VECTOR: A Hands-On Approach That Makes Electromagnetics Relevant To Students

C. F. Bunting and R. Alan Cheville, *Members, IEEE*

Abstract— A two course sequence in electromagnetics (EM) was developed to address a perceived lack of student learning and engagement observed in a traditional, lecture-based EM course. The two course sequence is named VECTOR: Vitalizing Electromagnetic Concepts To Obtain Relevance. This paper reports on the first course of the sequence. VECTOR incorporates active learning methods with three projects to address three inter-related objectives: 1) make the required EM course more relevant to students by demonstrating the impact of EM on emerging technologies, 2) teach students how to utilize modern EM simulation and characterization tools, and 3) improve student attitudes about the introductory EM course to help pipeline students into the electromagnetics-photonics specialization in the undergraduate program. To assess the effectiveness of VECTOR the course was taught as lecture for one semester then taught three semesters in the project-based format. Assessment indicates significant changes to how and what students learned. VECTOR was effective in meeting the first objective with mixed success on the others.

Index Terms—Electrical engineering education, Electromagnetic engineering education, Educational technology, Education, Electromagnetic fields

I Introduction And Background

At Oklahoma State University (OSU), as at many programs nationwide, electrical engineering students are required to take a single electromagnetics (EM) course. This course is taken in the junior year and typically has an enrollment of 30–70 students. The introductory course was previously taught in a lecture format with individually graded summative evaluation (homework and exams) comprising the largest part of the course grade. Over time faculty dissatisfaction arose from poor student performance and engagement, while students did not see the relevance of the course content.

The introductory EM course serves two student groups. One group takes the required EM course as part of their plan of study, specializing in some other area of electrical engineering. The second, smaller group—on average 10-20% of students—takes additional elective EM and photonics courses as part of their area of specialization within the department. The EM course has become more important for the non-specialist group since cross-disciplinary topics such as electromagnetic compatibility, photonics, and wireless communication require a working knowledge of EM. Most traditional EM courses and textbooks, however, focus on canonical problems and analytic skills that will only be needed by the second, smaller group of students. One wonders if the rigorous, analytic approach taken by many EM courses ironically maximizes the first group of students while minimizing the second group.

This paper describes a multi-year course reform effort to change the introductory EM course to better serve the needs of non-EM students and how the changes impacted student learning. The course reform was named VECTOR: Vitalizing Electromagnetics Concepts to Obtain Relevance. VECTOR is a two course sequence, the first course is taken by all ECEN students while the second course is required for students who specialize in electromagnetics. VECTOR moved analytic problems and formalism to the second course, replacing them by EM design projects that focus on how to mathematically define and solve problems using computational and analytical methods. This paper discusses the first, introductory course, a subsequent publication will discuss the second course.

The first course of VECTOR has three inter-related objectives: 1) make EM more relevant to students, 2) give students experience with modern simulation and characterization tools used for EM design and testing, and 3) improve student attitudes about EM. The first, core objective of making material more relevant arose from the observation that typical EM problems sacrifice authenticity to make them analytically tractable. Since engineering students employ active [1] and sensory [2] learning styles VECTOR teaches the applications and impact of EM before focusing on analytic solution techniques. To address the second objective, design projects gave students experience with modern simulation and characterization tools. VECTOR hypothesized that having students use tools they perceive as identical to those used by “real” engineers would make course material more relevant. The use of simulation and characterization tools also is hypothesized to help students affirm the validity of concepts by serving as formative evaluation of student understanding. The third objective, changing attitudes, arose from the fact that many students viewed the EM course as a “weed-out” course rather than a key component of their education. VECTOR hypothesizes that making EM relevant will improve students attitudes about the importance of this subject and results in more students choosing to specialize in the

EM/photonics area.

Changes to the course structure and content were made in order to meet the three objectives. In the lecture EM course students attended class three times per week, submitted a homework assignment once a week and had three exams over the fifteen week semester. Course material was introduced sequentially following the order in the textbook. VECTOR rearranged course material to teach EM in the context of design problems [3]. Three projects illustrate how EM is used in a real world scenario or problem. The first project illustrates electrostatics, the second project transmission lines, and the third project antennas and radiation. For each project one class period is used to introduce the project through a case study. Rather than weekly homework assignments students are assigned a reading assignment for each class period; a graded on-line electronic quiz allows them to test their understanding of the reading material before coming to class. Lecture is used sparingly; in two thirds of class periods students engage in active learning [4-6] as a team. Active learning exercises consist of analytic and computational problems related to the project that are due at the end of each class period. The instructor assists teams who have difficulties with in-class problems.

The out-of-class homework done in the lecture course is replaced in VECTOR with work on design projects. Students work on the project in two stages. Teams first design the project using computational modeling and visualization tools. In the second stage teams measure the characteristics of their design using test and measurement instrumentation. A report comparing the measured and simulated performance of the teams designs comprises a large portion of the course grade. The projects mimic the environment of practicing engineers, integrate communication and teamwork skills, and permit EM to be discussed in the context of social, economic, and ethical issues [7]. In both lecture and VECTOR exams are used for summative evaluation of students.

The remainder of this paper is divided into three sections. The first section outlines how VECTOR was designed and the reasoning behind the choice of educational techniques used. The second section details the three design projects and their common features. The final section reports on changes to student learning between the former lecture course and the project-driven VECTOR model.

II Course Design of VECTOR

Previous work has looked at improving conceptual understanding of electromagnetics in both freshman physics courses and junior year E&M courses [8-13]. In general, projects have focused on developing laboratory exercises or simulations [10, 12, 14, 15] rather than investigating student misconceptions. Faculty involved in VECTOR reviewed much of this work as well as drawing from previous work at OSU in reform of the photonics course sequences [16] before and during VECTOR.

It is known that students often do not obtain a valid conceptual understanding of electromagnetics [9] despite significant amounts of instruction. Misconceptions are pervasive and difficult to change. In the related field of photonics the longevity of misconceptions has been attributed to a student view of light being a `matter based' concept to students rather than a `process based' one [17]. As pointed out in the seminal paper by Chi et. al. [18], it is more difficult to correct a misconception when the correction requires a shift between ontological domains than if it remains in the same domain. In other words, when students perceive rays of light or electric field lines (processes) as having characteristics of physical solidity (matter) it can be very difficult to change their view. Later work [19] has shown that misconceptions about “direct” processes are easier to correct than misconceptions about “emergent” processes. Direct processes arise casually from events or actions and generally can be readily visualized by students since they correspond to processes students are likely to have experienced. Emergent processes on the other hand emerge from interactions of many particles or forces and the causal reasons for the process are not typically drawn from experience. Charge distributions, electric fields, and radiating systems are all examples of emergent processes.

To teach concepts based on emergent processes VECTOR used design activities that were relevant to students and relied on students using their understanding of emergent processes. Students applied EM concepts by designing and testing devices whose function can be understood conceptually. Since most undergraduates have difficulty with EM concepts VECTOR supported students by explicitly modeling the design process, i.e. showing students how basic concepts are related to and drive design decisions.

