

**THE DEVELOPMENT AND IMPLEMENTATION OF EM-VIZ, A  
3D UNDERGRADUATE ELECTROMAGNETIC ENGINEERING  
VISUALIZATION APPLICATION, WITH AN ASSESSMENT OF ITS RELATIVE  
EFFICACY FOR MINORITY VISUAL LITERACY AND ACHIEVEMENT**

Craig Scott, Kemi Ledaji-Osias, Tanya Capers, Kofi Nyarko  
Department of Electrical and Computer Engineering  
Morgan State University

**ABSTRACT**

Studies showing that students in undergraduate engineering exhibit a stronger preference for the active, sensing, visual and sequential learning styles indicate that virtual reality can potentially have a tremendous impact on engineering education. By providing learning environments rich in varied learning methods, educators can provide students with more diverse means of receiving and applying knowledge and information resulting in a more engaging and interactive educational setting. Such environments allow students to construct their own understanding of what they are studying through their interaction with the environment, and their use of the knowledge and skills that they already have to experiment and form a more conceptual understanding of the information. At Morgan State University, we have developed EM-Viz, a 3D electromagnetic visualization tool designed to support undergraduate electromagnetic students in gaining an understanding of the theory of electromagnetics and provide conceptual views that offer insight into the behavior of their associated fields. In this paper, we will explain the design and features of this tool and discuss the use of a low-cost semi-immersive VR system designed to provide a group-learning environment. This paper will also quantify the application of VR to engineering education by determining its significance and relative efficacy to student achievement. In preliminary subjective tests, students found that the application was very useful in that it provided an overall context on an otherwise difficult and frustrating subject. Also, preliminary analytical results of the integration of the EM-Viz tool into the course revealed that there was significant increase in student achievement, perhaps indicating that virtual reality maybe a possible instrument in addressing the needs in the education and training of future minority engineers.

**INTRODUCTION**

Currently colleges and universities are faced with an ever-increasing demand to optimize their curriculum and increase the content of their courses due to the rapid change of technology and its attendant introduction of new material into the curriculum<sup>1</sup>. It has become obvious within higher educational institutions that the sole reliance of faculty on traditional “chalk and talk” approaches is just not as effective as other more interactive methods.<sup>2</sup> Hence engineering educators are now making use of an increasing number of computer simulation packages to aid them in attaining their educational objectives.<sup>3</sup>

New paradigms in engineering and technology education emerge as our engineering community increases its utilization of new technologies in the distribution and acquisition of knowledge, and information.<sup>4</sup> The perpetual advancement of technology within our society necessitates the reassessment of engineering education’s traditional standards, methods and educational models in order to proactively address future needs in the training of engineers and technologists.<sup>5</sup> A successful engineering education model must include and initiate new and diverse methods in order to effectively determine and address the current and forthcoming needs in the training of engineers and technologists.

In an effort to implement a novel and effectual educational method within the undergraduate Electrical Engineering curriculum at Morgan State University, we developed an application called EM-Viz designed to visualize the conceptual nature of basic electromagnetic principles. The application’s ability to compute and visualize electromagnetic quantities and concepts increases students’ comprehension of these concepts, thus permitting them to appreciate the complexities of the material by allowing them to construct a physical mapping of

the conceptual theories, which facilitates the mastery of the mathematical concepts required in the study of the subject. Additionally the application permits the ability to reach students that have alternate learning styles, in order to provide experience-based education and to augment traditional laboratory facilities. The application's use of semi-immersive virtual reality (VR) simulations provides students with access to environments that would not otherwise be available to them.

VR is an emerging computer interface that has the potential to tremendously impact engineering education by providing students with new insights into their studies and permitting them to explore environments that would be otherwise inaccessible.<sup>6</sup> Consequently there is a visualization movement in modern computing whereby complex computations are presented graphically, allowing for deeper insights as well as heightened abilities to communicate data and concepts.<sup>7</sup> With the implementation of standard and novel visualization techniques, EM-Viz supports the learning processes by enhancing the students' understanding of three-dimensional spatial relationships, complex three-dimensional structures, dynamic models and simulations of physical and conceptual processes.<sup>8</sup>

This paper is segmented into five main areas. In section two, background information related to multimedia tools, three-dimensional simulation and visualization as it relates to engineering education is presented. Section three covers the objectives that were considered prior to the software design and implementation. The processes of the actual software system design, including related considerations are covered in section four. In section five the semi-immersive VR implementation of the application is discussed, and finally in section six the empirical procedures and resulting analysis is detailed.

