the results of a simple analysis of the class-level metrics comparing the test-last and test-first classes in sorted order by %difference with the middle metrics eliminated for space. A statistical analysis makes no sense in this

Metric	LVL	PD	EFF	BUG	MLOC	NBD	PAR
	Analysis of Variance (ANOVA) Results						
F-ratio	3.7641	2.2848	0.011882	0.23151	2.624	1.7494	1.6826
p-value	0.0563	0.135	0.9135	0.6319	0.1096	0.1901	0.1987
Significant?	No	No	No	No	No	No	No
	Two-sample t-test						
p-value	0.0110	0.1132	0.8912	0.5595	0.0967	0.2114	0.2375
df	65	53	71	70	50	41	37
Significant?	Yes	No	No	No	No	No	No
Higher Method	TF	TL	TF	TL	TL	TL	TL
TF Mean	0.16	17.24	30.45	0.27	22.10	2.74	1.24
Std Dev	0.22	17.01	70.80	0.47	28.53	1.74	0.62
TL Mean	0.07	23.31	28.79	0.32	33.17	3.33	1.46
Std Dev	0.07	14.22	33.32	0.25	25.21	1.95	0.78
%difference	122%	-26%	6%	-15%	-33%	-18%	-15%

Table 6.16: Analysis of Method Metrics for Graduate SE Experiment, Part 2

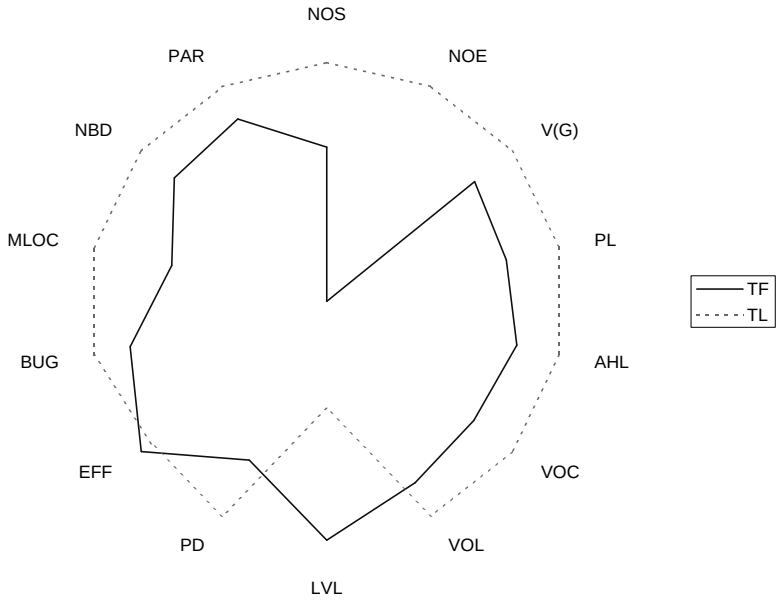

Figure 6.4: Graduate SE Experiment Method Metrics Radar Chart

case because the test-last team implemented the entire project in one class. The data is reported still and some trends can be identified. For instance the test-last class tends to be larger and more complex (MLOC, WMC, VOC, V(G)). Data from the undergraduate and graduate software engineering experiments will be combined in the next section to allow for a statistical analysis.

The test-last software uses a procedural approach. The entire project is implemented in a single class. The one class consists of many static methods invoked from the *main()* method. These concerns are reflected in the NSM and MLOC measures.

Project-Level Metrics

The project-level metrics are reported in Table 6.18. The data is reported in sorted order by %difference. From this view one notices that the test-last projects tend to be larger (LOC, MLOC), but the test-first project may be more complex (VG).

6.3.3 Productivity Results

This section reports, compares, and describes the volume of code produced and the amount of time students reported they spent on the projects. Unlike the undergraduate experiment, the three teams completed roughly the same project features although the interface and configurability did vary some between the projects.

Table 6.19 reports the amount of time each team spent on the project. Total effort includes time spent on all project activities including general meetings and research. Dev(elopment) Effort includes only time spent directly on the project including analysis, design, code, test, fix, and review.

Table 6.20 reports the size of the code implemented in terms of number of classes and lines of code. Although LOC can be a poor measure of productivity, it is interesting to see how widely the time to code ratios vary. The test-first teams invested roughly half as much development time as the test-last team. One of the test-first teams wrote nearly 3,000 lines of source and test code, while the other wrote only a little over 500 lines of source and test code in slightly more development time. Based on author observations, the Test-First 2 team seemed to struggle more with mastering the Java Programming Language which could account for the lower code volume. Nonetheless all of the teams managed to complete a core set of functionality.

The average size of methods suggests that teams using the test-first approach tend to write smaller methods. This was seen in the MLOC, VOL, and VOC metrics reported in previous sections.

Figure 6.5 displays how the teams spent their time on various phases of project development. The chart displays times by phase as percentages of each team's total time. This chart visualizes the fact that the two test-first teams had a fairly even

Metric	Higher Method	TF Mean	TF SDev	TL Mean	%diff
NIS	TL	0.00	0.00	1.00	-100%
NOE	TL	0.00	0.00	3.00	-100%
NOEAvg	TL	0.00	0.00	0.13	-100%
NSM	TL	1.69	2.36	24.00	-93%
CL	TL	55.62	41.32	657.00	-92%
NOS	TL	77.38	60.02	748.00	-90%
MLOC	TL	85.00	61.84	796.00	-89%
SL	TL	98.77	72.20	869.00	-89%
TL	TL	178.46	125.12	1522.00	-88%
PD	TL	66.29	56.92	559.35	-88%
PL	TL	523.20	396.49	4227.50	-88%
VOC	TL	119.08	100.84	937.00	-87%
WMC	TL	20.31	17.06	159.00	-87%
V(G)	TL	20.31	17.06	159.00	-87%
AHL	TL	542.31	391.59	4141.00	-87%
NPM	TL	1.46	2.76	11.00	-87%
VOL	TL	3123.47	2437.50	23066.31	-86%
BUG	TL	1.04	0.81	7.69	-86%
NOM	TL	3.85	4.85	24.00	-84%
EFF	TL	117.10	117.59	690.85	-83%
WMC	TL	35.54	33.33	208.00	-83%
NNP	TL	2.23	2.31	13.00	-83%
BL	TL	26.00	17.45	110.00	-76%
RFC	TL	16.46	6.72	65.00	-75%
IFO	TL	5.69	3.33	19.00	-70%
FO	TL	6.85	4.56	20.00	-66%
LVL	TL	0.63	1.20	1.77	-64%
AHLAvg	TF	235.61	168.05	172.54	37%
LVLAvg	TF	0.10	0.11	0.07	40%
VOLAvg	TF	1401.40	1131.46	961.10	46%
BUGAvg	TF	0.47	0.38	0.32	46%
EFFAvg	TF	56.92	56.58	28.79	98%

Table 6.17: Sorted Class Metrics for Graduate SE Experiment

Metric	TF Mean	TF StdDev	TL Mean	Higher Method	%diff
NOFavg	0.50	0.71	3.00	TL	-83%
LOC/Mod	54.21	34.12	144.50	TL	-62%
MLOCavg	28.94	14.23	33.17	TL	-13%
FIavg	1.55	0.64	1.75	TL	-11%
PARavg	1.29	0.11	1.46	TL	-11%
NBDavg	3.05	0.64	3.33	TL	-9%
CBOavg	2.46	0.93	2.50	TL	-2%
RMIavg	1.00	0.00	1.00	TL	0%
CAavg	0.00	0.00	0.00	N/A	0%
DITavg	0.00	0.00	0.00	N/A	0%
NOAavg	0.00	0.00	0.00	N/A	0%
NOCavg	0.00	0.00	0.00	N/A	0%
NOIavg	0.00	0.00	0.00	N/A	0%
NSFavg	0.00	0.00	0.00	N/A	0%
REU	0.00	0.00	0.00	N/A	0%
RMAavg	0.00	0.00	0.00	N/A	0%
RMDavg	0.00	0.00	0.00	N/A	0%
SPC	0.00	0.00	0.00	N/A	0%
FOavg	0.91	0.29	0.75	TF	21%
VGavg	10.51	2.64	8.67	TF	21%
SIXavg	0.01	0.01	0.00	TF	100%
LCOMavg	0.10	0.14	0.00	TF	100%
CEavg	0.50	0.71	0.00	TF	100%
NOMavg	2.25	1.77	0.00	TF	100%
VGmax	61.50	51.62	20.00	TF	208%
IFavg	34.72	49.10	1.00	TF	3372%

Table 6.18: Analysis of Project Metrics for Graduate SE Experiment

Team	Total Effort	Dev Effort	Dev Effort/LOC
Test-First 1	7765	4040	4.30
Test-First 2	10114	4525	12.53
Test-Last/No-Tests	11070	7440	8.58

Table 6.19: Graduate SE Effort in Minutes

Team	# of classes	LOC	Test LOC	LOC/method
Test-First 1	6	940	1999	22.38
Test-First 2	7	361	177	30.08
Test-Last	1	867	0	36.13

Table 6.20: Graduate SE Code Size Metrics

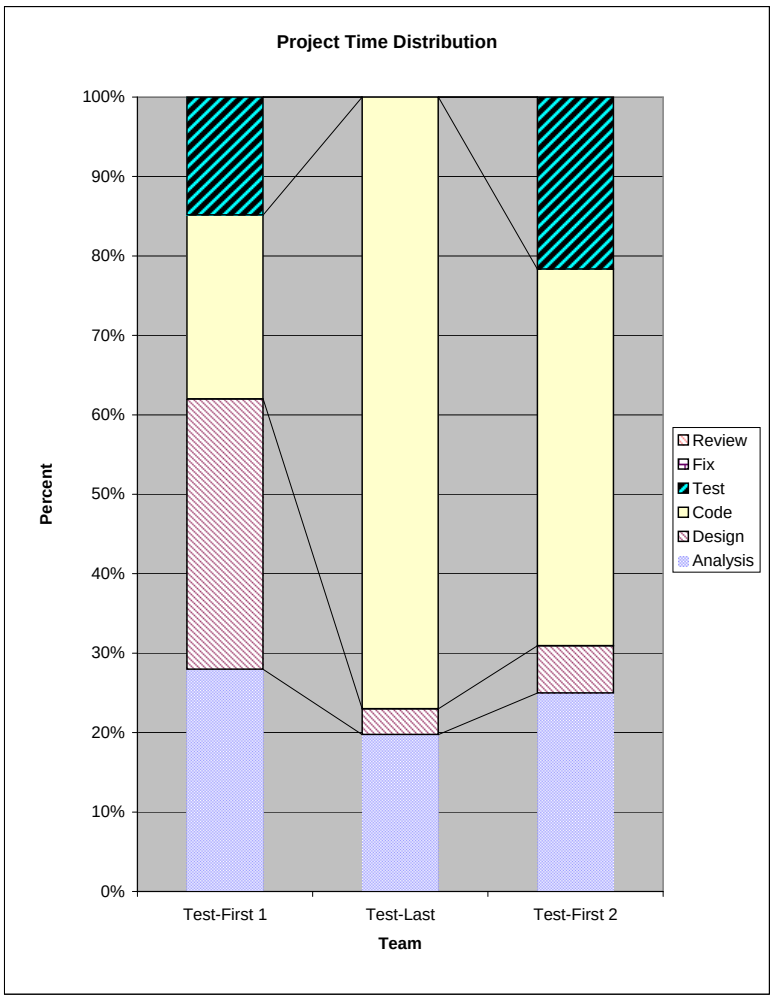

Figure 6.5: Graduate SE Time Distribution by Team.

distribution of project phases, whereas the test-last team spent an excessive amount of time coding.

6.3.4 Test Results

This section presents the test density and coverage measurements for the graduate software engineering experiment. Table 6.21 presents the testing metrics for the two test-first projects. Recall that the third team wrote no automated tests so they are not included here. As a result no comparison will be made here. Instead results from the undergraduate and graduate experiments will be combined in the final section of this chapter.

One of the test-first teams achieved very high test coverage metrics at 92% and 86% respectively. The second test-first team also achieved better than 50% line cov-

Metric	TF1	TF2
T/S Ratio	2.13	0.49
#Asserts/LOC	0.30	0.12
#Asserts/Class	31.11	4.5
#Asserts/Method	6.67	3.75
Line Coverage	92%	56%
Cond Coverage	86%	29%

Table 6.21: Test Metrics for Graduate SE Experiment

Metric	Testing Attitude	Test Timing	Design Attitude	TF Attitude	TL Attitude	Choice
paired t-test p-value	1.0000	0.0353	0.1950	0.5674	0.3765	0.3506
Significant	No	Yes	No	No	No	No
Higher Method	Post	Pre	Pre	Pre	Post	Pre
Pre Mean	3.78	2.78	2.89	2.88	2.89	0.33
Pre Std Dev	0.44	1.20	0.60	1.36	1.27	0.50
Post Mean	3.78	4.11	3.22	3.33	2.44	0.50
Post Std Dev	0.44	1.62	0.67	1.12	1.13	0.53
%difference	0%	48%	12%	16%	-15%	50%

Table 6.22: Graduate SE Programmer Opinion Changes

erage but only 29% conditional coverage. These results are encouraging compared to the undergraduate numbers. It seems likely that student maturity and perhaps industry experience contributed to the stronger numbers. Whereas undergraduates rarely have to maintain code they've written, professional programmers seem more likely to appreciate the value of testing knowing implications to future software maintenance.

6.3.5 Programmer Perceptions

This section describes the results from the pre and post experiment surveys. Table 6.22 reports results from the statistical analysis of the changes from the pre to post experiment for all programmers. Opinions moved toward a test-first approach. The only statistically significant change was in the timing of tests. However, as Figure 6.6 illustrates, even though programmer opinions from the post-experiment survey favor the test-first approach, only half of the programmers would choose to use it given the option.

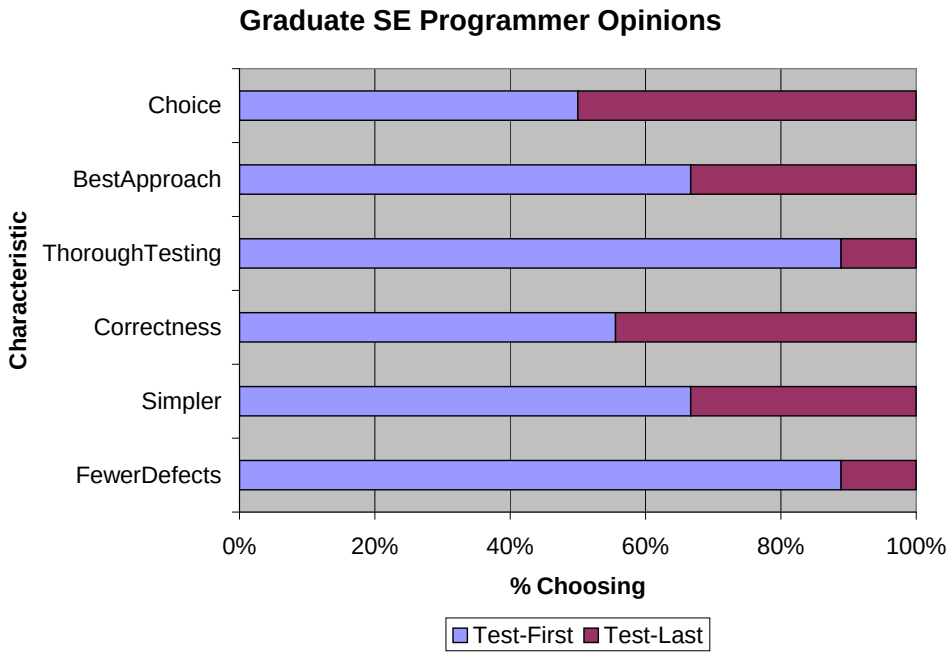

Figure 6.6: Graduate SE Programmer Opinions

6.3.6 Longitudinal Results

A longitudinal survey was administered via an email request and a web survey late in the Spring 2006 semester. One of the primary goals of the longitudinal survey was to measure voluntary usage of the test-first or test-last approach after having participated in the experiment.

Only three of the nine students completed the longitudinal survey. None of the three indicated using a test-first or test-last approach with automated unit tests on subsequent projects. Two of the three programmers indicated that they would choose to use the test-first approach on future projects given the choice.

6.4 Combined Software Engineering Experiment

The previous two sections reported results from the experiments in the undergraduate and graduate software engineering courses. Because the two courses used the same semester-long project, it seems appropriate to combine the data from the two experiments to increase confidence in the analysis. This section will report the combined results without repeating all of the experiment descriptions or the productivity or evaluative results.

Metric	NOS	NOE	V(G)	PL	AHL	VOC	VOL
	Two-sample t-test						
p-value	0.0479	0.0004	0.1952	0.1079	0.1306	0.0840	0.1914
Significant	Yes	Yes	No	No	No	No	No
Higher Method	TL	TL	TL	TL	TL	TL	TL
TF Mean	11.87	0.01	3.16	88.65	77.77	22.14	422.06
Std Dev	16.91	0.12	4.08	111.89	141.53	19.10	919.27
TL Mean	16.58	0.15	3.83	110.92	103.49	26.41	560.51
Std Dev	19.28	0.35	3.87	102.94	123.17	18.98	735.89
%difference	-28%	-90%	-17%	-20%	-25%	-16%	-25%

Table 6.23: Analysis of Method Metrics for Combined SE Experiments, Part 1

Metric	LVL	PD	EFF	BUG	MLOC	NBD	PAR
	Two-sample t-test						
p-value	0.3352	0.0811	0.5467	0.1915	0.1437	0.8054	0.4972
Significant?	No	No	No	No	No	No	No
Higher Method	TF	TL	TL	TL	TL	TL	TL
TF Mean	0.29	9.79	12.21	0.14	14.26	2.30	0.86
Std Dev	0.30	12.12	44.01	0.31	21.11	1.49	0.92
TL Mean	0.26	12.75	15.06	0.19	18.34	2.35	0.94
Std Dev	0.29	13.68	30.05	0.25	20.96	1.62	0.96
%difference	14%	-23%	-19%	-25%	-22%	-2%	-9%

Table 6.24: Analysis of Method Metrics for Combined SE Experiments, Part 2

6.4.1 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level.

Method-Level Metrics

Table 6.23 and Table 6.24 present the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods. A total of 148 test-first methods were compared to 103 test-last methods.

This analysis demonstrates statistically significant differences with only two of the fourteen metrics. Figure 6.7 illustrates the differences in a radar chart. Each of the metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the degree and consistency by which the means of the test-last and test-first metrics

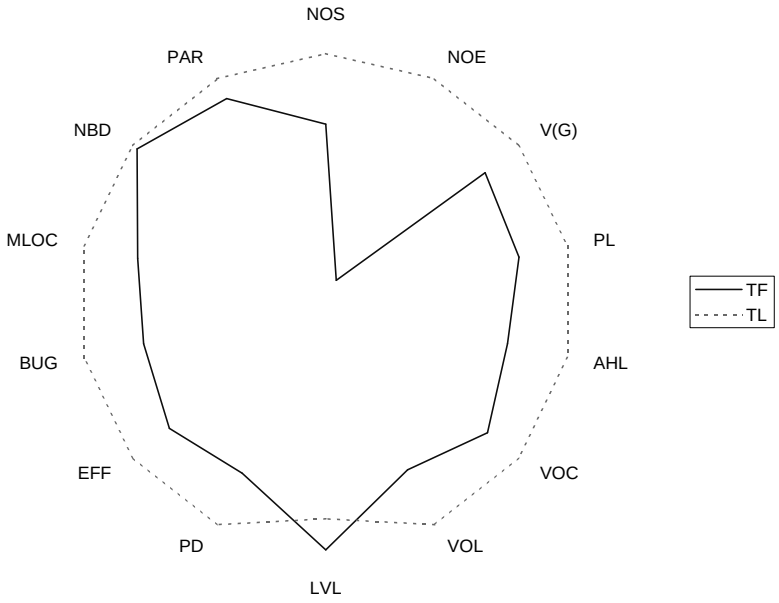

Figure 6.7: Combined SE Experiments Method Metrics Radar Chart

varied.

Although only the differences on size (NOS) and exceptions (NOE) are significant, this data implies and the radar chart illustrates that software developed with a test-last approach is larger (NOS, PL, AHL, VOC, and VOL), perhaps more robust (NOE), more complex (V(G), PD, NBD), and possibly less maintainable (PD, BUG) than software developed with a test-first approach.

Class-Level Metrics

Table 6.25 presents the results of an analysis of the class-level metrics comparing the test-last and test-first classes in sorted order by %difference with the middle metrics eliminated for space. Because the two experiments are combined, sufficient data exists for a statistical analysis.

The data indicates only a couple of possible trends. It appears that the test-first projects may have better reuse (FI, NII) and the test-last projects throw more exceptions (NOE) but may be larger (NSV, NSM, NOS, AHL, VOL, PL), may be more complex (WMC, V(G)) and may possibly have higher coupling (RFC, IFO). Only the exceptions and comment metric differences are statistically significant.

Project-Level Metrics

The combined project-level metrics are reported in Table 6.26. The data is reported in sorted order by %difference. From this view one notices that the test-first projects may be more abstract (RMA) and have better reuse (NOI, FI), but they may also have

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NSV	0.2879	No	TL	0.00	0.00	0.69	2.50	-100%
NIS	0.3332	No	TL	0.00	0.00	0.06	0.25	-100%
NOEAvg	0.0155	Yes	TL	0.01	0.04	0.29	0.42	-98%
NOE	0.0198	Yes	TL	0.06	0.34	0.94	1.34	-94%
NSM	0.2649	No	TL	0.77	1.63	2.69	6.54	-71%
NOS	0.2386	No	TL	48.49	57.54	106.75	186.51	-55%
AHL	0.2252	No	TL	317.74	388.59	666.19	1075.48	-52%
VOL	0.2406	No	TL	1724.42	2193.72	3608.30	6014.34	-52%
BUG	0.2406	No	TL	0.57	0.73	1.20	2.00	-52%
PD	0.2704	No	TL	40.01	52.55	82.07	143.31	-51%
NPM	0.3037	No	TL	1.60	4.74	3.19	5.14	-50%
PL	0.2243	No	TL	362.20	498.28	714.06	1066.57	-49%
EFF	0.3521	No	TL	49.89	88.37	96.96	187.88	-49%
WMC	0.2887	No	TL	12.91	15.31	24.63	41.49	-48%
V(G)	0.2887	No	TL	12.91	15.31	24.63	41.49	-48%
VOC	0.2239	No	TL	90.46	129.87	170.00	237.45	-47%
MLOC	0.3652	No	TL	78.42	67.81	132.29	209.35	-41%
SL	0.3425	No	TL	97.13	85.80	159.50	229.00	-39%
NOM	0.2673	No	TL	4.09	6.03	6.44	7.22	-37%
LCOM_HS	0.4145	No	TL	0.21	0.37	0.32	0.49	-35%
TL	0.4038	No	TL	172.67	133.98	264.14	384.94	-35%
CL	0.5524	No	TL	58.25	42.20	86.21	168.79	-32%
RFC	0.1650	No	TL	14.71	15.89	21.75	16.56	-32%
IFO	0.1004	No	TL	6.03	5.08	8.88	5.74	-32%
BL	0.2769	No	TL	21.42	15.09	31.21	30.52	-31%
LVL	0.5251	No	TL	1.20	1.63	1.66	2.59	-27%
NBD	0.1169	No	TF	2.81	1.31	2.17	1.10	29%
EFFAvg	0.6131	No	TF	23.14	43.30	17.87	29.26	30%
PFO	0.4551	No	TF	1.74	2.73	1.31	1.35	33%
CD	0.0261	Yes	TF	0.38	0.12	0.28	0.12	33%
FI	0.3081	No	TF	1.71	1.93	1.25	1.24	37%
PFI	0.3081	No	TF	1.71	1.93	1.25	1.24	37%
NOF	0.5141	No	TF	2.38	5.12	1.57	2.34	51%
LCOM_LH	0.2699	No	TF	2.06	3.65	1.31	1.01	57%
NLC	0.5786	No	TF	0.31	1.86	0.13	0.50	151%
NAC	0.5786	No	TF	0.31	1.86	0.13	0.50	151%
NII	0.0722	No	TF	0.34	0.48	0.13	0.34	174%
LCOM_CK	0.2860	No	TF	13.40	61.08	2.13	5.26	531%

Table 6.25: Sorted Class Metrics for Combined SE Experiments

higher coupling (CBO, FO), be more complex (VG), and be less cohesive (LCOM). None of the differences are statistically significant.

6.4.2 Test Results

This section presents the test density and coverage measurements for the combined undergraduate and graduate software engineering experiments. Table 6.27 presents the testing metrics for the test-first and test-last projects.

Line coverage is significantly better in the test-first projects. All other test metrics are much better in the test-first projects than the test-last projects, although the differences are not all statistically significant. It is clear though that students in software engineering courses are much more likely to write more tests with better test coverage when using a test-first approach than when using a test-last approach.

6.5 Programming 1 Experiment

This section describes an experiment conducted in the Computer Programming 1 (CS1) course in Fall 2005 at the University of Kansas.

6.5.1 Experiment Design and Context

This section will repeat and expand the experiment design and context presented in section 4.2.5.

This experiment was designed to examine the ability of beginning programmers to adopt the test-first and test-last development approaches, and to determine if the approach used affects the quality of software produced at this level.

Figure 4.27 from Chapter 4 illustrates the experiment flow in the CS1 experiment. Because early projects were small and required very little design, this experiment was conducted in the last half of the CS1 course. After students had completed three projects and covered topics such as basic syntax, iteration control structures, elementary functions, and simple data structures such as arrays, the author presented a guest lecture. The lecture was presented with the test-driven learning approach in which automated unit testing using *assert* statements was introduced in the context of a lecture on functions. Although the TDL approach can be used throughout a course, it also seems reasonable to introduce tests when functions are introduced as they are the primary testable unit. The pre-experiment survey was administered at the end of the guest lecture.

The lecture was then followed by two labs developed by the author and taught by graduate teaching assistants. The first lab introduced automated unit testing in the context of writing simple functions. The second lab reinforced practice with automated unit tests in the context of writing recursive functions, using reference

Metric	p-value	Sig?	TF Mean	TF StdDev	TL Mean	TL StdDev	Higher Method	%diff
NSFavg	0.4226	No	0.00	0.00	0.52	0.91	TL	-100%
LOC/Mod	0.3762	No	47.11	27.08	83.28	53.86	TL	-43%
NOFavg	0.8360	No	1.83	2.36	2.18	1.27	TL	-16%
RMIavg	N/A	No	1.00	0.00	1.00	0.00	N/A	0%
CAavg	N/A	N/A	0.00	0.00	0.00	0.00	N/A	0%
NOAavg	N/A	N/A	0.00	0.00	0.00	0.00	N/A	0%
REU	N/A	N/A	0.00	0.00	0.00	0.00	N/A	0%
SPC	N/A	N/A	0.00	0.00	0.00	0.00	N/A	0%
PARavg	0.8858	No	1.07	0.39	1.02	0.48	TF	5%
FIavg	0.7427	No	1.57	0.45	1.46	0.26	TF	7%
NBDavg	0.8064	No	2.72	0.73	2.51	1.15	TF	8%
MLOCavg	0.8717	No	22.56	14.95	20.55	13.60	TF	10%
LCOMavg	0.8893	No	0.19	0.19	0.17	0.23	TF	15%
NOMavg	0.8064	No	3.75	2.88	3.08	3.36	TF	22%
CBOavg	0.2815	No	2.55	0.68	1.89	0.63	TF	35%
VGavg	0.5630	No	7.82	5.02	5.53	3.74	TF	41%
SIXavg	0.2189	No	0.01	0.01	0.00	0.00	TF	100%
DITavg	0.4226	No	0.01	0.02	0.00	0.00	TF	100%
NOCavg	0.4226	No	0.02	0.04	0.00	0.00	TF	100%
RMDavg	0.4226	No	0.03	0.04	0.00	0.00	TF	100%
RMAavg	0.4226	No	0.03	0.04	0.00	0.00	TF	100%
CEavg	0.4226	No	0.33	0.58	0.00	0.00	TF	100%
NOIavg	0.4226	No	0.33	0.58	0.00	0.00	TF	100%
FOavg	0.1164	No	0.98	0.25	0.43	0.39	TF	129%
VGmax	0.3991	No	45.33	46.00	17.00	11.79	TF	167%
IFavg	0.4042	No	24.12	39.28	0.33	0.58	TF	7137%

Table 6.26: Analysis of Project Metrics for Combined SE Experiments

	Line Coverage	Cond Coverage	#Asserts/ LOC	#Asserts/ Class	#Asserts/ Method
TF Mean	64%	49%	0.20	12.72	3.99
Std Dev	25%	32%	0.09	15.96	2.56
TL Mean	8%	5%	0.01	0.58	0.07
Std Dev	14%	9%	0.02	1.01	0.12
%difference	673%	847%	2080%	2080%	5886%
Higher Method	TF	TF	TF	TF	TF
p-value	0.0394	0.1372	0.0656	0.3183	0.1174
Significant?	Yes	No	No	No	No

Table 6.27: Test Metrics for Combined SE Experiments

parameters, and function overloading. The labs introduced the difference between test-first and test-last programming and gave students hands-on experience with both approaches. Although some TDD training occurred in the lecture prior to administering the survey, the figure shows the survey coming before the training since most of the training, particularly the hands-on training, occurred after the survey in the labs.

After completing the two labs, students were then asked to complete two programming projects. The first project (Project 4) required students to create a data structure for representing a three-dimensional point and create functions that operate on such points. Functions included adding, subtracting, multiplying, and dividing points, as well as functions to determine of two points were equal and to calculate the Euclidean distance and dot product of two points. Students had not been introduced to classes so they generally used an array-based data structure and global functions in their solutions. As a result object-oriented metrics are not valid and will not be reported for this project.

Students with student IDs ending in an even number were asked to complete the first project with a test-first approach and students with student IDs ending in an odd number were asked to complete the first project with a test-last approach.

The second project (Project 5) required students to create class-based data structures for representing points and polygons. A textual user interface was to allow users to specify a number of points in a polygon and the program was to calculate the perimeter and area of that polygon. Test-first/test-last assignments were switched on the second project so students with student IDs ending in an odd number were asked to complete the second project with a test-first approach and students with student IDs ending in an even number were asked to complete the second project with a test-last approach.

At the beginning of the second project, students were provided with a solution to the first project that included a full set of automated unit tests. The post-experiment survey was then administered in labs following the completion of the second project.

6.5.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level. Class-level metrics will only be reported for project 5 as discussed in the previous section.

Method-Level Metrics

Table 6.28 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in project 4. These metrics will all

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.2286	No	TF	20.19	36.56	17.83	25.02	13%
V(G)	0.6470	No	TF	2.83	4.26	2.71	3.69	4%
AHL	0.8311	No	TF	55.59	78.16	54.64	68.09	2%
VOC	0.7669	No	TF	19.00	14.81	18.75	12.78	1%
VOL	0.6573	No	TF	267.95	508.83	255.22	427.94	5%
PD	0.8628	No	TF	5.18	4.36	5.13	3.52	1%
EFF	0.3904	No	TF	3119.10	15692.34	2403.07	10474.24	30%
BUG	0.5351	No	TF	0.05	0.10	0.04	0.08	8%
MLOC	0.3942	No	TF	15.99	25.18	14.81	19.33	8%
NBD	0.4801	No	TF	0.48	1.55	0.42	1.38	15%
PAR	0.0117	Yes	TF	2.04	1.31	1.84	1.35	11%

Table 6.28: Analysis of Method Metrics for CS1 Experiment, Project 4

compare with the Java-based method metrics and represent primarily method size and complexity.

Figure 6.8 illustrates the differences in a radar chart. Each of the metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the degree and consistency by which the means of the test-last and test-first metrics varied.

This data implies and the radar chart illustrates that software developed with a test-first approach is slightly worse in most metrics than software developed with a test-last approach. Test-first code was slightly larger and more complex and predicted to take more effort. The differences were small and the number of parameters was the only metric with a statistically significant difference.

Table 6.29 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in project 5. Figure 6.9 illustrates the differences in a radar chart. Interestingly the test-first project methods look much better in this project. In fact, in eight of the eleven metrics the improvements over the test-last methods are statistically significant. This data implies that beginning programmers using the test-first approach produce methods with lower size and complexity in object-oriented projects than methods produced with the test-last approach. One must question what affect the order of treatments had on the programmers. This question will be revisited in the testing section a bit later.

Figure 6.8: CS1 Experiment Method Metrics Radar Chart, Project 4

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.0050	Yes	TL	3.87	9.01	5.03	12.87	-23%
V(G)	0.0032	Yes	TL	1.06	0.79	1.18	1.21	-10%
AHL	0.0093	Yes	TL	9.06	24.48	13.07	51.38	-31%
VOC	0.0161	Yes	TL	4.32	8.36	5.12	9.71	-16%
VOL	0.0099	Yes	TL	38.99	123.42	61.11	289.31	-36%
PD	0.0105	Yes	TL	1.14	2.86	1.45	3.64	-21%
EFF	0.1231	No	TL	345.23	2954.57	958.05	14001.03	-64%
BUG	0.0228	Yes	TL	0.01	0.03	0.01	0.07	-39%
MLOC	0.0062	Yes	TL	3.23	6.37	4.08	9.84	-21%
NBD	0.3250	No	TL	0.04	0.35	0.05	0.44	-28%
PAR	0.1823	No	TF	0.70	1.05	0.66	0.92	7%

Table 6.29: Analysis of Method Metrics for CS1 Experiment, Project 5

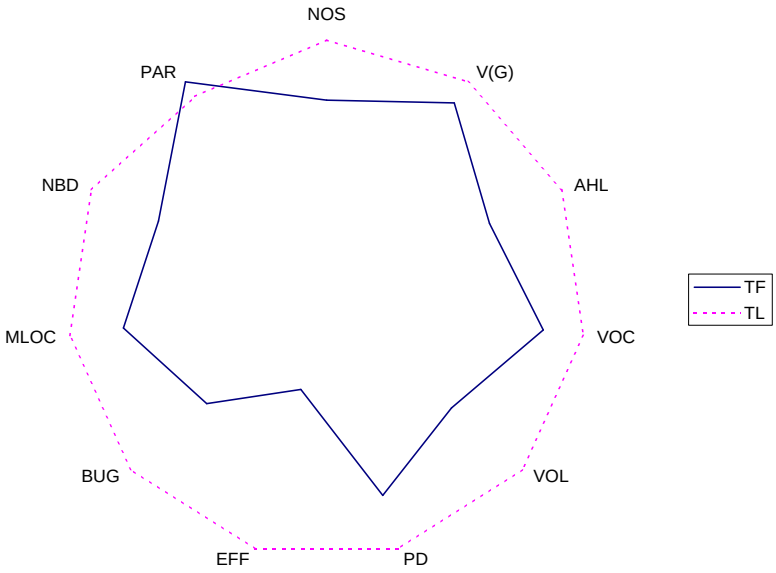

Figure 6.9: CS1 Experiment Method Metrics Radar Chart, Project 5

Class-Level Metrics

This section reports the class-level metrics analyzed for the second CS1 project (5). The first project is excluded because solutions were prescribed to be procedural and not use classes. The second project was the first one in which students used classes. This minimizes the relevance of these metrics, but they will be reported for completeness. Table 6.30 presents the class metrics in sorted order by % differences between test-first and test-last projects. Metrics with all zero values are omitted for space.

The data indicates that test-last projects tend to be larger (LOC, CSO) and more complex (WMC), but test-first projects tend to have more attributes (CSA) and parameters per method (NP). All differences are small and only the lines-of-code metric difference is statistically significant.

Project-Level Metrics

A small number of project-level metrics were collected and analyzed for the CS1 projects. Many of the project-level metrics are object-oriented metrics and Project 4 generally was not solved with objects and Project 5 had only one or two objects per solution. As a result these metrics are sparse. Table 6.31 and Table 6.32 present the project-level metrics for the two projects. Differences are small, but do follow the trend of switching from Project 4 to Project 5 along with the corresponding programmers as discussed earlier.

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
TLOC	0.1024	No	TL	18.87	11.10	24.10	27.26	-22%
LOC	0.0254	Yes	TL	16.61	4.48	19.13	9.42	-13%
Osavg	0.2924	No	TL	1.01	0.07	1.13	1.00	-10%
WMC	0.2573	No	TL	7.66	2.79	8.20	3.65	-7%
RFC	0.5605	No	TL	7.62	2.73	7.85	2.79	-3%
CSO	0.6427	No	TL	7.58	2.71	7.76	2.74	-2%
NOAC	0.6427	No	TL	7.58	2.71	7.76	2.74	-2%
PPPC	0.4407	No	TL	75.75	9.89	76.83	9.80	-1%
SLOC	0.7544	No	TL	14.78	3.19	14.91	3.06	-1%
CSAO	0.8268	No	TF	10.21	3.25	10.11	3.09	1%
NPavgC	0.3013	No	TF	0.85	0.62	0.78	0.35	9%
CSA	0.2164	No	TF	2.63	1.83	2.35	1.39	12%
NAAC	0.2164	No	TF	2.63	1.83	2.35	1.39	12%

Table 6.30: Sorted Class Metrics for CS1 Project 5

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
LOC/Mod	0.4071	No	TF	186.64	76.39	174.75	61.99	7%
VGavg	0.5269	No	TF	30.49	18.11	28.35	14.39	8%
MLOCavg			TF	20.46		18.06		13%

Table 6.31: Sorted Project Metrics for CS1 Project 4

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
MLOCavg			TL	4.41		5.62		-22%
VGavg	0.1746	No	TL	5.05	3.48	5.98	3.37	-16%
LOC/Mod	0.1299	No	TL	52.72	15.53	59.18	24.16	-11%
FIavg	0.8794	No	TL	0.46	0.51	0.48	0.52	-3%
IFavg	0.9928	No	TL	0.10	0.43	0.10	0.44	-1%
CBOavg	0.9604	No	TL	0.82	0.67	0.83	0.67	-1%
FOavg	0.8410	No	TF	0.36	0.22	0.35	0.23	3%

Table 6.32: Sorted Project Metrics for CS1 Project 5

6.5.3 Test Results

This section reports, compares, and describes the tests written by students in the CS1 projects. Students wrote automated unit tests as assert statements in a separate function. The number of assert statements written were counted and ratios were calculated for asserts per line-of-code, asserts per class, asserts per module, and asserts per method. The first project was generally solved with a procedural approach and the second project expected an object-oriented solution. Hence the object-oriented metrics were only calculated for the second project.

Many students commented out the assert statements before submitting their projects. Due to the large number of project submissions, it was impractical to reinstate and check all tests to see if they passed. As a result, no coverage or test success metrics were collected on the CS1 and CS2 projects. The assert counts included all assert statements, whether commented out or not, and were deemed a practical estimation of testing effort.

Table 6.33 reports the testing results for the CS1 projects 4 and 5. The test-first students wrote 52% more asserts in the first project. In the second project, the test-last programmers wrote 39% more asserts. Recall that in the first project, students with ID's ending in an even number were asked to use a test-first approach. Then in the second project students were asked to switch approaches. This data indicates that the same programmers wrote more tests in both projects regardless of the approach they used. Because there were no statistically significant differences in the two groups, one must question whether the first approach used somehow influenced the number of asserts written. Did this group write more asserts because they started out using the test-first approach? Did this approach somehow form a habit or appreciation for writing tests that persisted even when using a test-last approach? Additional studies could pursue these questions.

When the results from the two projects are combined, the test-first projects have a 163% higher #Asserts/Module value. This was the only statistically significant testing metric analyzed.

6.5.4 Productivity Results

This section reports, compares, and describes the volume of code produced and the amount of time students reported they spent on the projects. The test-first programmers on the first project reported spending 10% more time producing solutions that were 7% more lines of code than the test-last programmers. In the second project, the test-first programmers reported spending 11% more time producing solutions that were 11% smaller than the test-last solutions.

