AC 2008-1166: IMPLEMENTING AND ASSESSING A MODERN INTRODUCTORY PHYSICS COURSE AT A LARGE UNIVERSITY

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Implementing and Assessing a Modern Introductory Physics Course at a Large University

Abstract

Since 2006, the Georgia Institute of Technology has offered sections of an introductory physics course for scientists and engineers using the *Matter & Interactions* curriculum. *Matter & Interactions* (M&I), developed by R. Chabay and B. Sherwood at North Carolina State University, is an innovative introductory physics curriculum that emphasizes fundamental physical principles, the microscopic structure of matter, a more coherent formulation linking classical and modern content, and modeling complex systems through computation. We discuss our motivations for introducing the curriculum, implementation issues, and ongoing assessment.

Introduction

The calculus-based introductory physics course is a key component of the educational mission of the Georgia Institute of Technology, due to its status as one of the nation's leading universities in engineering education, and due to the sheer number of students that take the course. Nearly every student at Georgia Tech is required to take the two-semester introductory physics sequence, which has a combined enrollment of nearly 1700 students each semester. In recent years, significant shortcomings have been identified in the introductory physics sequence. In many cases, course GPA in the introductory physics courses has been significantly lower than other introductory courses at Georgia Tech. The fraction of students receiving D's or F's in the course has been approximately 25%. Consequently, the course is unpopular with students, and it receives frequent criticism in the campus student newspaper. In addition, an external review committee criticized the structure and outcomes of the introductory physics courses.

Aside from the specific problems with the introductory physics course at Georgia Tech, there are broader questions about what topics should be taught in the class and the proper sequencing of those topics. The calculus-based introductory physics course at most U.S. universities has typically followed the same sequence of the same topics for many decades. The traditional physics course is focused entirely on classical, pre-20^{th} century physics, addresses only macroscopic systems, and deals only with problems that can be solved analytically. One can question whether the traditional content and pedagogy of introductory physics is meeting the needs of modern science and engineering students, many of whom will pursue careers that are becoming more dependent on understanding matter at the microscopic level (e.g. nanotechnology, material science) and that will require computer modeling as well as analysis for solving complex problems.

As a result, faculty in the School of Physics at Georgia Tech became interested in modernizing both the content and pedagogy of the introductory physics course. Beginning in Summer 2006, the School has been offering sections of its introductory physics course for scientists and engineers using the *Matter & Interactions*[1,2] curriculum. *Matter & Interactions* (or M&I), developed by R. Chabay and B. Sherwood at North Carolina State University, is an innovative introductory calculus-based physics curriculum. It has several key features:

- **A focus on fundamental physical principles**, rather than a long list of specific equations, for solving problems. In M&I mechanics, three major principles (the momentum principle, the energy principle, and the angular momentum principle) drive the organization of the course and serve as the starting points for all analysis. For example, formulas for constant acceleration kinematics are de-emphasized—instead, the momentum principle (or Newton's 2nd Law in a discrete form) is used to explore a wider variety of motions.
- **An emphasis on the microscopic structure of matter and the connection between microscopic models and macroscopic behavior.** In mechanics, a ball-and-spring model of a solid is used as a way to explain such phenomena as elastic deformation, thermal energy, and the speed of sound in a solid. In electromagnetism, circuits are analyzed from a microscopic perspective, concentrating on the motion of electrons and the surface charges that build up through feedback effects.
- **A more coherent formulation linking classical and modern content.** Relativistic forms of momentum and energy are introduced. Quantized energy plays a central role, and quantum models of solids are used to develop a quantum statistical mechanical understanding of entropy, providing a link between mechanics and thermal physics.
- **Computer modeling of complex systems.** Students in the course write programs in the VPython computer language which apply a discrete form of the momentum principle iteratively through simple Euler integration. In this way, freshman and sophomores can study systems that would be too complex or impossible to do so analytically. Computer modeling also reinforces the theme that the same small number of principles can be used to predict a wide variety of behaviors. The VPython models also produce 3D graphics that enable visualization of complex phenomena.