## BACKGROUND

In this section, specific technologies related to engineering education are discussed. This discussion includes the use of multimedia tools as well as simulations and accompanying visualization. The benefits associated with three-dimensional simulation and visualization in engineering are also touched upon as well as any related issues.

In the early 1950's, a group of educators put together an extensive, highly detailed, classification of educational objectives, known as Bloom's Taxonomy of Educational Objectives<sup>9,14</sup>, which is widely used by educators today to judge the depth and appropriateness of their coverage of course material. The general categories of Bloom's Taxonomy are knowledge, comprehension, application, analysis, synthesis and evaluation. Montgomery and Fogler, in their classification scheme for interactive computer aided software, have noted that in addition to using Bloom's Taxonomy to identify skills to be practiced, it is also necessary to identify the best methods to teach the students, according to their individual learning styles.<sup>10</sup>

Two general factors influence how well people learn information<sup>11</sup>. The first is how that information is presented. The second is how students may interact with it while they learn. Several studies<sup>2</sup> found over several years, especially with electrical and mechanical engineering students, that 60% of the students show strong preferences for learning by visual methods as compared to only 5% with strong preferences for verbal learning styles. About 43% of students show strong preference for sensing styles compared to only 4% having strong preference for intuitive learning styles. In fact, students with strong preferences for the active, sensing, visual and sequential learning styles outweigh students with strong preferences for the reflective, intuitive, verbal and global learning styles by significant factors. Further studies have shown<sup>5</sup> that educational environments rich in varied learning methods provide students with a diverse means of receiving and applying knowledge and information resulting in a more engaging and interactive educational setting<sup>12</sup>. The reason why interaction with information is so important for students is because without it, the reciprocal process of assimilation and accommodation, through which new information is modified to fit existing schemata which are in turn adapted to make a better fit, are difficult if not impossible.<sup>11</sup>

Educators within engineering fields are gradually beginning to use graphics as a language to identify complex and challenging problems by expanding the linear style traditionally used in teaching and learning to a non-linear format that

expands the processing of information in a way that minimizes cognitive overload<sup>7</sup>. Interaction with such systems should include the ability of the student to modify the sequence in which information is presented, the number of times it can be visited, and the points of view from which it is inspected.<sup>13</sup> Furthermore students should, where appropriate, be able to take objects apart, look inside them, animate them and make them larger or smaller. Immersive virtual reality supports many of the stated requirements. If properly designed, three-dimensional, multi-sensory virtual “worlds” might be able to aid users in comprehending abstract information spaces by enabling them to rely on their biologically innate ability to make sense of physical space and perceptual phenomena.

#### OBJECTIVE FOR DEVELOPING EM-VIZ

The purpose for the development of the electromagnetic visualization application, EM-Viz, is to support undergraduate electromagnetic students in gaining an understanding of the theory of electromagnetics and to provide conceptual views that offer insight into the behavior of the associated concepts. Furthermore, EM-Viz is augmented with a low cost semi-immersive VR system to provide a group-learning environment accessible by typical educational institutions.

#### SOFTWARE SYSTEM DESIGN

Several considerations were given to the initial design and implementation of the electromagnetic visualization application. The preliminary design centered on a robust and comprehensive implementation of engineering electromagnetics, incorporating user specified symbolic coding and visualization. However, this approach proved to be unnecessarily complex and cumbersome to implement. In order to mitigate the cost of complexity, the application is designed around a unified graphical user interface, which is customized for each educational module to present information and parameters only relevant to subject at hand. This approach requires the students to use the application as a supplement to their course text.

## SOFTWARE REQUIREMENTS

EM-Viz is designed to encompass the basic requirements for effective computer interaction as stated earlier. The application is designed to allow students to modify the sequence in which course information is presented by modularizing related simulations while providing menu driven access. Intuitive controls allow configuration of related simulations, which are presented to the user through a sophisticated visualization engine. The resulting rendered scenes can be viewed from any angle at any distance within a three-dimensional environment. In order to provide a visualization environment that is not platform dependant while still utilizing an advanced visualization engine, the application was developed using a scientific visualization platform called AVS/Express. While the platform possesses extensive modules for scientific visualization it lacks some specific functions that were required. Hence, C++ was extensively used during the development of the application to provide the back-end electromagnetic simulation capabilities. Furthermore, the mathematical solver MATLAB is also linked to AVS/Express to provide capabilities that are beyond the scope of C++ coding.

