Collaborative-Adversarial Pair (CAP) Programming

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
December 18, 2009

Keywords: Collaborative-adversarial pair programming, CAP, pair programming, PP, collaborative programming, agile development, test driven development, empirical software Engineering

Abstract

The advocates of pair programming claim that it has a number of benefits over traditional individual programming, including faster software development, higher quality code, reduced overall software development cost, increased productivity, better knowledge transfer, increased job satisfaction and increased confidence in the resulting product, at only the cost of slightly increased personnel hours. While the concept of pair programming is attractive, it has some detraction. First, it requires that the two developers be at the same place at the same time. Second, it requires an enlightened management that believes that letting two people work on the same task will result in better software than if they worked separately. Third, the empirical evidence of the benefits of pair programming is mixed. Anecdotal and empirical evidence shows that pair programming is better suited for job training than for real software development. Pair programming is more effective than traditional single-person development if both members of the pair are novices to the task at hand. Novice-expert and expert-expert pairs have not been demonstrated to be effective.

This research proposes a new variant of pair programming called the *Collaborative-Adversarial Pair (CAP)* programming. Its objective is to exploit the advantages of pair programming while at the same time downplaying the disadvantages. Unlike traditional pairs, where two people work together in all the phases of software development, CAPs start by designing together; splitting into independent test construction and code implementation roles; then joining again for testing.

Two empirical experiments were conducted during the Fall 2008 and Spring 2009 semesters to validate CAP against traditional pair programming and individual programming. Forty two (42) volunteer students, undergraduate seniors and graduate students from Auburn University's Software Process class, participated in the studies. The subjects used Eclipse and JUnit to perform three programming tasks with different degrees of complexity. The subjects were randomly divided into three experimental groups: individual (Solo) programming group, pair programming (PP) group and collaborative adversarial pair (CAP) programming group in the ratio of 1:2:2. The results of this experiment point in favor of CAP development methodology and do not support the claim that pair programming in general reduces the overall software development time or increase the program quality or correctness.

To

My wife
Uma

and

My guru
Dr. David Ashley Umphress

Acknowledgments

I consider completing this dissertation to be the greatest accomplishment of my life thus far. This is a result of sacrifices and encouragement by full many individuals. Although it would not be possible for me to list them all, I would like to mention a handful without whom this accomplishment would have remained a dream.

It is with deep sense of gratitude that I acknowledge my indebtedness to my Ph.D. committee members; in particular, my advisor Dr. David A. Umphress. He has been a wise and dependable mentor and an exemplary role model in helping me achieve my professional goals. Dr. Umphress has always given me invaluable guidance, support and enthusiastic encouragement. Heartfelt thanks are also extended to other committee members, Dr. James Cross and Dr. Dean Hendrix for their suggestions and guidance which has greatly improved the quality of my work.

Special thanks goes to all forty two students (fall 2008 and spring 2009 software process class) who participated in the control experiments. I would also like to thank all the professors/teachers who have taught me (right from kindergarden to this date) and under whom I have worked as a Teaching Assistant at Auburn. The inspiration I have drawn from my long list of friends, right from my childhood to this date, deserves a special acknowledgement. From the bottom of my heart, I want to thank my parents, my in laws and my extended family for their love and support. Lastly, I would also like to thank my wife Mrs. Uma Rajendran, my son, Soorya Gokulan and my daughter Sneha for their love, support and unstinting faith.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ANOVA	Analysis of variance
BF	Brown and Forsythe's variation of Levene's test
C3	Chrysler Comprehensive Compensation
CAP	Collaborative-Adversarial Pair Programming
CRC	Class Responsibility Collaborator
CSP	Collaborative Software Process
GLM	General Linear Models
GUI	Graphical User Interface
IDE	Integrated Development Environment
IP	Individual Programming
J2EE	Java 2 Platform, Enterprise Edition
JDK	Java Development Kit
LOC	Lines of Code
OO	Object Oriented
PP	Pair Programming
PSP	Personal Software Process
Q-Q	Quintile-Quartile
SAS	Statistical Analysis Software
TDD	Test Driven Development

UML	Unified Modeling Language
XP	Extreme Programming

1. INTRODUCTION

One of the popular, emerging, and most controversial topics in the area of Software Engineering in the recent years is pair programming. *Pair programming* (PP) is a way of inspecting code as it is being written. Its premise – that of two people, one computer – is that two people working together on the same task will likely produce better code than one person working individually. In pair programming, one person acts as the “driver” and the other person acts as the “navigator.” The driver is responsible for typing code; the navigator is responsible for reviewing the code. In a sense, the driver addresses operational issues of implementation and the observer keeps in mind the strategic direction the code must take.

Though the history of pair programming stretches to punched cards, it gained prominence in the early 1990’s. It became popular after the publication in 1999 of *Extreme Programming Explained* by Kent Beck, where it was noted as one of the 12 key practices promoted by *Extreme Programming* (XP) [Beck 2000]. In recent years, industry and academia have turned their attention and interest toward pair programming [Arisholm et al. 2007, Canfora et al. Dec06] and it has been widely accepted as an alternative to traditional individual programming [Muller 2005].

The advocates of pair programming claim that it has many benefits over traditional individual programming, including faster software development, higher quality code, reduced overall software development cost, increased productivity, better knowledge transfer, increased job satisfaction and increased confidence in their work, only at the cost of slightly increased personnel hours [Arisholm et al. 2007].

While the concept of pair programming is attractive, it has some detraction. First, it requires that the two developers be at the same place at the same time. This is frequently not realistic in busy organizations where developers may be matrixed concurrently to a number of projects. Second, it requires an enlightened management that believes that letting two people work on the same task will result in better software than if they worked separately. This is a significant obstacle since software products are measured more by tangible properties, such as the number of features implemented, than by intangible properties, such as the quality of the code. Third, the empirical evidence of the benefits of pair programming is mixed: the works of Judith Wilson et al. [Wilson et al. 1993], John Nosek [Nosek 1998], Laurie Williams [Williams et al. 2000], Charlie McDowell et al. [McDowell et al. 2002], and Xu and Rajlich [Xu et al. 2006] support the costs and benefits of pair programming; experiments by Nawrocki and Wojciechowski [Nawrocki et al. 2001], Jari Vanhanen and Casper Lassenius [Vanhanen et al. 2005], Erik Arisholm et al. [Arisholm et al. 2007], Matevz Rostaher and Marjan Hericko [Rostaher et al. 2002], and Hanna Hulkko and Pekka Abrahamson [Hulkko et al. 2005] show that statistically there is no significant difference between the pair programming and solo programming.

Don Wells and Trish Buckley [Wells et al. 2001], Kim Lui and Keith Chan [Lui et al. 2006] and Erik Arisholm et al. [Arisholm et al. 2007] show that pair programming is more effective than traditional single-person development if both members of the pair are novices to the task at hand. Novice-expert and expert-expert pairs have not been demonstrated to be effective. According to Karl Boutin [Boutin 2000] many developers are forced to abandon pair programming due to lack of resources (e.g. due to small team size). He also observed that abandoning the pair programming in the middle of the project hindered the integration of new modules to the existing project.

This research proposes a new variant of pair programming called the *Collaborative-Adversarial Pair (CAP)* programming. Its objective is to exploit the advantages of pair programming while at the same time downplaying the disadvantages. Unlike traditional pairs, where two people work together in all the phases of software development, CAPs start by designing together; splitting into independent test construction and code implementation roles; then joining again for testing.

2. LITERATURE REVIEW

2.1. Pair Programming

Pair programming is a programming technique in which two people program all production code in a single machine using one keyboard and one mouse. The members of each pair are assigned two different roles. One partner with keyboard and mouse, known as *driver*[1], types and thinks about the best way to implement the current method in hand and the other partner, known as *navigator* or *observer*, watches or reviews the code being typed, looking for errors and thinks strategically about the feasibility of the overall approach, additional test cases to be addressed and the way to simplify the whole system in order to overcome the current problem [Beck 2000].

The following are some of the key points highlighted in the pair programming literature:

- Paring is dynamic and the people have to pair with different people in the morning and evening sessions. A programmer can pair with anyone in the development team [Beck 2000].
- Along with writing the code for test cases, the pairs also evolve the system's design. Pairs add value to almost all the stages of the system development including analysis, implementation, and testing [Beck 2000].

[1] There were no specific names given for the two partners by Kent Beck in his "Extreme Programming Explained". The names *driver* and *navigator* were originally used by Laurie Williams in her article called "Integrating pair programming into a software development process" [Williams 2001].

- The driver and observer are full partners and they exchange their roles quite often [Martin 2003, Wake 2002].
- The pair programming activity provides a means for real-time problem solving and real-time quality assurance [Pressman 2005].
- Pair programming is a social skill, not a technical skill. It has to be practiced with the people who already know how to do it [Wells 2001].
- Pair programming is not an activity in which one person programs and other person simply watches. Moreover, pair programming is not a tutoring activity in which the experienced partner teaches to the inexperienced ones. It is a conversation between two people understand together and trying to do simultaneous activity (analysis, design, implement, or test) [Beck 2000].

Even though the terms c*ollaborative programming (CP)* and p*air programming (PP)* are interchangeably used in literature, they are not the same. There are two fundamental differences between them. First there is no working protocol exclusively specified for collaborative programming; whereas, pair programming has a well defined working protocol which prescribes to continuously overlapping reviews and the creation of artifacts. Second, pair programming team is strictly restricted to two people and there is no such restriction for collaborative programming team; it may contain two or more people [Canfora et al. 2007].

2.1.1. Pair Programming History

The history of pair programming dates back to punched cards in the early 1940s when Von Neumann worked with IBM. But pair programming became popular only after Kent Beck published "Extreme Programming Explained" in 1999. The timeline of pair programming is discussed below:

Dave W. Smith, an Agile Software Project Leader and Coach, while discussing the history of Extreme Programming (XP), wrote, *"Jerry Weinberg told me that John Von Neumann's team at IBM used pair programming in much the same form that XP employs it now"* [Perl 2004].

In 1950's Fred Brooks, author of *The Mythical Man*, tried pair programming with his fellow graduate student Bill Wright when he was a graduate student [Williams et al. 2003].

E. W. Dijkstra recalled his pair programming experience in 1969 (What led to "Notes on Structured Programming" - EWD249), in the article EWD1308-5[2].

Dick Gabriel reported his pair programming experience as *"Pair programming was a common practice at the M.I.T. Artificial Intelligence Laboratory when I was there in 1972-73"* and in 1984, his team used pair programming in the Common Lisp Project [Williams et al. 2003].

In 1991 Flor observed and recorded exchanges between two collaborative programmers [Flor 1991].

In 1993, Judith D. Wilson, Nathan Hoskin and John T. Nosek [Wilson et al. 1993] of Temple University conducted a collaborative programming experiment with students.

Two books published in 1995 discussed pair programming. Larry Constantine, in his book titled *Constantine on Peopleware*, discussed about pair programming conducted at Whitesmith Ltd. Jim Coplien, in his book titled *Pattern Languages of Programming Design* claimed that pair developers can produce more than the sum of the two individual developers [McDowell et al. 2002].

In 1996, while working on the Chrysler Comprehensive Compensation System (commonly referred to as 'C3') Kent Beck and Ron Jeffries team adopted a new way of working

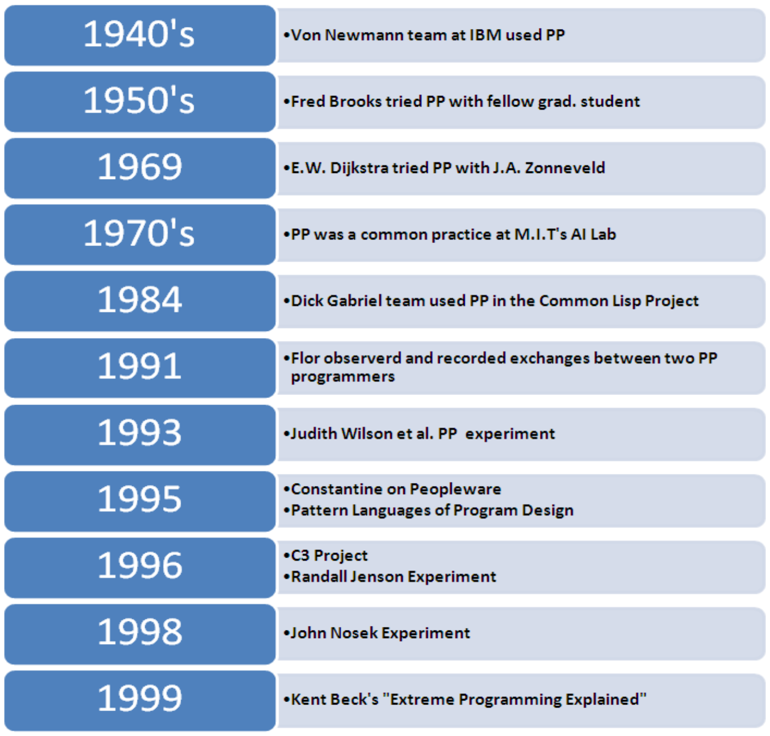
[2] The article EWD1308-5 was written in 2001 and EWD249 was published in 1969.

which is currently known as the Extreme Programming (XP), which employed pair programming as one of the core principles [Anderson et al. 1998].

Randall W. Jensen, Software Technology Support Center, Hill Air Force Base, reported his pair programming experience in 1996 as *"The undergraduate experience led me to propose an experiment in the application of what we called two-person programming teams. The term pair programming had not been coined at that time"* [Jensen 2003][3].

In 1998, John T. Nosek, Temple University, Philadelphia, conducted collaborative programming (similar to pair programming) experiment [Nosek 1998].

In 1999 Kent Beck published *Extreme Programming Explained* in 1999; pair programming is the one of the 12 core practices introduced in Extreme Programming [Beck 2000], familiarly known as XP.



1940's	•Von Newmann team at IBM used PP
1950's	•Fred Brooks tried PP with fellow grad. student
1969	•E.W. Dijkstra tried PP with J.A. Zonneveld
1970's	•PP was a common practice at M.I.T's AI Lab
1984	•Dick Gabriel team used PP in the Common Lisp Project
1991	•Flor observerd and recorded exchanges between two PP programmers
1993	•Judith Wilson et al. PP experiment
1995	•Constantine on Peopleware •Pattern Languages of Program Design
1996	•C3 Project •Randall Jenson Experiment
1998	•John Nosek Experiment
1999	•Kent Beck's "Extreme Programming Explained"

Figure 2.1: Pair Programming Time Line

[3] The paper was actually published only in 2003.

2.1.2. Benefits of Pair Programming

The proponents of pair programming claim that the pair programming software development provides the following benefits over the traditional individual software development:

- Increases software quality
- Increases productivity
- Increases design quality
- Increases program correctness
- Provides constant design and code review
- Reduces overall software development time and cost
- Helps in Team building, knowledge transfer and learning
- Enhances job satisfaction and confidence
- Helps in solving complex problems
- Reduces the effort need to develop a piece of code
- Reduces risk of project failures
- Reduces staffing risks

2.1.3. Drawbacks of Pair Programming

While the literature lists several benefits of pair programming, the detractors assert that pair programming has the following drawbacks:

- Doubles the developers required and development cost
- Increases the software development time
- Quality improvement also in question
- Not suitable for very large projects

- Suitable only for novice-novice pairs
- It is very intense
- It is good for job training, not for professional software development
- Bringing out personality conflicts and clashes between developers
- Coding styles, ego, or intimidation would only slow the developers down
- Programming is a solidarity activity
- Experienced programmers may refuse to share

2.2. Pair Programming Experiments

This section includes 12 out of 35 published collaborative and pair programming experiments and case studies in which (1) a comparison was made between pair programming and individual programming, and (2) evaluates one or more of the software metrics, namely program development time/cost, productivity (LOC/hr), program correctness (program readability and functionality), and job satisfaction. The remaining 23 experiments or case studies which did not include pairs verses individual comparison, software metrics evaluation and/or coding phase of the software development process were excluded in this section. For more information please see Appendix A, which lists all the pair programming experiments and case studies published so far and the reason why the experiment or case study was excluded from the analysis.

2.2.1. Judith Wilson et al. Experiment [Wilson et al 1993]

In 1993, Judith D. Wilson, Nathan Hoskin and John T. Nosek of Temple University conducted a collaborative programming experiment with 34 upper division undergraduate students of a database course (two sections). 14 students from the first section acted as the control groups (individuals) and 20 students in the second section were randomly grouped into 10 experimental (pairs) groups. The task was solving a “traffic light signal problem” in 60 minutes using Pascal, C, dBase III, or pseudo code.

The purpose of the study was to investigate: (1) readability and functionality of the solution, (2) confidence and enjoyment of the work, and (3) students in which group earn high grades. The results of the experiment were: (1) pairs produced slightly better readable and functional codes, (2) pairs expressed more confidence and enjoyment, and (3) ability had little effect on pair performance, i.e. high grade is significantly associated with individuals, but not with pairs.

The experiment indicates that collaboration helps novice programmers, collaboration helps solve informal problems, and collaboration helps students master analytical skills required to analyze and model problems.

2.2.2. The Nosek Experiment [Nosek 1998]

John T. Nosek, Temple University, Philadelphia, conducted a collaborative programming experiment in 1998 using 15 full-time system programmers. The subjects were divided into 5 control groups (individuals) and 5 experimental groups (pairs) on a truly random basis. The task was to write a database consistency-check script in the C programming language in 45 minutes on an X-window system.

The aim of the experiment was to find: (1) readability and functionality of the solution, (2) average problem solving time, (3) confidence and enjoyment of the work, and (4) how experienced programmers perform as compared to less experienced programmers. The results of the experiment were: (1) pairs programs were more readable and functional, (2) pairs took more time on average, (3) pairs expressed more confidence and enjoyment of their job, and (4) experienced programmers performed better than inexperienced ones.

The experiment indicates that collaboration improves problem solving process and improves programmer's performance.

2.2.3. Laurie Williams's Experiment [Williams et al. 2000]

Laurie Williams from University of Utah conducted a Pair Programming experiment in 1999 with 41 advanced undergraduate students in a Software Engineering course. The subjects were divided into 13 control groups (individuals) and 14 experimental groups (pairs). The individuals used Humphrey's Personal Software Process (PSP) and the pairs used Williams' Collaborative Software Process (CSP) to complete their tasks. The subjects were not selected randomly; instead, they were picked from among the 35 that initially indicated a preference for working collaboratively. The students were asked to code four class projects[4] over 6 weeks time, which was part of their course curriculum. The first project was used as *Pair-Jelling*[5] (initial adjustment) experiment.

The aim of the study was to find: (1) number of test cases passed, (2) average problem solving time, (3) number of defects in the programs, and (4) job satisfaction. The results of the experiment were: (1) pairs programs passed more test cases than individuals, (2) pairs spent 15% more time on average to solve a problem, (3) pairs code had 15% fewer defects than individuals, and (4) pairs expressed more job satisfaction.

[4] Programs size and programming language used were not mentioned in the paper.
[5] Tuckman's model (see Appendix B for more detail about Tuckman's model) is known as *Pair Jelling* in the pair programming literature [Lui et al. 2006]

2.2.4. Nawrocki and Wojciechowski Experiment [Nawrocki et al. 2001]

Jerzy Nawrocki and Adam Wojciechowski from the Poznan University of Technology conducted a pair programming experiment in the 1999/2000 winter semester using 21 students. The 21 subjects were randomly divided into three groups of 6, 5 and 5 in such a way that the average GPA of each group was the same. The first group used Watts Humphrey's Personal Software Process (PSP), the second and third groups used Extreme Programming (XP) as their development process. The individual group which used XP was called XP1 and the pairs group which used XP was called XP2. The students were asked to solve four C/C++ programs ranges between 150 and 400 LOC.

The aim of the study was to compare Extreme Programming (XP) with the Watts Humphrey's Personal Software Process (PSP). The results of the experiment were: (1) there was no difference in time between XP1 and XP2 groups, (2) pair programming was more predictable than other two approaches, (3) XP1 was the most efficient programming technology, and (4) there was no difference between PSP and XP2.

The experiment indicates that experimentation and test-oriented thinking reduces development time, pair programming with Extreme Programming (XP) was not efficient, XP1 was more efficient than PSP, pair programming was more predictable than individual programming, and rework for XP2 was slightly smaller compared with other two approaches.

2.2.5. Charlie McDowell et al. Experiment [McDowell et al. 2002]

In 2000/01, Charlie McDowell, Linda Werner, Heather Bullock and Julian Fernald from the University of California, Santa Cruz studied the effects of Pair Programming in an introductory programming course with approximately 600 students. A total of 172 students from the fall 2000 section were divided into 86 pairs (experimental group) and 141 students from the spring 2001 section were used as control group (individuals). The students were asked to complete 5 programming assignments[6].

The aim of the study was to find the effects of PP on performance in the course. The results of the experiment were: (1) pair programming improves program quality in terms of functionality and program readability, and (2) pair programming did not help the students learn their course material and independently apply their knowledge to new programs.

2.2.6. Rostaher and Hericko Experiment [Rostaher et al. 2002]

In 2002, Matevz Rostaher and Marjan Hericko from Slovenia conducted a pair programming experiment using 16 professional programmers. The 16 subjects were divided into 4 control groups (individuals) and 6 experimental groups (pairs) based upon their programming experience. The programmers were asked to develop a simple insurance contract administration system using six small stories in Smalltalk and its integrated development environment (IDE).

The purpose of the experiment was to get the time spent in percentage on each activity by the programmers, based on their experience level. The results of the experiment were: (1) there was no difference in average time spent by individuals and pairs, (2) experiment results did not favor pair programming.

The experiment indicates that acceptance tests must be written before the development, and refactoring caused more problems for programmers than did tests.

2.2.7. Muller Experiments [Muller 2005]

Matthias M. Muller, University of Karlsruhe, Germany conducted two experiments to compare pair programming with peer review. The first experiment was conducted in 2002; in 2003 the same experiment was repeated with 38 computer science students. The 38 subjects were

[6] Assignment sizes and programming languages are not mentioned

divided into 23 control groups (individuals) called *review groups* and 19 experimental groups (pairs). In the review group, an individual programmer developed the program, compiled it, had it reviewed by an unknown reviewer, and then conducted the testing. In the pair programming group, all the development activities were carried out by two programmers sitting in front of the same computer. The students were asked to solve polynomial and shuffle-puzzle problems using Java on both occasions.

The purpose of the study was to find the cost of pair programming and peer review methods. The results of the experiment were: (1) there was no difference in program correctness, and (2) for a similar level of correctness there was no difference in development cost.

The experiment indicates that pair and individual programmers can be interchanged in terms of cost.

2.2.8. Vanhanen and Lassenius Experiment [Vanhanen et al. 2005]

In 2004, Jari Vanhanen and Casper Lassenius, Helsinki University of Technology, Finland conducted a pair programming experiment using 10 computer science students. The 10 subjects were randomly divided into 2 control groups (individuals) and 3 experimental groups[7] (pairs). For a given requirement specification each team was asked to develop a distributed, multiplayer casino system within 400 hours using J2EE technologies.

The purpose of the experiment was to investigate pair programming effects, namely productivity, defects, design quality, knowledge transfer, and enjoyment of work at the development team level. The results of the experiment were: (1) the productivity of pairs was 29% less than individuals, (2) pairs code contained 8% fewer defects, but after delivery pairs had more defects, (3) pairs programs were less functional than individual's programs, (4) pairs

[7] In the middle of the project one pair abandoned pair programming without notice because they considered it inefficient.

design quality was slightly better than individuals, (5) knowledge transfer among pairs was better, and (6) pairs expressed less job satisfaction.

The experiment indicates that pair programming did not help in solving complex tasks; pair programming helped programmers in finding and fixing errors; and fewer defects in programs and better knowledge transfer among pairs indicates that pair programming may decrease further development costs of the system.

2.2.9. Hulkko and Abrahamsson Experiments [Hulkko et al. 2005]

Hanna Hulkko and Pekka Abrahamsson from Finland conducted two case studies on pair programming in 2004. In the first case study, master's students were the subjects and in the second case study, master's students as well as research scientists were the subjects. There were 4 to 6 teams in each control group (individuals) and in each experimental group (pairs), and they were asked to develop four different projects sizes ranging from 3700 to 7700 LOC using the Mobile-D[8] development process. The first project was developing Internet application using Java and JSP, and the remaining three were mobile application development using Mobile Java and Symbian C++.

The purpose of the study was to find the impact of pair programming on product quality. The results of the experiment were: (1) there was no difference in productivity between pairs and individuals, (2) pair programming is more suitable for learning and complex tasks, (3) the code produced by pair programming had lower adherence to coding standard, (4) readability of the programs were better in pairs code, and (4) there was no difference in program correctness between pairs and individuals.

[8] Mobile-D is an agile development approach developed by Pekka Abrahamsson et al [Abrahamsson et al. 2004]. In this approach development practices are based on Extreme Programming, method scalability is based on Crystal methodologies, and life-cycle coverage is based on Rational Unified Process.

The experiment indicates that pair programming did not provide the benefits claimed in the pair programming literature, and that productivity of pair programming was not consistently high.

2.2.10. Muller Experiment [Muller 2006]

Matthias M. Muller, University of Karlsruhe, Germany conducted a pair programming experiment using 18 computer science students. The 18 subjects were randomly divided into 8 control groups (individuals) and 5 experimental groups (pairs). Due the difficult programming task two individuals did not complete coding, so the modified control group was only 6 individuals. The students were asked to design, code and test an elevator control system using the Java programming language. Both the control and the experimental groups were initially paired for the design phase. Once the design was completed with a partner, the control group students were asked to code and test independently.

The primary purpose of the study was to find the impact of the pair design phase on pair programming and solo programming. The results of the experiment were: (1) there was no difference in program correctness, and (2) for a similar level of correctness there was no difference in development cost.

The experiment indicates: (1) there is no difference in development cost for both pair and individual programming, if similar level of program correctness is needed and (2) since the probability of building wrong solution is much lower for pairs, the pair programming process can be replaced by a pair design phase followed by a solo implementation phase.

2.2.11. Xu and Rajlich Experiment [Xu et al. 2006]

Shaochun Xu from Algoma University College, Laurentine University and Vaclav Rajlich from Wayne State University conducted a pair programming case study using 12 students. The control group was formed using 4 undergraduate computer science students from Algoma University College and the experimental group was formed using 8 undergraduate computer science students from Wayne State University. In Feb 2005, two pairs completed their work and the other two pairs completed their work in Jun 2005. All four individuals completed their work in Feb 2006.

The participants were asked to develop an application which computes bowling scores. The pairs were asked to develop the program using the Eclipse Java IDE along with Junit. There were no such restrictions for the individuals, so two of the four individuals used Eclipse and the remaining two individuals used Text Pad with the JDK. The pairs were asked to use Extreme Programming (XP) and Test Driven Development (TDD); whereas the individuals were asked to use the traditional Waterfall process.

The primary purpose of the study was to investigate the effect of Extreme Programming and Test Driven Development on game development. The results of the experiment were: (1) the productivity for pairs was very high compared with individuals, (2) pairs program had better design than individuals, (3) pairs wrote better quality code than individuals, and (4) pairs programs passed more test cases than individuals.

The experiment indicates that game developers can benefit from a XP-like approach, which includes pair programming.

2.2.12. Erick Arisholm et al. Experiment [Arisholm et al. 2007]

Erick Arisholm, Hans Gallis, Tore Dyba, and Dag I.K. Sjoberg conducted a pair programming experiment using 295 professional programmers from Norway, Sweden, and the UK. This was a two-phase experiment: the first phase, the individual programming phase, was conducted in 2001 using 99 programmers and the second phase, the pair programming phase, was conducted in 2004 and 2005 using 196 (98 pairs) programmers. The programmers were grouped into three categories, namely junior, intermediate, and senior based on an assessment of their Java programming experience by their project managers. The programmers were asked to add 4 new features to an existing coffee machine application using professional Java tools.

The primary purpose of the study was to evaluate pair programming with respect to system complexity and programmer expertise. The results of the experiment were: (1) there was no difference in development time between pairs and individuals, (2) there was no difference in program correctness between pair and individual programs, and (3) pairs required more effort than individuals to add new features.

The experiment indicates that the effect of pair programming on duration, effort and correctness depends on system complexity and not on programmer's expertise. The juniors were the beneficiaries from the pair programming and there was no benefit for intermediates and seniors from pair programming.

2.2.13. Summary of PP Experiments

Twelve pair programming experiments have been discussed in section 2.2.1 through 2.2.12. A synopsis of these experiments highlighting the name and year of the experiment, number of participants in the experiment, software process used, number of problems solved, programming language used, duration of experiment, lines of code, development methodology used, phases paired, and the experimental problem solved is shown in table 2.1.

Study	Year	Subjects (Ind + Pair)	Software Process		#Exp	Prog. Language	Duration	LOC	Dev. Method	Paring	Phases			Problem
			Ind	Pair							D	C	T	
Wilson et al. [Wilson etal. 1993]	1993	Students (14+10) Randomly selected	NA	NA	1	Pascal, C, dBase III, Pseudo Code	60 min	NA	SD	SP		X		Traffic signal problem
John Nosek [Nosek 1998]	1998	Professionals (5+5) Randomly selected	NA	NA	1	C	45 min	NA	SD	SP		X		Database consistency check script
Williams et al. [Williams et al. 2000]	1999	Students (13+14) Not randomly selected	PSP	CSP	M	NA	6 weeks	NA	SD	SP	X	X		4 home works
Nawrocki and Wojciechowski [Nawrocki et al. 2001]	1999/ 2000	Students (5+5) Randomly selected	XP	XP	M	C/C++	NA	150-400	TDD	SP		X		4 programs
McDowell et al [McDowell et al. 2002]	2000/ 2001	Students (141+86)	NA	NA	M	NA	Semester	NA	SD	SP		X		5 assignments
Rostaher et al. [Rostaher et al. 2002]	2002	Professionals (4+6)	XP	XP	1	Smalltalk	One day	NA	TDD	SP		X	X	Six stories
Matthias Müller [Muller 2005]	2002/ 2003	Students (23+19)	XP	XP	M	Java	NA	NA	TDD	SP		X		Polynomial & Shuffle Puzzle
Vanhanen and Lassenius [Vanhanen et al. 2005]	2004	Students (2+2) Randomly Selected	NA	NA	1	J2EE	400hr	NA	TDD	SP	X	X	X	Casino system
Hulkko and Abrahamson [Hulkko et al. 2005]	2004	Students & Research Scientists (4 to 6 + 4 to 6)	Mobile D	Mobile D	M	Java & JSP, Mobile Java, Symbian C++	NA	3700-7700	TDD	NA		X		One Internet application, 3 mobile application
Matthias Müller [Muller 2006]	2004	Students (6+5)	XP	XP	1	Java	NA	NA	TDD	SP	X	X	X	Elevator system
Xu and Rajlich [Xu et al. 2006]	2005, 2006	Students (4+4)	Water fall	XP	1	Eclipse, JDK	NA	NA	SD/ TDD	SP		X		Bowling game
Arisholm et al. [Arisholm et al. 2007]	2001, 2004/ 2005	Professionals (99+98)	NA	NA	1	Java Tools	8 hr	NA	NA	SP		X		Coffee machine

NA – Not Available XP– Extreme Programming SP- Static Pairing TDD- Test Driven Development D – Design
M – Multiple PSP– Personal Software Process DP – Dynamic Paring SD- Standard Development C – Code
CSP – Collaborative Software Process T – Test

Table 2.1: Summary of Pair Programming Experiments

Programming efficiency or productivity is the measure of Line of Code (LOC) produced per hour per programmer. Nawrocki and Wojciechowski [Nawrocki et al. 2001], Vanhanen and Lassenius [Vanhanen et al. 2005] and Hulkko and Abrahamson [Hulkko et al. 2005] show that the productivity of the pair programmers was not more than the individual programmers productivity; the only exception to this is the Xu and Rajlich [Xu et al. 2006] experiment.

John Nosek [Nosek 1998], Williams et al. [Williams et al. 2000], Nawrocki and Wojciechowski [Nawrocki et al. 2001], Rostaher et al. [Rostaher et al. 2002], Matthias Müller [Muller 2005], Xu and Rajlich [Xu et al. 2006], and Arisholm et al. [Arisholm et al. 2007] show that the time taken by the pair programmers to complete a task was more than the time taken by the individual programmers. Moreover, Nawrocki and Wojciechowski [Nawrocki et al. 2001] and Rostaher et al. [Rostaher et al. 2002] show that pairs took almost double the time than individual programmers.