Recall the testing results from these two projects indicated that the test-first programmers wrote more tests on the first project and fewer tests on the second project. The test lines of code are included in the total lines of code comparisons

Metric	#Asserts	#Asserts/ LOC	#Asserts/ Module	#Asserts/ Class	#Asserts/ Method
	Project 4				
p-value	0.1109	0.2555	0.0870		
Significant?	No	No	No		
Higher Method	TF	TF	TF		
TF Mean	5.85	0.03	5.85		
Std Dev	6.68	0.03	6.68		
TL Mean	3.85	0.02	3.72		
Std Dev	5.28	0.03	5.06		
%difference	52%	35%	57%		
	Project 5				
p-value	0.1094	0.2489	0.1271	0.1025	0.1873
Significant?	No	No	No	No	No
Higher Method	TL	TL	TL	TL	TL
TF Mean	1.89	0.01	0.63	0.96	0.13
Std Dev	2.94	0.02	0.98	1.48	0.21
TL Mean	3.10	0.02	1.01	1.59	0.20
Std Dev	4.18	0.02	1.38	2.10	0.26
%difference	-39%	-28%	-38%	-39%	-32%

Table 6.33: CS1 Test Metrics

Project	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
Project 4	0.8516	No	TF	95.26	5.72	95.05	5.30	0%
Project 5	0.6645	No	TL	87.77	13.91	89.04	14.72	-1%

Table 6.34: CS1 Project Evaluations

	Quality	Changes	Reuse
p-value	0.0459	0.0242	0.0233
Significant?	Yes	Yes	Yes
Higher Method	TF	TF	TF
TF Mean	3.98	3.90	3.69
Std Dev	1.25	1.24	1.34
TL Mean	3.25	3.06	2.88
Std Dev	1.74	1.76	1.64
%difference	22%	27%	28%

Table 6.35: CS1 Programmer Opinions on Project 5

here. This could explain the differences in the size of the solutions. The time data seems to indicated that beginning test-first programmers take slightly more time completing their solutions than the test-last programmers.

6.5.5 Subjective and Evaluative Results

This section presents results on student project grades. Table 6.34 reports results from an analysis of the grades assigned to the two CS1 projects. Graduate teaching assistants assigned the scores based on a rubric provided by the professor. Component scores were not tracked. The data indicates virtually no differences between the test-first and test-last groups.

6.5.6 Programmer Perceptions

This section describes the results from the pre and post experiment surveys. Table 6.35 reports the statistically significant differences on project 5. The test-first programmers indicated that they were more confident that the code they wrote was correct (Quality), they were more confident that they could make changes to their code without breaking things (Changes), and they were more confident that they could reuse their code in a future project (Reuse). The differences on project 4 were not statistically significant.

Despite what may have been positive experiences with the test-first approach, Figure 6.10 illustrates from the post experiment survey that only 10% of the CS1

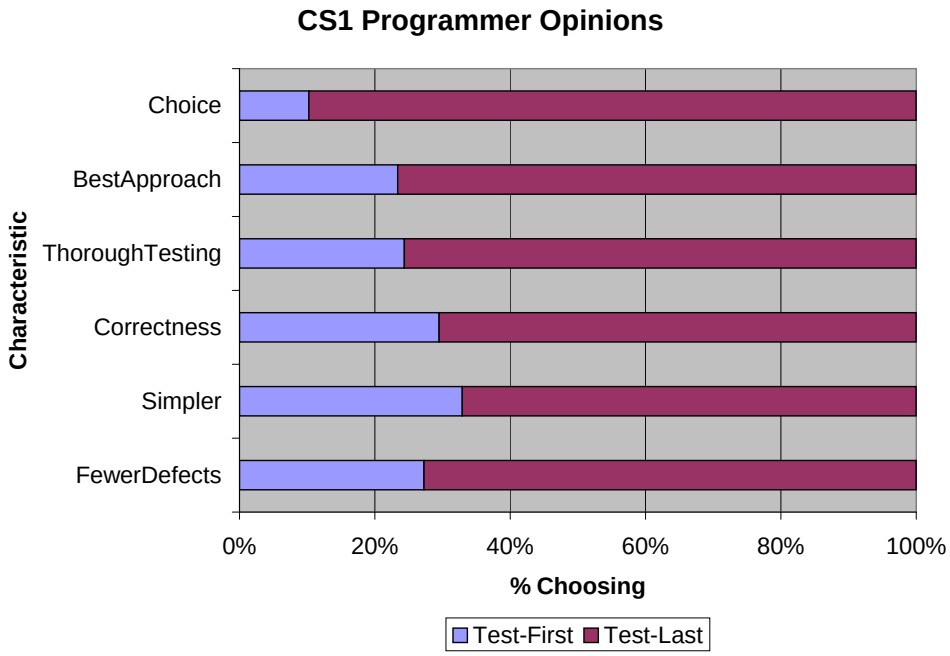

Figure 6.10: CS1 Programmer Opinions

programmers indicated that they would choose to use the test-first approach.

6.5.7 Longitudinal Results

This section describes the results from the longitudinal survey. Twenty-eight students completed the longitudinal survey in late Spring 2006. Ten of the twenty-eight (36%) reported using the test-first approach on a project where they had a choice. This number may be unusually high because many of these students participated in the CS2 experiment in Spring 2006. Twenty-one reported voluntarily using the test-last approach on a subsequent project. Only two students (7%) indicated that they would choose to use the test-first approach on future projects given the option. The data in this section has demonstrated that beginning programmers are clearly uneasy about adopting the test-first approach.

6.6 Programming 2 Experiments

This section presents results from the two experiments conducted in the Programming 2 (CS2) course at the University of Kansas in fall 2005 and spring 2006. Students in both experiments were allowed to self-select which approach (test-first or test-last) they used. Complete results will be presented for the fall 2005 experiment. However because only a very small number of students elected to use the

test-first approach in the second experiment, only partial results will be reported for the spring 2006 experiment.

6.6.1 Experiment Design and Context

This section will repeat and expand the experiment design and context presented in section 4.2.5.

This experiment was designed to examine the ability of immature programmers to adopt the test-first and test-last development approaches, and to determine if the approach used affects the quality of software produced at this level. The experiment was first conducted in Fall 2005 with thirty-six students. The experiment was then repeated in Spring 2006 with fifty-four students.

Figure 4.28 from Chapter 4 illustrates the experiment flow in the two CS2 experiments. Students were given a very brief (five minutes) introduction to test-first and test-last programming on the first day of the course, then given the pre-experiment survey. Students were introduced to automated unit testing using *assert* statements early in the semester in the third week lab. The lab presented examples and required hands-on exercises with automated tests using classes and simple and recursive functions. The lab presented both test-first and test-last approaches.

Students were then required to complete two programming projects. Students were asked to develop the projects with either a test-first or test-last approach. At the request of the course professor, students were allowed to self-select which approach they used. The following statement in the project description prescribes this requirement:

> You should develop this program in a ***test-first*** or a ***test-last*** manner as described in Lab 3. You may choose which approach you use, but use the approach throughout the development of the project. If you don't care which approach you use, choose test-first if your KUID starts with an even number and use test-last if your KUID starts with an odd number.

Table 6.36 reports the number of students electing to use each approach on the CS2 projects. The low test-first numbers reveal early programmer reluctance to adopt the test-first approach. The Spring 2006 test-first sample size is so low that many metrics from that experiment will not be considered. Many of the students in the Spring 2006 experiment participated in the Fall 2005 CS1 experiment. This aligns with the post experiment survey results from the CS1 experiment.

Each programming project was to be completed in two or three weeks. The first project in Fall 2005 required students to build an application that stored and manipulated a list of drivers with traffic citations. The application had a textual user interface that allowed the user to insert, delete, find, and print driver and citation information. The public interface for the main list data structure class (called

Approach	Fall 2005			Spring 2006		
	Project 1	Project 2	Project 3	Project 1	Project 2	Project 3
TF	6	6	4	1	3	2
TL	30	30	30	53	51	50

Table 6.36: Approach Selection in CS2 Projects

DriverTable) was prescribed in the project description. This class was specified to contain a statically allocated array for storing the driver and citation information. Although much of the interface for the one data structure class was specified, students were expected to design at least two other classes. The project description is provided in Appendix B.

The second project extended and modified the first project. The DriverTable class was to be modified internally to use a pointer-based linked list instead of an array-based list. The application was to allow multiple DriverTables and the class interface was modified slightly. Exceptions and some recursive functions were also added to the requirements. At the beginning of the second project, students were provided with a solution to the first project that included a full set of automated unit tests.

Students were asked to use a test-first or test-last approach in the remaining three projects of the semester. Software from these projects was also analyzed, but they were not originally a part of the experiment. At least two of these remaining projects had very procedural solutions (a grammar checker and an experimental profiler of sorting algorithms). Their design was more prescribed than the first two projects that were a part of the formal experiment.

The second CS2 experiment in Spring 2006 was designed to be similar to the first CS2 experiment that was conducted in Fall 2005. The Spring 2006 version required a set of two projects that were very similar to those in Fall 2005 but in a different domain (airline flights instead of traffic citations). In both experiments the post-experiment survey was administered after the completion of the third project.

6.6.2 Internal Quality Results

This section reports, compares, and describes the internal design quality metric results. The metrics are categorized at the method, class, and project level.

Method-Level Metrics

This section presents results of a method-level analysis on all six of the projects in the Fall 2005 and Spring 2006 CS2 experiments. The data for each project will be presented in a table and a radar chart as before. For the radar charts, each of the

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.0315	Yes	TF	8.33	24.30	4.98	17.15	67%
V(G)	0.1142	No	TF	1.30	2.09	1.08	1.74	20%
AHL	0.0577	No	TF	20.06	81.45	10.31	46.05	95%
VOC	0.0050	Yes	TF	6.05	13.28	3.61	11.13	67%
VOL	0.0903	No	TF	107.30	492.99	54.64	281.53	96%
PD	0.0258	Yes	TF	1.11	2.71	0.71	2.38	56%
EFF	0.1610	No	TF	1109.97	6893.39	507.66	3122.79	119%
BUG	0.0999	No	TF	0.01	0.06	0.01	0.04	81%
MLOC	0.0283	Yes	TF	7.13	21.22	4.16	14.31	72%
NBD	0.9598	No	TF	0.10	0.47	0.10	0.60	2%
PAR	0.7505	No	TF	0.69	0.97	0.67	1.02	3%

Table 6.37: Analysis of Method Metrics for CS2 Experiment, Project 1

metrics has been normalized by multiplying the metric mean for each group (test-first and test-last) by a normalizing factor. The normalizing factor is calculated by dividing the maximum mean of all metrics by the maximum mean of the two (test-first and test-last) groups for the metric being plotted. This chart demonstrates the degree and consistency by which the means of the test-last and test-first metrics varied. Some observations will be drawn at the end of the section.

Table 6.37 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in the Fall 2005 CS2 Project 1. Figure 6.11 illustrates the differences in a radar chart.

Table 6.38 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in the Fall 2005 CS2 Project 2. Figure 6.12 illustrates the differences in a radar chart.

Table 6.39 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in the Fall 2005 CS2 Project 3. Figure 6.13 illustrates the differences in a radar chart.

Table 6.40 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in the Spring 2006 CS2 Project 1. Figure 6.14 illustrates the differences in a radar chart.

Table 6.41 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in Spring 2006 CS2 Project 2. Figure 6.15 illustrates the differences in a radar chart.

Table 6.42 presents the results of the statistical analysis of the method-level metrics comparing the test-first and test-last methods in Spring 2006 CS2 Project 3. Figure 6.16 illustrates the differences in a radar chart.

The sequence of six radar charts are surprisingly consistent. The methods from the test-first projects tend to have better results for nearly all metrics and many of

Figure 6.11: CS2 Experiment Method Metrics Radar Chart, Project 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.0357	Yes	TF	8.97	25.10	6.05	20.87	48%
V(G)	0.0331	Yes	TF	1.39	1.58	1.20	1.80	16%
AHL	0.1330	No	TF	19.77	81.45	13.00	66.72	52%
VOC	0.0003	Yes	TF	7.55	13.11	4.88	12.34	55%
VOL	0.2615	No	TF	100.94	508.18	69.05	455.92	46%
PD	0.0015	Yes	TF	1.59	3.50	0.98	2.58	62%
EFF	0.5108	No	TF	1618.94	20765.41	876.86	14601.69	85%
BUG	0.2354	No	TF	0.02	0.10	0.01	0.07	63%
MLOC	0.0466	Yes	TF	7.83	22.81	5.32	18.63	47%
NBD	0.0433	Yes	TF	0.16	0.47	0.10	0.56	53%
PAR	0.8269	No	TF	0.79	1.06	0.78	1.03	2%

Table 6.38: Analysis of Method Metrics for CS2 Experiment, Project 2

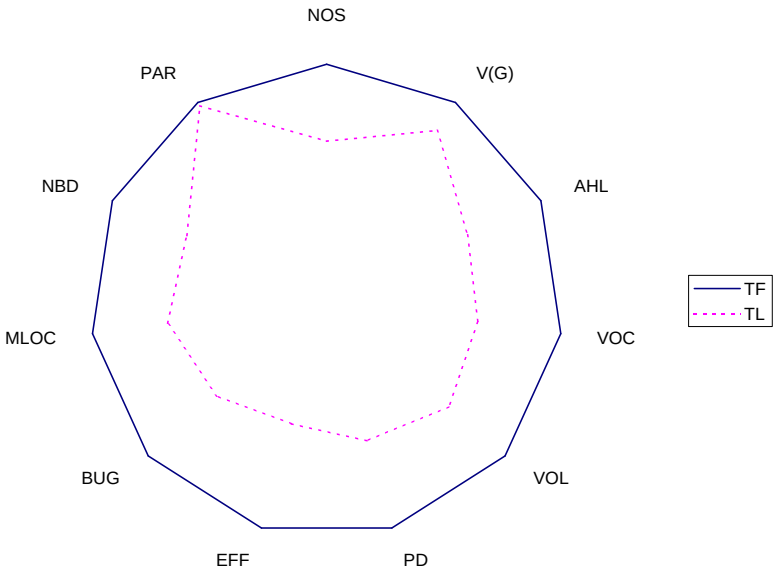

Figure 6.12: CS2 Experiment Method Metrics Radar Chart, Project 2

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.2249	No	TF	7.02	14.01	4.35	13.94	62%
V(G)	0.2687	No	TF	1.13	1.26	0.91	1.09	24%
AHL	0.1247	No	TF	15.61	34.23	7.42	28.70	110%
VOC	0.0351	Yes	TF	6.78	12.92	2.59	6.39	162%
VOL	0.1057	No	TF	76.37	188.08	29.66	117.04	158%
PD	0.2043	No	TF	1.42	2.83	0.85	3.06	67%
EFF	0.4555	No	TF	400.84	921.35	275.90	1927.71	45%
BUG	0.1508	No	TF	0.01	0.02	0.01	0.02	88%
MLOC	0.2279	No	TF	5.93	11.02	3.80	13.18	56%
NBD	0.1857	No	TF	0.26	0.68	0.12	0.40	111%
PAR	0.8115	No	TL	0.41	0.54	0.43	0.55	-5%

Table 6.39: Analysis of Method Metrics for CS2 Experiment, Project 3

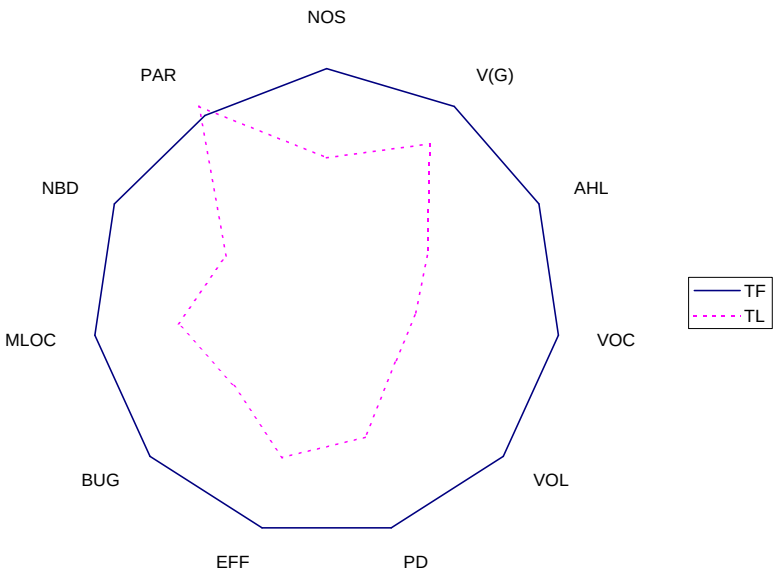

Figure 6.13: CS2 Experiment Method Metrics Radar Chart, Project 3

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.0011	Yes	TF	16.52	17.27	5.33	15.15	210%
V(G)	0.0450	Yes	TF	2.45	3.08	1.29	1.82	89%
AHL	0.0283	Yes	TF	22.52	30.29	9.91	32.43	127%
VOC	0.0024	Yes	TF	12.16	12.80	4.51	10.72	170%
VOL	0.1099	No	TF	100.36	175.66	48.08	192.04	109%
PD	0.0139	Yes	TF	3.08	4.21	1.10	3.05	180%
EFF	0.2752	No	TF	758.65	1674.30	418.57	3069.13	81%
BUG	0.0725	No	TF	0.02	0.03	0.01	0.03	129%
MLOC	0.0086	Yes	TF	10.68	12.63	4.27	11.66	150%
NBD	0.3013	No	TF	0.35	0.88	0.19	0.88	89%
PAR	0.3526	No	TF	0.97	1.11	0.78	1.13	24%

Table 6.40: Analysis of Method Metrics for Spring CS2 Experiment, Project 1

Figure 6.14: Spring CS2 Experiment Method Metrics Radar Chart, Project 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.0000	Yes	TF	12.99	20.80	4.19	16.99	210%
V(G)	0.0000	Yes	TF	1.43	1.47	0.93	1.05	54%
AHL	0.0063	Yes	TF	15.59	36.50	8.15	41.00	91%
VOC	0.0000	Yes	TF	7.83	11.85	3.16	10.36	148%
VOL	0.0708	No	TF	72.17	218.30	42.77	259.21	69%
PD	0.0000	Yes	TF	1.45	2.41	0.57	1.88	156%
EFF	0.7828	No	TF	440.63	2177.37	394.32	3803.64	12%
BUG	0.0517	No	TF	0.01	0.03	0.01	0.04	71%
MLOC	0.0000	Yes	TF	7.30	12.66	3.36	12.83	117%
NBD	0.0517	No	TF	0.12	0.42	0.06	0.40	105%
PAR	0.0310	Yes	TF	0.74	0.99	0.59	0.93	27%

Table 6.41: Analysis of Method Metrics for Spring CS2 Experiment, Project 2

Figure 6.15: Spring CS2 Experiment Method Metrics Radar Chart, Project 2

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
NOS	0.0071	Yes	TF	14.42	20.16	6.91	17.20	109%
V(G)	0.0125	Yes	TF	3.26	5.30	1.45	2.29	125%
AHL	0.0091	Yes	TF	36.75	66.45	12.88	40.06	185%
VOC	0.0005	Yes	TF	14.74	18.99	5.40	11.65	173%
VOL	0.0184	Yes	TF	193.15	400.70	63.91	228.84	202%
PD	0.0086	Yes	TF	3.48	5.55	1.47	4.09	137%
EFF	0.1098	No	TF	2493.45	7435.03	885.02	5442.03	182%
BUG	0.0410	Yes	TF	0.04	0.08	0.01	0.05	170%
MLOC	0.0023	Yes	TF	13.51	18.02	5.83	14.47	132%
NBD	0.0963	No	TF	0.60	1.46	0.27	1.13	123%
PAR	0.4830	No	TF	0.68	0.81	0.61	0.72	12%

Table 6.42: Analysis of Method Metrics for Spring CS2 Experiment, Project 3

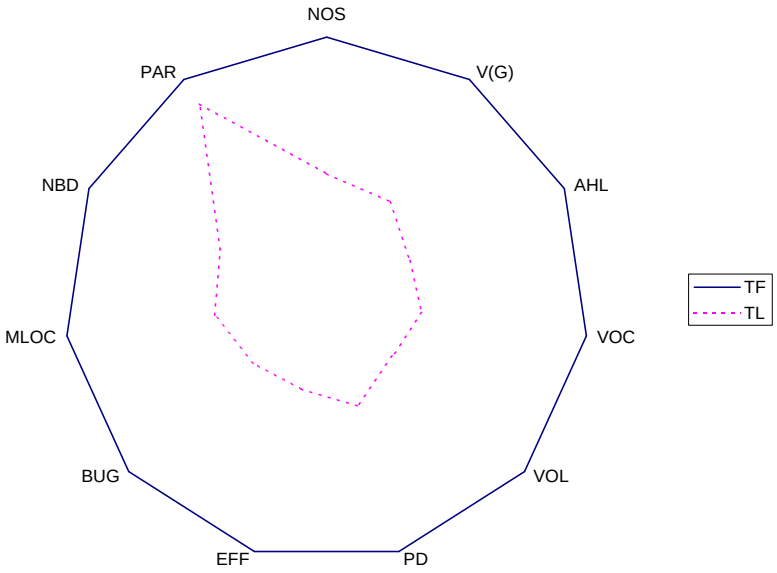

Figure 6.16: Spring CS2 Experiment Method Metrics Radar Chart, Project 3

the differences are statistically significant. In particular it appears that the test-first methods are smaller (MLOC, NOS) and less complex (V(G), VOC, AHL, NBD) than the test-last methods. Also the test-first methods tend to have similar and sometimes higher numbers of parameters (PAR) than the test-last methods.

Class-Level Metrics

This section reports the class-level metrics analyzed for the first two CS2 projects from the Fall 2005. The third project is excluded because it was primarily solved in a procedural fashion with few projects implementing classes. All three Spring 2006 experiment projects are excluded because there were so few programmers who chose to use a test-first approach. Table 6.43 and Table 6.44 present the class metrics in sorted order by % differences between test-first and test-last projects for these two projects. Metrics with all zero values are omitted for space.

The data indicates that the test-first programmers at this level may be more likely to produce larger solutions (TLOC) that are more complex (WMC), are less cohesive (LCOM), and have higher coupling (RFC).

Project-Level Metrics

Table 6.45, Table 6.46, and Table 6.47 present the project-level metrics for the three Fall 2005 CS2 projects. Because of the small test-first sample size, the Spring 2006 CS2 projects are not reported. The object-oriented metrics in Project 3 should not be given much weight because a majority of the solutions were implemented procedurally.

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	0.4197	No	TL	0.00	0.00	0.03	0.16	-100%
NAIC	0.5567	No	TL	0.00	0.00	0.11	0.65	-100%
NOCC	0.5567	No	TL	0.00	0.00	0.03	0.16	-100%
NOIC	0.8432	No	TL	0.00	0.00	0.27	1.63	-100%
PPPC	0.2572	No	TL	64.80	24.29	71.72	13.29	-10%
NPavgC	0.4448	No	TL	0.90	0.32	0.97	0.43	-8%
CSO	0.9193	No	TL	9.22	2.98	9.64	3.78	-4%
NOAC	0.7390	No	TL	9.22	2.98	9.64	3.78	-4%
CSAO	0.4917	No	TL	12.33	3.31	12.55	4.23	-2%
SLOC	0.8416	No	TL	17.33	3.31	17.52	4.34	-1%
LCOM	0.5546	No	TF	0.83	2.87	0.80	3.95	4%
CSA	0.9101	No	TF	3.11	1.60	2.91	1.56	7%
NAAC	0.9258	No	TF	3.11	1.60	2.91	1.56	7%
RFC	0.2989	No	TF	12.17	4.25	10.99	4.22	11%
Osavg	0.6567	No	TF	2.01	1.57	1.82	2.04	11%
WMC	0.1680	No	TF	15.17	7.47	12.41	7.03	22%
LOC	0.0948	No	TF	39.78	23.16	27.56	19.69	44%
TLOC	0.0258	Yes	TF	101.83	75.59	56.12	60.96	81%

Table 6.43: Sorted Class Metrics for Fall 2005 CS2 Project 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DIT	0.3190	No	TL	0.00	0.00	0.01	0.08	-100%
NAIC	0.3190	No	TL	0.00	0.00	0.01	0.17	-100%
NOCC	0.3190	No	TL	0.00	0.00	0.01	0.08	-100%
NOIC	0.3190	No	TL	0.00	0.00	0.06	0.75	-100%
PA	0.0024	Yes	TL	0.00	0.00	0.06	0.24	-100%
NPavgC	0.1254	No	TL	0.69	0.49	0.84	0.46	-18%
PPPC	0.1999	No	TL	56.21	36.42	65.32	32.96	-14%
CSA	0.8603	No	TL	2.13	2.20	2.20	2.26	-3%
NAAC	0.8603	No	TL	2.13	2.20	2.20	2.26	-3%
Osavg	0.9421	No	TL	1.23	0.95	1.25	1.61	-1%
SLOC	0.9828	No	TF	15.97	10.73	15.92	10.16	0%
CSAO	0.7626	No	TF	9.84	8.15	9.36	8.02	5%
CSO	0.6682	No	TF	7.72	6.65	7.16	6.54	8%
NOAC	0.6682	No	TF	7.72	6.65	7.16	6.54	8%
RFC	0.3004	No	TF	11.25	11.49	8.95	9.91	26%
LOC	0.1951	No	TF	33.81	31.53	25.93	26.14	30%
WMC	0.2821	No	TF	12.69	14.59	9.69	11.50	31%
LCOM	0.7651	No	TF	0.47	2.17	0.34	2.26	38%
TLOC	0.0840	No	TF	95.00	125.10	53.64	88.42	77%

Table 6.44: Sorted Class Metrics for Fall 2005 CS2 Project 2

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DITavg	0.1694	No	TL	0.00	0.00	0.03	0.11	-100%
NOCavg	0.1694	No	TL	0.00	0.00	0.03	0.11	-100%
VGavg	0.8840	No	TF	8.76	3.76	8.50	4.07	3%
FIavg	0.2374	No	TF	1.94	0.49	1.65	0.61	18%
LOC/Mod	0.4664	No	TF	72.23	33.67	61.09	21.71	18%
CBOavg	0.0926	No	TF	2.76	0.60	2.23	0.75	24%
FOavg	0.0532	No	TF	0.81	0.23	0.57	0.17	42%
MLOCavg			TF	10.57		6.78		56%
IFavg	0.1224	No	TF	2.98	2.43	1.12	1.29	165%

Table 6.45: Sorted Project Metrics for Fall 2005 CS2 Project 1

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
VGavg	0.2936	No	TL	5.97	3.02	7.54	3.58	-21%
LOC/Mod	0.7622	No	TL	58.31	26.22	61.84	17.10	-6%
FIavg	0.2500	No	TF	1.57	0.26	1.41	0.46	11%
CBOavg	0.0776	No	TF	2.25	0.29	1.95	0.56	15%
FOavg	0.0060	Yes	TF	0.68	0.07	0.54	0.18	25%
MLOCavg			TF	10.97		7.97		38%
DITavg	0.2579	No	TF	0.25	0.14	0.16	0.20	49%
NOCavg	0.2579	No	TF	0.25	0.14	0.16	0.20	49%
IFavg	0.1700	No	TF	1.68	1.20	0.87	1.01	93%

Table 6.46: Sorted Project Metrics for Fall 2005 CS2 Project 2

The data suggests that the test-first projects may have larger (LOC/Mod, MLOC) solutions with higher coupling (CBO, FO, IF). The test-last solutions may be slightly more complex (VG). Only the fan-out difference on Project 2 is significant.

6.6.3 Test Results

This section reports, compares, and describes the tests written by students in the CS2 projects. Similar to the CS1 experiment, students wrote automated unit tests as assert statements in a separate function. The number of assert statements written were counted and ratios were calculated for asserts per line-of-code, asserts per class, asserts per module, and asserts per method.

Many students commented out the assert statements before submitting their projects. Due to the large number of project submissions, it was impractical to reinstate and check all tests to see if they passed. As a result, no coverage or test

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
DITavg	0.3253	No	TL	0.00	0.00	0.02	0.09	-100%
NOCavg	0.3253	No	TL	0.00	0.00	0.02	0.09	-100%
FOavg	0.0831	No	TL	0.00	0.00	0.05	0.15	-100%
IFavg	0.1607	No	TL	0.00	0.00	0.03	0.12	-100%
VGavg	0.5645	No	TL	8.50	2.19	9.26	3.19	-8%
CBOavg	0.1708	No	TL	1.00	0.00	1.06	0.25	-6%
FIavg	0.5309	No	TL	1.00	0.00	1.01	0.12	-1%
LOC/Mod	0.4532	No	TF	40.92	9.11	36.72	13.37	11%
MLOCavg			TF	10.42		6.98		49%

Table 6.47: Sorted Project Metrics for Fall 2005 CS2 Project 3

Metric	#Asserts	#Asserts/ LOC	#Asserts/ Module	#Asserts/ Class	#Asserts/ Method
p-value	0.02456	0.0059	0.0263	0.0185	0.0145
Significant?	Yes	Yes	Yes	Yes	Yes
Higher Method	TF	TF	TF	TF	TF
TF Mean	34.00	0.06	4.72	9.13	1.29
Std Dev	43.14	0.06	6.15	11.44	1.46
TL Mean	11.61	0.02	1.58	2.87	0.45
Std Dev	17.80	0.03	2.48	5.03	0.88
%difference	193%	168%	200%	218%	186%

Table 6.48: CS2 Test Metrics

success metrics were collected on the CS1 and CS2 projects. The assert counts included all assert statements, whether commented out or not, and were deemed a practical estimation of testing effort.

Table 6.48 reports the aggregate testing results for all the CS2 projects. Individual results from each project are not reported to save space. The results provide strong support for the claim that test-first programmers write more tests, even at an early level. All results were significant.

6.6.4 Productivity Results

This section reports, compares, and describes the volume of code produced and the amount of time students reported they spent on the projects. The test-first programmers reported spending 13% less time producing solutions that were 12% larger in lines of code than the test-last programmers on all of the CS2 projects. Recall that the lines of code includes test lines of code and the previous section

Metric	p-value	Sig?	Higher Method	TF Mean	TF SDev	TL Mean	TL SDev	%diff
Project 1								
Score	0.0938	No	TF	88.83	8.95	79.47	21.01	12%
Correctness	0.4730	No	TF	40.50	8.38	37.23	15.30	9%
Style	0.0259	Yes	TF	28.33	2.34	24.67	6.63	15%
Output Format	0.0246	Yes	TF	10.00	0.00	8.63	3.16	16%
Error Checking	0.0136	Yes	TF	10.00	0.00	9.00	2.08	11%
Project 2								
Score	0.0435	Yes	TF	90.17	15.45	72.83	21.60	24%
Correctness	0.0110	Yes	TF	43.50	9.46	28.80	16.60	51%
Style	0.9037	No	TL	28.33	2.34	28.47	2.61	0%
Output Format	0.4592	No	TF	8.33	4.08	6.90	4.20	21%
Error Checking	0.0434	Yes	TF	10.00	0.00	8.67	3.46	15%
Project 3								
Score	0.5554	No	TF	92.75	8.54	89.77	10.26	3%
Correctness	0.4746	No	TF	59.25	7.68	55.94	10.18	6%
Style	0.7518	No	TL	28.50	1.91	28.84	1.34	-1%
Output Format	No			5.00	0.00	5.00	0.00	0%

Table 6.49: CS2 Project Evaluations

revealed that the test-first programmers wrote significantly more tests than the test-last programmers. The differences are not statistically significant, but this data leads one to believe that test-first programmers in CS2 may be more productive than test-last programmers.

6.6.5 Subjective and Evaluative Results

This section presents results on student project grades. Table 6.49 reports results from an analysis of the grades assigned to the three Fall 2005 CS2 projects. The Spring 2006 CS2 projects are ignored due to the small test-first sample size. Graduate teaching assistants assigned the scores based on a mutually agreed upon rubric. The total score (Score) is presented along with component scores that account for proper working of the software (Correctness), good internal design and programming style (Style), adherence to requirements in input/output (Output Format), and robust detection and handling of error conditions (Error Checking).

The data indicates that the test-first projects were deemed superior to the test-last projects in several categories in Project 1 and 2. Several of these differences are significant.

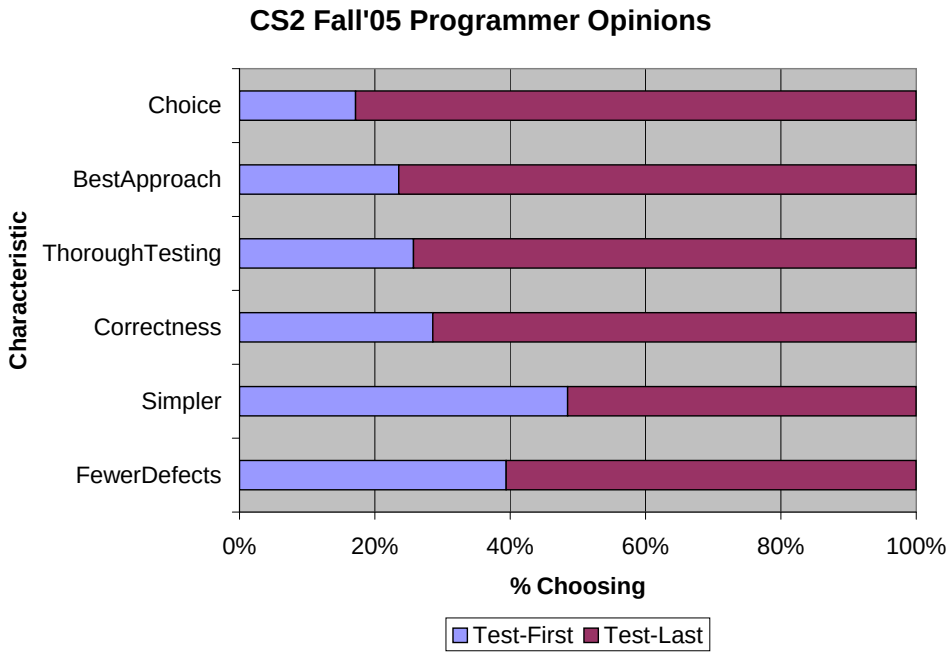

Figure 6.17: CS2 Fall 2005 Programmer Opinions

6.6.6 Programmer Perceptions

This section describes the results from the pre and post experiment surveys. Figure 6.17 illustrates programmer opinions from the Fall 2005 post experiment survey and Figure 6.18 illustrates programmer opinions from the Spring 2006 post-experiment survey. These charts coincide with the CS1 results and indicated that beginning programmers prefer the test-last approach. There were no statistically significant differences in programmer confidence between the students who used the test-first and test-last approaches.

6.6.7 Longitudinal Results

A longitudinal survey was administered in late Spring 2006 for the Fall 2005 CS2 experiment. Twelve students completed the survey. Fifty percent reported using a test-first approach on at least one subsequent project, and seventy percent reported using a test-last approach when given the choice. Three of the twelve (25%) indicated that they would choose the test-first approach if given the option on future projects.

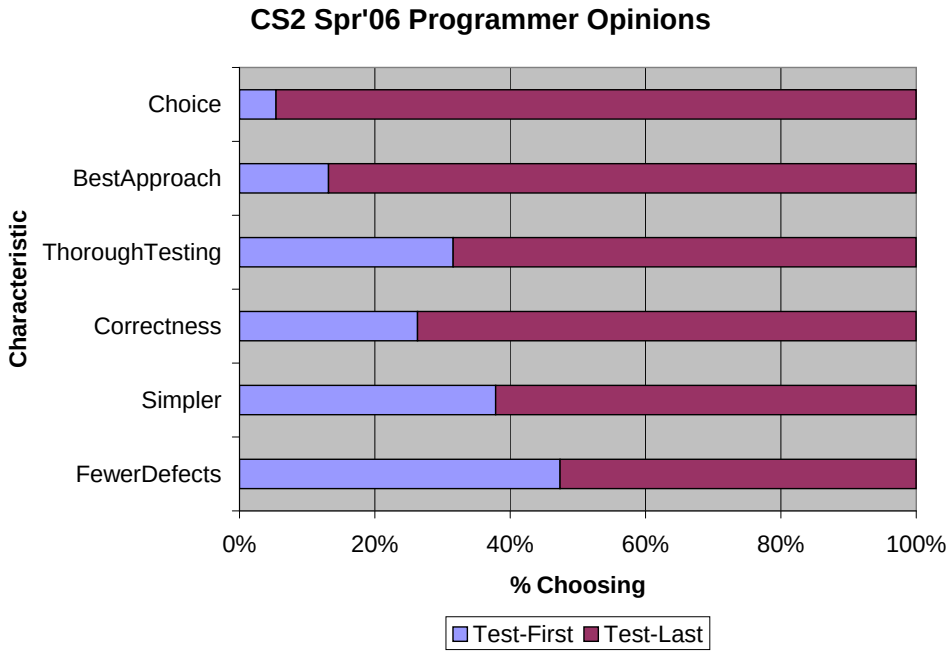

Figure 6.18: CS2 Spring 2006 Programmer Opinions

Chapter 7

Evaluation, Observation, and Discussion

This final chapter will summarize and evaluate the results of this research. Observations will be drawn and possible conclusions will be proposed. Future work will also be identified.

This research makes several substantial contributions. Foremost is the empirical evidence regarding the effects of test-driven development on internal software quality. Section 7.1 will summarize this evidence and categorize it in terms of the desirable quality attributes identified in Chapter 4. This evidence provides compelling motivation to adopt TDD in order to reduce code size and complexity, and increase programmer testing and testability. The evidence also raises interesting questions about how TDD affects coupling, cohesion, and reusability.

Section 7.2 discusses the external validity of the empirical results and reviews the significant impact that this research has already made. Peer-reviewed publications and conference presentations, awards and grants received, and external academic and industry presentations will be reviewed.

Several additional contributions result from this research and are discussed in Section 7.3. The research is the first significant examination of the effects of TDD on internal software quality. As such, it establishes a benchmark to be reviewed and evaluated. This work provides a framework for conducting replicated studies in similar and diverse environments that will reinforce and enlighten these results. In addition, this work contributes a novel approach to teaching computer science and software engineering that has already received an enthusiastic response in some circles.

Finally, the last section will summarize this work and propose future directions for related research.

7.1 Empirical Evidence of TDD Efficacy

The primary contribution of this research is the empirical evidence of the effects that applying TDD has on internal software quality. Chapter 5 and 6 presented a

large volume of empirical data along with some analysis. This section will summarize this data and revisit the initial hypotheses. Data will be grouped and visualized with bar charts to accommodate drawing conclusions. In the charts, bars to the right of zero indicate that the test-first project had the higher values. Bars to the left of zero indicate that the test-last project had the higher values. The longer the bar, the larger the difference between the test-first and test-last projects on that particular metric. The reader will need to pay particular attention to whether larger values are desirable or not. For instance with testing coverage, larger values are more desirable. However with complexity metrics, smaller values are generally more desirable.

The first section will focus on the significant improvements that the test-first approach has on software testing. The following sections will consider complexity, coupling, cohesion, and size metrics, then combine them to examine the effects of TDD on the four desirable software characteristics of understandability, maintainability, reusability, and testability. Finally the last section will address the qualitative evidence in programmer attitudes as collected through the experiment surveys.

7.1.1 Quantitative Evidence: Testing

Figure 7.1 displays the % differences in testing metrics between the test-first and test-last projects for the industry and academic software engineering course experiments and case study. In all of the testing metrics, higher values are generally more desirable.

This figure demonstrates how test-first programmers consistently wrote more tests with higher test coverage. Many of these differences were statistically significant including line coverage (Combined SE experiment, industry case study), conditional/branch coverage (industry case study), and Test to Source (T/S) Ratio (industry case study).

Figure 7.2 displays the % differences in testing metrics between the test-first and test-last projects for the beginning academic course experiments. In the first CS1 project, the test-first programmers wrote substantially more tests than the test-last programmers. However, in the second project when the programmers all switched from a test-first to a test-last approach, they still wrote substantially more tests. Similar results were observed in an industry experiment. As discussed in section 5.4, when the same professional developers completed a test-last project *after* having completed a test-first project earlier, their test volume and test-coverage stayed high, nearing the levels achieved on the test-first project.