#### GRAPHICAL USER INTERFACE DESIGN

The graphic user interface (GUI) design for the application is based on providing a consistent and unified environment for presenting various controls associated with the back-end simulation and front-end visualization. When EM-Viz is launched, the student is presented with a simple menu that lists the developed visualization modules. This “splash” menu can be launched at any time to allow for multiple executions of differing visualization modules permitting students to actively compare and interact with multiple concepts from varying chapters in their course outline.

Figure 1 shows the basic layout of the controls and visualization window utilized by EM-Viz. The controls dynamically change depending on the module selected and any appropriate sub-topics. Additionally the visualization window (1) automatically updates depending on the selections made in the control window (2). The user also has the ability to scale, translate and

automatically center objects in the visualization window by way of the mouse through the manipulation controls (3) at the bottom of the control window. The status of the application during time consuming activities such as complex renderings or simulations is indicated by the status bar (4). The application keeps track of and displays any related equations to the current activity (5) in order to always provide the student with the quantitative tools necessary to produce the conceptual renderings. Lastly, detailed help is available for the student prior or during an active session through the module's menu bar (6).

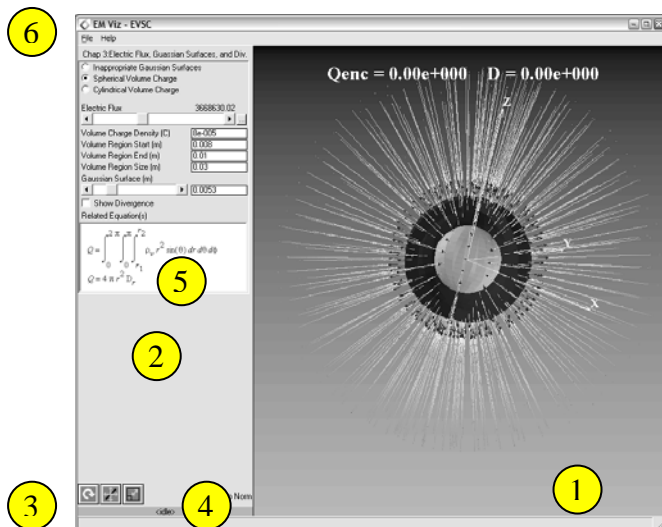


Figure 1. Basic layout of controls and visualization window

## MODULE CODING

EM-Viz employs a modular approach to visualizing the electromagnetic concepts discussed in typical course text in order to provide an environment conducive to experimentation and exploration on the students' own terms and at their own pace. Instead of focusing on the entire breath of material associated with electromagnetics, this research focused on creating a framework for simulating, controlling and visualizing general core concepts. With the established framework in place, future modules are easily created and integrated into the system. Currently the following core concepts have been integrated into the application: Coordinate Systems, Electric Field Intensity, Electric Flux, Gaussian Surfaces, Divergence, Energy and Potential. The following sections detail the development of these modules.

## COORDINATE SYSTEMS

Typically engineering students would much rather deal only with the Cartesian coordinate system<sup>15</sup>, but due to the fact the many electromagnetic problems possess a type of symmetry which pleads for a more logical treatment, this coordinate system is not always practical. In this section the student is presented with the Cartesian, Cylindrical and Spherical coordinate systems. When teaching coordinate systems with traditional methods, students are required to visualize the nature of three-dimensional volumes bounded by three-dimensional surface areas through which unit vectors coincide. Few students are successfully able to build these mental images relying only on the two-dimensional diagrams in the course text.

EM-Viz allows students to select their coordinate system and, in real-time, adjust the labeled bounding surfaces of a volume as shown in figure 2. By individually removing and restoring surfaces, the student is able to understand the nature of the primary axes and is better able to understand the symbolic representation of the differential volume. For cylindrical and spherical coordinate systems, students are also able to create a single point on the volume surface, which acts as the origin for three unit vectors. This point can then be translated along the volume's surface to conceptually indicate vector transformations. By locking the axis controls during manipulation, students can create the three mutually perpendicular surfaces of the spherical or cylindrical coordinate systems. All objects within the visualization window can be rotated, translated and zoomed to allow the student to examine the three-dimensional object from all possible perspectives.