The defect density is measured in terms of number of test cases passed [Williams et al. 2000, Xu et al. 2006] and/or relative defect density (defects/KLOC) [Williams et al. 2000, Hulkko et al. 2005]. Williams et al. [Williams et al. 2000] and Xu and Rajlich [Xu et al. 2006] show that the number of test cases passed by pairs programs were higher than individual programmers. Matthias Müller [Muller 2005] shows that programs written by pair groups and review groups have similar level of correctness. Arisholm et al. [Arisholm et al. 2007] report that the pairs did not produce more correct programs than individuals. Vanhanen and Lassenius [Vanhanen et al. 2005] report that after coding and unit testing the programs written by pairs had less defects; whereas, after the system testing and bug fixing the programs written by pairs had more defects than individuals.

Williams et al. [Williams et al. 2000] report that pairs programs had less defect density, but Hulkko and Abrahamson [Hulkko et al. 2005] show that pairs produced code with more defect density.

Wilson et al. [Wilson et al. 1993] and John Nosek [Nosek 1998] measure the code quality in terms of its *functionality*, the number of software components contained in the program, and *readability*, the number of comments the program contains; whereas, Xu and Rajlich [Xu et al. 2006] measured the code quality in terms of its elegances and readability.

Xu and Rajlich [Xu et al. 2006] show that the programs written by pairs were more readable and elegance, but Wilson et al. [Wilson et al. 1993] and John Nosek [Nosek 1998] show that statistically there was no significant difference in readability between the individual and pair programmers codes.

With respect to functionality the John Nosek [Nosek 1998] experiment shows that pair programs were more functional, whereas, in the Wilson et al. [Wilson et al. 1993] experiment, the individual programmers programs were more functional than pairs.

Based on the post experiment survey the experimenters calculate the programmer's job satisfaction and confidence on their work. John Nosek [Nosek 1998], Williams et al. [Williams et al. 2000], Vanhanen and Lassenius [Vanhanen et al. 2005], Xu and Rajlich [Xu et al. 2006] and Wilson et al. [Wilson et al. 1993] show that pairs expressed their satisfaction over pair programming. Wilson et al. [Wilson et al. 1993], John Nosek [Nosek 1998], and Williams et al. [Williams et al. 2000] show that pairs expressed their confidence on their work when using pair programming. The results of the above mentioned experiments with respect to the efficacy of pair programming are shown in table 2.2.

Study	Statistical Test	Productivity	Time /Cost	Correctness	Code Quality	Satisfaction	Confidence
Wilson et al. [Wilson et al. 1993]	t-test				No	No	Yes
John Nosek [Nosek 1998]	t-test		No		Yes	Yes	Yes
Williams et al. [Williams et al. 2000]	No statistical test†		No	Yes		Yes	Yes
Nawrocki and Wojciechowski [Nawrocki et al. 2001]	No statistical test	No	No				
Rostaher et al. [Rostaher et al. 2002]	t-test		No				
Matthias Müller†† [Muller 2005]	Mann-Whitney Test		No	No			
Vanhanen and Lassenius [Vanhanen et al. 2005]	No statistical test	No		No		Yes	
Hulkko and Abrahamson [Hulkko et al. 2005]	No statistical test	No		No			
Xu and Rajlich* [Xu et al. 2006]	No statistical test	Yes	No	Yes	Yes	Yes	
Arisholm et al. [Arisholm et al. 2007]	ANCOVA		No	No			

Yes – Supports PP claims (i.e., PP is beneficial than Individual programming)
No – Not Supports PP claims (i.e., PP is not beneficial than Individual programming)
† The authors claim that they used independent sample t-test, but the results were neither published nor used in the paper
†† Pair programming Vs Review (solo coding phase followed by two person inspection) experiment
* Experiment to validate Extreme Programming (XP) against Waterfall method in game development

Table 2.2: Summary of Pair Programming Experiments Results

2.3. The Pairing Activity

While much of the literature explains what pair programming is, it fails to answer some key questions:

- When to pair program?
- How to form pairs?
- How frequently partners have to switch their roles?
- When to exchange the partners?
- What the working environment should look like?
- Who owns the task at hand – the pair or a person?
- Who owns the code?
- Whether Extreme Programming or pair programming denies specialists?
- What is the role of programming languages and tools in pair programming?

2.3.1. When to Pair Program?

John Nosek [Nosek 1998] suggests that pair programming might be preferred over individual programming in situations like (1) speeding up development – if the organization wants to bring its product earlier to market for it to gain an edge over its competitors and (2) improving software quality – to produce a high quality product, which has very high profit margin. Thus pair programming is preferred when the organization need to develop high quality products in short time. Matthias Muller [Muller 2005] suggests that pair programming is a viable option for developing software with fewer failures.

Judith Wilson et al. [Wilson et al. 1993], Don Wells and Trish Buckley [Wells et al. 2001], Kim Lui and Keith Chan [Lui et al. 2006], and Erik Arisholm et al. [Arisholm et al. 2007] observe that novice programmers benefit from pair programming. Don Wells and Trish Buckley

[Wells et al. 2001] observe that novice-novice pairs work better than expert-novice pairs, because the novices feel that they are not intimidated and demoralized. Moreover the novices learned from each other while solving the problem. Don Wells and Trish Buckley [Wells et al. 2001] also suggest that people with equal experience should pair in order to achieve significant productivity and morale.

Studies by Jari Vanhanen and Casper Lassenius [Vanhanen et al. 2005] and Hanna Hulkko and Pekka Abrahamsson [Hulkko et al. 2005] show that pair programming helps in transferring the knowledge about the system among the team members; meaning, it enhances training.

Studies by Hanna Hulkko and Pekka Abrahamsson [Hulkko et al. 2005], Erik Arisholm et al. [Arisholm et al. 2007], Benedicenti and Paranjape [Benedicenti et al. 2001], Becker-Pechau et al. [Pechau et al.2003] and Gittins et al. [Gittins et al. 2001] show that pair programming is useful with complex tasks. Moreover, Erik Arisholm et al. [Arisholm et al. 2007] suggest that pair programming is effective when assigning complex maintenance tasks to junior programmers. Jari Vanhanen and Casper Lassenius [Vanhanen et al. 2005], on the other hand, show that pair programming does not help in solving complex tasks.

Xu and Rajlich quote Kent Beck [Beck 2000] as stating "that pair programming (or XP) is not suitable for very large projects" [Xu et al. 2006].

Ambu and Gianneschi [Ambu et al. 2003] suggest that pair programming is not suitable with tight deadlines.

Pair programming is not possible if the development team size is small [Boutin 2000]. Karl Boutin [Boutin 2000] reported that in his research and development lab the developers were forced to abandon pair programming due to lack of resources (i.e. due to small team size). At the same time Kent Beck [Beck 2000] suggests that XP is not possible when the development team size is more than 10. Table 2.3 summarizes the points discussed in this section.

When to Pair Program	When not to Pair Program
Need to speed up development	Large projects
To improve software quality	Tight deadlines
Require program with less failures	Very small team sizes and team size of >10
When the programmers are novice	
To solve complex tasks	
For job training	
Programmers of equal experience	

Table 2.3: When to Pair Program

2.3.2. Forming Pairs

According to Don Wells and Trish Buckley [Wells et al. 2001], people with equal experience should pair in order to achieve significant productivity and morale. They also suggest that an *experienced-novice* pair will not set up a proper pair relationship; instead it will set up only a teacher-student relationship, possibly creating a novice programmer morale problem. If experienced-novice pairs tied up for a longer session of pair programming then both will get uninterested, exhausted, and demoralized. They also suggest that novice programmers should be paired with other novice programmers so that both will learn from each other. Once novice programmers begin to gain confidence then they can be paired with an experienced partner.

2.3.3. Role Switching

Role switching is the process of the driver and the navigator exchanging their roles. Kent Beck [Beck 2000] does not directly say anything about switching roles in the pair programming definition but implied such with *"Set up your desks so two people can sit side by side and shift the keyboard back and forth without having to move their chairs"* when he was describing the development activity. Matevz Rostaher and Marjan Hericko [Rostaher et al. 2002] suggest that role switching rhythm (the high frequency of role switching, more than 20 times per day, and short phases of uninterrupted activity, 5 minutes in average) is essential for test-first pair programming.

According to William Wake [Wake 2002], role switching can be done every couple of minutes or a few times an hour. Robert Martin suggests that whenever the driver gets tired or stuck, the navigator should take over the driver's job. This is normally happens several times an hour.

Matevz Rostaher and Marjan Hericko [Rostaher et al. 2002] observed that role switching occurred 21 times per day on average for all programmers and 42 times per day on average for experienced programmers. They also observed that uninterrupted activity lasted 5 minutes in average for all programmers and 3 minutes for experienced programmers. Lippert et al. [Lippert et al. 2001] observed that the physical working environment (seating arrangement) plays a crucial part in role switching. Conventional seating arrangement hinders the frequent role switching. Once the seating is rearranged, pairs switch their roles more frequently (the seating arrangement is discussed more detail in section 2.3.5).

2.3.4. Partner Exchange

The main idea behind rotating developers among different pairs is to spread the system knowledge to every member of the development team.

Kent Beck [Beck 2000] says *"Paring is dynamic"*, meaning, people have to pair with different people in the morning and evening sessions, and a programmer can pair with anyone in the development team. William Wake [Wake 2002] suggests that the developers have to exchange their partners every day and some developers will exchange their partners more often depending upon the situation. Robert Martin [Martin 2003] suggests that every member of the development team should try all the activities of the current iteration and that he/she has to partner with every member in the team. He also suggests that every programmer has to work in at least in two different pairs.

2.3.5. Workplace Layout

To emphasize the importance of the workplace layout for pair programming's success in DaimlerChrysler C3 project, Kent Beck [Beck 2000] writes *"I was brought in because of my knowledge of Smalltalk and objects, and the most valuable suggestion I had was that they should rearrange the furniture"*.

According to Kent Beck [Beck 2000], a reasonable work place is important for any project's success. Kent Beck [Beck 2000] and Lippert et al. [Lippert et al. 2001] suggest that the physical environment (i.e., the desk and seating arrangement) plays a critical role in pair programming. This was confirmed by the result of the survey conducted by Laurie Williams and Robert Kessler [Williams et al. 2000b] in which 96% of the programmers agreed that proper workplace layout was critical to their pair programming success. Lippert et al. [Lippert et al. 2001] also observed that the conventional seating arrangement hindered the frequent role switching, and once the seating was rearranged, the pairs switched their roles more frequently.

For the success of pair programming, developers need to communicate with their partners and with other members of the team as well [Beck 2000, Williams et al. 2003]. The pair programming layout must be arranged in such a way that it allows inter-pair and intra-pair communications.

Kent Beck [Beck 2000] defines the working environment for pair programming as follows:

> *"Common office layouts don't work well for XP. Putting your computer in a corner, for example, doesn't work, because it is impossible for two people to sit side-by-side and program. Ordinary cubicle wall heights don't work well—walls between cubicles should be half-height or eliminated entirely. At the same time, the team should be separated from other teams".*
>
> *"One big room with little cubbies around the outside and powerful machines on tables in the middle is about the best environment I know".*

The DaimlerChrysler C3 work area [Beck 2000] is shown in figure 2.2. Six computers were placed on two large tables and pairs were allowed to sit at any available machine.

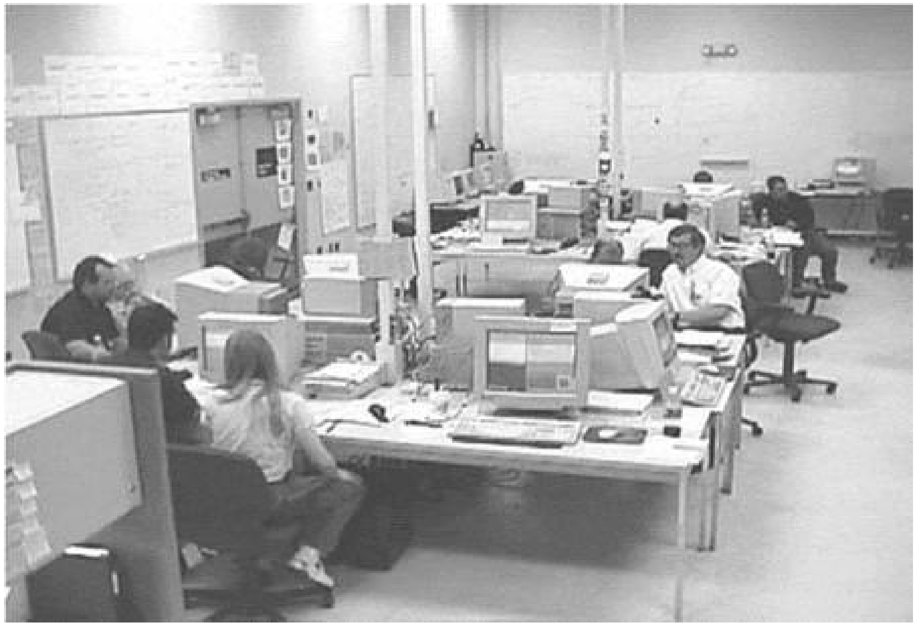


Figure 2.2: The DaimlerChrysler C3 work area [Beck 2000]

According to Laurie Williams and Robert Kessler [Williams et al. 2000b, Williams 2003], pair programmers should able to slide the keyboard and mouse back and forth without moving their chairs. There are two programming layouts[9] shown in figure 2.3. Laurie Williams and Robert Kessler [Williams et al. 2000b] preferred the layout in the right over the layout in the left.

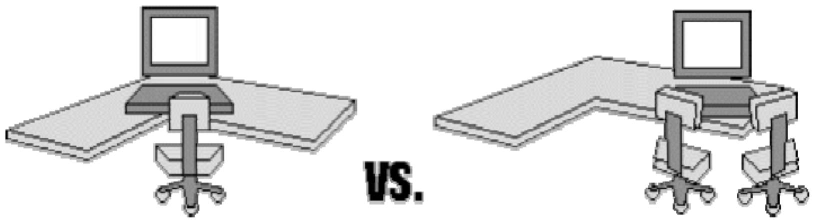


Figure 2.3: Pair Programming Workplace Layout [Wiki]

To facilitate the inter-pair and intra-pair communications, RoleModel Software, Holly Springs, NC developed a workstation layout, in which 6 tables are arranged as shown in figure 2.4 [Williams et al. 2003].

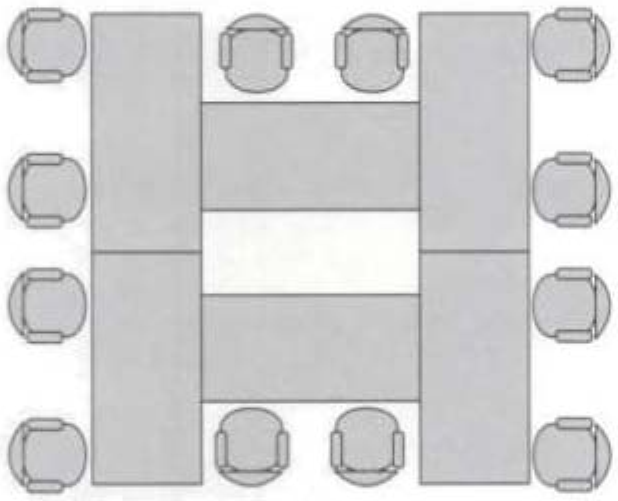


Figure 2.4: RoleModel Software Workstation Layout [Williams et at. 2003]

[9] This layout[Wiki] was contributed by Beck and Cunningham [Williams et al. 2000b]

When Lippert et al. [Lippert et al. 2001] started developing their JWAM framework using Extreme Programming (XP), they started programming using the conventional working layout consisting of desks with fixed cabinets at their sides as shown in figure 2.5. Although this layout permitted them to do pair programming, they found out that role switching was not easy. Once they realized that due to this physical environment the role switching occurred only a few times per day, they rearranged the furniture as shown in figure 2.6, which, in turn, enhanced their roles switching activity. But from their experience they suggest that the "Circle table" layout shown in figure 2.7 would be a better choice for pair programming. However, Lippert et al. [Lippert et al. 2001] have not provided reasoning for their proposed pair programming layout and the physical layout has not been tested.

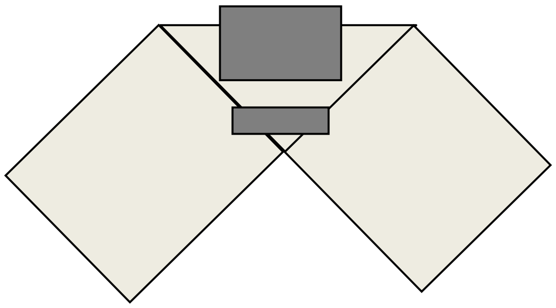


Figure 2.5: Conventional Environment [Lippert et al. 2001]

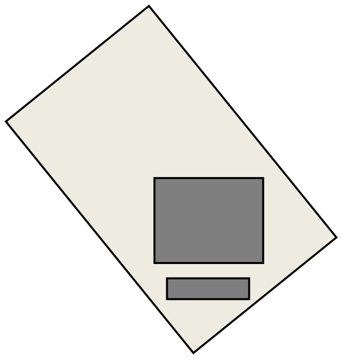


Figure 2.6: Rearranged Environment for Better Role Switching [Lippert et al. 2001]

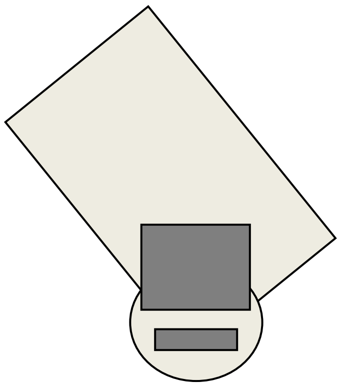


Figure 2.7: “Circle table” for pair programming [Lippert et al. 2001]

2.3.6. Task Responsibility

In pair programming, two programmers write code for a user story. Pairing is a dynamic activity, in which a developer may need to pair with more than one developer to finish the task at hand. This raises the question “who is responsible for the task at hand?” If a task needs some special technologies like GUI or database then who is responsible to carry out that task?

According to William Wake [Wake 2002], a single developer owns the task at hand. The developer responsible for the task may partner with one person for one aspect of the task and someone else for another aspect of the task.

Robert Martin [Martin 2003] clearly indicates that no programmer is responsible or has authority over any technology; everybody has to work in all technologies.

2.3.7. Code Ownership

Since the code for a task is written by many developers in the development team, no individual developer has ownership rights. The entire team owns the code, i.e. collective code ownership [Beck 2000, Wake 2002].

2.3.8. XP/PP Deny Specialists?

Robert Martin [Martin 2003] states

"This doesn't mean that XP denies specialists. If your specialty is GUI, you are most likely to work on GUI tasks, but you will also be asked to pair on middleware and database tasks. If you decide to learn a second specialty, you can sign up for tasks and work with specialists who will teach it to you. You are not confined to your specialty".

2.3.9. Role of Programming Languages and Tools in PP

Jerzy Nawrocki and Adam Wojciechowski [Nawrocki et al. 2001] suggest that pair programming described by Extreme Programming is less efficient than reported by earlier researchers. From Table 2.4 it is apparent that pair programming experiments conducted using Extreme Programming (XP) do not support the claims of pair programming. This confirms Jerzy Nawrocki's and Adam Wojciechowski's [Nawrocki et al. 2001] claim that XP tailored for single person use produces better results than XP used with pair programming.

Looking closer at the results of pair programming experiments listed in Table 2.4, it is clear that pairs do not outperform the individual programmers when the same working environment or software process were provided to the programmers. Moreover, XP with modern object-oriented programming languages such as Smalltalk and Java seems to be less effective for pair programming. This may be due to the modern compilers and/or development environments and tools available for the programmers; e.g., the navigator role was effectively replaced or even enhanced by the modern compilers and IDE. Table 2.5 also suggests that the advantage or benefits of having a navigator (an extra pair of eyes or an extra brain) for continuous code review in pair programming has been diminished by the arrival of modern programming languages and professional development tools.

From Table 2.6, we can observe that the pair programming implemented with Test Driven Development (TDD) as prescribed by XP, does not outperform individual programming. This may be due to the TDD used in XP, which allows developers to define the exact functionality of the method before the actual code implementation. This means that every developer knows in advance exactly what he/she is going to implement. In this way, every developer is capable of implementing the module by himself without the help of the partner.

Study	Software Process		Programming Language	Result
	Ind.	Pair		
Williams et al. [Williams et al. 2000]	PSP	CSP	C++	Supports PP claims
Xu and Rajlich [Xu et al. 2006]	Water Fall	XP	Eclipse, JDK	Supports PP claims
Hulkko and Abrahamson [Hulkko et al. 2005]	Mobile D	Mobile D	Java & JSP, Mobile Java, Symbian C++	Not supports PP claims
Nawrocki and Wojciechowski [Nawrocki et al. 2001]	XP	XP	C/C++	Not supports PP claims
Rostaher et al. [Rostaher et al. 2002]	XP	XP	Smalltalk	Not supports PP claims
Matthias Müller [Muller 2005]	XP	XP	Java	Not supports PP claims

Table 2.4: Effects of Software Processes on PP

Programming Language	**Study**	**Result**
Pascal, C/C++	Wilson et al. [Wilson et al. 1993]	Supports PP claims
	John Nosek [Nosek 1998]	Supports PP claims
	Williams et al. [Williams et al. 2000]	Supports PP claims
	Nawrocki and Wojciechowski [Nawrocki et al. 2001]	Not supports PP claims
Smalltalk	Rostaher et al. [Rostaher et al. 2002]	Not supports PP claims
Java	Matthias Müller [Muller 2005]	Not supports PP claims
	Xu and Rajlich† [Xu et al. 2006]	Supports PP claims
	Hulkko and Abrahamson [Hulkko et al. 2005]	Not supports PP claims
Professional Java Tools	Vanhanen and Lassenius [Vanhanen et al. 2005]	Not supports PP claims
	Arisholm et al. [Arisholm et al. 2007]	Not supports PP claims
† - The main aim of the experiment is to evaluate the Extreme Programming (XP) against Waterfall model in game development; not pair programming versus individual programming experiment.		

Table 2.5: Effects of Programming Languages on PP

Development Method	**Study**	**Software Process**		**Result**
		Ind.	**Pair**	
Standard Development	Wilson et al. [Wilson et al. 1993]	NA	NA	Supports PP claims
	John Nosek [Nosek 1998]	NA	NA	Supports PP claims
	Williams et al. [Williams et al. 2000]	PSP	CSP	Supports PP claims
	Vanhanen and Lassenius [Vanhanen et al. 2005]	NA	NA	Not supports PP claims
Test Driven Development	Rostaher et al. [Rostaher et al. 2002]	XP	XP	Not supports PP claims
	Matthias Müller [Muller 2005]	XP	XP	Not supports PP claims
	Hulkko and Abrahamson [Hulkko et al. 2005]	Mobile D	Mobile D	Not supports PP claims
	Nawrocki and Wojciechowski [Nawrocki et al. 2001]	XP	XP	Not supports PP claims

Table 2.6: Effects of Software Development Methods on PP

2.4. The Effect of Pair Programming on Software Development Phases

One of the basic requirements of pair programming is that all production code must be programmed by pairs, which, in turn, doubles the developers required to complete a project and also almost doubles the development cost. Unquestionably this is a waste of resource; though the proponents of pair programming claim that *"pair programming increases initial development time but saves time in the long run because there are fewer defects"* [Cockburn et al. 2000]. Up to now there is no empirical evidence for their claim. Because the amount of skill required to carry out the various phases of software process are different, there is no guarantee that pair programming will produce the same results in all the phases. The results of the Hanna Hulkko and Pekka Abrahamson [Hulkko et al. 2005] case studies suggest that pair programming was more useful in the beginning of the project and that the pair programming effort steadily decreased in the subsequent iterations and again increased in the final iteration (defect correction after system test).

The main aim of this section is to explore whether pairing up of developers is required in all the phases of software development, or if there an alternate way to minimize the pair-up times between these developers, in order to maximize the resource utilization and reduce the development cost.

2.4.1. Pair Design

Due to the asymmetrical nature of the design and code phases, we cannot expect all the benefits of pair-coding to apply to pair-design as well [Canfora et al. Sep 06]. Various studies highlight the benefits of pair-design. According to Laurie Williams et al. [Williams et al. 2000], pair-analysis and pair-design are more critical than pair-implementation, and pair-analysis and pair-design are critical for pair success. They also state that *"It is doubtless true that two brains are better than one when performing analysis and design"*.

Emilio Bellini et al. [Bellini et al. 2005] reveal that pair-design was more predictable than individual design and helped the developers to understand the system while developing it. This learned knowledge about the system can help developers in developing the project with less rework.

The pair-design experiment conducted by Gerardo Canfora et al. [Canfora et al. Sep 06] in September 2006, suggests that pair-design will also produce all anticipated benefits of pair-coding. Their experimental results show that pairs produced better design in less time than individuals. Moreover, with respect to effort and quality, the pair design was more predictable than individual design (i.e. the standard deviation of pair metrics was smaller than the one of solos). They also suggest that the industry can use pair design in critical situations and also in situations with short deadlines, lack of resources, and lack of skilled personnel. The pair design experiment conducted by Gerardo Canfora et al. [Canfora et al. Dec 06] in December 2006, suggests that pair design slows down the task but improves quality. They also found that the quality of pair design was more predictable (i.e. the standard deviation obtained by pairs was smaller than the one of solos) than individual design quality.

Matthias M. Muller [Muller 2006] conducted a pair programming experiment using 18 computer science students. The 18 subjects were randomly divided into 8 control groups (individuals) and 5 experimental groups (pairs). The students were asked to design, code and test an elevator control system using Java. Both control and experimental groups were initially paired for the design phase. Once the design was completed with the partner, the control group students were asked to code and test independently. The results show that the costly pair programming process (design, code and test) can be replaced by a less expensive process of pair-design phase followed by individual code and test phases.

On the other hand, Hiyam Al-Kilidar et al. [Al-Kilidar et al. 2005] found the effects of pair work on the quality of designs to be mixed. In the first module, pairs produced better quality design than solos. In the second module, the pairs and solos interchanged their roles; solos became pairs and pairs became solos. There was no significant difference in design quality between pairs and solos.

Pairs produced slightly better design than individuals in Jari Vanhanen's and Casper Lassenius's [Vanhanen et al. 2005] experiment. In Xu's and Rajlich's experiment [Xu et al. 2006], pairs developed better design than individuals.

The summary of the pair-design experiments is shown in Table 2.7.

Study	Result
Emilio Bellini et al†. [Bellini et al., 2005]	Pair design was more predictable than individual design Knowledge transfer about the system was higher among pairs than solos
Hiyam Al-Kilidar et al†. [Al-Kilidar et al., 2005]	Mixed results about the design quality
Vanhanen and Lassenius‡ [Vanhanen et al. 2005]	Pairs produced slightly better design than individuals
Gerardo Canfora et al†. [Canfora et al., Sep 06]	Pair design was better than individual design Pairs took less time than individuals Pair design was more predictable than individual design
Gerardo Canfora et al†. [Canfora et al., Dec 06]	Pair design was better than individual design Pairs took more time than individuals Pair design was more predictable than individual design
Matthias Muller‡ [Muller, 2006]	Pair programming can be replaced by pair design followed by individual code and test
Xu and Rajlich‡ [Xu et al. 2006]	Pair program had better design than individual program

†These experiments had only design phase and there were no coding and testing phases
‡ These were pair programming experiments which includes design phase

Table 2.7: Summary of Pair Design Experiments

We can conclude the following, from the work to date:

- Pair design improves design quality
- Pair design is more predictable than individual design in terms of effort and quality
- The development time for the pair design and individual design has mixed results

- Pair programming can be replaced with pair design phase followed by individual code and test phases in order to reduce cost.

2.4.2. Pair Coding

The pair-coding in Extreme Programming is almost nothing but pair programming itself. Laurie Williams and Robert Kessler [Williams et al., 2000] claim that pair-analysis and pair-design is more critical than pair-implementation. They also report that for simple and routine work, pairs split the work and do it individually in a more effective manner than when they work as pairs. In addition to this, the programmers report that for detail-oriented tasks, such as GUI drawing, the partners in the pair do not help much.

Many researchers including Williams et al. [Williams et al. 2000], Muller and Tichy [Muller et at. 2001], Lui and Chen [Lui et al. 2003], Hulkko and Abrahamsson [Hulkko et al. 2005], and Erik Arisholm et al. [Arisholm et al. 2007] report that pair programming is useful only for complex tasks and not useful for simple and routine tasks.

With respect to program quality (in terms of functionality and readability), pair programming experiments show mixed results. Wilson et al. [Wilson et al. 1993], John Nosek [Nosek 1998], McDowell et al [McDowell et al. 2002], and Xu and Rajlich [Xu et al. 2006] show that pairs produced better quality code than individuals; whereas Vanhanen and Lassenius [Vanhanen et al. 2005] and Hulkko and Abrahamson [Hulkko et al. 2005] show that individuals produced better quality code than pairs.

Regarding program correctness (i.e. number of test cases passed), again, pair programming experiments registered mixed results. Williams et al. [Williams et al. 2000] and Xu and Rajlich [Xu et al. 2006] show that pairs programs pass more test cases; whereas, Matthias Müller [Muller 2005], Hulkko and Abrahamson [Hulkko et al. 2005], Matthias Müller [Muller

2006], and Arisholm et al. [Arisholm et al. 2007] show that there is no difference in program correctness between pair and individual programs.

Almost all experiments show that pairs spend more time than individuals, which indicating that pair-coding is a rather slow and expensive technology.

The conclusion of pair-coding is,

- Pair coding phase is not as important as pair design phase
- Pair coding is slow and expensive
- Pair coding is useful only for complex tasks not for simple and/or routine tasks
- Empirical evidence is mixed regarding program quality
- Empirical evidence is mixed regarding program correctness

2.4.3. Pair Testing

Laurie Williams et al. [Williams et al., 2000] claim that pair-testing is the least critical phase in the pair programming process and that pairs can split up to run test cases on two computers as long as defects are identified.

Hulkko and Abrahamson [Hulkko et al, 2005] show that the relative amount of effort spent on the defect correction phase (performed after system test) of the project is very high. Jari Vanhanen and Casper Lassenius [Vanhanen et al., 2005] observed that pairs write code with fewer defects, but are less careful in system testing. They also suggest that unless the pairs do careful system testing, the benefits (fewer defects) they obtain in coding phase of pair programming will be lost. Pairs delivered system with more defects as compared with individual programmers. This is due to the reason that individuals found and removed more defects before delivery than pairs.

2.5. Alternatives to Traditional Pair Programming [Confer 2009]

Collaborative-Adversarial Pair (CAP) programming is a variant of the pair programming concept advocated by many agile techniques. CAP was developed at Auburn University several years ago as part of a commercial cell-phone software project. In 2003, Dr. David Umphress were asked by Rocket Mobile, Inc., a west-coast firm that specializes in cell phone software development, to reverse engineer one of their BREW products and rewrite it in JME. The effort was directed by Dr. David Umphress and the team consisted of two doctoral students – Brad Dennis and William "Amos" Confer – who each had six or seven years of industrial software development experience. The team purposely adopted an XP-like process because they believed that it gives them the greatest visibility into the project, and because it allowed them to deliver the product to the customer in increments for reliability testing. The team quickly determined that pair programming was not working. Both developers were highly independent and felt they each knew best how to build the code. Too, they worked different parts of the day: one developer was a morning person and the other was a night person. They overlapped two hours a day, at best. The team evolved over the first month of the project the idea of the collaborative-adversarial pair as the most realistic way we could produce reliable software. After the initial development, Amos and Dr Chapman used it in the senior capstone design course that is part of the Bachelor of Software Engineering and Bachelor of Wireless Engineering. The Collaborative-Adversarial Pair (CAP) programming process employed a synchronize-and-stabilize approach to development.

3. RESEARCH DESCRIPTION

The primary purpose of this research is to create and/or formally define a stable and reliable agile software development methodology called Collaborative-Adversarial Pair (CAP) programming. We see CAP as an alternative to traditional pair programming in situations where pair programming is not beneficial or is not possible to practice.

The primary objectives of this research are:

- To identify the pair-programming process, as well as the effectiveness, advantages, and disadvantages of pairs.
- To define the *Collaborative-Adversarial Pair (CAP)* process whose objective is to exploit the advantages of pair programming while at the same time downplaying its disadvantages.
- To evaluate *Collaborative-Adversarial Pair (CAP)* programming against pair programming and traditional individual programming in terms of productivity, correctness and job satisfaction.