In the Fall CS2 projects, the test-first programmers continued to use the test-first approach for all three projects and they consistently wrote more tests than the test-last programmers. In the Spring CS2 project, however, only one programmer claimed to use the test-first approach on the first project, but no tests were found in their project. As a result the chart displays that the test-last programmers wrote

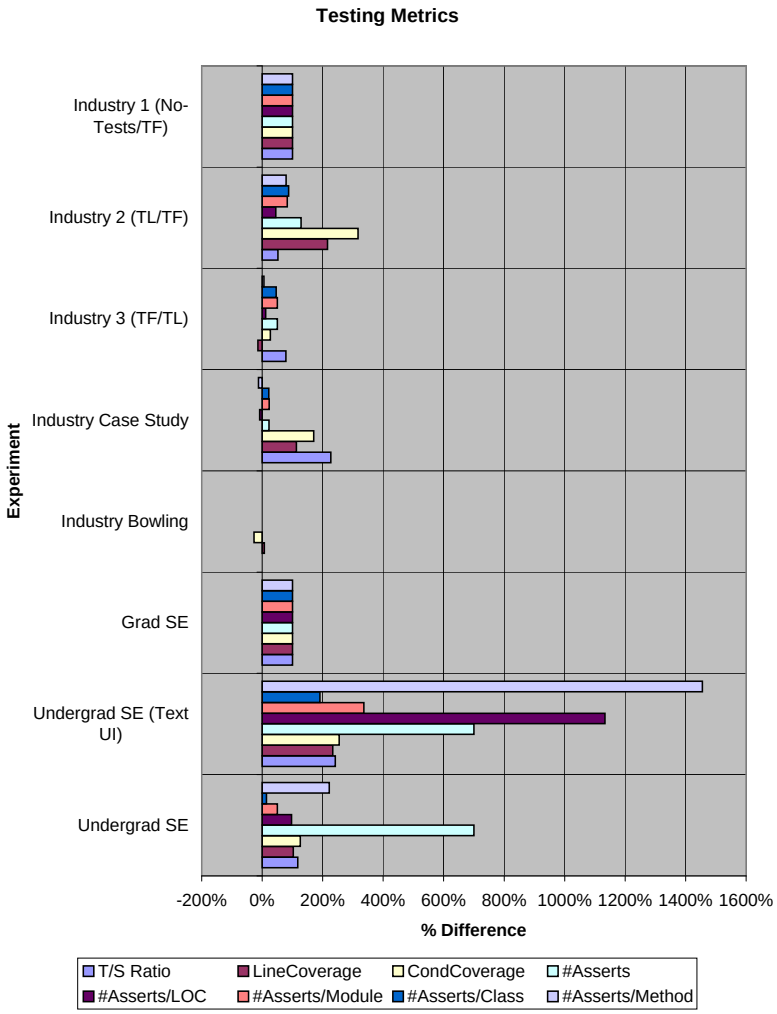

Figure 7.1: % Differences in Testing (Mature Developers)

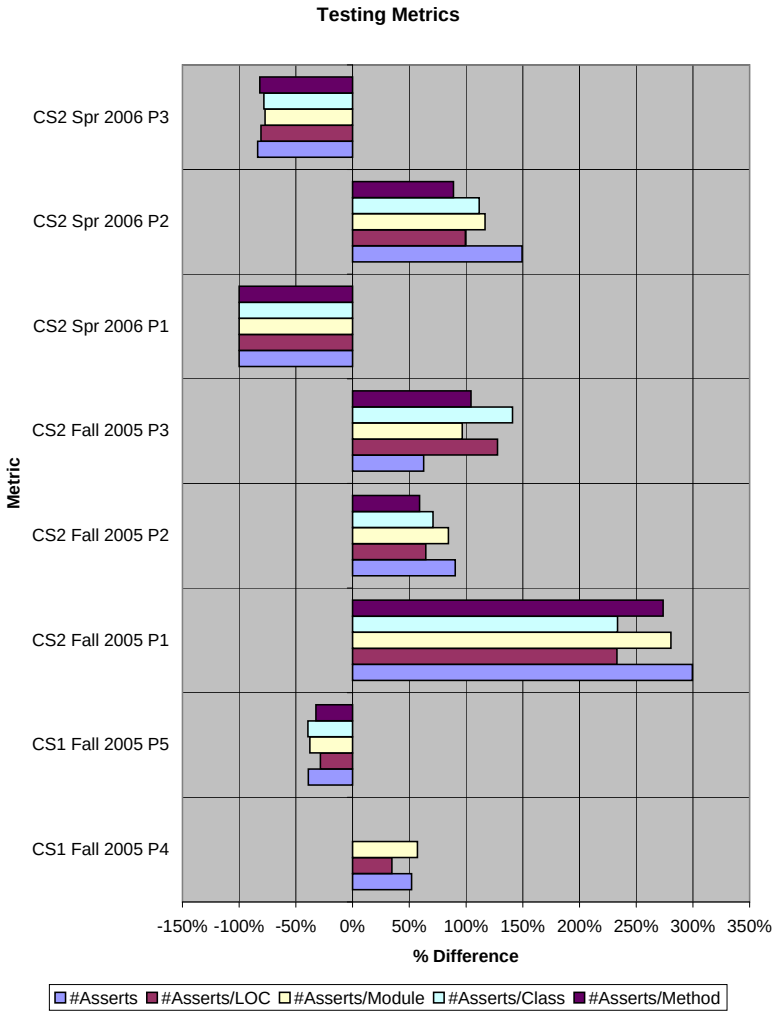

Figure 7.2: % Differences in Testing (Beginning Developers)

more tests. However, in the second project three developers used the test-first approach and wrote on average more tests than the test-last programmers. In the third project, two developers reported using the test-first approach and they wrote on average fewer tests than the test-last programmers.

Due to the small number of test-first programmers in the Spring CS2 experiment, and the discrepancy of no tests in the first test-first project, the validity of the results from the Spring CS2 experiment is questionable.

This data supports the rejection of the **T1** and **T2** hypotheses in Table 4.1. Programmers consistently wrote a higher volume of tests with higher test coverage with the test-first approach. Although not all differences were statistically significant, enough were to give strong support to this conclusion.

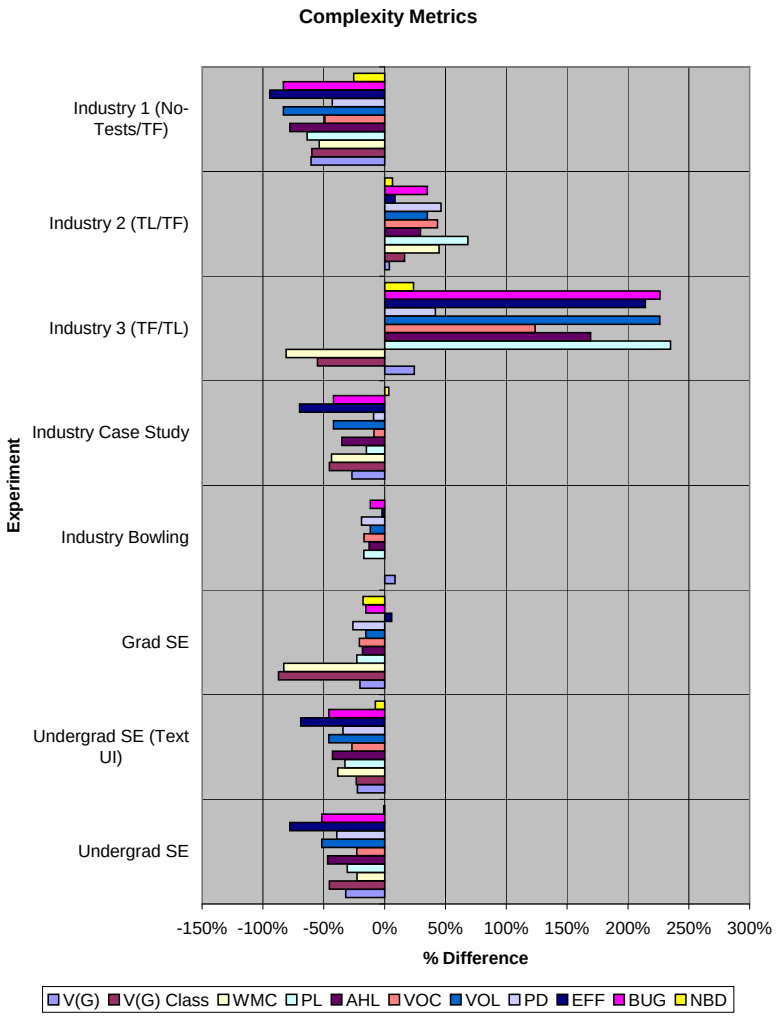

Figure 7.3: % Differences in Complexity (Mature Developers)

7.1.2 Quantitative Evidence: Complexity

Figure 7.3 displays the % differences in complexity metrics between the test-first and test-last projects for the industry and academic software engineering course experiments and case study. Figure 7.4 displays the % differences in complexity metrics between the test-first and test-last projects for the beginning academic course experiments. In all of the complexity metrics, lower values are generally more desirable.

The complexity figures tell an interesting story. It appears that beginning developers tend to write more complex software when using the test-first approach with one exception. However more mature developers tend to write more complex code with the test-last approach with two exceptions.

Two of the three exceptions noted might be explained by the observations from

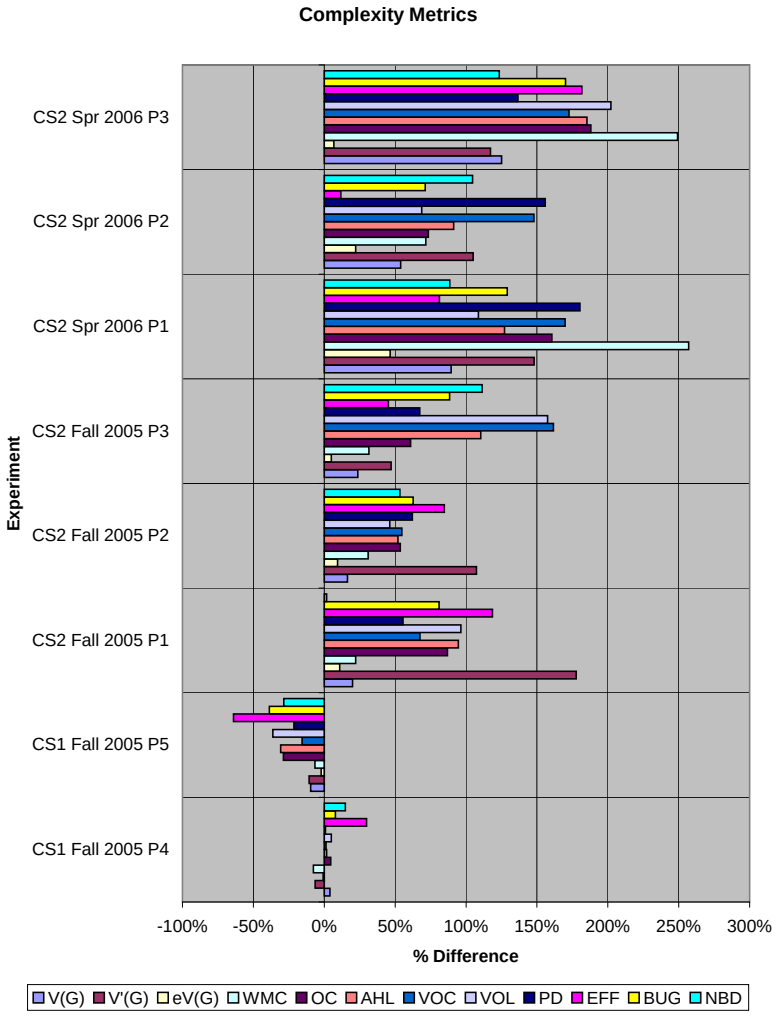

Figure 7.4: % Differences in Complexity (Beginning Developers)

Experiment	V(G)	V(G) Cls	WMC	PL	AHL	VOC	VOL	PD	EFF	BUG	NBD
UGrad SE	Y			Y	Y	Y	Y	Y	Y	Y	
UGrad SE (TUI)					Y	Y	Y	Y	Y	Y	
Grad SE	Y			Y	Y	Y					
Ind Bowling											
Ind CS	Y		Y		Y		Y		Y	Y	
Ind 3 (TF/TL)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Ind 2 (TL/TF)						Y		Y			
Ind 1 (NT/TF)	Y			Y	Y	Y	Y	Y	Y	Y	Y

Table 7.1: Complexity Metrics w/Statistically Significant Differences (Mature Developers)

Chapter 5 and Chapter 6. There we noted that many metrics switched/improved when programmers used the test-last approach *after* having completed a project with the test-first approach. The second CS1 project and the industry experiment 3 both involved teams applying the test-last approach after having recently completed a project with the test-first approach. In the second CS1 project the test-last developers (who previously used the test-first approach) produced more complex code. In the industry experiment 3 the test-first approach produced higher values on the method-level complexity measures, but the test-last approach produced higher values on the class-level complexity measures. Perhaps the influence of experience with the test-first approach provides a residual effect that extends through future projects.

The remaining exception is in the industry experiment 2 where the test-first approach produced code that was generally more complex. The likely difference here is that the two projects are of differing types. The test-last project was a utility project with library code available for many projects. The test-first project was a complete web application.

If these exceptions are ignored or if the explanations provided are valid, then the conclusions are that beginning developers tend to write more complex code with the test-first approach and more mature developers tend to write less complex code with the test-first approach. Many of these differences were statistically significant. Figure 7.1 and Figure 7.2 report which differences were statistically significant at $p < .05$. A 'Y' in a cell indicates that the metric was significant for that experiment. None of the experiments in Figure 7.2 had statistically significant differences for the WMC and EFF metrics so they are omitted for formatting. Although not conclusive, this data supports the possible rejection of the **Q1** hypothesis for mature developers.

Experiment	V(G)	V'(G)	eV(G)	OC	AHL	VOC	VOL	PD	BUG	NBD
CS1 F05 P4										
CS1 F05 P5	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CS2 F05 P1			Y			Y		Y		
CS2 F05 P2	Y		Y			Y		Y		Y
CS2 F05 P3						Y				
CS2 S06 P1	Y	Y	Y	Y	Y	Y		Y		
CS2 S06 P2	Y	Y	Y	Y	Y	Y		Y		
CS2 S06 P3	Y	Y		Y		Y	Y	Y	Y	

Table 7.2: Complexity Metrics w/Statistically Significant Differences (Beginning Developers)

7.1.3 Quantitative Evidence: Coupling

Figure 7.5 displays the % differences in coupling metrics between the test-first and test-last projects for all of the experiments in which the typical solution contained at least two objects. The two CS1 projects and the CS2 project 3 were typically solved with a procedural approach or only a single class so they are excluded. The Spring 2006 CS2 projects are also excluded because the test-first sample size was so small. For both coupling metrics, lower values are generally more desirable.

This chart seems to indicate that the test-first approach increases coupling. The two exceptions are the industry experiments 2 and 3. These projects were noted as exceptions in the complexity measures and the same rationale could apply here. Industry experiment 2 compares dissimilar projects (library vs web application) and industry experiment 3 involves a test-last approach just after having completed a test-first approach project.

The CS2 project 2 average fan out was the only metric with a statistically significant difference. Thus we cannot claim that the test-first approach increases coupling, but it points to an interesting trend that merits further evaluation. It may not be a surprise that the test-first approach could increase coupling. The sections on complexity and size indicate that the test-first approach seems to cause developers to write smaller, less complex methods and classes. More connections between these units may result.

An interesting question is whether the increased coupling is a good or bad coupling. Coupling can be bad when it is rigid and changes in one module cause changes in another module. However it can be argued that some coupling can be good, particularly when the coupling is either configurable or uses abstract connections such as interfaces or abstract classes. Such code can be considered to be highly flexible and thus more maintainable and reusable. Figure 7.6 illustrates the abstractness in the experiments. The metrics indicate the creation (NOI, NOA, RMA) and use (NII) of interfaces and abstract classes.

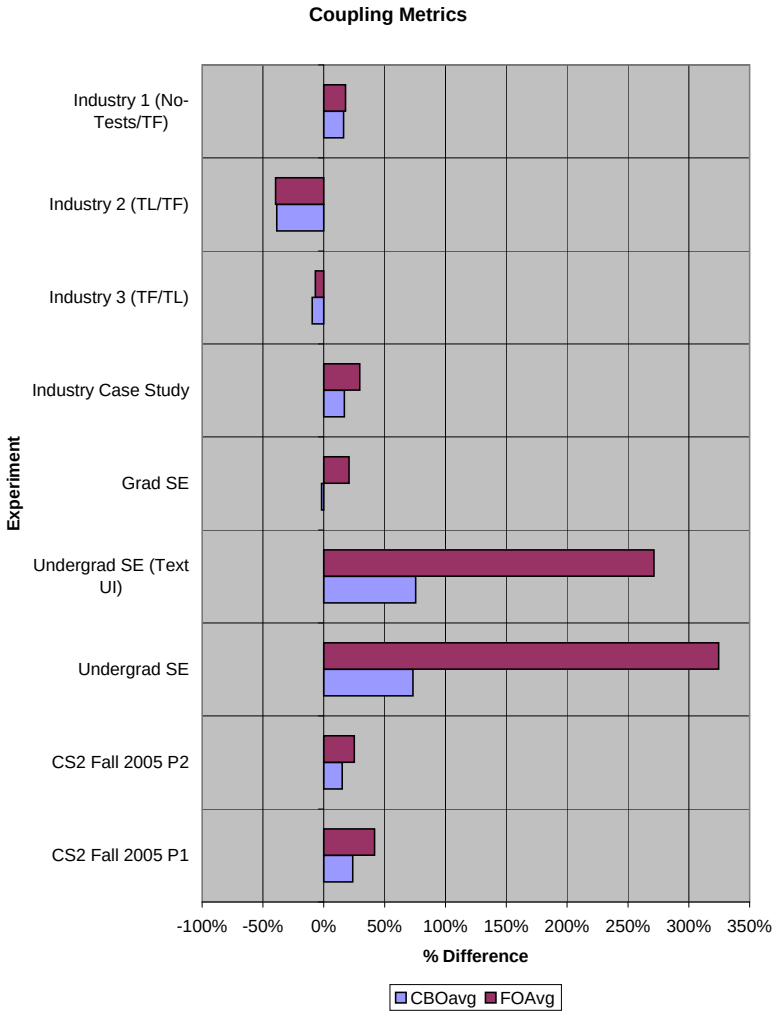

Figure 7.5: % Differences in Coupling (All OO Experiments)

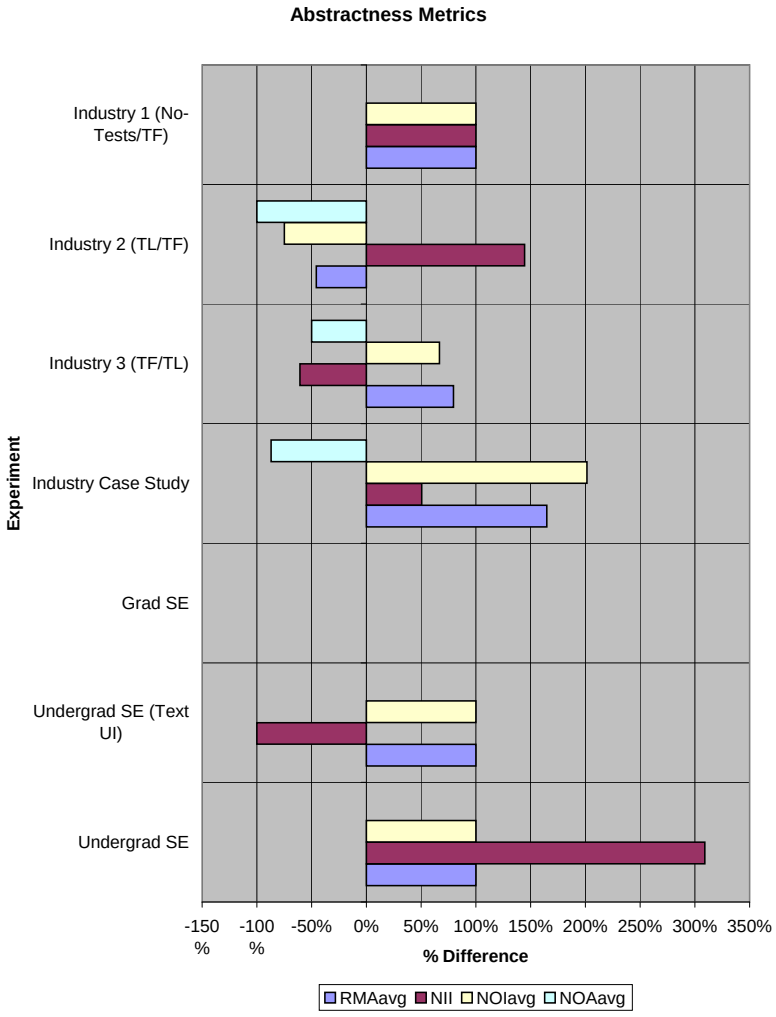

Figure 7.6: % Differences in Abstractness (All OO Experiments)

This figure does not give a conclusive answer, but in a majority of cases, the test-first approach resulted in what appear to be more abstract projects. Again some discrepancies are expected such as the high number of interfaces defined in the industry experiment 2 test-last library project and the corresponding use of those and other interfaces (NII) in the test-first web application project of the same experiment. It is also good to note again that some of the industry projects adopted frameworks that encouraged the use of interfaces and the Dependency Injection design pattern as discussed in Chapter 4.

The possible increased abstractness just discussed indicates that the higher coupling in the test-first projects may be a good kind of coupling, resulting in more flexible software.

Three additional metrics seem informative when considering coupling. Figure 7.7 illustrates the differences in the average number of method parameters (PAR), the information flow ($IF = Fan - In^2 * Fan - Out^2$), and the response for class (RFC). For readability three IF values were scaled down from 3372%, 663%, 2086% respectively to 300%.

The PAR and IF measures seem to indicate a high volume of interaction and data passing between units in the test-first projects. This could be a result of the increased testing discussed earlier. Test-first developers often report writing more parameters so that a method can be more easily configured and tested. The high IF values in the test-first projects may indicate high reuse (fan-in) combined with many connections between smaller units. This increased number of connections between smaller units is somewhat reflected in the RFC values as well. RFC indicates the number of methods available to be invoked by a class.

It is difficult to draw clear conclusions regarding coupling in these experiments. There are some indications that the test-first approach may increase coupling, although there is evidence that this could be a desirable type of coupling through abstractions. Few differences were statistically significant so little can be said with confidence. In contrast to the complexity metrics these results do not lend support to rejecting the **Q1** null hypothesis.

7.1.4 Quantitative Evidence: Cohesion

Like the coupling measures, the empirical results are mixed regarding the effects of the test-first/test-last approach on cohesion. Attempts at determining trends resulted in two charts discussed here.

Figure 7.8 reports the differences in the average LCOM metric for all of the experiments in which the typical solution contained at least two objects. LCOM stands for Lack of Cohesion of Methods. Unlike most other metrics reported, *lower* LCOM values are desirable, indicating better cohesion. As has become the trend, industry experiments 2 and 3 appear to be exceptions to the trend of test-first projects having a higher LCOM value. Plausible explanations for the exceptions seem harder to

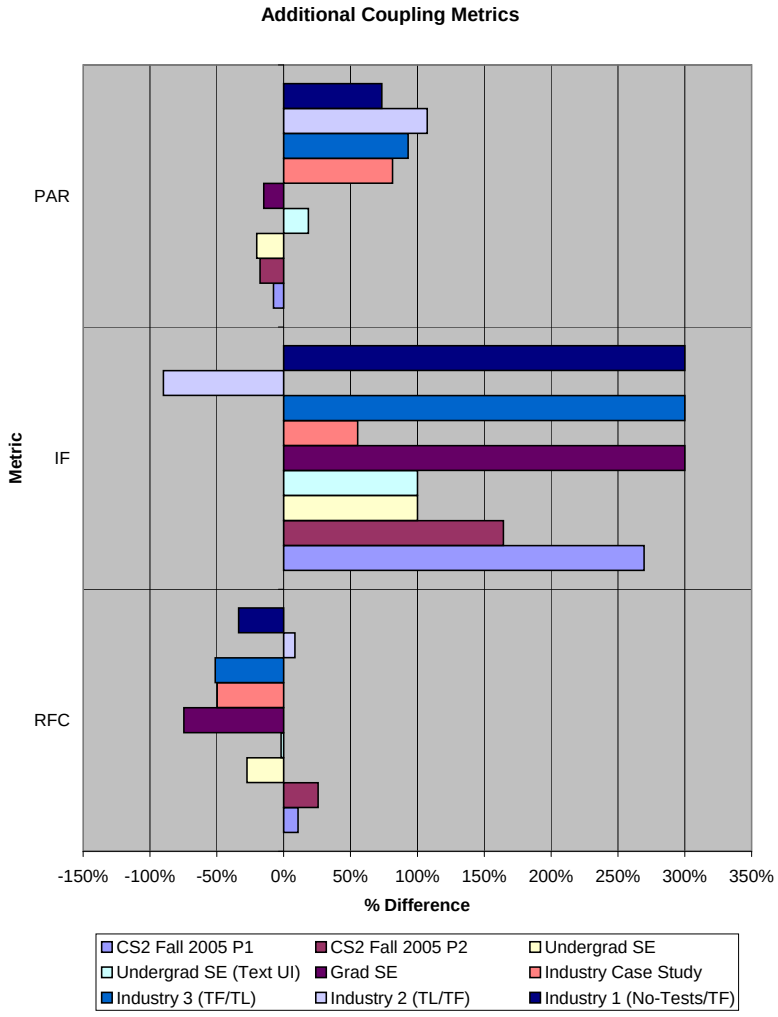

Figure 7.7: % Differences with Additional Coupling Metrics (All OO Experiments)

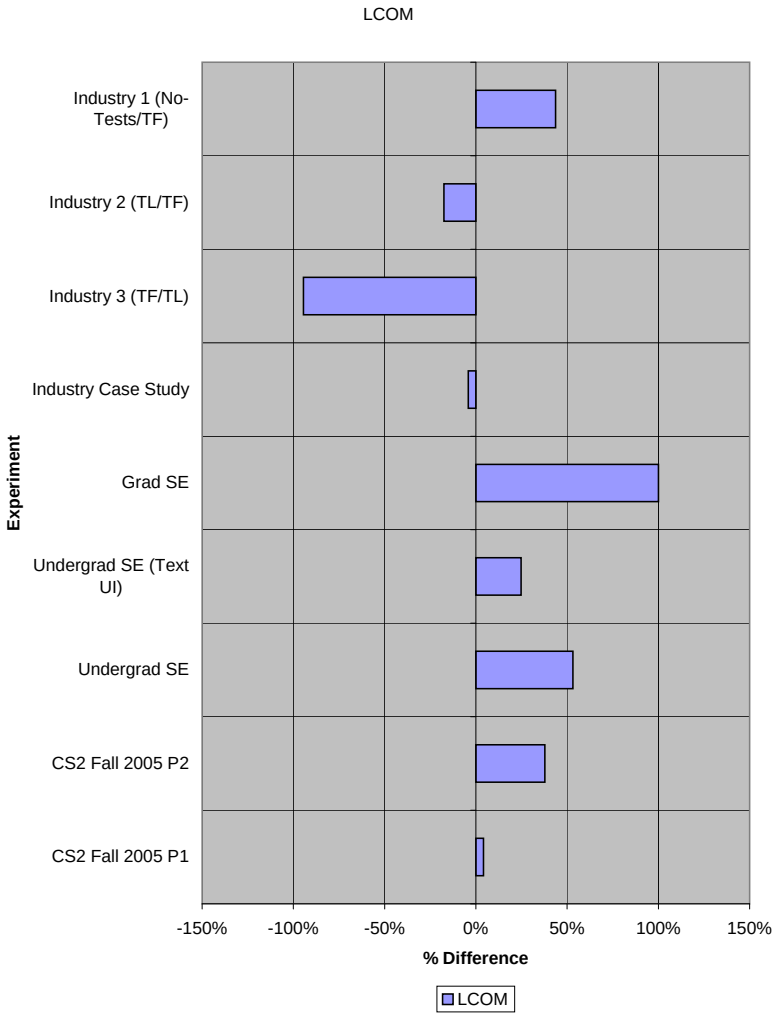

Figure 7.8: % Differences in LCOM Metric (All OO Experiments)

come by in the case of cohesion. One might expect the test-last/library project of industry experiment 2 to have more cohesion than the test-first web application, but this is not the case. Similarly it seems that the LCOM difference in industry experiment 3 would be much smaller if the proposed residual test-first effect discussed earlier applies. None of the differences were statistically significant so perhaps there is nothing that can be said about the effects of the test-first/test-last approach on cohesion.

Figure 7.9 demonstrates the consistency in the academic experiments with cohesion related metrics. In all of these experiments the test-first project had worse cohesion (higher LCOM), more methods, and more classes. The comparison with number of methods and number of classes makes sense with the academic experiments because all the projects within an experiment were solutions to the same problem. This was not the case in the industry experiments, except for the industry

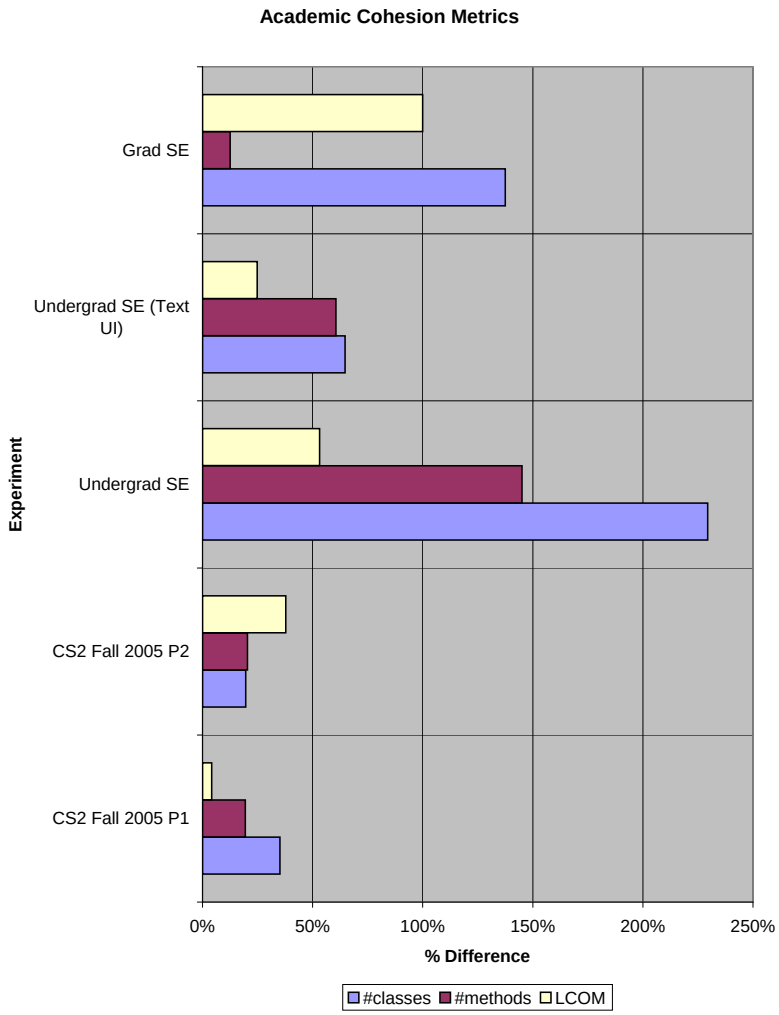

Figure 7.9: % Differences in Cohesion Metrics (Academic Experiments)

training/bowling experiment. The higher number of methods and classes with the test-first approach was anticipated as smaller units are more testable, but the corresponding decrease in cohesion is perhaps surprising. One might expect solutions with more classes to have smaller and more cohesive classes. However this does not appear to be the case. Two of the differences in number of methods and number of classes in the CS2 projects were statistically significant.

Like the coupling measures, there are some indications that the test-first approach may decrease cohesion. However differences were not statistically significant. As a result, the cohesion metrics do not lend support to rejecting the **Q1** null hypothesis.

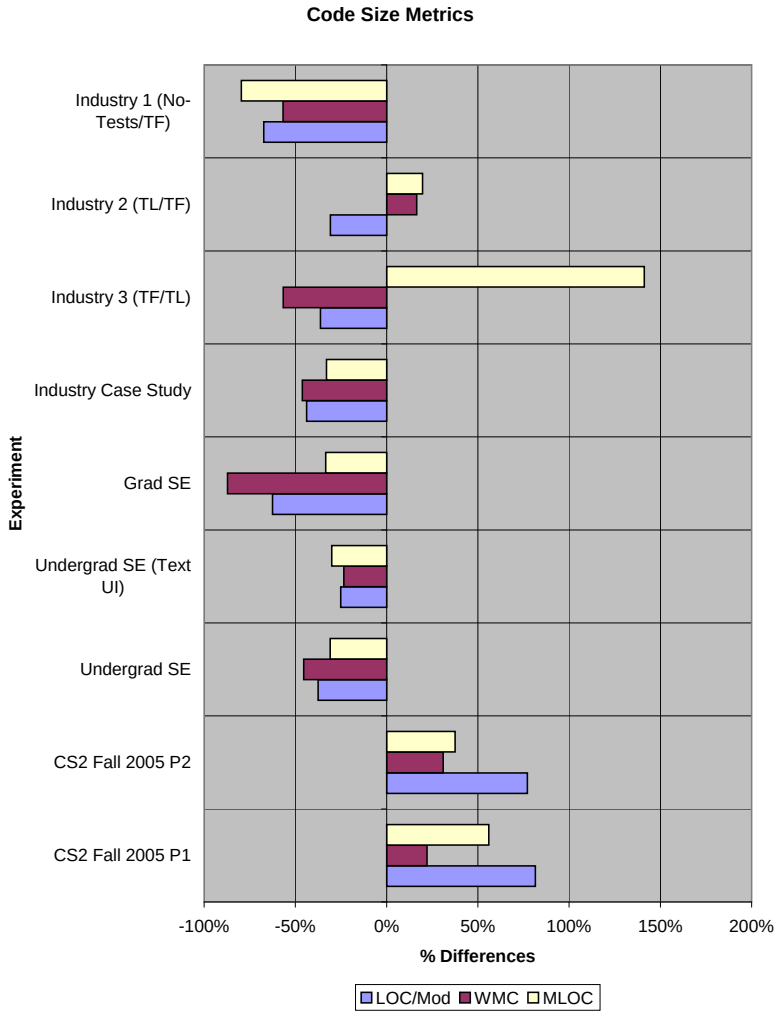

Figure 7.10: % Differences in Code Size Metrics (All OO Experiments)

7.1.5 Quantitative Evidence: Size

This section considers differences in software size metrics. Figure 7.10 compares differences in all of the experiments in which the typical solution contained at least two objects. The three measures displayed are the average lines of code per module (LOC/Mod), the weighted methods per class (WMC) which is an indicator of the number of methods and their complexity in a class, and the average lines of code per method (MLOC). The chart reveals the trend that beginning developers tend to write larger methods and classes with the test-first approach, but that this trend seems to reverse as developers mature. Again we have a couple of exceptions with industry experiments 2 and 3. The LOC/Mod metric was statistically significant for the industry case study. This was the only experiment with enough modules to consider this a valid comparison.

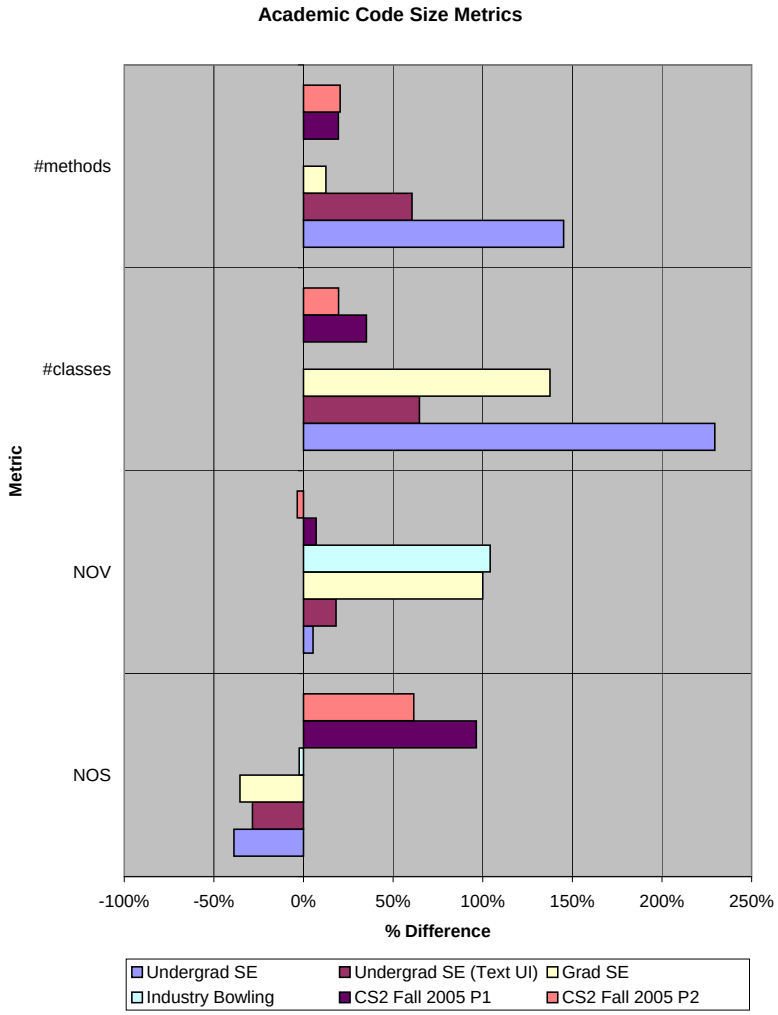

Figure 7.11: % Differences in Academic Size Metrics

Figure 7.11 reports additional size metrics for the academic experiments that can be compared in total because they involve the same requirements. We see here that test-first developers consistently implemented more classes and methods with more variables, and that the total number of statements in a solution reversed in favor of smaller test-first solutions as developers matured. The number of methods, number of classes, WMC and NOS differences were statistically significant in the CS1 and CS2 experiments. The higher test-first NOS values are likely caused by the inclusion of more tests in the test-first solutions. Test code was separated from source code in all experiments except the CS1 and CS2 experiments.

Code size metrics are often criticized, but they are useful in some respects. Less code is generally more maintainable. Smaller modules are generally more reusable and testable. These results indicate that the test-first approach seems to influence mature developers to write more, smaller methods and classes.

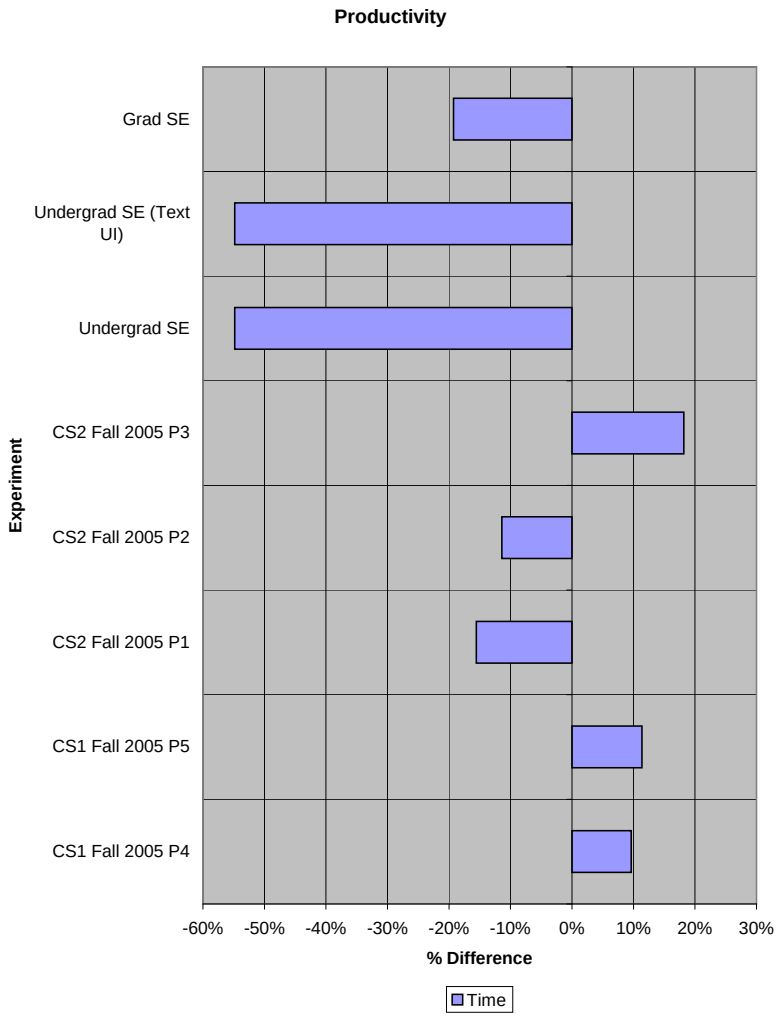

Figure 7.12: % Differences in Programmer Productivity (Academic Experiments)

7.1.6 Quantitative Evidence: Productivity and Evaluation

Programmer productivity was examined in the academic experiments. Students reported the time they spent on each development project and comparisons were made between the test-last and test-first groups. Figure 7.12 reports the % differences between the groups for each experiment. The Spring 2006 CS2 experiments are again excluded for lack of test-first examples. The bars to the left of zero indicate that the test-last programmers took more time on the project. Bars to the right of the zero indicate that the test-first programmers took more time on the project. This chart indicates that the test-first programmers were more productive on all of the projects with predominately object-oriented designs. Despite this trend, none of the differences were statistically significant so we are unable to reject the **P1** null hypothesis.

