AC 2008-249: INTEL: INTERACTIVE TOOLKIT FOR ENGINEERING EDUCATION

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InTEL : Interactive Toolkit for Engineering Learning

Abstract

Statics, a foundational engineering course, introduces a unique approach to problem solving, which is characterized by model-based reasoning. The major intended course outcome is for students to develop the ability to create and utilize free body diagrams as a mechanism for describing and constraining a problem. This ability to abstract and define an idealized problem from complex objects in the world or textual descriptions ratchets the engineer's ability to solve the problem. Sadly, however, students routinely leave this course having learned to "plug and chug" or jump to a mathematical equation without first defining the problem in a diagrammatic form that articulates the underlying principles. This can lead to serious problems in future courses as the fundamental approach to engineering problem solving has not been understood or embraced. As a foundational course, difficulties here can impact student academic confidence resulting in a diminished sense of self-efficacy that is particularly problematic when amplified by gender and under-represented (URM) minorities issues. And such faltering so early in the major can cause a student to leave engineering.

While difficulties in the course arise for several reasons, our project seeks to address the problem of context. Our hypothesis is that women and minorities particularly, and students generally, are more likely to do well in statics when the problems are placed in the context of real world usefulness. An approach to teaching that effectively scaffolds students' efforts at model building and connects abstract principles/concepts to real world, every day applications will benefit all students while promoting diversity in engineering. Towards that end, we are developing InTEL (Interactive Toolkit for Engineering Education), a computer-based manipulable environment that supports teaching and learning in statics by mapping images from real-world environments to abstract diagrams for 2D and 3D equilibrium problems. With such digital technology, statics professors will be able to offer students important scaffolding for developing model-based reasoning by contextualizing abstract concepts and principles in lifelike models. Interacting with and manipulating these models will help students develop the kind of intuition that characterizes engineering reasoning and problem solving.

Introduction

Numerous national studies have pointed to the need to increase enrollment in engineering programs and to graduate a more diverse population of engineers, although the exact numbers and level of training remain controversial[1]. China, India, and other developing countries produce many more engineers than the United States [2], while many industrialized nations, including the United Kingdom, South Korea, Germany, and Japan, produce a higher percentage of science and engineering graduates than the U.S. [3]. Currently one fourth of the U.S. science and engineering workforce is over 50 and one third of them were born outside the U.S.[3], but visa restrictions and increased international competition are expected to reduce the number of international students studying and remaining to work in the United States engineering workforce after graduation [4]. African American, Hispanic and other racial/ethnic minorities make up 6% of the S&E workforce, and women make up 25%. These percentages contrast sharply with the demographics of these groups in the current overall population and workforce; by 2020 over 40% of college-aged students will be racially/ethnically diverse[3].

Currently, the U.S. engineering workforce remains 90% white and male; engineering, in particular, has not attracted women and URMs. Baccalaureate degrees received by both URMs and women in engineering peaked in 1999-2000 and have trended downward since then [5]. A recent study conducted by Engineers Dedicated to a Better Tomorrow used the NSF WebCASPAR database to document that although about one half of earned baccalaureate degrees in S&E as a whole go to women, in physics, engineering, engineering technology, and computer science, these rates dropped to one in five [6]. While women earned 20% of engineering and 14% of engineering technology degrees, substantial variation occurred among the sub-disciplines in engineering. Civil Engineering (24%), Electrical (14%) and Mechanical Engineering (14%) lagged behind Chemical Engineering (35%) and "all other engineering fields" (29%) [6]. A study released simultaneously by the same group revealed that although the percentage of baccalaureates in S&E awarded to URM-combined (16.4%) is just slightly below that seen in all academic disciplines (16.9%), the percentage of baccalaureates awarded to URM-combined considering engineering and the five closely related fields (14.7%) is significantly less than the corresponding percentage seen for S&E as a whole (16.4%) [7]. Although some variations occur among the racial/ethnic groups, Blacks are especially underrepresented in each subdiscipline of engineering.

A substantial body of research has uncovered factors that deter women from engineering, including the following: a technical experience gap relative to their male peers [8]; lower self-confidence than their male peers [9]; poor quality of classroom experience that leaves women feeling isolated, unsupported and discouraged [10]; not perceiving the practical applications of engineering [9]; not perceiving the creativity and inventiveness of engineering [9]; not perceiving the social usefulness of engineering, particularly to help people [9]. URMs experience similar deterrents, particularly concerning the request for practical applications and the need to overcome the experience gap [7]. **In short, research documents that women and URMs are attracted to engineering when they can see its "specific and tangible contributions to society and in bettering local communities, our nation, and the world" [11]** (Engineers Dedicated to a Better Tomorrow, 2006c, p. 2).