3.1. The CAP Process [Umphress 2008]

The Collaborative-Adversarial Pair (CAP) programming process employs a synchronize-and-stabilize approach to development. As shown in Figure 3.1, the features are grouped into prioritized feature sets then build the sets in a series of software cycles, one set per cycle.

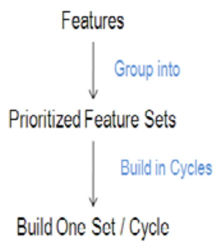


Figure 3.1: CAP Development Activity

The CAP development cycle is shown in Figure 3.2. Each cycle starts with the entire project team reviewing the features to be built. It is here that the customer requirements are translated into product requirements by converting user stories into *"developer stories,"* which are essentially manageable units of work that map to user stories. Progress is tracked by two measures: the ratio of the number of users stories built to the total number of user stories, and the ratio of the developer stories completed to the total number of developer stories to be built in the cycle. The first measure expresses progress to the customer; the second measure tracks internal progress.

After the feature review, the team moves into collaborative-adversarial mode (see Figure 3.3). The developers work together collaboratively to identify how to architect and design the features. They use this time to clarify requirements and discuss strategy. They then walk through their design with the overall project leader. After the design is approved, they move into adversarial roles. One developer is assigned the responsibility of implementing the design and the other developer is given the task of writing black-box test cases for the various components. The goal of the implementer is to build unbreakable code; the goal of the tester is to break the code. Note that the implementer is still responsible for writing unit-level white-box tests as part of his development efforts (see Figure 3.4). Once both developers have completed their tasks, they run the code against the tests. Upon discovering problems, the pair resumes their adversarial positions: the tester verifies that the test cases are valid and the implementer repairs the code and adds a corresponding regression unit test. In some cases, the test cases are not valid and are, themselves, fixed by the tester.

At the conclusion of the test phase, the team moves to a post mortem step. Here, the team (including the project manager) reviews the source code and the test cases. The purpose of the review is to 1) ensure the test cases are comprehensive and 2) identify portions of the code that are candidates for refactoring and not to find bugs; so the team does not walk through the code at a statement-by-statement level. This has been found to be so tedious that the participants quickly become numb to any problems. It is assumed that the majority of defects are caught in the blackbox functional tests or in the whitebox unit tests. Any gaps in test cases are captured as additional developer stories; refactoring tasks are done likewise. These developer stories receive a high enough priority that they are among the first tasks completed in the subsequent software development cycle.

A new development cycle begins again by following the post mortem step.

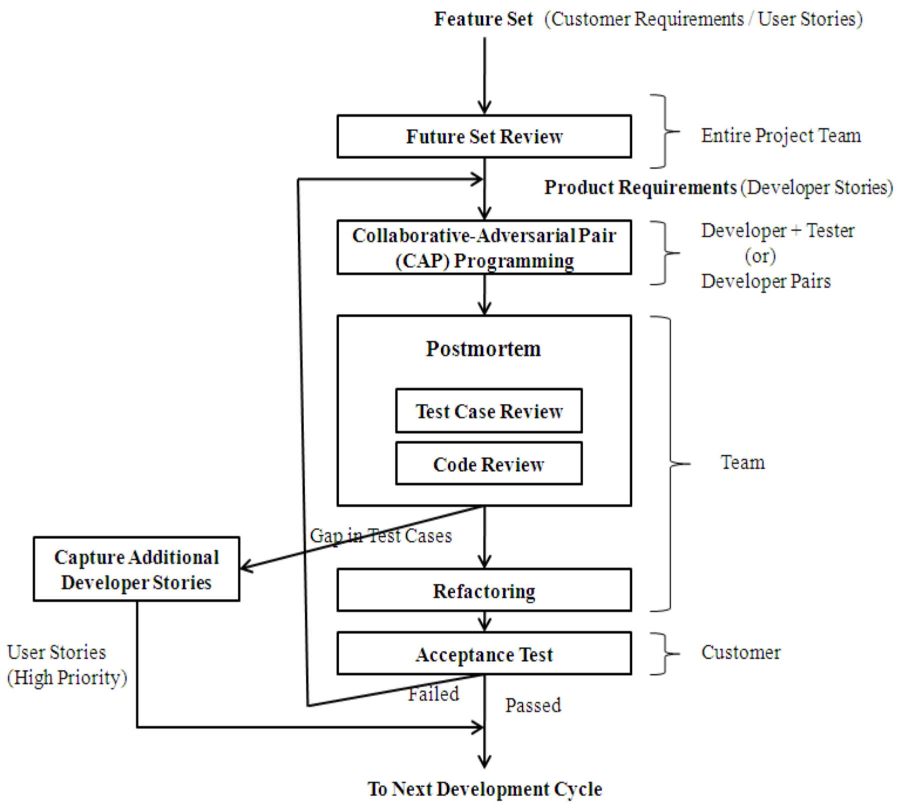

Feature Set (Customer Requirements / User Stories)
Future Set Review
Entire Project Team
Product Requirements (Developer Stories)
Collaborative-Adversarial Pair (CAP) Programming
Developer + Tester (or) Developer Pairs
Postmortem
Test Case Review
Code Review
Team
Gap in Test Cases
Capture Additional Developer Stories
Refactoring
Acceptance Test
Customer
User Stories (High Priority)
Failed
Passed
To Next Development Cycle

Figure 3.2: CAP Development Cycle

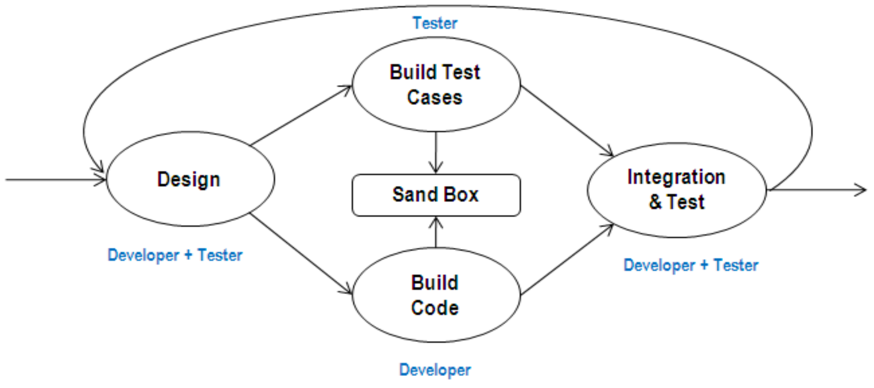


Figure 3.3: Collaborative-Adversarial Pairs (CAP)

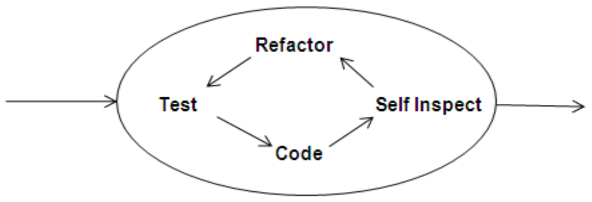


Figure 3.4: Build Code / Unit Implementation in CAP

3.1.1. Design

CAP uses Class Responsibility Collaborator (CRC) cards to design the software. A brainstorming tool used widely in the design of object-oriented software, the CRC cards were invented by *Ward Cunningham* [Beck et al. 1989]. CRC cards are usually created from 4" x 6" index cards and are used to determine which classes are needed and how they will interact. A CRC card contains the following information:

1. The class name.
2. Its super class.
3. The responsibilities of the class.
4. The names of other classes with which the class will collaborate to fulfill its responsibilities.

Figure 3.5 illustrates a template CRC card.

Class Name:	
Super Class Name:	
Responsibilities	Collaborators

Figure 3.5: A Class-Responsibility-Collaborator (CRC) index card

3.1.2. Black Box Test Cases

In *functional testing (or behavioral testing)*, every program is considered to be a function that maps values from its input domain to values in its output range. The functional testing is also called *black box* testing, because testing does not depend on the content or implementation of the function. Black box testing is completely based on the external specifications (i.e. inputs and outputs) of the function and is usually data driven.

With functional testing, test cases are developed only from external descriptions of the software, including specifications, requirements, and design. The functional test cases have the following two distinct advantages:

1. They are independent from software implementation. Implementation changes do not affect the test cases and vice-versa.
2. They can be developed in parallel with the implementation, which, in turn, reduces the overall project development interval.

The functional test cases may suffer from the following two drawbacks:

1. There may be a redundancy in the developed test cases.
2. There can be a probability that portions of the software may be untested.

3.1.3. Unit Implementation

Implementation refers to programming and is intended to satisfy the requirements in the manner specified by the detailed design. *Unit* (or software component or module) refers to the smallest part of the implementation that will be separately maintained. Normally a unit or software component is a set of collaborating classes. In some cases, a component may contain a single class. The unit implementation procedure in CAP is given below, which follows the Test-Driven Development (TDD) approach:

1. Write a test unit
2. Compile the test.
    - It should fail to compile because the code that the test calls has not been implemented
3. Implement the methods/write code
    - Refactor first if necessary
    - Do not compile yet
    - Follow the coding standard
    - Code in a manner that is easiest to verify
4. Self-inspect the code.
    - Do not compile/execute yet
    - Be convinced that the code does the required job (the compiler will never do this because it merely checks the syntax).
    - Fill out the code inspection checklist
    - Record the time and defect logs
5. Compile the code
    - Repair syntax defects
    - Record time and defect log
6. Run the test and see it pass.
7. Refactor for clarity and to remove duplication
8. Repeat from the top

3.1.3.1. Unit Test

Unit test is used to verify the software component or module of software design. Because a component is not a stand-alone program, a driver and/or stub software must be developed for each unit test. The unit test environment is shown in figure 3.6. A *driver* is a main program (in many applications) that accepts test case data, passes such data to the component to be tested, and prints relevant results. A *stub* is a dummy subprogram, serving to replace module that are subordinate to (called by) the component to be tested. It uses the subordinate module's interface, may do minimal data manipulation, provides verification of entry, and returns control to the module undergoing testing. To simplify unit testing, the designed component must be highly cohesive. When only one function is addressed by a component, the number of test cases is reduced and errors can be more easily predicted and uncovered.

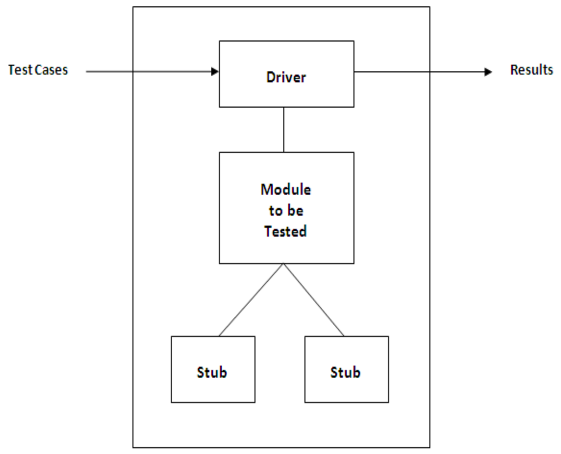


Figure 3.6: Unit Test Environment

3.1.4. Testing in CAP Vs PP

The pair programming methodology uses the white box testing strategy, which has the following drawbacks:

1. Since the white box test cases are developed from program source code, there is no way to recognize whether all the specified behaviors are implemented or not.
2. It is very difficult to employ white-box testing on purchased or contracted software because its internal structure is unknown.

On the other hand, the black box techniques alone are not sufficient enough to identify all the test cases; indeed, both white box and black box approaches are needed. By combining the black box and white box testing techniques, we will get the following benefits:

1. The redundancy and gaps problems of black box testing can be recognized and resolved.
2. White box testing aids in identifying behaviors that are not in the specification (such as a virus). This will never be revealed by black box functional testing.

The CAP testing procedure judiciously combines the functional (black box) and structural (white box) testing to provide the confidence of functional testing and the measurement of structural testing.

3.1.5. Refactoring

Refactoring is the process of changing software's internal structure, in order to improve design and readability and reduce bugs, without changing its observable behavior. Martin Fowler [Fowler 1999] suggests that refactoring has to be done in three situations: when adding new function to the software, when fixing a bug, and when we review the code (i.e., whenever new idea arises at the time for code review or when the code is identified as being too complex). The first two cases will be covered by the refactoring session of the unit implementation. Since CAP incorporates the code review session after integration and test, an additional refactoring phase is necessary. Refactoring also helps developers to review someone else’s code and helps the code review process to have more concrete results [Fowler 1999].

4. APPLIED RESULTS AND RESEARCH VALIDATION

Two empirical experiments were conducted during fall 2008 and spring 2009 to validate CAP against traditional pair programming and individual programming. The subjects used Eclipse and JUnit to perform three programming tasks with different degrees of complexity.

4.1. Subjects

Forty two (42) volunteer students from the Software Process class, a combined class of undergraduate seniors and graduate students, participated in the study. All participants had already taken software modeling and design (using UML) and computer programming courses such as C, C++ and Java. Out of fourteen students, 11 students had 1 to 5 years of industrial programming experience, two had no or less than one year programming experience, and one student had more than 5 years programming experience. Four students had prior pair programming experience.

4.2. Experimental Tasks

The subjects were asked to solve the following three programming problems in Java (Test Driven Development using Eclipse):

Problem1: Write a program which reads a text file and displays the name of the file, the total number of occurrences of a user-input string the total number of non-blank lines in the file, and the count the number of lines of code according to the LOC Counting Standard used in PSP, Personal Software Process [Humphrey 2005]. You may assume that the source code adheres to the LOC Coding Standard. This assignment should not determine if the coding standard has been followed. The program should be capable of sequentially processing multiple files by repeatedly prompting the user for file names until the user enters a file name of "stop". The program should issue the message, "I/O error", if the file is not found or if any other I/O error occurs.

Problem2: Write a program to list information (name, number of methods, type, and LOC) of each proxy in a source file. The program should also produce an LOC count of the entire source file. Your program should accept as input the name of a file that contains source code. You are to read the file and count the number of lines of code according to our LOC Counting Standard. You may assume that the source code adheres to the LOC Coding Standard. This assignment should not determine if the coding standard has been followed. The exact format of the application-user interaction is up to you.

- A "proxy" is defined as a recognizable software component. Classes are typical proxies in an object-oriented systems; subprograms are typical proxies in traditional functionally-decomposed systems.
- If you are using a functionally-decomposed (meaning, non-OO) approach, the number of methods for each proxy will be "1". If you are using an OO approach, the number of methods will be a count of the methods associated with an object.

Probelm3: Write a program to calculate the planned number of lines of code given the estimated lines of code (using PSP's PROBE Estimation Script). Your program should accept as input the name of a file. Each line of the file contains four pieces of information separated by a space: the name of a project and its estimated LOC (LOCe), planned LOC (LOCp), and actual LOC (LOCa). Read this file and echo the data to the output device. Accept as input from the keyboard a number which represents the estimated size (E) of a new project. Output the calculations of each decision and the responding planned size (P), as well as the PROBE decision designation (A, B, or C) used to calculate P. For each decision, indicate why it is/isn't valid. The exact format of the application-user interaction is up to you.

- Your software should gracefully handle error conditions, such as non-existent files and invalid input values.
- Round P up to the nearest multiple of 10.

4.3. Hypotheses

$H0_1$ (Time/Cost$_{Overall}$): The overall software development cost of CAP is equal or higher than PP in average.

Ha_1 (Time/Cost$_{Overall}$): The overall software development cost of CAP is less than PP in average.

$H0_2$ (Time/Cost$_{Overall}$): The overall software development cost of CAP is equal or higher than individual programming in average.

Ha$_2$ (Time/Cost$_{\text{Overall}}$): The overall software development cost of CAP is less than individual programming in average.

H0$_3$ (Time/Cost$_{\text{Coding}}$): The cost of CAP coding phase is equal or higher than the cost of PP coding phase in average.

Ha$_3$ (Time/Cost$_{\text{Coding}}$): The cost of CAP coding phase is less than cost of PP coding phase in average.

H0$_4$ (Time/Cost$_{\text{Coding}}$): The cost of CAP coding phase is equal or higher than the cost of individual programming coding phase in average.

Ha$_4$ (Time/Cost$_{\text{Coding}}$): The cost of CAP coding phase is less than cost of individual programming coding phase in average.

H0$_5$ (Correctness): The number acceptance tests failed in CAP is equal or higher than the number of acceptance tests failed in PP in average.

Ha$_5$ (Correctness): The number acceptance tests failed in CAP is less than the number of acceptance tests failed in PP in average.

4.4. Cost

To study the cost of overall software development, we compared the total development time, measured in minutes, of all the phases. Both pair programming (PP) and individual programming (IP) consisted of design, coding and test phases; whereas, the CAP consisted of test case development phase in addition to the PP phases. The IP, PP and CAP total software development costs were calculated as per the following formulas:

$Cost_{Total}^{IP}$= Time$_{\text{Design}}$ + Time$_{\text{Coding}}$ + Time$_{\text{Test}}$

$Cost_{Total}^{PP}$= 2* (Time$_{\text{Design}}$ + Time$_{\text{Coding}}$ + Time$_{\text{Test}}$)

$Cost_{Total}^{CAP}$= 2* (Time$_{\text{Design}}$ + Time$_{\text{Test}}$) + Time$_{\text{Coding}}$ + Time$_{\text{TestCaseDevelopment}}$

To study the cost of coding phase, we compared the coding time, measured in minutes, of the coding phase. The IP, PP and CAP coding phase costs were calculated as per the following formulas.

$$Cost_{Code}^{IP} = \text{Time}_{\text{Coding}}$$

$$Cost_{Code}^{PP} = 2 * (\text{Time}_{\text{Coding}})$$

$$Cost_{Code}^{CAP} = \text{Time}_{\text{Coding}}$$

4.5. Program Correctness

To study the program correctness, the number of post-development test cases, black-box test cases developed from the specifications, passed by programs developed by IP group, PP group and CAP group were compared.

4.6. Experiment Procedure

1. *Consent Process:* At the beginning of the course both in fall 2008 and in spring 2009 the IRB (Auburn University Institutional Review Board) approved informed consent for the project was handed out and students were given the chance to volunteer to participate. The researcher provided information to students about the project, handed out consent forms, answered any questions students raised by the students, and requested that the forms be returned the following class; so students had at least one intervening day to review all aspects of consent. The researcher returned the following class and answered the questions, if any, and collected the consent forms.

2. *Pre-Test:* In the pre-test all the subjects were asked to solve two programming problems individually in order to measure their programming skills.
3. *Pre-Experiment Survey:* Each subject was asked to complete a survey questionnaire which collected demographic information such as age, class level (senior/graduate), programming languages known, experience level, and pair programming experience.
4. *Assigning the Subjects to Experimental Groups:* Based on the pre-test's result and the survey, the subjects were divided into groups of five. The subjects were randomly selected from each group and assigned to the three experimental groups: individual programming (IP) group, pair programming (PP) group, and collaborative adversarial pair (CAP) programming group.
5. *Workshop:* Before the actual control experiments started there was a workshop for all the subjects. First, a lecture was arranged to explain the concepts of collaborative-adversarial pair programming, pair programming, and unit testing, and acceptance testing. Then, a pair programming practice session (known as pair-jelling exercise) was conducted, which enabled the programmers to understand the pair programming practices.
6. *Control Experiments:*
    a. *Control Experiment-1 (Dynamic Pairs):* Three programming exercises were given to each experimental group. The subjects in both the PP group and the CAP group were randomly paired-up with a partner in their own group to do the first problem. After the first problem the pairs rotated within their own group (i.e., a PP pair interchanged partners with another PP pair and a CAP pair interchanged partners with another CAP pair). The new rotated pairs completed the second problem. The group's pairs rotated once again to do the third problem.

b. *Control Experiment-2 (Static Pairs):* Three programming exercises were given to each experimental group. The subjects in both the PP group and the CAP group were randomly paired-up with a fixed partner to do all three exercises. The subjects in the IP group were asked to complete all the three exercises alone.

Figure 4.1 summarizes the experimental procedure.

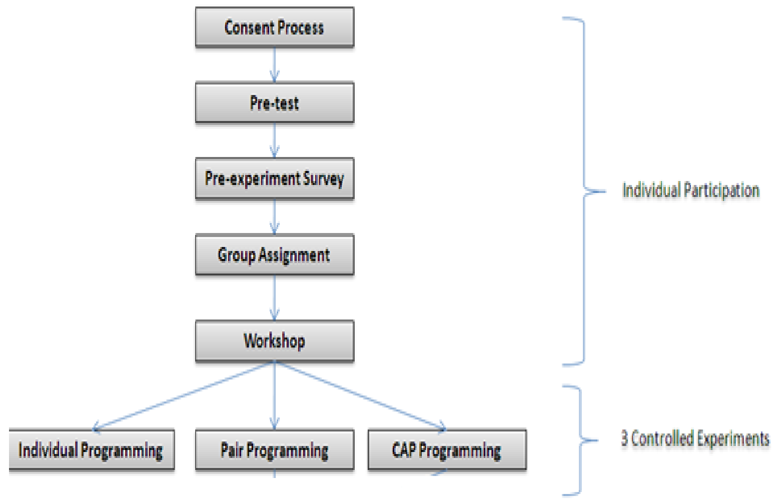


Figure 4.1: Experimental Procedure

The design of the experiments is shown figure 4.2.

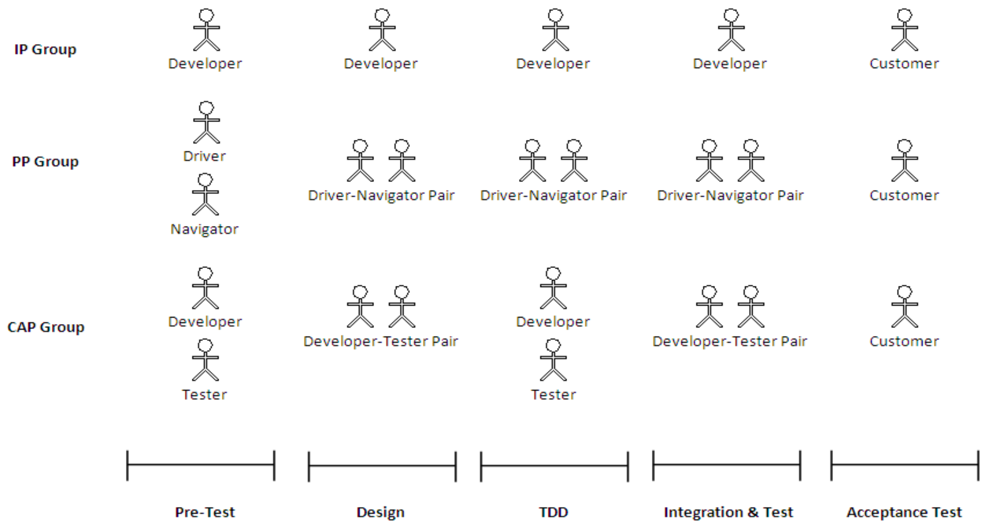


Figure 4.2: Experimental Setup

4.7. RESULTS

4.7.1. Statistical Test Selection

Statistical tests are of two types: parametric and non-parametric. Each parametric test depends on several assumptions, such as the data must follow the normal distribution, the sample size should be within a specified range, and there shouldn't be any outliers in the data. When its assumptions are met, a parametric test is more powerful than its corresponding non-parametric test. Non-parametric methods do not depend on the normality assumption, work quite well for small samples, and are robust to outliers.

Student's t-Test is suitable for smaller sample sizes (e.g. <30). The "normal curve z test" is more suitable for larger samples (e.g. ≥30). For polytomous independents (i.e. if the samples are subdivided into many distinct subordinate parts) the analysis of variance, ANOVA, tests are more suitable.

Therefore, it is clear that before we could finalize which statistical tests were most suitable to validate the CAP, we needed to analyze the data whether it satisfies the normality and no outlier properties or not.

We used a Q-Q plot of residuals[10] and SAS's GLM procedure to test for normality. The Q-Q plot is a plot of residuals in sorted order (Y-axis) against the value those residuals should have if the distribution of the residuals were normal; i.e., it shows the *observations* on the X-axis plotted against the *expected normal scores (Z-scores, known as quintiles)* on the Y-axis. The line shows the ideal normal distribution with mean and standard-deviation of the sample. If the points roughly follow the line, then the sample has normal distribution. The SAS's GLM procedure uses the method of least squares to fit general linear models. The GLM procedure with BF

[10] The *residual* of a sample is the difference between the sample and the observed *sample* mean.

(Brown and Forsythe's variation of Levene's test) option allows us to test the normality of the sample.

We used a box plot to identify outliers, i.e., data points which are numerically distant from the rest of the data. In a box plot the outliers are indicated using circles.

4.7.2. Empirical Experiment-1 (Dynamic Pairs-Fall 2008) Test Results

4.7.2.1. Test for Normality

Figures 4.3 and 4.4 show the Q-Q plot of residuals for the total software development time and coding time, respectively. The points on the Q-Q plots of residuals lie nearly on the straight line, which indicates that both the total software development time and the coding time data follows normal distribution.

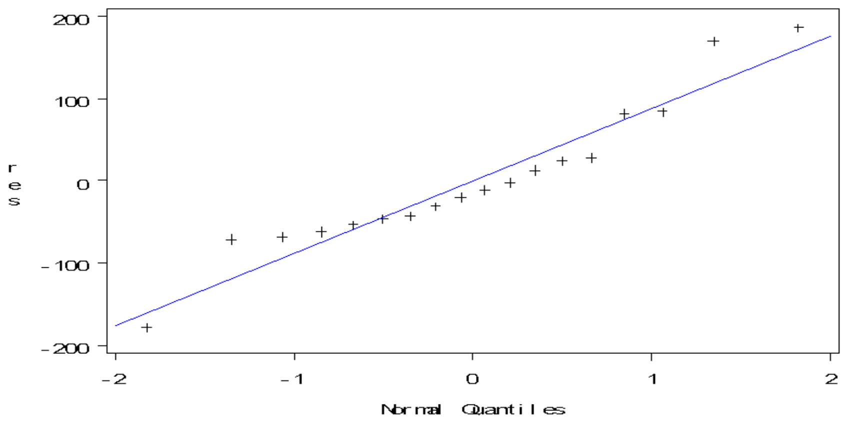


Figure 4.3: Q-Q Plot of Residuals (Dynamic Pairs Total Software Development Time)

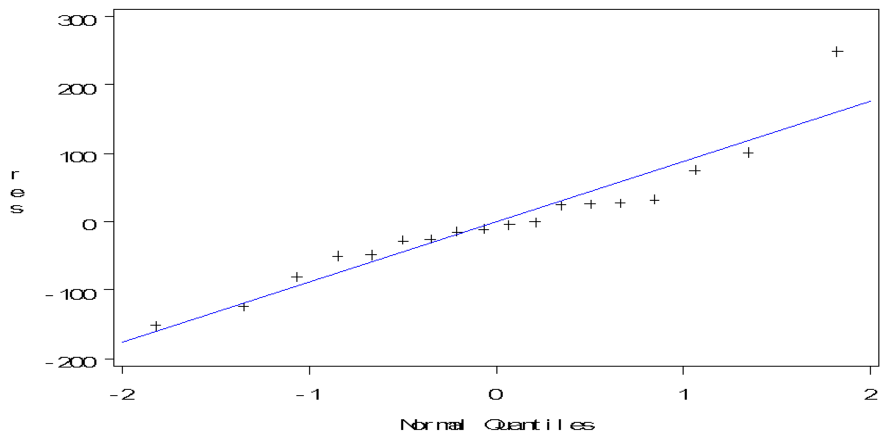


Figure 4.4: Q-Q Plot of Residuals (Dynamic Pairs Coding Time)

Figures 4.5 and 4.6 show the results of the SAS's "GLM procedure with BF option" for total software development time and coding time, respectively. In both Figure 4.5 and 4.6 the P value of all experiments are insignificant at 5% significant level (p>0.05), which indicates that statistically there is no significant evidence to reject the normality; i.e., both the overall software development time and the coding time data follows normal distribution.

```
                      Tests for Normality

Test                  --Statistic---    -----p Value------

Shapiro-Wilk          W     0.935497    Pr < W      0.2423
Kolmogorov-Smirnov    D     0.154598    Pr > D     >0.1500
Cramer-von Mises      W-Sq   0.08843    Pr > W-Sq   0.1507
Anderson-Darling      A-Sq  0.548835    Pr > A-Sq   0.1396
```

Figure 4.5: Test for Normality (Dynamic Pairs Total Software Development Time)

```
                      Tests for Normality

Test                  --Statistic---    -----p Value------

Shapiro-Wilk          W     0.919181    Pr < W      0.1250
Kolmogorov-Smirnov    D     0.189357    Pr > D      0.0866
Cramer-von Mises      W-Sq  0.088422    Pr > W-Sq   0.1507
Anderson-Darling      A-Sq  0.545294    Pr > A-Sq   0.1423
```

Figure 4.6: Test for Normality (Dynamic Pairs Coding Time)

4.7.2.2. Outliers

The box plots for the total software development time and coding time are given in Figures 4.7 and 4.8 respectively. There are no circles in Figures 4.7 and 4.8, which indicates that there are no outliers either in PP's overall software development time and coding time or in CAP's overall software development time and coding time.

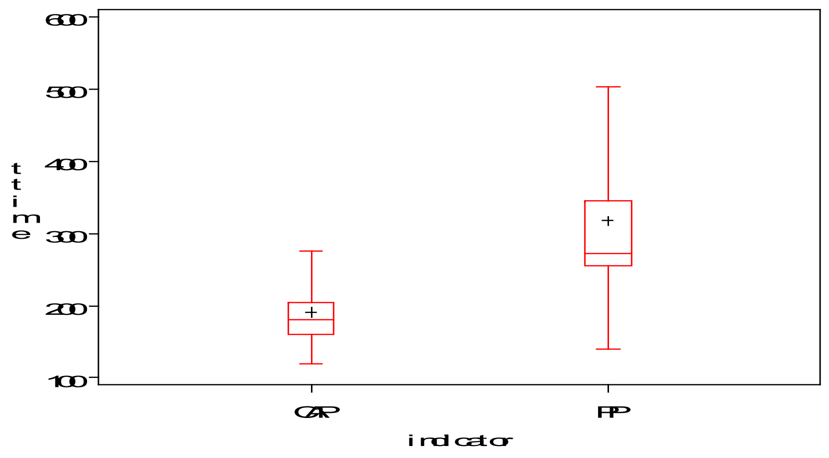


Figure 4.7: Box plot (Dynamic Pairs Total Software Development Time)

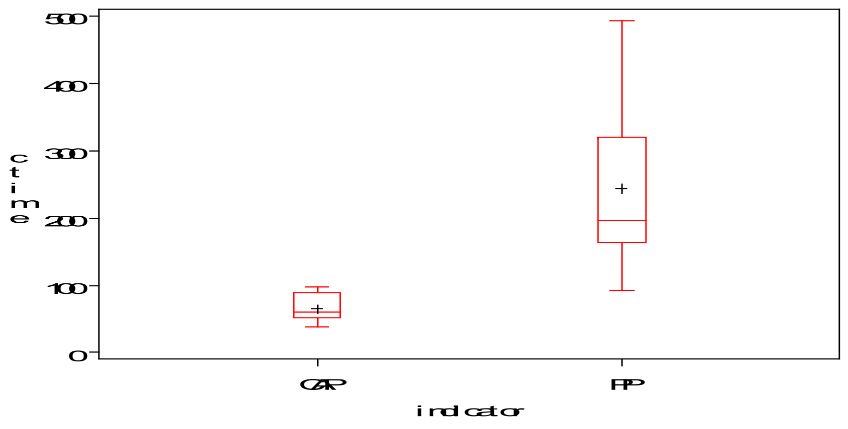


Figure 4.8: Box plot (Dynamic Pairs Coding Time)

4.7.2.3. Statistical Test Determination for Experiment-1

The sample size was 18 (9 experiments completed by PP group plus 9 experiments completed by CAP group). Since the sample size was small, we used Student's t-Tests to compare the CAP groups' means with the PP groups' means. The t-Test depends on several assumptions:

- If the sample size is less than 15, then the data for the t-Test should be strictly normal.
- If the sample size is between 15 and 40, then the data may be partially normal, but it should not contain outliers.
- When sample size is more than 40, then the data may be markedly skewed.

Our sample size was 18, and both total development time and coding time followed normal distribution, and there were no outliers. Consequently, Student's t-Test was identified as suitable for comparing both the CAP total software development time means with the PP total software development time means, and the CAP coding time means with the PP coding time means.

