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Teaching Electromagnetic Fields with Computer Visualization

Yeqin Huang, Bill W. Yang, Robert Adams,
Brian Howell, James Z. Zhang, and Kenneth Burbank
Department of Engineering and Technology
Western Carolina University, Cullowhee, NC 28723, USA
yhuang@email.wcu.edu

Abstract

The subject of electromagnetic fields is one of the most difficult subjects in the undergraduate curriculum of electrical engineering. Unlike mechanics, which deals with concrete objects, electromagnetics deals with intangible fields distributed in space, a concept that is abstract and difficult to gain insight. Students usually feel overwhelmed by the sophistication of the theory and, consequently, lose interest in learning. It is therefore not surprising that electromagnetic fields have motivated a variety of developments in education techniques designed to simplify it conceptually. In this paper, the strategy of computer visualization is explored for effective teaching. An assessment based on multiple-choice examination is done for evaluations of effectiveness of learning.

Introduction

It is a widely held and often articulated view that the subject of electromagnetic fields is one of the most difficult subjects in the curriculum of electrical engineering. Nevertheless, electromagnetic theory is the foundation of all electrical engineering. Electrical engineering students need a fundamental knowledge of the concepts and principles of electromagnetic fields. Therefore, intensive efforts have been made in past years to explore effective teaching strategies [1, 2, 3].

Vision plays an important role in improving comprehension and perception of electromagnetic fields. One reason electromagnetic fields is considered by students to be a difficult course is because electromagnetic fields, being vector functions of space and time, are conceptually abstract and hard to visualize. Invisibility is a considerable obstacle on the way to understanding physical phenomena.

The primary motivation here is to highlight physical concepts by offering students a mental image of electromagnetic phenomena. Taking advantage of computer graphics and simulations, students are exposed to the computer visualization of electromagnetic fields. It is observed that visual aids integrated with lectures help students develop a better conceptual understanding of electromagnetic phenomena. Meanwhile, computer simulations allow students to explore the solutions in their own efforts and in every detail, hence, deepening their understanding of the subject matter.

Course Outline

The course objective is to provide students an understanding of electromagnetic fields. Upon completion of the course, the students are supposed to accomplish the following goals:

1. Demonstrate an understanding of basic concepts of electric and magnetic fields.
2. Demonstrate an understanding of Coulomb's law, Gauss' law, Ampere's law, and Faraday's law.
3. Develop solutions to electrostatic and magnetostatic engineering problems by applying basic electromagnetic laws and mathematical concepts.

To avoid complicating matters by coping with mathematical concepts and electromagnetic laws simultaneously, the course begins with a short review of vector analysis. This approach separates mathematic theorems from physical concepts and avoids deviating students' attention from the understanding of physical laws in the flow of concepts.

After a brief review of coordinate systems and transformation, electrostatics is introduced as the first course block. The second block is devoted to magnetostatics, followed by an introduction to Faraday's law and Maxwell's equations. The list below shows the topics covered in the course:

- Coulomb's law and electric field intensity
- Gauss's law and electric flux density
- Electric potential
- Conductors and electrostatic shielding
- Dielectrics and capacitance
- Continuity equation
- Boundary conditions
- Poisson's and Laplace's equations
- Biot-Savart's law
- Ampere's law
- Magnetic flux density
- Magnetic forces, torque, and moment
- Magnetic materials and inductance
- Magnetic circuits
- Faraday's law
- Displacement current
- Maxwell's equations

Computer Visualization of Electromagnetic Fields

Electromagnetic field theory is undoubtedly a subject that is elegant in structure and rigorous in formulation. However, many students whose aptitudes do not incline them to mathematic abstraction may shy away from this course because of the abstraction and invisibility of the concepts involved in the theory. This difficulty can be alleviated by taking advantage of computer graphics and simulations.