Matter & Interactions is currently used at several large U.S. institutions. The efforts to implement M&I at Georgia Tech are part of a larger collaborative project with researchers at North Carolina State University and Purdue University to investigate issues associated with adopting reform curricula at large universities, as well as to assess the effectiveness of M&I in developing students' conceptual understanding of physical principles and problem-solving skills.

Implementation

There are many difficulties to making sweeping curricular reforms at large institutions. The faculty responsible for teaching the introductory curriculum must first be convinced of the need for reform; without faculty support, large changes are nearly impossible. After this, support must be provided to faculty as they learn the both philosophy underlying the new curriculum as well as the specific details of teaching it. Furthermore, because of the large numbers of students enrolled in the course, much of infrastructure is necessary for maintaining the course. Our approach in implementing M&I was to make gradual changes in all these areas.

M&I was first offered at Georgia Tech as a small, pilot section of about 40 students, taught by a post-doctoral fellow hired expressly for the purpose of assisting in implementing and teaching the curriculum. As shown in Table 1, the number and size of lecture sections using the M&I curriculum have expanded since then. By spring 2008, approximately 30 percent of students enrolled in the introductory physics sequence were in M&I-based sections. The number of instructors who have taught or are currently teaching M&I has grown to five (four professors and one post-doc). To overcome barriers to faculty adoption, we have used variations on an apprenticeship model. We convinced two new faculty hires, both of whom would be teaching Intro Physics for the first time, to teach M&I courses (one in Spring 07, one in Fall 07). One member of the research team—an experienced M&I instructor—also taught an M&I course in the same semester, and worked closely with the new faculty members on course content and logistics. In summer 2007, another member of our research team co-taught an M&I-based Intro Physics II (electromagnetism) course with a veteran professor who did not have M&I experience. Grant money from the M&I collaboration effort (see Acknowledgements) was used to supplement the professor's summer salary. Reactions from these faculty members to M&I has been very positive, and other faculty members have expressed interest in trying the curriculum. We plan to use this apprenticeship model, including the co-teaching approach, in future semesters.

Table 1. Expansion of M&I sections.

Semester	**M&I Intro Physics I (mechanics)**	**M&I Intro Physics II (electromagnetism)**
Summer 06	1 section, 40 students	None
Fall 06	1 section, 120 students	1 section, 45 students
Spring 07	2 sections, 200 students total	1 section, 150 students
Summer 07	None	1 section, 150 students
Fall 07	1 section, 150 students	2 sections, 300 students total
Spring 08	2 sections, 300 students total	2 sections, 300 students total

In addition to the lectures, the M&I course entails many changes in the laboratory component of the course. In the M&I labs, there is a strong connection between lab and lecture content—the activities in lab each week are designed to explore and reinforce the concepts being discussed in lecture that particular week. (In contrast, many of the labs in the traditional introductory course at Georgia Tech are on topics different from what is discussed in lecture that week.) Because of this, laboratory teaching assistants (TAs) need to be familiar with the content of the course. The M&I labs are taught in an interactive studio style, where students engage in hands-on experiments, computer modeling activities, and group problem solving. Because of this, labs ideally require more than one TA per 20-student section, and special TA training is required.

In Spring 2006, a small number of graduate TAs were trained in the labs for both semester of M&I. These TAs served as experienced TAs in future semesters, and were supplemented with new TAs who were trained "just-in-time" during weekly course meetings. To make up for TAs lost from the pool each semester, a larger number of TAs new to M&I are assigned to the course each summer. In addition, in Spring 2007 we hired undergraduate TAs to assist graduate TAs in the labs. These undergrads were students who had taken the M&I course and performed well in it. They, like graduate TAs, are required to attend weekly meetings.

Assessment

Ongoing assessment of the M&I courses has focused in two areas. The first is student understanding of basic physical concepts as measured by standardized multiple choice instruments administered pre and post-instruction to both traditional and M&I sections in various semesters. In the first semester mechanics course, we administered the Force Concept Inventory (FCI)[3], an instrument commonly used at many institutions to measure understanding of force and motion concepts. In the second semester mechanics course, we used the Brief E&M Assessment (BEMA)[4], which consists of qualitative and semi-quantitative questions that cover a broad set of topics found in the typical introductory electromagnetism course[5], including electric and magnetic fields and forces, potential differences, circuits, and magnetic induction.