4.7.2.4. Total Software Development Time (Hypothesis 1)

The total software development time for the PP groups and the CAP groups are shown in Table 4.1. The PP groups took 285 minutes in average for Problem1, 446 minutes in average for Problem2, and 223 minutes in average for Problem3; whereas, the CAP groups took only 166 minutes (42% less than PP groups) in average for Problem1, 208 minutes (53% less than PP groups) in average for Problem2, and 199 minutes (11% less than PP groups) in average for Problem3. The average time taken to solve all the three problems is 954 minutes for the PP groups and 573 minutes (40% less than PP groups) for the CAP groups.

Method	Problem1	Problem2	Problem3
CAP-G1	180	275	120
CAP-G2	148	189	273
CAP-G3	171	160	204
Average	**166**	**208**	**199**
PP-G1	250	488	272
PP-G2	342	346	256
PP-G3	264	504	140
Average	**285**	**446**	**223**

Table 4.1: Total Software Development Time (Dynamic Pairs)

Figure 4.9 shows the average time taken by PP groups and CAP groups for the total software development for the given three problems.

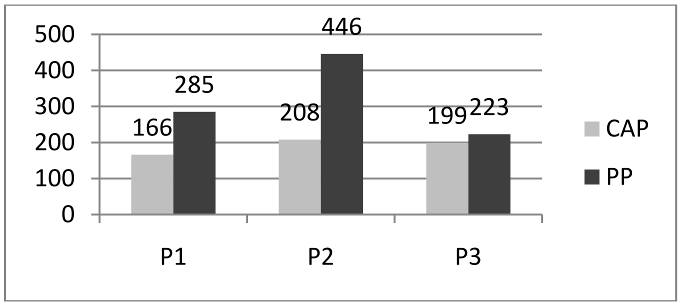


Figure 4.9: Average Total Software Development Time (Dynamic Pairs)

The box plot in Figure 4.10 shows the total time taken by all 18 pairs (3x3 programs completed by PP groups and 3x3 programs completed by CAP groups). The boxes contain 50% of the data points, the line between lower border and box contain 25% of data points, and the line between the box and upper border contain another 25% data points. The plus mark in the plot (box) indicates the mean value and the horizontal line in the middle of the box indicates the median value. *The plot indicates that all the nine CAP programs took less time than the mean value of the PP programs.*

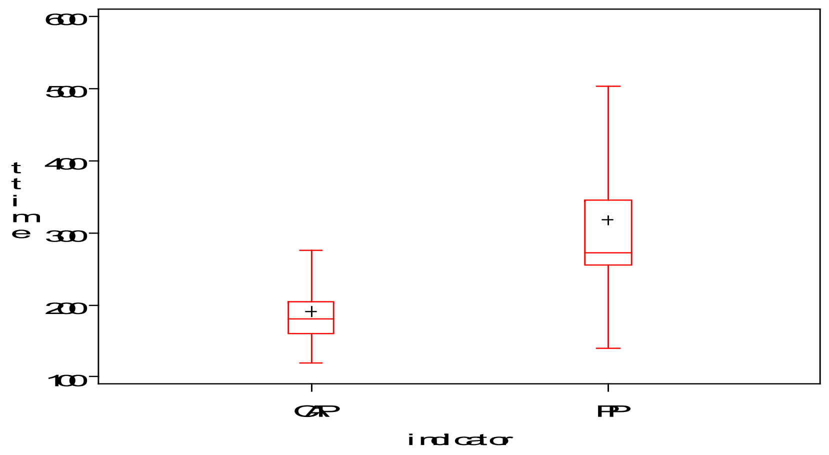


Figure 4.10: Total Software Development Time (Dynamic Pairs)

The Student's t-Test results are shown in Figure 4.11. The p-value in the equality of variances test is significant at the 5% significant level (p<0.05), which indicates that the data has unequal variance, so we have to take the unequal variance t-Test result, which is p=0.0129(2 sided t-value). Since p<0.05, there is insufficient support for the hypothesis H0$_1$ that the overall software development cost or time of CAP is equal or higher that PP in average.

```
                                  The TTEST Procedure
                                      Statistics

                            Lower CL          Upper CL  Lower CL            Upper CL
Variable  indicator       N    Mean     Mean      Mean   Std Dev  Std Dev    Std Dev  Std Err

ttime     CAP             9   150.51  191.11    231.72    35.682   52.826      101.2   17.609
ttime     PP              9   227.85     318    408.15    79.219   117.28     224.68   39.094
ttime     Diff (1-2)          -217.8  -126.9    -35.99    67.741   90.955     138.43   42.877

                                        T-Tests
             Variable    Method           Variances      DF    t Value    Pr > |t|

             ttime       Pooled           Equal          16      -2.96      0.0092
             ttime       Satterthwaite    Unequal      11.1      -2.96      0.0129

                                 Equality of Variances

                 Variable    Method       Num DF    Den DF    F Value    Pr > F

                 ttime       Folded F          8         8       4.93    0.0368
```

Figure 4.11: t-Test Results (Dynamic Pairs Total Software Development Time)

Decision: Reject $H0_1$ in favor of Ha_1 since p-value < α (α=0.05). Thus we have sufficient statistical evidence to conclude that the overall software development cost or time of CAP is less than PP in average.

4.7.2.5. Coding Time (Hypothesis 3)

The coding time for the PP groups and the CAP groups are shown in Table 4.2. The PP groups took 192 minutes in average for Problem1, 371 minutes in average for Problem2, and 170 minutes in average for Problem3; whereas, the CAP groups took only 65 minutes (66% less than PP groups) in average for Problem1, 52 minutes (86% less than PP groups) in average for Problem2, and 79 minutes (54% less than PP groups) in average for Problem3. The average time taken to solve all the three problems is 733 minutes for PP groups and 196 minutes (73% less than PP groups) for CAP groups.

Method	**Problem1**	**Problem2**	**Problem3**
CAP-G1	38	55	51
CAP-G2	91	61	98
CAP-G3	65	40	89
Average	**65**	**52**	**79**
PP-G1	92	272	194
PP-G2	320	346	196
PP-G3	164	494	120
Average	**192**	**371**	**170**

Table 4.2: Coding Time (Dynamic Pairs)

Figure 4.12 shows the average time taken by PP groups and CAP groups for the coding phase of the software development for the given three problems.

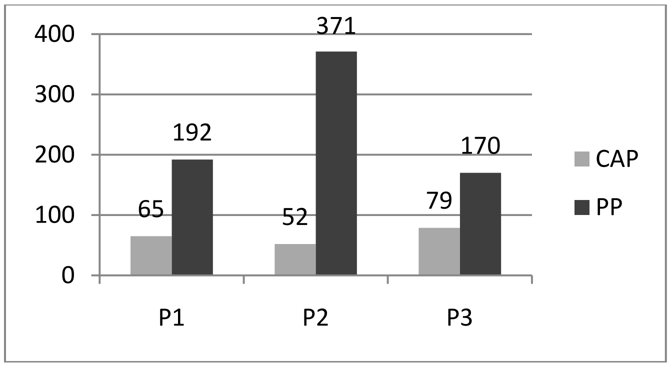


Figure 4.12: Average Coding Time (Dynamic Pairs)

The box plot in Figure 4.13 shows the coding time taken by all 18 pairs (3x3 programs completed by PP groups and 3x3 programs completed by CAP groups). *The plot indicates that all the nine CAP programs took less time than 75% PP programs.*

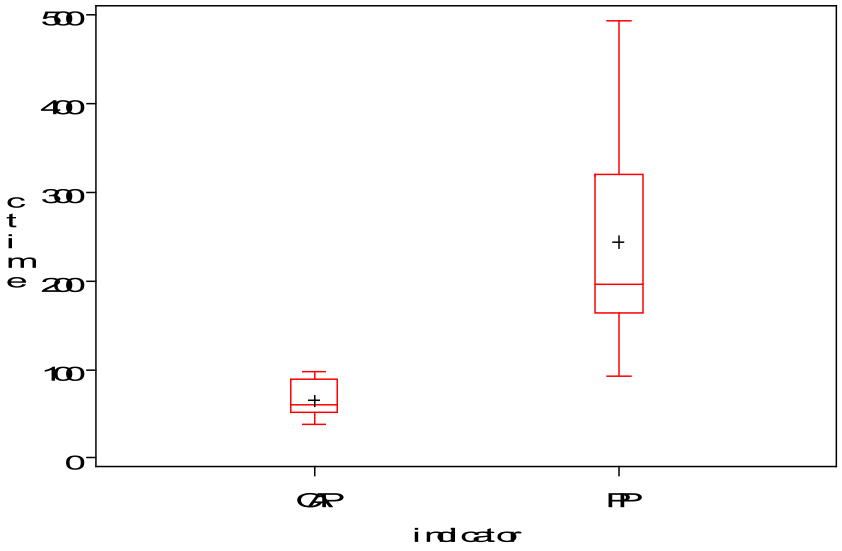


Figure 4.13: Box plot (Dynamic Pairs Coding Time)

The Student's t-Test results are shown in Figure 4.14. The p-value in the equality of variances test is significant in the 5% significant level ($p<0.05$), which indicates that the data has unequal variance, so we have to take the unequal variance t-Test result, which is P=0.0028 (2 sided t-value). Since $P<0.05$, there is insufficient support for the hypothesis $H0_3$ that the cost of the CAP coding phase is equal or higher that PP coding phase in average.

```
                                        The TTEST Procedure
                                            Statistics

                           Lower CL          Upper CL  Lower CL           Upper CL
Variable  indicator       N      Mean      Mean      Mean   Std Dev  Std Dev   Std Dev   Std Err

ctime     CAP             9    48.133   65.333    82.534    15.115   22.377     42.87    7.4591
ctime     PP              9    146.56   244.22    341.89    85.821   127.06    243.41    42.352
ctime     Diff (1-2)           -270.1   -178.9    -87.72    67.942   91.226    138.84    43.004

                                              T-Tests
             Variable     Method            Variances      DF     t Value     Pr > |t|

             ctime        Pooled            Equal          16       -4.16       0.0007
             ctime        Satterthwaite     Unequal       8.5       -4.16       0.0028

                                      Equality of Variances
                 Variable     Method       Num DF     Den DF     F Value     Pr > F

                 ctime        Folded F          8          8       32.24    <.0001
```

Figure 4.14: t-Test Results (Dynamic Pairs Coding Time)

Decision: Reject $H0_3$ in favor of Ha_3 since p-value < α (α=0.05). Thus we have sufficient statistical evidence to conclude that the cost of CAP coding phase is less than the cost of PP coding phase in average.

4.7.2.6. Program Correctness (Hypothesis 5)

The number of post-development test cases passed by the PP group programs and the CAP group programs are shown in Table 4.3 and Figure 4.15. The acceptance tests were conducted by a disinterested party. Specifically, a graduate teaching assistant for the introductory Java course was recruited to do this. The tester was not involved in any other way with the experiment. The total numbers of test cases passed by the PP groups was 13, 17, and 29 for

Problem1, Problem2, and Problem3 respectively. Whereas, the total numbers of test cases passed by the CAP groups was 16, 20, and 30 for Problem1, Problem2, and Problem3 respectively.

Group	Problem1	Problem2	Problem3
PP1	5/6	6/8	10/10
PP2	4/6	8/8	9/10
PP3	4/6	3/8	10/10
Total	**13/18**	**17/24**	**29/30**
CAP1	5/6	8/8	10/10
CAP2	5/6	8/8	10/10
CAP3	6/6	4/8	10/10
Total	**16/18**	**20/24**	**30/30**

Table 4.3: The number of test cases passed (Dynamic Pairs)

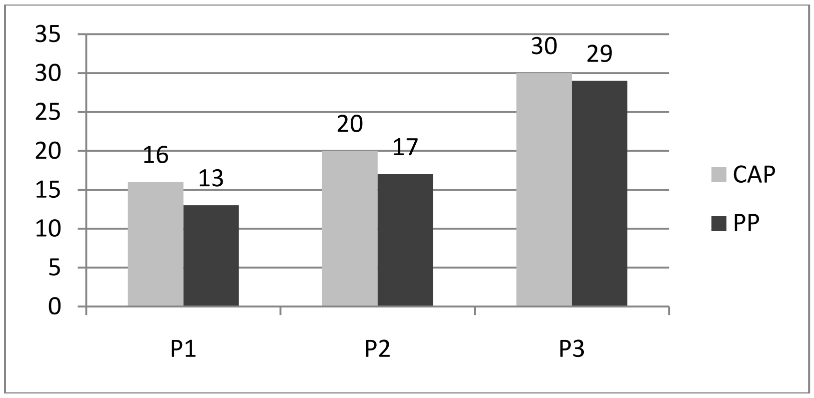


Figure 4.15: The number of test cases passed (Dynamic Pairs)

Table 4.3 indicates that the number of acceptance tests failed in CAP is less than the number of acceptance tests failed in PP. Therefore, there is insufficient support for the hypothesis $H0_5$.

Decision: Reject $H0_5$ in favor of Ha_5. We have sufficient evidence to conclude that the number of acceptance tests failed in CAP is less than the number of acceptance tests failed in PP.

4.7.3. Empirical Experiment-2 (Static Pairs-Spring 2009) Test Results

4.7.3.1. Test for Normality

Figures 4.16 and 4.17 show the Q-Q plot of residuals for the total software development time and coding time, respectively. The points on Figure 4.16 lie nearly on the straight line; whereas, the points on Figure 4.17 do not follow the straight line, which indicates that the total software development time data follows normal distribution whereas the coding time data is not.

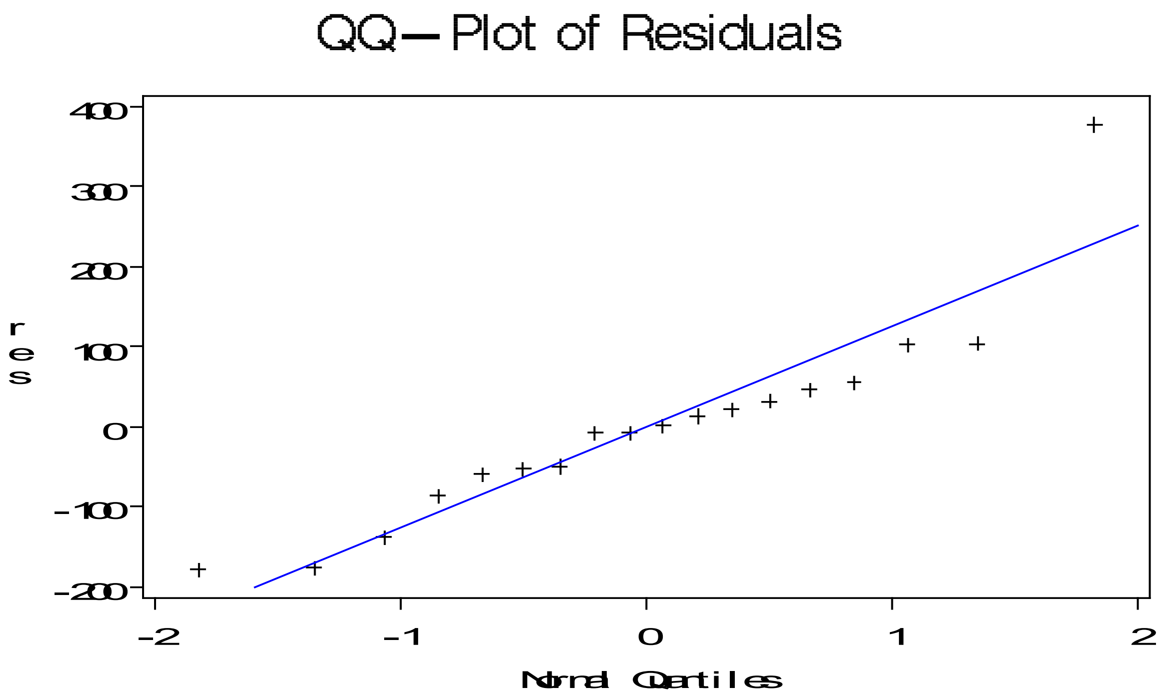


Figure 4.16: Q-Q Plot of Residuals (Static Pairs Total Software Development Time)

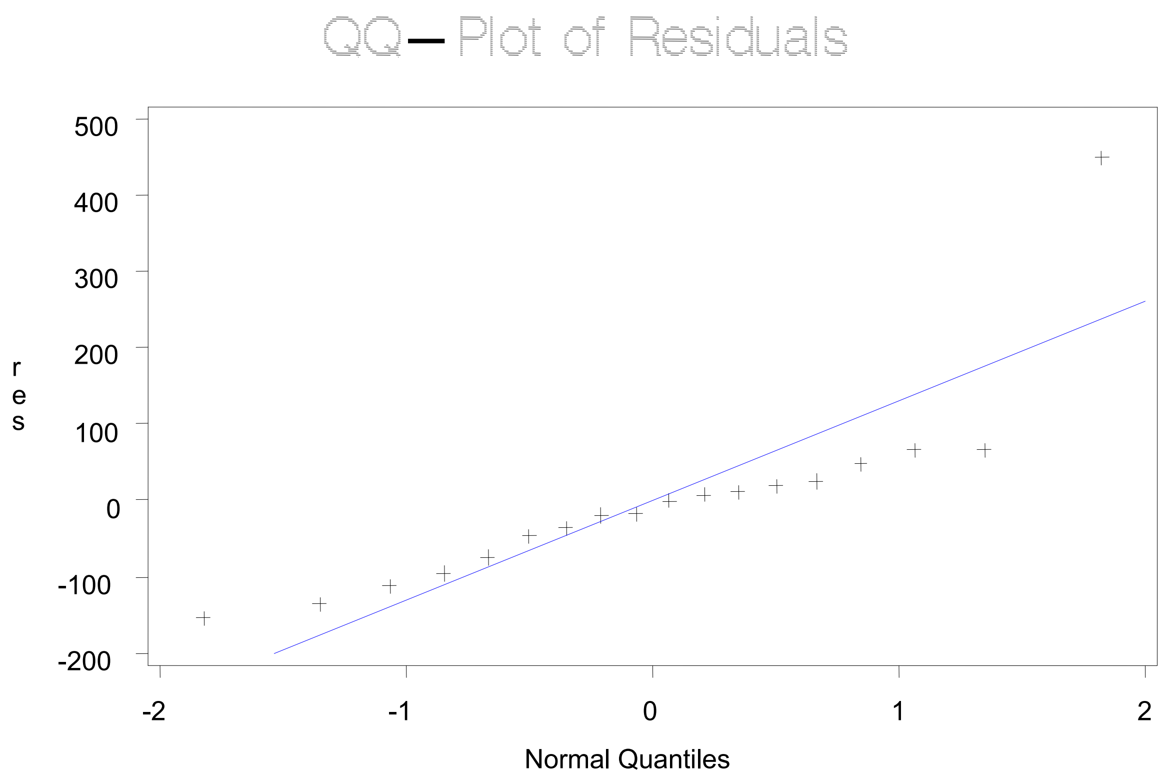


Figure 4.17: Q-Q Plot of Residuals (Static Pairs Coding Time)

Figures 4.18 and 4.19 show the results of the SAS's "GLM procedure with BF option" for total software development time and coding time, respectively. In Figure 4.18 the p value of all tests (expect Shapiro-Wilk test) are insignificant at 5% significant level (p>0.05), which indicates that statistically there is no significant evidence to reject the normality; i.e., the overall software development time data follows normal distribution. In Figure 4.19 the p value of all tests are not insignificant at 5% significant level (p<0.05), which indicates that statistically there is significant evidence to reject the normality; i.e., the coding time data does not follow normal distribution.

```
                              Tests for Normality

           Test                  --Statistic---    -----p Value------

           Shapiro-Wilk          W     0.881142    Pr < W      0.0273
           Kolmogorov-Smirnov    D     0.161488    Pr > D     >0.1500
           Cramer-von Mises      W-Sq  0.084384    Pr > W-Sq   0.1751
           Anderson-Darling      A-Sq  0.618083    Pr > A-Sq   0.0929
```

Figure 4.18: Test for Normality (Static Pairs Total Software Development Time)

```
                              Tests for Normality

           Test                  --Statistic---    -----p Value------

           Shapiro-Wilk          W     0.749179    Pr < W      0.0003
           Kolmogorov-Smirnov    D     0.248771    Pr > D     <0.0100
           Cramer-von Mises      W-Sq  0.196178    Pr > W-Sq  <0.0050
           Anderson-Darling      A-Sq  1.297565    Pr > A-Sq  <0.0050
```

Figure 4.19: Test for Normality (Static Pairs Coding Time)

4.7.3.2. Outliers

The box plots for the total software development time and coding time are given in Figures 4.20 and 4.21 respectively. There are no circles in Figures 4.20 and 4.21, which indicates that there are no outliers either in PP's overall software development time and coding time or in CAP's overall software development time and coding time.

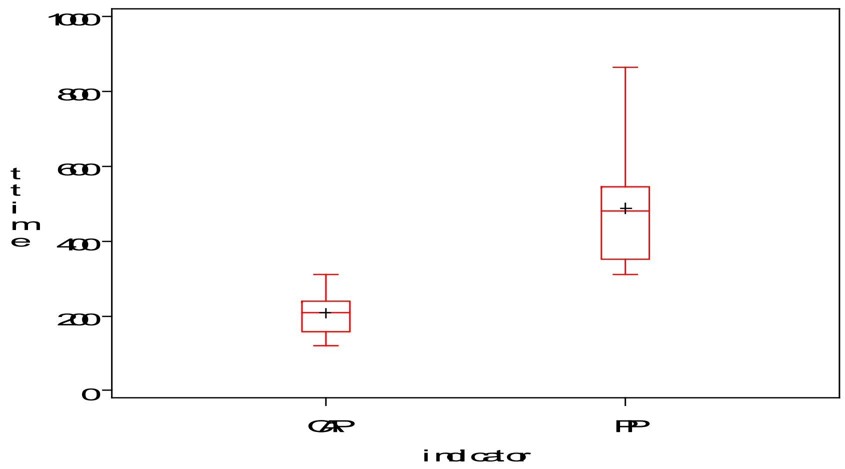


Figure 4.20: Box plot (Static Pairs Total Software Development Time)

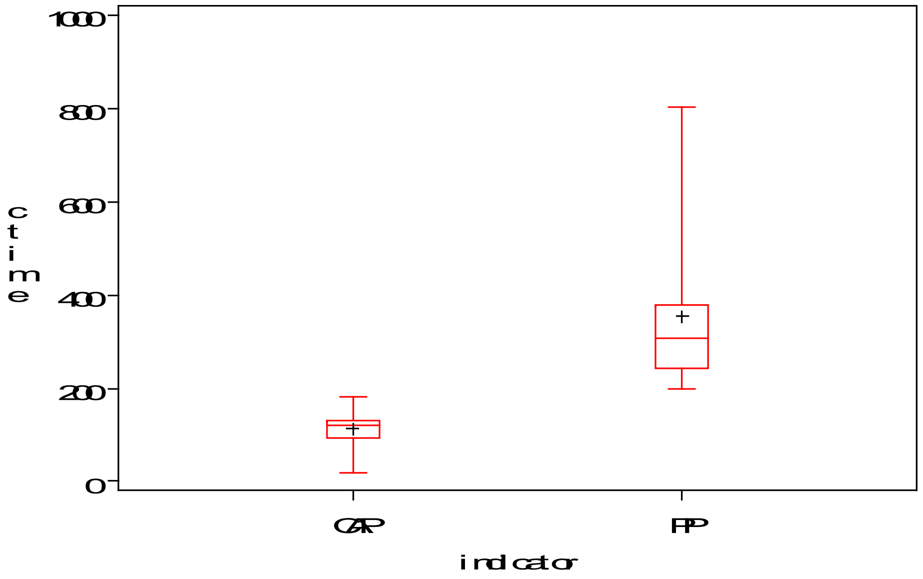


Figure 4.21: Box plot (Static Pairs Coding Time)

4.7.3.3. Statistical Test Determination for Experiment-2

The sample size was 18 (9 experiments completed by PP groups plus 9 experiments completed by CAP groups). Since the sample size was small, we used t-Tests to compare the CAP groups' means with the PP groups' means.

Our sample size was18, the total development time followed normal distribution, and there were no outliers. Consequently Student's t-Test was used to compare the CAP total software development time means with the PP total software development time means. Since the coding time data was not normally distributed. The Wilcoxon Mann-Whitney U test was used to compare the CAP coding time means with the PP coding time means.

4.7.3.4. Total Software Development Time (Hypothesis 1)

The total software development time for the PP groups and the CAP groups are shown in Table 4.4. The PP groups took 603 minutes in average for Problem1, 484 minutes in average for Problem2, and 377 minutes in average for Problem3; whereas, the CAP groups took only 197 minutes (67% less than PP groups) in average for Problem1, 192 minutes (60% less than PP groups) in average for Problem2, and 236 minutes (37% less than PP groups) in average for Problem3. The average time taken to solve all the three problems was 1464 minutes for PP groups and 625 minutes (57% less than PP groups) for CAP groups.

Method	Problem1	Problem2	Problem3
CAP-G1	159	200	311
CAP-G2	210	122	156
CAP-G3	222	254	240
Average	**197**	**192**	**236**
PP-G1	592	544	312
PP-G2	350	480	510
PP-G3	866	428	310
Average	**603**	**484**	**377**

Table 4.4: Total Software Development Time (Static Pairs)

Figure 4.22 shows the average time taken by PP groups and CAP groups for the total software development for the given three problems.

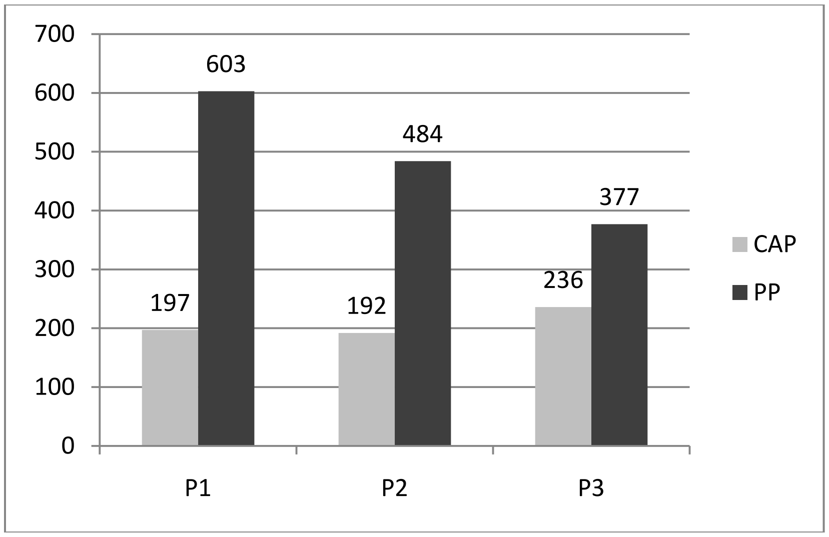


Figure 4.22: Average Total Software Development Time (Static Pairs)

The box plot in Figure 4.23 shows the total time taken by all 18 pairs (3x3 programs completed by PP group and 3x3 programs completed by CAP group). *The plot indicates that all the nine CAP programs took less time than the least value of the PP program groups.*

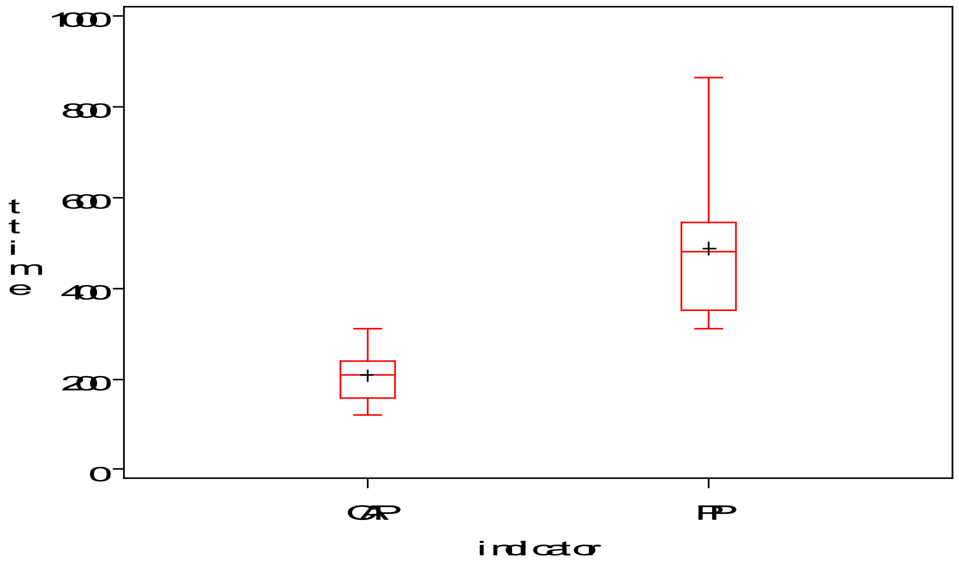


Figure 4.23: Total Software Development Time (Static Pairs)

The Student's t-Test results are shown in Figure 4.24. The p-value in the equality of variances test is significant in the 5% significant level ($p<0.05$), which indicates that the data has unequal variance, so we have to take the unequal variance t-Test result, which is $P=0.0011$(2 sided t-value). Since $P<0.05$, there is insufficient support for the hypothesis $H0_1$ that the overall software development cost or time of CAP is equal or higher that PP in average.

```
                                        The TTEST Procedure

                                             Statistics

                                  Lower CL          Upper CL  Lower CL           Upper CL
Variable  indicator        N        Mean     Mean      Mean   Std Dev  Std Dev   Std Dev  Std Err

ttime     CAP              9      163.97   208.22    252.47    38.885   57.569    110.29    19.19
ttime     PP               9      354.12      488    621.88    117.65   174.17    333.67   58.057
ttime     Diff (1-2)              -409.4   -279.8    -150.2    96.605   129.71    197.41   61.147

                                        T-Tests

             Variable    Method           Variances      DF    t Value    Pr > |t|

             ttime       Pooled           Equal          16      -4.58      0.0003
             ttime       Satterthwaite    Unequal      9.73      -4.58      0.0011

                                 Equality of Variances

                 Variable    Method      Num DF    Den DF    F Value    Pr > F

                 ttime       Folded F         8         8       9.15    0.0052
```

Figure 4.24: t-Test Results (Static Pairs Total Software Development Time)

Decision: Reject $H0_1$ in favor of Ha_1 since p-value < α ($\alpha=0.05$). Thus we have sufficient statistical evidence to conclude that the overall software development cost or time of CAP is less than PP in average.

4.7.3.5. Coding Time (Hypothesis 3)

The coding time for PP group and CAP group are shown in Table 4.5. The PP groups took 437 minutes in average for Problem1, 319 minutes in average for Problem2, and 306 minutes in average for Problem3; whereas, the CAP groups took only 81 minutes (81% less than

PP groups) in average for Problem1, 117 minutes (63% less than PP groups) in average for Problem2, and 142 minutes (54% less than PP groups) in average for Problem3. The average time taken to solve all the three problems was 1062 minutes for PP groups and 340 minutes (68% less than PP groups) for CAP groups.

Method	Problem1	Problem2	Problem3
CAP-G1	18	113	124
CAP-G2	132	77	121
CAP-G3	94	161	180
Average	**81**	**117**	**142**
PP-G1	308	242	218
PP-G2	200	380	420
PP-G3	804	336	280
Average	**437**	**319**	**306**

Table 4.5: Coding Time (Static Pairs)

Figure 4.25 shows the average time taken by PP groups and CAP groups for the coding phase of the software development for the given three problems.