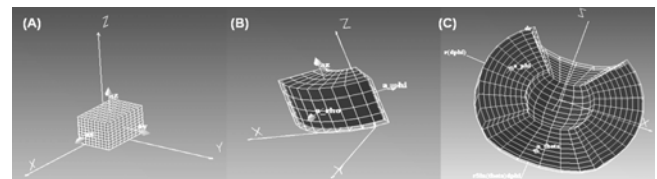


Figure 2. (a) Cartesian, (b) cylindrical, and (c) spherical coordinate volumes

## ELECTRIC FIELD INTENSITY

This module illustrates the concepts of electric field intensity by way of Coulumb's Law. When

the student selects the Single Point Charge option from the control panel, the C++ based simulation obtains the user specified charge quantity from the control panel and generates a spherical vector field which is then visualized and displayed by the rendering engine as illustrated in figure 3(a). The color and size of the arrow glyphs represent the intensity or magnitude of the field at that point. Values closer to a red hue represent high intensity values, while values closer to a blue hue represent low intensities, similarly the larger the arrow the higher the intensity and vice versa. The student can also scale or decimate the vector quantities as well as display and adjust both an isosurface and an isovolume of the vector field as demonstrated in figure 3(b). The isosurface control slider adjusts the value of the constant surface generated and is useful in determining the symmetry of the field as displayed in figure 3(b). In order to correlate the simulation results with their own calculations, the student may enable “Node Picking” which displays the electric field intensity at a given point adjusted by  $r$ ,  $\theta$ , and  $\phi$  control sliders. An example of Node Picking is displayed in figure 3(c).

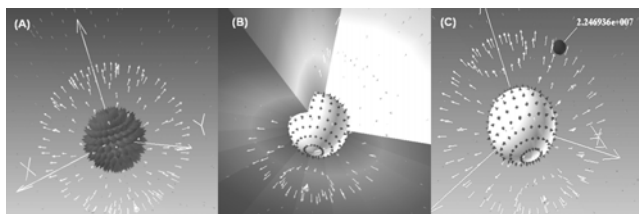


Figure 3. (a) Electric field vectors of point charge (b) with isosurface and isovolume mapping and (c) node picking

The concept of point-charge distributions is also simulated and visualized within this module. The student indicates the number of point charges and their associated charge quantities, after which, the back-end simulates the distribution. The symmetry of the net electric field can easily be observed by activating a translucent isosurface.

The student is also presented with the option of visualizing an infinite or finite line charge. The visualization for the infinite line charge is illustrated in Figure 4(a). The uniform nature of the line charge is further illustrated by the translucent isovolume. Figure 4(b) illustrates the finite line charge being rendered with a few more visualization options. Once again the translucent isovolume indicates the non-uniform nature of

the finite line charge, while an orthogonal data slice shows the magnitude of the electric field at the specified plane. In order to eliminate the possibility that the student may misinterpret the vector information provided by the application as stating that some of the larger red vectors are positioned further out than some of the green adjacent vectors due to their size, the student may use spherical glyphs positioned on the orthogonal slice plane to view the magnitude of the electric field at varying positions, as show in figure 4(c).

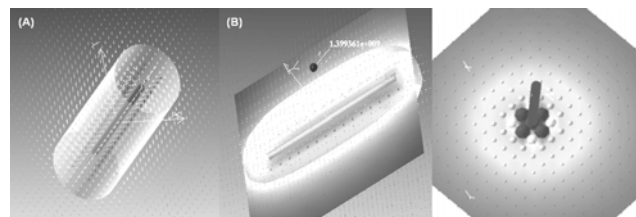


Figure 4. (a) Infinite line charge, (b) finite line charge, and (c) magnitude visualization of finite line charge electric field slice

This module also encompasses a sheet charge routine that simulates and visualizes a sheet charge as shown in figure 5.