Experiment	Time	Score	Correctness	Style	Output Format	Error Checking
CS1 Fall 2005 P4	No	No				
CS1 Fall 2005 P5	No	No				
CS2 Fall 2005 P1	No	No	No	Yes	Yes	Yes
CS2 Fall 2005 P2	No	Yes	Yes	No	No	Yes
CS2 Fall 2005 P3	No	No	No	No		

Table 7.3: Statistical Significance in Evaluation Differences

The productivity measures must be considered alongside an evaluation of the product produced by the student programmers. If students report spending less time on an inferior product, little can be said. Figure 7.13 reports the differences in student grades on the CS1 and CS2 projects. The grades were assigned by graduate teaching assistants and evaluate student projects in terms of overall score, external correctness (observable features), program style (design quality, code style), output format, and degree of error checking for exceptional inputs.

The test-first projects were graded higher in the first two CS2 projects and the other project differences were negligible. Several of these differences were statistically significant as reported in Table 7.3. No numeric grades were collected in the software engineering courses so they are excluded. The author observed student presentations in each of the software engineering courses. Based on these observations, the test-first products were judged to be at least as good as the test-last products. This data indicates that programmers using the test-first approach *may* be more productive while producing equal or better quality products than test-last developers. The data supports rejecting the **Q1** hypothesis but only for the CS2 projects.

7.1.7 Qualitative Evidence: Programmer Attitudes

Programmer opinions of the test-first and test-last approaches were measured in each of the experiments. All programmers participating in the experiments were asked to complete surveys at three points: prior to the experiment, shortly after the experiment, and several months after the experiment.

Figures 7.14 and 7.15 report programmer opinions of the test-first and test-last approaches from the post-experiment surveys. The results have been grouped by developer maturity. CS1 and CS2 programmers are in the "Beginning" group, and industry programmers and student programmers from the software engineering courses are in the "Mature" group. The corresponding questions ask programmers to choose:

1. which approach they would choose in the future (Choice)

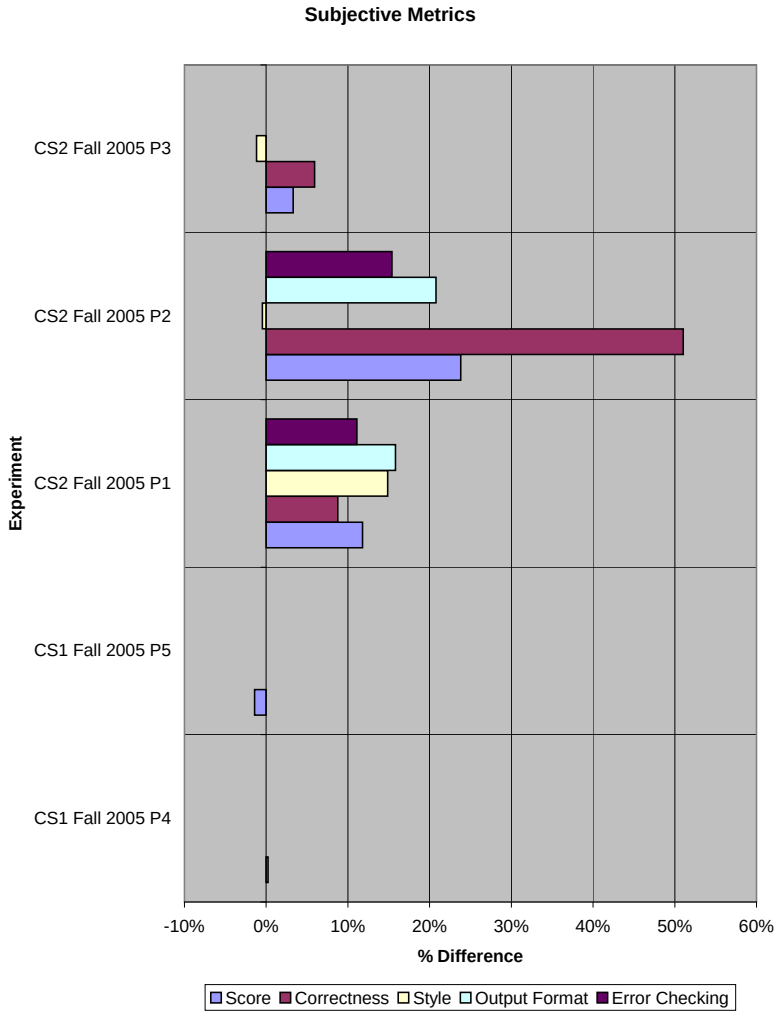

Figure 7.13: % Differences in Program Evaluations (Academic Experiments)

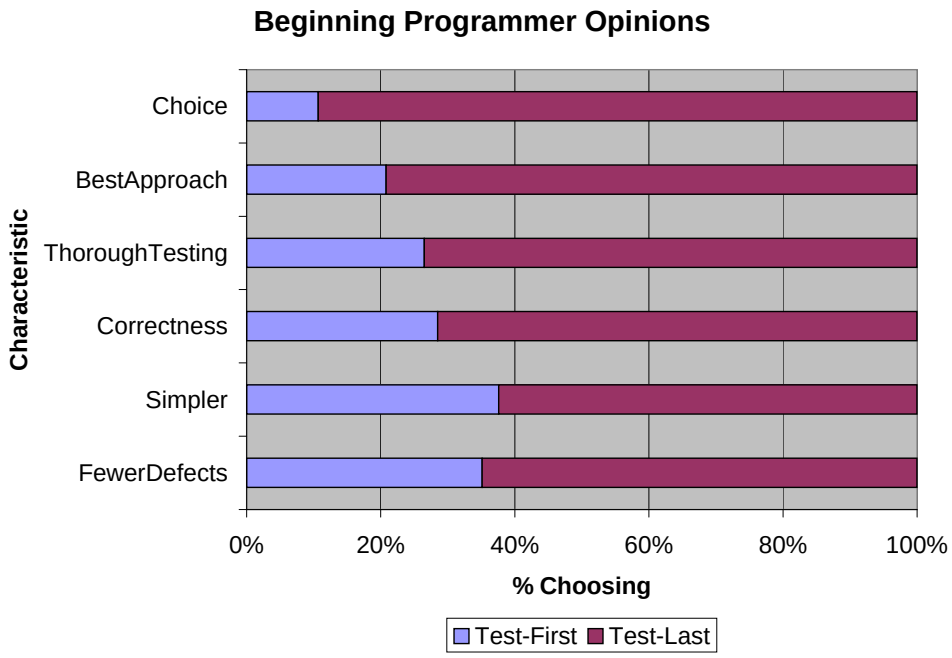

Figure 7.14: Beginning Programmer Opinions of Test-First/Test-Lest Methods

2. which approach was the best for the project(s) they completed (BestApproach)
3. which approach would cause them to more thoroughly test a program (ThoroughTesting)
4. which approach produces a correct solution in less time (Correct)
5. which approach produces code that is simpler, more reusable, and more maintainable (Simpler)
6. which approach produces code with fewer defects (FewerDefects)

The charts illustrate that beginning programmers think the test-last approach is better and are more likely to choose it whereas more mature programmers think the test-first approach is better and are more likely to choose it. The longitudinal survey reported very similar results with 86% of beginning programmers choosing the test-last approach and 87% of mature programmers choosing the test-first approach. The two groups also vary on language (C++ and Java) and corresponding automated unit-testing frameworks which may influence programmer opinions as well.

One should also note that the percentage of programmers choosing the test-first method is always slightly less than the programmer opinions on other desirable characteristics. In other words, despite recognizing many valuable benefits of the test-first approach, some programmers are still unwilling to choose it. A number of comments on the surveys corresponded with this trend. Several programmers noted

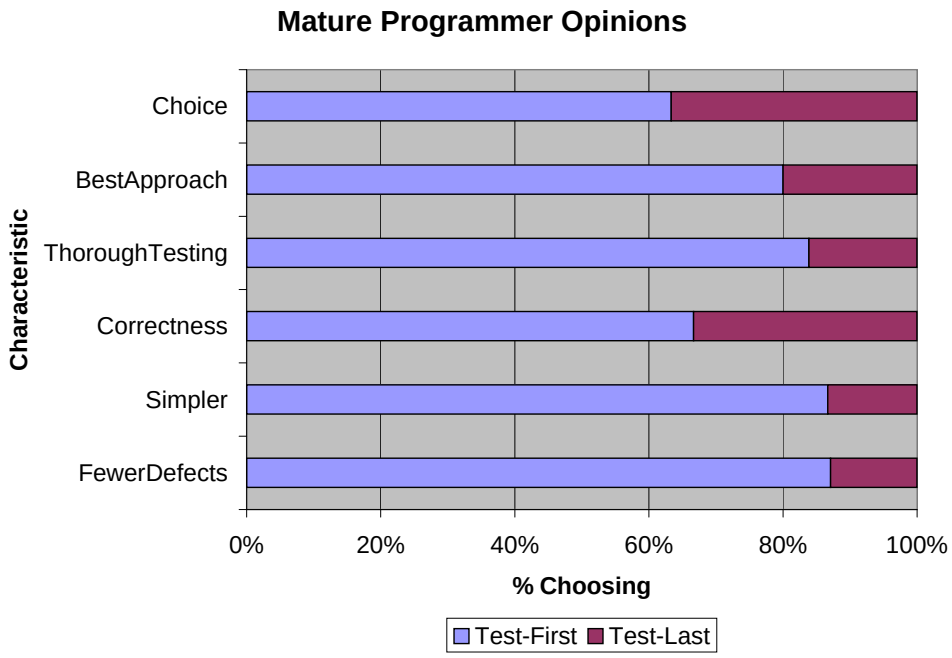

Figure 7.15: Mature Programmer Opinions of Test-First/Test-Lest Methods

that even though they thought the test-first approach was better, they perceived it as being more difficult or very different from what they were comfortable with.

The beginning programmer survey data from Figure 7.14 was divided into two groups: those who used the test-first approach on at least one project and those who only used the test-last approach on all projects. The former group contained a total of 65 programmers and the latter group had 88 programmers. Figure 7.16 reports the percent of programmers preferring the test-first and test-last approaches on the six characteristics out of programmers who used the test-first approach on at least one project. Figure 7.17 reports the same information for the programmers who used the test-last approach on all projects.

Likewise the mature programmer survey data from Figure 7.15 was divided into two groups: those who used the test-first approach on at least one project and those who only used the test-last approach on all projects. The former group contained a total of 16 programmers and the latter group had 15 programmers. Figure 7.18 reports the percent of programmers preferring the test-first and test-last approaches on the six characteristics out of programmers who used the test-first approach on at least one project. Figure 7.19 reports the same information for the programmers who used the test-last approach on all projects.

These charts demonstrate that mature programmers who try the test-first approach almost unanimously like and choose the test-first approach. Beginning programmers clearly have a preference for the test-last approach. However, the charts illustrate that trying the test-first approach significantly increases the likelihood

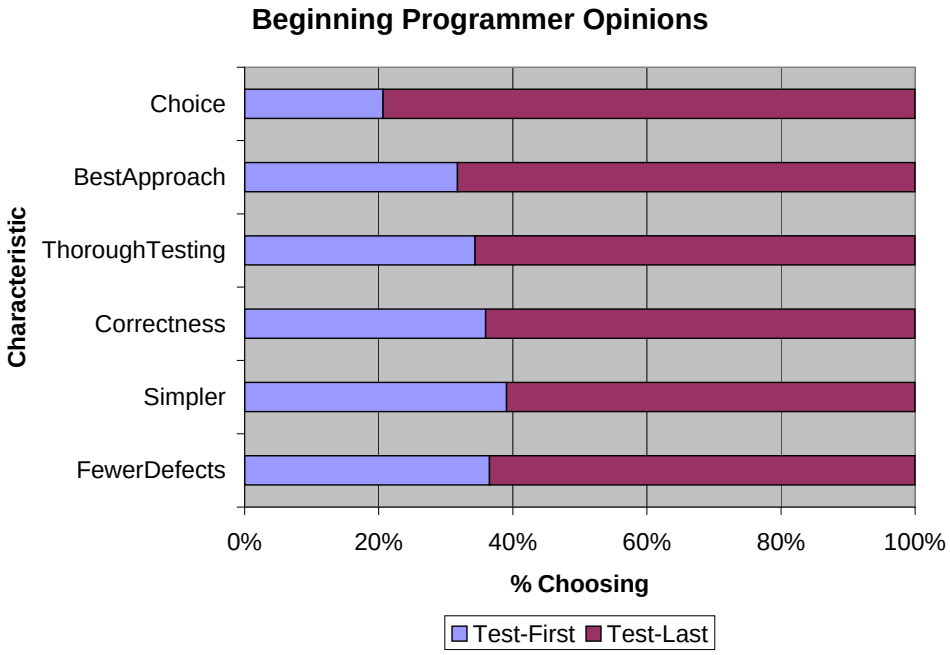

Figure 7.16: Opinions of Beginning Programmer with TF Experience

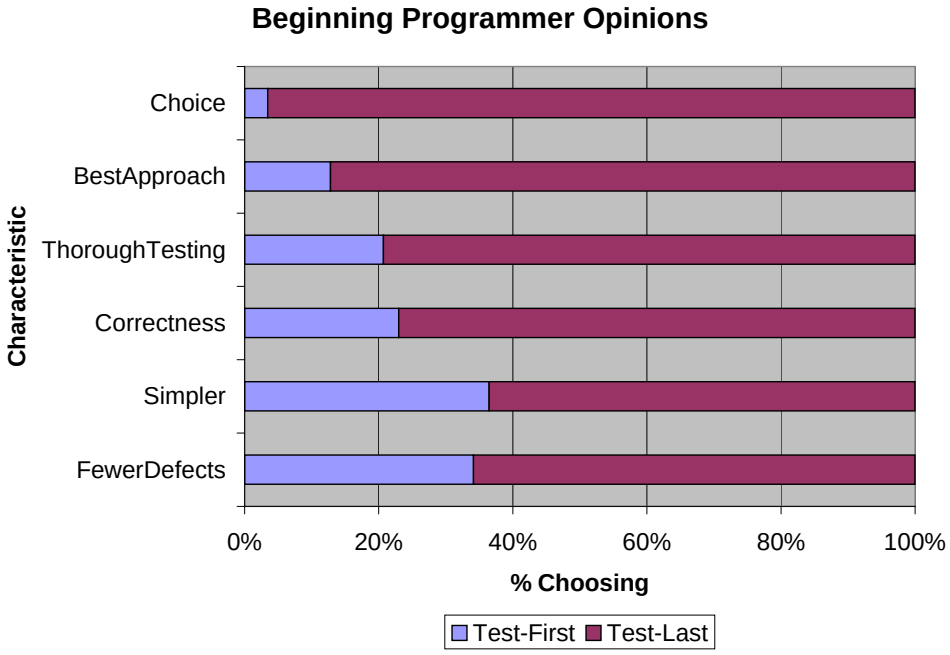

Figure 7.17: Opinions of Beginning Programmer with Only TL Experience

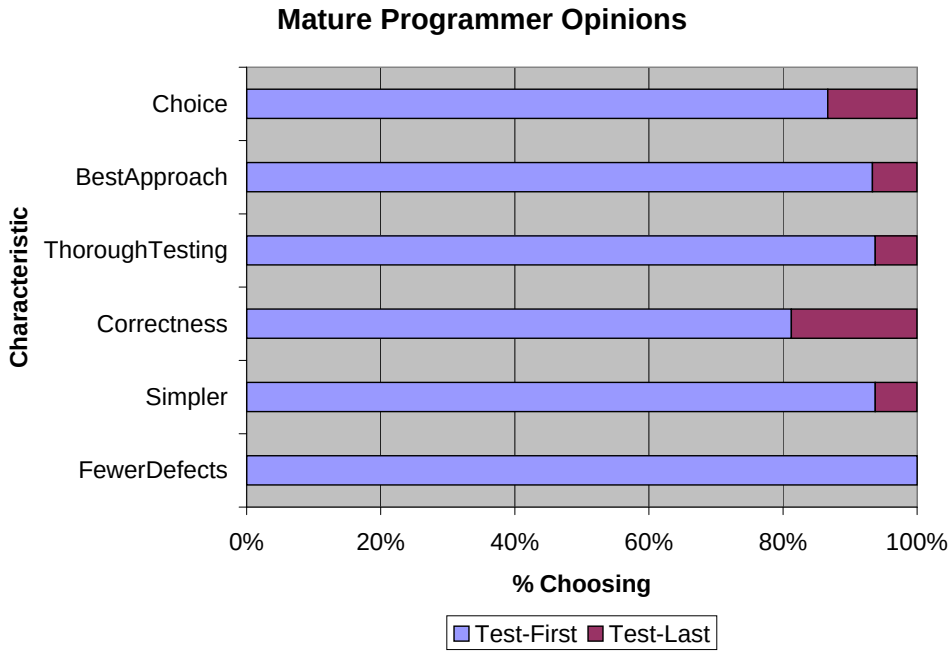

Figure 7.18: Opinions of Mature Programmer with TF Experience

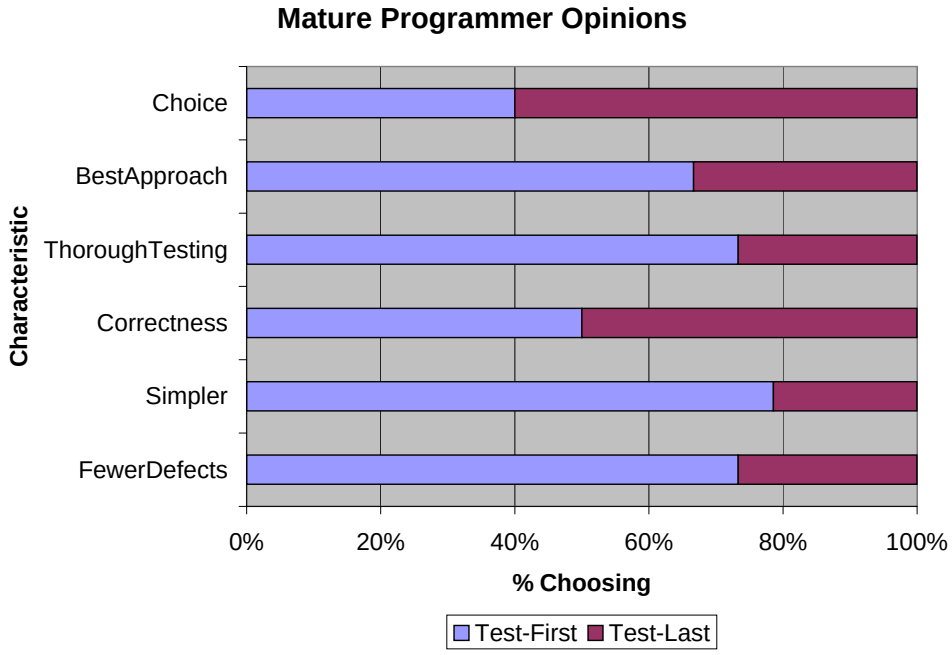

Figure 7.19: Opinions of Mature Programmer with Only TL Experience

that programmers will see benefits with and may choose the test-first approach.

Hypothesis **O1** examines whether programmers prefer the test-first or test-last approach. In the pre-experiment survey, beginning programmers had a statistically significant higher opinion of the test-last approach over the test-first approach. Additionally 76% indicated that they would choose the test-last approach. Mature programmers had a slightly (not statistically significant) higher opinion of the test-first approach and 62% indicated that they would use the test-first approach if given the chance. As a result, we must keep the **O1** null hypothesis and assume that programmers in general do not prefer the test-first approach.

Hypothesis **O2** examines programmer opinions after having tried the test-first approach. The differences in choice as reported in Figures 7.16, 7.17, 7.18, and 7.19 are statistically significant for both the beginning and mature developers. Therefore we can claim that developers (both beginning and mature) who try the test-first approach are significantly more likely to choose the test-first approach over the test-last approach. Despite this significant difference, a majority of beginning developers still would choose the test-last approach, while a majority of mature developers would choose the test-first approach. These results allow us to reject the **O2** null hypotheses for mature developers and claim that mature programmers prefer the test-first approach. Although the improvement is significant for beginning developers, we still cannot say that they prefer the test-first approach.

7.1.8 Empirical Evidence Summary and Conclusions

Complexity, coupling, cohesion, size, and testing were identified as relevant components of the four quality characteristics: understandability, maintainability, reusability, and testability. Table 7.4 summarizes the results in these categories from the previous sections. The table reports which approach had desirable values. A 'TL' in a cell indicates that the test-last approach produced more desirable values for the corresponding experiment and characteristic. A 'TF' in a cell indicates that the test-first approach produced the more desirable values. Blank cells indicate that results were not valid or available for that particular experiment. The value 'Mixed' indicates that neither approach was consistently better for component metrics. Values reported in red indicate that at least some of the metric differences for that characteristic were statistically significant.

As discussed in the previous sections and illustrated here, it appears that the test-first approach did improve internal software quality for mature developers in terms of complexity, size, and testing. In addition, mature developers who have applied the test-first approach prefer it over a test-last approach. The evidence is significant enough to make the following claims:

1. Mature developers applying the test-first approach are likely to write less complex code than they would write with a test-last approach.

Experiment	Complexity	Coupling	Cohesion	Size	Testing
CS1 Fall 2005 P4	TL				TF
CS1 Fall 2005 P5	TF				TL
CS2 Fall 2005 P1	TL	TL	TL	TL	TF
CS2 Fall 2005 P2	TL	TL	TL	TL	TF
CS2 Fall 2005 P3	TL				TF
CS2 Spr 2006 P1	TL				TL
CS2 Spr 2006 P2	TL				TF
CS2 Spr 2006 P3	TL				TL
Undergrad SE	TF	TL	TL	TF	TF
Undergrad SE (Text UI)	TF	TL	TL	TF	TF
Grad SE	TF	Mixed	TL	TF	TF
Industry Bowling	TF				
Industry Case Study	TF	TL	TF	TF	TF
Industry 3 (TF/TL)	TL	TF	TF	Mixed	TF
Industry 2 (TL/TF)	TL	TF	TF	Mixed	TF
Industry 1 (No-Tests/TF)	TF	TL	TL	TF	TF

Table 7.4: Quality Comparison Summary

2. Mature developers applying the test-first approach are likely to write more smaller units (methods and classes) than they would write with a test-last approach.

3. Developers at all levels applying the test-first approach are likely to write more tests and achieve higher test coverage than with a test-last approach.

4. Mature developers who have applied both the test-first and test-last approach are more likely to choose the test-first approach.

There was no clear best approach in terms of coupling and cohesion. It appears that a test-last approach may be best for beginning developers in terms of complexity, coupling and cohesion, but the test-first approach is preferable in terms of testing. However external evaluations of the CS2 projects revealed some statistically significant improvements in observed quality with the test-first projects.

Coupling, cohesion, complexity, size, and testing were identified as components of the desirable quality characteristics of understandability, maintainability, reusability, and testability. We cannot make the claim that the test-first approach improves all of the characteristics completely. Hence we cannot reject the **Q1** null hypothesis. However, this research has demonstrated that the test-first approach can cause significant quality improvements by lowering code complexity, reducing the size of methods and classes, and increasing developer testing. The evidence merits rejecting the **T1** and **T2** null hypotheses.

Further, section 6.2.2 provided evidence that code developed in a test-first manner and covered by automated unit tests was of a higher quality than code not covered by such tests. This evidence was not sufficient to reject the **Q2** null hypothesis, but some measures approached statistical significance. Given that the test-first approach was shown to consistently improve test volume and test coverage, it is likely that the simple existence of better tests will improve the internal quality of software. Combining this with the improvements in complexity and size provide compelling motivation for organizations to consider adopting TDD.

The academic experiments revealed that test-first programmers tended to be more productive, implementing equivalent or better solutions in less time. The differences were not statistically significant so we cannot reject the **P1** null hypothesis.

Measures of programmer opinions indicated that programmers do not initially prefer the test-first approach so we must keep the **O1** null hypothesis. However opinions of the test-first approach significantly improve with practice. Some evidence indicates that opinions of the test-last approach may actually decrease with practice. Mature developers who have tried the test-first approach do prefer the test-first approach to the extent that we can reject the **O2** null hypothesis.

7.2 Evaluation and External Validity

External validity involves demonstrating that results discovered in one study can be reproduced elsewhere, and that the results generalize to broader environments. Three approaches are taken to evaluate this research. First, while the research was being designed and conducted, informal reviews were requested from a number of sources. Computer science faculty and dissertation committee members at the University of Kansas reviewed the proposed studies in the oral comprehensive exam, as the experiments were being integrated into the courses, and at the end of the first experiment. In addition, the author participated in the Doctoral Symposium at the OOPSLA'05 conference. In this forum, five faculty reviewers critiqued and advised the research plans and early results. At least one of the reviewers had recent experience with empirical software engineering studies of this nature. Additional advice and reviews were requested from outside faculty and researchers including Laurie Williams from North Carolina State University and Steve McConnell with Construx Software.

The second evaluation of this research resulted from the range of experiments and their environments, as well as the case study conducted in a professional environment. Similar results across a range of academic and industry environments strengthen the results, while differing results raise questions. As demonstrated in the previous section, a number of similar results emerged in all or nearly all of the experiments. Some differences also emerged, pointing to possible effects of environment and programmer maturity. Other differences have less obvious causes

and indicate that either the approach used has no effect on those aspects, or that confounding factors existed and further experiments are necessary.

The third evaluation of this research involves external peer-review. The following sections discuss the publications and conference presentations, awards and grants, and external presentations resulting from this research. This research has enjoyed very positive responses in a wide range of venues. Reviewer comments, publication acceptance, and a prestigious international award serve as meaningful confirmation of the research's validity.

7.2.1 Peer-Reviewed Publications

This research resulted in the following six peer-reviewed publications to date.

1. The background and framing of the problem appeared as a cover feature in the September 2005 issue of *IEEE Computer* [45]. This provided very wide exposure early in the research.

2. Results from the first empirical study in the undergraduate software engineering course were published and presented at the IEEE 19th Conference on Software Engineering Education and Training (CSEE&T'06) in North Shore, Oahu in April 2006 [49].

3. The test-driven learning approach described in Appendix A was published and presented at the ACM Technical Symposium of the Special Interest Group on Computer Science Education (SIGCSE'06) in Houston, Texas in March 2006 [50].

4. The research approach and early results were presented in the Doctoral Symposium and an extended abstract was published at the ACM SIGPLAN Conference on Object Oriented Programming, Systems, Languages, and Applications (OOPSLA'06) in San Diego, California in October 2005 [47].

5. The research approach and early results were presented in the Poster Session and ACM Student Research Competition, and an extended abstract was published at the ACM SIGPLAN Conference on Object Oriented Programming, Systems, Languages, and Applications (OOPSLA'06) in San Diego, California in October 2005 [48].

6. The research approach and intermediate results were published in a full paper in the ACM Digital Library in conjunction with receiving third place in the Grand Finals of the ACM Student Research Competition [46].

The final results are being prepared for submission to *IEEE Transactions on Software Engineering* and a high level summary will be prepared for submission to *IEEE Software*.

7.2.2 Awards and Grants

This research enjoyed significant external recognition. Most notably the author was presented with the third place award in the Grand Finals of the ACM Student Research Competition sponsored by Microsoft. The award was presented along with the Turing Award and other prestigious awards at the annual ACM Awards Banquet at the Westin St. Francis Hotel in San Francisco May 20, 2006.

Following the first two stages of the competition, the author was awarded third place in the ACM Student Research Competition (SRC) at the OOPSLA'05 conference in San Diego, CA in October 2005. This award qualified the author to participate in the Grand Finals of the ACM SRC.

In summer 2005 the author received an ACM SIGCSE Special Projects Award in support of the development and dissemination of the test-driven learning approach. In addition, the author was accepted to and given travel support for the OOPSLA'05 Doctoral Symposium in San Diego, CA and the NSF-sponsored Academy of Software Engineering Educators and Trainers (ASEE&T'06) symposium at the CSEE&T'06 conference in North Shore, Oahu.

7.2.3 Presentations

The author was fortunate to present this research in a number of venues. An earlier section mentioned the conference presentations in the OOPSLA'05 Doctoral Symposium, the OOPSLA'05 Poster Session, the SIGCSE'06 paper presentation, and the CSEE&T'06 paper presentation. In addition, the research was presented at OOPSLA'05 to a panel of distinguished judges in the second round of the ACM Student Research Competition.

TDD training and research results were also presented in multi-day training sessions at Cessna Aircraft Company and Engenio Information Systems (formerly LSI Logic). Also because the author was applying for faculty positions, a number of presentations were given on interview trips to universities across the United States.

7.3 Additional Contributions

In addition to the significant empirical results, this research contributes a framework for conducting empirical TDD studies which can be replicated. Further, this research offers a pedagogical approach to teaching test-driven development.

7.3.1 Framework for Empirical TDD Studies

A valuable by-product of this research is a framework for conducting future studies of TDD efficacy. Despite attempts to make this set of experiments as comprehensive

as possible, it is unlikely that a single set of studies can explore all aspects of a development approach. Plus as was noted earlier, additional studies will be necessary to provide external validity through additional environments. By documenting how this study was conducted and providing instruments, tools, and methods, future studies can be completed more efficiently.

All assessment tools including the pre and post experiment attitude surveys, information on software metric collection and analysis tools, and TDD training materials are available through the appendices of this document and on the web. A home for test-driven development education has been established on the web at `http://www.simexusa.com/tdl/`. It is hoped that this site will evolve and grow to facilitate the community-driven communication of ideas on test-driven development, particularly in undergraduate education.

7.3.2 Pedagogical Contributions

Appendix A describes the test-driven learning approach developed in this research. It is the opinion of the author that the TDL approach has tremendous potential for improving computer science pedagogy. A particular advantage of the TDL approach is that it requires no additional instruction time. It provides a strategy to improve testing and design at virtually no cost besides the learning curve for the instructor.

Computer science educators have expressed enthusiastic interest in TDL. The TDL approach was presented at the national technical symposium of the ACM Special Interest Group on Computer Science Education (SIGCSE) in Houston, Texas in March 2006. The presentation was very well attended and received significant interest with a long line of questioners following the talk. In a presentation the following day, Lucas Layman from North Carolina State University highlighted the TDL approach as an important idea that computer science educators should consider adopting. After learning about TDL in the Doctoral Symposium at OOPSLA'06, Robert Kessler from the University of Utah declared he now knew how he was going to teach his next course. Also, following the presentation of the first academic experiment at the Conference on Software Engineering Education and Training (CSEE&T) in Hawaii in April 2006, a significant portion of the questions focused on the TDL approach.

The TDL approach was only briefly utilized in the undergraduate Programming 1 (CS1) and Programming 2 (CS2) experiments. It is hoped that the enthusiasm over TDL will result in the approach being attempted and studied in a full semester. It is possible that complete lab or course text books will be written incorporating TDL.

7.4 Summary and Future Work

Despite many significant advances, software construction is still plagued with many failures. Development organizations struggle to make intelligent development method adoption decisions due to a lack of maturity and a general lack of empirical evidence of what methods are best in what contexts. While some individual programmers and organizations have learned to value and apply disciplined, yet flexible methods, students do not generally graduate with these skills.

Test-driven development is a disciplined development practice that promises to improve software design quality while reducing defects with no increased effort. This research carefully examined the potential of TDD to deliver these benefits. Empirical software engineering methods were applied in a set of formal controlled longitudinal studies with undergraduate and graduate students at the University of Kansas and professional programmers in a Fortune 500 company.

This research has demonstrated that TDD can and is likely to improve some software quality aspects at minimal cost over a comparable test-last approach. In particular it has shown statistically significant differences in the areas of code complexity, size, and testing. These internal quality differences can substantially improve external software quality (defects), software maintainability, software understandability, and software reusability.

Additional empirical studies should replicate the experiments of this research in similar and new environments. It is anticipated that the author will replicate this experiment in 2006-2007 in the year-long senior capstone sequence of the software engineering major at California Polytechnic State University at San Luis Obispo, California. This environment will examine mature undergraduate students working on a much larger project for an external client.

This research revealed a number of differences between TDD acceptance and efficacy in beginning and mature developers. These two groups also had the confounding factor of using different languages (C++ and Java) and test frameworks (asserts and JUnit). Futures studies should examine if the use of Java and JUnit improves TDD acceptance and efficacy in early programming courses.

Future studies could examine the question of how much up-front software architecture and design work should ideally be completed before engaging in the TDD process. These studies should consider scale and safety concerns of the projects.

An interesting situation was noted when the CS1 and industry experiment 3 programmers went from a test-first to a test-last approach. In these situations, testing volume and coverage stayed high, near the levels of the test-first projects. Future studies could examine whether this trend continues over time. One could study whether test-first programmers continue to write high volumes of tests with high test coverage, or whether these achievements taper over time.

In a private email, Steve McConnell of Construx Software suggested several additional studies such as comparing the test-first approach to an approach that in-

cluded formal inspections. Another suggestion was to study the learning curve of the test-first approach as well as programmer discipline with the test-first approach in practice. Some of the professional programmers in the study noted the high-level of discipline required to stay with the test-first approach on a daily basis.

This research also has demonstrated that students at a certain maturity level can learn and apply TDD effectively. Pedagogical tools and resources have been developed and disseminated through the test-driven learning approach. These experiments only applied the TDL approach in a small portion of several courses. Future studies should examine their efficacy when applied throughout an entire course. The TDL resources may have the potential to revolutionize in a subtle but substantial way the methods by which computer programming is taught.

As a result, it is believed that this research can have a significant impact on the state of software construction. Some software development organizations will be convinced to adopt TDD in appropriate situations. New textbooks can be written applying the test-driven learning approach. As students learn to take a more disciplined approach to software development, they will carry this approach into professional software organizations and improve the overall state of software construction.

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Appendix A

Test-Driven Learning

Test-driven learning (TDL) is an approach to teaching computer programming that involves introducing and exploring new concepts through automated unit tests. TDL offers the potential of teaching testing for free, of improving programmer comprehension and ability, and of improving software quality both in terms of design quality and reduced defect density.

This paper introduces test-driven learning as a pedagogical tool. It will provide examples of how TDL can be incorporated at multiple levels in computer science and software engineering curriculum for beginning through professional programmers. In addition, the relationships between TDL and test-driven development will be explored.

Initial evidence indicates that TDL can improve student comprehension of new concepts while improving their testing skills with no additional instruction time. In addition, by learning to construct programs in a test-driven manner, students are expected to be more likely to develop their own code with a test-driven approach, likely resulting in improved software designs and quality.

A.1 Introduction to TDL

Programmers often learn new programming concepts and technologies through examples. Instructors and textbooks use examples to present syntax and explore semantics. Tutorials and software documentation regularly present examples to explain behaviors and proper use of particular software elements. Examples, however, typically focus on the use or the interface of the particular software element, without adequately addressing the behavior of the element.

Consider the following example from the Java 1.5 API documentation:

```
void printClassName(Object obj)
{
  System.out.println("The class of " + obj +
```

```
            " is " + obj.getClass().getName());
}
```

While this is a reasonable example of how to access an object's class and corresponding class name, it only reveals the desired interface. It teaches nothing about the underlying behavior. To see behavior, one must compile and execute the code. While it is desirable to encourage students to try things out on their own, this can be time consuming if done for every possible example, plus it significantly delays the presentation/feedback loop.

As an alternative, we can introduce a simple automated unit test that demonstrates both the interface and the expected behavior. For instance, we could replace the above example with the following that uses the assert keyword[1]:

```
void testClassName1()
{
  ArrayList al = new ArrayList();
  assert al.toString().equals("[]");
  assert al.getClass().getName()
         .equals("java.util.ArrayList");
}
```

This example shows not only the same interface information as the original example in roughly the same amount of space, but it also shows the behavior by documenting the expected results.

A second example below demonstrates the same interface using an `Integer`. Notice how these two examples also reveal the `toString()` results for an empty `ArrayList ("[]")` and an `Integer ("5")`.[2]

```
void testClassName2()
{
  Integer i = new Integer(5);
  assert i.toString().equals("5");
  assert i.getClass().getName()
         .equals("java.lang.Integer");
}
```

These examples demonstrate the basic idea of test-driven learning:

[1] Although assert has existed in many languages for some time, the assert keyword was introduced in Java with version 1.4 and requires extra work when compiling and running:
javac -source 1.4 ClassTest.java
java -ea ClassTest

[2] If the `toString()` information is deemed distracting, this first assert could simply be left out of the example.

- Teach by example
- Present examples with automated tests
- Start with tests

Teaching by example has a double meaning in TDL. First TDL encourages instructors to teach by presenting examples with automated tests. Second, by holding tests in high regard and by writing good tests, instructors model good practices that contribute to a number of positive results. Students tend to emulate what they see modeled. So as testing becomes a habit formed by example and repetition, students may begin to see the benefits of developing software with tests and be motivated to write tests voluntarily.

The third aspect of TDL suggests a test-first approach. TDL could be applied in either a test-first or a test-last manner. With a test-last approach, a concept would be implemented, then a test would be written to demonstrate the concept's use and behavior. With a test-first approach, the test would be written prior to implementing a concept. By writing a test before implementing the item under test, attention is focused on the item's interface and observable behavior. This is an instance of the test-driven development (TDD) [17] approach that will be discussed in section three.

A.2 TDL Objectives

Teaching software design and testing skills can be particularly challenging. Undergraduate curriculums and industry training programs often relegate design and testing topics to separate, more advanced courses, leaving students perhaps to think that design and testing are either hard, less important, or optional.

This paper introduces TDL as a mechanism for teaching and motivating the use of testing as both a design and a verification activity, by way of example. TDL can be employed starting in the earliest programming courses and continuing through advanced courses, even those for professional developers. The lead author has integrated TDL into CS1 and a four-day C++ course for experienced professional programmers. Further, TDL can be applied in educational resources from textbooks to software documentation.

Test-driven learning has the following objectives:

- Teach testing for free
- Teach automated testing frameworks simply
- Encourage the use of test-driven development
- Improve student comprehension and programming abilities

- Improve software quality both in terms of design and defect density

Some have suggested that if objects are the goal, then we should start by teaching objects as early as the first day of the first class [8]. TDL takes a similar approach. If writing good tests is the goal, then start by teaching with tests. If it is always a good idea to write tests, then write tests throughout the curriculum. If quality software design is the goal, then start by focusing on habits that lead to good designs. Test-first thinking focuses on an object's interface, rather than its implementation. Test-first thinking encourages smaller, more cohesive and more loosely coupled modules [17], all characteristics of good design.

Examples with tests take roughly the same effort to present as examples with input/output statements or explanations. As a result, TDL adds no extra strain on a course schedule, while having the benefit of introducing testing and good testing practices. In other words TDL enables one to teach testing for free. It is possible that the instructor will expend extra effort moving to a test-driven approach, but once mastered, the instructor may find the new approach simpler and more reusable because the examples contain the answers.

By introducing the use of testing frameworks gradually in courses, students will gain familiarity with them. As will be seen in sections four and five, tests can use simple mechanisms such as assert statements, or they can utilize powerful frameworks that scale and enjoy widespread professional support. Depending on the language and environment, instructors may introduce testing frameworks early or gradually.

When students observe both the interface and behavior in an example with tests, they are likely to understand a concept more quickly than if they only see the interface in a traditional example. Further, if students get into the habit of thinking about and writing tests, they are expected to become better programmers.

A.3 Related Work

Test-driven learning is not a radical new approach to teaching computer programming. It is a subtle, but potentially powerful way to improve teaching, both in terms of efficiency and quality of student learning, while accomplishing several important goals.

TDL builds on the ideas in Meyer's work on Design by Contract [61]. Automated unit tests instantiate the assertions of invariants and pre- and post-conditions. While contracts provide important and rigorous information, they fail to communicate and implement the use of an interface in the efficient manner of automated unit tests. Contracts have been suggested as an important complement to TDD [42]. The same could be said regarding TDL and contracts.

TDL is expected to encourage adoption of TDD. Although its name implies that TDD is a testing mechanism, TDD is as much or more about analysis and design as

it is about testing, and the combination of emphasis on all three stands to improve software quality. Early research reports mixed results [45] regarding quality and productivity improvements from TDD particularly on small software projects, however recent research [27] suggests that a test-first approach increases the number of tests written and improves productivity, increasing the likelihood of higher quality software with similar or lower effort.