To model the design process for students both topics and concepts were matched to design projects. Through brainstorming sessions faculty broke topics from the textbook into three defining questions: 1) how do charges apply force and carry energy 2) why don’t circuits work the same way at high frequencies, and 3) how are energy and information sent through space? A project was chosen to illustrate each of the three questions. To illustrate fields and charge students designed a device that created a spatial potential distribution as an interface to a remotely controlled vehicle. To learn why circuits behaved differently at high frequencies students built a stripline filter with given impedance and S parameter to send data to an antenna on the vehicle control system. To learn how energy and information were sent through space students designed a patch antenna to efficiently send RF signals to the remotely operated vehicle to maximize the control range. All projects were based on the same remote control vehicle system to permit students to revisit engineering concepts [20]. The topics traditionally taught in the course were matched to the questions. Two topics—Biot-Savart and Ampere’s Laws, and magnetic energy and vector potential—did not align with a project and were de-emphasized.

Participating faculty chose teaching techniques that would make the material relevant to the students. At the start of each of the modules a case study was used to introduce students to the topics through open-ended, student-led discussion. The case studies [21] were written to have students play the role of design engineers researching technologies to be used in the design of a wireless robot controller. The case study [22] placed the project in a context relevant to students, introduced basic concepts and terminology, allowed class discussion of introductory concepts, and increased attendance [23].

Students worked on teams both to develop teamwork skills and to draw from the reported benefits of teamwork [24]. Teams consisted of four students and team membership remained constant for all three projects. To help ensure well defined individual responsibilities [24] students were given different roles on each project. The four complementary roles were project manager, project scientist, project engineer and logistics officer. No formal training in teamwork was provided although students did engage in some team building exercises at the start of the semester.

Classroom activities were chosen that supported the design projects. Faculty decided to use active learning to address the predominant learning styles of engineering students by adopting a modified form of team learning [25] from an undergraduate photonics course [16]. Readings on a specific concept were assigned for each class period from text, web, or other resources. A web based formative quiz was due before class. Each student received immediate feedback on their performance and was able to take the quiz multiple times with the highest grade they obtained recorded; some quiz problems changed each repetition. On-line quizzes accounted for 15% of the course grade. The quizzes helped prepare students for class since they had already worked with ideas that were reinforced through active learning.

Three different teaching modalities were used during class to address diversity of student learning styles [1, 2]. A review lecture placed concepts in the context of the project. A team active learning assignment related concepts from the quizzes to the project. Alternatively, meeting in a computer lab provided training and guidance on numerical simulation.

The goals of team design projects—an important part of VECTOR—were to illustrate application of concepts, be practical and authentic, and balance student time constraints with sufficient challenge. Since students may not have had sufficient expertise to realize when they were pursuing non-productive directions on projects, each project was broken into two related parts: a design phase and project fabrication and testing. Teams first submitted a design proposal of the project and received feedback on design errors or misconceptions. To reduce the time spent by students the project was built by a TA. Teams tested performance using shared test and measurement instruments and self-scheduled lab hours.

Each project concluded with a team report that compared simulation with the measured characterization of the project. VECTOR used written rather than oral reports [26]. Three different report formats were used: a five page white paper for the first project, a poster for the second project, and a longer scientific report for the third project. To help ensure consistency in project evaluation and grading, a scoring rubric was made available to students at the time the report was assigned. Each of the reports included a reflective statement by individual students and peer evaluation, a vital part of team learning [25]. Written exams were given near the end of each project and a comprehensive final focused on traditional calculations and conceptual understanding (plotting electric fields, identifying paths of zero work, radiation behavior).

To summarize, VECTOR reduced the focus on analytic problems and the mathematical processes typically found in an introductory fields course. Course topics and concepts were mapped to projects that demonstrated the application of EM across multiple disciplines. Projects were supported by formative evaluation done outside of class and active learning in class. Students used numerical simulations to design devices and then compared the measured performance of these devices to the predicted performance. Written communication was heavily emphasized. In making these changes less time was spent explaining EM to students through lectures, students performed significantly fewer analytic calculations, and spent less time out of class working individually on homework problems.

III VECTOR Projects

The VECTOR projects that illustrate authentic applications of electromagnetics are described in this section along with illustrative examples of student work and features common to each project Further details can be found in [21] or by contacting the corresponding author.

A Touch Pad Sensor Project

To teach fundamentals of electrostatics a project was adapted from published laboratory exercises using resistive paper to simulate potential distributions in dielectrics [26, 27]. A voltage is applied to metal contacts on conductive paper (10 kΩ per square) and point by point measurements allow students to visualize potential distributions [28]. In VECTOR two sets of parallel conductive paint contacts were applied to resistive paper as shown in Fig. 1. A 10 VDC bias was applied alternatively between each set of contacts while isolating the other contacts using FET switches. The position of the probe can be determined from X and Y potential if the potential distribution can be calculated.

Student teams designed a touch pad interface to steer a remotely controlled vehicle. Students first learned finite difference methods in class then performed finite element simulations using COMSOL Multiphysics® [29] to calculate a contact shape that created a linear potential across the center part of the resistive paper. On-line quizzes helped students visualize potential and field distributions in two dimensions [30]. Stencils fabricated using a computer controlled printed circuit board mill allowed student designed contacts to be reproduced using conductive paint. Students measured the potential distributions using an analog to digital converter with a LabView® interface.

Teams tested the linearity of their touch pad design by moving the probe in concentric squares; Fig. 2(a) shows a typical measurement of a contact design that did not create linear fields. Potential measurements were used to calculate the field gradient, Fig. 2(b).

The touch pad was then used to steer a radio controlled vehicle, Fig 2(c), so teams could experience the scenario introduced in the case study. To control the vehicle a voltage pair from the touch pad was used to reference a look-up table that sent a text string over a 2.4 GHz wireless data link. The vehicle had an embedded microcontroller that controlled speed, direction, and LED lights. Teams' ability to control the car gave them immediate visual feedback on the effectiveness of their design of their design and those of other teams. It turned out to be difficult to create contacts with sufficient linearity to accurately control the vehicle due to the effect of small changes in contact shape and inhomogeneities in the resistive paper. Later iterations of this project used simple parallel contacts with add small conductive patches to the center part of the resistive paper. Each patch forms an equipotential region with the potential dependent upon the position, size, and shape of the contact. Student teams were given the X and Y voltages needed to control the car and had to design a pad with patches positioned correctly to provide sufficient control of the vehicle.

B High Frequency Interconnect Project

The second project had teams design microstrip filters using concepts of distributed inductance, capacitance, and impedance. The case study built on the previous project by having students design a filter element near the data communication frequency of 2.4 GHz. Students used a custom MatLab graphical user interface (GUI) for the "first pass" filter design then refined the design using Sonnet® [31] and COMSOL Multiphysics®. Example programs enabled students [29] to visualize fields from transmission line filter elements.

The passband and stopband frequency near 2.4 GHz assigned to teams determined the number of inductive or capacitive transmission line segments that made up the filter. Multiphysics allowed students to visualize the field distributions of their filters and calculate the capacitance from the stored energy. Teams calculated the S parameters of their filters numerically using Sonnet Lite Plus. Filters were fabricated by course TA's on photo-sensitized Rogers 3003 material. Each team measured the complete S parameters of their filter using an Agilent 8722ES vector network analyzer. Fig. 3 shows student data of the Matlab and Sonnet simulations as well as the measured S_{21} parameter [32]. Students were asked to explain discrepancies between measurements and simulations and discuss the sensitivity of their design to small changes in geometry.