The second main area of assessment has been how each course affects students' abilities to solve complex problems. Part of the design philosophy of M&I is its emphasis on starting from a small number of basic physical principles and working through in a systematic way, rather than the use of specialized equations, formula memorization, and pattern-matching of solutions to example problems. As a way to compare the problem solving approaches of students from each course, several final exam problems common to both the M&I and traditional courses were given to students over several semesters.

BEMA Results

The BEMA has been administered to 16 Intro Physics II sections at Georgia Tech since Fall 2006. Eleven of these sections used the traditional curriculum, while five used M&I. In five cases, the BEMA was given only post-instruction; in all other cases students took both the pre-test and post-test. Table 2 summarizes the results from each individual section. Note that the number of students who actually took the test in each section varied for reasons having to do with the logistics of administering the test. For example, in the M&I sections, the BEMA was given in the labs, which typically have high attendance. In sections T1 through T8, the BEMA was given in lecture, but students were informed that it would count for bonus credit. Sections T8 through T11 also gave students bonus credit for taking the BEMA, but the test was given in an optional evening time outside of the usual class time. In section T6 and T7, students were given the BEMA on the last day of class, when attendance is typically low.

Table 2. Summary of pre and post-test BEMA averages for Intro Physics II sections.

Sec. ID	Class size	N (pre)	Pre %	N (post)	Post %
M1	43	43	24.5	40	59.8
M2	156	n/a	n/a	149	59.7
M3	154	n/a	n/a	148	57.4
M4	146	138	27.7	138	59.5
M5	149	140	24.7	139	55.9
T1	248	231	22.9	204	41.2

T2	240	219	22.9	195	40.7
T3	220	203	25.7	136	51.9
T4	238	212	25.1	144	50.8
T5	203	n/a	n/a	144	38.3
T6	134	n/a	n/a	29	45.2
T7	157	n/a	n/a	36	44.5
T8	118	88	27.8	73	54.8
T9	135	112	26.5	84	51.6
T10	162	128	25.3	103	50.3
T11	155	127	25.8	98	49.5

Note that in cases where the pre-test was given, the average pre-test score ranged from about 22% to 27%. Making the assumption that each class enters Intro Physics II with approximately the same average performance on the BEMA, it is useful to compare just the post-test scores. Figure 1 plots the average BEMA post-test percentage for each section. With the exception of section T8, the M&I sections consistently outperform the traditional sections.