TDL was inspired by the Explanation Test [17] and Learning Test [17] testing patterns proposed by Kent Beck, Jim Newkirk, and Laurent Bossavit. These patterns were suggested as mechanisms to coerce professional programmers to adopt test-driven development.

The Explanation Test pattern encourages developers to ask for and provide explanations in terms of tests. The pattern even suggests that rather than explaining a sequence diagram, the explanation could be provided by "a test case that contains all of the externally visible objects and messages in the diagram." [17]

The Learning Test pattern suggests that the best way to learn about a new facility in an externally produced package of software is by writing tests. If you want to use a new method, class, or API, first write tests to learn how it works and ensure it works as you expect.

TDL expands significantly on the Explanation and Learning Test ideas both in its approach and its audience. Novice programmers will be presented with unit tests as examples to demonstrate how programming concepts are implemented. Further, programmers will be taught to utilize automated unit tests to explore new concepts.

While the idea of using automated tests as a primary teaching mechanism is believed to be a new idea, the approach of requiring students to write tests in lab and project exercises has a number of predecessors. Barriocanal [13] documented an experiment in which students were asked to develop automated unit tests in programming assignments. Christensen [22] proposes that software testing should be incorporated into all programming assignments in a course, but reports only on experiences in an upper-level course. Patterson [67] presents mechanisms incorporated into the BlueJ [54] environment to support automated unit testing in introductory programming courses.

Edwards [25] has suggested an approach to motivate students to apply TDD that incorporates testing into project grades, and he provides an example of an automated grading system that provides useful feedback. TDL pushes automated testing even earlier, to the very beginning in fact.

A.4 TDL in Introductory Courses

Test-driven learning can be applied from the very first day of the very first programming course. Textbooks often begin with a typical "Hello, World!" example or the declaration of a variable, some computation and an output statement. The

following is a possible first program in C++:

```
#include <iostream>
using namespace std;

int main()
{
  int age;
  cout << "What is your age in years?" << endl;
  cin  >> age;
  cout << "You are at least "
       << age * 12
       << " months old!" << endl;
}
```

This approach requires the immediate explanation of the language's input/output facilities. While this is a reasonable first step, a TDL approach to the same first program might be the following:

```
#include <cassert>

int main()
{
  int age = 18;
  int ageInMonths;
  ageInMonths = age * 12;
  assert(ageInMonths == 216);
}
```

Notice how use of the `assert()` macro from the standard C library is used, rather than a full-featured testing framework. Many languages contain a standard mechanism for executing assertions. Assertions require very little explanation and provide all the semantics needed for implementing simple tests. The assert approach minimizes the barriers to introducing unit testing, although it does bring some disadvantages. For instance, if there are multiple assert statements and one fails, no further tests are executed. Also, there is no support for independent tests or test suites. However, because the programs at this level are so small, the simplicity of assert statements seems to be a reasonable choice.

As a later example, a student learning to write *for* loops in C++ might be presented with the following program:

```
#include <iostream>
#include <cassert>
using namespace std;
```

```
int sum(int min, int max);

int main()
{
  assert(sum(3,7)==25);
  cout << "No errors encountered" << endl;
}

// This function sums the integers
//   from min to max inclusive.
// Pre: min < max
// Post: return-value = min + (min+1) + ...
//   + (max-1) + max
int sum(int min, int max)
{
  int sum = 0;
  for(int i=min;i<=max;i++)
  {
    sum += i;
  }
  return sum;
}
```

In a lab setting, the student might then be asked to write additional unit tests to understand the concept. For instance, they might add the following assert statements:

```
assert(sum(-2,2) == 0);
assert(sum(-4,-2) == -9);
```

Later they might be asked to write unit tests for a new, unwritten function. In doing so, they will have to design the function signature and perhaps implement a function stub. This makes them think about what they are going to do before they actually do it.

Once the programmer ventures beyond the lab into larger projects, tests can be separated into a `run_tests()` function and tests can be partially isolated from each other by placing them in independent scopes as in the following example:

```
#include <cassert>

class Exams
{
```

```
  public:
    Exams();
    int getMin();
    void addExam(int);
  private:
    int scores[50];
    int numScores;
};

void run_tests();

int main()
{
  run_tests();
}

void run_tests()
{
  { //test 1 Minimum of empty list is 0
    Exams exam1;
    assert(exam1.getMin() == 0);
  } //test 1

  { //test 2
    Exams exam1;
    exam1.addExam(90);
    assert(exam1.getMin() == 90);
  } //test 2
}
```

TDL should not compete with other approaches in introductory courses. Rather TDL should complement and integrate well with various programming-first [2] approaches such as imperative-first, objects-first, functional-first, and event-driven programming among others.

A.5 TDL in later courses

TDL is applicable at all levels of learning. Advanced students and even professional programmers in training courses can benefit from the use of tests in explanations.

As students gain maturity, they will need more sophisticated testing frameworks. Fortunately a wonderful set of testing frameworks that go by the name xUnit have emerged following the lead of JUnit [34]. The frameworks generally support

independent execution of tests (i.e. execution or failure of one test has no effect on other tests), test fixtures (common test set up and tear down), and mechanisms to organize large numbers of tests into test suites.

The final example below demonstrates the use of TDL when exploring Java's `DefaultMutableTreeNode` class. Such an example might surface when first introducing tree structures in a data structures course, or perhaps when a programmer is learning to construct trees for use with Java's `JTree` class. Notice the use of the `breadthFirstEnumeration()` method and how the assert statements demonstrate not just the interface to an enumeration, but also the behavior of a breadth first search. A complementary test could be written to explore and explain depth first searches. In addition, notice that this example utilizes the JUnit framework.

```
import javax.swing.tree.DefaultMutableTreeNode;

import junit.framework.TestCase;

public class TreeExploreTest extends TestCase {
 public void testNodeCreation() {
   DefaultMutableTreeNode node1 =
        new DefaultMutableTreeNode("Node1");
   DefaultMutableTreeNode node2 =
        new DefaultMutableTreeNode("Node2");
   DefaultMutableTreeNode node3 =
        new DefaultMutableTreeNode("Node3");
   DefaultMutableTreeNode node4 =
        new DefaultMutableTreeNode("Node4");
   node1.add(node2);
   node2.add(node3);
   node1.add(node4);
   Enumeration e = node1.breadthFirstEnumeration();
   assertEquals(e.nextElement(),node1);
   assertEquals(e.nextElement(),node2);
   assertEquals(e.nextElement(),node4);
   assertEquals(e.nextElement(),node3);
 }
}
```

A.6 Assessment and Perceptions

A short experiment was conducted in two CS1 sections at the University of Kansas in Spring 2005. The two sections were taught by the same instructor using a popular C++ textbook. The experiment was conducted in three fifty-minute lectures

and one fifty-minute lab that covered the introduction of classes and arrays. While both sections had been introduced previously to the `assert()` macro, during this experiment the first section was instructed using TDL and the second section was presented examples in a traditional manner using standard output with the instructor explaining the expected results.

At the end of the experiment, all students were given the same short quiz. The quiz covered concepts and syntax from the experiment topics. In order to make the two sections homogeneous, two outliers (36 and 48 out of 100 on the first exam prior to the TDL experiment) were removed from the sample, leaving all students with first exam scores above 73. The results given in Table A.1 indicate that the TDL students scored about ten percent higher on the quiz than the non-TDL students. While a larger study is needed before drawing any conclusions, the results indicate that TDL can be integrated without negative consequences and support further investigation into potential benefits.

	Students	**Exam 1** 100 total	**Quiz 1** 10 total
TDL	13	86.15	7.84
Non-TDL	14	86.71	7.14

Table A.1: TDL vs. Non-TDL Mean Scores

To gauge programmer perceptions of Test-First and Test-Last programming, a survey was conducted at the beginning of a range of courses at the University of Kansas including CS2, an undergraduate software engineering course, and a graduate software engineering course. Additionally, the survey was conducted at the end of a four-day training course for professional software developers in a large corporation after exposure to TDL. Students were briefly introduced to the differences between Test-First and Test-Last programming, then asked their opinions of the two approaches and asked which approach they would use given the choice. Results are summarized by course in Table A.2 and by years of programming experience in Table A.3. The Test-First (TF) and Test-Last (TL) opinions were recorded on a five-point scale with 0 being the most negative and 4 the most positive.

As the data shows, while the groups all had similar opinions of the Test-First and Test-Last approaches, the more experienced programmers were much less likely to choose a Test-First approach. Comments recorded on the surveys indicated that the predominant reason was a tendency to stick with what you know (Test-Last). Perhaps it is no surprise that younger students are more open to trying new ideas, but this points to the fact that early introduction of good ideas and practices may minimize resistance.

Course	No. of Students	Avg. TF Opinion	Avg. TL Opinion	Choose TF
CS2	28	2.71	2.75	54%
SE	10	2.63	3.70	50%
SE(grad)	12	2.91	2.83	67%
Industry	14	2.85	3.14	29%

Table A.2: TDD Survey Responses by Course

Exp. (Yrs)	No. of Students	Avg. TF Opinion	Avg. TL Opinion	Choose TF
<=10	55	2.75	3.00	55%
>10	10	2.75	3.00	22%

Table A.3: TDD Survey Responses by Experience

A.7 Conclusions of early TDL study

This chapter has proposed a novel method of teaching computer programming by example using automated unit tests. Examples of using this approach in a range of courses have been provided, and the approach has been initially assessed. Connections between this approach and test-driven development were also explored.

This research has shown that less experienced students are more open to adopting a Test-First approach, and that students who were taught for a short time with the TDL approach had slightly better comprehension with no additional cost in terms of instruction time or student effort. In addition, the benefits of modeling testing techniques and introducing automated unit testing frameworks have been noted.

Additional empirical research and experience is needed to confirm the positive benefits of TDL without negative side-effects, but the approach appears to have merit. It seems reasonable that textbooks, lab books, and on-line references could be developed with the TDL approach. Some materials are already available online at http://www.simexusa.com/tdl/.

Appendix B

TDL and TDD Training Materials

This appendix presents several instructional materials developed in conducting this research. Samples include lecture slides, labs and project descriptions.

B.1 Sample Academic Materials

B.1.1 CS1 Lecture Slides

The following slides were used in the CS1 guest lecture introducing automated unit testing and the test-first and test-last approaches.

Automated Unit Testing

EECS 168 Programming 1
David Janzen

Perfection is Impossible

- No one writes perfect code the first time, every time
- How do we find out if code is correct?
  - Testing
- Forms of testing
  - **Compiling** tests for valid syntax
  - **Acceptance testing** involves running the program as a user testing for correct operation
  - **Unit testing** involves testing individual units (functions)
- Once we know there are defects, we must fix them through code review and debugging

Exhaustive Testing is Impossible

- Even a simple one-parameter function can have an infinite number of inputs

```
float square(float number)
{
   return number * number;
}
```

- So we test with a representative set of input/output combinations

  -14.8, -1, 0, 0.0001, 5.987, 22, 1025.9

Manual Unit Testing

- Individual units can be tested by writing drivers

```
// This function sums the integers from min to max inclusive.
// Pre: min < max
// Post: return-value = min + (min+1) + ...  + (max-1) + max
int sum(int min, int max);

int main()
{
  int first, second;
  cout << "Enter two integers, the first smaller" << endl;
  cin >> first >> second;
  cout << "sum(" << first << "," << second << ") is "
       << sum(first,second) << endl;
  return 0;
}
```

Automatic Unit Testing

- Individual units can be tested by writing automated tests with assert()
- assert() takes one boolean parameter

```
#include <cassert>
int sum(int min, int max);

int main()
{
  assert(sum(0,2) == 3);
  assert(sum(-2,2) == 0);
  assert(sum(3,7) == 25);
  return 0;
}
```

assert()

- If assert's parameter is false, then program execution is halted and a message is given

```
#include <cassert>
int sum(int min, int max);

int main()
{
  assert(sum(3,7) == 15);
  return 0;
}
```

```
$./a.out
assertion "sum(3,7) == 15" failed: file "sumtest.cpp", line 36
```

Assert() alternative

- The following[1] gives extra information

```
#include <cassert>
#define Assert(b,s) { if (!(b)) s; assert(b); }
int sum(int min, int max);

int main()
{
   Assert(sum(3,7) == 15,
          cout << "sum(3,7) = " << sum(3,7) << endl);
   return 0;
}
```

```
$./a.out
sum(3,7) = 25
assertion "sum(3,7) == 15" failed: file "sumtest.cpp", line 40
```

1. Contributed by Dr. John Gauch

Organizing Tests

```
#include <cassert>
void run_tests();
int sum(int min, int max);

int main()
{
  run_tests();
  //what the program actually does
  return 0;
}
void run_tests()
{
  assert(sum(0,2) == 3);
  assert(sum(-2,2) == 0);
  assert(sum(3,7) == 25);
}
```

```
int sum(int min, int max)
{
  int sum=0;
  for(int i=min;i<=max;i++)
  {
    sum += i;
  }
  return sum;
}

int sumrec(int min, int max)
{
  if(min == max)
  {
    return min;
  }
  if(min < max)
  {
    return min + sumrec(min+1,max);
  }
}
```

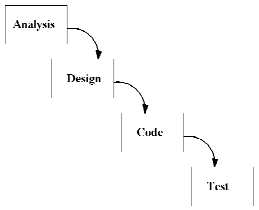
```
void run_tests()
{
  assert(sum(3,7) == 25);
  assert(sumrec(3,7) == 25);

  assert(sum(-2,3) == 3);
  assert(sumrec(-2,3) == 3);

  assert(sum(-5,5) == 0);
  assert(sumrec(-5,5) == 0);
}
```

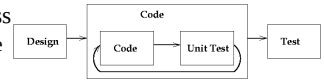
When do we test?

- Traditional linear/waterfall model
- "Big design up-front"

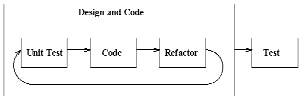


Test-First vs. Test-Last

- Test-Last process
  1. Design software
  2. Write code
  3. Write unit tests
  4. Repeat to 2



- Test-First process
  1. Write a unit test
  2. Write code to make test pass
  3. Refactor code and test
  4. Repeat to 1



B.1.2 Sample CS1 Lab

EECS 168 - Laboratory Assignment 6
The objective of this laboratory assignment is to introduce you to the notion of "problem decomposition" using functions. We will focus on defining new functions, calling functions, using return values, and debugging functions. In addition, automated unit testing with **assert()** will be covered. This assignment has the following steps:

1. Generating random numbers

   The **rand** function generates a random integer between 0 and RAND_MAX (a symbolic constant defined in the <stdlib.h> header file). The minimum value of RAND_MAX must be at least 32767. If we want a to generate random numbers to simulate the throw of a dice, then all we need is numbers between 1 - 6. To achieve this the mod % operator is used:
   1 + rand % 6 will return a random number from 1 to 6.

   The **rand** function is actually a pseudo-random number generator. Calling rand repeatedly produces a sequence of numbers that appears to be random. However, the sequence repeats itself each time the program is executed. The following example illustrates this.

   The given program is a simulation of a very basic online Roulette spinning wheel. It is based on a single number bet. The returns usually are 35 to 1. Cut and paste this program into a cpp file and execute more than once. Follow the sequence of values closely.

```
//-------------------------------------------------------
// Roulette.cpp
// Program to demonstrate rand() and srand() functions.
// Author Suchit Batheja
// Fall 2003
//-------------------------------------------------------

#include < iostream >
#include < cstdlib >
#include < ctime >
using namespace std;

int main()
{
   int Number;
   double Bet;
   int Roule = 0;
```

```
   // Repeat until user quits
   char Ch = 'y';
   while ((Ch == 'Y') || (Ch == 'y'))
   {
      // Get number
      Number = -1;
      while ((Number < 0) || (number > 36))
      {
        cout << "enter number to bet on (between 0 - 36) "
             << endl;
        cin >> Number;
      }

      // Get bet
      Bet = 0.0;
      while (Bet <= 0.0)
      {
        cout << "enter bet amount" << endl;
        cin >> Bet;
      }

      // Spinning the wheel
      Roule = rand() % 37;

      // After Spinning
      cout << "lucky number is  " << roule << endl;
      if (number == roule)
      {
         cout << "congratulations!! you have won "
              << (35 * bet) << endl;
      }
      else
      {
         cout << "oops you lost. better luck next time :-("
              << endl;
      }
      cout << endl << "play again y/n" << endl;
      cin >> Ch;
   }
   return 0;
}
```

If you noticed, the random number sequence generated over different executions are the same. This is useful if you wish to run the same experiments again, but not good for a game of chance. To overcome this problem a function called **srand(unsigned int)** can be used to change the starting point of the sequence.

If the seed remains the same over multiple executions then the sequence generated is again pseudo random. If the seed is made based on the system time, it will be different every time we run the program and we will get a different random sequence every time. Insert this line of code in your program: **srand(time(NULL));** The seed is now set to the current time. Now see how lucky you get.

Program output

2. Writing automated unit tests with assert()

   Another useful function (actually its a macro) in the C++ standard library is **assert()** . assert() is defined in the standard include file cassert. assert() takes one parameter which is a boolean expression. If the expression evaluates to true, then nothing happens when the assert() is executed. If the expression evaluates to false, then the program halts at that point and prints a message indicating the line and the expression of the failing assert().

   assert() statements can be added to your programs to test your code. For instance, the following program uses assert() to verify that the sum() function works correctly.

```
//--------------------------------------------------------
// sum.cpp
// Program to demonstrate assert() macro.
// Author David Janzen
// Fall 2005
//--------------------------------------------------------
 #include <iostream>
 #include <cassert>
 using namespace std;

 int sum(int min, int max);

 int main()
 {
   assert(sum(3,7)==25);
```

```
  assert(sum(-2,3)==3);
  assert(sum(-5,5)==0);
  cout << "No errors encountered" << endl;
}

// This function sums the integers
//   from min to max inclusive.
// Pre: min < max
// Post: return-value = min + (min+1) + ...
//   + (max-1) + max
int sum(int min, int max)
{
  int sum = 0;
  for(int i=min;i<=max;i++)
  {
    sum += i;
  }
  return sum;
}
```

Add three more assert statements to test the sum() function. For instance, pass in two negative numbers or make both parameters the same number.

Your main function

3. User defined functions

   The following functions can be used to calculate the volumes of three different solids. Show how you should call each of these functions in the main function to perform the specified tasks. Make sure the data types on parameters and return values match the function definitions.

```
//-------------------------------------------------------
// Author: John Gauch
// Date:   Fall 2003  //tests added by David Janzen Fall 2005
//-------------------------------------------------------
#include <iostream>
#include <cassert>
using namespace std;

// Function prototypes
```

```
float cubeVolume( float sideLength );
double sphereVolume( float sidelength );
int cylinderVolume( float radius, int height );

// Calculate the volume of a cube
float cubeVolume( float sideLength )
{
   return ( sideLength * sideLength * sideLength );
}

// Calculate the colume of a sphere
double sphereVolume( float radius )
{
   return ( (4.0 / 3.0) * 3.14159 * radius * radius * radius );
}

// Calculate the volume of a cylinder
int cylinderVolume( float radius, int height )
{
   return (int) ( 3.14159 * radius * radius * height );
}

// Main function to test volume functions
int main( int argc, char * argv[] )
{
   // Use assert() to write a test to compute
   // the volume of a cube whose sides are 4 long

   // Use assert() to use a sphere radius and output volume

   // Use assert() to calculate the volume of a Pepsi can

   cout << "No errors encountered" << endl;

return 0;
}
```

Your main function

4. Write a short function

   N Factorial is equal to the product of all integers from 1 to N. Specifically,

factorial(N) = N x (N-1) x (N-2) x ... x 2 x 1. Write an **iterative function** that performs the N Factorial calculation. The function should take an int as a parameter and return an int as the result of the function.

Write a short program that uses assert() to test your factorial function. Place all your assert() statements in a run_tests() function like this:

```
void run_tests();

int main()
{
  run_tests();
}

void run_tests()
{
  { //test 1
    assert(  /* fill this in */ );
  } //test 1

  { //test 2
    assert(  /* fill this in */ );
  } //test 2
}
```

Tests like these are called **unit tests** because you are testing one unit (a function) of your program. Writing tests after you have written some code is called **test-last** programming. An alternative is to do **test-first** programming where you write a test first, then write a function to make the test pass, then repeat to write another test. Notice that test-last programming primarily uses tests to verify that the code works correctly, while test-first programming forces you to make design decisions such as the function name, the function parameters, the function return type, and the function's expected behavior when you are writing the test. We will apply a test-first approach in lab next week.

Now that you have tested your factorial function, extend your program so that it prompts the user for a value of the N to calculate factorial. The program should output the result of the calculation, then prompt the user again. It should prompt the user until the user enters a value of zero. Then the program should exit. Leave the tests in the program. You can comment out the call to run_tests() if you don't want them run.

Here is a sample of what your output might look like:

```
> Enter value of N: 3
Factorial(N) = 6
> Enter value of N: 5
Factorial(N) = 120
> Enter value of N: 0
End of program.
```

Your factorial program

5. Run the program

   Test the program you created by calculating two or three typical values and copy the output of the program below. See if you can "break" the program by changing what you input. Tests like these are called **integration tests** because you are putting everything together, or if the user is running them they are called **acceptance tests** because you are seeing if the whole program functionality is acceptable. Cut and paste your results below.

   Your program output

6. Debugging a program

   The following program uses functions to generate the multiplication table of the number passed to the function. It was developed without any unit tests. Identify the errors present in the program and correct them. Add comments to the program to explain what each function does.

```
//-------------------------------------------------------
// Author: Abhishek Shivadas
// Date:   Fall 2003
//-------------------------------------------------------

#include <iostream>
using namespace std;

void multiply_by_two(int number);
int multiply_by_three(int number);

int main()
```

```
{

    float number_two;
    char  number_three;
    int number_four;

    cout << "Enter the Number to multiply by two:" << endl;
    cin >> number_two;

    cout << "Enter the Number to multiply by three:" << endl;
    cin >> number_three;

    cout << "Enter the Number to multiply by four:" << endl;
    cin >> number_four;
}

void multiply_by_two(float number)
{
    int i;
    for(i = number; i <= 9; i++)
        cout << i << "times 2 is" << number * 2;

    return i;

}

int multiply_by_three(int number)
{
    int i;
    for(i == number; i <= 9; i++)
    {
           number = number * 3;
               cout << i << "times 3 is" << number * 3;
           return number;
    }

}

int multiply_by_four(int number)
{
    int i;
    boolean finished_calculating = true;
```

```
    for(i = number; i <= 9; i++)
        cout << i << "times 4 is" << number * 4;

    return finished_calculating;
}
```

Create a C++ program called Number_Functions.cpp, and use “cut” and “paste” to copy the text above into the same. What errors do you get when you try to compile the program? Before you start correcting these errors, edit the file to add comments describing the purpose of the program, the author, and date at the top of Number_Functions.cpp. Now, start entering your corrections to make the compile errors go away. As a general rule, it is best to start with the first error message and recompile until that error is corrected.

For each correction, make a comment near the code you corrected indicating what you did. This way, you can remember what you did. When you work on joint programming projects everyone can keep track of changes to the code by reading everyone’s comments. Ponder over the warnings which appear while compiling the code and if possible try to correct the warnings as well. The output of the above program should be like this:

```
"Number" times "2 or 3 or 4" is "Answer"
         .
         .
         .
         .
         .
9 times "2 or 3 or 4" is "Answer"
```

Corrected code

Output here

7. Submit Your Work

   This lab assignment will be submitted electronically to the TAs once you fill in the fields below and click on the “submit” button. You do NOT need to print a copy of this document to hand in.

   Your full name: Your kuid number:

   If you are ready to send the lab to the grader, click on the submit button. Otherwise, go back and fill in any missing pieces and then submit your work.

B.1.3 Sample CS2 Lab

EECS 268 - Laboratory 3

The primary objective of this lab is to learn testing approaches to improve programming practice. Automated unit testing with assert() will be covered. Secondary objectives include a review of programming with objects, and managing header files and implementation files.

Testing and Debugging Discussion
No one writes perfect code the first time, every time.

Even after code **compiles** , it must be tested to verify that it works the way the *programmer* thinks it should work (**unit** and **integration testing**) and the way the *client* thinks it should work (**acceptance testing**).

Tests may reveal **defects** in the code and defects must be corrected. Often defects can be located and corrected simply by looking at the code and thinking about it. Sometimes defects are more difficult to find and fix. One approach with these types of defects is to insert output statements into the code. This approach however is not recommended as it is often very time-consuming and frustrating, plus it introduces changes to the very code that you are testing and debugging. Another approach is to use a **debugger** . A debugger is a tool that lets you "walk" through the program one line at a time and inspect variables (see their current values) as you go. Last week in lab, we discussed debugging and gained experience with the Data Display Debugger (DDD) software. Debuggers are useful tools for finding the causes of defects after we already know there is a defect. Testing is used to discover the *existence* of defects.

Entire programs can be tested directly by running the program with various inputs and checking for corresponding outputs. This process can be **manual** (by hand) or it can be **automated** using scripts, input/output files, file redirection, and diff tools. Individual units (e.g. functions) can also be tested directly by writing unit tests. We will look at a mechanism for writing **automated unit tests** in lab today. Automated unit tests can be written before and as you write your program (**Test-First**) or they can be written after you have written your program (**Test-Last**). The great thing about automated unit tests is that you can run them over and over again very quickly. If you make a change to your code, you can immediately run the tests to see if you broke anything. **Writing automated unit tests with assert()** Suppose you are writing a Date class. The code written so far might look like the following:

In file *Date.h*

```
class Date {
public:
  Date();
  Date(int,int,int);
  int getMonth();
  int getDay();
  int getYear();
private:
  int month;
  int day;
  int year;
};
```

In file *Date.cpp*

```
#include "Date.h"

Date::Date()
{
  month = 0;
  day = 0;
  year = 0;
}

Date::Date(int m, int d, int y)
{
  month = m;
  day = d;
  year = y;
}

int Date::getMonth()
{
  return month;
}

int Date::getDay()
{
  return day;
}

int Date::getYear()
{
```

```
  return year;
}
```

Although this code is fairly simple and probably works correctly, how would we test it? One approach is to write automated unit tests using the assert() macro. assert() is defined in the standard include file cassert. assert() takes one parameter which is a boolean expression. If the expression evaluates to true, then nothing happens when the assert() is executed. If the expression evaluates to false, then the program halts at that point and prints a message indicating the line and the expression of the failing assert(). A test driver might look like the following:

In file *driver.cpp*

```
#include "Date.h" #include <cassert>

void run_tests();

int main()
{
  run_tests();
}

void run_tests()
{
  { //test 1
    Date d;
    assert(d.getMonth() == 0);
    assert(d.getDay() == 0);
    assert(d.getYear() == 0);
  }
  { //test 2
    Date d(6,14,1924);
    assert(d.getMonth() == 6);
    assert(d.getDay() == 14);
    assert(d.getYear() == 1924);
  }
}
```

This test driver consists of two unit tests. Each test has been isolated in its own block and labelled with a comment. All of the unit tests have been separated in a function called run_tests(). This keeps the tests separate from the actual code, and makes it easy to turn off the tests if you want to (e.g. comment out the call to run_tests()). Note that you can still have main() perform whatever actions you would normally put in main().

Assignment Part 1
Create a directory for this lab. Copy the three files from above into this directory and create a Makefile to compile them (see instructions from Lab 1 if you need help with creating the Makefile). Compile and run the program. If there are no errors, then nothing is printed and you are returned to a prompt.

Assignment Part 2
Now introduce an error just to see what would happen. For instance, change the first assert to be

```
assert(d.getMonth() == 3);
```

instead of

```
assert(d.getMonth() == 0);
```

Compile and run the program again to see what is printed when the test fails.

Correct the test and make sure the tests all pass.

Assignment Part 3
What would happen if we put in a month larger than 12 or less than 1? Let's say that we want our Date class to set the month to 1 if it is given a month outside the range 1 to 12. Later we will learn about a better solution to this problem in the form of **exceptions** , but for now we will just set the month to 1 for bad input. Add a test that checks to see that giving a month larger than 12 results in the month being set to 1. Add the code so that if months are outside the range 1 to 12, then the month is set to 1. Add similar code to set day to 1 if it is outside the range 1 to 31, and add tests to see if it works. For now you may ignore leap years and assume that all months have 31 days. **Test-First Programming** Now suppose you want to add new functionality to your Date class such as a new member function that allows you to add a number of days to a Date. You have two choices. You could write the new member function first, then write additional tests to see if your function works correctly. Or you could write the test first, run it (it should fail, if it doesn't, ask why not), then implement the code to make the test pass.

Test-first programming (or **test-driven development**) involves the following steps:

1. Write a new test
2. Write just enough code to make the test pass
3. Improve the structure of the code and the test

4. repeat to 1

Completing the first three steps should be kept fairly short, maybe only about 15 minutes. That means your tests are very focused and specific, not too broad or complex.

Assignment Part 4
Write a test to call the function (that doesn't yet exist) that adds a number of days to a Date object. Run the test, see it fail, then write the simplest code you can think of to make it pass (don't worry about wrapping around to the next month or year in your first test, for example add 3 to January 2). Check the code and the test to see if they are the simplest and cleanest that they can be. Now write another simple test and make sure it works as well. If not, fix the code and/or the test. Now write another test, perhaps one that causes the month to increment (e.g. add 5 to March 30). Again, don't worry about leap years, but do account for different length months.
Months with 28 or 29 days: February
Months with 30 days: April, June, September, November
Months with 31 days: January, March, May, July, August, October, December

Continue this process in a test-first manner until you are happy with the new function and confident that it works correctly. **Test-Last Programming** Test-last programming is similar to test-first except the tests are written after the code is implemented, not before. Notice that a test-last approach focuses on verifying that the code you wrote works correctly. A test-first approach influences design decisions because you have not yet written the code. With a test-first approach, you decide the name of a function, its parameters, and its return types (i.e. its interface) as well as its expected behavior when you write the test. A test-last approach assumes you've already made these design decisions before you wrote the code that you are now testing.

Assignment Part 5
Use a test-last approach to add another function to the Date class that allows you to add a number of months to a Date (hint: you might have it call the function that adds a number of days).

Assignment Part 6
Using a test-first approach, add tests and the code to make sure that the two functions that you created above correctly handle leap years. If a test fails, remember that you can use DDD to step through your new code. The following rules define leap year calculation:

1. Years divisible by four are leap years, unless...
2. Years also divisible by 100 are not leap years, except...
3. Years divisible by 400 are leap years.

Assignment Part 7
Using either a test-first or a test-last approach, define a new class called Person with the following members

- instance variables
  - private firstName:string
  - private lastName:string
  - private payday:Date
- accessors and mutators for each instance variable
- incrementPayDay():void which moves the payday to two-weeks later

Be sure to define the class in a header file, e.g. Person.h, and implement it in a separate implementation file, e.g. Person.cpp. Be sure all instance variables are declared private. Adjust your Makefile accordingly. Use the *same approach* (test-first or test-last) until you are finished with this part.

Assignment Part 8
When you are finished with all of the above, submit all header files, implementation files and your Makefile as specified in the submission guidelines. Indicate whether you used a test-first or a test-last approach in Part 7 by adding either TL (for test-last) or TF (for test-first) to the name of your tar file. For example, FirstLastLab3TL.tar.gz for a test-last program.

B.1.4 Sample CS1 Project

EECS 168 - Programming Assignment 4
Contributed by Dr. John Gauch

1. Problem Statement:

Most programming languages have built in data types for integers, floating point numbers, and characters, but there are many programming applications that require specialized data types. For example, in computer graphics we need to store (x,y,z) coordinates that define lines, planes, and other geometric objects.

The purpose of this programming assignment is to design, implement, and test a data structure for storing (x,y,z) coordinates together with a collection of operations on these three-dimensional points. The assignment has three "hidden" goals: 1) to give students exposure to the concept of abstract data types, 2) to give students more experience with arrays and functions, and 3) to give students practice developing and testing moderate sized pieces of software.

There are many ways to represent (x,y,z) points in C++, but for this assignment you are required to use a one-dimensional array of length three integers for each point in your program. Specifically, if you declare "int point[3];" then x will be stored in point[0], y will be stored in point[1], and z will be stored in point[2]. All of your arithmetic and geometric operations on (x,y,z) points will make this assumption, and expect these arrays as input/output parameters.

Data structures are pretty boring unless there are useful operations you can perform on them that assist in the implementation of an application. For this assignment, you are required to design, implement, and test the following operations:

Input - create a function that reads three consecutive numbers from the user and stores these in the x, y, and z coordinates of a point.

Output - create a function that prints points in the following format (1,3,5), with round brackets and commas separating the x, y, and z coordinates.

Equal - create a function that compares two (x,y,z) points and returns true if they are equal to each other and false otherwise. This function should be very helpful for testing and debugging subsequent operations.

Addition (A), subtraction (S), multiplication (M), division (Q) - create four functions that take two points as input, and perform the corresponding arithmetic operation to create the output. Remember, operations are done on a coordinate-by-coordinate basis, so (1,2,3) + (6,4,2) = (7,6,5).

Euclidean Distance (E) - create a function that calculates the Euclidean distance between two (x,y,z) points. The result should be a scalar. Distance calculations are used in computer graphics to decide if one object is near another object, which is very useful for preventing people from going through walls in video games.

Dot product (D) - create a function that calculates the dot product (also known

as the inner product) of two points. The result should be a scalar. The dot product is used in computer graphics to see if two vectors are perpendicular, which occurs when their dot product is zero.

Cross product (C) - create a function that calculates the cross product (also known as the outer product) of two points. The result should be another (x,y,z) point. The cross product is used in computer graphics to calculate the direction that is perpendicular to two other vectors, which is helpful for finding surface normals.

Finally, to test all of your operations, you need to implement a main program that reads and executes a series of point operations using the single character short forms above. For example, the command to calculate (1,2,3) + (6,4,2) would take the form "A 1 2 3 6 4 2". Your program should output "(7,6,5)". Your program should read and execute commands until an end-of-file is reached or until the user types "X" for exit.

Honors Students: Design and implement your program so it can handle N-dimensional points. You will need to pass the size of each point together with the coordinates into each of the functions above. Note that cross products only work for 3-dimensional points, so you will have to modify that function accordingly. When you are implementing your command line interpreter, you will need to add the size of the array as the second argument before the list of coordinate values. For example, if N=2 you would enter "A 2 3 4 5 6" to calculate the value of (3,4) + (5,6). Since we have not learned about dynamic memory allocation yet, your program can allocate 'big' static arrays and waste some space.

2. Design:

The specifications for this program are fairly detailed, but there is still a lot of software design that must be done before you start programming. First of all, you need to find out what the formulas are for all of the operations above. Are there any special cases for these formulas that need to be considered? Then you need to think about the control flow for this program. How do you want to break the problem into pieces? How will you put these pieces together?

3. Implementation:

Start your program with comments based on your design and add portions of code a little at a time. Compile and test your program on a regular basis, so you always have something that runs, even if it only does part of the job. Make sure you have completed the easy tasks before you start writing code for the harder tasks.

For this assignment, we would like you to keep track of the time you spend developing your program so you can develop time management skills and so we can learn about how long students take to complete projects as they learn more about C++ and develop their skills. We will not be using this information to assign grades,

so short or long times are not a plus or a minus. One easy way to keep track of your time is to add a comment at the top of the file with the start and end time of each of your programming sessions. It is also helpful to add some notes on what you did during this time. When you are finished, you can add a comment with total programming time.

4. Testing and Debugging:

In the labs you have learned about two approaches for software testing that make use of the "assert" function. In the "test first" approach, you write the software to test pieces of your program before you actually implement that operation. In the "test last" approach you write the testing software after you implement an operation. In both cases, you correct problems as they are discovered, and develop your working program in an incremental way.

For this assignment, we would like students with even KUIDs to develop and test their programs using the "test first" approach, and students with odd KUIDs to use the "test last" approach. In a later assignment, you can switch to the opposite testing approach so you can decide which method suits your programming style.

We want to see what testing you performed while developing your program, so please do not delete your assert code. Instead you can comment it out when you are finished testing that portion of the code.

5. Documentation:

When you have completed your C++ program, write a short report (less than one page long) describing what the objectives were, what you did, and the status of the program. Does it work properly for all test cases? Are there any known problems? Save this report in a separate text file to be submitted electronically.

6. Project Submission:

In this class, we will be using electronic project submission to make sure that all students hand their programming projects and labs on time, and to perform automatic analysis of all programs that are submitted. When you have completed the tasks above go to the class web site to submit your documentation, C++ program, and testing files.

The dates on your electronic submission will be used to verify that you met the due date above. All late projects will receive reduced credit (50% off if less than 24 hours late, no credit if more than 24 hours late), so hand in your best effort on the due date.

You should also PRINT a copy of these files and hand them into your teaching assistant in your next lab. Include a title page that has your name and kuid, and attach your hand written design notes from above.

B.1.5 Sample CS2 Project

EECS 268: Fall 2005 Programming Project 1
Project Objective
To practice abstraction, recursion, automated unit-testing, and creation of a basic List ADT.

Instructions
The division of motor vehicles wants you to write a program that will keep track of some drivers with traffic citations. Define a class Person with instance variables to store:

1. Driver's license number.
2. Name of a driver including first and last names.
3. Number of citations issued in the past three years.

Define a class DriverTable with an array of Person objects stored in ascending order by licNumber.

DriverTable(see below for a more detailed description of each class member)
-drivers -size -findIndex(in licNumber: integer, in first: integer, in last: integer, out index: integer) {query} +createTable() +copyTable(in copyMe: DriverTable) +destroyTable() +isEmpty(): boolean {query} +getLength(): integer {query} +insert(in newDriver: Person, out success: boolean) +getDriver(in index: integer, out item: Person) {query} +remove(in licNumber: integer, out success boolean) +findDriver(in licNumber: integer, out item: Person, out success: boolean) {query}

If you are a little confused on exactly what each of the DriverTable methods should be doing then this information may be of some help.

Instance Variables:

- drivers - This is a static sized array of Person objects. Since the spec does not say how big your array should be it is up to you to decide.

- size - This is the number of Person objects in the array. Perhaps size is a misleading identifier for the variable since size might imply array capacity instead of the number of people in the array.

Instance Methods:

- findIndex - This method is an "internal" (i.e. private) method that searches for a given person. This method must be implemented as a recursive binary search. The first and last parameters of the method are the indices of the array to be searched. The method returns the index of the person with the given license number. You can return -1 to indicate no person with given number exists.
- createTable - This method simply resets the DriverTable object to an empty array with zero people. For this project the method is not that interesting (you only have to assign the the number of people to zero), but in Project 2 it will be more interesting.
- copyTable - This method copies the people in the DriverTable object parameter into the "this" DriverTable object. You probably won't ever call this method in Project 1, but it may come in handy for Project 2.
- destroyTable - Like createTable, this method resets the DriverTable object to an array with zero people. Again, it will be more interesting in Project 2. Also, like copyTable, you probably won't use it in Project 1.
- isEmpty - This method simply returns true if and only if the DriverTable object has zero Person objects in it. Otherwise it returns false.
- getLength - This method returns the number of people in the DriverTable.
- insert - This method inserts a Person object into the array in ascending order based on license number and returns true if and only if the person could be inserted. An example of when the method should return false is when there is no more room in the array to insert another person. How are you going to handle duplicate license numbers? Although the project description does not specifically mention how to handle the situation, allowing duplicate license numbers doesn't make much sense and you should disallow it.
- getDriver - This method returns the driver at a certain ordinal position in the list of Person objects. Although arrays are indexed starting at position zero, general lists start with one. Hence, when one is passed in as the index then you will return driver[0]. You will find this method useful when you display the entire list of people. The project does specify how to handle invalid indices. Thus, that decision is left to you. Acceptable solutions include returning a null Person object, returning an additional boolean value, and using exceptions.

- remove - This method removes the Person object with the associated license number and returns true if and only if that person was removed. Hence, the method returns false when the license number was not found. This method must utilize the findIndex method.
- findDriver - This method returns the Person associated with a given license number and returns true if and only if a person with that license number could be found. This method must utilize the findIndex method.

Input
In an input file, a sequence of commands will be given with one command per line. You are required to write a driver program to process the following commands.