The focus of computer visualization for the course is placed on leading students to gain insight of the fundamental concepts. Lectures on fundamental concepts are usually started with a statement of laws or principles, followed by a number of examples designed for interpretations of the physical meaning of the laws and concepts. The examples are carefully chosen in such a way that each example covers one aspect of the theory and is easy for students to understand. All of the examples, as a whole, form a complete interpretation of the theory. The COMSOL Multiphysics® solver is used for the computer simulations in a variety of electromagnetic problems. After observation of the examples, students are led to review the concepts and focus attention on the significant factors of the theory.

The advantage of this approach is to allow students to concentrate on the physical meaning of the abstract concepts, hence, to get an in-depth understanding of the theory. The approach to integrate computer visualization with the lectures is the combination of visual aid demonstration in class and homework assignments for computer simulations. To present the shift from mathematical abstraction to computer visualization, some examples are provided below.

A. Point Charge Placed at the Center of a Conducting Shell

As an example of the applications of Gauss' law, this problem is first solved manually to show students how to calculate the electric field with the existence of spherical symmetry. The field lines plotted in Figure 1 are then used to demonstrate that the field is spherically symmetric and in radial direction. Two fundamental concepts are covered in this illustration: Gauss' law and spherical symmetry.

Figure 2 illustrates the simulation results of electrical potential in the conducting shell. The simulation is used to help students understand the concept of equipotential surface. Due to the spherical symmetry of the system in this example, the equipotential surfaces are concentric spheres.

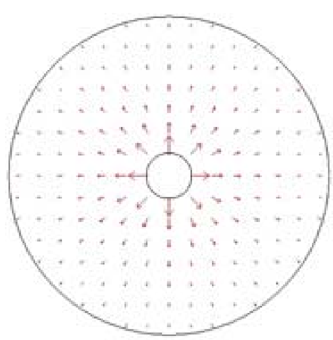

Figure 1. Electrostatic Field in a Spherical Shell

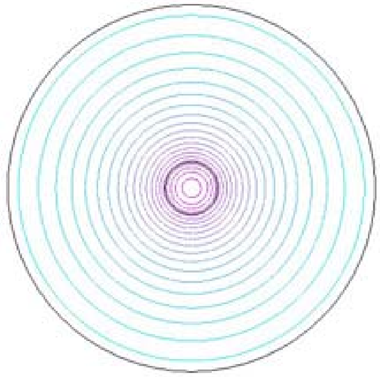

Figure 2. Electric Potential in a Spherical Shell

B. Boundary Value Problems

Electric potential fields within a source free region bounded by known potentials can be represented by solutions of Laplace's equation. The method of separation of variables is introduced for solving problems with canonical boundaries. A two-dimensional problem with a rectangular boundary is selected as a module to provide students with a fundamental knowledge of boundary value problems. In this example, the potential is positive on the right side of the rectangular boundary and zero on the rest of the boundary. Following basic steps of the method of separation of variables, the solution is obtained in terms of an infinite series of eigenfunctions. Computer simulation as a visual aid is introduced after mathematical manipulations of Laplace's equation.