C Patch Antenna Project

A continuation of the case study of young engineers designing a control system for a remote vehicle introduced the third project. Student teams designed and characterized a 2.4 GHz wireless communication patch antenna used to transmit control data to the car. The project helped students visualize propagation of energy and simple radiating systems (antennas and Maxwell's equations). Design parameters were the center frequency of the antenna, bandwidth, and the reflection coefficient of the antenna feed line. Teams chose the geometry, size, and thickness of their antenna printed circuit board substrate using a custom-designed Matlab GUI that suggested geometries for the antenna. Teams then simulated the antennas using Sonnet, calculating the frequency dependent S_{11} parameter over the first and second resonant modes, the spatial current distribution in the antenna at resonant frequencies for the first and second resonant modes, and the far field radiation pattern of the antenna at first and second modes. The antenna dimensions were iteratively adjusted to achieve specifications and the shape of the feedline was designed to correctly impedance match the antenna. A sensitivity analysis was performed to determine how the S parameter changed with the antenna geometry. A student-designed patch antenna is shown in Fig. 4(a) along with the current distribution and sensitivity analysis, Fig. 4(b, c).

Antennas were fabricated by teaching assistants and an SMA connector was soldered on to the end of feedline to let teams perform measurements. Teams measured the S parameters of the antenna using a vector network analyzer. The radiation pattern was measured using a small anechoic chamber in conjunction with an Agilent E4418B RF power meter.

D Common Features

The three projects shared common features defined by the course learning objectives: each project was introduced by an in-class discussion of a case study, students selected pre-defined roles that rotated between projects, and portions of each project were modeled to students through active learning exercises in the classroom. All projects emphasized technical communication; the entire project grade was based solely on the project report. The first and third projects required a written report while the second project had the teams present a poster. To ensure consistency and minimize subjective grading students were given a template for each report and projects were graded using a rubric [32, 33]. Report templates supported the learning objectives of VECTOR by requiring teams to describe the background and purpose of the project, compare the results of simulations and measurements, create a table of specifications of their device, and provide a list of citations. Creating a table of specifications gave students experience in making quantitative judgments on the success of their design and related EM concepts to practical engineering concerns.

Additional elements common to each project were individual reflective statements and peer evaluation. Students were asked to write a one page self reflection statement that covered their contribution, the most and least valuable aspects of the project to their future goals, and how their team performed. The reflective statements were designed to have students place learning in the larger context of their own educational goals making the project relevant (outcome #1) and also to provide feedback to the instructors to identify course elements that were problematic or negatively affected student attitude (outcome #3). Reflection has been shown to promote deeper understanding [35]. Peer evaluation was used as a necessary component of team learning to allow team performance to have an impact on the grade assigned on a project [24]. A peer evaluation tool was developed for VECTOR that has since been validated in other courses [36]. Students evaluated peer contributions to each project, and ratings were used to scale grades, which gave less discernment on the reported scores [37] but also increased the potential negative impact of not participating in team projects.

IV Evaluation of Changes to Student Learning

This section provides three viewpoints on how transitioning from a traditional lecture course to VECTOR affected how and what students learn. The first viewpoint analyzes VECTOR's success at achieving the three learning outcomes defined at the start of the project. The second point of view examines changes in how students learned electromagnetics. VECTOR is finally evaluated by looking at changes to student learning and attitude that were not anticipated at the start of the project. Here, the focus is on processes rather than outcomes- what caused changes to student learning and how can they be replicated and improved?

To permit comparisons between the traditional course and VECTOR the EM course was first taught as a lecture course. The instructor had taught the course for the previous four semesters ensuring comparisons were made to a well organized lecture course taught by an experienced instructor with extremely high teaching evaluations. Material was developed for VECTOR over the summer and the course was then taught on an annual basis for three consecutive years. The authors' experiences with other course reform efforts have indicated that three iterations of a course is approximately the time required for major course reform to become effective. This observation will be discussed later. Sample sizes ranged from N = 47 to N = 35 students over the course of the study.

The study of how student learning changed during VECTOR was subject to several limitations. VECTOR was not a rigorous pre-post intervention since evaluation was used to change both content and pedagogy; results between semesters are not directly comparable. Changes were also made to the undergraduate curriculum during the period VECTOR was run. These included adding the second EM course and teaching the first EM course once a year on OSU's main campus and once a year on the Tulsa campus. Tulsa sections were taught using lecture. It was not possible to select students or randomize samples; students were free to self-select whether they wished to take the televised lecture course from the Tulsa campus offered in the spring semester, travel to Tulsa to attend the lecture, or take VECTOR in the fall semester. While there may be some effect due to self selection, this effect is likely small due to the two courses being offered during alternate semesters and the fact that this course is required for graduation.

A Project Outcomes

The first viewpoint from which VECTOR is evaluated is achievement of the project outcomes: to make the required electromagnetics course more relevant to students, to integrate modern research tools, and to improve student attitudes about EM. To measure how relevant students perceived EM, an on-line Student Assessment of Learning Gains (SALG) [22] survey was given at the end of the semester. Response rates averaged over 80%. While recent studies have cast doubt on student's abilities to self-report their level of knowledge [38], the SALG asks students to self-assess changes to their learning over a relatively short time period and assesses changes to skills, cognition, and attitude, important for VECTOR goals.

Students' responses to the question "How relevant was this class to what you will be doing in your career as an engineer?" are shown in Fig. 5(a). The number of students who indicated that the course was very relevant to their career increased after implementation of VECTOR. Four questions on the SALG asked about issues related to relevance: why EM was important for engineers to know, how the course was related to other courses in the curriculum, whether the skills they developed would be useful in the future, and how engineers worked in the "real world". The change in the mean student response is shown in Fig. 5(b) for the initial lecture course and the three subsequent semesters of VECTOR. High values (> 3) represent increases while low scores (< 3) indicate little to no increase.

The second outcome of VECTOR was to integrate modern research tools into the course. It is difficult to make a quantitative comparison between lecture and VECTOR since the structure of VECTOR ensured this goal would be met to some degree. For example VECTOR students reported they learned less from lecture [39] and more from computer modeling; this result is expected since lecture was replaced with active learning.

The effect of integrating software and hardware tools into the EM course was thus determined by qualitative analysis of individual reflective statements in student project reports. While 20% of students reported that hardware and software tools were the most valuable aspect of the course, 30% saw them as the least valuable aspects. Students who valued these experiences saw broad applicability of the tools. Those who reported less value either viewed the tools as only applying to a narrow range of specialized problems they would not use again, or focused on technical difficulties with using the tools. Technical difficulties arose from introducing projects, software, and instruments that were not fully debugged or without sufficient documentation. The fact that students saw broadly applicable tools such as finite element simulation software as having little application outside their project may indicate that for some students the projects over-contextualized learning. Demonstrating the broad applicability of the tools to a wider range of problems would improve VECTOR.

The third outcome of VECTOR is to improve student attitudes about the introductory EM course to help pipeline students into the electromagnetics-photonics specialization in the undergraduate program. One question on the SALG asked students about their enthusiasm for the material taught in the course. There were no statistically significant ($p < 0.05$) changes between lecture and any iteration of VECTOR of either the mean or distribution of student responses.