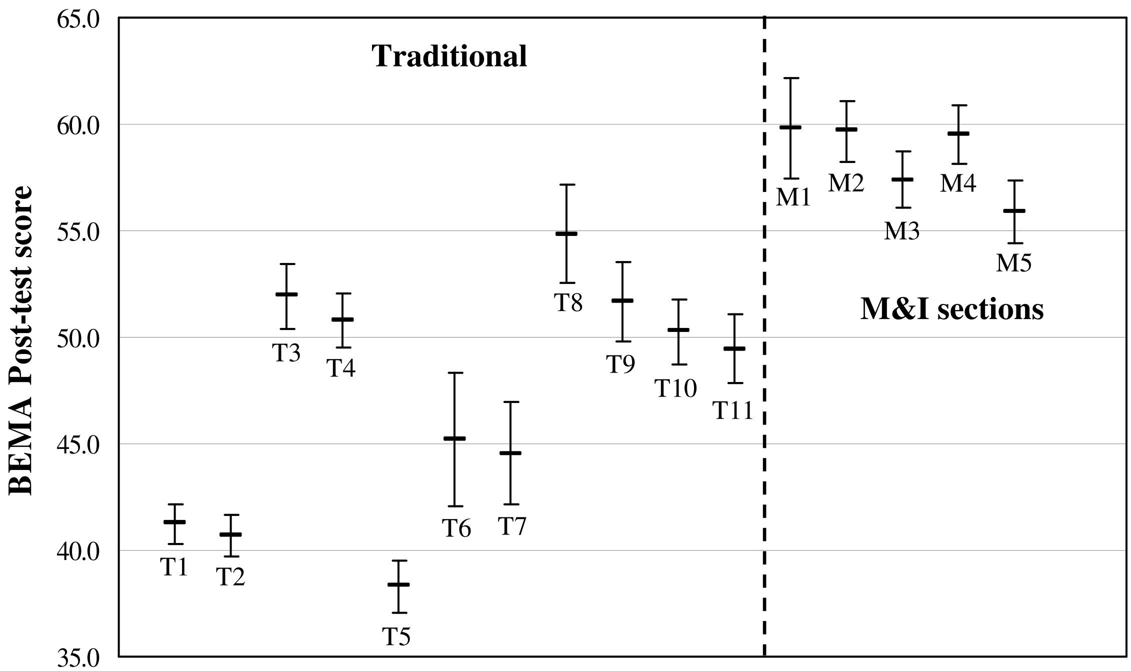

Figure 1. BEMA average post-test percentages by section (+/- standard errors).

For those sections where a pre-test was administered, pre-test and post-test data for each student that took both were matched and a raw gain (post minus pre) was calculated. Figure 2 shows the average matched raw gains for each section, while Figure 3 shows the average normalized gain by section. The average normalized gain, or <g> factor, is defined as the average of the gain from pre-test to post-test divided by the maximum possible gain, or (post% – pre%)/(100% - pre%). This factor attempts to control for the differing average pre-test scores among introductory physics classes and therefore provide a meaningful point of comparison across different classes and even different institutions. Again, section T8 excepted, students in the M&I sections on average had noticeably larger raw gains and normalized gains in BEMA performance after instruction than students in the traditional sections.

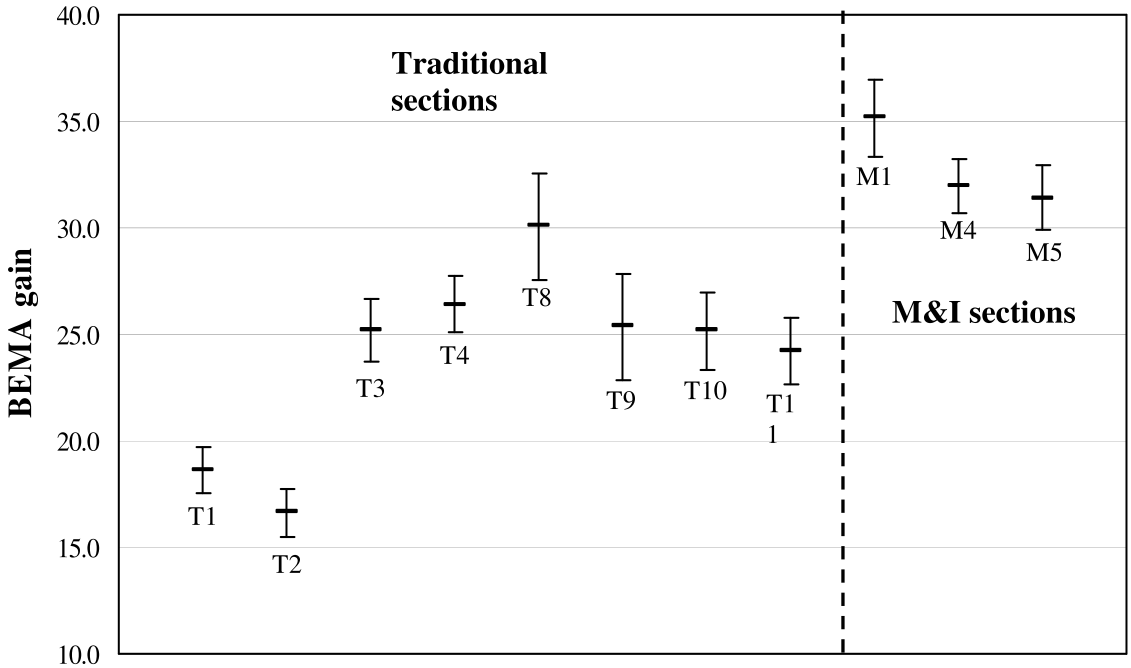

Figure 2. BEMA average raw gains (post % - pre %) by section (+/- standard errors).

