InTEL: Promoting Learning and Retention in a Statics Class

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 have been 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. China, India, and other developing countries produce many more engineers than the United States, 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. 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., 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. 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.
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. 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. 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; lower self-confidence than their male peers; poor quality of classroom experience that leaves women feeling isolated, unsupported and discouraged; not perceiving the practical applications of engineering; not perceiving the creativity and inventiveness of engineering; not perceiving the social usefulness of engineering, particularly to help people. URMs experience similar deterrents, particularly concerning the request for practical applications and the need to overcome the experience gap. 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” (Engineers Dedicated to a Better Tomorrow, 2006c, p. 2).

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. 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.

**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) is primarily responsible for designing the problems and developing their solutions.
2- The digital media team (Ashmore, Schrank/Thomas/Upton/Truesdell) 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](http://intel.gatech.edu). Our research activities to date include:

**Demographic Data Collection**

Since the beginning of the project, summer 2007, we retrieved baseline data, disaggregated by gender, race/ethnicity, and major on individuals taking Statics as a required course; we also retrieved comparable data on individuals pursuing other majors in Engineering who took Statics as a technical elective.

Starting 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. Since Dr. Valle teaches Statics every semester, the data collecting continues year-round.

**Survey Development and Deployment**

Since fall 2007 we’ve administered a survey at the beginning of the semester to all classes taught by Dr. Valle, differentiating the results between the sections who will see the InTEL software
during their semester, and those who will not. The purpose of this survey is to evaluate students’ thoughts regarding the course at the very beginning. They answer questions such as “On a scale of 1 through 5, how well prepared do you feel for Statics?” and no calculations or equations are given. At the end of each semester we administered an exit survey, asking the same questions but slightly altered to take into account the fact that the students have known learned Statics (or so we hope!). This post-course survey also differentiates between those who used the software and those who didn’t. Both surveys use the Web Monkey system.

**Exercise Design and Development**

We clarified our goal of creating exercises for every major topic in the course. We refined 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:

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>PROBLEM</th>
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<tbody>
<tr>
<td>Moment, Free Body Diagram</td>
<td>Seesaw</td>
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<tr>
<td>Frame</td>
<td>Arm-Purse</td>
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<tr>
<td>Truss: Method of Joint/Method of Section</td>
<td>Minneapolis Bridge</td>
</tr>
<tr>
<td>Point Load, Centroid</td>
<td>Squat Machine</td>
</tr>
<tr>
<td>Distrib. Load, Centroid (mix of distributed and point loads, inclined distributed load)</td>
<td>New Orleans Levee</td>
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<td>3D</td>
<td>3D Door</td>
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<tr>
<td>Friction</td>
<td>Spiderman climbing</td>
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<td>Internal Forces</td>
<td>Bookshelf</td>
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Most of these have Solutions and/or Graphics posted to our internal website.

Spring 2009 is the first semester when we have enough problems to deploy as homework, rather than as demonstrations during lectures or as extra-credit assignments. The problems given are:
1. arm and purse problem, to illustrate equilibrium of one body,
2. keyboard problem, to illustrate frames,
3. bicycle problem, to illustrate trusses (within a frame).

Figure 1 shows the main presentation screen for the arm and purse problem. As mentioned earlier, this is a frame problem, but we assign it to students as a two-step, one body equilibrium problem at the beginning of the semester. The first body they study is the lower arm, and they must solve for the unknown forces in the biceps and the elbow. The second body they study is the entire arm (lower arm, upper arm, and biceps). On that body, they must solve for the loads at the shoulder E (which is assumed to be a fixed support, for static determinacy).
**Figure 1 – Arm and Purse Problem**

Figures 2 a&b show an idealized rendering of a keyboard. The goal is to calculate the forces at the ground as well as in the central bar that holds the keyboard support together. This is a frame problem, with two multi-force members (the long diagonal beams) and a two-force member (the central bar).
Figures 3 a&b show a woman riding a bike at constant speed (no linear or rotational acceleration, so, this exercise still represents a statics situation). The goal of this exercise is to calculate all forces in each structural member of the bike. The front member, linking the handle to the front wheel, is a multi-force member, but all other members in the bike are two-force members and form local small triangular trusses. So this is a frame problem, with most members forming a simple truss. The forces in those two-force members are solved using the method of joints.