The ABET criteria, especially criterion 3, for better engineering education overlap with strategies that have been shown to be particularly effective for the recruitment, success, and retention of women and minorities[12]. **Of particular importance is offering students extended experience in experimentation, observation, and holistic problem-solving, through interactive methods.** Engineering is an intrinsically "hands-on profession," historically learned by apprenticeship, but increasingly distanced from laboratory experiences [13]. With previous generations of engineering students, it was common for extended experience opportunities to occur prior to entering university. Backyard explorations and repair of the family car, disassembly and reassembly of common household devices or machines often served as the starting point for developing what engineering educators refer to as "intuition". With advent of the digital age and the computerization of many consumer products, such exploration became a thing of the past. Thus, as engineering educators know, today's students lack the extended hands-on experiences of exploring the component parts and workings of mechanical devices that served previous generations so well. And female students rarely if ever had these opportunities even when they were more widely available. However, it is these extended physical experiences that build confidence, nurture an embodied intuition about how the physical world works and, thus serve to close the technical experience gap. Although some universities have been successful in creating hands-on lab experiences [14] these methods do not scale well to the large lecture courses that are the staple of engineering education. Nevertheless, it would be good if students could build their own bridges and operate their own backhoes, because students need extended experience in trial and error and manipulation of objects that display the physics of the real world.

Research also tells us that women and minorities are more likely to do well when problems are placed in a context of real world usefulness [15]. Use of problems applied to issues of social and personal relevance is thus another educational strategy that can impact retention. In contrast to conventional textbook problems that focus on fundamental principles found in beams, trusses, and peaveys, without reference to how they are employed (or what a peavey might be and why someone would use it), problems that provide a richer social context allow students to see how engineers help people. Research has shown that women in particular do better at solving problems when they are framed by a specific situation of human need [16] and women's enrollments are closer to men's in fields like biomedical engineering where there is a clear altruistic purpose. However, engineering examples are usually devoid of context, and students find it hard to map the problems back to the real world. The challenge then for engineering education is to identify specific interventions that can successfully nurture disciplinary engagement early in the curricular sequence, for it is often these first experiences that verify or refute prior aspirations to pursue an engineering degree.

Statics is a foundational course that introduces the engineering approach to problem solving, which is a unique, model-based mode of reasoning. At the heart of the Statics course is an understanding of the **free-body diagram** and its pivotal function in describing and constraining a problem. The ability to abstract and define a problem from objects in the world or textual descriptions by forming an appropriate idealized model ratchets the engineer's ability to solve the problem. Sadly however, students routinely leave this course having learned to "plug and chug" or jump to a mathematical equation without first defining the problem in a diagrammatic form that articulates the underlying principles. In short, they rely on rote application of equations without understanding that the mathematics are an outcome of a preliminary step of model formation. Difficulty in this fundamental cognitive act of model building can cause a lack of confidence and a diminished sense of self-efficacy that is particularly problematic when amplified by gender and URM issues.

An approach to teaching and learning statics that effectively scaffolds students' efforts at model building and connects abstract problems with multiple real world applications would be of benefit to all students and would be particularly helpful in promoting diversity in engineering. One notable step in this direction is the recent textbook *Statics: Analysis and Design of Systems in Equilibrium,* in which the authors, Sheri D. Sheppard and Benson H. Tongue, include extensive real world case studies such as the Golden Gate Bridge and build problem sets around a methodology that make explicit use of the free-body diagram, including such sketches in plentiful illustrations [17]. But the page-based examples do not allow for manipulation, so the arrows on the page can remain hard to map to the physical interplay of objects in space. A computer-based interactive system in which images from the real world are mapped to abstract diagrams, and in which both display interactions of objects in space (e.g. frame versus truss problems, friction, etc) can help students to make these crucial connections.