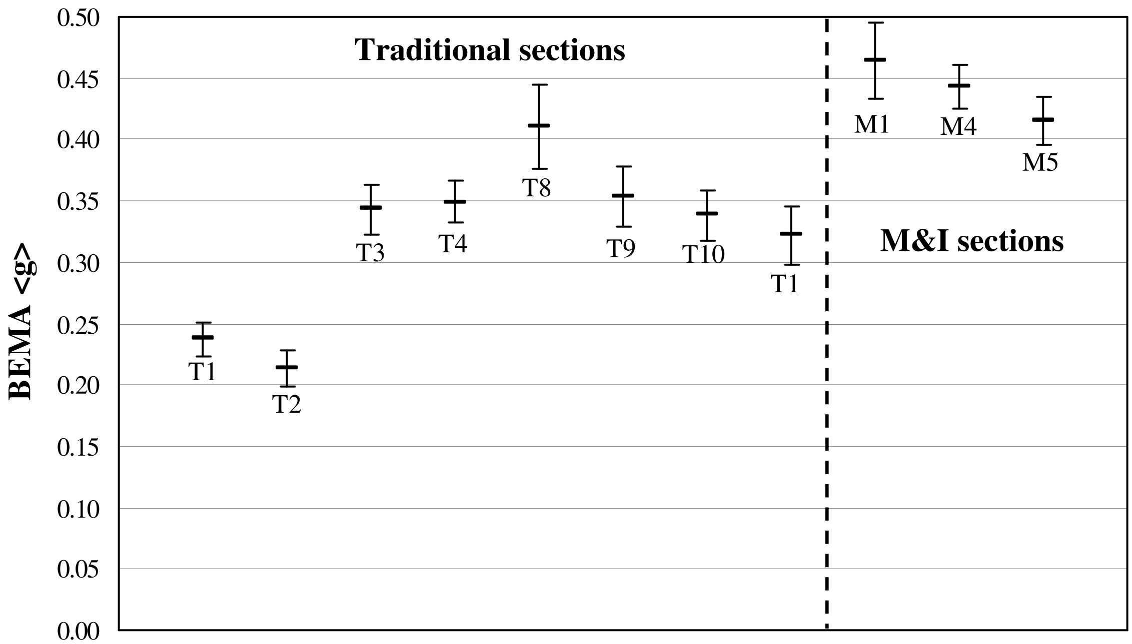

Figure 3. BEMA average normalized gains by section (+/- standard errors).

FCI Results

The FCI has been administered to Intro Physics I classes at Georgia Tech for several years. Average normalized gains are commonly reported as a summary statistic for FCI results because there tends to be wide variability in students' knowledge of mechanics concepts prior to instruction. For example, students entering a high school physics course may score 20% on the FCI pre-test, while well-prepared students entering a premier science and engineering university may have a pre-test score as large as 60% or 70%. It then becomes particularly important to take incoming performance into account and to measure the fraction of possible gain. (This is less of an issue with electromagnetism—very few students have had much prior exposure to the topics discussed in introductory E&M course.) Hake[5] surveyed results from a large number of introductory physics classes across many institutions and found that classes that used interactive pedagogy had an average <g> of 0.48, approximately two standard deviations higher than the average <g> of 0.23 for classes using traditional pedagogy. The average normalized gain for Intro Physics I at Georgia Tech in past years has ranged from approximately 0.3 to 0.5.

As a specific example, we focus on the results from the Fall 2006 semester. Table 3 lists the results for the FCI for Intro Physics I sections at Georgia Tech in Fall 2006, three of which (identified as sections A, B, and C) used the traditional curriculum and one of which (section M) used M&I. The average pre-test score of the M&I section was noticeably higher than for the other sections; this may be because the M&I section was advertised as a more challenging alternative to the traditional course, perhaps causing more highly motivated students to enroll. Despite the high pre-test average, the post-test average was nearly identical to those of the other sections, and as shown in Figures 4 and 5, both the average raw gain and normalized gain for the M&I section were significantly lower than in the other sections.

Table 3. Summary of FCI results for Intro Physics I sections in Fall 2006.