Since improving student attitudes was done in part to increase the number of students who pursue additional elective courses in EM and photonics, looking at enrollment of elective courses may serve as a proxy for attitude. At the start of VECTOR the ECEN department implemented student “areas of specialization” in 2003 in response to internal changes driven by EC-2000. At this time students were asked to choose a coherent series of five to seven elective courses from six different areas in the undergraduate program. In 2004 less than 5% of graduates were in the EM&P area; this is expected since few students had graduated with a declared area at this time. In 2005 18% of graduates were in EM&P, 7% in 2006, and in 2007 35% of the graduates are in this area. While there is expected to be wide annual variation in these numbers, VECTOR initially seems to be having a positive impact on recruiting students into this area. These numbers may also be affected by elective photonics courses previously converted to an active learning format [16].

B Changes to Student Learning

The second viewpoint from which to examine the impact of VECTOR on students is by examining changes to how students learned or what they saw as the most valuable resources to learning. Changes between lecture and VECTOR student responses from the SALG were analyzed using a t-test [40] with $p < 0.05$ taken as the level of significance. In order from the largest reported change to the smallest significant change VECTOR students reported learning more from: projects, on-line quizzes, and computer modeling. Students reported learning less in VECTOR compared to lecture from: lecture, studying for and taking exams and tests, the instructor, homework, and reading the textbook. The conclusion from these results is straightforward: students learn from the tools they are given. As the Zen koen elegantly states it, "The Zen way of doing things is to do them" [41]. Learning to use modern engineering tools requires students have access to these tools and be given assignments that require their use.

Did the fact that students reported that they learned less from summative exams mean their performance on solving analytic problems decreased? Due to changes in exam questions and format it was not possible to directly answer this question by looking at pre-post performance on given problems. Faculty, however, observed few substantive changes to how well students performed on examinations. One observation was that students generally performed better on aspects of visualizing EM fields in VECTOR but did not make substantial improvements in solving procedural problems requiring near transfer of concepts. Despite an emphasis on acquiring and plotting data students also had difficulty performing data analysis on exam problems unless the data was provided in a format they had seen previously.

Further support for the conclusion that students' ability to solve examination problems did not decline with VECTOR comes from examination of scores on the EM portion of the Fundamentals of Engineering (FE) test. The standardized FE score [42]—comparing the performance of ECEN students to the national average—is shown in Fig. 6; positive numbers indicate ECEN students outperformed peers. The vertical lines are the uncertainty of scores using the suggested Z statistic value [42]. The requisite EM course is nominally taken in the junior year, although some students wait until their senior year. Since the majority of students who take the FE are seniors the effects of VECTOR on FE exam scores should lag implementation, but this lag is likely not greater than one year.

Qualitative analysis of individual reflective statements about what aspects of VECTOR that students saw as the most and least valuable also provided insight into how students learned. While nearly all students could list a concrete experience or activity they saw as most valuable, nearly 40% of students were unable to write something substantive for the least valuable aspect of VECTOR. Statements were collected for the 2003 and 2004 years of VECTOR and grouped into similar categories for analysis. Overall the most valuable aspects of VECTOR were teamwork (35% of responses), the use of hardware and software tools (20%), illustration and application of concepts (20%), and seeing how to apply what they learned in class (10%). The least valuable aspects were the software used (20%), the need to learn details of the instrumentation (10%), and the focus on written communication (7%).

C Dynamic Evolution of VECTOR

Finally VECTOR is examined from the viewpoint of continuing evolution; i.e. how unanticipated changes to student learning and attitudes stimulated dynamic changes to the course. The following paragraphs report both on changes made during the duration of VECTOR as well as the lessons drawn from these changes.

The initial offering of VECTOR provided extremely mixed feedback to faculty. For example student responses to the question “How much to you feel you learned in this class compared to other classes you have taken at OSU?”, Fig. 7, shows a positively weighted normal distribution of responses in the lecture course. The initial offering of VECTOR in 2003 saw significant drops in students' self-assessment of overall learning gains compared to other courses with a bi-modal distribution of responses. The bimodal distribution was also seen in other SALG questions and open-ended comments. Students either loved or hated VECTOR, few remained neutral. As VECTOR evolved an increasing number of students reported they learned more than other classes. However the fraction of students reporting they learned much less remained higher than lecture. While it is not possible to make clear causal attribution, there are several complimentary reasons that likely had some effect in producing the changes seen in Fig. 7.

One of the most important changes to VECTOR was increasing faculty comfort with the teaching methods used. The course converted entirely from lecture to active learning in 2003. Since the instructor had little prior experience implementing active learning, teams, case studies, or project-based learning they reported focusing more on the process of teaching and less on content or application. As the instructor became more comfortable with the teaching methods used their effectiveness increased. This interpretation is supported by student self-reports of the impact of the major teaching methods of VECTOR on learning gains for each of the three semesters of VECTOR reported here. As shown in Figs. 5(b) and 7(b) the effectiveness of VECTOR pedagogies increased over the three year project period. VECTOR reiterates the importance of making iterative changes to courses [2].

Corroboration of SALG numeric data was obtained from analysis of open-ended SALG responses. The types of comments differed substantially between lecture and

VECTOR. In general student comments for the lecture course were primarily focused on the instructor and the difficulty of the course. Few substantive comments were made either about the method or structure of the course presumably because students were habituated to lecture. Under VECTOR there was a significant change in both the tone and content of open-ended comments. Comments were much more polarized, reflecting higher levels of dissatisfaction among some students. Positive comments often focused on the relevance of some activity to what students thought they would be doing in the future; they thought the course prepared them for their career. Of the negative comments, most focused on the structure of the course and the fact the instructor was not perceived to be doing any teaching. Comments tended to be much more positive on reflective statements than on SALG responses, perhaps because they were not anonymous.

Open-ended SALG responses showed that in 2003 one of the most problematic aspects of VECTOR was how fair students perceived the grading to be. Transitioning to a new style of teaching/learning made students uncomfortable. Faculty were not sufficiently aware—despite reports in the literature [2]—of the stress that would be created. It became clear during this project that creating a secure environment for students in which their efforts are immediately rewarded is critical to this type of curriculum reform. Faculty responded to these concerns in several ways. Later iterations of VECTOR informed students at the start of the semester that the course would be different from other courses, but that the grading standards would be at least as fair and objective. Additionally faculty were much more cognizant of the need for rapid feedback on their grades, peer evaluations, and overall performance in the class.

Another aspect of VECTOR that students found difficult was the use of teams. Until VECTOR few students in the program had much experience working on teams. Lack of formal training resulted in some students not functioning effectively on teams and being uncomfortable with peer or self evaluation. Students also reported that the work was not evenly divided among team member despite assigning roles. Despite these reported difficulties, SALG responses corroborated by evaluation of reflective statements indicate that students were better able to function on a team by the end of VECTOR and they saw that the experience prepared them for a career or the capstone design experience.

The student time commitment of VECTOR was monitored; students initially indicated that the on-line quizzes given prior to each class were extremely time intensive. The quizzes, initially written to be similar to homework problems with multiple steps, were changed to reduce the time required. Bloom's Taxonomy [43] was used to rate questions, focusing out-of-class preparation on the "remember" and "understand" levels of the taxonomy. To minimize the length of quizzes questions which did not direct student learning to the most important materials in a reading assignment were dropped.