Computing technology is particularly appropriate for modeling and computer simulations that incorporate physical principles and mathematical relationships and have been utilized since the 1980s for exploratory, open-ended learning. Computer models offer a way to address the problem of embodied experiences without having to provide jackhammers. They improve on the fixed 2D textbook presentation without requiring the extra time and resources of a true hands-on building experience. Seymour Papert was among the first to advocate the use of exploratory models to allow students to learn by observing the rules by which objects behave [18]. Most recent work has stressed the importance of giving students more focused, goal-directed tasks within a simulated environment. Students do best when simulations are presented in a problem-oriented way, with hints and provocative questions generated by the system and with monitoring of their results [19]. Human computer interaction studies make clear that such tools must be designed based on an iterative process of formative evaluation. Furthermore, interactive methods using creative technology can overcome the poor quality of classroom experience and competitive methods that deter women, because they allow students to try things out in the privacy of individual exploration, and because they can offer direct feedback for guesses. Computer models offer a safe place to fail and can provide hints that scaffold success. Interactive methods can also improve the quality of classroom instruction by providing brief periods of active problem solving and cooperative learning that break up the alienating monotony of the traditional lecture [15, 20, 21]. Furthermore, a computer-based system in which socially contextualized images from the real world (such as the rebuilding of a home destroyed in a hurricane) are mapped to abstract diagrams will help students to make the crucial connection between the engineering methods and human needs. Such strategies that incorporate interests and expectations of women and URMs, also overlap with the attributes of more flexible thinking envisioned for the Engineer of 2020 [2].

Approach

Our funding was awarded on March 1 2007. Our group is roughly divided into three teams that work both independently and together on various tasks that are often inter-related:

1- The engineering team (Jacobs, Valle, Lee) is primarily responsible for designing the problems and developing their solutions.
2- The digital media team (Ashmore, Schrank/Thomas/Upton) works on programming and visual implementation of the computer simulations.
3- The evaluation team (Newstetter, Harrell) works on clarifying the learning goals and conducting assessment.

In addition, Prof. Rosser is in charge of the overall project goals, especially the goal of contributing to the retention of women and URMs in Engineering.

We have created a public website where we post completed exercises as well as news of the project. The public website is viewable at http://intel.gatech.edu. Our research activities to date include:

Demographic Data Collection

During spring and summer 2007, we retrieved baseline data, disaggregated by gender, race/ethnicity, and major on individuals taking Statics for fall 2005, spring 2006, fall 2006, and spring 2007 as a required course; we also retrieved comparable data on individuals pursuing other majors in Engineering who took Statics as a technical elective.

In fall 2007, we collected data, disaggregated by gender, race/ethnicity, and major on individuals taking the sections of Statics where the exercises developed under the project were implemented, and on sections of Statics where the exercises were not implemented.

Survey Development and Deployment

During spring and summer 2007, we drafted an attitude survey to be given at the beginning and end of every semester, and we piloted it with summer semester students.

In fall 2007 we administered a revised survey at the beginning of the semester to 4 classes taught by Dr. Valle, two of which were later exposed to the first computer-based exercises as classroom demonstrations and an extra credit assignment. At the end of the semester we administered the exit survey using the Web Monkey system which we will continue to use for the rest of the project.

Platform Research and Choice

The first requirement for the InTEL platform is portability. The software should be easily accessible to students, and the best solution to this is to allow exercises and work to be done on the web. The second requirement is visual capacity and the ability to perform physical simulation. Finally, we desired platforms that were non-proprietary and open source. With these requirements in mind, we chose to implement the software in Java, using the Java Monkey Engine as a stable graphical engine. We selected the Open Dynamics Engine as a system for conducting physical simulations.

Exercise Design and Development

We clarified our goal of creating exercises for every major topic in the course. We are refining the topics lists and compiling a set of problems to cover them. The Engineering team is providing project descriptions and solutions, while the Digital Media team is revising the specifications, expanding the code to cover new operations as needed, and creating 2D and 3D models. A few such problems are listed below:

TOPIC	PROBLEM
Moment, Free Body Diagram	Seesaw
Frame	Arm-Purse
Truss: Method of Joint/Method of Section	Minneapolis Bridge
Point Load, Centroid	Squat Machine
Distrib. Load, Centroid (mix of distributed	New Orleans Levee

and point loads, inclined distributed load)	
3D	3D Door
Friction	Spiderman climbing
Internal Forces	Bookshelf

Most of these have Solutions and/or Graphics posted to our internal website. As of December 2007, we have only deployed one with students: the Arm-Purse Frame problem which 32 students did as an extra credit assignment at the end of Fall semester. We also deployed a simpler Arm-Purse exercise as a lecture demonstration.