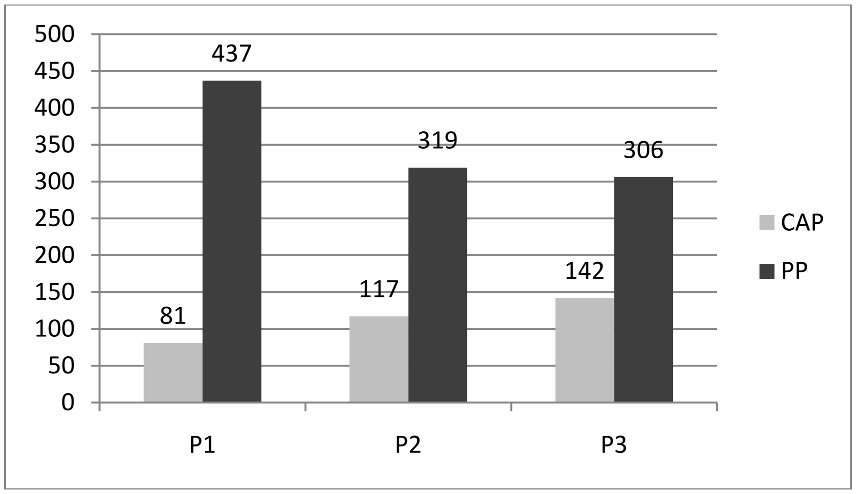


Figure 4.25: Average Coding Time (Static Pairs)

The box plot in Figure 4.26 shows the coding time taken by all 18 pairs (3x3 programs completed by PP group and 3x3 programs completed by CAP group). *The plot indicates that all the nine CAP programs took less time than the least value of the PP program group.*

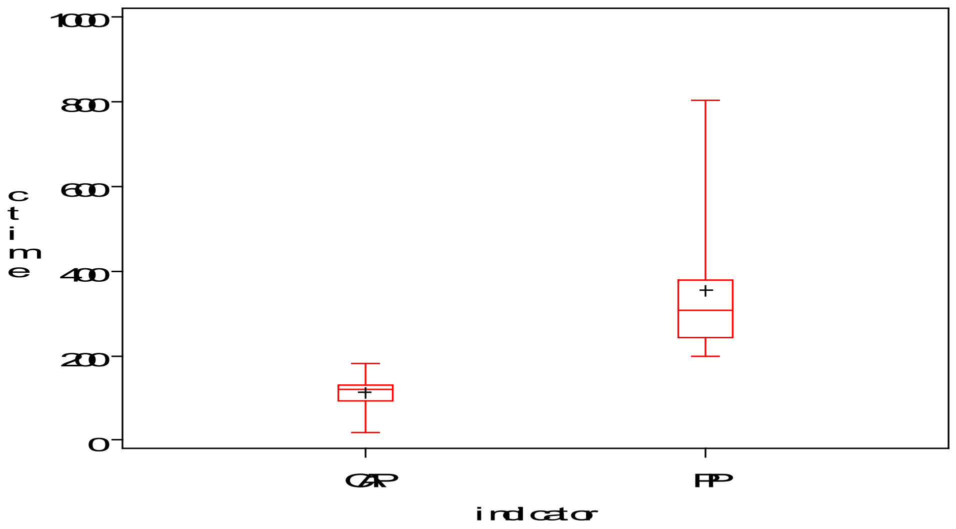


Figure 4.26: Box plot (Static Pairs Coding Time)

The Wilcoxon Mann-Whitney U test results are shown in Figure 4.27. The P value is 0.0026 (2 sided t-value). Since $P<0.05$, there is insufficient support for the hypothesis $H0_3$ that the cost of the CAP coding phase is equal or higher that PP coding phase in average.

```
             Wilcoxon Two-Sample Test

      Statistic (S)                 45.0000

      Normal Approximation
      Z                             -3.5321
      One-Sided Pr <  Z              0.0002
      Two-Sided Pr > |Z|             0.0004

      t Approximation
      One-Sided Pr <  Z              0.0013
      Two-Sided Pr > |Z|             0.0026

      Exact Test
      One-Sided Pr <=  S           2.057E-05
      Two-Sided Pr >= |S - Mean|   4.114E-05

    Z includes a continuity correction of 0.5.
```

Figure 4.27: Wilcoxon Mann-Whitney U test Results (Static Pairs Coding Time)

Decision: Reject $H0_3$ in favor of Ha_3 since p-value < α (α=0.05). Thus we have sufficient statistical evidence to conclude that the cost of CAP coding phase is less than the cost of PP coding phase in average.

4.7.4. Combined Test Results (CAP Vs PP)

4.7.4.1. Test for Normality

Figures 4.28 and 4.29 show the Q-Q plot of residuals for the total software development time and coding time respectively. The points on Figure 4.28 lie nearly on the straight line; whereas, the points on Figure 4.29 do not follow the straight line, which indicates that the total software development time data follows normal distribution whereas the coding time data is not.

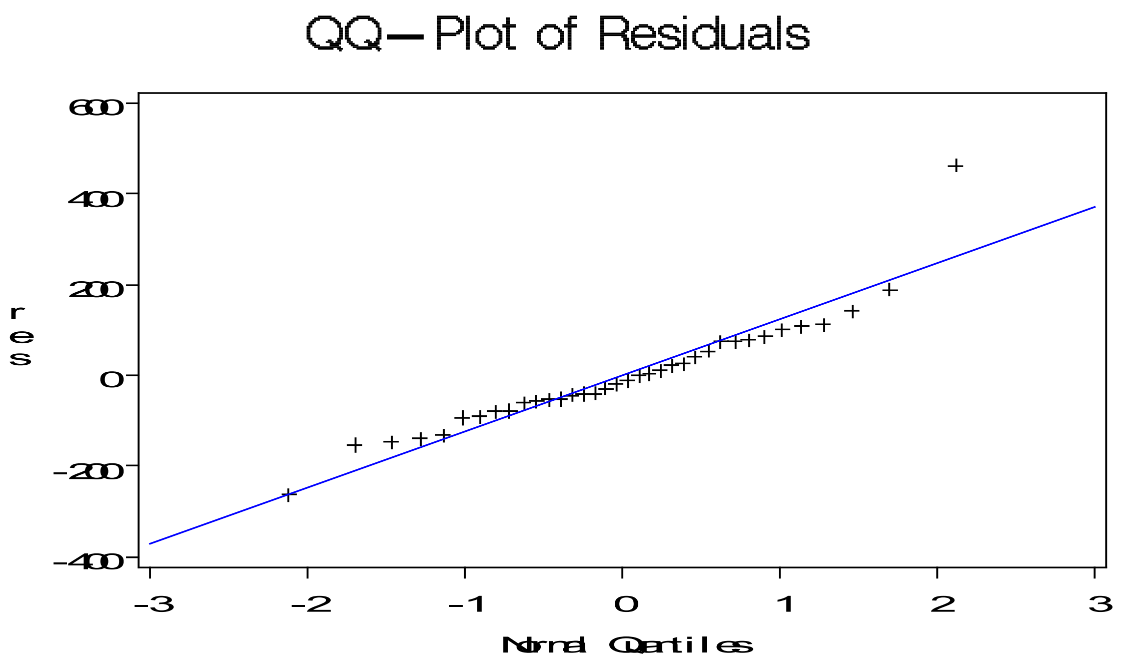


Figure 4.28: Q-Q Plot of Residuals (Combined CAP Vs PP Total Software Development Time)

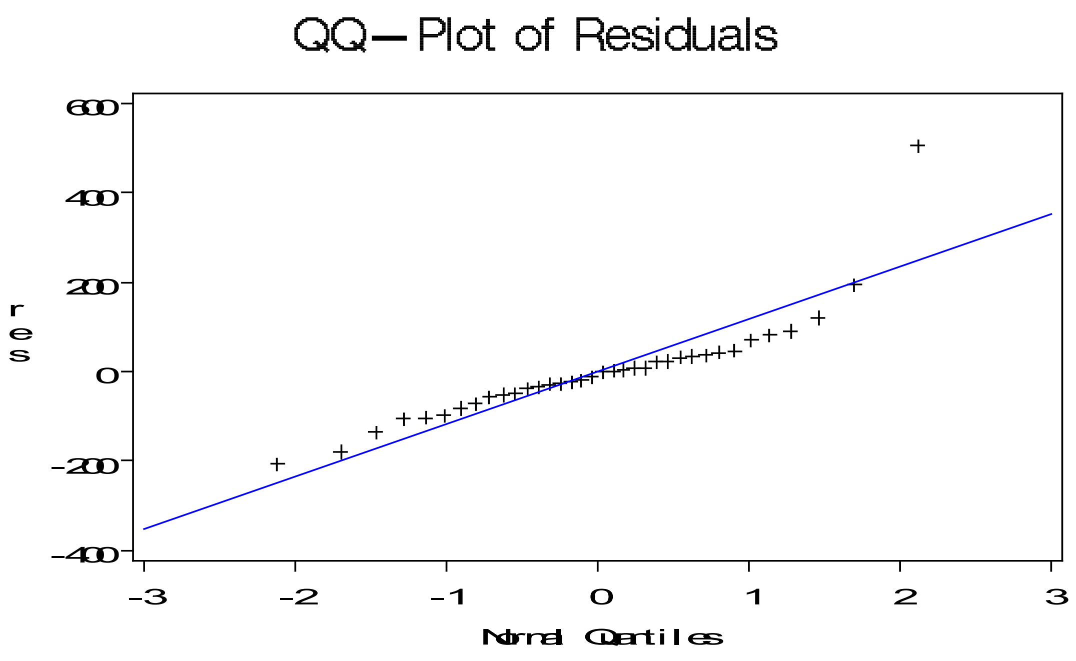


Figure 4.29: Q-Q Plot of Residuals (Combined CAP Vs PP Coding Time)

Figures 4.30 and 4.31 show the results of the SAS's "GLM procedure with BF option" for total software development time and coding time respectively. In Figure 4.30 the p value of all tests (expect Shapiro-Wilk test) are insignificant at 5% significant level (p>0.05), which indicates that statistically there is no significant evidence to reject the normality; i.e., the overall software development time data follows normal distribution. In Figure 4.31 the p value of all tests are not insignificant at 5% significant level (p<0.05), which indicates that statistically there is significant evidence to reject the normality; i.e., the coding time data does not follow normal distribution.

```
                         Tests for Normality

Test                  --Statistic---    -----p Value------

Shapiro-Wilk          W     0.910577    Pr < W      0.0067
Kolmogorov-Smirnov    D     0.100131    Pr > D     >0.1500
Cramer-von Mises      W-Sq  0.085478    Pr > W-Sq   0.1755
Anderson-Darling      A-Sq  0.657534    Pr > A-Sq   0.0829
```

Figure 4.30: Test for Normality (Combined CAP Vs PP Total Software Development Time)

```
                           Tests for Normality

Test                  --Statistic---    -----p Value------

Shapiro-Wilk          W     0.821607    Pr < W     <0.0001
Kolmogorov-Smirnov    D     0.179058    Pr > D     <0.0100
Cramer-von Mises      W-Sq  0.230129    Pr > W-Sq  <0.0050
Anderson-Darling      A-Sq  1.443171    Pr > A-Sq  <0.0050
```

Figure 4.31: Test for Normality (Combined CAP Vs PP Coding Time)

4.7.4.2. Outliers

The box plots for the total software development time and coding time are given in Figures 4.32 and 4.33 respectively. There are no circles in Figures 4.32 and 4.33, which indicates that there are no outliers either in PP's overall software development time and coding time or in CAP's overall software development time and coding time.

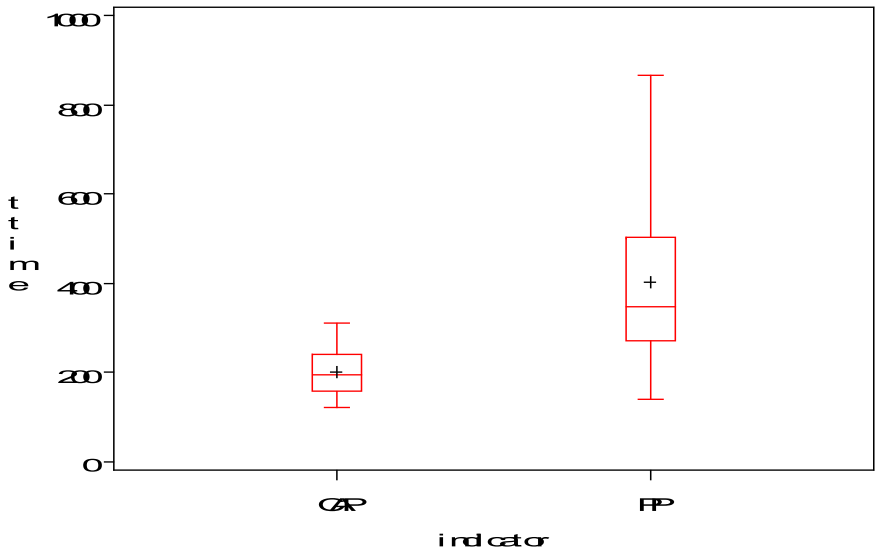


Figure 4.32: Box plot (Combined CAP Vs PP Total Software Development Time)

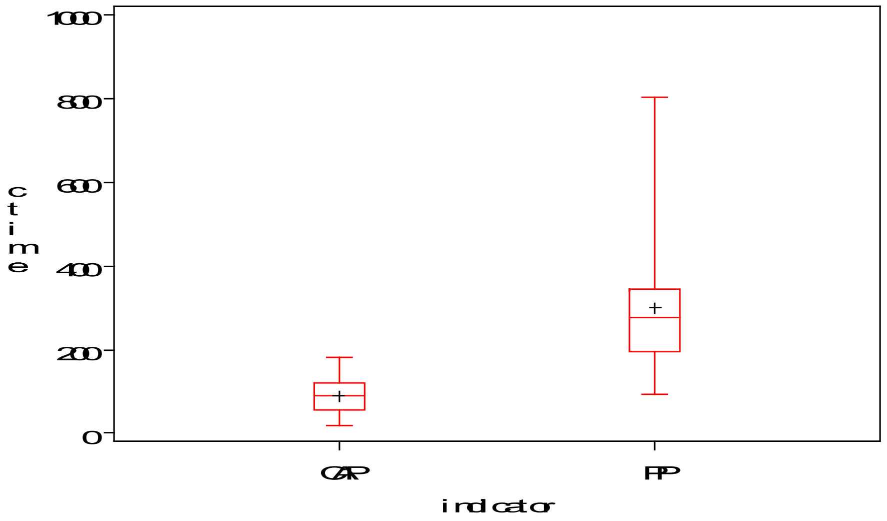


Figure 4.33: Box plot (Combined CAP Vs PP Coding Time)

4.7.4.3. Statistical Test Determination for the Combined CAP Vs PP Data

The sample size was 36 (18 experiments completed by PP groups plus 18 experiments completed by CAP groups). Since the sample size was small, we used t-Tests to compare the CAP groups' means with the PP groups' means.

Our sample size was 36, the total development time followed normal distribution, and there were no outliers. Consequently Student's t-Test was used to compare the CAP total software development time means with the PP total software development time means. Since the coding time data was not normally distributed. The Wilcoxon Mann-Whitney U test was used to compare the CAP coding time means with the PP coding time means.

4.7.4.4. Total Software Development Time (Hypothesis 1)

The total software development time for PP group and CAP group are shown in Table 4.6. The PP groups took 444 minutes in average for Problem1, 465 minutes in average for Problem2, and 300 minutes in average for Problem3; whereas, the CAP groups took only 182 minutes (59% less than PP groups) in average for Problem1, 200 minutes (57% less than PP groups) in average for Problem2, and 218 minutes (27% less than PP groups) in average for Problem3. The average time taken to solve all the three problems is 1209 minutes for PP groups and 600 minutes (50% less than PP groups) for CAP groups.

Method	Problem1	Problem2	Problem3
CAP-G1	180	275	120
CAP-G2	148	189	273
CAP-G3	171	160	204
CAP-G4	159	200	311
CAP-G5	210	122	156
CAP-G6	222	254	240
Average	**182**	**200**	**218**
PP-G1	250	488	272
PP-G2	342	346	256
PP-G3	264	504	140
PP-G4	592	544	312
PP-G5	350	480	510
PP-G6	866	428	310
Average	**444**	**465**	**300**

Table 4.6: Total Software Development Time (Combined CAP Vs PP)

Figure 4.34 shows the average time taken by PP groups and CAP groups for the total software development for the given three problems.

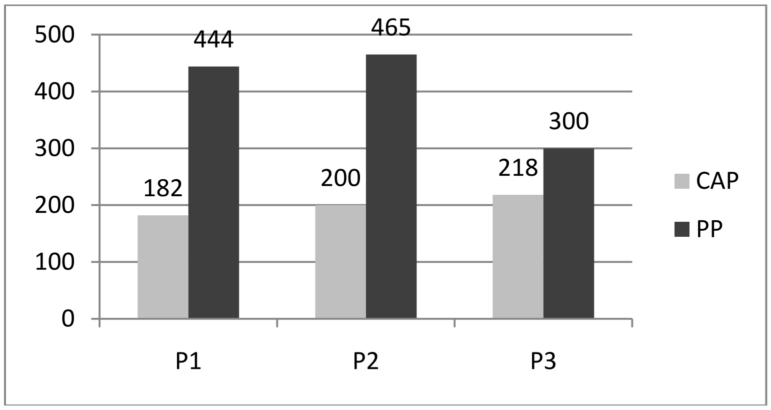


Figure 4.34: Average Total Software Development Time (Combined CAP Vs PP)

The box plot in Figure 4.35 shows the total time taken by all 36 pairs (6x3 programs completed by PP groups and 6x3 programs completed by CAP groups). *The plot indicates that all the nine CAP programs took less time than the least value of the PP program groups.*

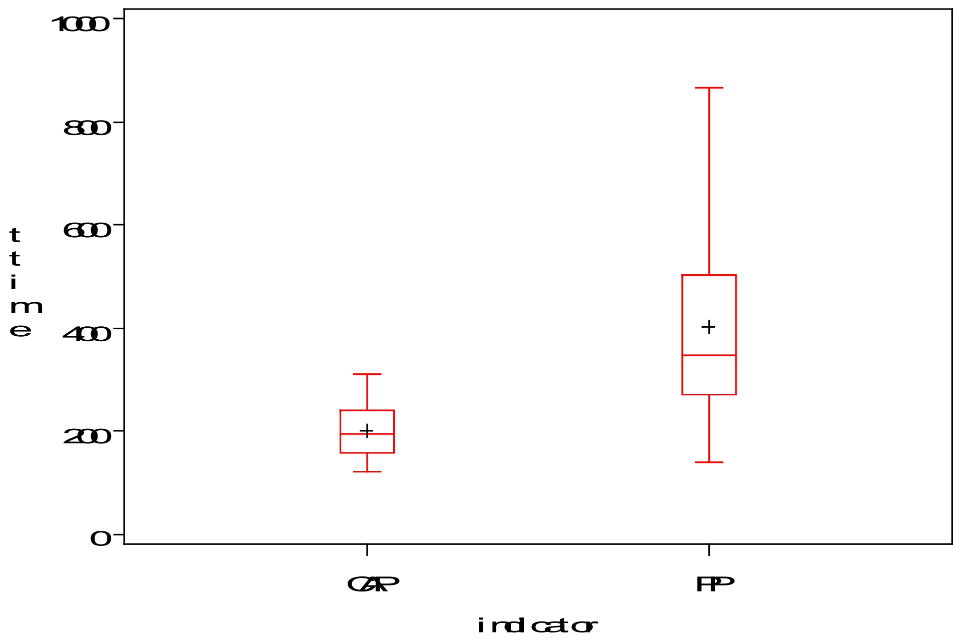


Figure 4.35: Box Plot (Combined CAP Vs PP Total Software Development Time)

The Student's t-Test results are shown in Figure 4.36. The p-value in the equality of variances test is significant in the 5% significant level (p<0.05), which indicates that the data has unequal variance, so we have to take the unequal variance t-Test result, which is P<0.0001(2 sided t-value). Since P<0.05, there is insufficient support for the hypothesis $H0_1$ that the overall software development cost or time of CAP is equal or higher that PP in average.

```
                                       The TTEST Procedure

                                          Statistics

                                Lower CL          Upper CL  Lower CL            Upper CL
Variable  indicator       N       Mean      Mean      Mean   Std Dev  Std Dev   Std Dev  Std Err

ttime     CAP            18     172.66  199.67    226.68    40.759   54.317    81.429   12.803
ttime     PP             18      319.2     403     486.8    126.45   168.52    252.63    39.72
ttime     Diff (1-2)            -288.1  -203.3    -118.5    101.27    125.2    164.03   41.733


                                           T-Tests

             Variable     Method           Variances      DF     t Value     Pr > |t|

             ttime        Pooled           Equal          34       -4.87       <.0001
             ttime        Satterthwaite    Unequal      20.5       -4.87       <.0001


                                     Equality of Variances

                 Variable     Method      Num DF     Den DF     F Value     Pr > F

                 ttime        Folded F        17         17        9.63    <.0001
```

Figure 4.36: t-Test Results (Combined CAP Vs PP Total Software Development Time)

Decision: Reject $H0_1$ in favor of Ha_1 since p-value < α (α=0.05). Thus we have sufficient statistical evidence to conclude that the overall software development cost or time of CAP is less than PP in average.

4.7.4.5. Coding Time (Hypothesis 3)

The coding time for PP groups and CAP groups are shown in Table 4.7. The PP groups took 315 minutes in average for Problem1, 340 minutes in average for Problem2, and 238 minutes in average for Problem3; whereas, the CAP groups took only 73 minutes (77% less than PP groups) in average for Problem1, 85 minutes (75% less than PP groups) in average for Problem2, and 111 minutes (53% less than PP groups) in average for Problem3. The average time taken to solve all the three problems was 893 minutes for PP groups and 269 minutes (70% less than PP groups) for CAP groups.

Method	Problem1	Problem2	Problem3
CAP-G1	38	55	51
CAP-G2	91	61	98
CAP-G3	65	40	89
CAP-G4	18	113	124
CAP-G5	132	77	121
CAP-G6	94	161	180
Average	**73**	**85**	**111**
PP-G1	92	272	194
PP-G2	320	346	196
PP-G3	164	494	120
PP-G4	308	242	218
PP-G5	200	380	420
PP-G6	804	336	280
Average	**315**	**340**	**238**

Table 4.7: Coding Time (Combined CAP Vs PP)

Figure 4.37 shows the average time taken by PP groups and CAP groups for the coding phase of the software development for the given three problems.

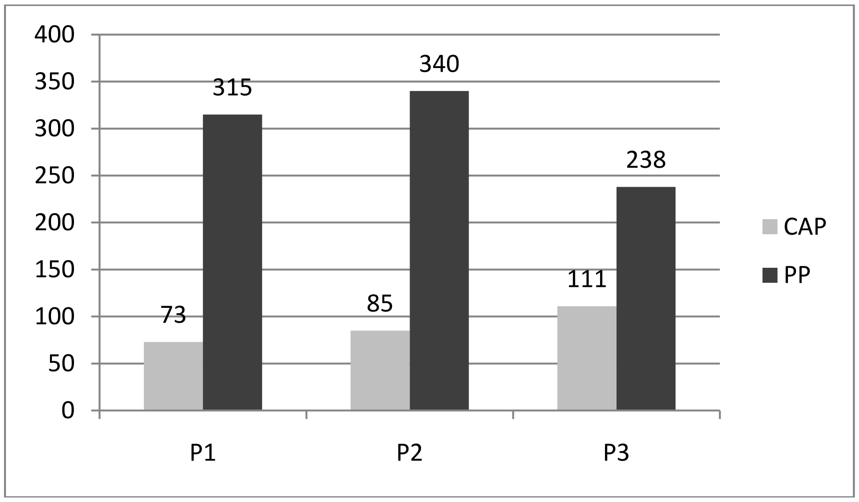


Figure 4.37: Average Coding Time (Combined CAP Vs PP)

The box plot in Figure 4.38 shows the coding time taken by all 36 pairs (6x3 programs completed by PP group and 6x3 programs completed by CAP group). *The plot indicates that all the nine CAP programs took less time than 75% PP programs.*

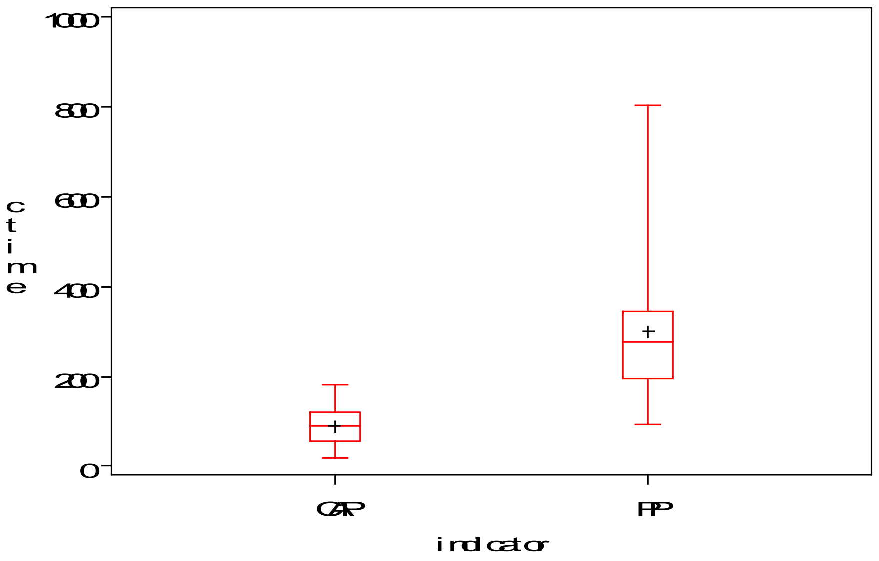


Figure 4.38: Box plot (Combined CAP Vs PP Coding Time)

The Wilcoxon Mann-Whitney U test results are shown in Figure 4.39. The p value is <0.0001 (2 sided t-value). Since p<0.05, there is insufficient support for the hypothesis $H0_3$ that the cost of the CAP coding phase is equal or higher that PP coding phase in average.

```
                    Wilcoxon Two-Sample Test

            Statistic (S)                185.0000

            Normal Approximation
            Z                             -4.6667
            One-Sided Pr <  Z              <.0001
            Two-Sided Pr > |Z|             <.0001

            t Approximation
            One-Sided Pr <  Z              <.0001
            Two-Sided Pr > |Z|             <.0001

            Exact Test
            One-Sided Pr <=  S          5.598E-08
            Two-Sided Pr >= |S - Mean|  1.120E-07

          Z includes a continuity correction of 0.5.
```

Figure 4.39: Wilcoxon Mann-Whitney U test Result (Combined CAP Vs PP Coding Time)

Decision: Reject $H0_3$ in favor of Ha_3 since p-value < α (α=0.05). Thus we have sufficient statistical evidence to conclude that the cost of CAP coding phase is less than the cost of PP coding phase in average.

4.7.5. CAP Vs IP Test Results

4.7.5.1. Test for Normality

Figures 4.40 and 4.41 show the Q-Q plot of residuals for the total software development time and coding time, respectively. The points on the Q-Q plots of residuals lie nearly on the straight line, which indicates that both the total software development time and the coding time data follows normal distribution.

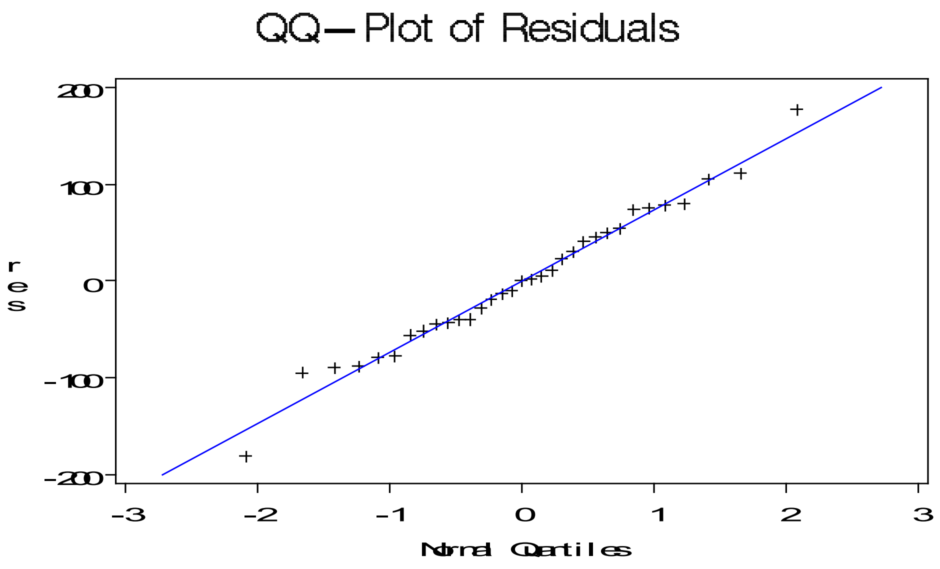


Figure 4.40: Q-Q Plot of Residuals (CAP Vs IP Total Software Development Time)

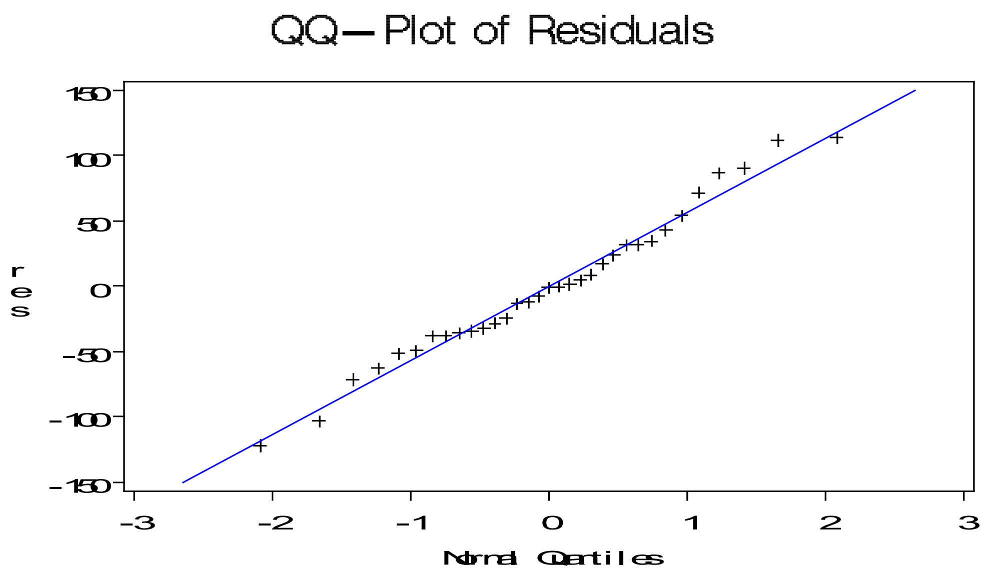


Figure 4.41: Q-Q Plot of Residuals (CAP Vs IP Coding Time)

Figures 4.42 and 4.43 show the results of the SAS's "GLM procedure with BF option" for total software development time and coding time, respectively. In both Figure 4.42 and 4.43 the p value of all experiments are insignificant at 5% significant level (p>0.05), which indicates that statistically there is no significant evidence to reject the normality; i.e., both the overall software development time and the coding time data follows normal distribution.

```
                     Tests for Normality

Test                  --Statistic---    -----p Value------

Shapiro-Wilk          W      0.98787    Pr < W      0.9667
Kolmogorov-Smirnov    D     0.068654    Pr > D     >0.1500
Cramer-von Mises      W-Sq  0.021278    Pr > W-Sq  >0.2500
Anderson-Darling      A-Sq  0.176827    Pr > A-Sq  >0.2500
```

Figure 4.42: Test for Normality (CAP Vs IP Total Software Development Time)

```
                          Tests for Normality

Test                  --Statistic---    -----p Value------

Shapiro-Wilk          W     0.980243    Pr < W      0.7936
Kolmogorov-Smirnov    D     0.075714    Pr > D     >0.1500
Cramer-von Mises      W-Sq  0.036181    Pr > W-Sq  >0.2500
Anderson-Darling      A-Sq   0.24686    Pr > A-Sq  >0.2500
```

Figure 4.43: Test for Normality (CAP Vs IP Coding Time)

4.7.5.2. Outliers

The box plots for the total software development time and coding time are given in Figure 4.44 and 4.45 respectively. There are no circles in Figures 4.44 and 4.45, which indicates that there are no outliers either in PP's overall software development time and coding time or in CAP's overall software development time and coding time.