I licNumber Name Number // insert a new driver
R licNumber // remove a driver with given licNumber
G index // find and output driver info of the given index
F licNumber // find and output info on driver
D // output info on all drivers in Table

Sample input file:

I 41109 Chris Johnson 18
I 32298 Martha Smith 2
I 81132 Hillary Clinton 4
G 2
D
R 12345
R 32298
D
I 42112 Laurie Evans 0
F 81132
D

Sample output file:

Insert driver 41109 Chris Johnson 18

Insert driver 32298 Martha Smith 2

Insert driver 81132 Hillary Clinton 4

The driver in 2 position is: 41109 Chris Johnson 18

Current driver table has drivers:
32298 Martha Smith 2
41109 Chris Johnson 18
81132 Hillary Clinton 4
Driver 12345 can not be removed

Driver 32298 is removed

Current driver table has drivers:
41109 Chris Johnson 18
81132 Hillary Clinton 4

Insert driver 42112 Laurie Evans 0

Driver 81132 Hillary Clinton 4 is found

Current driver table has drivers:
41109 Chris Johnson 18
42112 Laurie Evans 0
81132 Hillary Clinton 4

General Requirements

1. You may not use any global variables.
2. Each class must be defined with a pair of files: a header file describing the methods and instance variables, and a c++ file with the implementations.
3. Only header files may be #include-ed. Each c++ source file must be separately compiled via directives in your *makefile* .
4. *All* instance variables in *all* classes must be declared **private**.
5. The *friend* keyword cannot be used.
6. Your program must use argc/argv to take a single argument, the input file.
7. Methods remove() and findDriver() must call the internal findIndex() method.
8. You must use the recursive binary search algorithm in findIndex().
9. You should develop this program in a ***test-first*** or a ***test-last*** manner as described in Lab 3. You may choose which approach you use, but use the approach throughout the development of the project. If you don't care which approach you use, choose test-first if your KUID starts with an even number

and use test-last if your KUID starts with an odd number. Indicate which approach you used by adding TL or TF to your project submission tar file.

10. Keep **track of the time** you spend on this project and send the total in the project submission email.

Style Requirements

1. Your code must be well modularized. Your *main* function should simply call a couple other functions; they in turn should be well modularized. (See the **Modularity** section on pages 27-28 of the text and **follow those guidelines**.)

2. You must use an appropriate documentation style, including comments describing the purpose of methods and in-line comments. (See, for example, the "Key Concepts" section on page 43 of the text.)

3. Follow the code paragraphing conventions summarized on pages 40-42 of the text.

Submission
Read and follow the submission instructions when you are ready to submit your lab.

Grading

- Correctness (includes "General Requirements"): 50
- Style (includes "Style Requirements"): 30
- Output Format: 10
- Error Checking: 10

B.1.6 Sample SE Project

EECS810: Principles of Software Engineering Team Projects — Fall 2005

Professor Hossein Saiedian

Team Project

Our software engineering class will be divided into groups of 3–4 students. Large groups are chosen partly to challenge students in issues related to project management. Each team should elect a team leader (or administrator, or manager) who will be responsible for coordinating the activities of the other team members as well as communicating with the instructor. Teams are encouraged to assign other roles to the members, such as 'Project Administrator,' 'Deputy Project Administrator,' 'Configuration Manager,' 'Quality Assurance Manager,' 'Maintenance Engineer,' etc. The team administrator would also be responsible for final technical decisions as well as making sure everyone comes to meetings and does their share of work. The final implementation should be in Java 1.4 (do not use 1.5). One of the UNIX-based systems on campus (e.g., eno.eecs.ku.edu) is acceptable but PC-based systems are also OK. You must strive for operating systems compatibility. The projects will take most of the semester with major write-ups at approximately 2/3-week intervals (1-week interval during summer sessions).

Brief Project Description

Many web-authoring systems and certain application software (e.g., Microsoft FrontPage) as well as practically all web browsers provide for a facility to create and edit HTML pages. The resulting pages may provide nice looking web pages but the actual HTML code is usually awful and consists of badly formed lines (too long or too short), unnecessary white "space" (white space, tabs, blank lines), redundant and superfluous tags, and unaligned statements.

You are requested to specify the requirements and then develop a software that takes as input a file containing HTML code and produces a "pretty-printed" version of the contents of that file (where each line of code is a maximum of n characters, redundant and superfluous tags, and white spaces are removed, and when necessary, bodies of certain tags are indented, etc.). The objective is to make the HTML code readable and manually editable.

You are encouraged to complete this project in teams of three or four individuals. You must strive for conforming to IEEE standards when possible.

Development Process

You should divide your development efforts into two iterations. The first iteration should develop a "core" set of requirements including a text-based interface, per-line character limits, and removal of white space. The second iteration should

add functionality such as tag body indentation and removing redundant and superfluous tags. The second iteration should also add a GUI-based interface for selecting the input/output files, specifying parameters (e.g., number of target characters per line), and displaying the output HTML in a window.

Your team will be asked to apply either a test-last or test-first development approach. Test-first programming (also called test-driven development) is the practice by which an automated test case is written before the code is implemented. The implemented code is written to pass the test case. The design of the system emerges as the programmer repeatedly writes tests, then writes the code to make the tests pass, then improves both the code and tests in short rapid iterations. Test-last programming is the practice by which a test case is written after the code is implemented. The design of the system is usually developed before any substantial amount of code is written. You are expected to write automated unit tests using JUnit whether you are applying a test-first or test-last approach.

Professionalism is Important

You will be graded on the quality of the work you produce, not on how many hours a week you spend on it. Use your energy and time wisely. However, you are requested to create professionally-looking documents, not only for "clients," but also for communication among yourselves. Portfolios, labeled theme binders, etc., are recommended. Choose a name for your group and always write team members' names on the project assignments you turn in. Each part of project worths approximately 50 points and is graded based on accuracy, consistency, and completeness of its contents as well as its organization (e.g., appropriate title, section and paragraph names) and appearance (e.g., consistent page numbers). For each document to be turned in, include a title that identifies the document (e.g., "Requirements Specification for the ... System"), the name of the team, names of the team members, course title, instructor's name, and date.

Even though it is expected that some members of your group will be better writers, some better programmers, and so on, you are not to divide the labor on these grounds. This class is to be a learning experience, and each of you should get a substantial amount of practice in all of these areas, not just the ones you are already good at. You will not be graded directly on your writing style, but good writing often conveys ideas more clearly than poor writing. Thus, it is to your advantage to organize your thoughts and write well. Note that document length is not equivalent to quality. Also, it is a good idea to use the same editor and document preparation system for all documents to make modifications and elaboration into a more detailed document easier.

It is very important that project assignments be completed on time to allow you to complete the entire project on schedule.

Keep a Log of Your Activities

Everyone should maintain a log of the time you spent on the project and a description of what you did during that time. The logs will help you see how you spend your time and help you make better predictions of the time needed by the different phases of a software project.[1] It is also a good idea to record the reason for a computer run, the amount of CPU time, the changes since the last time, the result of run, and so forth. It would always be interesting to look back and see how much time you really spent on the project in front of a terminal and how much you spent away from it.

Project Demonstration and Presentation

The last weeks of classes are reserved for project presentations and demonstrations. Presentations should be formal and will take place in the classroom. All team members should participate and contribute to the presentations. Each team will also have about 30 minutes to present the best features of your system and allow some time for questions and feedback from the audience. If your system has been properly debugged, you can let the audience tell you what to type to show off your error handling and user help facilities. Everyone in the group should participate. You can have each person explain their part of the system or have one person typing while another is talking. You may want to give out a short description of your project. Because the time is so short, it is important to practice what you are going to say and do. A complete, bound version of your project should be turned in during the last week of classes.

Your completed project worths about 40% of your overall grade for the course. The completed project will be graded at the end of the semester for completeness, correctness, documentation, consistency and uniformity.

Essential Project Deliverables and Completion Dates

The following are essential project deliverables and their expected completion dates:

1. **Software Project Management Plan** ..... September 12
2. **Software Requirements Specification and User's Manual** ..... September 19
3. **Software Design**
   (a) Design for entire system (test-last groups) ..... October 17
   (b) Design from iteration 1 (test-first groups) ..... October 17
   (c) Design updated from iteration 2 (test-first groups) ..... October 31

[1] In fact, many industrial organizations require this sort of time-keeping.

4. **Implemented/Tested Product** ..... November 21

   Turn in a binder. Your team project binder should include:

   - An updated version of all previous parts of the project
   - A manual with clear instructions on how to install and run
   - A printed copy of the source program
   - Source program and executable code on a floppy or a CD

5. **Weekly Deliverables** ..... Every Monday

   Every Monday the project leader should turn in the following items electronically (to saiedian@eecs.ku.edu and cc: djanzen@eecs.ku.edu):

   - time logs for each individual team member
   - summary report with team totals by activity
   - software (including JUnit tests) written to date
   - software metrics to date

   The time logs and summary report should report time spent by activity (e.g. requirements analysis, design, coding/unit testing, integration testing, meetings, etc.). The logs and report should account for the previous week (Sunday through Saturday).

   Software should include production and test code along with build scripts. Software should only include "checked-in" code so that only one version of code is submitted.

   Software metrics should report data aggregated by production and test code. You are encouraged to use a metrics collection tool such as CCCC (http://sourceforge.net/projects/cccc).

6. **Presentations** ..... December 5

   Presentations and demonstrations should be limited to 30 minutes and should include an explanation of the software architecture, your team approach to designing the solution, and sample demos. Live demos are fine, provided that you have prepared everything (e.g., compiled programs, prepared test files, etc) in advance. Also, discuss any noble feature of your product (e.g., extensibility, portability) as well as any limitations that it has.

Project Points: 300

Each of the above deliverables worths 50 points. Furthermore, "time log," documentation, summary reports, and measurement collection also 50 points (they are a required part of the project).

Although some may activities require more efforts, points are equally distributed to emphasize the importance of each.

B.1.7 Sample SE Time Sheet

Table B.1 contains a sample time sheet submitted by each team in the software engineering semester-long projects.

Time Sheet	Name:			Week Ending:				
	Enter data in minutes							
Date	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Total
Learning Tools								0
Research								0
General Team Meeting								0
General Project Mgmt								0
Analysis								0
Design								0
Coding								0
Unit Testing								0
Integration Testing								0
Regression Testing								0
Fixing Defects								0
Code Documentation								0
Code Reviews								0
User Documentation								0
Project Presentation								0
								0
								0
								0
								0
								0
								0
Total	0	0	0	0	0	0	0	0

Table B.1: Sample Time Sheet

B.2 Sample Professional Training Materials

B.2.1 Sample TDD Training Slides

Introduction to JUnit and Test-Driven Development

David Janzen

EECS 810 Principles of Software Engineering

eXtreme Programming (XP)

- Core Practices
  - Whole Team/On-Site Customer
  - Planning Game
  - Small Releases
  - Customer Tests
  - Collective Ownership
  - Coding Standard
  - Continuous Integration
  - Metaphor
  - Sustainable Pace
  - Test-Driven Development
  - Pair Programming
  - Simple Design
  - Refactoring
  - See http://www.xprogramming.com/xpmag/whatisxp.htm
  - See "Extreme Programming Explained: Embrace Change" by Kent Beck

Extreme Best Practices

- If *customer feedback* is good
  - then have a customer always on-site
- If *code reviews* are good
  - then always perform code reviews through pair programming
- If *early integration* is good
  - then continuously integrate
- If *unit-testing* is good
  - then require unit-tests and do them first
  - plus make them automated so they are run often

Test-Driven Development

- Disciplined development approach
- Emerging as stand-alone practice from agile methods
  - Utilized in agile and traditional development processes
- Reverses traditional micro workflow
  - test ➡ code code ➡ test
- More about design than testing[1]
- Supported by automated testing frameworks
- Also known as
  - Test-First Programming
  - Test-Driven Design

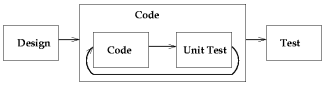
1. Beck, "Aim, Fire", IEEE Software 2001

Types of Testing

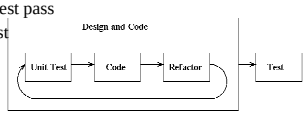
- Unit Testing ★ (TDD focuses here)
  - Testing individual units (typically methods)
  - White/Clear-box testing performed by original programmer
- Integration and Functional Testing
  - Testing interactions of units and testing use cases
- Regression Testing
  - Testing previously tested components after changes
- Stress/Load Testing
  - How many transactions/users/events/… can the system handle?
- Acceptance Testing
  - Does the system do what the customer wants?

TDD Flow

- Test-last process
  1. Design software
  2. Write code
  3. Write unit tests
  4. Repeat to 2



- TDD process
  1. Write a unit test
  2. Write code to make test pass
  3. Refactor code and test
  4. Repeat to 1



Simple TDD Example

```
//Write a test in test folder
package bank;
import junit.framework.TestCase;
public class TestBank extends TestCase {
    public void testCreateBank() {
        Bank b = new Bank();
        assertNotNull(b);
    }
}
```

```
//Test and fail
>javac TestBank.java
//won't compile because Bank class doesn't exist
```

Simple TDD Example

```
//Write Bank class in src folder
package bank;
public class Bank {
    public Bank() {
    }
}
```

```
//Test and pass
>javac TestBank.java
//now we need a driver to execute this and other tests and tell us if
    they pass or fail; JUnit to the rescue
```

Introduction to JUnit

- JUnit is a Unit Testing framework
- Developed by Erich Gamma and Kent Beck
- Freely available at junit.org
- Installs simply
  - Unzip junit.zip into a directory
  - Add junit.jar (with path) to CLASSPATH
- Multiple TestRunners

  java junit.swingui.TestRunner TestBank

  java junit.textui.TestRunner TestBank

  java junit.awtui.TestRunner TestBank

Introduction to JUnit

- Tests can be automatically discovered with reflection
- Tests can be organized into suites
- Each unit test is run in its own classloader to avoid side effects
- Standard resource initialization and reclamation methods (setUp and tearDown)
- Integration with other tools such as Ant and Eclipse

JUnit HowTo

- Import the JUnit framework

```
import junit.framework.*;
```

- Create a subclass of TestCase

```
public class TestBank extends TestCase {
```

- Write methods in the form testXXX()
- Use assertXXX() methods

```
public void testCreateBank() {
    Bank b = new Bank();
    assertNotNull(b);
}
```

- Compile test and functional code; Run a TestRunner to execute tests; Keep the bar green!

JUnit from the Command Line

- From the test directory, compile TestBank.java with **javac –sourcepath ..\src –d . TestBank.java**
- Run the JUnit tests that you just wrote with **java junit.swingui.TestRunner TestBank**
- Keep the bar green!

JUnit in Eclipse

- Eclipse has integrated JUnit
- Create a new project in Eclipse
  1. Select File->New->Project
  2. Select "Java Project" and click Next
  3. Give the project the name "TDDExamples"
  4. Create src and test source folders
  5. Select the Libraries tab and then click "Add External Jars", find and select the junit.jar on your system (look in Eclipse/plugins/org.junit_3.8.1/)
  6. Click Finish

Organizing projects

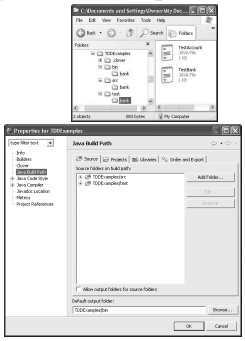
- The more classes in a package or project, the more tests you will have
- When you ship your production code, you won't want to include the testing code
- How do you keep production and testing code separate, but in the same package so the test code has access to everything?

Organizing projects

- One solution is to create "separate but equal" parallel packages
- Place the source code and test code in the same package, but in separate directory structures
- See the bank package to the right

Organizing projects in Eclipse

- Create a project named TDDExamples.
- Setup the parallel packages (bank under src and test folders).
- Set the build path to include bank/src and bank/test and to output to bank/bin.

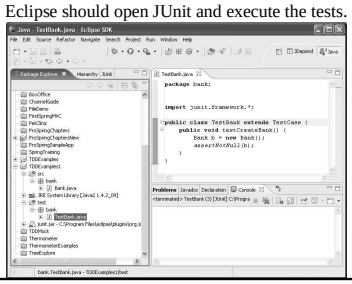


Running JUnit in Eclipse

- Right-click on TestBank.java and select

  Run->Run As->JUnit Test

  Eclipse should open JUnit and execute the tests.



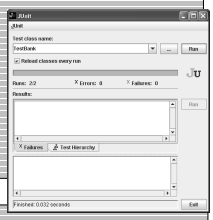
Simple TDD Example: Second Test

```
import junit.framework.TestCase;
public class TestBank extends TestCase {
    public void testCreateBank() {
        Bank b = new Bank();
        assertNotNull(b);
    }
    public void testCreateBankEmpty() {
        Bank b = new Bank();
        assertEquals(b.getNumAccounts(),0);
    }
}
```

```
//Test and fail
>javac TestBank.java
//won't compile because Bank doesn't have getNumAccounts()
```

Simple TDD Example: Second Test

```
//Write Bank class in src folder
public class Bank {
    public Bank() {
    }
    public int getNumAccounts() {
        return 0;
    }
}
```



```
//Test and pass
>javac TestBank.java
//run JUnit and see two tests pass
```

Simple TDD Example: Third Test

```
import junit.framework.TestCase;
public class TestBank extends TestCase {
    …
    public void testAddAccount() {
        Bank b = new Bank();
        Account a = new Account("John Doe",123456,0.0);
        b.addAccount(a);
        assertEquals(b.getNumAccounts(),1);
    }
}
```

```
//Test and fail
>javac TestBank.java
//won't compile because Bank doesn't have addAccount()
```

Simple TDD Example: Account Test

```
import junit.framework.TestCase;
public class TestAccount extends TestCase {
    public void testCreateAccount() {
        Account a = new Account("John Doe",12345,0.0);
        assertNotNull(a);
    }
}
```

```
//Test and fail
>javac TestAccount.java
//won't compile because Account doesn't exist
```

Simple TDD Example: Account Test

```
//Write Account class in src folder
public class Account {
    private int accountNum;
    private String accountOwner;
    private double balance;
    public Account(String owner, int num, double bal) {
        accountNum = num;
        accountOwner = owner;
        balance = bal;
    }
}
```

```
//Test and pass
>javac TestAccount.java
//run JUnit and see tests pass
```

Simple TDD Example: Third Test

```
import java.util.*;
public class Bank {
    private ArrayList accounts;
    public Bank() {
        accounts = new ArrayList();
    }
    public int getNumAccounts() {
        return accounts.size();
    }
    public void addAccount(Account a) {
        accounts.add(a);
    }
}
```

```
//Test and pass
>javac TestBank.java
```

JUnit Exercise

- Add another test to test/TestAccount.java that tests a new method withdraw(double)
- Add the code to src/Account.java that implements withdraw(double)
  - Subtracts the parameter from the balance
- Add another test to test/TestBank.java that tests a new method removeAccount(int)
- Add the code to src/Bank.java that implements removeAccount(int)
  - Search accounts for one with the parameter as the account number, then remove it with remove(int index)

Fixtures

- Notice redundancy in test methods

```
import junit.framework.TestCase;
public class TestBank extends TestCase {
    public void testCreateBank() {
        Bank b = new Bank();
        assertNotNull(b);
    }
    public void testCreateBankEmpty() {
        Bank b = new Bank();
        assertEquals(b.getNumAccounts(),0);
    }
}
```

- Common test setup can be placed in a method named setUp() which is *run before each test*

setUp()

```
import junit.framework.*;
public class TestBank extends TestCase {
    private Bank b;
    public void setUp() {
        b = new Bank();
    }
    public void testCreateBank() {
        assertNotNull(b);
    }
    public void testCreateBankEmpty() {
        assertEquals(b.getNumAccounts(),0);
    }
    public void testAddAccount() {
        Account a = new Account("John Doe",123456,0.0);
        b.addAccount(a);
        assertEquals(b.getNumAccounts(),1);
    }
}
```

setUp() is run before *each* test

tearDown()

- tearDown() is run after each test
  - Used for cleaning up resources such as files, network, or database connections

```
import junit.framework.TestCase;
public class TestBank extends TestCase {
    private Bank b;
    public void setUp() {
        b = new Bank();
    }
    public void tearDown() {
        b = null;
    }
    …
}
```

tearDown() is run after *each* test

TestSuites

- TestCases can be organized into TestSuites
- If no TestSuite is defined, then all code is placed in a default TestSuite and test cases are discovered automatically.
- You can explicitly create a TestSuite that contains some or all TestCases or other TestSuites you want.

TestSuite()

- Each TestCase class can have a suite() method

```
import junit.framework.*;
public class TestBank extends TestCase {
    private Bank b;
    public static Test suite() {
        return new TestSuite(TestBank.class);
    }
    public void setUp() {
        b = new Bank();
    }
    public void testCreateBank() {
        assertNotNull(b);
    }
    …
```

Combining all TestSuite()

- Each TestCase class can have a suite() method

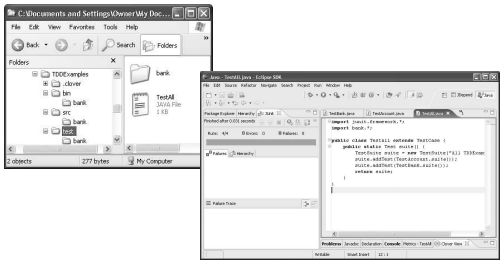
```
import junit.framework.*;
import bank.*;

public class TestAll extends TestCase {
    public static Test suite() {
        TestSuite suite = new TestSuite("All TDDExamples tests");
        suite.addTest(TestAccount.suite());
        suite.addTest(TestBank.suite());
        return suite;
    }
}
```

Could add TestBank.class if TestBank doesn't have suite() defined

Combining all TestSuite()

- Now you can just run TestAll to execute all tests



Other forms of Assert

- Look at the Javadocs for Assert
  - http://www.junit.org/junit/javadoc/3.8.1/index.htm
- Note the many forms of assertEquals
- Note the forms that take a string as the first parameter
  - String provides documentation printed in JUnit on failure

Other forms of Assert

- Note additional methods such as
  - assertTrue
  - assertFalse
  - assertNotNull
  - assertNull
  - assertSame
  - assertNotSame
  - fail
    - Used with complex logic to determine failure, and when testing exceptions

Testing Exceptions

- Suppose we changed the requirements of our Account class so that it should throw an exception if it is given a negative balance
- How do we test to see if the exception is thrown correctly?

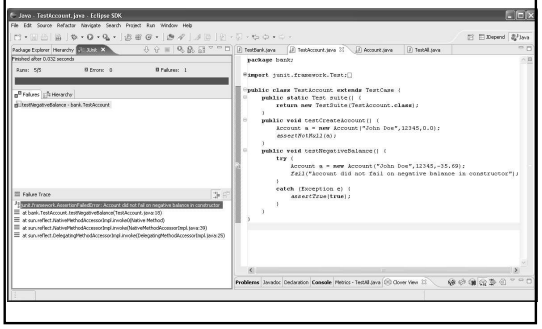
Testing Exceptions

- Exceptional behavior can be difficult to test with integration and functional tests, but JUnit enables simple exception testing
- Approach:
  - Force an exception to be thrown
  - Follow it with a fail statement to detect if the exception is not thrown
  - Catch the exception and assert that it was caught

Testing Exceptions TestCase

```
package bank;
import junit.framework.*;
public class TestAccount extends TestCase {
    public void testNegativeBalance() {
        try {
            Account a = new Account("John Doe",12345,-35.69);
            fail("Account did not fail on negative balance in constructor");
        }
        catch (Exception e) {
            assertTrue(true);
        }
    }
}
```

Testing Exceptions Failure



Testing Exceptions Example

```
package bank;

public class Account {
    private int accountNum;
    private String accountOwner;
    private double balance;
    public Account(String owner, int num, double bal) throws Exception {
        accountNum = num;
        accountOwner = owner;
        balance = bal;
        if (bal < 0.0) {
            balance = 0.0;
            throw new Exception("Negative balance not allowed.");
        }
    }
}
```

Testing Exceptions Not Thrown

- Second Approach:
  - Place a fail statement in the catch handler to make sure an exception was not thrown

```
package bank;
import junit.framework.*;
public class TestAccount extends TestCase {
    public void testCreateAccount() {
        try {
            Account a = new Account("John Doe",12345,0.0);
            assertNotNull(a);
        } catch (Exception e) { fail("Should not throw exception"); }
    }
```

Allowing TDD to drive design

- Suppose we need to add the ability to get the account with the largest balance

```
public class TestBank extends TestCase {
    public void testGetLargestAccount() {
        try {
            Account small = new Account("Bob Jones",45678,12.34);
            b.addAccount(small);
            Account big = new Account("Jim Smith",12345,123456.78);
            b.addAccount(big);
            Account medium = new Account("Sam Smith",67890,1234.56);
            b.addAccount(medium);
            assertEquals(b.getLargest().getBalance(),big.getBalance(),.01);
        } catch (Exception e) {}
    }
```

Note use of delta with doubles

Allowing TDD to drive design

```
import java.util.*;
public class Bank {
    private ArrayList accounts;
    public Bank() {
        accounts = new ArrayList();
    }
    public int getNumAccounts() {
        return accounts.size();
    }
    public void addAccount(Account a) {
        accounts.add(a);
    }
    public Account getLargest() {
        return ((Account)(accounts.get(0)));
    }
}
```

ArrayList is hard-coded

This won't work!
Need ability to sort easily

Selecting Internal Data Structure

- Bank is currently coupled to ArrayList
- There are many possible data structures with corresponding advantages/disadvantages
  - ArrayList (low overhead but slow sorting)
  - TreeSet (high overhead but fast sorting)
  - TreeMap (high overhead, sorting, fast individual access)

Selecting Internal Data Structure

- java.util.Collection provides an ***interface*** for adding/removing elements
  - ArrayList, TreeSet, TreeMap all implement it
- java.util.SortedSet extends Collection and adds a last() method
  - TreeSet implements it
  - Because it is an interface, other classes can implement it as well.

Allowing TDD to drive design

- Allow the client to "inject" the data structure

```
public void testGetLargestAccount() {
  try {
    Bank b = new Bank(new TreeSet(new Comparator() {
        public int compare(Object first, Object second) {
          if (((Account)first).getBalance() < ((Account)second).getBalance())   return -1;
          else if  (((Account)first).getBalance() > ((Account)second).getBalance())   return 1;
          else                                                                  return 0;
        }
    }));
    Account small = new Account("Bob Jones",45678,12.34);
    b.addAccount(small);
    Account big = new Account("Jim Smith",12345,123456.78);
    b.addAccount(big);
    Account medium = new Account("Sam Smith",67890,1234.56);
    b.addAccount(medium);
    try {
        Account largest = b.getLargest();
        assertEquals(largest.getBalance(),big.getBalance(),.01);
    } catch (Exception e) { fail(e.toString()); }
  } catch (Exception e) { fail(e.toString()); }
}
```

Dependency Injection/ Inversion of Control

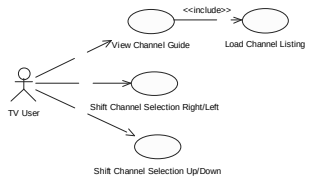
```
public class Bank {
    private Collection accounts;
    public Bank() {
        accounts = new ArrayList();
    }
    public Bank(Collection c) {
        accounts = c;
    }
    …
    public Account getLargest() throws Exception {
        if (accounts instanceof SortedSet)
            return ((Account)((SortedSet)accounts).last());
        else
            throw new Exception("Accounts not sorted");
    }
}
```

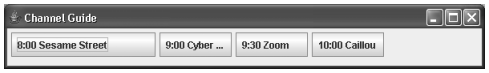
Coupled to interface only

Default data structure

Exception allows various collections safely

TDD Example with Input File and GUI





Test Channel Guide Model

```
public void testChannelGuideFromFile() {
 try {
  PrintWriter dout = new PrintWriter(new FileWriter("tvlistings.txt"));
  dout.println("Sesame Street:8:0:60");
  dout.println("Cyber Chase:9:0:30");
  dout.println("Zoom:9:30:30");
  dout.println("Caillou:10:0:30");
  dout.println("Mr. Rogers:10:30:30");
  dout.println("Zooboomafoo:11:0:30");
  dout.println("Arthur:11:30:30");
  dout.close();
 } catch(IOException e) { System.out.println(e);}

 ChannelGuide cg = new ChannelGuide("tvlistings.txt");
 assertEquals(cg.numShows(),7);
}
```

Test Channel Guide GUI

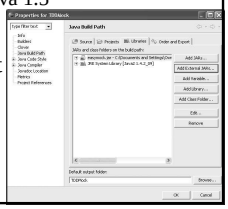
```
public class TestChannelGuideGUI extends TestCase {
  public void testMoveRight() {
    ChannelGuideGUI cgui = new ChannelGuideGUI("tvlistings.txt");
    ListIterator it = cgui.cg.currentStartIterator();
    assertEquals(((Show)it.next()).getTitle(),"Sesame Street");
                          //create move right action
    cgui.showPanel.getActionMap().get("panel.right").
                  actionPerformed(new ActionEvent(this, 0, ""));
    it = cgui.cg.currentStartIterator();
                          //verify new start
    assertEquals(((Show)it.next()).getTitle(),"Cyber Chase");
                          //verify button text
    assertEquals(cgui.showButtons[0].getText(),"9:00 Cyber Chase");
  }
  ...
}
```

Testing with Mock Objects

- A *mock object* is an object created to stand in for an object that your code will be collaborating with. Your code can call methods on the mock object, which will deliver results as set up by your tests.
- In other words, in a fine-grained unit test, you want to test only one thing. To do this, you can create mock objects for all of the other things that your method/object under test needs to complete its job.

EasyMock

- EasyMock is a third-party library for simplifying creating mock objects
- Download EasyMock1.2 for Java1.3 from www.easymock.org
  - EasyMock 2.0 depends on Java 1.5
- Extract download
- Add easymock.jar to project



Testing Bank with EasyMock

```
package bank;
import java.util.Collection;
import org.easymock.MockControl;
import junit.framework.TestCase;
public class TestBank extends TestCase {
    private Bank b;
    private MockControl control;
    private Collection mock;
    protected void setUp() {
        control = MockControl.createControl(Collection.class);
        mock = (Collection) control.getMock();
        b = new Bank(mock);
    }
    public void testNumAccounts() {
            mock.size();
            control.setReturnValue(7);
            control.replay();
            assertEquals(b.getNumAccounts(),7);
            control.verify();
    }
}
```

Import MockControl

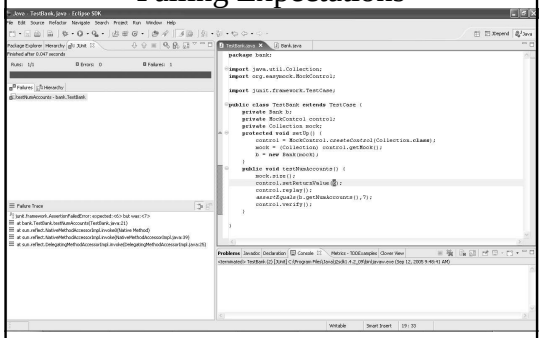
Collection is mock. We want to test Bank, not Collection

Recording what we we expect: size() should be called, returning 7

Turn on mock with replay()

Check expectations with verify()

Failing Expectations



Testing getLargest() with EasyMock

```
package bank;
import java.util.SortedSet;
import org.easymock.MockControl;
import junit.framework.TestCase;
public class TestBank extends TestCase {
    …
    public void testGetLargest() {
            control = MockControl.createControl(SortedSet.class);
            SortedSet mock = (SortedSet) control.getMock();
            b = new Bank(mock);
            mock.last();
            try{
                    control.setReturnValue(new Account("Richie Rich",77777,99999.99));
                    control.replay();
                    assertEquals(b.getLargest().getBalance(),99999.99,.01);
            } catch (Exception e) { fail("testGetLargest should not throw exception"); }
            control.verify();
    }
}
```

last() should be called on mock

When to use Mock Objects

- When the real object has non-deterministic behavior (e.g. a db that is always changing)
- When the real object is difficult to set up
- When the real object has behavior that is hard to cause (such as a network error)
- When the real object is slow
- When the real object has (or is) a UI
- When the test needs to query the object, but the queries are not available in the real object
- When the real object does not yet exist

* from http://c2.com/cgi/wiki?MockObject

B.2.2 Bowling Assignment

Bowling Exercise:
Write the Java code to calculate and print the score of a game of bowling. The rules of bowling are given below. Input should be read from a file. Each line of the input file should contain one game. The file format is:

bowlerID: frame1throw1 frame1throw2, frame2throw1 frame2throw2, ..., frame10throw1 frame10throw2 frame10throw3

where

a. bowlerID is an integer with up to 8 digits

b. If throw1 is 10 in a frame then throw2 will be blank

c. Throw3 in frame10 may not exist

For instance, one line might be:

12345: 6 2, 8 1, 10, 4 0, 6 4, 2 3, 5 4, 10, 8 2, 4 5

The program should print the bowlerID and final score of all games to an output file in the same order as the games were in the input file. The program should be invoked with a command-line interface like the following:

Bowling input.txt output.txt

An Overview of the Rules of Bowling [58]

Bowling is a game that is played by throwing a cantaloupe-sized ball down a narrow alley toward ten wooden pins. The object is to knock down as many pins as possible per throw.

The game is played in ten frames. At the beginning of each frame, all ten pins are set up. The player then gets two tries to knock them all down.

If the player knocks all the pins down on the first try, it is called a “strike,” and the frame ends.

If the player fails to knock down all the pins with the first ball, but succeeds with the second ball, it is called a “spare.”

After the second ball of the frame, the frame ends even if there are still pins standing.

A strike frame is scored by adding ten, plus the number of pins knocked down by the next two balls, to the score of the previous frame.

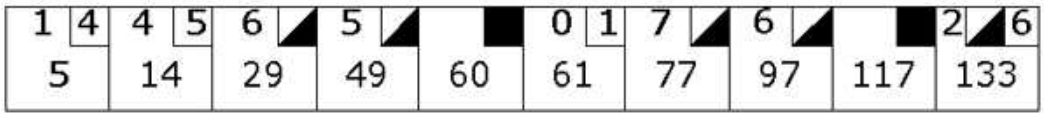
A spare frame is scored by adding ten, plus the number of pins knocked down by the next ball, to the score of the previous frame.

Otherwise, a frame is scored by adding the number of pins knocked down by the two balls in the frame to the score of the previous frame.

If a spare is thrown in the tenth frame, the player may throw one more ball to complete the score of the spare.

Likewise, if a strike is thrown in the tenth frame, then the player may throw two more balls to complete the score of the strike.

Thus, the tenth frame may have three balls instead of two.



The score card above shows a typical, if rather poor, game. A darkened triangle indicates a spare. A darkened square indicates a strike.

In the first frame, the player knocked down 1 pin with his first ball and four more with his second. Thus, his score for the frame is a five.

In the second frame, the player knocked down four pins with his first ball and five more with his second. That makes nine pins total, added to the previous frame makes fourteen.

In the third frame, the player knocked down six pins with his first ball and knocked down the rest with his second for a spare. No score can be calculated for this frame until the next ball is rolled.

In the fourth frame, the player knocked down five pins with his first ball. This lets us complete the scoring of the spare in frame three. The score for frame three is ten, plus the score in frame two (14), plus the first ball of frame four (5), or 29. The final ball of frame four is a spare.

Frame five is a strike. This lets us finish the score of frame four which is 29 + 10 + 10 = 49.

Frame six is dismal. The first ball went in the gutter and failed to knock down any pins. The second ball knocked down only one pin. The score for the strike in frame five is 49 + 10 + 0 + 1 = 60.

The rest you can probably figure out for yourself.

Hints on Java I/O found in Examples/Bowling/Bowling.java:

```
import java.io.*;
import java.util.StringTokenizer;

public class Bowling {
  public static void main(String []args) {
    BufferedReader in = null;
    PrintWriter out = null;
    if (args.length < 2) {
      System.out.println("Usage: Bowling <inputfile> <outputfile>");
      System.exit(0);
    }
    try {
      in = new BufferedReader(new FileReader(args[0]));
    } catch (IOException e) {
      System.out.println("Unable to open input file");
      System.exit(0);
```

```
    }
    try {
      out = new PrintWriter(new FileWriter(args[1]));
    } catch (IOException e) {
      System.out.println("Unable to open output file");
      System.exit(0);
    }
    try {
      String line;
      int bowlerID;
      int ball;
      while((line = in.readLine()) != null) {ă
        StringTokenizer t = new StringTokenizer(line," ");
        bowlerID = Integer.parseInt(t.nextToken());
        while(t.hasMoreTokens()) {
          ball = Integer.parseInt(t.nextToken());
        }
        out.print(bowlerID);
        out.print(' ');
        out.println("score goes here");
      }
      out.close();
    }
    catch (IOException e) {
      System.out.println("Something went wrong processing file");
      System.exit(0);
    }
  }
}
```

Appendix C

Custom-built Analysis Tools

This appendix presents several listings of software developed by the author for automating metric collection and analysis. These listings are only a subset of the code written. The listings include Ant scripts and Java source code.