Analysis of reflective statements showed that while very few students reported that the conceptual or theoretical aspects of VECTOR had value in the first year, nearly 30% reported this as the most valuable aspect in the second year. This increase arose from the instructor becoming more capable and changes to the way the instructor interacted with students in the classroom. In the second year the instructor discontinued the weekly review lectures and adopted a student-driven question and answer session. The instructor and TA also became more proactive in helping teams during the in-class active learning assignments.

V Conclusions

VECTOR, a multiyear course reform effort designed to make electromagnetics more relevant to students, created major changes to how students learned. Students reported learning *more* from simulations, projects, team members, and work outside of class while learning *less* from the instructor and exams. The changes to student learning became more positive and significant as faculty became more effective at using active learning and the course evolved based on evaluation. VECTOR succeeded in the primary goal of increasing the relevance of EM to undergraduate students. Whether VECTOR met the other goals of successfully integrating engineering tools and changing students' attitude is not as clear. While students report learning more from simulation and measurement tools, many students have trouble transferring this knowledge to other engineering contexts. Analysis of examination problems shows that while VECTOR did not create significant gains in traditional measures of EM knowledge there were no significant losses.

What is a realistic assessment of the advantages and disadvantages compared to lecture? There are several disadvantages; one is that the time commitment of students is increased compared to lecture. Students report spending more time out of class on electronic quizzes and labs than they did on homework. Despite the increase in time, VECTOR covers less material than was covered in lecture and places less emphasis on analytic solutions. There is not a commensurate drop in student ability to solve analytic problems, however. Another potential disadvantage is that students are not exposed to as coherent and organized a presentation of EM as can be achieved in lecture. The increased reliance on individual reading outside of class means that students' conception of EM may differ from that of the instructor.

The advantages of VECTOR are generally more experiential than content-based. The incidence of academic dishonesty is considerably lower; there are less opportunities to copy others' work and less motivation to do so. Class attendance is much higher than lecture and students are much more engaged in class. Students report they are better able to apply EM concepts to actual systems and devices, but still exhibit many characteristics of novices. Compared to the lecture class students are confronted with more challenging and multi-dimensional problems that do not have simple or singular solutions. While there is wide variation how well students' handle these problems while undergraduates, graduates of the program have reported that these experiences were highly beneficial. Students report benefits from the environment of VECTOR which fosters collaboration and teamwork.

Note that many of the changes in student learning which VECTOR created are difficult to classify simply as "good" or "bad" outside of the context of a given degree program. Changes are simply different; a program that seeks to provide more hands-on learning experiences, have students acquire and evaluate data, or provide team experiences in the context of engineering design would benefit from VECTOR. However VECTOR would not be appropriate for a program that wanted to communicate the formalism of EM and have students solve well-posed analytic problems.

VECTOR has had a lasting impact on all participants and the department as a whole. Faculty found that VECTOR provided a rich sandbox for experimentation and innovation in an effort to better integrate undergraduate teaching and learning with faculty research in classroom settings. The involved faculty have permanently changed the style and methods of teaching and have become more discerning adopters of new teaching methods. Students have been exposed to skills which make them more independent learners, vital to their success in as practicing engineers in a global economy or in obtaining an advanced degree. Student teams have simulated EM design problems, interpreted data, and reported the meaning of their results. While there is wide variation between team performance, most succeeded to some extent. Students have become better at functioning on teams. The department has commenced an internal dialog with implications on student learning, the process of student learning, and the assessment of individual students.

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Charles F. Bunting (S’89-M’94) was born in Virginia Beach, Virginia in 1962. He received his A.A.S. in Electronics Technology from Tidewater Community College in 1985, the B.S. degree in Engineering Technology from Old Dominion University in 1989. He received the M.S. degree in Electrical Engineering from Virginia Polytechnic Institute and State University (Virginia Tech) in 1992. In 1994 he was awarded the Ph.D. in Electrical Engineering from Virginia Tech.

From 1994 to 2001 Dr. Bunting was an assistant/associate professor at Old Dominion University in the Department of Engineering Technology where he worked closely with NASA Langley Research Center on electromagnetic field penetration in aircraft structures and reverberation chamber simulation using finite element techniques.

In the Fall of 2001 he joined the faculty of Oklahoma State University as an associate professor. He is the director of the Robust Electromagnetics and Field Testing and Simulation Laboratory (REFTAS) with a research emphasis on statistical electromagnetics, electromagnetic characterization and application of reverberation chambers, characterization of electromagnetic compatibility of telecommunications and electronics systems in aircraft and shipboard environments. Additional research interests include computational electromagnetics as applied to biological sensors and applied research in engineering education.

R. Alan Cheville (M’95) was born in Palo Alto California in 1964 and received the BSEE in 1986, MEE in 1987, and Ph.D. in 1994 from Rice University, Houston, Texas, USA

He is currently an associate professor in electrical and computer engineering at Oklahoma State University, Stillwater, Oklahoma, USA. He researches and publishes in the fields of ultrafast optoelectronics, specifically terahertz time-domain spectroscopy. He also conducts research in engineering education with broad interests in how students develop the characteristics associated with engineers.

Dr. Cheville is a member of the Optical Society of America and the American Society of Engineering Education.