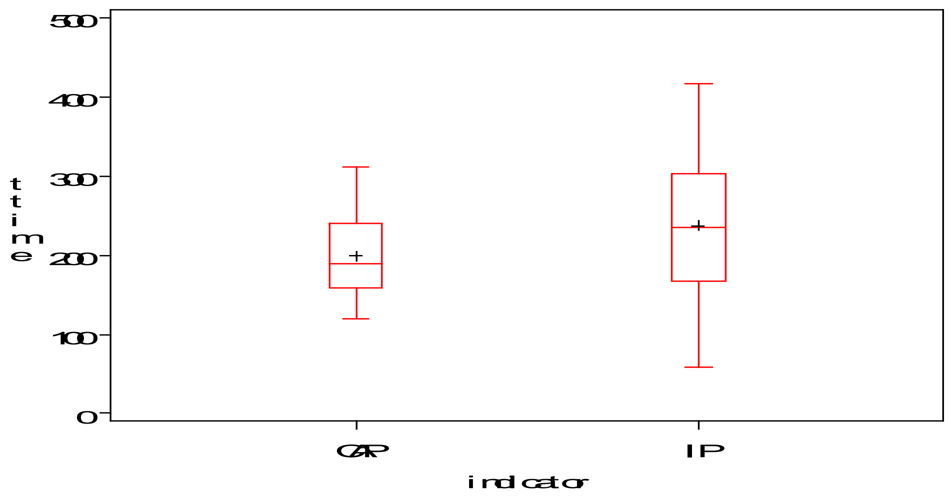


Figure 4.44: Box plot (CAP Vs IP Total Software Development Time)

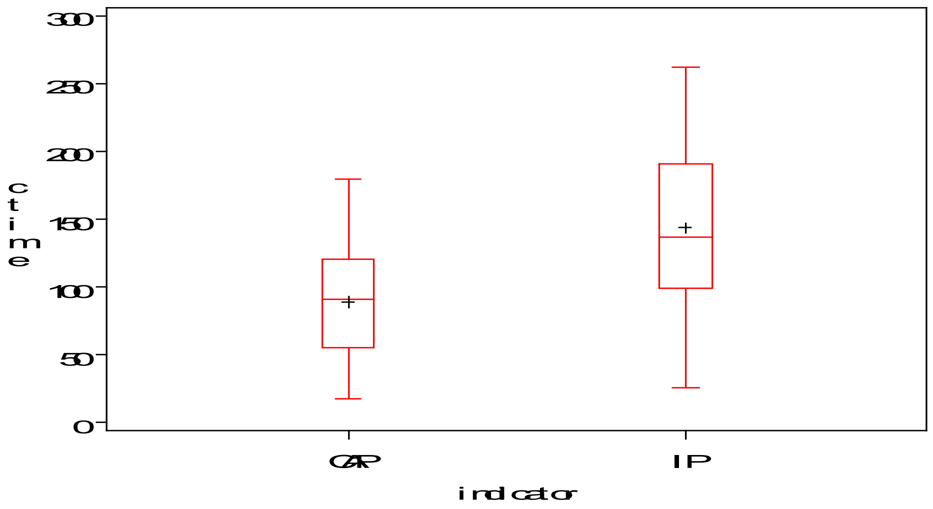


Figure 4.45: Box plot (CAP Vs IP Coding Time)

4.7.5.3. Statistical Test Determination for the CAP VS IP Data

The sample size was 33 (15 experiments completed by IP groups plus 18 experiments completed by CAP groups). Since the sample size was small, we used Student's t-Tests to compare the CAP groups' means with the IP groups' means.

Our sample size was 33, and both total development time and coding time followed normal distribution, and there were no outliers. Consequently, Student's t-Test was identified as suitable for comparing both the CAP total software development time means with the IP total software development time means, and the CAP coding time means with the IP coding time means.

4.7.5.4. Total Software Development Time (Hypothesis 2)

The total software development time for the IP groups and the CAP groups are shown in Table 4.8. The IP groups took 233 minutes in average for Problem1, 280 minutes in average for Problem2, and 207 minutes in average for Problem3; whereas, the CAP groups took only 182 minutes (22% less than IP groups) in average for Problem1, 200 minutes (29% less than IP groups) in average for Problem2, and 218 minutes (5% more than IP groups) in average for Problem3. The average time taken to solve all the three problems is 720 minutes for the IP groups and 600 minutes (17% less than IP groups) for CAP groups.

Method	**Problem1**	**Problem2**	**Problem3**
CAP-G1	180	275	120
CAP-G2	148	189	273
CAP-G3	171	160	204
CAP-G4	159	200	311
CAP-G5	210	122	156
CAP-G6	222	254	240
Average	**182**	**200**	**218**
IP-G1	318	227	150
IP-G2	184	417	345
IP-G3	152	290	59
IP-G4	270	145	195
IP-G5	242	320	285
Average	**233**	**280**	**207**

Table 4.8: Total Software Development Time (CAP Vs IP)

Figure 4.46 shows the average time taken by PP groups and CAP groups for the total software development for the given three problems.

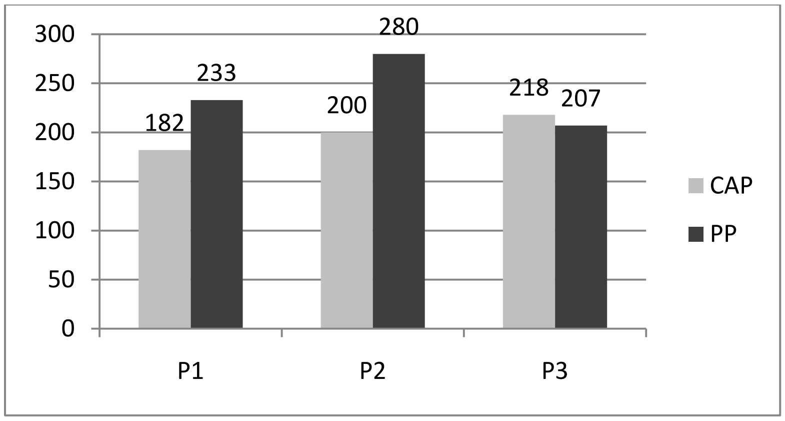


Figure 4.46: Average Total Software Development Time (CAP Vs IP)

The box plot in Figure 4.47 shows the total time taken by all 33 programs (5x3 programs completed by IP groups and 6x3 programs completed by CAP groups).

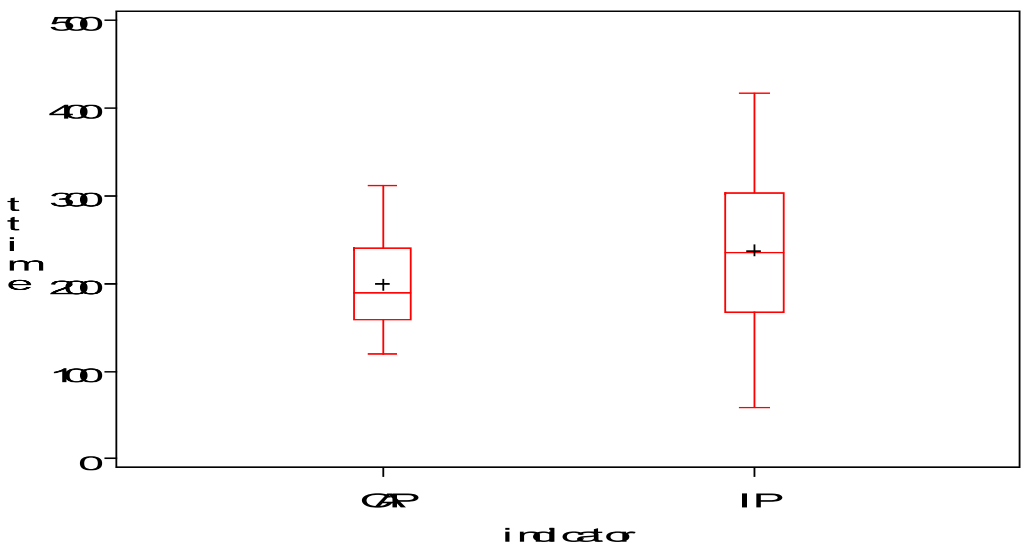


Figure 4.47: Total Software Development Time (CAP Vs IP)

The Student's t-Test results are shown in Figure 4.48. The p-value in the equality of variances test is not significant in the 5% significant level (p>0.05), which indicates that the data has equal variance, so we have to take the equal variance t-Test result, which is p=0.1532 (2 sided t-value). Since p>0.05, there is sufficient support for the hypothesis $H0_2$ that the overall software development cost or time of CAP is equal or higher that IP in average.

Decision: Do Reject $H0_2$ in favor of Ha_2 since p-value > α (α=0.05). Thus we do not have sufficient statistical evidence to conclude that the overall software development cost or time of CAP is less than IP in average.

```
                                       The TTEST Procedure
                                            Statistics

                                  Lower CL             Upper CL  Lower CL             Upper CL
Variable  indicator        N        Mean      Mean       Mean   Std Dev   Std Dev    Std Dev   Std Err

ttime     CAP             17      170.63    199.41     228.19    41.691    55.978     85.194    13.577
ttime     IP              16      189.15    237.69     286.22    67.282    91.081     140.97     22.77
ttime     Diff (1-2)              -91.59    -38.28     15.034    60.162    75.043     99.768    26.139

                                       T-Tests

             Variable    Method           Variances      DF     t Value     Pr > |t|

             ttime       Pooled           Equal          31       -1.46      0.1532
             ttime       Satterthwaite    Unequal      24.6       -1.44      0.1614

                                 Equality of Variances

                 Variable    Method       Num DF     Den DF     F Value    Pr > F

                 ttime       Folded F         15         16        2.65    0.0622
```

Figure 4.48: t-Test Results (CAP Vs IP Total Software Development Time)

4.7.5.5. Coding Time (Hypothesis 4)

The coding time for IP group and CAP group are shown in Table 4.9. The IP groups took 124 minutes in average for Problem1, 183 minutes in average for Problem2, and 137 minutes in average for Problem3; whereas, the CAP groups took only 73 minutes (41% less than IP groups) in average for Problem1, 85 minutes (54% less than IP groups) in average for Problem2, and 111 minutes (19% less than IP groups) in average for Problem3. The average time taken to solve all the three problems was 444 minutes for IP groups and 269 minutes (39% less than IP groups) for CAP groups.

Method	Problem1	Problem2	Problem3
CAP-G1	38	55	51
CAP-G2	91	61	98
CAP-G3	65	40	89
CAP-G4	18	113	124
CAP-G5	132	77	121
CAP-G6	94	161	180
Average	**73**	**85**	**111**
IP-G1	112	116	85
IP-G2	26	165	235
IP-G3	147	262	45
IP-G4	135	110	140
IP-G5	202	260	180
Average	**124**	**183**	**137**

Table 4.9: Coding Time (CAP Vs IP)

Figure 4.49 shows the average time taken by IP groups and CAP groups for the coding phase of the software development for the given three problems.

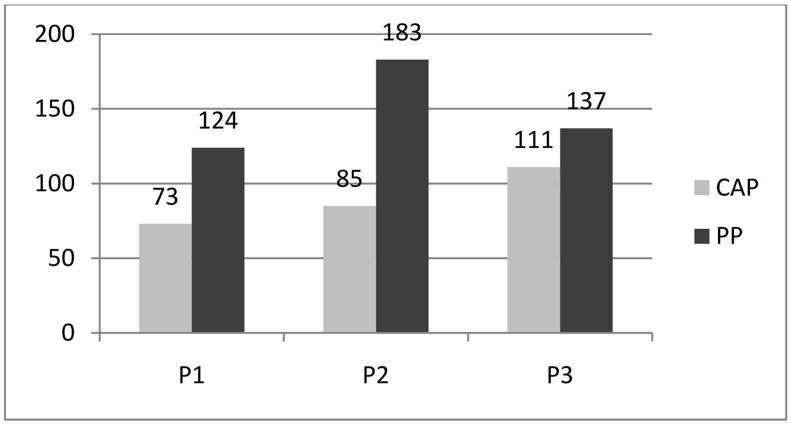


Figure 4.49: Average Coding Time (CAP Vs IP)

The box plot in Figure 4.50 shows the coding time taken by all 33 programs (5x3 programs completed by IP groups and 6x3 programs completed by CAP groups). *The plot indicates that all the nine CAP programs took less time than the 25% IP programs.*

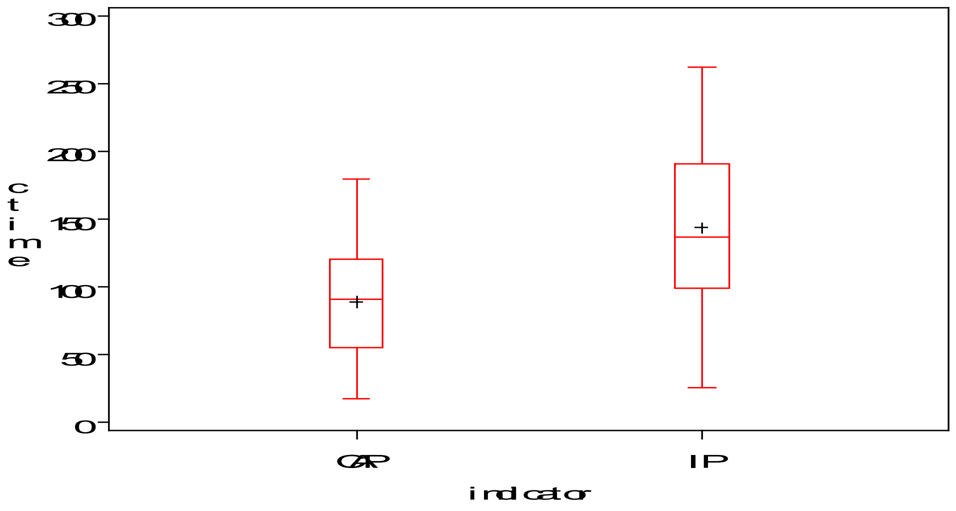


Figure 4.50: Box plot (CAP Vs IP Coding Time)

The Student's t-Test results are shown in Figure 4.51. The p-value in the equality of variances test is not significant in the 5% significant level (p>0.05), which indicates that the data has equal variance, so we have to take the equal variance t-Test result, which is p=0.0113 (2 sided t-value). Since p<0.05, there is insufficient support for the hypothesis $H0_4$ that the cost of the CAP coding phase is equal or higher that IP coding phase in average.

```
                                          The TTEST Procedure

                                              Statistics
                                 Lower CL             Upper CL   Lower CL              Upper CL
Variable   indicator         N       Mean      Mean       Mean    Std Dev   Std Dev     Std Dev   Std Err

ctime      CAP              17     66.218    89.353     112.49     33.511    44.996       68.48    10.913
ctime      IP               16     106.87    144.31     181.76     51.906    70.267      108.75    17.567
ctime      Diff (1-2)               -96.59    -54.96     -13.33      46.98    58.601      77.908    20.412

                                         T-Tests
             Variable     Method           Variances       DF     t Value     Pr > |t|

             ctime        Pooled           Equal           31       -2.69       0.0113
             ctime        Satterthwaite    Unequal       25.3       -2.66       0.0135

                                  Equality of Variances

                 Variable     Method       Num DF     Den DF     F Value     Pr > F

                 ctime        Folded F         15         16        2.44     0.0868
```

Figure 4.51: t-Test Results (CAP Vs IP Coding Time)

Decision: Reject $H0_4$ in favor of Ha_4 since p-value < α (α=0.05). Thus we have sufficient statistical evidence to conclude that the cost of CAP coding phase is less than the cost of IP coding phase in average.

4.7.6. Results Summary

To test the first four hypotheses, i.e., for comparing both the average CAP total software development time with the PP total software development time, and the average CAP coding time with the PP coding time, Student's t-test or Mann-Whitney U test was used. If the data follows a normal distribution and there were no outliers, then we used Student's t-test; otherwise we used Mann-Whitney U test. To test the fifth hypothesis, i.e., comparing the CAP groups program correctness with the PP groups program correctness, we simply compared the number of post-developed test cases passed by programs developed by each group.

4.7.6.1. Total Software Development Time

$H0_1$ (The overall software development cost of CAP is equal or higher than PP in average): For the dynamic pairs (i.e., the control experiment conducted in Fall 2008), the static pairs (i.e., the control experiment conducted in Spring 2009), and combined data the hypothesis 1 was not supported with p=0.0129, p=0.0011, and p<0.0001 respectively. Thus we have sufficient statistical evidence to accept the alternative hypothesis that the overall software development cost or time of CAP is less than PP in average.

The average time taken to solve all the three problems is 954 minutes for the Dynamic Pairs PP groups and 573 minutes (40% less than PP) for the Dynamic Pairs CAP groups. The average number of acceptance test passed by Dynamic Pairs PP groups' programs is 59/72

(82%); whereas, the average number of acceptance test passed by Dynamic Pairs CAP groups' programs is 66/72 (92%). Moreover, all the nine Dynamic Pairs CAP programs took less time than the mean value of the Dynamic Pairs PP programs.

The average time taken to solve all the three problems is 1464 minutes for the Static Pairs PP groups and 625 minutes (57% less than PP) for the Static Pairs CAP groups. Moreover, all the nine Static Pairs CAP programs took less time than the least value of the Static Pairs PP program groups.

$H0_2$ (The overall software development cost of CAP is equal or higher than individual programming in average): The hypothesis is supported with p=0.1532. Thus we have sufficient support for the null hypothesis to conclude that the overall software development cost or time of CAP is equal or greater than IP in average.

The average coding time taken to solve all the three problems is 720 minutes for IP groups and 600 minutes (17% less than IP) for CAP groups.

4.7.6.2. Coding Time

$H0_3$ (The cost of CAP coding phase is equal or higher than the cost of PP coding phase in average): For the dynamic pairs (i.e., the control experiment conducted in Fall 2008), the static pairs (i.e., the control experiment conducted in Spring 2009), and combined data the hypothesis 1 was not supported with p=0.0028, p=0.0026, and p<0.0001 respectively. Thus we have sufficient statistical evidence to accept the alternative hypothesis that the coding phase cost or time of CAP is less than PP in average.

The average coding time taken to solve all the three problems is 733 minutes for Dynamic Pairs PP groups and 196 minutes (73% less than PP) for Dynamic Pairs CAP groups. Moreover, all the nine Dynamic Pairs CAP programs coding time took less than 75% Dynamic Pairs PP programs coding time.

The average coding time taken to solve all the three problems is 1062 minutes for Static Pairs PP groups and 340 minutes (68% less than PP) for Static Pairs CAP groups. Moreover, all the nine Static Pairs CAP programs coding time took less than the least value of the Static Pairs PP programs coding time.

$H0_4$ (The cost of CAP coding phase is equal or higher than the cost of individual programming coding phase in average): The hypothesis is not supported with p=0.0113. Thus we have sufficient statistical evidence to accept the alternative hypothesis that the coding phase cost or time of CAP is less than IP in average.

The average time taken to solve all the three problems was 444 minutes for IP groups and 269 minutes (39% less than IP) for CAP groups.

4.7.6.3. Program Correctness

$H0_5$ (The number acceptance tests failed in CAP is equal or higher than the number of acceptance tests failed in PP in average): The number of acceptance tests failed in CAP is less than the number of acceptance tests failed in PP. Therefore, there is insufficient support for the hypothesis. Hence we accept the alternative hypothesis that the number acceptance tests failed in CAP is less than the number of acceptance tests failed in PP in average.

A summary of the four control experiments and their results are given in Table 4.10.

Control Experiments	**Null Hypothesis**	**Sample Size**	**Data Properties**	**Statistical Test**	**Result**	**Reject?**
Control Experiment-1 (CAP Vs PP, Dynamic Pairs, Fall 2008)	$H0_1$ (Time/$Cost_{Overall}$)	18	Normal Unequal Variance No Outliers	Student t-Test	p=0.0129	Yes
	$H0_3$ (Time/$Cost_{Coding}$)		Normal Unequal Variance No Outliers	Student t-Test	p=0.0028	Yes
	$H0_5$ (Correctness)		Not Applicable	None	Number of Acceptance Test cases failed in CAP is less than PP	Yes
Control Experiment-2 (CAP Vs PP, Static Pairs, Spring 2009)	$H0_1$ (Time/$Cost_{Overall}$)	18	Normal Unequal Variance No Outliers	Student t-Test	p=0.0011	Yes
	$H0_3$ (Time/$Cost_{Coding}$)		Not Normal Unequal Variance No Outliers	Mann-Whitney U Test	p=0.0026	Yes
Combined CAP Vs PP	$H0_1$ (Time/$Cost_{Overall}$)	36	Normal Unequal Variance No Outliers	Student t-Test	p<0.0001	Yes
	$H0_3$ (Time/$Cost_{Coding}$)		Not Normal Unequal Variance No Outliers	Mann-Whitney U Test	p<0.0001	Yes
CAP Vs IP	$H0_2$ (Time/$Cost_{Overall}$)	33	Normal Equal Variance No Outliers	Student t-Test	p=0.1532	No
	$H0_4$ (Time/$Cost_{Coding}$)		Normal Equal Variance No Outliers	Student t-Test	p=0.0113	Yes

Table 4.10: Summary of Control Experiments and their Results

4.8. Observations

We have implemented two different strategies of pairing during the control experiment. In Fall 2008, we adopted the dynamic pairing technique and in Spring 2009, we adopted the static pairing technique (see section 4.6 for more detail about dynamic and static pairing). During this one year period, the subjects completed 105 problems. Here are some interesting observations we have made during this period:

1) Existing empirical evidence [Williams et al. 2000], shows that the overall software development time or cost of pair programmers is at the highest in the beginning of the project due to pair-jelling, and decreases considerably as the project progresses. The dynamic pairs' pair programming experiment's empirical evidence shows that no regularity in the development of the productivity rates or decrease in development time could be detected between projects; whereas, we observed an improvement in productivity or decrease in development time (see Figure 4.52), for Static Pairs due to the pair-jelling effect as the project progressed.

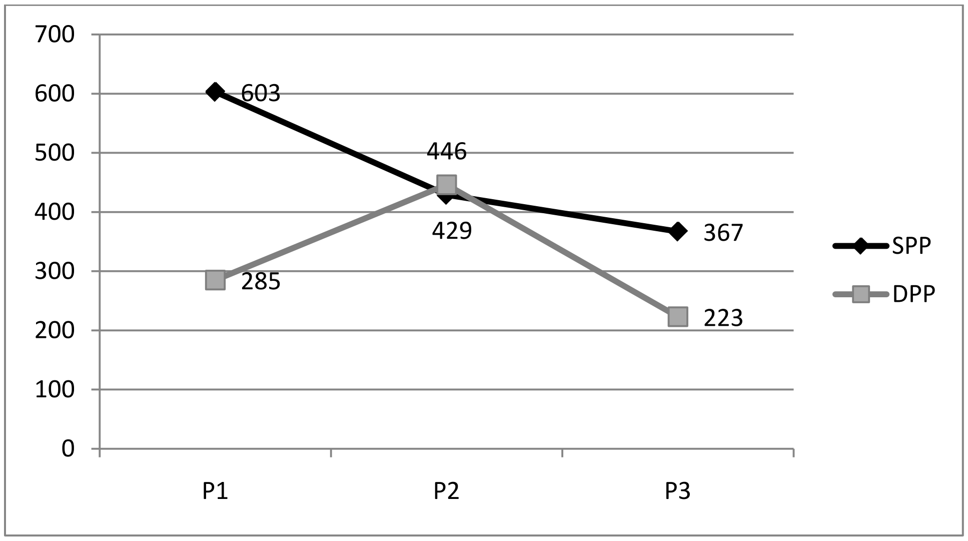


Figure 4.52: Average Software Development Time for Static PP and Dynamic PP

2) The static PP helps the programmers to solve routine or similar kinds of problems (Problem1 and Problem2 in our case) faster than dynamic PP programmers as shown in Figure 4.52. But, the dynamic pairing (both the dynamic PP and the dynamic CAP) helps the programmers to solve a new kind of problem (problem 3 in our case) faster than its static counterpart. This we can observe from Figure 4.52 and Figure 4.53.

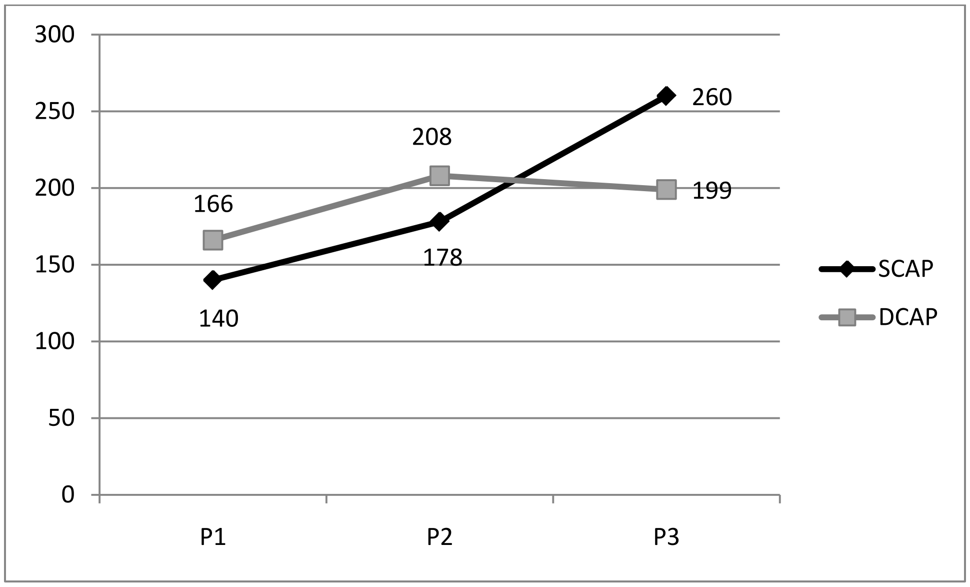


Figure 4.53: Average Software Development Time for Static CAP and Dynamic CAP

3) The productivity of the dynamic PP groups is better than static PP groups. The average time taken to solve all three problems for dynamic PP groups is 954 minutes; whereas, it took 1399 minutes (32% more than dynamic PP groups) for static PP groups. At the same time, we did not observe any difference in productivity between static CAP groups and dynamic CAP groups; the average time taken to solve all three problems for dynamic CAP groups and static CAP groups is 573 minutes and 578 minutes respectively.

4) One of the major benefits of collaborative programming is pair-pressure [Williams et al. 2000]. During the entire control experiment period we observed the existence of pair-pressure among both the CAP programmers and the pair programmers. When they met both partners worked intensively and were motivated to complete their assigned task within the specified time period. This motivation was lagging with individual programmers; some individual programmers even withdrew in the middle of the experiment. At the same time, we did not observed any gain in productivity and/or quality improvements by the pair programmers due to pair-pressure as indicated by [Williams et al. 2000].

5) We have observed that the pairs in CAP discuss more in design time and create concrete designs in contrast to their PP counterparts. The pairs in CAP also know that after the design phase they will play on adversarial role in the implementation stage (the goal of the implementer is to build working software, whereas the goal of the tester is to break the software in CAP). We believe this forces them to discuss more in the design stage before moving to the implementation stage. Since the PP developers know that they are going to have a partner throughout the entire development phases, we feel that the confidence of having a partner in the development stage turns into overconfidence and they do not discuss much in the design stage. Furthermore, this overconfidence leads to a design that is not concrete which in turn, causes them to change their design more often in the coding phase and spend 50% more time than their CAP counter parts.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

In this research we have proposed a new stable and reliable agile software development methodology called Collaborative-Adversarial Pair (CAP) programming. We see CAP as an alternative to traditional pair programming in situations where pair programming is not beneficial or is not possible to practice. The CAP was evaluated against traditional pair programming and individual programming in terms of productivity and program correctness. The empirical evidence shows that traditional pair programming is an expensive technology and does not necessarily produce programs with better quality as claimed by the pair programming advocates.

The empirical evidence shows that better quality programs can be produced in 40% less time using the dynamic pairs CAP programming technique than the dynamic pair programming technique, better or equal quality programs can be produced in 57% less time using the static pairs CAP programming technique than the static pair programming technique, and overall, better or equal quality programs can be produced with a much cheaper cost (50% less overall software development time than traditional PP) using the CAP programming technique. The empirical evidence also shows that CAP is a cheaper technology than individual programming; using CAP we can produce programs of equal or better quality with 17% reduction in overall software development cost on average.

The empirical evidence shows that better or equal quality code can be produced in 73% less time using the dynamic pairs CAP programming technique than the dynamic pair programming technique, better or equal quality code can be produced in 68% less time using the static pairs CAP programming technique than the static pair programming technique, and overall, better or equal quality code can be produced with a much cheaper cost (70% less than traditional PP) using CAP programming technique. The empirical evidence also shows that CAP is a cheaper technology than individual programming; using CAP we can produce code of equal or better quality with 39% reduction in coding cost on average.

It is expected that CAP will retain the advantages of pair programming while at the same time downplaying the disadvantages. In CAP, units are implemented by single developers (whereas two developers are developing a unit in pair programming) and functional test cases can be developed in parallel with unit implementation. This, in turn, reduces the overall project development interval. The CAP testing procedure judiciously combines the functional (black box) and structural (white box) testing, which provides the software with the confidence of functional testing and the measurement of structural testing. The CAP allows us to confidently test and add the purchased or contracted software modules to the existing software. Finally, the functional test cases in the CAP allow us to change the implementation without changing the test cases and vice-versa.

5.2. Future Work

- The external validity, the ability of the experimental results to apply to the world outside the research environment – over variations in persons, settings, treatments, and outcomes, of the empirical research design is very important for any research study. We have carefully planned our CAP validation to meet these external validity requirements. Though the software development environment provided by us closely matches the industrial software development environment, clearly the experimental system and tasks in this experiment were small compared with industrial software systems and tasks. Therefore, we cannot rule out the possibility that the observed results would have been different if the system and tasks had been larger. Hence, validation of the results with professional programmers in an industrial setting would be beneficial.
- We aim to design, build, and test a stable and reliable new agile software development methodology called *Team Collaborative-Adversarial Pair (TCAP) Programming*, which is suitable for the software development teams. To achieve our goal, we employ the CAP process as a basic building block to design and build the TCAP.
- Currently we have integrated and validated the CAP methodology into the Extreme Programming process. In the future, we are planning to integrate the CAP into the other agile development methodologies as well.
- We are also planning to develop tool set to support CAP methodology.