C.1 Ant Script

The following Ant script invokes CCCCRunner to generate CCCC metrics, AssertCounter to parse and count assert statements, and CCCCDriver to parse, consolidate, and write CCCC, EclipseMetrics, and assert metrics to comma-delimited spreadsheet files.

```
<!-- Run this from the directory that includes proj1 -->

<project name="build.xml" default="all">
    <path id="runtime.classpath">
        <pathelement location="bin"/>
        <pathelement location="."/>
    </path>
    <target name="execCCCC" depends="compile">
        <java classname="CCCCRunner">
            <classpath refid="runtime.classpath"/>
            <arg value="268proj1"/>
        </java>
        <java classname="CCCCRunner">
            <classpath refid="runtime.classpath"/>
            <arg value="268proj2"/>
        </java>

    <!-- Repeat for all projects -->
```

```
</target>
<target name="countAsserts" depends="compile">
    <java classname="AssertCounter">
        <classpath refid="runtime.classpath"/>
        <arg value="268proj1"/>
        <arg value="cpp"/>
    </java>
    <java classname="AssertCounter">
        <classpath refid="runtime.classpath"/>
        <arg value="268proj2"/>
        <arg value="cpp"/>
    </java>

<!-- Repeat for all projects -->

</target>
<target name="clean">
    <delete dir="bin"/>
</target>
<target name="init">
    <mkdir dir="bin"/>
</target>
<target name="compile" depends="init">
    <javac srcdir="src" destdir="bin">
        <classpath refid="runtime.classpath"/>
    </javac>
</target>
<target name="ccccProcess" depends="compile">
    <java classname="CCCCDriver" >
        <classpath refid="runtime.classpath"/>
        <arg value="268proj1"/>
    </java>
    <java classname="CCCCDriver" >
        <classpath refid="runtime.classpath"/>
        <arg value="268proj2"/>
    </java>

<!-- Repeat for all projects -->

</target>
<target name="all"
   depends="compile,execCCCC,countAsserts,ccccProcess">
</target>
```

```
</project>
```

C.2 CCCCRunner

```
import java.io.File;

public class CCCCRunner {
  public static void main(String [] args) {
    try {
        File f = new File(args[0]);
        String [] dirs = f.list();
        for(int i=0;i<dirs.length;i++) {
          File dir = new File(args[0] + File.separator + dirs[i]);
          if (dir.isDirectory()) {
             System.out.println("CCCC Processing " + args[0] +
                                File.separator + dirs[i]);
             String comando [] = {"C:/Program Files/CCCC/cccc.exe",
                                  "*.cpp", "*.h", "*.java" };
             Runtime.getRuntime().exec(comando,null,dir);
          }
        }
    } catch (Exception e) {}
  }
}
```

C.3 AssertCounter

```
import java.io.File; import java.io.FileOutputStream;

public class AssertCounter {
  public static void main(String [] args)
  {        //expects dir name and "cpp" or "java"
    if (args.length < 2) {
       System.out.println("usage: AssertCounter <dir> <extension>");
       System.exit(-1);
    }
    if (!(args[1].equals("cpp") || args[1].equals("java"))) {
       System.out.println("usage: AssertCounter <dir> <extension>");
       System.out.println("<extension> must be \"cpp\" or \"java\"");
       System.out.println("You gave "+args[0]+" and "+args[1]);
```

```
      System.exit(-1);
    }
    try {
      File f = new File(args[0]);
      String [] dirs = f.list();
      for(int i=0;i<dirs.length;i++) {
        File dir = new File(args[0] + File.separator + dirs[i]);
        if (dir.isDirectory()) {
          System.out.println("Counting asserts " + args[0] +
                             File.separator + dirs[i]);
          FileOutputStream fos1 = new FileOutputStream(dir +
                    File.separator + "assertCount1.txt",false);
          Runtime rt = Runtime.getRuntime();
          Process proc = rt.exec("find /C \"assert\" *." +
                                          args[1],null,dir);
          StreamGobbler outputGobbler =
            new StreamGobbler(proc.getInputStream(),"OUTPUT",fos1);
          outputGobbler.start();
          proc.waitFor();
          outputGobbler.join();
          fos1.flush();
          fos1.close();
        }
      }
     } catch (Throwable t) {
        t.printStackTrace();
     }
   }
}
```

C.4 CCCCDriver

```
import java.io.BufferedReader; import java.io.File; import
java.io.FileInputStream; import java.io.FileWriter; import
java.io.IOException; import java.io.InputStreamReader; import
java.io.PrintWriter;

public class CCCCDriver {
  private static MetaDataProcessor mdp;
  public static void main(String [] args) {
    try {
```

```
      mdp = new MetaDataProcessor("All.csv");
      PrintWriter out =
        new PrintWriter(new FileWriter(args[0] + ".csv"));
      printHeadings(out);
      File f = new File(args[0]);
      String [] dirs = f.list();
      for(int i=0;i<dirs.length;i++) {
         out.print(dirs[i]);
         File dir = new File(args[0] + File.separator + dirs[i]);
         if (dir.isDirectory()) {
            System.out.println("CCCC Analyzing " + args[0] +
                               File.separator + dirs[i]);
            printMetrics(out,args[0],dirs[i],dir);
         }
       }
       out.close();
    } catch (Exception e) { System.out.println(e.toString()); }
    System.out.println("Output is in " + args[0] + ".csv");
}
private static void printHeadings(PrintWriter out) {
    out.print("KUID,");
    out.print("Approach,");
    out.print("Time,");
    out.print("Score,");
    out.print("Correctness,");
    out.print("Style,");
    out.print("Output Format,");
    out.print("Error Checking,");
    out.print("LOC,");
    out.print("#modules,");
    out.print("#classes,");
    out.print("#methods,");
    out.print("LOC/module,");
    out.print("Complexity,");
    out.print("Complexity/module,");
    out.print("IF,");
    //repeat for all metrics


    out.println();
}
private static void printMetrics(PrintWriter out,
             String project, String id, File dir) {
```

```
String file = dir.toString() + File.separator +
              ".cccc/cccc.xml";
CCCCAnalyzer ca = new CCCCAnalyzer(file);
String emafile = dir.toString() + File.separator +
                 "metrics.xml";
EclipseMetricsAnalyzer ema =
      new EclipseMetricsAnalyzer(emafile);
Project p = null;
if (mdp != null) {
    p = mdp.getProject(project,id);
}

String loc,modules,classes,methods;
int asserts;
if (p != null) {
    out.print("," + p.getApproach());
    out.print("," + p.getTime());
    out.print("," + p.getScore());
    out.print("," + p.getCorrectness());
    out.print("," + p.getStyle());
    out.print("," + p.getOutputFormat());
    out.print("," + p.getErrorChecking());
}
else {
    out.print(", , , , , , , ");
}
out.print("," + (loc = ca.getAttribute("lines_of_code")));
out.print("," + (modules = ca.getAttribute("number_of_modules")));
out.print("," + (classes = ca.getNumClasses()));
out.print("," + (methods = ca.getNumMethods()));
out.print("," + ca.getAttribute("lines_of_code_per_module"));
out.print("," + ca.getAttribute("McCabes_cyclomatic_complexity"));
out.print("," +
  ca.getAttribute("McCabes_cyclomatic_complexity_per_module"));
out.print("," + ca.getAttribute("IF4"));
\\repeat for CCCC metrics


out.print("," + ema.getProjectAttributeValue(1,"NSM","value"));
out.print("," + ema.getProjectAttributeValue(1,"NSM","avg"));
//repeat for all Eclipse Metrics
```

```
    out.print("," + (asserts = getAsserts(dir)));
    float iloc,imodules,iclasses,imethods;
    iloc = Integer.parseInt(loc);
    imodules = Integer.parseInt(modules);
    iclasses = Integer.parseInt(classes);
    imethods = Integer.parseInt(methods);
    if (iloc > 0) {
       out.print("," + (asserts/iloc));
    }
    else {
       out.print(", ");
    }
    if (imodules > 0) {
       out.print("," + (asserts/imodules));
    }
    else {
        out.print(", ");
    }
    if (iclasses > 0) {
        out.print("," + (asserts/iclasses));
    }
    else {
        out.print(", ");
    }
    if (imethods > 0) {
        out.print("," + (asserts/imethods));
    }
    else {
        out.print(", ");
    }

    out.println();
}
private static int getAsserts(File dir) {
    int count = 0;
    try {
        FileInputStream fis = new FileInputStream(dir +
            File.separator + "assertCount1.txt");
        InputStreamReader isr = new InputStreamReader(fis);
        BufferedReader br = new BufferedReader(isr);
        String line=null;
        while ( (line = br.readLine()) != null) {
```

```
            int index = line.lastIndexOf(':');
            if(index>0) {
               count += Integer.parseInt(line.substring(index+2));
            }
          }
      } catch (IOException ioe) {
          ioe.printStackTrace();
      }
      return count;
  }
}
```

C.5 CCCC Analyzer

```
import java.io.File; import java.io.IOException;

import javax.xml.parsers.DocumentBuilder; import
javax.xml.parsers.DocumentBuilderFactory; import
javax.xml.parsers.FactoryConfigurationError; import
javax.xml.parsers.ParserConfigurationException;

import org.w3c.dom.Document; import org.w3c.dom.NodeList; import
org.xml.sax.SAXException; import org.xml.sax.SAXParseException;

public class CCCCAnalyzer {
    private Document doc;
    public CCCCAnalyzer(String fileName) {
        try {
            File f = new File(fileName);
            doc = DocumentBuilderFactory.newInstance().
                        newDocumentBuilder().parse(f);
        } catch (Exception e) {
            System.out.println("Could not parse " + fileName);
        }
    }

    public String getAttribute(String att) {
        NodeList nodes = doc.getElementsByTagName(att);
        return nodes.item(0).getAttributes().
               getNamedItem("value").getNodeValue();
    }
```

```
public String getNumClasses() {
    NodeList nodes =
      doc.getElementsByTagName("procedural_summary");
    nodes = nodes.item(0).getChildNodes();
    int count=0;
    for(int i=1;i<nodes.getLength();i=i+2) {  //for each module
        if(validClassName(nodes.item(i).getChildNodes().item(1).
                          getChildNodes().item(0).toString()))
            count++;
    }
    return new Integer(count).toString();
}
public String getNumMethods() {
    NodeList nodes = doc.getElementsByTagName("oo_design");
    nodes = nodes.item(0).getChildNodes();
    int count=0;
    for(int i=1;i<nodes.getLength();i=i+2) {  //for each module
        if(validClassName(nodes.item(i).getChildNodes().item(1).
           getChildNodes().item(0).toString())) {
            count = count + new Integer(nodes.item(i).
                getChildNodes().item(3).getAttributes().
                getNamedItem("value").getNodeValue()).intValue();
        }
    }
    return new Integer(count).toString();

}
private boolean validModuleName(String name) {
    if(     name.equals("String") ||
            name.equals("String[]") ||
            name.equals("Vector") ||
            name.equals("ArrayList") ||
            name.equals("Integer") ||
            name.equals("Double") ||
            name.equals("Long") ||
            name.equals("Boolean") ||
            name.equals("ofstream") ||
            name.equals("ifstream") ||
            name.equals("ostream") ||
            name.equals("istream") ||
            name.equals("iostream") ||
            name.equals("bool") ||
```

```
            name.equals("string") ||
            name.equals("int") ||
            name.equals("short") ||
            name.equals("long") ||
            name.equals("unsigned int") ||
            name.equals("unsigned short") ||
            name.equals("unsigned long") ||
            name.equals("char") ||
            name.equals("float") ||
            name.equals("long double") ||
            name.equals("double"))
        return false;
    else return true;
}
private boolean validClassName(String name) {
    if(name.equals("anonymous") ||
            name.equals("String") ||
            name.equals("String[]") ||
            name.equals("Vector") ||
            name.equals("ArrayList") ||
            name.equals("Integer") ||
            name.equals("Double") ||
            name.equals("Long") ||
            name.equals("Boolean") ||
            name.equals("ofstream") ||
            name.equals("ifstream") ||
            name.equals("ostream") ||
            name.equals("istream") ||
            name.equals("iostream") ||
            name.equals("bool") ||
            name.equals("string") ||
            name.equals("int") ||
            name.equals("short") ||
            name.equals("long") ||
            name.equals("unsigned int") ||
            name.equals("unsigned short") ||
            name.equals("unsigned long") ||
            name.equals("char") ||
            name.equals("float") ||
            name.equals("long double") ||
            name.equals("double"))
        return false;
```

```
    else return true;
}

private String getMaxTemplate(String tagName, int index) {
    NodeList nodes = doc.getElementsByTagName(tagName);
    nodes = nodes.item(0).getChildNodes();
    int max=0;
    for(int i=1;i<nodes.getLength();i=i+2) {  //for each module
        if(validClassName(nodes.item(i).getChildNodes().item(1).
                          getChildNodes().item(0).toString())) {
            int current = new Integer(nodes.item(i).
                getChildNodes().item(index).getAttributes().
                getNamedItem("value").getNodeValue()).intValue();
            if (current > max)
                max = current;
        }
    }
    return new Integer(max).toString();
}
private String getAvgTemplate(String tagName, int index) {
    NodeList nodes = doc.getElementsByTagName(tagName);
    nodes = nodes.item(0).getChildNodes();
    int sum=0;
    int count=0;
    for(int i=1;i<nodes.getLength();i=i+2) {  //for each module
        if(validClassName(nodes.item(i).getChildNodes().item(1).
                          getChildNodes().item(0).toString())) {
            int current = new Integer(nodes.item(i).
                getChildNodes().item(index).getAttributes().
                getNamedItem("value").getNodeValue()).intValue();
            sum += current;
            count++;
        }
    }
    return new Double(((double)sum)/count).toString();
}
private String getMaxProcTemplate(String tagName, int index) {
    NodeList nodes = doc.getElementsByTagName(tagName);
    nodes = nodes.item(0).getChildNodes();
    int max=0;
    for(int i=1;i<nodes.getLength();i=i+2) {  //for each module
        if(validModuleName(nodes.item(i).getChildNodes().item(1).
```

```
                                getChildNodes().item(0).toString())) {
                    int current = new Integer(nodes.item(i).
                        getChildNodes().item(index).getAttributes().
                        getNamedItem("value").getNodeValue()).intValue();
                    if (current > max)
                        max = current;
                }
            }
            return new Integer(max).toString();
        }
        private String getAvgProcTemplate(String tagName, int index) {
            NodeList nodes = doc.getElementsByTagName(tagName);
            nodes = nodes.item(0).getChildNodes();
            int sum=0;
            int count=0;
            for(int i=1;i<nodes.getLength();i=i+2) {  //for each module
                if(validModuleName(nodes.item(i).getChildNodes().item(1).
                                getChildNodes().item(0).toString())) {
                    int current = new Integer(nodes.item(i).
                        getChildNodes().item(index).getAttributes().
                        getNamedItem("value").getNodeValue()).intValue();
                    sum += current;
                    count++;
                }
            }
            return new Double(((double)sum)/count).toString();
        }

        public String getMaxLOCperModule() {
            return getMaxProcTemplate("procedural_summary",3);
        }

        public String getMaxComplexityPerModule() {
            return getMaxProcTemplate("procedural_summary",5);
        }

        //repeat for all aggregate metrics

    }
```

Appendix D

Metrics

This appendix summarizes some of the metrics used in analyzing software.

D.1 Robert C. Martin Suite

The following metrics and definitions come from [58].

Afferent Coupling (CA)

The number of classes outside a package that depend on classes inside the package.

Efferent Coupling (CE)

The number of classes inside a package that depend on classes outside the package.

Instability (I)

CE / (CA + CE)

Abstractness (A)

The number of abstract classes (and interfaces) divided by the total number of types in a package.

Normalized Distance from Main Sequence (D)

| A + I - 1 |, this number should be small, close to zero for good packaging design.

D.2 Eclipse Metrics

The following metrics and definitions come from [75] and [43].

D.2.1 Class Metrics

Specialization Index

Average of the specialization index, defined as NORM * DIT / NOM.

Number of Overridden Methods

Total number of methods in the selected scope that are overridden from an ancestor class.

D.3 JStyle

The following definitions come from JStyle 5.0 online help [78].

D.3.1 Project-wide Metrics

Number of Packages

Total number of distinct packages in the project. A package in Java conveniently groups similar packages. Classes that are not defined in a package belong to the default package, represented in JStyle as "#default#".

Number of Modules

The total number of source files included in the project.

Number of Interfaces

The total number of interfaces (public and nonpublic) defined in the project.

Number of Classes

The total number of classes defined in the project. This measure includes top-level (public and nonpublic), local, and inner classes. Not included in the measure are classes that are referenced but whose definitions are not available in the project.

Number of Public Classes

The total number of classes defined using the "public" qualifier. Public classes that belong to a package can be referenced in other packages, whereas nonpublic classes cannot be referenced that way.

Number of Final Classes

The total number of classes defined using the "final" qualifier. This includes public as well as nonpublic classes. By definition, a final class does not allow another class to be derived from it.

Number of Abstract Classes

The total number of classes defined using the “abstract” qualifier. This includes public as well as nonpublic classes.

Number of Top-level Classes

The total number of classes (public and nonpublic) defined at the top level. The measure does not include inner, local and anonymous classes.

Number of Inner Classes

The total number of non-static inner classes (public and nonpublic) in the project. Includes inner classes at all levels of nesting, not just top-level ones.

Number of Nested Classes

A nested class is a "static" class defined inside another class. This measure gives the total number of such nested classes (public and nonpublic, at all levels of nesting) in the project.

Number of Local Classes

A Local class is one that is defined within code blocks such as a method body, constructor or initialization block. Such a class is inaccessible outside of the block in which it is defined. Local classes cannot be qualified as "public" or "static".

This measure gives the total number of local classes in the project, including anonymous classes.

Number of Anonymous Classes

Total number of anonymous classes in the project. An anonymous class has no name. It is defined as part of the "new" expression, and has the form

```
new InterfaceOrBaseClass(args) {
   // body
}
```

Reuse ratio

The reuse ratio (U) is given by

U = Number of superclasses/Total number of classes

Specialization ratio

This ratio measures the extent to which a superclass has captured abstraction. The specialization ratio (S) is given as

S = Number of subclasses / Number of superclasses

Average Inheritance Depth

The inheritance structure can be measured in terms of depth of each class within its hierarchy. The Average Inheritance Depth is given as

Av. Inheritance Depth = Sum of depth of each class / Number of classes

Class Hierarchy Depth

In an object-oriented design, the application domain is modeled as a hierarchy of classes. This measure indicates the maximum depth of any class in a project.

Number of Native Methods

A native method is a Java method implemented in a "native" language, usually C or C++.

This measure provides a count of the total number of native methods in all the classes that have been included in a project.

Number of methods per class

This measure indicates the number of methods that have been explicitly defined in a class. It does not include the methods inherited from a super class.

Method size

This measure denotes the total number of statements per method of a project.

D.3.2 Module-wide Metrics

Total Lines

This measure provides a count of the total number of lines in a module. It includes the source lines, blank lines, and comment lines.

Comment Lines

This measure indicates the total number of comment lines in a module.

Blank Lines

This measure indicates the total number of blank lines in a module.

Source Lines

This measure indicates the total number of actual lines of code (LOC) in a module.

Comment Density

The comment density is given by the formula: Comment density = Number of comment lines / Total number of lines

JStyle reports comment density for individual modules.

Number of Classes & Interfaces

This measure indicates the total number of classes and interfaces defined in a module.

D.4 Class-wide Metrics

Inheritance Depth

The Inheritance Depth of a class indicates its position in the class hierarchy. In Java, the Object class is the root of all classes and is at level 0. A class directly derived from Object is at level 1 and so on. For this measure to be reported correctly for

your project, make sure that all external classes are correctly resolved. Unresolved classes may cause an incorrect depth to be reported.

Number of Interfaces Implemented

A Java class may implement zero or more interfaces. This measure indicates the total number of interfaces implemented by a class.

Number of classes implementing interface

This measure provides a count of the total number classes implementing an interface.

Number of Instance Variables

This measure provides the total number of instance variables in a class.

Number of Static Variables

This measure provides the total number of static variables in a class.

Number of Static Methods

This measure indicates the total number of the static methods in the class.

Number of Instance Methods

This measure indicates the total number of instance methods that have been explicitly defined in a class.

Number of Native Methods

This measure indicates the number of native methods declared in a class.

Number of Primitive Methods

This metric is a measure of the total number of methods in a class that use only private fields.

Number of NonPrimitive Methods

This measure indicates the total number of methods in a class that do not use private fields.

Number of Methods

This measure provides a count of the total number of methods that have been explicitly defined in a class.

Weighted Methods Complexity (WMC)

WMC calculates the structural complexity on a class level. In a class of n methods, each of cyclomatic complexity $V_{ij}(G)$, the Weighted Methods Complexity is calculated as per the following formula.

$WMC = \sum_{j=1}^{n} V_{ij}(G)$, where i represents the ith class.

Response For Class (RFC)

This measure captures the size of the response set of a class. The response set of a class consists of all the methods called by local methods. RFC is the sum of the number of local methods and the number of methods called by local methods. It is given by $RFC = |RS|$, where $RS = M_i \cup j\{R_{ij}\}$

Here M_i represents the set of all methods in the class (total n) and $\{R_{ij}\}$ represents the set of methods called by M_i.

An equivalent definition is
RFC = NLM + NRM,
where,
NLM = number of local methods
NRM = number of remote methods.

Lack of Cohesion of Methods (LCOM)

The cohesion of a class is characterized by how closely the local methods are related to the local instance variables in a class. LCOM is defined as the number of disjoint (that is, non-intersecting) sets of local methods.

For all computations of LCOM, constructors, and methods that are abstract, static, or synthesized (by the compiler - JStyle) are not taken into consideration. Similarly, static fields and synthesized fields are ignored. Also local and anonymous classes defined inside a method are not considered as part of the method but are treated as independent classes and hence have no impact on the LCOM of the outer class. Similarly, inner classes do not have any impact on the LCOM of a class. The fields and methods used are those that belong to the class for which LCOM is computed, super classes and super interfaces are not taken into consideration.

LCOM (Chidamber-Kemerer)

Chidamber and Kemerer define LCOM as a count of the number of method pairs whose similarity is zero minus the count of method pairs whose similarity is not zero. The degree of similarity, Ψ between two methods is given by $\Psi(M1, M2) = |_1 \cap |_2$

If there are no common properties then, similarity = 0.

Consider a class C with n methods M_1, M_2, ...M_n. Let $\{I_j\}$ = set of instance variables used by method M_i. There are n such sets $\{I_1\}$...$\{I_n\}$.

If $P = \{(I_i, I_j), I_i \cap I_j = \emptyset\}$ and
$Q = \{(I_i, I_j), I_i \cap I_j \neq \emptyset\}$ then
If $(P > Q)$, LCOM(Chidamber-Kemerer) = P-Q
Otherwise, LCOM(Chidamber-Kemerer) = 0

For a perfectly cohesive class the value of LCOM (Chidamber-Kemerer) is 0, and for a totally non-cohesive class the LCOM (Chidamber-Kemerer) value equals (n(n-1))/2 where n represents the total number of methods present in the class.

LCOM (Li-Henry)

Li and Henry defined LCOM as the number of disjoint sets of methods, where any two methods in the same set share at least one local instance variable.

In LCOM (Li-Henry), a value of 1 represents a perfectly cohesive class, whereas for a totally non-cohesive class the value equals the total number of methods present in the class.

LCOM (Henderson-Sellers)

Consider a set of methods $\{M_i\}(i = 1, ...m)$ accessing a set of attributes $\{A_j\}(j = 1, ...a)$. Let the number of methods which access each datum be $Mu(A_j)$. Then

$LCOM* = ((1/a \sum_{j=1}^{a} m(A_j)) - m)/1 - m$

The value of LCOM (Henderson-Sellers) is 0 for a perfectly cohesive class and greater than 0 for non-cohesive classes.

Number of Inner Classes

This metric indicates the total number of (non-static) inner classes defined in a class.

Number of Inner Static Classes

This measure indicates the total number of top-level static classes defined in a class.

Number of Local Classes

This measure denotes the total number of local classes in various methods of a class including anonymous local classes.

Number of Anonymous Classes

This measure gives the number of anonymous classes in various methods of a class.

Number of Children

This measure gives a count of the number of classes that are directly derived from a class.

Fan-in

This measure indicates the total number of classes that are dependent on a particular class. Only the classes that are directly dependent on a class are considered for calculating Fan-in.

For example, if two classes A and B use class C, the Fan-in of class C is 2.

A large value of Fan-in is suggestive of high reuse.

Fan-out

This measure gives the number of classes that are used by a particular class. All the classes that are directly used by a class including inherited classes are considered for calculating the Fan-out. For example, if class A uses three classes B, C, and D, then Fan-out for class A is 4 (this value includes the Object class too).

A large value of Fan-out is suggestive of tight coupling.

Intra-Package Fan-in

This metric is a measure of the number of classes that are dependent on a specific class within a package.

Intra-Package Fan-out

This measure provides a count of the number of classes that are used by a specific class within a package.

Inter-package Fan-in

This measure indicates the number of classes outside a package that are dependent on a specific class.

Inter-package Fan-out

This metric denotes the number of classes outside a package that is used by a specific class.

D.4.1 Method-wide Metrics

Number of Statements

This measure indicates the actual number of statements in a method.

Number of Exceptions thrown

This measure indicates the number of exceptions thrown by a method.

Cyclomatic Number

Cyclomatic number proposed by McCabe is one of the widely used measures to understand the structural complexity of a program. This number, based on a graph-theoretic concept, counts the number of linearly independent paths through the program.

If G is the control flow graph of program P, and G has e edges (arcs) and n nodes, then Cyclomatic number

V(G) = e - n + 2

Or, more simply, if d is the number of decision nodes in G, then Cyclomatic number

V(G) = d + 1

The value of d for the Java constructs is listed below.

Java Constructs	Value of d
if...then	1
if...then...else	1
for	1
while	1
do...while	1
case statements	1

JStyle computes V(G) for every method in a class, not to the module as a whole.

Note that this computation of Cyclomatic number is different from that in the Control Flow Graph. To know more about this, see Difference in Cyclomatic Number calculation.

Halstead Measures

Halstead observed that any computer program could be viewed as a sequence of tokens that can be classified as either operators or operands. This is because all programs are reduced to a sequence of machine language instructions, each of which consists of an operator code and one or more operand addresses. The basic metrics for these tokens are listed below.

n_1 = number of unique operators
n_2 = number of unique operands
N_1 = Total number of operators
N_2 = Total number of operands

All the Halstead measures that are listed below are calculated using the above parameters.

Program Length

Program length is defined as $N = N_1 log n_1 + N_2 log n_2$

Actual Halstead Length

Generally, any symbol or keyword in a program that specifies an action to be taken by the computer is considered as an operator. Examples are arithmetic operations (+,-,*,/), and instructions such as READ, WHILE, GOTO, etc. Most punctuation marks in a program are also classified as operators. Other tokens, representing variables, constants, or other forms of data, are considered operands. For example, let us consider an assignment statement:

a = b

This expression contains one operator (=) and two operands (a and b)

The length N of a program in number of token is therefore $N = N_1 + N_2$

Program's Vocabulary

A program's vocabulary is given as the sum of number of unique operators and operands. That is,

$Programvocabulary(n) = n_1 + n_2$

Program Volume (V)

The volume of a program is related to the number of mental comparisons required to write a program of length N. This measure is given by: $V = Nlog_2 n$

In the above expression, $N = N_1 + N_2$ and $n = n_1 + n_2$.

Substituting these values in the expression for volume, we get $V = (N_1+N_2)log_2(n_1+n_2)$

Program Level (L)

Program Level L is defined as
$L = 2n_2/n_1N2$

Program Difficulty (D)

Difficulty is the inverse of Program Level.
$D = 1/L$

Development Effort (E)

Development Effort is defined as
$E = V/L$

Bug Predicted

Bug predicted is defined as
Bugs predicted = Volume/3000

D.5 Krakatau Professional

The following metrics and definitions come from [77]. Some minor corrections have been made.

D.5.1 Project Metrics

DPIT - Depth of Project class Inheritance Tree

This metric measures the maximum depth of the class inheritance tree for the whole project. Large values for DPIT tend to indicate that leaf classes will be inheriting many methods and members from parent classes making their behaviour difficult to

predict. Of course, deep inheritance also indicates that classes are less specialised and so increases possibilities for reuse.

NORC - Number Of Root Classes

This measures the number of discrete class hierarchies present in the project. A large value for NORC will suggest that a large amount of effort for testing will be required (since test cases for each hierarchy will need to be developed). This metric must be interpreted carefully where (for example) all classes inherit from the 'Object' class; technically there is only one class hierarchy but notionally and practically there could be more.

LOC - Lines Of Code

Lines Of Code is the traditional measure of size for a project. LOC includes source code lines, whitespace lines and comment lines and so is a more primitive measure than SLOC.

SLOC - Source Lines Of Code

SLOC measures the number of lines containing actual program source code. SLOC is LOC minus whitespace lines and comment lines. Because SLOC measures only source code lines, some consider it a better guide to actual project size than LOC.

NFILES - Number of Files

NFILES measures the number of files in a project. This metric is a primitive measure of project size.

MHF - Method Hiding Factor

MHF is a metric from the MOOD (Metrics for Object-Oriented Development) suite. MHF is calculated as a fraction. The numerator is the sum of the invisibilities of all methods defined in all classes. The invisibility of a method is the percentage of the total classes from which this method is not visible. The MHF denominator is the total number of methods defined in the project.

AHF - Attribute Hiding Factor

AHF is a metric from the MOOD (Metrics for Object-Oriented Development) suite. AHF is calculated as a fraction. The numerator is the sum of the invisibilities of all attributes defined in all classes. The invisibility of an attribute is the percentage of

the total classes from which this method is not visible. The AHF denominator is the total number of attributes defined in the project.

MIF - Method Inheritance Factor

MIF is a metric from the MOOD (Metrics for Object-Oriented Development) suite and is calculated as a fraction. The MIF denominator is the sum of inherited methods in all classes in the project. The MIF denominator is the total number of available methods (locally defined plus inherited) for all classes.

AIF - Attribute Inheritance Factor

AIF is a metric from the MOOD (Metrics for Object-Oriented Development) suite and is calculated as a fraction. The AIF numerator is the sum of inherited attributes in all classes in the project. The AIF denominator is the total number of available attributes (locally defined plus inherited) for all classes.

POF - Polymorphism Factor

POF is a metric from the MOOD (Metrics for Object-Oriented Development) suite and is calculated as a fraction. The POF numerator is the sum of overriding methods in all classes. This is the actual number of possible different polymorphic situations. Indeed, a given message sent to a class can be bound, statically or dynamically, to a named method implementation. The latter can have as many shapes (morphos) as the number of times this same method is overridden (in that class's descendants). The POF denominator represents the maximum number of possible distinct polymorphic situations for that class as the sum for each class of the number of new methods multiplied by the number of descendants. This maximum would be the case where all new methods defined in each class would be overridden in all of their derived classes.

COF - Coupling Factor

COF is a metric from the MOOD (Metrics for Object-Oriented Development) suite and is calculated as a fraction. The COF denominator stands for the maximum possible number of couplings in a system with TC classes. The client-supplier relation (represented by Cc => Cs) means that Cc(client class) contains at least one non-inheritance reference to a feature (method or attribute) of class Cs (supplier class). The COF numerator then represents the actual number of couplings not imputable to inheritance.

AVCALLS - Average number of calls

The metric measures the average number of calls made by methods and functions in the call tree.

AVPATHS - Average Paths

The average number of paths in the call tree. As the value of this metric increases, the testing and debugging becomes more difficult. This measures the difficulty of testing. Applications with large values of component levels may contain a large number of untested paths that tend to be unexpectedly executed. This problem can plague client/server applications.

COM_LOC - Comment Lines of Code

This metric measures the total number of lines of code in the project which contain comments.

COM_RAT - Comment Ratio

This metric measures the ratio of comment lines of code (COM_LOC) to total lines of code including whitespace and comments (LOC).

TCOM_RAT - True Comment Ratio

This metric measures the ratio of comment lines of code (COM_LOC) to source lines of code (excluding whitespace and comments (SLOC).

D.5.2 File Metrics

LOC - Lines Of Code

The number of lines of code in a file provides a primitive measure of effort taken to understand or maintain the contents of that file.

SLOC - Source Lines Of Code

This metric measures only the number of lines in a file containing source code. SLOC is LOC minus whitespace lines and comment lines.

NTC - Number of Top-level Classes

The number of top-level classes in a file should usually not exceed 1. If there is more than one top-level class, then this file may be considered particularly unusual or complex.

NTM - Number of Top-level Methods

Under normal circumstances, it is quite reasonable to have several top-level methods in a file.

N1 - Total Number of Operators

N1 is the total number of operators used in a file. This is used as an input to the Halstead Software Science metrics.

N2 - Total Number of Operands

N2 is the total number of operands used in a file. This is used as an input to the Halstead Software Science metrics.

n1 - Number of Unique Operators

n1 is the number of unique operators used in a file. This is used as an input to the Halstead Software Science metrics.

n2 - Number of Unique Operands

n2 is the number of unique operands used in a file. This is used as an input to the Halstead Software Science metrics.

N - Halstead Program Length

N is calculated as N1+N2 and is a general measure of program length for a given file.

n - Halstead Program Vocabulary

n is calculated as n1+n2 and is a measure of the number of unique operands and operators used in a particular file. This can provide an impression of comprehensibility/complexity for that file.

V - Halstead Program Volume

V is the program volume metric from the Halstead Software Science metrics. This is calculated as V=N*(LOG2 n).

D - Halstead Difficulty

D is the difficulty metric from the Halstead Software Science metrics. This is calculated as D=(n1/n2)*(N2/n2).

E - Halstead Effort

E is the effort metric from the Halstead Software Science metrics. This is calculated as E=D*V.

AVCALLS - Average Calls

AVCALLS measures the average number of calls to subordinate logical units from methods and functions in a particular file. Therfore, this metric is a measure of FAN-OUT.

C_COM - C style comments

This metric measures the number of C style (/* ... */) comments used in a particular file. This can help to measure the extent of documentation for a file.

CPP_COM - C++ style comments

This metric measures the number of C++ style (// ...) comments used in a particular file. This can help to measure the extent of documentation for a file.

COM_LOC - Comment Lines of Code

COM_LOC measures the number of lines of code in a file which contain comments. Lines containing more than one comment are only counted once. Like C_COM and CPP_COM, COM_LOC is a measure of the extent of documentation in a source file.

COM_RAT - Comment Ratio

This metric measures the ratio of comment lines of code (COM_LOC)ăto total lines of code including whitespace and comments (LOC).

TCOM_RAT - True Comment Ratio

This metric measures the ratio of comment lines of code (COM_LOC) to source lines of code (excluding whitespace and comments (SLOC).

D.5.3 Class Metrics

CSA - Class Size in Attributes

CSA measures class size by counting the number of attributes of a class (not including inherited attributes). If a class has a high number of attributes, it may be wise to consider whether it would be appropriate to divide the class into subclasses.

CSO - Class Size in Operations

CSO measures class size by counting the number of operations (methods) in a class (not including inherited methods). If a class has a high number of methods, it may be wise to consider whether it would be appropriate to divide the class into subclasses.

CSAO - Class Size in Attributes and Operations

CSAO is the sum of CSA and CSO. Results should be interpreted as for the individual CSA and CSO metrics.

PPPC - Percentage of Package, Public and Protected members in a Class

Members which have package level protection are visible to other classes in the same package. Public members are available to classes in all packages and protected members are available to subclasses. Therefore, extensive use of such members violates the encapsulation principle. This metric allows us to see the proportion of 'vulnerable' members in a class. A large proportion of such members means that the class has high potential to be affected by external classes and means that increased effort will be needed to test such a class thoroughly.

NOCC - Number Of Child Classes

This metric counts the number of classes which inherit from a particular class (i.e. the number of classes in the inheritance tree down from a class). As this value increases, it is obvious that the particular class is being re-used well. However, it is also important to consider that where there are many child classes, are they all genuinely appropriate members of the parent class? In this case, the abstraction of

the class may be poor. It is also true that as NOCC increases, the amount of testing required for each child class will increase.

DIT - Depth in Class Inheritance Tree

This metric reports how deeply a class resides in the class inheritance tree. High values imply that a class is quite specialised.

RFC - Response For a Class

This metric measures the number of methods that can be invoked in response to a message to an object of a class. For larger values of RFC, it is obvious that required testing effort becomes greater as does the overall design complexity of the class.

CBO - Coupling Between Object classes

The value for CBO is the number of classes which a particular class refers to. This is a measure of how cohesive (and therefore reusable) a particular class is likely to be. References can be uses of classes as member types, parameter types, method local variable types or casts.

LOCM - Lack Of Cohesion of Methods

LOCM measures the percentage of methods that do not access a specific attribute averaged over all attributes in the class. A low percentage indicates high coupling between methods which indicates high testing effort (since many methods can affect the same attributes) and potentially low reusability.

NOOC - Number of Operations Overridden by a Class

NOOC measures the number of inherited operations which a class overrides. High values for NOOC tend to indicate design problems; subclasses 'should' generally add to and extend the functionality of the parent classes rather than overriding them.

NOAC - Number of Operations Added by a Class

This metric measures the number of operations added by a class (inherited operations are not counted). As this value becomes larger for a class, the functionality of that class becomes increasingly distinct from that of the parent classes. In this case, it should be considered whether this class should genuinely be inheriting from the parent or if it could be broken down into several, smaller classes.

WMC - Weighted Methods per Class

WMC is a count of the methods in a class (weighted according to complexity). The value of WMC can indicate whether this class is likely to be suitable for re-use.

CSI - Class Specialisation Index

CSI provides a measure of specialisation for a class. The higher value for CSI, the more likely that a particular class does not conform to the abstraction of it's super-classes.

OSavg - Average Operation Size

This metric provides a measure of the average size of the operations (methods) for a particular class. Any conventional functional metric can be used to determine operation 'size' but the standard cyclomatic complexity metric (and variations of this) will yield 'realistic' results. In OO development, it is desirable to have small, fine-grained methods, so highă values for OSavg are a warning that it may help improve code quality if some methods in the class were broken down.

NPavgC - Average Number of Parameters for methods in a Class

Methods with a high number of parameters generally require considerable testing (as their input can be highly varied). Also, large numbers of parameters lead to more complex, less maintainable code. This metric provides an average number of parameters for methods in a class (not including inherited methods).

AC - Attribute Complexity

Attribute Complexity is defined as the sum of R(i) where R(i) is the value of each attribute in the class evaluated from the table below. Summing R(i) for a class gives this metric value. AC is from the work of Chen & Lu.

Type	Value
Boolean/Integer	1
Char	1
Real	2
Array	3-4
Pointer	5
Record, Struct or Object	6-9
File	10

OpCom - Operation Complexity

The definition for operation complexity is the sum of O(i) where O(i) is operation i's complex value as McCabe complexity V(g). Summing the O(i) for each operation in the class gives this metric value.

LOC - Lines Of Code comprising a Class

LOC is a primitive metric to measure the size of a class. It is included for traditional reasons.

D.5.4 Method Metrics

NP - Number of Parameters

NP is simply a measure of the number of parameters that a method accepts. High values for NP can mean that a method will require extensive testing (since the range of possible inputs may be greater). As a rule of thumb, methods with many parameters also tend to be more specialised and so are less likely to be reusable.

V(G) - Cyclomatic Complexity

Cyclomatic Complexity measures the number of possible paths through an algorithm by counting the number of distinct regions on a flowgraph. This represents the cognitive complexity of the method.

V'(G) - Enhanced Cyclomatic Complexity

V'(G) brings together the notions of cyclomatic and operational complexity (by dividing OC by V(G)). This provides the average operational complexity for decision points in a method and is a strong indicator of the overall cognitive complexity of the method.

eV(G) - Essential Complexity

eV(G) is a measure of the structure of testable paths in a component. Values exceeding the threshold (7) usually signal an unstructured implementation of control logic. To calculate, we develop a directed graph to represent the control structure of the logical unit. This graph should contain only the four basic and simple structured constructs: sequence, selection, iteration and case. We only keep structures which contain occurences of unstructured constructs (break, continue, goto) and recalculate complexity on this graph. This measures the difficulty and feasibility of

the testing as the presence of unstructured constructs increases effort of testing as well as future code modifications.

LOC - Method Lines Of Code

LOC is a primitive metric to measure the size of a method. It is included for traditional reasons.

OC - Operational Complexity

This metric assigns weights to operations which can occur in expressions. The values of weights for all the expressions in a method are summed to provide a value for OC. This is complementary to V(G) since it looks at the complexity of the expressions which are being evaluated rather than the number of decision points in the method.

RLOC - Relative Lines Of Code

This metric measures the lines of code in a method relative to the containing class. This is a primitive means to measure the proportional significance of a method.

NEST - Maximum Number of Levels

Since the 1950's, cognitive sciences studies have shown that groups that contain more than seven pieces of information are increasingly harder for people to understand in problem solving. To measure this, we count the number of If...Then or If...Then...Elses in a nest. Logical units with a large number of nested levels may need implementation simplification and process improvement.

N1 - Total Number of Operators

N1 is the total number of operators used in a file. This is used as an input to the Halstead Software Science metrics.

N2 - Total Number of Operands

N2 is the total number of operands used in a file. This is used as an input to the Halstead Software Science metrics.

n1 - Number of Unique Operators

n1 is the number of unique operators used in a file. This is used as an input to the Halstead Software Science metrics.

n2 - Number of Unique Operands

n2 is the number of unique operands used in a file. This is used as an input to the Halstead Software Science metrics.

N - Halstead Program Length

N is calculated as N1+N2 and is a general measure of program length for a given file.

n - Halstead Program Vocabulary

n is calculated as n1+n2 and is a measure of the number of unique operands and operators used in a particular file. This can provide an impression of comprehensibility/complexity for that file.

V - Halstead Program Volume

V is the program volume metric from the Halstead Software Science metrics. This is calculated as V=N*(LOG2 n).

D - Halstead Difficulty

D is the difficulty metric from the Halstead Software Science metrics. This is calculated as D=(n1/n2)*(N2/n2).

E - Halstead Effort

E is the effort metric from the Halstead Software Science metrics. This is calculated as E=D*V.

CALLS - Number of Calls

CALLS is the number of calls from a method/function to subordinate logical units (methods/functions). This is a measure of the degree of FAN-OUT.

BRANCH - Number of Branching Nodes

Higher values indicate possible use of “gotos” and/or abnormal exits from control structures such as loops. This problem is an indicator of unstructured design and increases the testing difficulty. For components written in C, a higher value may be permitted due to the legitimate use of C “breaks” in a “switch” statement.

OAC - Operation Argument Complexity

OAC is defined as the sum of P(i) where P(i) is the value of each argument i in each operation in the class evaluated from the table below.

Type	Value
Boolean/Integer	1
Char	1
Real	2
Array	3-4
Pointer	5
Record, Struct or Object	6-9
File	10

ANION - Adjusted Number of Input/Output Nodes

ANION is an adjusted measure of the number of input/output nodes in a given method/function. Programming practices today state that there should be one way into a module and one way out. This measures the difficulty of testing the control logic of the software. Logical units with a large number of input/output nodes may need implementation simplification and process improvement. ANION is adjusted to behave intelligently where redundant “return” statements exist.

NION - Number of Input/Output Nodes

NION is a measure of the number of input/output nodes in a given method/function. Programming practices today state that there should be one way into a module and one way out. This measures the difficulty of testing the control logic of the software. Logical units with a large number of input/output nodes may need implementation simplification and process improvement. ANION is adjusted to behave intelligently where redundant “return” statements exist.

CONTROL - Number of control statements

This is a measure of the number of control statements (selection, iteration) in a method/function.

EXEC - Number of executable statement

This is a measure of the number of executable statements in a method/function.

NSTAT - Number of statements

NSTAT is a measure of the total number of statements in a method/function. This is calculated as CONTROL+EXEC.

CDENS - Control Density

This is a measure of the “richness” of decision nodes in a module. A high density module will be more difficult to maintain than a less dense one. We count the number of control statements and the number of complex executable statements. Control density is the ratio of control statements to the total number of statements.