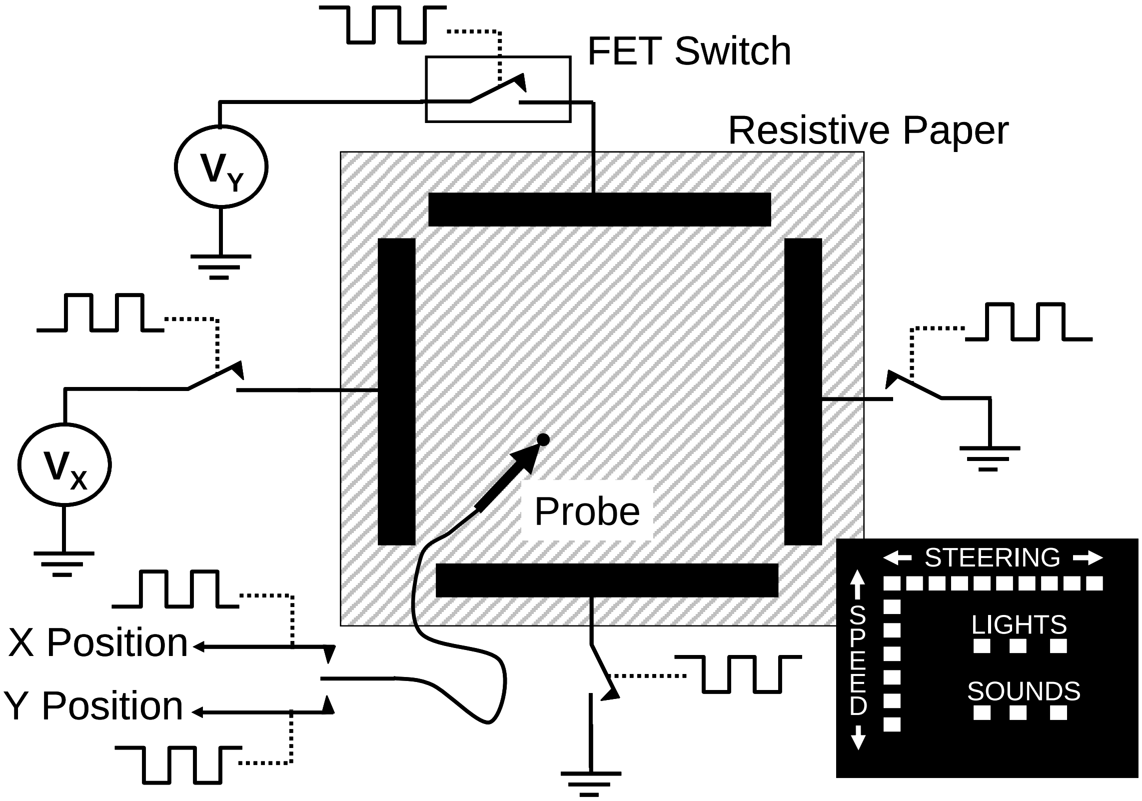

Fig. 1: Diagram of “electrostatic” position sensor project showing four conductive contacts that are biased as shown to extract X and Y position of the measurement probe. The stencil in the lower right corner is placed on top of the pad to operate the radio controlled vehicle.

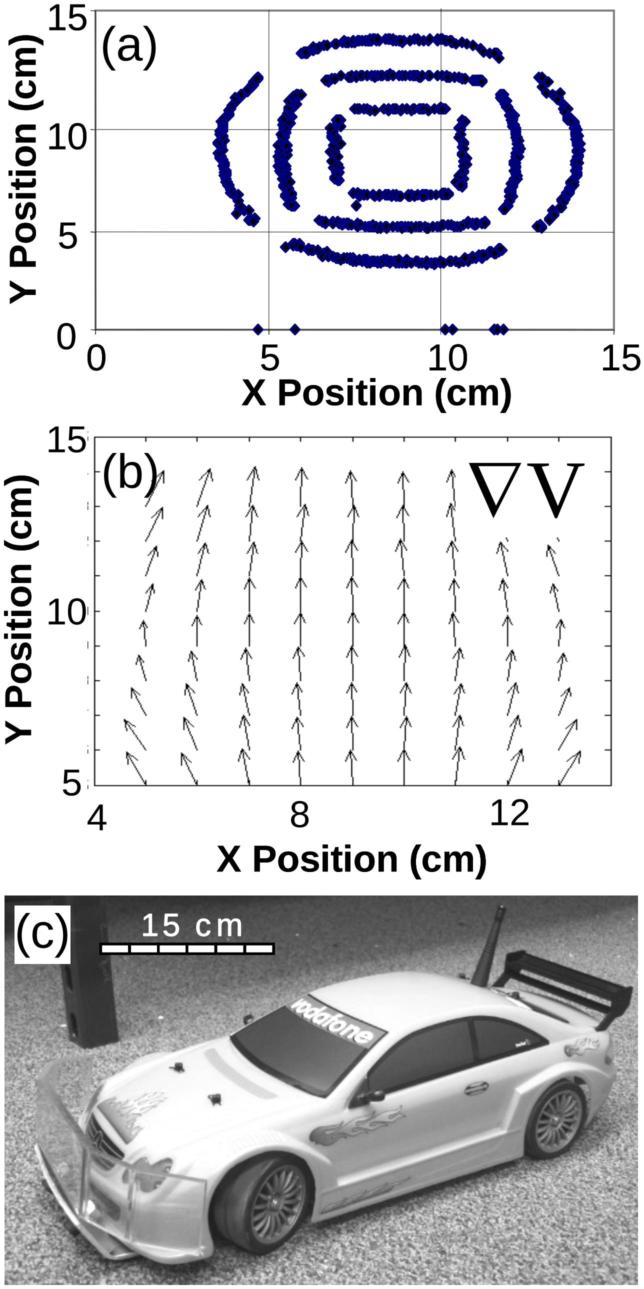

Fig. 2: A measurement of the potential using a overlay stencil of concentric squares is shown in (a) and the associated field gradient in (b). The 1/10th scale car controlled by the touch pad is shown in (c).

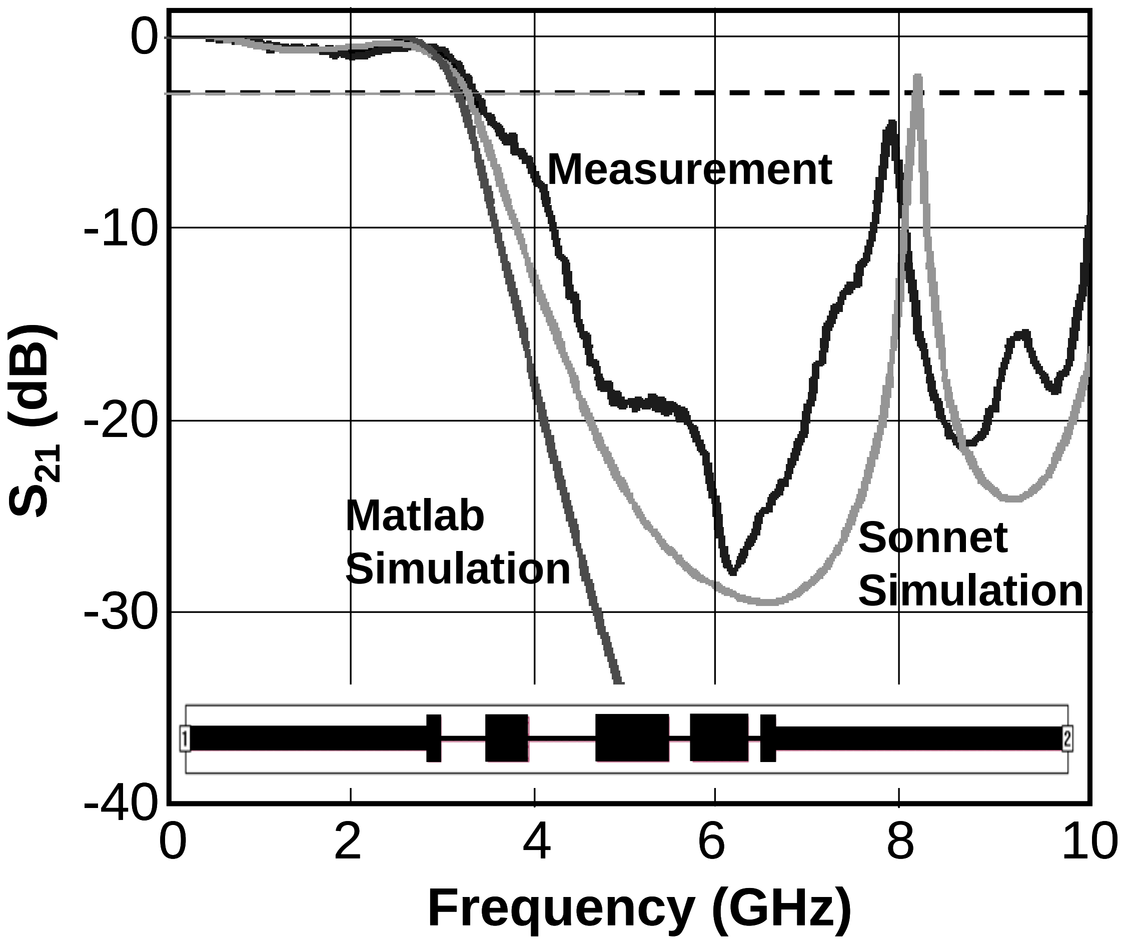

Fig. 3: Randomly chosen simulations and measurements of a team's filter design. The S_{21} measurements and Matlab and Sonnet simulations are shown. The stripline filter is shown in the inset at the bottom of the figure.