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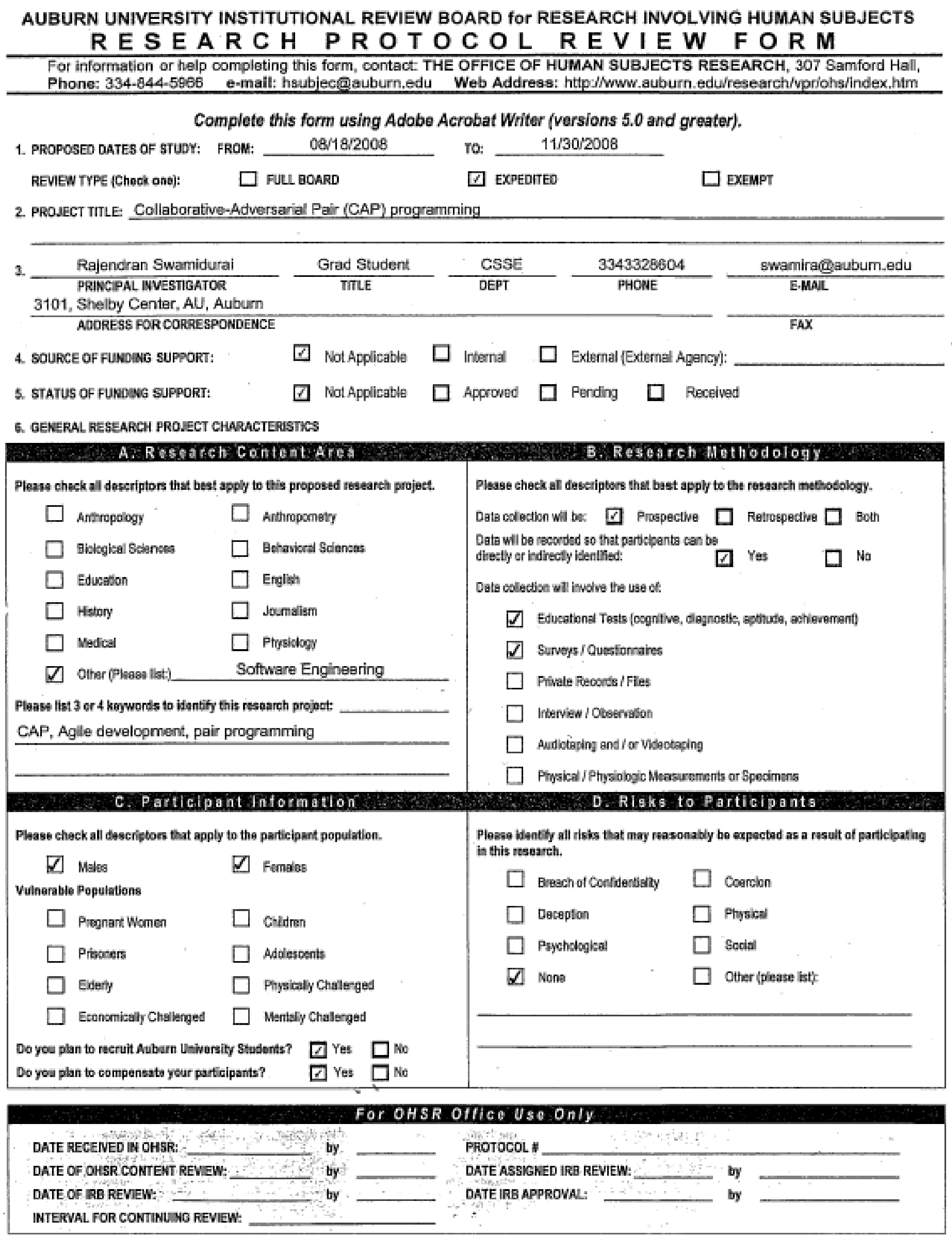
Appendix-A

Pair Programming Experiments Analyzed

S. No	Study	Year	Selected?	Comments
1	Wilson et al. [Wilson et al., 1993]	1993	Y	
2	Nosek [Nosek, 1998]	1998	Y	
3	Williams et al. [Williams et al., 2000]	1999	Y	
4	Nawrocki and Wojciechowski [Nawrocki et al., 2001]	1999/ 2000	Y	
5	McDowell et al [McDowell et al., 2002]	2000/ 2001	Y	
6	Baheti et al.	2002	N	Distributed PP experiment
7	Rostaher et al.	2002	Y	
8	Heiberg et al.	2003	N	Not PP Vs Solo experiment, it is a PP VS 2 person team experiment
9	Canfora et al.	2007	N	Design phase only
10	Müller [Muller, 2005]	2002/ 2003	Y	
11	Vanhanen and Lassenius [Vanhanen et al., 2005]	2004	Y	
12	Madeyski	2006	N	Design phase only
13	Müller [Muller 2006]	2005	Y	
14	Monvorath et al.	2004, 2005	N	Compares the PP Vs Inspection techniques practiced only in Thailand.
15	Xu and Rajlich [Xu et al., 2006]	2005, 2006	Y	
16	Canfora et al.	2005	N	Each subjects performed both PP and solo programming alternatively
17	Arisholm et al. [Arisholm et al., 2007]	2001, 2004/ 2005	Y	
18	Hulkko and Abrahamson [Hulkko et al, 2005]	2004	Y	
19	Lui and Chan [Lui et al. 2006]	2005	N	Repeat experiment compares Novice-Novice pairs against Expert-Expert pairs.
20	Jensen	1996	N	Not PP Vs Solo experiment, only pairs experiment
21	Mendes et al.	2005	N	PP used as a teaching tool
22	Carver et al.	2007	N	PP used as a teaching tool
23	Carole and Chou	2007	N	PP used as a teaching tool
24	Cliburn	2003	N	PP used as a teaching tool
25	Phongpaibul and Boehm	2006	N	Comparison of pair development and software inspection in Thailand
26	McDowell et al.	2003	N	PP used as a teaching tool
27	McDowell et al.	2003	N	PP used as a teaching tool
28	Cubranic and Storey	2005	N	Pairs of first year CS students used to evaluate a prototype
29	Hanks et al.	2004	N	PP used as a teaching tool
30	Gehringer	2003	N	PP used as a teaching tool
31	Nagappan et al.	2003	N	PP used as a teaching tool
32	Succi et al.	2001	N	Only job satisfaction analysis
33	Bellini et al.,	2005	N	Design phase only
34	Al-Kilidar et al.	2005	N	Design phase only
35	Canfora et al.	2006	N	Design phase only

APPENDIX-B

IRB Documents



AUBURN UNIVERSITY INSTITUTIONAL REVIEW BOARD for RESEARCH INVOLVING HUMAN SUBJECTS

RESEARCH PROTOCOL REVIEW FORM

For information or help completing this form, contact: THE OFFICE OF HUMAN SUBJECTS RESEARCH, 307 Samford Hall, Phone: 334-844-5966 e-mail: hsubjec@auburn.edu Web Address: http://www.auburn.edu/research/vpr/ohs/index.htm

Complete this form using Adobe Acrobat Writer (versions 5.0 and greater).

1. PROPOSED DATES OF STUDY: FROM: 08/18/2008 TO: 11/30/2008

REVIEW TYPE (Check one): FULL BOARD [✓ EXPEDITED] EXEMPT

2. PROJECT TITLE: Collaborative-Adversarial Pair (CAP) programming

3.

Rajendran Swamidurai	Grad Student	CSSE	3343328604	swamira@auburn.edu
PRINCIPAL INVESTIGATOR	TITLE	DEPT	PHONE	E-MAIL
3101, Shelby Center, AU, Auburn				
ADDRESS FOR CORRESPONDENCE				FAX

4. SOURCE OF FUNDING SUPPORT: [✓ Not Applicable] Internal External (External Agency): ______

5. STATUS OF FUNDING SUPPORT: [✓ Not Applicable] Approved Pending Received

6. GENERAL RESEARCH PROJECT CHARACTERISTICS

A. Research Content Area

Please check all descriptors that best apply to this proposed research project.

Anthropology	Anthropometry
Biological Sciences	Behavioral Sciences
Education	English
History	Journalism
Medical	Physiology
[✓ Other (Please list:)] Software Engineering	

Please list 3 or 4 keywords to identify this research project: CAP, Agile development, pair programming

B. Research Methodology

Please check all descriptors that best apply to the research methodology.

Data collection will be: [✓ Prospective] Retrospective Both

Data will be recorded so that participants can be directly or indirectly identified: [✓ Yes] No

Data collection will involve the use of:

- [✓ Educational Tests (cognitive, diagnostic, aptitude, achievement)]
- [✓ Surveys / Questionnaires]
- Private Records / Files
- Interview / Observation
- Audiotaping and / or Videotaping
- Physical / Physiologic Measurements or Specimens

C. Participant Information

Please check all descriptors that apply to the participant population.

[✓ Males] [✓ Females]

Vulnerable Populations

Pregnant Women	Children
Prisoners	Adolescents
Elderly	Physically Challenged
Economically Challenged	Mentally Challenged

Do you plan to recruit Auburn University Students? [✓ Yes] No

Do you plan to compensate your participants? [✓ Yes] No

D. Risks to Participants

Please identify all risks that may reasonably be expected as a result of participating in this research.

Breach of Confidentiality	Coercion
Deception	Physical
Psychological	Social
[✓ None]	Other (please list):

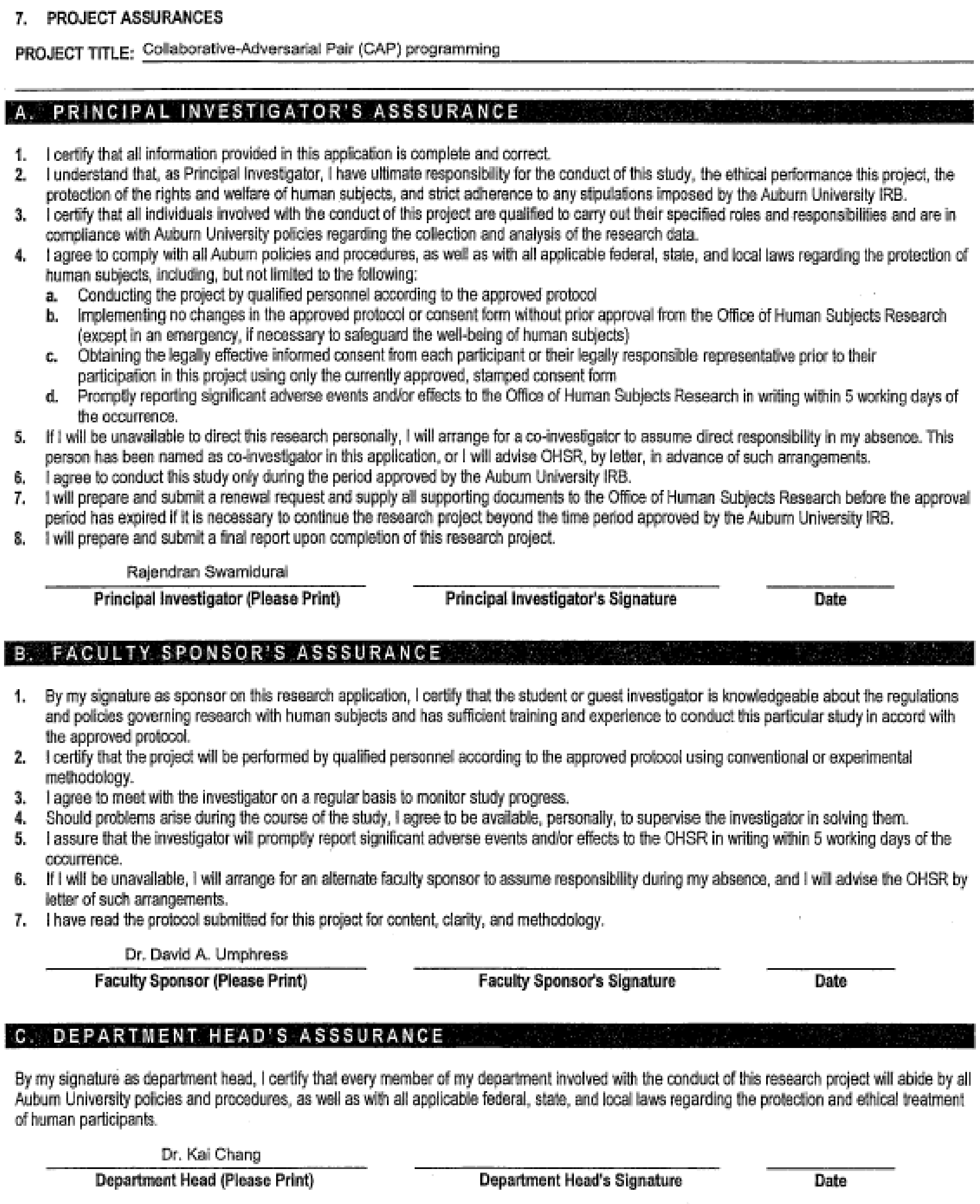
For OHSR Office Use Only

DATE RECEIVED IN OHSR: ______ by ______ PROTOCOL # ______

DATE OF OHSR CONTENT REVIEW: ______ by ______ DATE ASSIGNED IRB REVIEW: ______ by ______

DATE OF IRB REVIEW: ______ by ______ DATE IRB APPROVAL: ______ by ______

INTERVAL FOR CONTINUING REVIEW: ______



7. **PROJECT ASSURANCES**

PROJECT TITLE: Collaborative-Adversarial Pair (CAP) programming

A. PRINCIPAL INVESTIGATOR'S ASSSURANCE

1. I certify that all information provided in this application is complete and correct.
2. I understand that, as Principal Investigator, I have ultimate responsibility for the conduct of this study, the ethical performance this project, the protection of the rights and welfare of human subjects, and strict adherence to any stipulations imposed by the Auburn University IRB.
3. I certify that all individuals involved with the conduct of this project are qualified to carry out their specified roles and responsibilities and are in compliance with Auburn University policies regarding the collection and analysis of the research data.
4. I agree to comply with all Auburn policies and procedures, as well as with all applicable federal, state, and local laws regarding the protection of human subjects, including, but not limited to the following:
   a. Conducting the project by qualified personnel according to the approved protocol
   b. Implementing no changes in the approved protocol or consent form without prior approval from the Office of Human Subjects Research (except in an emergency, if necessary to safeguard the well-being of human subjects)
   c. Obtaining the legally effective informed consent from each participant or their legally responsible representative prior to their participation in this project using only the currently approved, stamped consent form
   d. Promptly reporting significant adverse events and/or effects to the Office of Human Subjects Research in writing within 5 working days of the occurrence.
5. If I will be unavailable to direct this research personally, I will arrange for a co-investigator to assume direct responsibility in my absence. This person has been named as co-investigator in this application, or I will advise OHSR, by letter, in advance of such arrangements.
6. I agree to conduct this study only during the period approved by the Auburn University IRB.
7. I will prepare and submit a renewal request and supply all supporting documents to the Office of Human Subjects Research before the approval period has expired if it is necessary to continue the research project beyond the time period approved by the Auburn University IRB.
8. I will prepare and submit a final report upon completion of this research project.

Rajendran Swamidurai		
Principal Investigator (Please Print)	**Principal Investigator's Signature**	**Date**

B. FACULTY SPONSOR'S ASSSURANCE

1. By my signature as sponsor on this research application, I certify that the student or guest investigator is knowledgeable about the regulations and policies governing research with human subjects and has sufficient training and experience to conduct this particular study in accord with the approved protocol.
2. I certify that the project will be performed by qualified personnel according to the approved protocol using conventional or experimental methodology.
3. I agree to meet with the investigator on a regular basis to monitor study progress.
4. Should problems arise during the course of the study, I agree to be available, personally, to supervise the investigator in solving them.
5. I assure that the investigator will promptly report significant adverse events and/or effects to the OHSR in writing within 5 working days of the occurrence.
6. If I will be unavailable, I will arrange for an alternate faculty sponsor to assume responsibility during my absence, and I will advise the OHSR by letter of such arrangements.
7. I have read the protocol submitted for this project for content, clarity, and methodology.

Dr. David A. Umphress		
Faculty Sponsor (Please Print)	**Faculty Sponsor's Signature**	**Date**

C. DEPARTMENT HEAD'S ASSSURANCE

By my signature as department head, I certify that every member of my department involved with the conduct of this research project will abide by all Auburn University policies and procedures, as well as with all applicable federal, state, and local laws regarding the protection and ethical treatment of human participants.

Dr. Kai Chang		
Department Head (Please Print)	**Department Head's Signature**	**Date**

8. PROJECT ABSTRACT: Prepare an abstract (400-word maximum) that includes: I.) A summary of relevant research findings leading to this research proposal; II.) A concise purpose statement; III.) A brief description of the methodology; IV.) Expected and/or possible outcomes, and V.) A statement regarding the potential significance of this research project. ***Please cite relevant sources and include a "Reference List" as Appendix A.***

Pair programming, advocated by many agile software development techniques, such as Extreme Programming, was promoted in the early 1990's as a way of inspecting code as it is being written. Its premise – that of two people, one computer – is that two people working together on the same task will likely produce better code than one person working individually. While the concept of pair programming is attractive, it has some detraction. First, it requires that the two developers be at the same place at the same time. Second, it requires an enlightened management that believes that letting two people work on the same task will result in better software than if they worked on it separately. Third, the empirical evidence of the benefits of pair programming is mixed; though John T. Nosek [Nosek, 1998], Laurie Williams [Williams et al., 2000], Xu and Rajlich [Xu et al., 2006] experiments support the costs and benefits of pair programming, experiments like Nawrocki and Wojciechowski [Nawrocki et al., 2001], Jari Vanhanen and Casper Lassenius [Vanhanen et al., 2005], Erik Arisholm et al. [Arisholm et al., 2007] show that statistically there is no significant difference between the pair programming and solo programming.

Collaborative-Adversarial Pair (CAP) programming is a variant of the pair programming developed at AU while working on a cell-phone software construction project. Its objective is to exploit the advantages of pair programming while at the same time downplaying the disadvantages. Unlike traditional pairs, where two people work together in all the phases of software development, CAPs start by designing together; splitting into independent test construction and code implementation roles; then joining again for testing.

The purpose of this study is to evaluate the Collaborative – Adversarial Pair (CAP) programming in terms of the software metrics namely productivity, correctness and job satisfaction against pair programming and traditional individual(solo) programming. This study will use a series of three controlled experiments and a survey to to collect the required data. The students from COMP 5700/6700 class offered in fall'08 by the co-investigator of CSSE dept, AU will participate in this study. The overall goal is to improve the agile software development methodology which is widely used in senior design projects in various universities including AU as well as in software development industries. The potential significance of this study is to create a valid and reliable model for agile software development. This model is especially useful for universities and companies in situations where pair programming is not beneficial and/or not possible to practice.

9. PURPOSE & SIGNIFICANCE.

a. Clearly state all of the objectives, goals, or aims of this project.

The purpose of this study is to evaluate the Collaborative – Adversarial Pair (CAP) programming in terms of the software metrics namely productivity, correctness and job satisfaction against pair programming and traditional individual(solo) programming.

The outcome of this study will produce a stable and reliable new agile software development methodology called CAP. The CAP can be a substitute for the most talked and controversial agile practice, known as pair programming, in universities and software industries where pair programming is not beneficent and/or not possible to practice.

b. How will the results of this project be used? (e.g., Presentation? Publication? Thesis? Dissertation?)

The study result will be used in the principal investigator's PHD dissertation. Additionally, the result of this study will be disseminated through conference presentations, and publications in scholarly journals.

10. KEY PERSONNEL INVOLVED WITH DATA COLLECTION. Identify each individual involved with the conduct of this project and describe his or her roles and responsibilities related to this project. Be as specific as possible.

Individual: Rajendran Swamidurai **Title:** Grad Student **Dept/ Affiliation:** CSSE
Roles / Responsibilities:

The roles and responsibility of the principal investigator are the facilitation of workshop and experiments in the software process lab, dept. of CSSE, AU and conducting a lecture to brief the study procedure and concepts, conducting the survey, collect and analyze the data and disseminate findings based on this research project.

Individual: Dr. David A. Umphress **Title:** Associate Prof. **Dept/ Affiliation:** CSSE
Roles / Responsibilities:

The roles and responsibilities of this investigator are providing support, mentoring and supervising all the activities of the principal investigator.

Individual: ____________ **Title:** ________ **Dept/ Affiliation:** ____________
Roles / Responsibilities:

Individual: ____________ **Title:** ________ **Dept/ Affiliation:** ____________
Roles / Responsibilities:

Individual: ____________ **Title:** ________ **Dept/ Affiliation:** ____________
Roles / Responsibilities:

11. LOCATION OF RESEARCH. List all locations where data collection will take place. Be as specific as possible.

The control experiments will be conducted in the Software Process Lab, Department of CSSE, 3134, Shelby Center, AU.

12. PARTICIPANTS.

a. Describe the participant population you have chosen for this project.

All participants in the study will be at least 19 years of age. The participants will be the students from the COMP 5700/6700 Software Process class of CSSE dept, AU; it is a combined class of undergraduate seniors(COMP 5700) and graduate students (COMP 6700).

What is the minimum number of participants you need to validate the study? 25

What is the maximum number of participants you will include in the study? 50

b. Describe the criteria established for participant selection. (If the participants can be classified as a "vulnerable" population, please describe additional safeguards that you will use to assure the ethical treatment of these individuals.)

Potential participants will be male and female undergraduate seniors and graduate students who have already taken software modeling & design and computer programming courses such as C, C++ and Java. Since the COMP 5700/6700 has the pre-requisite of software modeling and computer programming courses, we have chosen the students from this course.

No participants in the study are classified as "vulnerable".

c. Describe all procedures you will use to recruit participants. ***Please include a copy of all flyers, advertisements, and scripts and label as Appendix B.***

At the beginning of the course in Fall 2008 the IRB - approved informed consent for the project will be handed out and students will be given the chance to volunteer to participate.

The principal investigator will provide information to students about the project, hand out consent forms, answer any questions students may have, and request that the forms be returned the following class. So students will have at least one intervening day to review all aspects of consent. He will return the following class to answer any questions and to collect the consent forms.

What is the maximum number of potential participants you plan to recruit? 50

d. Describe how you will determine group assignments (e.g., random assignment, independent characteristics, etc.).

First a pre-test and a survey will be conducted to measure the programming skills of the subjects and their pair programming experience; based on the outcome the subjects will be divided into two groups, namely an experienced group and a novice group. From these two groups the subjects will be randomly selected and assigned to the three experimental groups: Individual (Solo) programming group, pair programming (PP) group and collaborative adversarial pair (CAP) programming group in the ratio of 1:2:2.

e. Describe the type and amount and method of compensation for participants.

Each participants will be rewarded with extra credit points equivalent to one major homework assignment.

13. **PROJECT DESIGN & METHODS. Describe the procedures you will plan to use in order to address the aims of this study. (NOTE: Use language that would be understandable to a layperson. Without a complete description of all procedures, the Auburn University IRB will not be able to review protocol. If additional space is needed for #13, part b, save the information as a .pdf file and insert after page 6 of this form.)**

a. **Project overview. (Briefly describe the scientific design.)**

We plan to evaluate the Collaborative - Adversarial Pair (CAP) programming by conducting three controlled experiments and a survey. Data entered on time record log and error record log will be analyzed using statistical methods to compare the CAP against the pair programming and traditional individual programming. Participants feedback through survey will be used to evaluate the job satisfaction.

b. **Describe all procedures and methods used to address the purpose.**

1. Pre-Test: In the pre-test all the subjects will be asked to solve a programming problem individually in order to measure their programming skills.

2. Pre-Experiment Survey: Each subject will be asked to complete a survey questioner which collects the information such as their age, class level (senior/graduate), programming languages known & experience, pair programming experience.

3. Assigning the Subjects to Experimental Groups: Based on the pre-test's result and survey the subjects will be divided into two groups namely, an experienced group and a novice group. From these two groups the subjects will be randomly selected and assigned to the three experimental groups: Individual (Solo) programming group, pair programming (PP) group and collaborative adversarial pair (CAP) programming group in the ratio of 1:2:2.

4. Workshop: Before the actual control experiments starts there will be a workshop for all the subjects. First, a lecture will be arranged to explain the concepts of collaborative-adversarial pair programming, pair programming, unit test and acceptance test. Then, a pair programming practice session (known as pair-jelling exercise), which enables the programmers to understand the pair programming practices.

5. Control Experiments: Three programming exercises will be given to each experiment groups (solo group, PP group, and CAP group). The solo group will do the experiments individually one at a time. The PP group and CAP group will pair-up to do the first experiment. After the fist experiment the pairs will be rotated within their own group (i.e., A PP pair will interchange his/her pair with another PP pair and a CAP pair will interchange his/her pair with another CAP pair). The new rotated pairs will complete the second experiment. Once again the group's pairs will be rotated to do the third experiment.

6. Job Satisfaction Survey: After the controlled experiments each subjects will be asked to fill a post job-satisfaction survey questioner.

c. **List all instruments used in data collection. (e.g., surveys, questionnaires, educational tests, data collection sheets, outline of interviews, scripts, audio and/or video methods etc.)** ***Please include a copy of all data collection instruments that will be used in this project and label as Appendix C.***

1. Pre-experiment survey
2. Job-satisfaction survey
3. Time record log
4. Error record log

d. **Data Analysis: Explain how the data will be analyzed.**

Data from survey will be analyzed with quantitative measures. Data from time record log and error record logs will be analyzed using statistical methods.

14. **RISKS & DISCOMFORTS: List and describe all of the reasonable risks that participants might encounter if they decide to participate in this research.** ***If you are using deception in this study, please justify the use of deception and be sure to attach a copy of the debriefing form you plan to use and label as Appendix D.***

There is no associated risk or discomfort with this study.

15. PRECAUTIONS. Describe all precautions you have taken to eliminate or reduce risks that were listed in #14.

Not Applicable

16. BENEFITS.

a. List all realistic benefits participants can expect by participating in this study.

The participants will learn pair programming concepts which are extensively used in many software development companies. Moreover they will learn very useful practical software development skills such as test-driven development, how to conduct unit and acceptance testing, team work, team communication etc.

b. List all realistic benefits for the general population that may be generated from this study.

Overall expected outcomes include but are not limited to a) a improved agile software development model, b) a new valid and reliable model alternate for traditional pair programming known as collaborative adversarial pairs (CAP), which can be used in universities and software development companies where pair programming is not beneficial and/or nor possible to practice.

17. PROTECTION OF DATA.

a. Will data be collected as anonymous? ☐ Yes [✓ No] *If "YES", go to part "g".*

b. Will data be collected as confidential? ☐ Yes [✓ No]

c. If data is collected as confidential, how will the participants' data be coded or linked to identifying information?

d. Justify your need to code participants' data or link the data with identifying information.

e. Where will code lists be stored?

f. Will data collected as "confidential" be recorded and analyzed as "anonymous"? ☐ Yes ☐ No

g. Describe how the data will be stored (e.g., hard copy, audio cassette, electronic data, etc.), where the data will be stored, and how the location where data is stored will be secured in your absence.

The data will be stored electronically, on the computer hard drive of the principal investigator, which is located in 3134, Shelby center, AU. The computer is password protected.

h. Who will have access to participants' data?

Rajendran Swamidurai, Principal Investigator
Dr. David A. Umphress, Co-investigator

i. When is the latest date that the data will be retained?

Data will be confidential and retained one year after the approval date of this proposal.

j. How will the data be destroyed? (NOTE: Data recorded and analyzed as "anonymous" may be retained indefinitely.)

Data printouts will be shredded and electronic devices containing the data will be erased.

PROTOCOL REVIEW CHECKLIST

All protocols must include the following items:

☑ **1.** Research Protocol Review Form (All signatures included and all sections completed)

☑ **2.** Consent Form or Information Letter (examples are found on the OHSR website)

☑ **3.** Appendix A "Reference List"

☐ **4.** Appendix B if flyers, advertisements, generalized announcements or scripts are used to recruit participants.

☑ **5.** Appendix C if data collection sheets, surveys, tests, or other recording instruments will be used for data collection. Be sure to mark each of the data collection instruments as they are identified in section # 13, part c.

☐ **6.** Appendix D if a debriefing form will be used.

☐ **7.** If research is being conducted at sites other than Auburn University or in cooperation with other entities, a letter from the site / program director must be included indicating their cooperation or involvement in the project. NOTE: If the proposed research is a multi-site project, involving investigators or participants at other academic institutions, hospitals or private research organizations, a letter of IRB approval from each entity is required prior to initiating the project.

☐ **8.** Written evidence of acceptance by the host country if research is conducted outside the United States.

IRB Appendix- A

References

Appendix – A: References

[Arisholm et al., 2007]	Erik Arisholm, Hans Gallis, Tore Dyba, and Dag I.K. Sjøberg, Evaluating Pair Programming with Respect to System Complexity and Programmer Expertise, IEEE Transactions on Software Engineering, Vol. 33, No. 2, February 2007
[Nawrocki et al., 2001]	Nawrocki, J. and Wojciechowski, A., 2001. Experimental Evaluation of pair programming. In: Proceedings of the European Software Control and Metrics Conference (ESCOM 2001). ESCOM Press, 2001, pp. 269– 276.
[Nosek, 1998]	John T. Nosek, The Case for Collaborative Programming, Communications of the ACM March 1998/Vol. 41, No. 3
[Vanhanen et al., 2005]	Jari Vanhanen and Casper Lassenius, Effects of Pair Programming at the Development Team Level: An Experiment, 2005 IEEE
[Williams et al., 2000]	Laurie Williams, Robert R. Kessler, Ward Cunningham, Ron Jeffries, Strengthening the Case for Pair Programming, July/August 2000 IEEE SOFTWARE
[Xu et al., 2006]	Shaochun Xu, Vaclav Rajlich, Empirical Validation of Test-Driven Pair Programming in Game Development, Proceedings of the 5th IEEE/ACIS International Conference on Computer and Information Science and 1st IEEE/ACIS International Workshop on Component-Based Software Engineering, Software Architecture and Reuse (ICIS-COMSAR'06)

IRB Appendix- B

(Not Applicable)

Appendix – C

Data Collection Instruments

C1: Pre-Experiment Survey & Job Satisfaction Survey

Pre – Experiment Survey

(All information collected will be kept strictly confidential, per informed consent agreement)

1. Name: ____

2. Gender: ___Male ___Female

3. Age: ___18 ___19-20 ___21-22 ___23-24 ___25+

4. What is your Academic Major? ________________ **Minor?** _________________

5. Class level

__Freshman __Sophomore __Junior __Senior __Graduate

6. Do you know Java programming languages?

__Yes __No **If "No" go to question 8**

7. How well you know Java?

__Excellent __Very good __Good __Average __Below Average

8. If your answer is "NO" for question number 6, then what programming language are you most proficient in?

__C __C++ __C#

5. How long have you been a programmer in industry/research?

__Less than 1 year __1 - 5 years __More than 5 years

6. How long have you been practicing pair programming?

__Not at all __Less than 1 year __1 - 2 years __More than 2 years

7. Did you ever practice test-driven development for your past projects?

__Yes __No

8. Did you ever practice unit-testing tools such as JUnit for your past projects?

__Yes __No

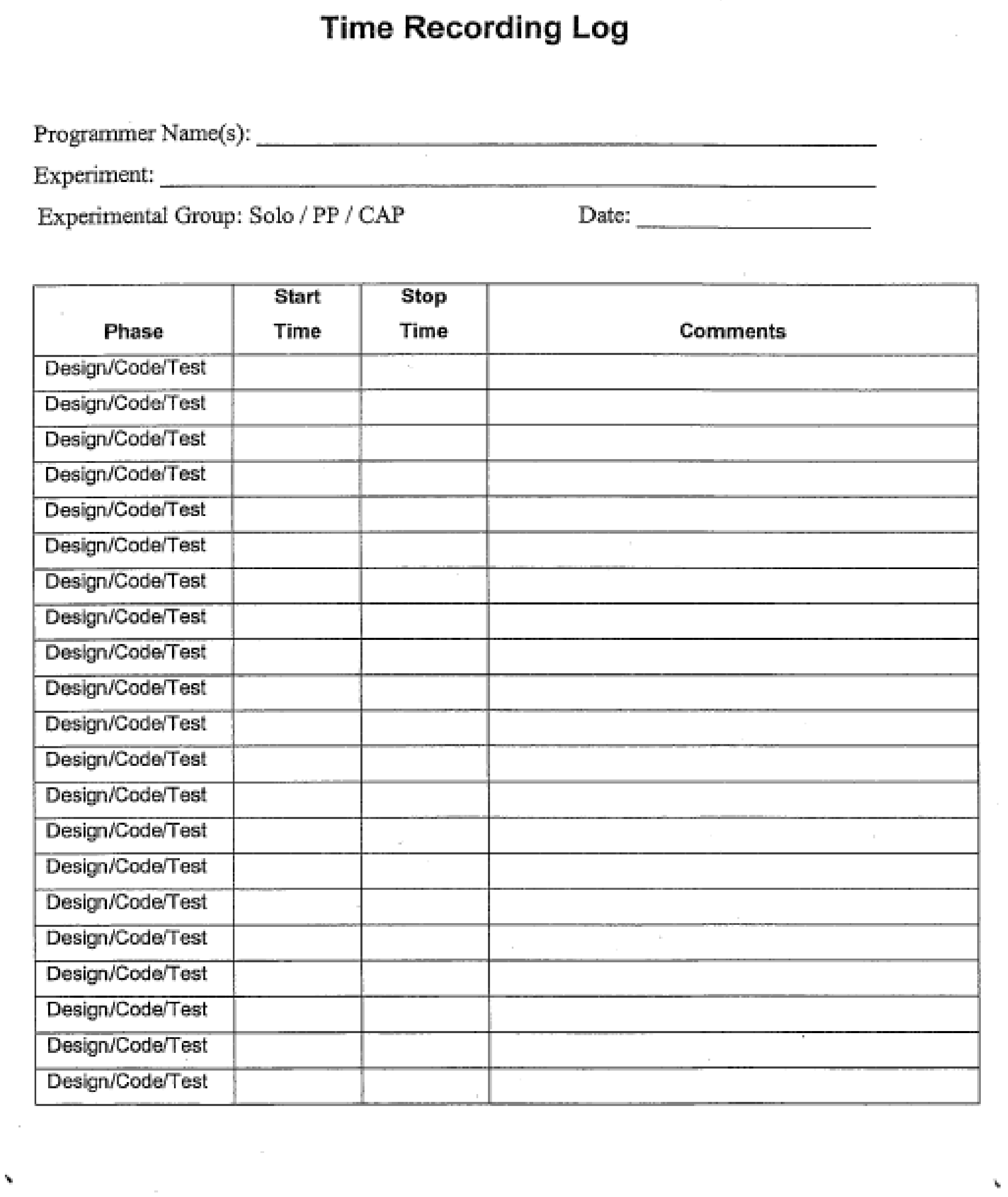
9. Did you ever practice Black box testing for your past projects?