Figure 1 shows the main presentation screen for this exercise:

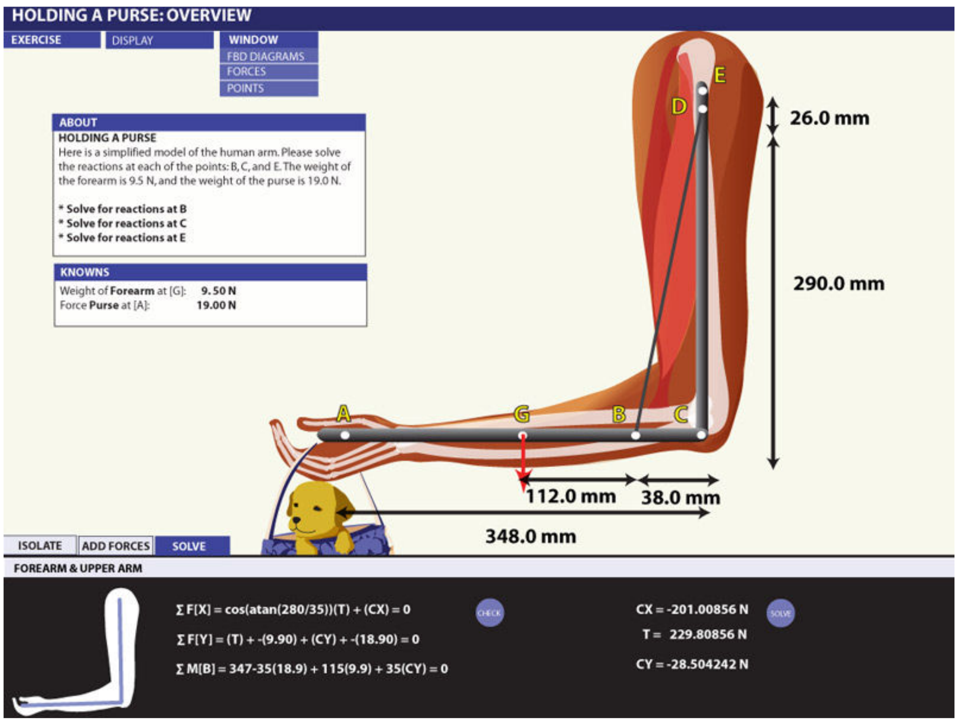

Figure 1 – Arm and Purse Problem

Figure 2 shows an idealized rendering of the Minneapolis Bridge, which will be developed to serve as a truss problem that illustrates both the method of joints and the method of sections. We also hope to show that this was a so-called simple truss, with no redundancy, so that the failure of one structural element meant the failure of the entire structure.

Figure 3 shows a woman performing a Smith-machine assisted squat. The purpose of this exercise is to discuss the contact force between the woman's shoulders and the barbell, as well as the ensuing normal and friction forces at her feet as she (slowly) performs the exercise.