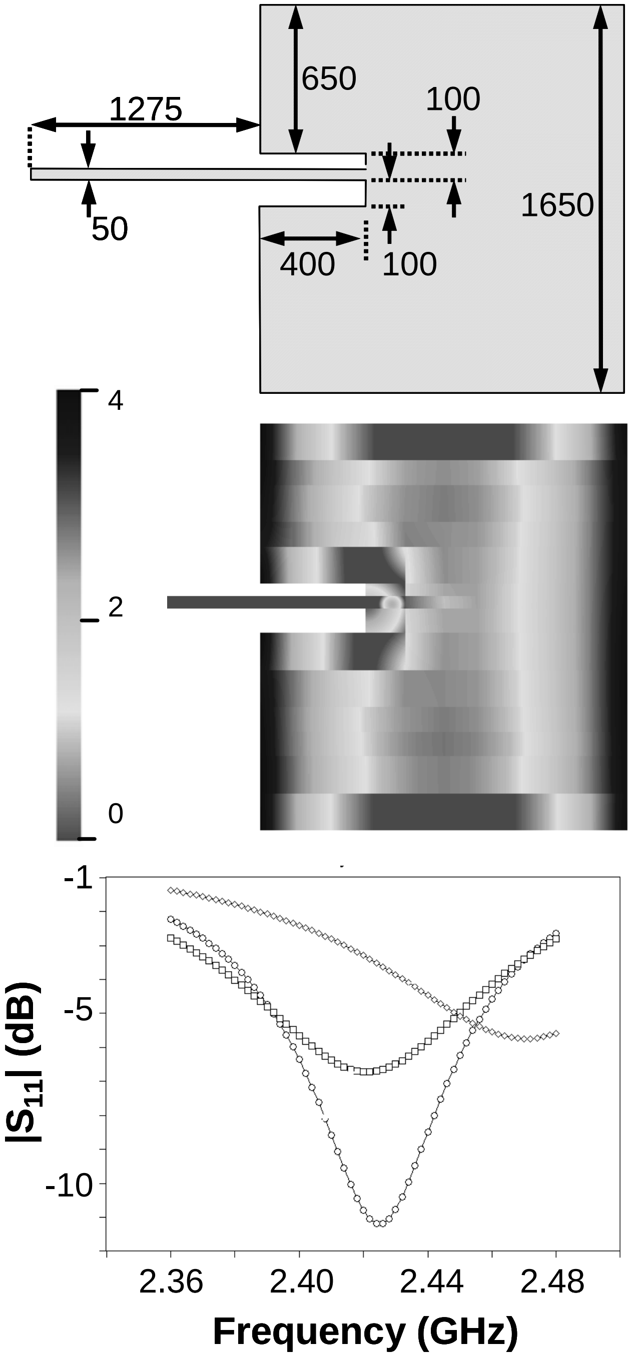

Fig. 4: A patch antenna designed by a randomly chosen student team is shown in (a) with all dimensions in mils (0.001” = 0.025 mm). The current distribution at 2.4 GHz is shown in (b). A sensitivity analysis of the S_{11} parameter to changes in antenna shape performed by the students is shown in (c).

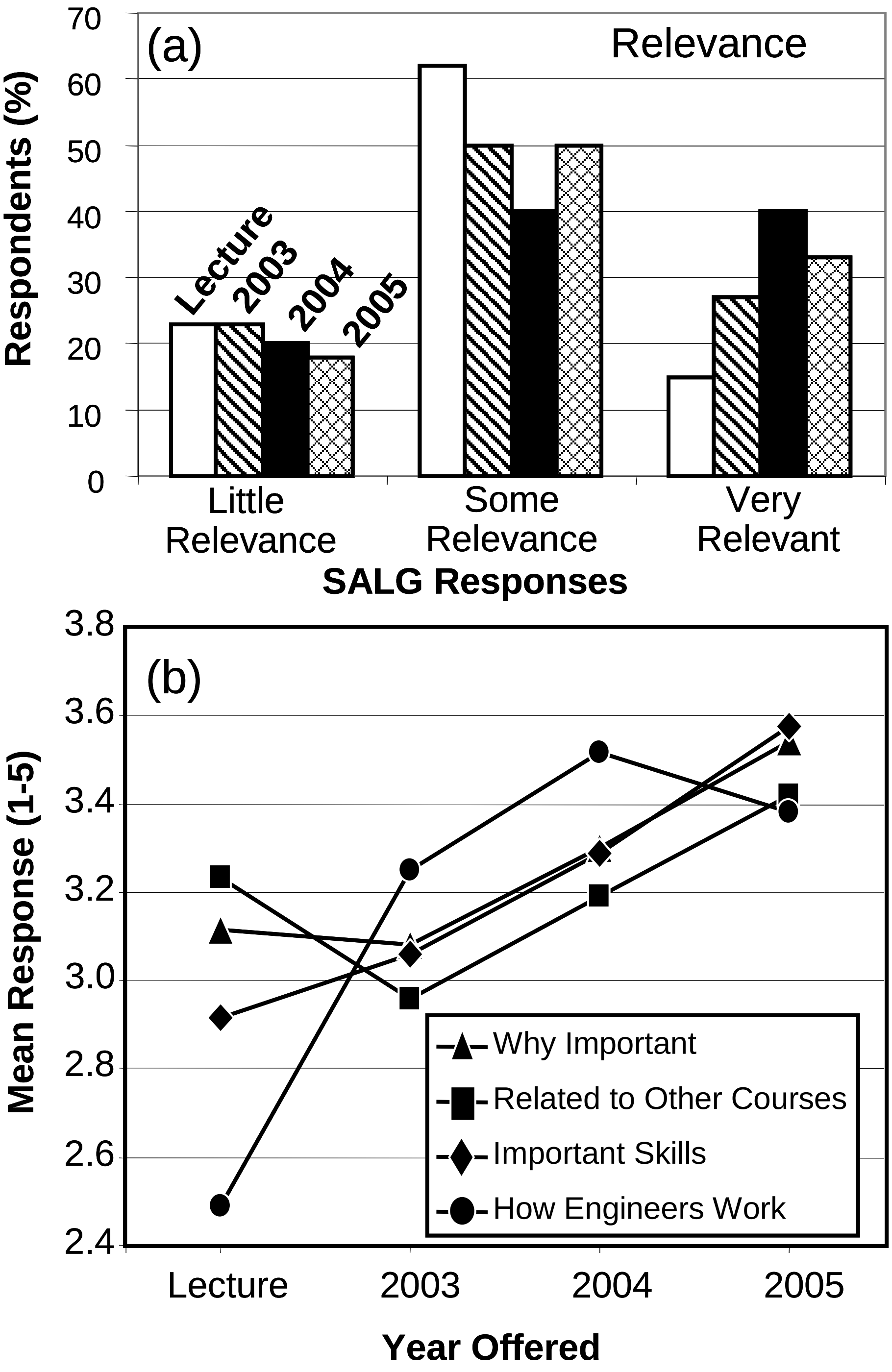

Fig. 5: The percentage of student responses on the SALG question about overall relevance of the EM course for each year of the study is shown in (a). Changes to SALG scores (1-5) for components of relevance over the course of the project are shown in (b).