Sec. ID	Class size	N (pre)	Pre %	N (post)	Post %	Raw gain	<g>
A	153	139	**45.8**	103	**70.1**	26.7	0.48
B	213	182	**47.3**	158	**64.0**	18.3	0.34
C	210	194	**42.0**	140	**61.3**	20.1	0.35
M	133	127	**54.1**	116	**64.7**	11.0	0.23

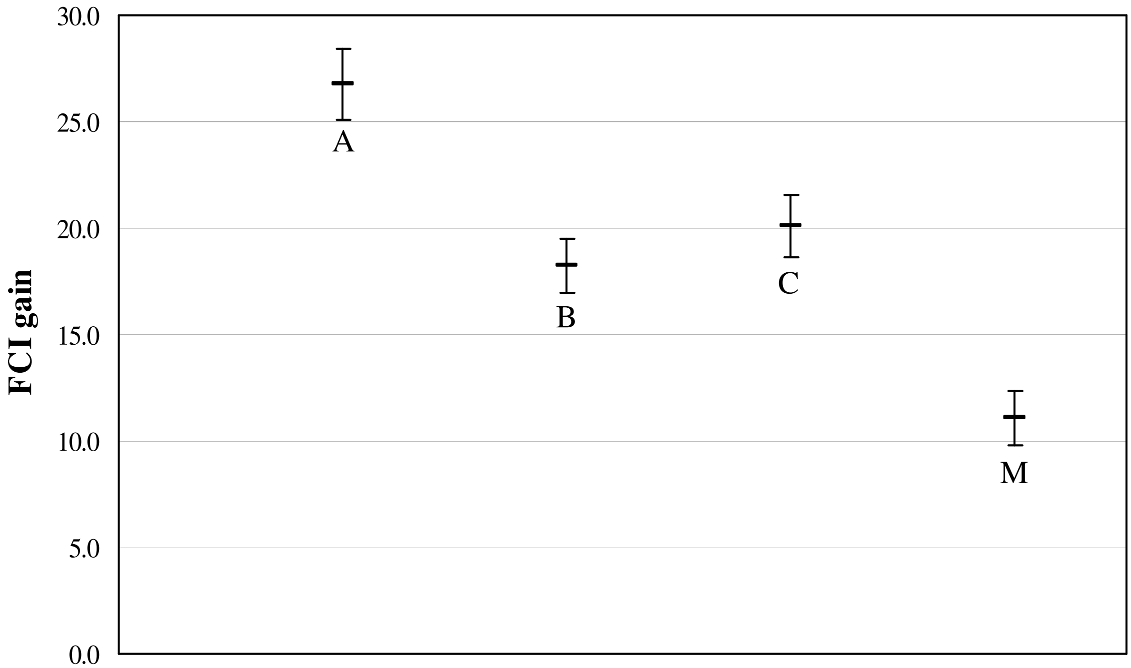

Figure 4. FCI average raw gains (post % - pre %) by section (+/- standard errors). Section M is M&I course, all others are traditional.