__Yes __No

Appendix – C

Data Collection Instruments

C2: Time and Defect Recording Logs



Time Recording Log

Programmer Name(s): ______________________________

Experiment: ______________________________

Experimental Group: Solo / PP / CAP   Date: ______________

Phase	Start Time	Stop Time	Comments
Design/Code/Test			
Design/Code/Test			
Design/Code/Test			
Design/Code/Test			
Design/Code/Test			
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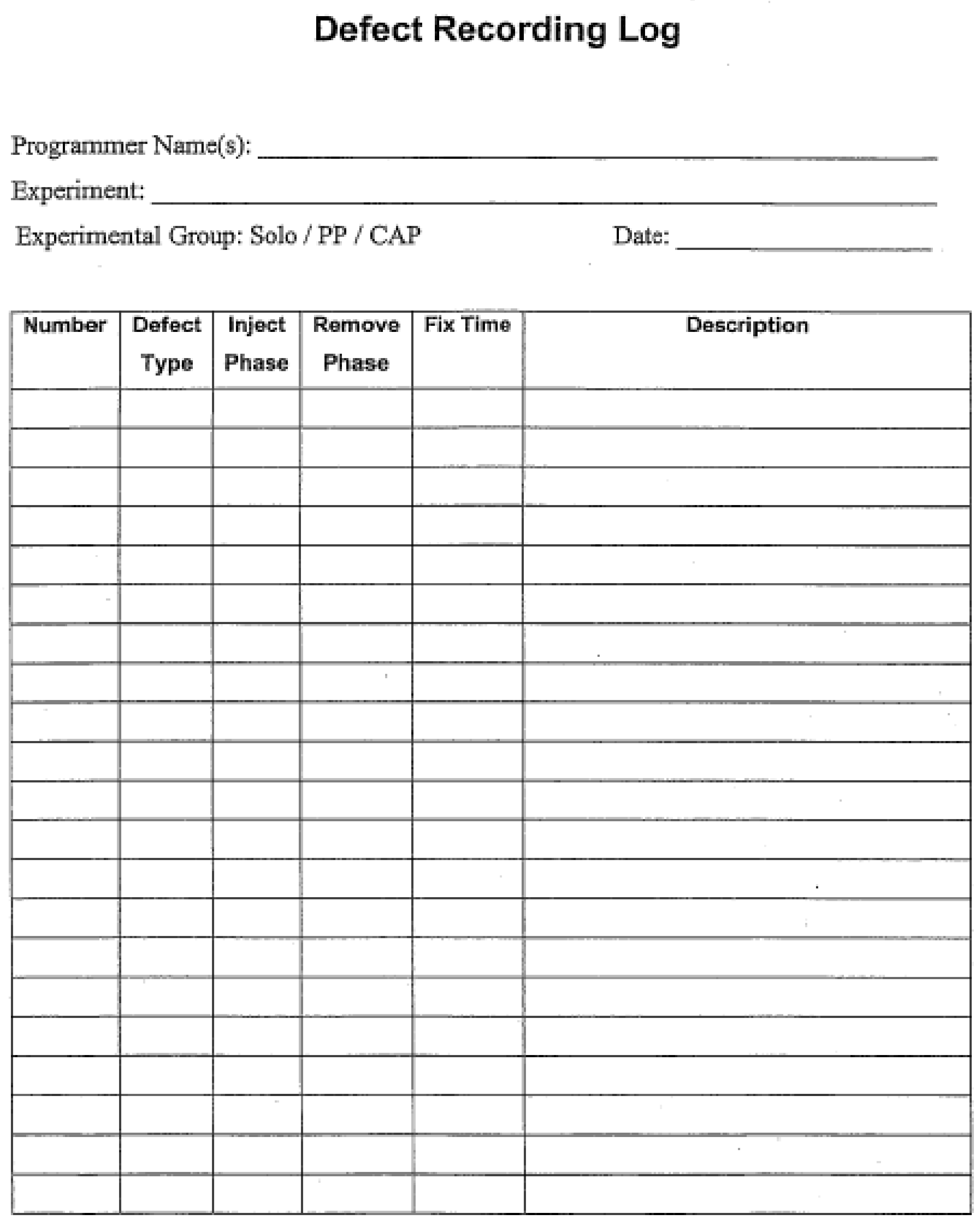


Defect Recording Log

Programmer Name(s): ______________________________

Experiment: ______________________________

Experimental Group: Solo / PP / CAP Date: ______________

Number	Defect Type	Inject Phase	Remove Phase	Fix Time	Description

Appendix – C

Data Collection Instruments

C3: Sample Control Experiment Problems

Problem: Write a program which reads a text file and displays the name of the file, the total number of occurrences of a user-input string the total number of non-blank lines in the file, and count the number of lines of code according to our LOC Counting Standard. You may assume that the source code adheres to the LOC Coding Standard. This assignment should not determine if the coding standard has been followed. The program should be capable of sequentially processing multiple files by repeatedly prompting the user for file names until the user enters a file name of "stop". The program should issue the message, "I/O error", if the file is not found or if any other I/O error occurs.

Notes on Requirements: Below is a hypothetical test scenario for your program:

```
Application:  Enter a file name (or "stop"):
       User:  assignment1Test1.txt
Application:  Enter search term.
       User:  Dog
Application:  The file "assignment1Test1.txt" has 150 lines.
              assignment1Test1.txt has 89 LOC
Application:  The string "dog" occurs 20 times.
Application:  Enter a file name (or "stop"):
       User:  Assignment2.java
Application:  Enter search term.
       User:  If
Application:  The file "Assignment2.java" has 220 lines.
              Assignment2.java has 168 LOC
Application:  The string "if" occurs 5 times.
Application:  Enter a file name (or "stop"):
       User:  InvalidFileName.txt
Application:  File name:  I/O error
Application:  Enter a file name (or "stop"):
       User:  Stop
Application:  Program stopped
```

Problem: Write a program to list information (name, number of methods, type, and LOC) on each proxy in a source file. The program should also produce an LOC count of the entire source file.

Notes on Requirements: Your program should accept as input the name of a file that contains source code. You are to read the file and count the number of lines of code according to our LOC Counting Standard. You may assume that the source code adheres to the LOC Coding Standard. This assignment should not determine if the coding standard has been followed.

Below is the hypothetical scenario for your program:

```
Application:  Enter source code file name (or "stop"):
       User:  Assignment1xls.java
Application:  Proxy information for Assignment1xls.java is:
Application:  Proxy name          Type            Method count     LOC
Application:  Main                Logic                1           10
Application:  Readfile            IO                   1           17
Application:  Total LOC:                    30
Application:  Enter source code file name (or "stop"):
       User:  Assignment2xls.java
Application:  Proxy information for Assignment2xls.java is:
Application:  Proxy name          Type            Method count     LOC
Application:  Main                Logic                1           10
Application:  File                IO                   3           20
Application:  Token               Data                 3           17
Application:  LocCounter          Data                 2           5
Application:  Display             IO                   1           22
Application:  Total LOC:                    76
Application:  Enter source code file name (or "stop"):
       User:  Assignment3xls.java
              ...
Application:  Enter source code file name (or "stop"):
       User:  Stop
Application:  Program stopped
```

The exact format of the application-user interaction is up to you.

- A "proxy" is defined as a recognizable software component. Classes are typical proxies in an object-oriented systems; subprograms are typical proxies in traditional functionally-decomposed systems.
- If you are using a functionally-decomposed (meaning, non-OO) approach, the number of methods for each proxy will be "1". If you are using an OO approach, the number of methods will be a count of the methods associated with an object.

Problem: Write a program to calculate the planned number of lines of code given the estimated lines of code.

Notes on Requirements: Your program should accept as input the name of a file. Each line of the file contains four pieces of information separated by a space: the name of a project and its LOCe, LOCp, and LOCa. Read this file and echo the data to the output device. Accept as input from the keyboard a number which represents the estimated size (E) of a new project. Output the calculations of each decision (see below) and the responding planned size (P), as well as the PROBE decision designation (A, B, or C) used to calculate P. For each decision, indicate why it is/isn't valid.

Below is a hypothetical test scenario that you should model in your program:

```
Application:  Enter a file name:
       User:  assignment4Test.txt
Application:  Name                LOCe      LOCp      LOCa
Application:  Project1            284       485       674
Application:  Project2            163       209       226
Application:  ...                 ...       ...       ...
Application:  Project11           123       234       136
Application:  Project12           456       456       468
Application:  Enter the new estimated lines of code (or stop):
       User:  183
Application:  Decision A
Application:  r = 0.71
Application:  B0 = -100
Application:  B1= 1.34
Application:  Unsuitable:  B0 is invalid
Application:
Application:  Decision B
Application:  r = 0.89
Application:  B0 = 37
Application:  B1 = 1.27
Application:  Suitable
Application:
Application:  Decision C
Application:  B1= 1.1
Application:  Unsuitable: A previous decision has been chosen
Application:
Application:  The planned lines of code is 270 (Decision B).
Application:  Enter the new estimated lines of code (or stop):
       User:  ...
Application:  Enter the new estimated lines of code (or stop):
       User:  Stop
Application:  Program stopped
```

The exact format of the application-user interaction is up to you.

Your software should gracefully handle error conditions, such as non-existent files and invalid input values.

Round P up to the nearest multiple of 10.

Dear Rajendran,

Your protocol entitled "Collaborative-Adversarial Pair (CAP) Programming" was reviewed by the IRB. There was not enough information provided for the IRB to complete the review. Additional information and revisions must be received and approved.

The IRB's comments are as follows:

- CITI must be completed before final approval can be given. (Please clip the attached form to your completion report and forward to the office.)

- #12b - Students are considered a vulnerable population.

- #12c - It is assumed that the PI is not their teacher - is the faculty advisor the instructor? This may still be a coercive environment. Will this experiment involve the entire class as a teaching method regardless of whether they consent? If so, have someone else consent them and keep the forms until after grades are submitted. Then researchers can then know whose data they can use.

- #12e - What if they do not want to participate? Unless the experiment is required as part of the course syllabus, you will need to provide an alternate activity for those who do not want to participate to earn the extra credit.

- #13b - Include the consent process. Will these activities occur during class time or outside of class?

- #14 - There are coercion and confidentiality risks. (Also check these in #6D on the cover page.)

- #15 - Indicate how recruitment will be conducted so as to not coerce students to participate. How will data be coded to protect the identity of participants?

- #16 - These benefits may be expected if the activities are not part of the normal class instruction. If the activities would occur normally, the research is only asking that their data be used by the researcher, and there would be no personal benefit by participating in the exercise since they would be doing it for the class anyway.

- #17b - Check "yes"

- #17c through e - Please respond.

- #17g - Include the location of the signed consent documents on campus during and for 3 years after the study ends.

- Consent - revisions may be required after considering the above comments. Please change "participate" to "participating" in the fourth paragraph. In the "If you have questions..." paragraph, please add phone numbers.

- Survey - It's suggested that you use a code list and number, and no names.

- Please call the IRB reviewer, Dr. Kathy Jo Ellison, to discuss these requests (4-6761).

Please submit a revised protocol to the Office of Human Subjects Research, with a memo that outlines the changes you make. If you make any changes to the documents other than those already approved by the IRB, please bring them to the reviewer's attention in the memo.

Please note: You are not authorized to initiate any part of your submitted research protocol that involves humans as subjects until the IRB provides final written approval for you to proceed, including the return to you of your informed consent. You will need to use the stamped version when you consent participants and provide a copy for them to keep.

If you have any questions or concerns, please let us know.

PLEASE NOTE THAT FOR ANY RESEARCH CONDUCTED AFTER AUGUST 1, 2008, THE IRB REQUIRES THAT ALL MEMBERS OF A RESEARCH TEAM, INCLUDING THE FACULTY ADVISOR, MUST HAVE COMPLETED THE CITI ON-LINE TRAINING IN HUMAN PARTICIPANT RESEARCH PROTECTIONS. FOR MORE INFORMATION, GO TO http://www.auburn.edu/research/vpr/ohs/resources.htm

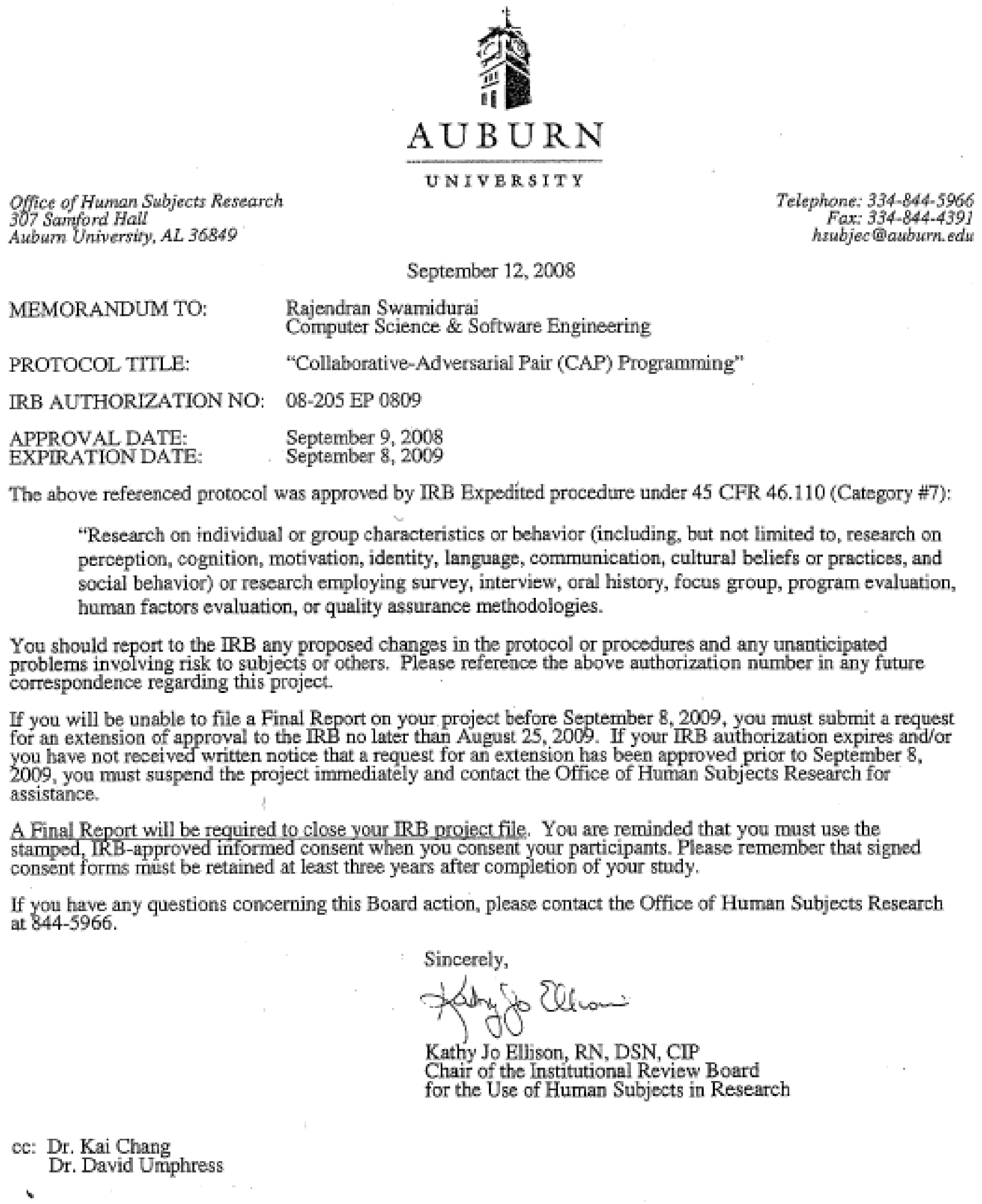
Best wishes,
Susan

13 (b)

1. Consent Process: At the beginning of the course in Fall 2008 the IRB - approved informed consent for the project will be handed out and students will be given the chance to volunteer to participate. The principal investigator will provide information to students about the project, hand out consent forms, answer any questions students may have, and request that the forms be returned the following class. So students will have at least one intervening day to review all aspects of consent. He will return the following class to answer any questions and to collect the consent forms.

15.
Confidentiality risk will be eliminated /minimized through the use of a designated person to handle all identifiable data and to create anonymous data files for analysis. All identifiable data will be kept in a secure location and destroyed after one year. This person (...) will be responsible for creating a code list and data file with no identification information. The code list will be kept by (...) in a secure location and destroyed at project's end. Data analysis will be completed anonymously.

The instructor of record for the course will not introduce the study or ask for volunteers. The Principal Investigator or (...) will provide information to students about the project, hand out consent forms, answer any questions students may have, and request that the forms to be returned the following class. So students will have at least one intervening day to review all aspects of consent. The Principal Investigator or (...) will return the following class to answer any questions and to collect the consent forms; so that the coercion risk also will be eliminated / minimized.



AUBURN

UNIVERSITY

Office of Human Subjects Research
307 Samford Hall
Auburn University, AL 36849

Telephone: 334-844-5966
Fax: 334-844-4391
hsubjec@auburn.edu

September 12, 2008

MEMORANDUM TO:	Rajendran Swamidurai Computer Science & Software Engineering
PROTOCOL TITLE:	"Collaborative-Adversarial Pair (CAP) Programming"
IRB AUTHORIZATION NO:	08-205 EP 0809
APPROVAL DATE: EXPIRATION DATE:	September 9, 2008 September 8, 2009

The above referenced protocol was approved by IRB Expedited procedure under 45 CFR 46.110 (Category #7):

> "Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

You should report to the IRB any proposed changes in the protocol or procedures and any unanticipated problems involving risk to subjects or others. Please reference the above authorization number in any future correspondence regarding this project.

If you will be unable to file a Final Report on your project before September 8, 2009, you must submit a request for an extension of approval to the IRB no later than August 25, 2009. If your IRB authorization expires and/or you have not received written notice that a request for an extension has been approved prior to September 8, 2009, you must suspend the project immediately and contact the Office of Human Subjects Research for assistance.

A Final Report will be required to close your IRB project file. You are reminded that you must use the stamped, IRB-approved informed consent when you consent your participants. Please remember that signed consent forms must be retained at least three years after completion of your study.

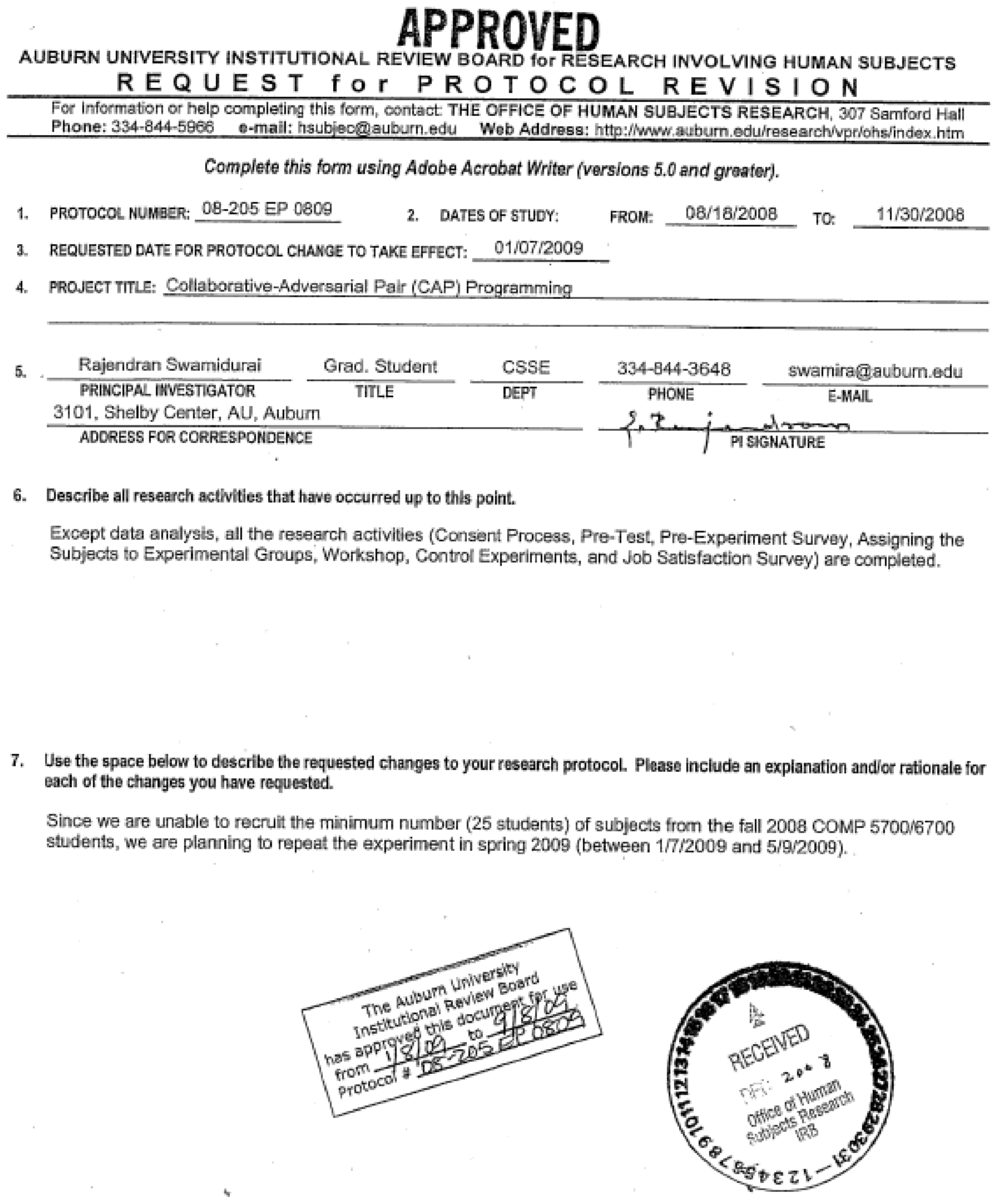
If you have any questions concerning this Board action, please contact the Office of Human Subjects Research at 844-5966.

Sincerely,

[illegible]

Kathy Jo Ellison, RN, DSN, CIP
Chair of the Institutional Review Board
for the Use of Human Subjects in Research

cc: Dr. Kai Chang
Dr. David Umphress



APPROVED

AUBURN UNIVERSITY INSTITUTIONAL REVIEW BOARD for RESEARCH INVOLVING HUMAN SUBJECTS

REQUEST for PROTOCOL REVISION

For information or help completing this form, contact: THE OFFICE OF HUMAN SUBJECTS RESEARCH, 307 Samford Hall
Phone: 334-844-5966 e-mail: hsubjec@auburn.edu Web Address: http://www.auburn.edu/research/vpr/ohs/index.htm

Complete this form using Adobe Acrobat Writer (versions 5.0 and greater).

1. PROTOCOL NUMBER: 08-205 EP 0809 2. DATES OF STUDY: FROM: 08/16/2008 TO: 11/30/2008

3. REQUESTED DATE FOR PROTOCOL CHANGE TO TAKE EFFECT: 01/07/2009

4. PROJECT TITLE: Collaborative-Adversarial Pair (CAP) Programming

5.

Rajendran Swamidurai	Grad. Student	CSSE	334-844-3648	swamira@auburn.edu
PRINCIPAL INVESTIGATOR	TITLE	DEPT	PHONE	E-MAIL

3101, Shelby Center, AU, Auburn
ADDRESS FOR CORRESPONDENCE

[illegible]
PI SIGNATURE

6. **Describe all research activities that have occurred up to this point.**

Except data analysis, all the research activities (Consent Process, Pre-Test, Pre-Experiment Survey, Assigning the Subjects to Experimental Groups, Workshop, Control Experiments, and Job Satisfaction Survey) are completed.

7. **Use the space below to describe the requested changes to your research protocol. Please include an explanation and/or rationale for each of the changes you have requested.**

Since we are unable to recruit the minimum number (25 students) of subjects from the fall 2008 COMP 5700/6700 students, we are planning to repeat the experiment in spring 2009 (between 1/7/2009 and 5/9/2009).

The Auburn University Institutional Review Board has approved this document for use from 1/8/09 to 9/18/09 Protocol # 08-205 EP 0809

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8. Identify any changes in the anticipated risks and / or benefits to the participants.

NA

9. Identify any changes in the safeguards or precautions that you will use to address the changes in the anticipated risks.

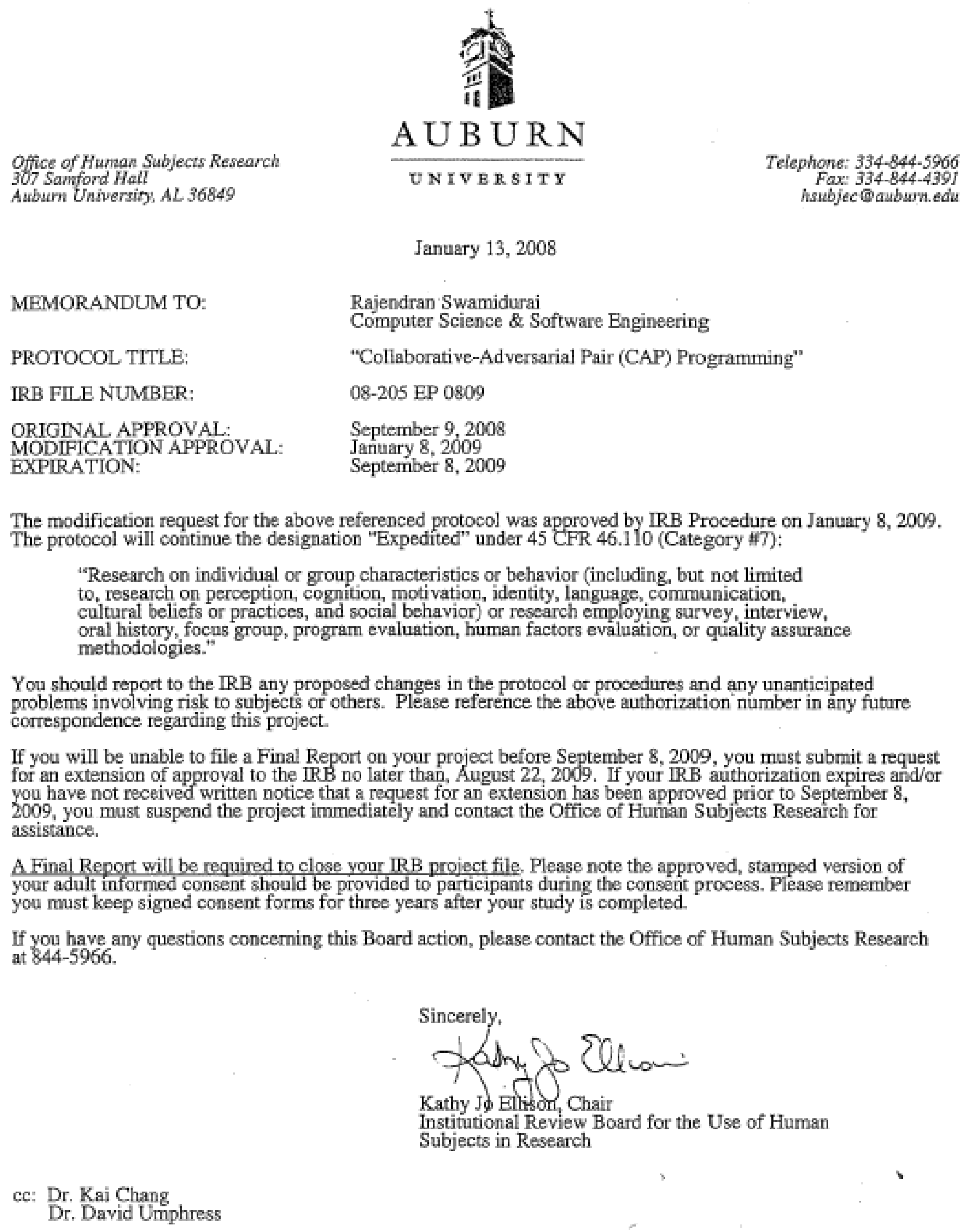
NA

10. Attach any additional supporting documentation you feel may assist the IRB in evaluating your request for protocol revisions.

11. If research is being conducted at sites other than Auburn University or in cooperation with other entities, a letter from the site / program director must be included acknowledging their acceptance of the proposed changes.

12. Attach a copy of the "stamped" IRB approved consent form you are currently using.

13. Attach a revised copy of the consent document that includes updated information regarding the requested changes. (Be sure to review the OHSR website for current consent document guidelines and updated contact information.)



AUBURN UNIVERSITY

Office of Human Subjects Research
307 Samford Hall
Auburn University, AL 36849

Telephone: 334-844-5966
Fax: 334-844-4391
hsubjec@auburn.edu

January 13, 2008

MEMORANDUM TO:	Rajendran Swamidurai Computer Science & Software Engineering
PROTOCOL TITLE:	"Collaborative-Adversarial Pair (CAP) Programming"
IRB FILE NUMBER:	08-205 EP 0809
ORIGINAL APPROVAL:	September 9, 2008
MODIFICATION APPROVAL:	January 8, 2009
EXPIRATION:	September 8, 2009

The modification request for the above referenced protocol was approved by IRB Procedure on January 8, 2009. The protocol will continue the designation "Expedited" under 45 CFR 46.110 (Category #7):

> "Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies."

You should report to the IRB any proposed changes in the protocol or procedures and any unanticipated problems involving risk to subjects or others. Please reference the above authorization number in any future correspondence regarding this project.

If you will be unable to file a Final Report on your project before September 8, 2009, you must submit a request for an extension of approval to the IRB no later than, August 22, 2009. If your IRB authorization expires and/or you have not received written notice that a request for an extension has been approved prior to September 8, 2009, you must suspend the project immediately and contact the Office of Human Subjects Research for assistance.

A Final Report will be required to close your IRB project file. Please note the approved, stamped version of your adult informed consent should be provided to participants during the consent process. Please remember you must keep signed consent forms for three years after your study is completed.

If you have any questions concerning this Board action, please contact the Office of Human Subjects Research at 844-5966.

Sincerely,

[illegible]

Kathy Jo Ellison, Chair
Institutional Review Board for the Use of Human
Subjects in Research

cc: Dr. Kai Chang
Dr. David Umphress

AUBURN UNIVERSITY
SAMUEL GINN COLLEGE OF ENGINEERING
DEPARTMENT OF COMPUTER SCIENCE AND SOFTWARE ENGINEERING

(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT.)

INFORMED CONSENT for a Research Study entitled
"Collaborative – Adversarial Pair Programming"

You are invited to participate in a research study to evaluate Collaborative Adversarial Pair programming against pair programming and traditional individual programming. The study is being conducted by Mr. Rajendran Swamidurai, Graduate Student, under the direction of Dr. David A. Umphress, in the Auburn University Department of Computer Science & Software Engineering. You were selected as a possible participant because you are enrolled in COMP 5700/6700 and are age 19 or older.

What will be involved if you participate? If you decide to participate in this research study, you will be asked to complete a pre-experiment survey, a post experiment job satisfaction survey, and three programming exercises (between 1/7/2009 and 5/9/2009). Your total time commitment will be approximately 7 hours.

Are there any risks or discomforts? There are coercion and confidentiality risks associated in participating in this study. These risks are minimized by ensuring that all data is kept confidential and that no information concerning the study is revealed to the course instructor until after the study has ended and course grades have been submitted.

Are there any benefits to yourself or others? By participating in this study, you can expect to learn pair programming concepts which are extensively used in many software development companies. Moreover you will learn very useful practical software development skills such as test-driven development, how to conduct unit and acceptance testing, team work, team communication etc. We cannot promise you that you will receive any or all the benefits described.

Will you receive compensation for participating? To thank you for your time you will be rewarded with extra credit points equivalent to one major homework assignment.

Are there any costs? No

If you change your mind about participating? You can withdraw at anytime during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University, the Department of Computer Science and Software Engineering or with the instructor of the course.

Participant's initials ______________

The Auburn University
Institutional Review Board
has approved this document for use
from 1/8/09 to 9/8/09
Protocol # 08-205 EP 0809

Page 1 of 2

Your privacy will be protected. Any information obtained in connection with this study will remain confidential. Information obtained through your participation may be used in the principal investigator's PhD dissertation. Additionally, the result of this study will be disseminated through conference presentations, and publications in scholarly journals.

If you have questions about this study, please ask them now or contact Mr. Rajendran Swamidurai at Tel: 334-844-3648 and email:swamira@auburn.edu. A copy this document will be given to you to keep.

If you have questions about your rights as a research participant, you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334) – 844 – 5966 or e-mail at hsubjec@auburn.edu or IRBChair@auburn.edu.

HAVING READ THE INFORMATION PROVIDED YOU MUST DECIDE WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES YOUR WILLINGNESS TO PARTICIPATE.

Participant's Signature Date	[illegible] 18 Dec 2008 Investigator obtaining consent Date
Printed Name	RAJENDRAN SWAMIDURAI Printed Name
	[illegible] 11 Dec 2008 Principal Investigator Date
	David A. Umphress Printed Name
	Co-Investigator Date
	Printed Name

The Auburn University
Institutional Review Board
has approved this document for use
from 1/8/09 to 9/8/09
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Page 2 of 2