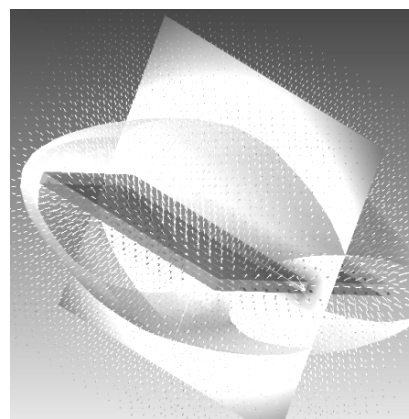


Figure 5. Sheet charge visualization

### ELECTRIC FLUX, GAUSSIAN SURFACES, AND DIVERGENCE

This module capitalizes on the students’ knowledge of electric flux and Gaussian surfaces. During the process of solving problems dealing with Gaussian surfaces, students often express an inability to visualize these surfaces. To aid the student in understanding the nature of Gaussian surfaces this module provides renderings of two “inappropriate” Gaussian surface configurations as seen in figure 6. Figure 6(a) shows a spherical volume charge density within a cylindrical

Gaussian surface through which electric flux lines permeate. For comparison, normal vectors to the Gaussian surface are displayed. The colors of the Gaussian surface represent the dot products of the electric flux and the surface normal, where values are mapped from blue to red in increasing order. From this display, the student should immediately see that the dot product does not produce a constant value, thus not satisfying one of the two conditions outlined in their text. To further verify these findings, the student can reduce the field data to a partial slice as indicated in figure 6(b). Similar results can be obtained by examining a cylindrical volume charge density within a spherical Gaussian surface, as shown in figure 6(c) and (d).

Students are also able to visualize spherical and cylindrical volume charge densities. With user specified control parameters the back-end simulator generates the volumes, vector fields and Gaussian surfaces displayed in figure 7, where the translucent gold surface represents the Gaussian surface. The students possess the ability to dynamically adjust the size of the Gaussian surface and simultaneously monitor the charge enclosed and the total flux leaving the surface as for the spherical and cylindrical volume charge densities.

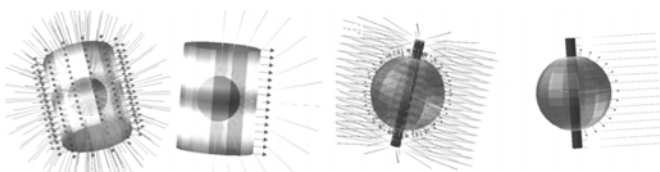


Figure 6. (a) Spherical volume charge within cylindrical Gaussian surface with (b) partial field slice and (c) Cylindrical volume charge within spherical Gaussian surface with (d) partial field slice

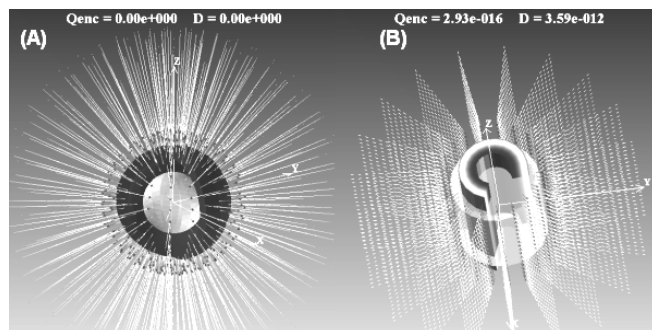


Figure 7. (a) Spherical and (c) cylindrical volume charge densities and respective Gaussian surfaces

## ENERGY AND POTENTIAL

In this module the student is allowed to view the visualization for a potential gradient from three preset potential fields. These three fields were pre-selected for simplicity and to illustrate a field for Cartesian, Spherical, and Cylindrical coordinate systems respectively. Each of the potential volume configurations has the option to show the potential volume and the electric field vectors. The electric field vectors are obtained by taking the negative gradient of the potential volume. The gradient operator indicates the maximum space rate of change of the scalar potential quantity, and the direction in which the maximum occurs. Furthermore, EM-Viz is capable of simulating a dipole arrangement and visualizing the result using orthogonal slices, isosurfaces, potential contours, electric field vectors and streamlines as demonstrated in Figure 8.