QCP_MAINT - Quality Criteria Profile (Maintainability)

MAINTAINABILITY=3 * Halstead Length + Number of statements + Maximum levels + 2 * Cyclomatic Number + Number of Branching Nodes

QCP_CRCT - Quality Criteria Profile (Correctness)

CORRECTNESS=Halstead Difficulty + Number of statements + 2 * Cyclomatic Number

Appendix E

Metrics Tools

This appendix presents a comparison of twelve metrics tools evaluated in conducting this research. Identifying, acquiring, and determining the metrics produced by each tool was a non-trivial task. The results of this search are presented here in hopes of aiding other researchers.

Table E.1, Table E.2, and Table E.3 present the metrics produced by the twelve metrics tools. All metrics generated by any of these tools are listed. In the "Level" column, M indicates Method, C indicates Class, P indicates Project, K indicates Package, and F indicates File.

Table E.4 assigns abbreviation names for each metric tool and identifies what languages each tool supports.

Table E.5, Table E.6, and Table E.7 present the metrics produced by each of the twelve metrics tools. An 'x' indicates that a tool generates that particular metric. The table identifies what metrics are generated by which tools and identifies overlap between tools.

Metric	Metric Description	Level
TLOC	Total Lines of Code	M,C,P
CA	Afferent Coupling	K
RMD	Normalized Distance	K
NOC	Number of Classes	K
NOC	Number of Classes	P
SIX	Specialization Index	C,K
RMI	Instability	K
NOF	Number of Attributes	C,File,K
NOP	Number of Packages	P
MLOC	Method Lines of Code	M
WMC	Weighted methods per Class	C,File,K
WMCv	Weighted methods per Class (visible/public)	
NORM	Number of Overridden Methods	C,File,K
NBD	Nested Block Depth	M,C,File,K
PAR	Number of Parameters	M,C,File,K
NRP	Number of Return Points	M,C,P
IC	Interface complexity (params + returns)	M,C,P
RMA	Abstractness	K
NOI	Number of Interfaces	P
CE	Efferent Coupling	K
NOM	Number of Modules (Files)	P
NPC	Number of Public Classes	P
NFC	Number of Final Classes	P
NAbC	Number of Abstract Classes	P
NTC	Number of Toplevel Classes	P
NTSC	Number of Toplevel(Static Inner Class)	P
NIC	Number of Inner Classes	P
NLoC	Number of Local Classes	P
NAC	Number of Anonymous Classes	P
REU	Reuse ratio	P
SPC	Specialization ratio	P
AID	Average Inheritance Depth	P
CHD	Class Hierarchy Depth	P
NNM	Number of Native Methods	P
NMC	Number of methods per class - Mean	P
NMCs	Number of methods per class - Standard Deviation	P

Table E.1: Metrics Description 1

Metric	Metric Description	Level
MSAvg	Method size - Mean	P
MSSd	Method size - Standard Deviation	P
TL	Total Lines	File
CL	Comment Lines	File
COM	Comment Lines	C,P
C_COM	in-line comments	File,P
BL	Blank Lines	File
SL	Source Lines	File
NCSS	Source Lines	M,C,K
CD	CommentDensity	File
L_C	lines of code per line of comment	
DIT	Depth of Inheritance Tree	C
NII	Number of Interfaces Implemented	C
NCI	Number of classes implementing interface	C
NIV	Number of Instance Variables	C
NSV	Number of Static Variables	C
NOV		C
NIM	Number of Instance Methods	C
NSM	Number of Static Methods	C
NNM	Number of Native Methods	C
NPM	Number of Primitive Methods	C
NNP	Number of NonPrimitive Methods	C
NOM	Number of Methods	C
WMC	Weighted Methods Complexity	C
RFC	Response For Class	C
LCOM_CK	Lack of Cohesion of Methods(Chidamber-Kemerer)	C
LCOM_LH	LCOM (Li-Henry)	C
LCOM_HS	LCOM (Henderson-Sellers)	C
NIC	Number of Inner Classes	C
NIS	Number of Inner Static Classes	C
NLC	Number of Local Classes	C
NAC	Number of Anonymous Classes	C
NOC	Number of Children	C
FI	Fan-in	C
FO	Fan-out	C
PFI	Intra-Package Fan-in	C
PFO	Intra-Package Fan-out	C
IFI	Inter-package Fan-in	C
IFO	Inter-package Fan-out	C
NOS	Number of Statements	M

Table E.2: Metrics Description 2

Metric	Metric Description	Level
NOE	Number of Exceptions thrown	M
V(G)	Cyclomatic Number	M
FC	functional complexity (interface + cyclomatic)	M
MVG	McCabe's Cyclomatic Complexity	M,C,P
PL	Halstead Program Length	M
AHL	Actual Halstead Length	M
VOC	Halstead Program's Vocabulary	M
VOL	Halstead Program Volume	M
LVL	Halstead Program Level	M
PD	Halstead Program Difficulty	M
EFF	Halstead Development Effort	M
BUG	Halstead Bug Predicted	M
MI	Halstead Maintainability Index	
Javadocs	lines of Java docs	
M_C	Cyclomatic Complexity per comment	C,P
IF4	Information Flow	C,P
IF4v	Information Flow (visible)	C,P
IF4c	Information Flow (concrete)	C,P
CBO	coupling between objects	C
NOTe	Number of exported types	K
CYC	Cyclic Dependencies	K
DIP	Dependency Inversion Principle	C
DCYC	Direct Cyclic Dependency	K
EP	Encapsulation Principle	K
LSP	Limited Size Principle	K
AVPATHS	average depth of paths	P
NSC	number of semicolons	P
ANION	adjusted number of I/O nodes	M
BRANCH	number of abnormal exits	M
CDENS	control density	M
CONTROL	number of control statements	M
RLOC	relative size of code	M
eVG	essential complexity	M
V'G	extended complexity	M
AHF	attribute hiding factor	P
AIF	attribute inheritance factor	P
MHF	method hiding factor	P
MIF	method inheritance factor	P
POC	polymorphism factor	P
NEST	nests of like constructs	

Table E.3: Metrics Descriptions 3

Tool	Abbreviation	Language Supported
CMT++	CM	C++
Essential Metrics	EM	C++
depend.sh (ObjectMentor)	DP	C++
CCCC	CC	C,C++,Java
RSM	RS	C,C++,C#,Java
Eclipse Metrics	EC	Java
Jstyle 5.0	JS	Java
JavaNCSS	JN	Java
Jdepend	JD	Java
RefactorIT	RI	Java
CMJava	CM	Java
Essential Metrics	EJ	Java

Table E.4: Metrics Tool Language Support

Metric	CM	EM	DP	CC	RS	EC	JS	JN	JD	RI	CM	EJ
TLOC	x	x		LOC	x	x				x	x	x
CA			x			x			x	x		
RMD			x			x			x	x		
NOC		x				x		x	x	x		x
NOC				NOM			x					
SIX	x					x						
RMI			x			x			x	x		
NOF						x						
NOP						x	x					
MLOC						x						
WMC		x		WMC1		x		x				x
WMCv				x								
NORM						x						
NBD						x						
PAR		x			x	x				x		x
NRP					x							
IC					x							
RMA			x			x			x	x		
NOI						x	x					
CE			x			x			x	x		
NOM		x					x					x
NPC							x					
NFC							x					
NAbC							x		x	x		
NTC	x				x		x		x	x		
NTSC							x					
NIC							x					
NLoC							x					
NAC							x					
REU							x					
SPC							x					
AID							x					
CHD		x					x					x
NNM	x						x					
NMC							x					
NMCs							x					

Table E.5: Metrics Tool Comparison 1

Metric	CM	EM	DP	CC	RS	EC	JS	JN	JD	RI	CM	EJ
MSAvg							x					
MSSd							x					
TL							x					
CL							x					
COM		x		x	x					CLOC		x
C_COM		x										x
BL					x		x					
SL							x					
NCSS	x	x		LOC	x			x		x	x	x
CD		x					x			x		x
L_C				x								
DIT				x	x	x	x			x		
NII							x					
NCI							x					
NIV							x					
NSV						NSF	x					
NOV							x					
NIM							x					
NSM						x	x					
NNM							x					
NPM							x					
NNP							x					
NOM		x				x	x	Functions				x
WMC							x			x		
RFC		x					x			x		x
LCOM_CK							x					
LCOM_LH							x					
LCOM_HS	x					LCOM	x					
NIC							x	Classes				
NIS							x					
NLC							x					
NAC							x					
NOC				x		NSC	x			x		
FI				x			x					
FO				x			x					
PFI							x					
PFO							x					
IFI							x					
IFO							x					
NOS							x					

Table E.6: Metrics Tool Comparison 2

Metric	CM	EM	DP	CC	RS	EC	JS	JN	JD	RI	CM	EJ
NOE							x					
V(G)	x	x			x	x	x	CCN		x	x	x
FC					x							
MVG				x								
PL		x					x					x
AHL							x					
VOC		x					x					x
VOL	x	x					x				x	x
LVL		x					x					x
PD		x					x					x
EFF		x					x					x
BUG	x						x				x	
MI	x	x									x	x
Javadocs								x				
M_C				x								
IF4				x								
IF4v				x								
IF4c				x								
CBO	x			x								
NOTe										x		
CYC										x		
DIP										x		
DCYC										x		
EP										x		
LSP										x		
AVPATHS		x										x
NSC		x										x
ANION		x										x
BRANCH		x										x
CDENS		x										x
CONTROL		x										x
RLOC		x										x
eVG		x										x
V'G		x										x
AHF		x										x
AIF		x										x
MHF		x										x
MIF		x										x
POC		x										x
NEST		x										x

Table E.7: Metrics Tool Comparison 3

Appendix F

Surveys

This appendix presents the survey instruments used in this research.

F.1 Academic Pre-Experiment Survey

Survey on Programming Attitudes EECS 268 Programming II

This survey is designed to evaluate your programming experience and your perceptions and use of testing and design practices.

What is your KU ID? _____

Previous College Computer Science Courses (programming based)
How many college computer science courses have you taken at KU or elsewhere that contained a substantial computer programming component?

__ 0
__ 1
__ 2
__ 3
__ 4 or more

Previous Other Computer Science Courses (programming based)
How many non-college computer science courses have you taken that contained a substantial computer programming component?

__ none
__ 1 semester in high school
__ 2 semesters in high school
__ 3 or more semesters in high school
__ 1 semester or more elsewhere (short course or vocational school)

Previous Computer Programming Experience
Please rate your level of competence with the following programming languages? Circle one number for each language/group of languages. Use the following scale:

1. Never programmed in this language.
2. Minimal experience. Maybe compiled a test program.
3. Some experience. Wrote one or two small programs.
4. Substantial experience. Wrote several small to medium-sized programs.
5. Extensive experience. Wrote many programs.

C++	1 2 3 4 5
Java	1 2 3 4 5
Visual Basic	1 2 3 4 5
Python, Perl or other scripting based languages	1 2 3 4 5
JavaScript, html, ASP or other web based languages	1 2 3 4 5
Other, please specify _____	1 2 3 4 5

Time Since Last Programming
When did you last write a computer program in the following language? Circle one number for each language/group of languages. Use the following scale:

1. Never programmed in this language before.
2. Within last three months.
3. Four to twelve months ago.
4. One to three years ago.
5. More than three years ago.

C++	1 2 3 4 5
Java	1 2 3 4 5
Visual Basic	1 2 3 4 5
Python, Perl or other scripting based languages	1 2 3 4 5
JavaScript, html, ASP or other web based languages	1 2 3 4 5
Other, please specify _____	1 2 3 4 5

Attitude Towards Testing
How important is it to test computer programs that you have written?

___ not important, I never make mistakes
___ not important, my projects are only for a grade in the class
___ somewhat important, so I do a little bit of testing
___ important; I try to test my programs if I still have time before the deadline
___ very important; a project is not done until it is thoroughly tested

Test Timing
When do you write tests for your programs?

___ never
___ after I think the entire program is complete
___ after I think an important portion of the program is complete (such as a class)
___ after I think a small portion of the program is complete (such as a single function)
___ before I have written any code
___ before I have written a new important portion of the program (such as a class), but after I have tested other code that is finished
___ before I have written a new small portion of the program (such as a single function), but after I have tested other code that is finished

Automated Testing Use
Do you ever write automated tests for your programs?

___ yes, all the time
___ yes, but only some of the time
___ yes, I tried it once
___ no, if I test, it is by hand (run program and look at output)

Automated Testing Frameworks
Have you ever used an automated testing framework like JUnit or CppUnit?

___ yes, I use an automated testing framework often
___ yes, I have used an automated testing framework before
___ no, I have never used an automated testing framework

Attitude Toward Design
How important is it to design computer programs before they are written?

___ not important, I just start programming and don't think about the design
___ not important, I develop the design as I write the code
___ somewhat important, so I do a little bit of design before I start writing code
___ important; I try to design most of my programs before I start writing code
___ very important; I never start programming until I have a thorough design complete

Design Techniques
How do you design your programs?

___ I don't design, I just write code
___ I use visual models like the UML or flowcharts
___ I sketch the design in the code with class declarations before writing any function definitions
___ I write out the design in natural language
___ I use a combination of visual models and natural language
___ I let the design evolve as I write the code; I document the design with visual models and/or natural language
___ I let the design evolve as I write the code; the code is the design documentation

Attitude Towards Test-First Programming
Test-first programming is the practice by which an automated test case is written before the code is implemented. The implemented code is written to pass the test case. The design of the system emerges as the programmer repeatedly writes tests, then writes the code to make the test pass, then improves both the code and tests in short rapid iterations.
What is your opinion of test-first programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Attitude Towards Test-Last Programming
Test-last programming is the practice by which a test case is written after the code is implemented. The design of the system is usually developed at least partially before any code is written.
What is your opinion of test-last programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Choosing Between Test-First and Test-Last Programming
If you had a choice of writing code with a test-first or test-last approach, which would you choose?

___ test-first
___ test-last

Why?

Age
How old are you today?

___ 18 to 22 years
___ 23 to 26 years
___ 27 to 35 years
___ over 35 years

Gender
What is your gender?

___ Male
___ Female

Race
Which category best fits your race?

___ White
___ African or African American
___ Asian
___ Hispanic
___ Other

Classification
How does the university currently classify you?

___ Freshman
___ Sophomore
___ Junior
___ Senior
___ Graduate
___ Other

Major
What is your major?

___ Computer Science
___ Computer Engineering
___ Electrical Engineering
___ Other: please specify

Overall GPA
What is your overall GPA?

___ 3.5 – 4.0
___ 3.0 – 3.5
___ 2.5 – 3.0
___ 2.0 – 2.5
___ 1.5 – 2.0
___ 1.0 – 1.5
___ below 1.0

Major GPA
What is your GPA in your major?

___ 3.5 – 4.0
___ 3.0 – 3.5
___ 2.5 – 3.0
___ 2.0 – 2.5
___ 1.5 – 2.0
___ 1.0 – 1.5
___ below 1.0

Additional Comments
Is there anything else related to this study that you would like to comment on that we have missed or that you would like to add?

F.2 Academic Post-Experiment Survey

Survey on Programming Attitudes EECS 268 Programming 2
This survey is designed to evaluate your programming experience and your perceptions and use of testing and design practices.

KUID

What is your KU ID? _____

Approach Used
What approach did you use on the projects completed in class so far?

Test-First Test-Last Neither

Project 1 (array-based DriverTable) _____ _____ _____
Project 2 (linked-list DriverTable) _____ _____ _____

Project 3 (grammar) _____ _____ _____

Confidence of Software Quality
I am confident that the code I wrote for Project 1 and 2 is correct.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Confidence of Software Changes
I am confident that I could make changes to the code I wrote for Project 1 and 2 without breaking things.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Confidence of Software Reuse
I am confident that I could reuse the code I wrote for Project 1 and 2 in another future project.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Attitude Towards Testing
How important is it to test computer programs that you have written?

___ not important, I never make mistakes
___ not important, my projects are only for a grade in the class
___ somewhat important, so I do a little bit of testing
___ important; I try to test my programs if I still have time before the deadline
___ very important; a project is not done until it is thoroughly tested

Test Timing
When do you think is the best time to write tests for your programs?

___ never
___ after I think the entire program is complete
___ after I think an important portion of the program is complete (such as a class)
___ after I think a small portion of the program is complete (such as a single function)
___ before I have written any code
___ before I have written a new important portion of the program (such as a class), but after I have tested other code that is finished
___ before I have written a new small portion of the program (such as a single function), but after I have tested other code that is finished

Automated Testing Use
Did you write automated tests for the programs in Project 1 and 2?

___ yes, all the time
___ yes, but only some of the time
___ yes, I tried it once
___ no, all my testing was done by hand (run program and look at output or use debugger)

Automated Testing Frameworks
I think it is a good idea to write automated unit tests with assert() statements.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Attitude Toward Design
How important is it to design computer programs before they are written?

___ not important, it works fine to just start programming and not think about the design
___ not important, it works fine to develop the design as the code is written
___ somewhat important, it is a good idea to do a little bit of design before writing code
___ important; it is good to design most of a program before writing code
___ very important; never start programming until a thorough design is complete

Design Techniques
What do you think is the best approach to design a program?

___ Don't design, just write code

___ Use visual models like the UML or flowcharts
___ Sketch the design in code with class declarations before writing function definitions
___ Write out the design in natural language
___ Use a combination of visual models and natural language
___ Let the design evolve as the code is written; document the design with visual models and/or natural language
___ Let the design evolve as the code is written; the code is the design documentation

Attitude Towards Test-First Programming
Test-first programming is the practice by which an automated test case is written before the code is implemented. The implemented code is written to pass the test case. The design of the system emerges as the programmer repeatedly writes tests, then writes the code to make the test pass, then improves both the code and tests in short rapid iterations.
What is your opinion of test-first programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Attitude Towards Test-Last Programming
Test-last programming is the practice by which a test case is written after the code is implemented. The design of the system is usually developed at least partially before any code is written.
What is your opinion of test-last programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code with fewer defects, test-first or test-last?

___ test-first

___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code that is simpler, more reusable, and more maintainable, test-first or test-last?

___ test-first
___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces a correct solution in less time, test-first or test-last?

___ test-first
___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, do you think you are more likely to thoroughly test a program with the test-first or the test-last approach?

___ test-first
___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, for the course project you just completed, which do you think was the best approach, test-first or test-last?

___ test-first
___ test-last

Why?

Choosing Between Test-First and Test-Last Programming
If you had a choice of writing code with a test-first or test-last approach, which would you choose?

___ test-first
___ test-last

Why?

Additional Comments
Is there anything else related to this study that you would like to comment on that we have missed or that you would like to add?

F.3 Industry Pre-Experiment Survey

Survey on Programming Attitudes
This survey is designed to evaluate your programming experience and your perceptions and use of testing and design practices.

College Education
Check the most appropriate description of your college experience.

___ Never attended college
___ Attended some college, no computer-related courses
___ Attended some college, some computer-related courses
___ Completed BA/BS, non-computing major/minor
___ Completed BA/BS, computing-related major/minor
___ Completed BA/BS and some graduate work, non-computing major/minor
___ Completed BA/BS and some graduate work, computing-related major/minor
___ Completed graduate degree (MS/PhD), non-computing major/minor
___ Completed graduate degree (MS/PhD), computing-related major/minor

Work Experience
How many years have you worked in a computing-related job?

___ <1
___ 1-5
___ 6-10
___ 11-20
___ >20

Employee ID
What is your Employee ID? _____

Age
How old are you today?

___ < 25 years
___ 26 to 35 years
___ over 35 years

Gender
What is your gender?

___ Male
___ Female

Race
Which category best fits your race?

___ White
___ African or African American
___ Asian
___ Hispanic
___ Other

Computer Programming Experience
How many years have you worked in a job that had a significant computer programming component?

___ <1
___ 1-5
___ 6-10
___ 11-20
___ >20

Previous Computer Programming Experience
Please rate your level of competence with programming languages prior to this class. Circle one number for each language/group of languages. Use the following scale:

1. Never programmed in this language.
2. Minimal experience. Maybe compiled a test program.
3. Some experience. Wrote one or two small programs.
4. Substantial experience. Wrote several small to medium-sized programs.
5. Extensive experience. Wrote many programs.

C++	1 2 3 4 5
Java	1 2 3 4 5
Visual Basic	1 2 3 4 5
Python, Perl or other scripting based languages	1 2 3 4 5
JavaScript, html, ASP or other web based languages	1 2 3 4 5
Assembly	1 2 3 4 5
Other, please specify	1 2 3 4 5

Time Since Last Programming
When did you last write a computer program in the following languages prior to this class? Circle one number for each language/group of languages. Use the following scale:

1. Never programmed in this language before.

2. Within last three months.
3. Four to twelve months ago.
4. One to three years ago.
5. More than three years ago.

C++	1 2 3 4 5
Java	1 2 3 4 5
Visual Basic	1 2 3 4 5
Python, Perl or other scripting based languages	1 2 3 4 5
JavaScript, html, ASP or other web based languages	1 2 3 4 5
Assembly	1 2 3 4 5
Other, please specify	1 2 3 4 5

Testing Knowledge
Do you know the difference between unit testing and integration testing?

___ yes
___ no, but I've heard those terms
___ no, I have no idea what you are talking about

Attitude Towards Testing
How important is it to unit test computer programs that you have written?

___ not important, I never make mistakes
___ not important, my projects are not for production or someone else will test it
___ somewhat important, so I do a little bit of unit testing
___ important; I try to unit test my programs if I still have time before the deadline
___ very important; my part is not done until it is thoroughly unit tested

Test Timing
When do you write unit tests for your programs?

___ never
___ after I think the entire program is complete
___ after I think an important portion of the program is complete (such as a class)
___ after I think a small portion of the program is complete (such as a single function)
___ before I have written any code
___ before I have written a new important portion of the program (such as a class), but after I have tested other code that is finished
___ before I have written a new small portion of the program (such as a single function), but after I have tested other code that is finished

Automated Testing Use
Do you ever write automated unit tests for your programs?

___ yes, all the time
___ yes, but only some of the time
___ yes, I tried it once
___ no, if I test, it is by hand (run program and look at output)

Automated Testing Frameworks
Have you ever used an automated testing framework like JUnit or CppUnit?

___ yes, I use an automated testing framework often
___ yes, I have used an automated testing framework before
___ no, I have never used an automated testing framework

Attitude Toward Design
How important is it to design computer programs before they are written?

___ not important, I just start programming and don't think about the design
___ not important, I develop the design as I write the code
___ somewhat important, so I do a little bit of design before I start writing code
___ important; I like most of the design complete before I start writing code
___ very important; I never start programming until I have a thorough design complete

Design Techniques
How do you design your programs?

___ I don't design, I just write code
___ I use visual models like the UML or flowcharts
___ I sketch the design in code with class declarations before writing function definitions
___ I write out the design in natural language
___ I use a combination of visual models and natural language
___ I let the design evolve as I write the code; I document the design with visual models and/or natural language
___ I let the design evolve as I write the code; the code is the design documentation

Attitude Towards Test-First Programming
Test-first programming is the practice by which an automated test case is written before the code is implemented. The implemented code is written to pass the test case. The design of the system emerges as the programmer repeatedly writes tests, then writes the code to make the test pass, then improves both the code and tests in short rapid iterations.
What is your opinion of test-first programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Attitude Towards Test-Last Programming
Test-last programming is the practice by which a test case is written after the code is implemented. The design of the system is usually developed at least partially before any code is written.
What is your opinion of test-last programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Choosing Between Test-First and Test-Last Programming
If you had a choice to writing code with a test-first or test-last approach, which would you choose?

___ test-first
___ test-last

Why?

F.4 Industry Post-Experiment Survey

Survey on Programming Attitudes
This survey is designed to evaluate your programming experience and your perceptions and use of testing and design practices.

Employee ID
What is your Employee ID? _____

Confidence of Software Quality
I am confident that the code I wrote for the course exercise is correct.

___ strongly agree

___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Confidence of Software Changes
I am confident that I could make changes to the code I wrote for the course exercise without breaking things.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Confidence of Software Reuse
I am confident that I could reuse the code I wrote for the course exercise in a future project.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Attitude Towards Testing
How important is it to unit test computer programs that you have written?

___ not important, I never make mistakes
___ not important, my projects are not for production or someone else will test it
___ somewhat important, so I do a little bit of unit testing
___ important; I try to unit test my programs if I still have time before the deadline
___ very important; my part is not done until it is thoroughly unit tested

Test Timing
When do you think is the best time to write tests for your programs?

___ never
___ after I think the entire program is complete
___ after I think an important portion of the program is complete (such as a class)
___ after I think a small portion of the program is complete (such as a single function)

___ before I have written any code
___ before I have written a new important portion of the program (such as a class), but after I have tested other code that is finished
___ before I have written a new small portion of the program (such as a single function), but after I have tested other code that is finished

Automated Testing Use
Did you write automated tests for the program in the course exercise?

___ yes, all the time
___ yes, but only some of the time
___ yes, I tried it once
___ no, all my testing was done by hand (run program and look at output or use debugger)

Automated Testing Frameworks
I think it is a good idea to write automated tests.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree

Attitude Toward Design
How important is it to design computer programs before they are written?

___ not important, it works fine to just start programming and not think about the design
___ not important, it works fine to develop the design as the code is written
___ somewhat important, it is a good idea to do a little bit of design before writing code
___ important; it is good to design most of a program before writing code
___ very important; never start programming until a thorough design is complete

Design Techniques
What do you think is the best approach to design a program?

___ Don't design, just write code
___ Use visual models like the UML or flowcharts
___ Sketch the design in code with class declarations before writing function definitions
___ Write out the design in natural language
___ Use a combination of visual models and natural language

___ Let the design evolve as the code is written; document the design with visual models and/or natural language
___ Let the design evolve as the code is written; the code is the design documentation

Coding Effort
How many minutes do you estimate you spent writing the code for the course exercise?

___ (in minutes)

Code Completeness
What percent of the course project requirements do you think you implemented?

___ % (0-100%)

Attitude Towards Test-First Programming
Test-first programming is the practice by which an automated test case is written before the code is implemented. The implemented code is written to pass the test case. The design of the system emerges as the programmer repeatedly writes tests, then writes the code to make the test pass, then improves both the code and tests in short rapid iterations.
What is your opinion of test-first programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Attitude Towards Test-Last Programming
Test-last programming is the practice by which a test case is written after the code is implemented. The design of the system is usually developed at least partially before any code is written.
What is your opinion of test-last programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code with fewer defects, test-first or test-last?

___ test-first
___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code that is simpler, more reusable, and more maintainable, test-first or test-last?

___ test-first
___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces a correct solution in less time, test-first or test-last?

___ test-first
___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, do you think you are more likely to thoroughly test a program with the test-first or the test-last approach?

___ test-first
___ test-last

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, for the course exercise you just completed, which do you think was the best approach, test-first or test-last?

___ test-first
___ test-last

Why?

Choosing Between Test-First and Test-Last Programming
If you had a choice of writing code with a test-first or test-last approach, which would you choose?

___ test-first
___ test-last

Why?

Additional Comments
Is there anything else related to this study that you would like to comment on that we have missed or that you would like to add?

F.5 Industry Design Quality Review Scorecard

Quality Review Thank you for agreeing to review projects for this study! Your input is very valuable. This scorecard is designed to evaluate the quality of one software project. Please read the project description here. Note the CVS name for checking the source code out in order to complete the review. If you are unsure how to do this, please contact David Janzen at david@simexusa.com or 316-288-0469. Once you have checked out the project source code, spend no more than one to two hours reading through the code. Do not contact the authors as one objective of this exercise is to measure the understandability of the code. Then complete the following survey. Thank you again for your time.

Employee ID
What is your employee ID? _____

Software Development Experience
How many years have you been developing software professionally?

___ less than 1
___ 1 to 2
___ 3 to 5
___ 6 to 10
___ 11 to 20
___ 20 or more
___ No answer

Highest Degree
Select the most appropriate description of your college experience.

___ Never attended college
___ Attended some college, no computer-related courses
___ Attended some college, some computer-related courses
___ Completed BA/BS, non-computing major/minor
___ Completed BA/BS, computing-related major/minor
___ Completed BA/BS and some graduate work, non-computing major/minor
___ Completed BA/BS and some graduate work, computing-related major/minor
___ Completed graduate degree (MS/PhD), non-computing major/minor
___ Completed graduate degree (MS/PhD), computing-related major/minor
___ No answer

Project Reviewed
What project are you reviewing?

Understandability
Overall, how would you rate the software you reviewed in terms of understandability?
Understandability refers to the ability of a typical developer in your organization to read and understand the design and code of the system without significant assistance. Design/code simplicity and architectural clarity/consistency are contributing factors to good understandability.

___ 1 - Very difficult to understand
___ 2
___ 3 - Average understandability
___ 4
___ 5 - Very easy to understand
___ No answer

Maintainability
Overall, how would you rate the software you reviewed in terms of maintainability?
Maintainability refers to the ability of a typical developer in your organization to maintain the design and code of the system without significant assistance. Low coupling, high cohesion, and simplicity are contributing factors to good maintainability.

___ 1 - Very difficult to maintain
___ 2
___ 3 - Average maintainability
___ 4
___ 5 - Very easy to maintain
___ No answer

Reusability
Overall, how would you rate the software you reviewed in terms of reusability and extensibility?
Reusability refers to the ability of a typical developer in your organization to reuse and/or extend the design and code of the system without significant assistance. Low coupling, high cohesion, simplicity and the use of mechanisms such as interfaces and certain design patterns such as factory and template method are contributing factors to good maintainability.

___ 1 - Very difficult to reuse/extend
___ 2
___ 3 - Average reuseability/extensibility
___ 4
___ 5 - Very easy to reuse/extend
___ No answer

Testability
Overall, how would you rate the software you reviewed in terms of testability? Testability refers to the ability of a typical developer in your organization to test the system without significant assistance. Low coupling, high cohesion, simplicity and the use of certain design patterns are contributing factors to good testability.

___ 1 - Very difficult to test
___ 2
___ 3 - Average testability
___ 4
___ 5 - Very easy to test
___ No answer

Overall Design Quality
Overall, how would you rate the software you reviewed in terms of overall design quality?

___ 1 - Very low design quality
___ 2
___ 3 - Average design quality
___ 4
___ 5 - Very high design quality
___ No answer

Feel free to make any additional comments here.

F.6 Academic Longitudinal Survey

Survey on Programming Attitudes - EECS Follow-Up Survey
This survey is designed to evaluate your programming experience and your perceptions and use of testing and design practices during the *current* semester (not last semester when you were in 268).

KUID
What is your KU ID? _____

Programming-Based Courses
How many courses are you enrolled in this semester that require programming projects?

___ 0
___ 1
___ 2

__ 3
__ 4
__ 5 or more
__ No answer

Programs Written
How many programs have you written this semester (for classes or otherwise)?

__ 0
__ 1
__ 2
__ 3
__ 4
__ 5 or more
__ No answer

Option to Write Automated Tests
Of the programs in the previous question, on how many programs could you have chosen to write automated unit tests (such as with JUnit, assert(), ...)?

__ 0
__ 1
__ 2
__ 3
__ 4
__ 5 or more
__ No answer

Write Automated Tests
Of the programs in the previous question, on how many programs did you choose to write automated unit tests (such as with JUnit, assert(), ...)?

__ 0
__ 1
__ 2
__ 3
__ 4
__ 5 or more
__ No answer

Test-Last Approach
Of the programs in the previous question, on how many programs did you choose to use a test-last approach?

__ 0

__ 1
__ 2
__ 3
__ 4
__ 5 or more
__ No answer

Test-First Approach
Of the programs in the previous question, on how many programs did you choose to use a test-first approach?

__ 0
__ 1
__ 2
__ 3
__ 4
__ 5 or more
__ No answer

Automated Testing Use
To what degree did you write automated tests for your programs this semester?

__ all the time
__ only some of the time
__ I tried it once
__ none, all my testing was done by hand (run program and look at output or use debugger)
__ No answer

Confidence of Software Quality
I am confident that the code I wrote this semester is correct.

__ strongly agree
__ agree
__ somewhat agree
__ neither agree or disagree
__ somewhat disagree
__ disagree
__ No answer

Confidence of Software Changes
I am confident that I could make changes to the code I wrote this semester without breaking things.

__ strongly agree

___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree
___ No answer

Confidence of Software Reuse
I am confident that I could reuse the code I wrote this semester in another future project.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree
___ No answer

Attitude Towards Testing
How important is it to test computer programs that you have written?

___ not important, I never make mistakes
___ not important, my projects are only for a grade in the class
___ somewhat important, so I do a little bit of testing
___ important; I try to test my programs if I still have time before the deadline
___ very important; a project is not done until it is thoroughly tested
___ No answer

Test Timing
When do you think is the best time to write tests for your programs?

___ never
___ after I think the entire program is complete
___ after I think an important portion of the program is complete (such as a class)
___ after I think a small portion of the program is complete (such as a single function)
___ before I have written any code
___ before I have written a new important portion of the program (such as a class), but after I have tested other code that is finished
___ before I have written a new small portion of the program (such as a single function), but after I have tested other code that is finished
___ No answer

Automated Testing Frameworks
I think it is a good idea to use automated testing frameworks like JUnit.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree
___ No answer

Attitude Toward Design
How important is it to design computer programs before they are written?

___ not important, it works fine to just start programming and not think about the design
___ not important, it works fine to develop the design as the code is written
___ somewhat important, it is a good idea to do a little bit of design before writing code
___ important; it is good to design most of a program before writing code
___ very important; never start programming until a thorough design is complete
___ No answer

Design Techniques
What do you think is the best approach to design a program?

___ DonŠt design, just write code
___ Use visual models like the UML or flowcharts
___ Sketch the design in code with class declarations before writing function definitions
___ Write out the design in natural language
___ Use a combination of visual models and natural language
___ Let the design evolve as the code is written; document the design with visual models and/or natural language
___ Let the design evolve as the code is written; the code is the design documentation
___ No answer

Attitude Towards Test-First Programming
Test-first programming is the practice by which an automated test case is written before the code is implemented. The implemented code is written to pass the test case. The design of the system emerges as the programmer repeatedly writes tests, then writes the code to make the test pass, then improves both the code and tests in short rapid iterations. What is your opinion of test-first programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects

___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project
___ No answer

Attitude Towards Test-Last Programming
Test-last programming is the practice by which a test case is written after the code is implemented. The design of the system is usually developed at least partially before any code is written. What is your opinion of test-last programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code with fewer defects, test-first or test-last?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code that is simpler, more reusable, and more maintainable, test-first or test-last?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces a correct solution in less time, test-first or test-last?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, do you think you are more likely to thoroughly test a program with the test-first or the test-last approach?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, for the course project you just completed, which do you think was the best approach, test-first or test-last?

___ test-first
___ test-last
___ No answer

Why?

Choosing Between Test-First and Test-Last Programming
If you had a choice of writing code with a test-first or test-last approach, which would you choose?

___ test-first
___ test-last
___ No answer

Why?

Additional Comments
Is there anything else related to this study that you would like to comment on that we have missed or that you would like to add?

F.7 Industry Longitudinal Survey

Survey on Programming Attitudes - Industry Follow-Up Survey
This survey is designed to evaluate your programming experience and your perceptions and use of testing and design practices.

Employee ID
What is your employee ID? _____

Software Development Experience
How many years have you been developing software professionally?

___ less than 1
___ 1 to 2
___ 3 to 5
___ 6 to 10
___ 11 to 20
___ 20 or more
___ No answer

Highest Degree
Select the most appropriate description of your college experience.

___ Never attended college
___ Attended some college, no computer-related courses
___ Attended some college, some computer-related courses
___ Completed BA/BS, non-computing major/minor
___ Completed BA/BS, computing-related major/minor
___ Completed BA/BS and some graduate work, non-computing major/minor
___ Completed BA/BS and some graduate work, computing-related major/minor
___ Completed graduate degree (MS/PhD), non-computing major/minor
___ Completed graduate degree (MS/PhD), computing-related major/minor
___ No answer

Programs Written
In the last six months, how would you characterize your programming experience?

___ I have not been programming, but working on other things
___ Less than 10% of my time has been spent programming
___ I have spent about 10% to 50% of my time programming
___ I have spent more than half my time programming
___ No answer

Option to Write Automated Tests
Of the programs that you have worked on in the last six months, on how many programs could you have chosen to write automated unit tests (such as with JUnit)?

___ None
___ Less than 10%
___ 10% to 50%
___ More than 50%
___ All of them
___ No answer

Write Automated Tests
Of the programs you've written in the last six months, on how many programs did you choose to write automated unit tests (such as with JUnit)?

___ None
___ Less than 10%
___ 10% to 50%
___ More than 50%
___ All of them
___ No answer

Test-Last Approach
Of the programs in the previous question, on how many programs did you choose to use a test-last approach?

___ None
___ Less than 10%
___ 10% to 50%
___ More than 50%
___ All of them
___ No answer

Test-First Approach
Of the programs in the previous question, on how many programs did you choose to use a test-first approach?

___ None
___ Less than 10%
___ 10% to 50%
___ More than 50%
___ All of them
___ No answer

Automated Testing Use
To what degree did you write automated tests for your programs in the last six months?

___ all the time
___ only some of the time
___ I tried it once
___ none, all my testing was done by hand (run program and look at output or use debugger)
___ No answer

Confidence of Software Quality
I am confident that the code I wrote in the last six months is correct.

___ strongly agree
___ agree

___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree
___ No answer

Confidence of Software Changes
I am confident that I could make changes to the code I wrote in the last six months without breaking things.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree
___ No answer

Confidence of Software Reuse
I am confident that I could reuse the code I wrote in the last six months in another future project.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree
___ No answer

Attitude Towards Testing
How important is it to test computer programs that you have written?

___ not important, I never make mistakes
___ not important, my projects are not critical
___ somewhat important, so I do a little bit of testing
___ important; I try to test my programs if I still have time before the deadline
___ very important; a project is not done until it is thoroughly tested
___ No answer

Test Timing
When do you think is the best time to write tests for your programs?

___ never
___ after I think the entire program is complete

___ after I think an important portion of the program is complete (such as a class)
___ after I think a small portion of the program is complete (such as a single function)
___ before I have written any code
___ before I have written a new important portion of the program (such as a class), but after I have tested other code that is finished
___ before I have written a new small portion of the program (such as a single function), but after I have tested other code that is finished
___ No answer

Automated Testing Frameworks
I think it is a good idea to use automated testing frameworks like JUnit.

___ strongly agree
___ agree
___ somewhat agree
___ neither agree or disagree
___ somewhat disagree
___ disagree
___ No answer

Attitude Toward Design
How important is it to design computer programs before they are written?

___ not important, it works fine to just start programming and not think about the design
___ not important, it works fine to develop the design as the code is written
___ somewhat important, it is a good idea to do a little bit of design before writing code
___ important; it is good to design most of a program before writing code
___ very important; never start programming until a thorough design is complete
___ No answer

Design Techniques
What do you think is the best approach to design a program?

___ Don't design, just write code
___ Use visual models like the UML or flowcharts
___ Sketch the design in code with class declarations before writing function definitions
___ Write out the design in natural language
___ Use a combination of visual models and natural language
___ Let the design evolve as the code is written; document the design with visual models and/or natural language

___ Let the design evolve as the code is written; the code is the design documentation
___ No answer

Attitude Towards Test-First Programming
Test-first programming is the practice by which an automated test case is written before the code is implemented. The implemented code is written to pass the test case. The design of the system emerges as the programmer repeatedly writes tests, then writes the code to make the test pass, then improves both the code and tests in short rapid iterations. What is your opinion of test-first programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project
___ No answer

Attitude Towards Test-Last Programming
Test-last programming is the practice by which a test case is written after the code is implemented. The design of the system is usually developed at least partially before any code is written. What is your opinion of test-last programming?

___ I don't think it would ever work
___ I think it might be a good approach on small projects
___ I think it might be a good approach on projects where programmers have a lot of programming experience
___ I think it might be a good approach on projects where programmers understand the domain well
___ I think it might be a good approach on any project
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code with fewer defects, test-first or test-last?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces code that is simpler, more reusable, and more maintainable, test-first or test-last?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, which approach do you think produces a correct solution in less time, test-first or test-last?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, do you think you are more likely to thoroughly test a program with the test-first or the test-last approach?

___ test-first
___ test-last
___ No answer

Perception of Test-First and Test-Last Programming
Regardless of the approach you used, for the most recent project you just completed, which do you think would have been the best approach, test-first or test-last?

___ test-first
___ test-last
___ No answer

Why?

Choosing Between Test-First and Test-Last Programming
If you had a choice of writing code with a test-first or test-last approach, which would you choose?

___ test-first
___ test-last
___ No answer

Why?

Additional Comments
Is there anything else related to this study that you would like to comment on that we have missed or that you would like to add?