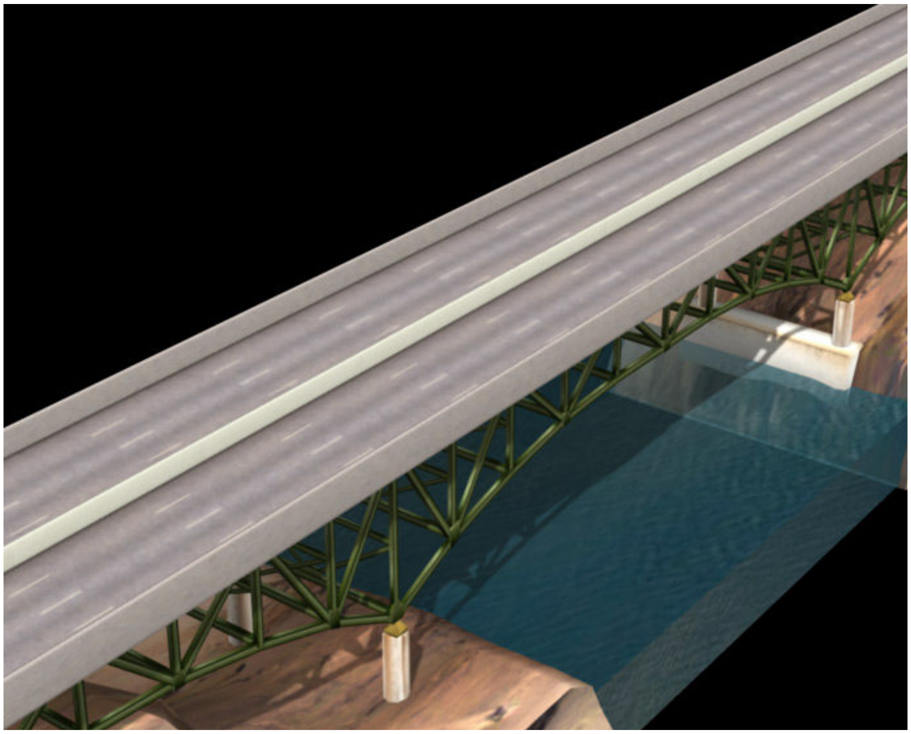

Figure 2 – The Minneapolis Bridge

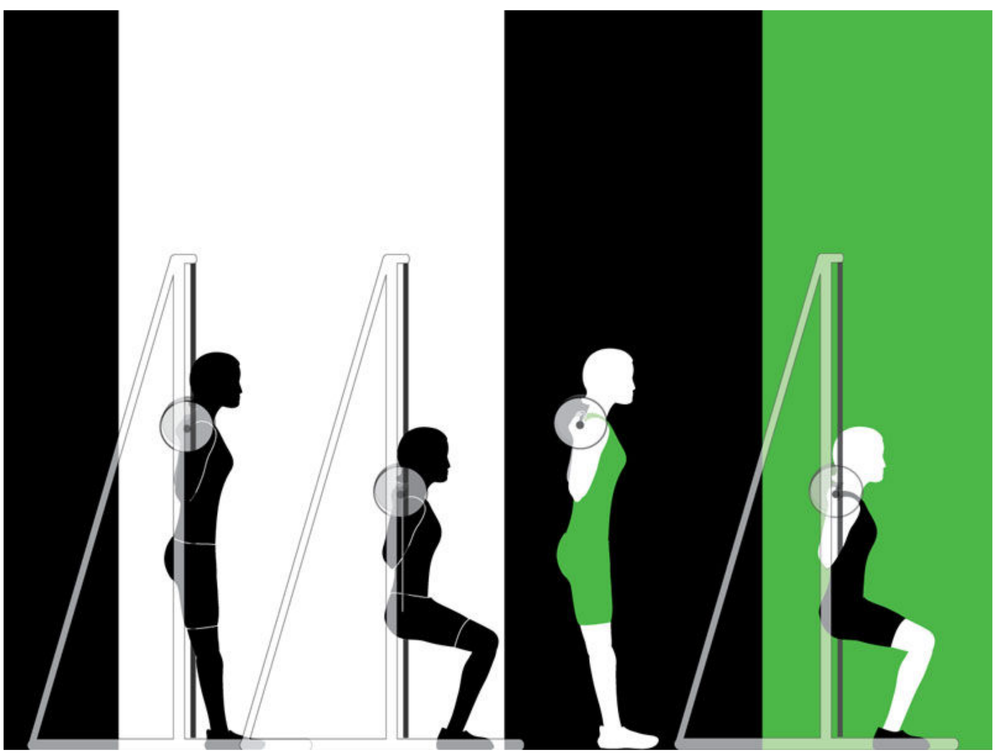

Figure 3 – Woman Performing a Squat on the Smith Machine

The ability to implement problems in digital form provides the opportunity to re-examine the process of problem solving. We spent a considerable amount of time clarifying the process the students should employ and determining what feedback and what kinds of visual displays would be most suitable to our goals. We settled on a method that shows the Free Body Diagram as an overlay on a depiction of a real world object, like a human arm or a bridge. We also allowed students to hide layers so they could work with the FBD alone or with the contextualized view.

Exercise Deployment and Testing

We demoed a simplified version of the Arm-Purse problem (2D equilibrium) to two of Dr. Valle's four sections of Statics in Fall 2007 (the other two sections were the control group and never saw any computer simulations during the semester). The testing went well and Dr. Valle found it to be helpful in conveying the concepts of the lesson. One result of this testing is that we are considering making an alternate visual display for the system optimized for classroom presentation, since the fonts and color choices posed some difficulties in visibility.

We recruited graduate students to test the exercises in the presence of team member Daniel Upton. We used graduate students because they were masters of the course material and could therefore focus on and articulate problems with the interface. We revised the interface after each of these tests.

We then invited students to try a problem in the exercise for extra credit at their convenience from the web during the last week of classes. Students in the control group of 2 sections who had not been exposed to the InTEL system in class were given the option of a comparable paper-based extra credit problem. 31 students tried the online system and 2 were able to solve the problem. In the control group, 32 students handed in problems and 2 solved it correctly. Comments collected from the on-line system will be used to revise the exercise and the general InTEL interface and to improve the available technical support.