In the future, we plan to develop a truss-only exercise based on the the Minneapolis Bridge (see Figure 4 below), which will illustrate 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.
Exercise Deployment

As mentioned previously, this is the first semester when some of the exercises we’ve developed are incorporated into Dr. Valle’s homework assignments. In the past, we did extensive testing, using both undergraduate and graduate volunteers. As a result, we found both bugs in the solving process and problems with the interface, and worked to solve both. We are now confident that we have as foolproof an interface as possible, and that we’ve covered most of the bugs students can create. As we develop additional exercises, we will incorporate more of them as homework.

We have also made the exercises available to Dr. Sheri Sheppard, Professor in the Department of Mechanical Engineering at Stanford University. Statics at Stanford is run quite differently than at Georgia Tech: it includes labs, recitations, projects, and multiple Teaching Assistants. Dr. Sheppard provided the exercises to student volunteers to solve as part of a project. The experience was positive, and Dr. Sheppard plans to include more such exercises the next time she teaches Statics.

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. 13,14 have used think aloud protocols extensively to analyze students’ conceptual and procedural knowledge while using computer simulations of thermodynamics problems. Litzinger et. al also used think aloud protocols extensively to understand how engineering students use models as part of problem solving 15.

Throughout 2008, we conducted multiple think aloud sessions as described in 16. All interviewees were student volunteers from Dr. Valle’s sections. Major results from analysis of the think aloud data are:

1. Student mistakes can be caused by a variety of misconceptions:
   - Conceptual / definition:
     - What is a beam vs. a bar?
     - Fixed vs Pinned vs Roller support
   - Notation: confusion between \( M_A \), the moment at A, and \( \Sigma M_A \) which is the sum of all moments acting on the structure at point A (and may include \( M_A \))
   - Diagrammatic: problems with the FBD, such as forgetting moments and/or forces on it, or putting them in the wrong location.
   - Class of Problems: does this problem require analysis of just the entire structure, or just parts of it, and if so, which parts? Is it a truss or a frame pb? Students may overly simplify or complicate a problem if they don’t understand what is asked of them.

2. Are engineering students “global” (i.e. they need to see the big picture) or “sequential” (i.e. they prefer to learn concepts in sequence)?

3. Mistakes such as not putting a moment at a fixed support may be caused by so-called “incommensurable abstraction.” Students think of static systems as in a ‘state,’ whereas domain experts think of them as a ‘process,’ whereby the structure is in general moving (hence being subjected to forces and moments), which just so happen to cancel out in a statics situation. Typically, students have a very hard time dealing with such concepts, because they’re working off of unconscious assumptions (‘there is no movement, i.e. there is no force nor moment’) they don’t even realize are wrong, let alone can correct.

We have refined the software by including several short problems that directly address these misconceptions. For example, we have a short problem that asks students to link a given support (say, pin) to its correct symbol (the triangle) and a correct everyday object (for example, a door handle). This will make the software much more powerful by helping students correct misconceptions before it’s too late in the semester.

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 plan to focus future think alouds on students’ opinion of the software. Do they see the applet as an affordance to learning Statics, or would they rather not use it? – as is commonly the situation in many classes that routinely use software problems (notably in Physics) despite great student resistance.

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. 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.

3. We will, of course, keep adding to our library of problems in order to cover all topics of the course. This will help us expose our students more and more to the InTEL tools, and hopefully positively impact both their grades in the class and overall satisfaction with engineering.

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 free-body diagrams and incommensurable abstractions like moments.

Literature Review