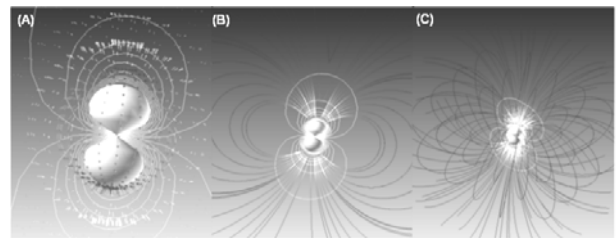


Figure 8. (a) Electric and potential field of a dipole with (b) partial and (c) full electric field streamlines

## SEMI-IMMERSIVE VR IMPLEMENTATION

As discussed earlier, there are several benefits to incorporating VR in educational material. However, this research focused on semi-immersive VR technology as opposed to full immersive VR. The decision was made in order to reduce the cost of development and implementation, which should allow more educational facilities to employ the tool. Additionally, fully immersive VR is not practical for group environments such as classrooms and serves to isolate the student from supporting course material and input devices.

A cost effective stereoscopic projection system composed of a single 1GHz PC with 512 MB of memory, two DLP projectors (Infocus LP 530), polarizing filters, a dual head NVidia Quadro4 900XGL graphics card, a silver projection screen, and polarized glasses, was developed. The system

works by first rendering a scene using the OpenGL graphics library. On the hardware level of the graphics card, the scene is captured from two different perspectives meant to simulate the position of each eye in the physical world. These two streams are fed out on each of the digital video outputs into two separate projectors where the polarizing filters on each of the projectors filter the light into two directions which are displaced by 90 degrees for maximum separation in order to reduce cross talk. The light is projected on a special silver screen manufactured to preserve the polarization, so when viewed with polarized glasses, which are aligned to the same angle as the polarizing filters, each eye received the intended video stream creating a very convincing three-dimensional view. The result is a system that greatly enhances the user's ability to discern depth which improves user navigation and interaction within the three-dimensional environment.

#### EMPIRICAL PROCEDURES AND ANALYSIS

At Morgan State University, Electromagnetic Theory & Applications I (EEGR303) is an upper level course required for the fulfillment of a Bachelor of Science Degree in Electrical Engineering. An experimental procedure was conducted to ascertain the effectiveness of the EM-Viz tool within the EEGR303 course curriculum. The goal was to assess if EM-Viz would affect student achievement and disposition towards learning complex theory and concepts, such as those in the electromagnetics course. A total of 28 minority students were enrolled in this course during the fall 2002 semester at the time this study took place.

#### ASSESSMENT DESIGN

To assess the efficacy of the EM-Viz tool on student understanding and comprehension of electromagnetic theory and applications, several tests were implemented into the normal course curriculum. In addition to the tests, surveys were placed on Blackboard, an internet-based course management system, to solicit subjective feedback on the lectures and the application. Students utilized the EM-Viz application for three of the five chapters covered during the course. After the completion of a chapter, students were administered a pre-test of which

the results were used as a baseline for evaluating student comprehension. Following the pre-test, the instructor demonstrated concepts of the chapter using the VR setup of EM-Viz, after which, students were given a homework assignment. The students were allowed to use EM-Viz, which had been installed in every computer lab within the engineering facility, to assist in the completion of their assignment. On the day students submitted their homework, they received a more challenging final test. This test was a measure of student development since the pre-test.

When students utilized the EM-Viz application, the system logged their identity, session time, and duration. This information was used to identify any correlations between student performance and their usage of the application. Also, students were administered some chapter projects as well as a final project inclusive of the concepts and equations covered in the curriculum. The final project elicited group interaction and required a final report with an oral presentation. The oral presentation allowed a panel of 4 graduate researchers, all of which took part in the development of the course procedures, to test the conceptual knowledge the students gained during the course.

#### STUDENT ASSESSMENTS

Assessment tools and results can be broken down into three sources of information: diagnostic test and student background survey, measures of student performance, and student evaluations.

#### BEGINNING OF THE SEMESTER ASSESSMENTS AND SURVEYS

The 28 students/subjects enrolled in the EEGR303 course were administered a diagnostic test the first week of the course; the intent was to identify any biases that could affect the results of this study, such as any prior knowledge concerning electromagnetic theories and concepts. The diagnostic test revealed that none of the students had any prior knowledge in this area. In addition, the students were given a beginning of the semester survey to gain background information on the students, which gauged the students' skills and expectations of the course. The students were asked of any prior

experience with three-dimensional educational environments, computer usage, and so forth. All of the students had a moderate amount of experience with computers; they enjoyed using computers, but none had actively used any technology in conjunction with their course studies. The students were administered an internet-based learning styles survey to gauge their predisposition towards a particular learning style. The results indicated that the subjects were sequential (71%), visual (79%), sensing (63%), and active (63%) learners, which correlates to the previous<sup>2</sup> findings.