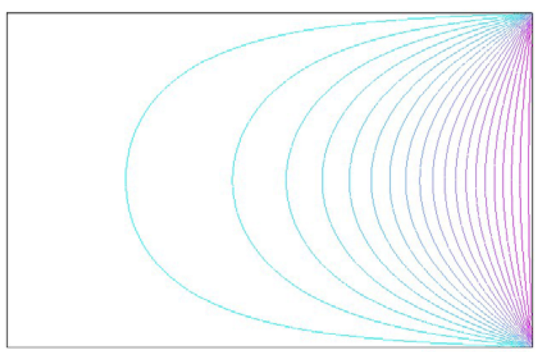

Figure 3. The Electric Potential in a Bounded Rectangular Region

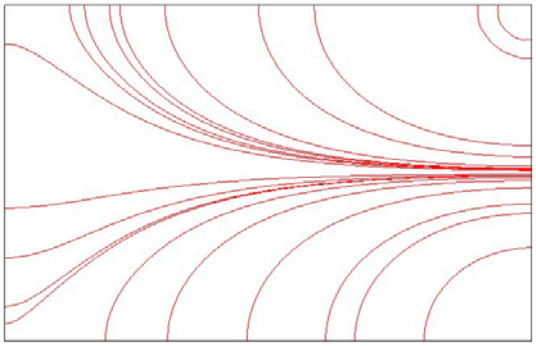

Figure 4. The Electric Field in a Bounded Rectangular Region

The goal of the analytical approach is primarily to transform electromagnetic problems into mathematical expressions. For some students, this is a hard task and relies heavily on the students' mastery of mathematics. For those students whose interest is primarily in the applications of the theory rather than in the mathematical abstraction or the beauty of the theory, the potential lines shown in Figure 3 and field lines in Figure 4 are more appealing than the derivation of analytical solutions. Numerical results shown in the figures provide students with an alternative observation of boundary value problems, thereby generating their insight into the concepts.

Unlike analytical approaches in which the complexity of the problem depends heavily on the geometry of the boundary, numerical approaches can be easily implemented to boundaries beyond rectangular shapes. Computer simulation of electric potential and fields in a circularly bounded region with piecewise boundary conditions, as shown in Figures 5 and 6, are an educational outreach to the context of undergraduate EM courses in which only rectangular boundaries are dealt with.

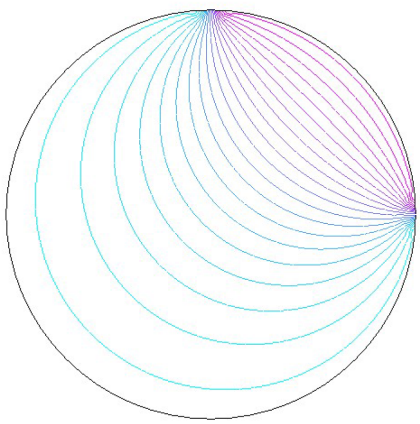

Figure 5. The Electric Potential in a Circular Region with Piecewise Dirichlet Boundary Conditions

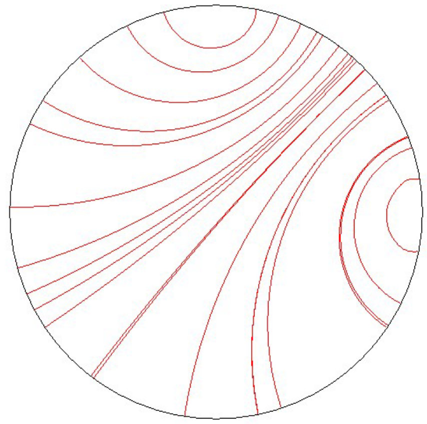

Figure 6. The Electric Field in a Circular Region with Piecewise Dirichlet Boundary Conditions

Assessment Method

A multiple choice examination with 25 questions was used for the assessment; 12 of them are from the Electromagnetic Concepts Inventory [4]. All the questions were designed for testing whether or not students understand the fundamental concepts. No essential calculations were involved with the questions. Students were not allowed to use calculators in the examination.

Question 4: Consider two parallel conducting plates, both are infinite in extent. A voltage V is applied across the plates as shown below, suppose S is a closed surface in the region between the two plates, and ϕ is the electric flux over S. Which of the following statements is true?

(a) $\phi = 0$
(b) ϕ is a positive constant
(c) ϕ is a negative constant
(d) ϕ is proportional to the area of S
(e) ϕ is proportional to the voltage V

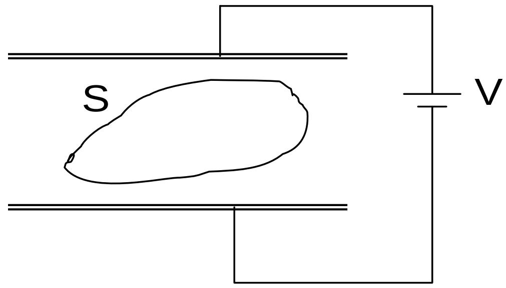

Figure 7. Sample Question

Figure 7 shows one sample question. This question is designed to test the concept of electric flux and Gauss' law. In this question, since there is no electric charge enclosed by the surface S, according to Gauss' law, the answer should be (a).