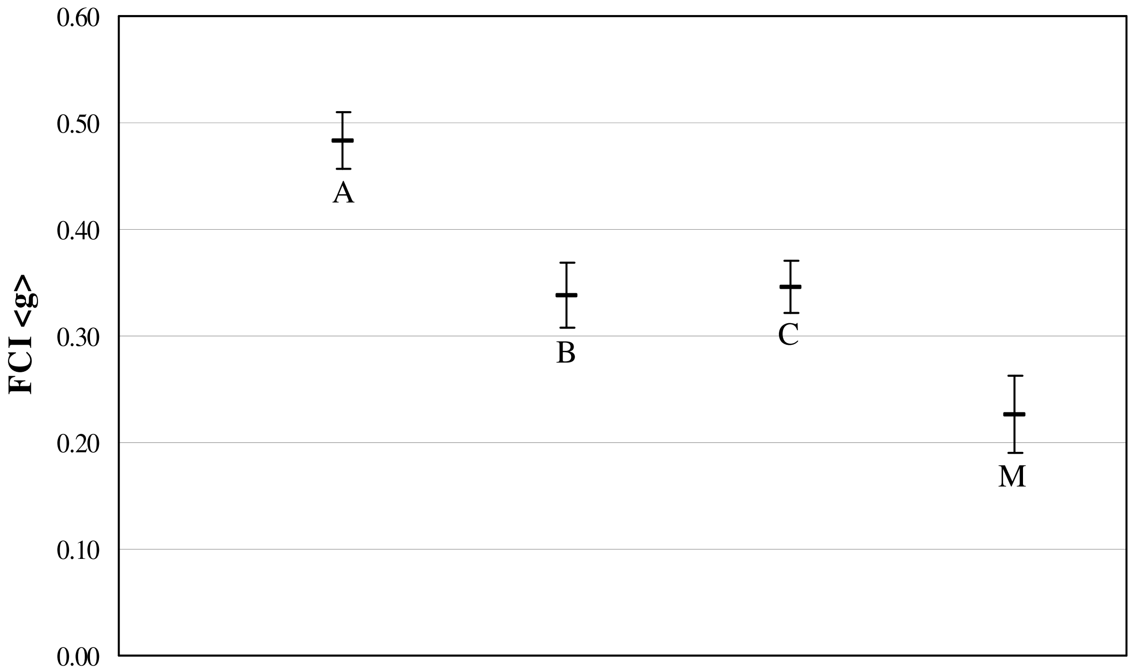

Figure 5. FCI average normalized gains by section (+/- standard errors). Section M is M&I course, all others are traditional.

The FCI results for the M&I course are particularly disappointing considering the innovative content and pedagogy of the curriculum. In addition to modern content, instructors in M&I make use of in-class multiple-choice questions on new concepts in the lectures, where students respond using hand-held electronic remotes. These lecture questions, as well as the interactive studio labs, are two commonly used "interactive engagement" methods that often lead to improved FCI gains as discussed by Hake and others. We comment on possible reasons for this discrepency and describe our research efforts to help shed light on it in the Discussion section below.

Common exam questions

Several common final exam questions were given to both traditional and M&I courses, both in mechanics (Fall 2006 and Spring 2007) and E&M (Spring 2007). Instructors agreed to place certain identical problems on their respective final exams on topics that they found both interesting and fair for their students to answer. The strategy we used to analyze students' solutions was to break the solution path of the problem into a series of binary (yes or no) decisions. For example, if the first step in solving the problem is to invoke Newton's Second Law, this step is examined, and if present in the student's solution, is coded as present. In addition, for certain problems, common incorrect approaches were observed for a large number of participants, and the frequency of these errors were recorded.

Assessing the results of these problems is a currently ongoing effort. We have found, however, that for the mechanics courses, choosing problems that lead to meaningful comparisons with conclusive results is very difficult. There is limited content in common between the M&I and traditional mechanics courses (a less serious issue in E&M). Because the FCI was developed in the context of traditional physics mechanics courses, the problems on it are typically ones that students in the traditional course had seen many times before. Students in M&I, who were less familiar with these problems, tended to write more detailed solutions that developed from fundamental principles, whereas traditional course students' solutions were often terse, as if solved by rote. More systematic analyses of students' answers, however, are required to confirm this. We also plan to revise how problems are chosen in future comparisons.

In the electromagnetism course, a clearer picture emerged with one particularly difficult problem that was given to one traditional section (T7 in Table 2) and an M&I section (M2). The problem, shown in Figure 6, was a classic application of Faraday's Law of Induction, where a changing magnetic field through a region of space within a closed metal loop induces an electric current in the loop. Students were given the changing magnetic field as a function of time and asked to find the magnitude and direction of the induced current. Although both the traditional and M&I sections had difficulty with the problem, there were some striking differences in performance, as shown in Table 4. In particular, students in the M&I section were much more successful in choosing the correct fundamental principle needed to tackle the problem; 43% of the traditional course students used a completely incorrect principle (often Ampere's Law) to start the problem, while only 15% of the M&I students made such a fundamental error. Fifty-one percent of the M&I students were able to find the magnitude of the current (ignoring minor calculational errors) as compared to 32% of the traditional students, and 57% used correct reasoning to find the correct direction of the current, as opposed to 36% of the traditional students.