Learning Assessment

One of the goals of our work is to understand and describe the cognitive process of students interacting with Statics material and to provide exploratory insights into the nature of these students' cognitive process, and especially its failures. The method we used, called verbal protocol analysis or think aloud, is often used in psychology, especially in the field of expert/novice research. In a think aloud protocol, participants are asked to verbalize what they are thinking as they complete a task, without interpretations or summaries of those thoughts (unless those are a natural part of the thought process). Taraban et. al. [22,23] have used think aloud protocols extensively to analyse students' conceptual and procedural knowledge while using computer simulations of thermodynamics problems. Litzenger et. al. also used think aloud protocols extensively to understand how engineering students use models as part of problem solving [24].

Over the first two weeks in November, Sneha Harrell conducted 8 think aloud sessions (the protocol is given in the Appendix) in which subjects solved a Statics problem provided by Prof. Jacobs and Dr. Valle on paper, while articulating their process. Two of the subjects were experts

(Jacobs and Valle) and the other 6 were student volunteers from Dr. Valle's sections. The sessions were videotaped and the results were screened and analyzed in a team meeting on Monday December 17.

Major results from analysis of the think aloud data are:
1. Students lack structured ways of proceeding through free body diagram construction. Specifically, students lacked a clear process by which they could draw the *component* free body diagrams comprising a frame problem.
2. Students showed evidence of a misconception that they should sum forces at a node, instead of over a structure.
3. Students had difficulty with providing direction to forces correctly.
4. Students lacked understanding of what a moment was, at times drawing it in locations that showed they had very fundamental misconceptions of the concept. Multiple students added a moment as a resisting force.

We will conduct further think alouds in the coming semesters, including think alouds using the software.

Conclusion and Future Work

Based on our work so far, here are our recommendations for further study:
1. We should attempt to understand how students are conceptualizing a moment; including moments caused by a fixed support (versus, say, a pin support). This could be done with protocols that look specifically at such supports in diagrams (both 2D and 3D) and ask students to explain where a moment exists or doesn't exist and why.
2. We should focus next steps on engaging students deeply in diagram recognition and generation across 2D and 3D representations such that we can identify *why* students had the types of difficulties we saw with free-body diagrams. For instance we could give students a problem, including a free body diagram that is not labeled with direction of forces, although the forces themselves are labeled and simply ask them to add the directions. We could develop such insertion problems for pins and moments as well. Such problems will provide important practice opportunities that focus students on various aspects of proper free body diagram generation that our recent findings have shown students have difficulty with.

We propose that software allows for the possibility of a risk-free environment for experimentation and practice. We should do our best to capitalize on this and engage students in as much problem solving as possible, especially focusing on the free-body diagrams.

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Appendix

Protocol for the Think Aloud:

In conducting a think aloud with the participants in this study we followed the following process:

1. Introduction to the think aloud method. In order to introduce the participant to the think aloud method I read out loud a prepared statement that mimics the SRI International Protocol. The statement reads as follows:

   "I have asked you to participate in this study because I am interested in learning about what students think about when they work on statics problems. The best way we have of finding out what students are thinking about is to have them talk out loud while they work on problems. So, as you work on this statics problem, I would like you to say out loud everything you might be thinking or saying to yourself silently. Whether you think it's a big thing or a little thing, relevant or not relevant, just say whatever is in your mind. Also, if at any point, you have any questions regarding the problems please use your own judgment because once we have started I will not be able to answer any questions. Additionally, I am not a statics expert and there's a good chance I wouldn't be able to help you even if you did ask. The only time I may jump in is if you have fallen silent for a prolonged period of time and then I might just remind you to continue thinking aloud. I'll be sitting here and I may type some notes as you are working so don't mind me. After you are done we will have a chance to sit down and debrief. Do you have any questions before we begin?"

2. Concurrent Verbal Protocol without prompting except to remind them to think aloud if they fell silent for 7-10 seconds (Ayala et al, 2002).

3. Retrospective Verbal Protocol using the question "What were you thinking as you worked on the problem?" (ibid.)

4. Retrospective Verbal Protocol with further prompting (only if necessary) using the question "Were there any particular strategies you employed while working on the problems?" This was only used if in the previous bullet the subject did not sufficiently address the strategies they used (ibid.)