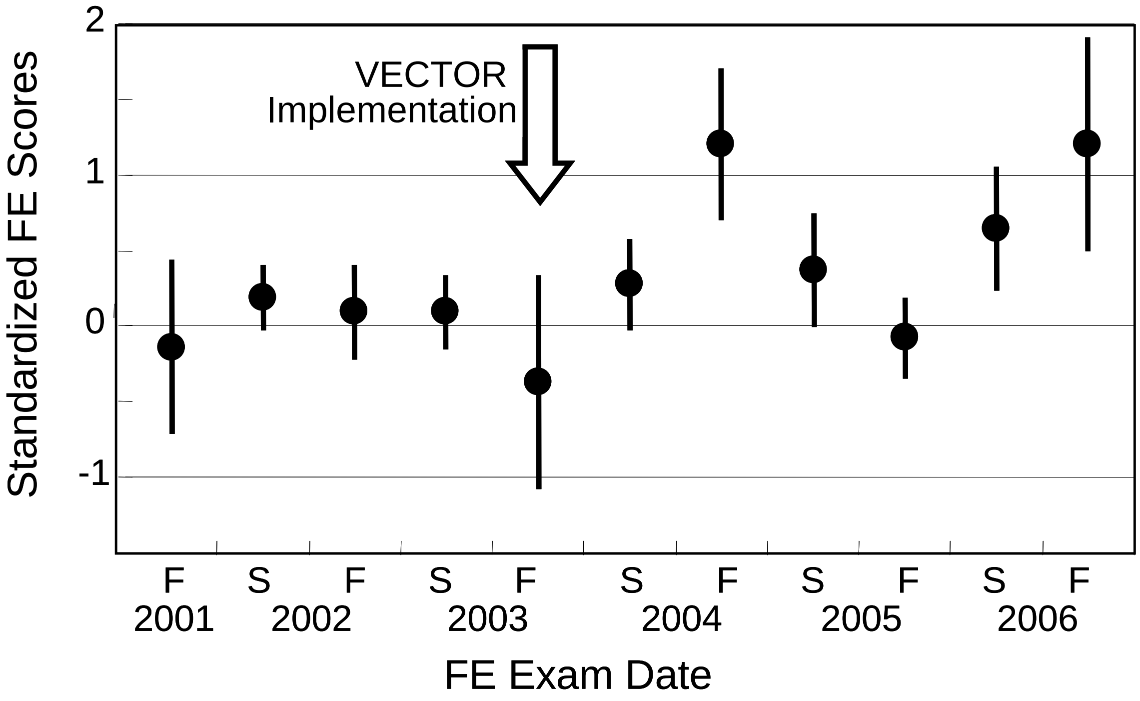

Fig. 6: Changes to mean FE examination scores on the EM questions of the subject exam before and after implementation of VECTOR.

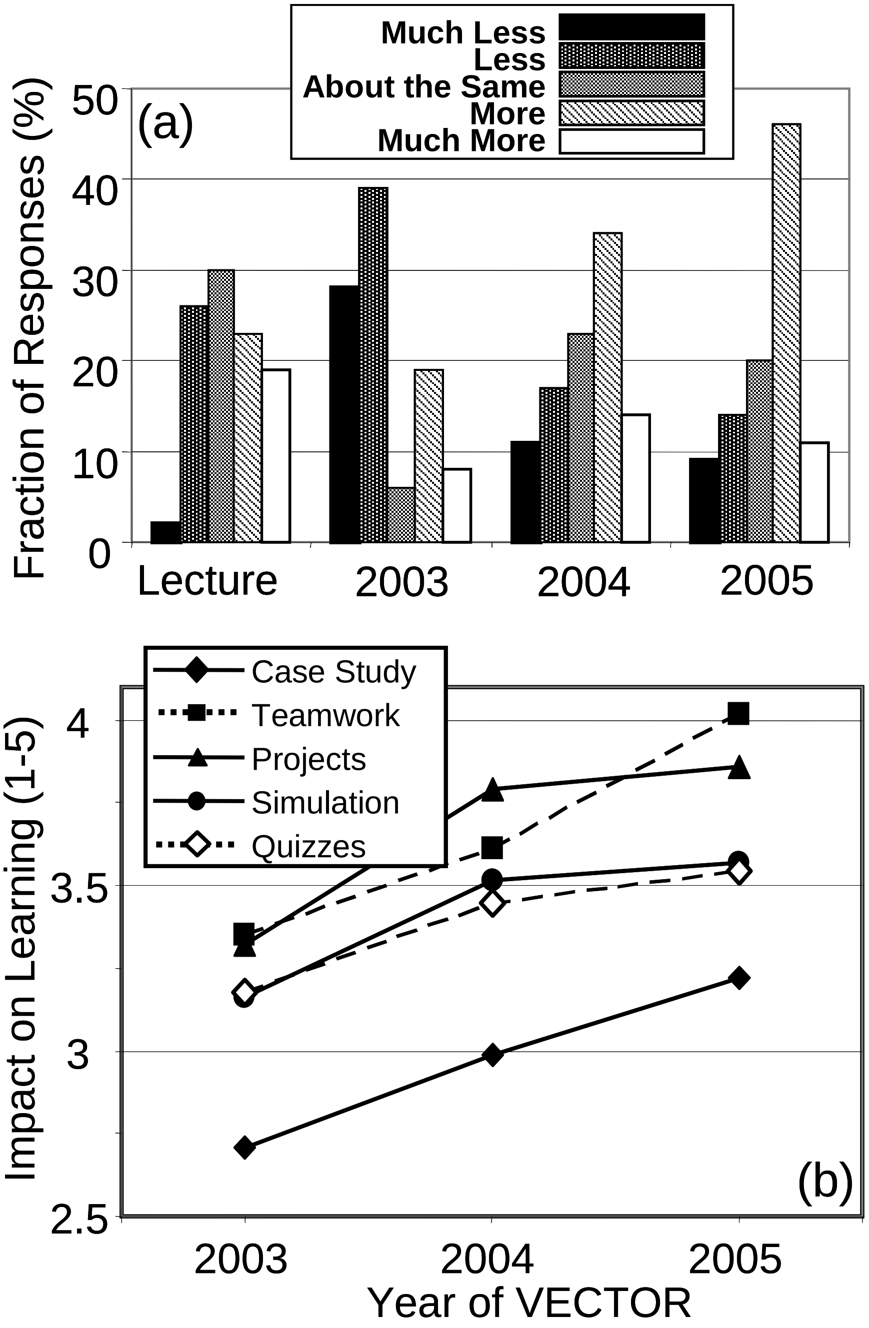

Fig. 7: (a) Student responses to the question “How much to you feel you learned in this class compared to other classes you have taken at OSU?” show how VECTOR evolved over time. Changes to how students rated the impact of VECTOR pedagogies over three years are shown in (b).