### CLASS PERFORMANCE METRICS

The assessments came through the following comparisons of tests performance:

- Lecture Style A to Lecture Style B: the average pre-test scores of the entire class to the average final test scores of the entire class
- Group A to Group B: the average scores of the students who did not use the application to the average scores of the students that did use the application
- Project 3 to Projects 4 & 5: Comparison between scores when EM-Viz was utilized and not utilized at all

### LECTURE STYLE A TO LECTURE STYLE B

A comparison was made between metrics for the traditional versus EM-Viz lectures. Figure 12 shows the pre-test and final test performance for the three chapters; it can be observed that the sections, in which EM-Viz was used, consistently yielded a larger performance improvement. In Chapter 1, Coordinate Systems, there was a 12% performance increase over the traditional pedagogy; Chapter 2, Electric Field Intensity, resulted in a 16% improvement; and chapter 3, Gauss' Law, yielded a 41% improvement.

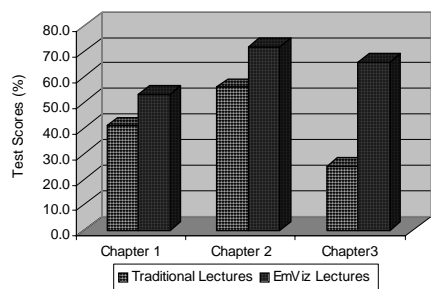


Figure 12. Student performance results for chapters 1 – 3

The performance results indicated a correlation between the students' performance and their usage of the application. The average time spent using the tool for all three chapters was 6 hours, but all of the students that worked with the tool beyond the average time, were consistently within the top 15% of their class and displayed a stronger command of the material when conducting their final project presentations. Table 1 shows the results of analysis on the scores for both lecture styles.

Measure	Traditional Lectures Mean (S.D.)*	EM-Viz Lectures Mean (S.D.)*	Significance Level
Chapter 1	41.1 (49.2)	53.3 (40.5)	0.02
Chapter 2	56.4 (19.1)	71.6 (20.9)	0.001
Chapter 3	25.1 (36.5)	65.9 (38.0)	< 0.01

\*standard deviation

Table 1. Class Performance Results. Significance levels for Students' T-Test

### GROUP A TO GROUP B

The use of EM-Viz was made strictly voluntary, but students were encouraged to use the application. There were only two instances where a student did not use the application. The first student was absent the day of the chapter 2 demonstration of the application. Additionally he did not use the application for the homework assignment. This student displayed relatively no improvement between the pre-test and final test scores. However, for the next chapter, the student worked with the application for 2 hours, and had the highest improvement between the pre-test and final test. The second student used the application for the first two chapters, but not for the third chapter. This student had constantly been in top 15%, however, for the third chapter, while there was a slight improvement in the scores between the two pedagogies, the student's score was far below average.

### PROJECT 3 TO PROJECT 4

EM-Viz was not utilized for Chapters 4 and 5 to further evaluate the usefulness of the application. For chapters 3-5, students were given projects where they could use any resources they wanted to get the projects done. The projects were designed to test their conceptual knowledge of the chapter, and their understanding of the concepts



and the related applications of the theories. Table 2 displays the results of the projects:

Chapter	Percentage
Chapter 3	91%
Chapter 4	70%
Chapter 5	76 %

Table 2. Average grade percentage for chapter projects

Table 2 reinforces the improvement in conceptual comprehension the students gained from the utilization of EM-Viz.

### CONCLUSION

In this paper we presented the application EM-Viz, a 3D electromagnetic visualization application designed to support undergraduate electromagnetic students in gaining an understanding of the theory of electromagnetics. By providing a learning environment rich in visual learning methods, students are presented with a more diverse means of receiving and applying knowledge and information resulting in a more engaging and interactive educational setting. This paper also quantified the application of EM-Viz to engineering education by determining its significance and relative efficacy to student achievement. Subjective tests indicated that students found the application to be very useful in that it provided an overall context on an otherwise difficult and frustrating subject. Furthermore, analytical results of the integration of the EM-Viz application into the course revealed that there was a significant increase in student achievement, indicating that three-dimensional interactive simulation and visualization maybe a possible instrument in addressing the needs in the education and training of future engineers.

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