A uniform magnetic field is present in a circular region of radius 6 cm. In this region at any given time, the magnetic field may be pointing directly out of the page (in the +z direction), directly into the page (in the –z direction), or it may be zero. The z-component of the magnetic field in this region changes with time according to the function $B_z = Kt^2 - P$, where t is time, $K = 0.12$ T/s^2, and $P = 3.0$ T. Outside of the 6 cm radius, the magnetic field is always zero.

A thin metal ring of radius 11 cm is concentric with the region of magnetic field. The ring has a resistance of 1.3×10^{-3} Ω.

(a) At time $t = 3$ s, find the magnitude of the induced current in the metal ring.

(b) At time $t = 3$ s, find the direction of the induced current in the metal ring (clockwise, counter-clockwise, or zero), and briefly explain your reasoning.

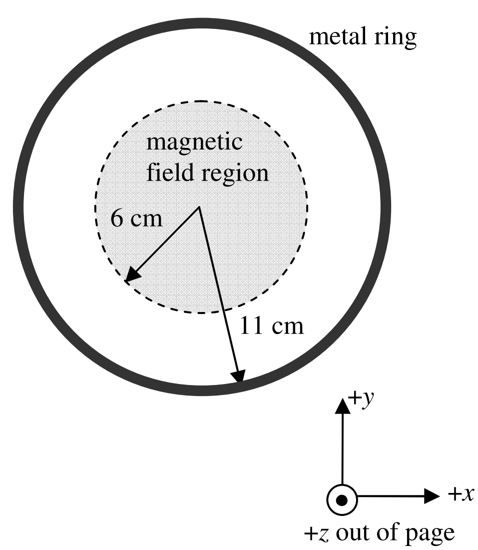

Figure 6. Magnetic induction problem given to both a traditional and M&I Intro Physics II section on the final exam, Spring 2007.

Table 4. Results of common final exam magnetic induction problem, Spring 2007.

Feature of student solution:	**Trad. EM sec. N=157**	**M&I EM sec. N=152**
Completely correct (magnitude & direction)	17%	28%
Used **correct approach** to find magnitude of the current (with possible minor errors)	32%	51%
Used **wrong principle** to find magnitude	43%	15%
Correct direction with correct reasoning	36%	57%

Discussion

Results of both standardized qualitative assessments and initial analyses of student solutions to complex problems show that the second semester electromagnetism M&I course is generating positive results. The course seems to be meeting the goals of providing students with a deeper understanding of basic principles in electromagnetism and greater skill in using these principles to tackle complex problems. M&I FCI results from the mechanics courses, however, have been disappointing. One possible explanation is that the FCI is couched in the language and emphasis of the traditional physics course. For example, the FCI has a large number of items dealing with constant acceleration projectile motion, a topic that is heavily emphasized in the traditional course. M&I de-emphasizes constant acceleration kinematics in favor of impulse and changes in momentum. However, the concepts covered by the FCI are still important, and we feel that M&I students can and should be able to master them with proper training in how to invoke the physics concepts they learn. We must also keep in mind that the FCI covers only a small number of the concepts discussed in the introductory physics course. Measurements and comparisons still need to be made with regard to each curriculum's affect on students' understanding of energy, angular momentum, and the structure of matter, for example.

To learn more about the details of students' reasoning on force and motion problems, we are currently conducting a study using a think-aloud protocol methodology[6]. Volunteers who have previously taken an introductory mechanics course, either M&I or traditional, are observed solving problems taken from the FCI in a one-on-one interview setting. The problems chosen are those on which M&I students performed the poorest as compared to traditional course students, and deal with topics such as constant acceleration kinematics, identification of forces, and Newton's 2nd and 3rd Laws of motion. While solving these problems, volunteers are instructed to talk out loud about how they are reasoning through each problem. This technique is useful in getting insight into what knowledge is invoked when solving a problem, and what difficulties students have on specific problems. From this study, we hope to gain a better understanding of what aspects of M&I students' understanding of these concepts is lacking, or where their understanding is not being invoked. We expect that these insights will guide us in making improvements to instruction.

Acknowledgments

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