Figure 8 is another sample question for testing whether or not students understand the connection between field and potential. It can be seen from the curve that the point at which the potential function has largest slope of decrease is point C; therefore, the answer is (c).

Question 9: The electric potential V in a region is a function of coordinate x, and V(x) is shown in the figure. Consider the electric field at points A, B, C, D, and E. The largest field intensity is at point:

(a) A (b) B (c) C (d) D (e) E

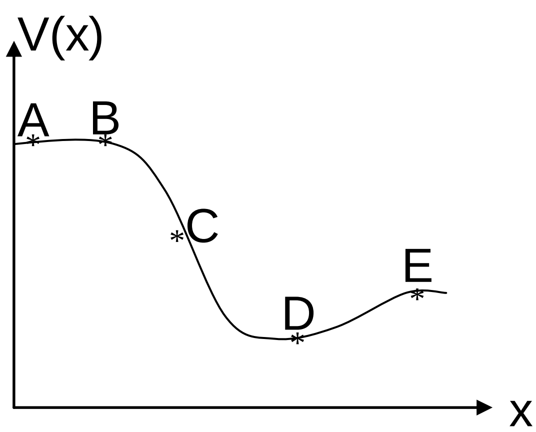

Figure 8. Sample Question

Assessment results are presented in Figure 9, which shows the percentage of correct answers for each question. It is observed that for 15 of these 25 questions, more than 70 percent of students gave correct answers. The concepts covered by these 15 questions are listed as follows:

- Coulomb's law
- Gauss' law.
- Ampere's law
- Faraday's law
- Electric potential
- Connection between field and potential
- Boundary conditions
- Electrostatic induction and shielding
- Gradient of potential functions
- Capacitance

- Properties of conductors
- Torque on a current loop in a magnetic field
- Conservative nature of electrostatic field

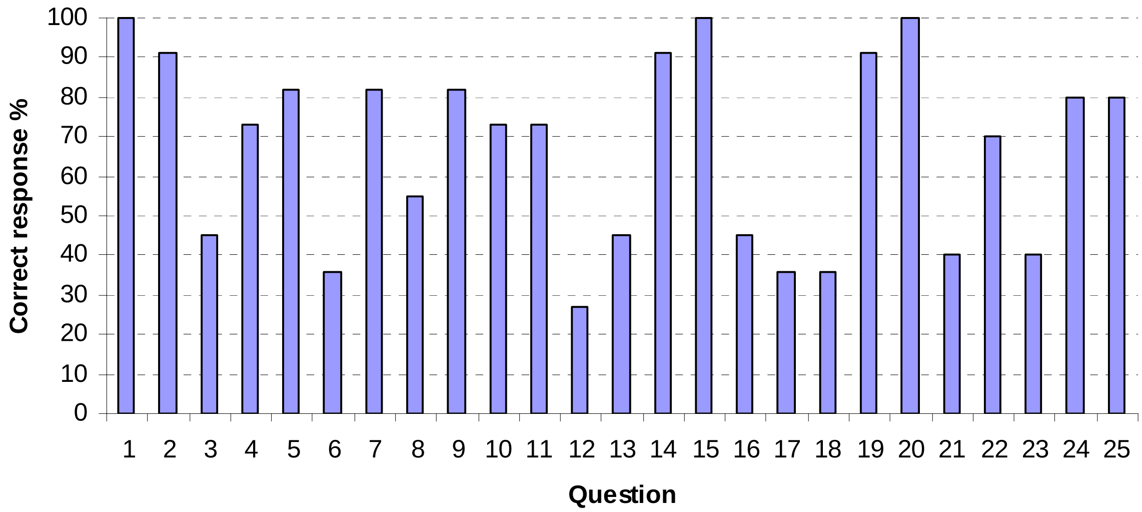

Figure 9. Results of Assessment

Conclusion

The experience gained using computer visualization for teaching electromagnetic fields has been described. Computer visualization of electromagnetic phenomena and introducing physical concepts are combined to accomplish the course objectives. Assessment results indicate that the desired effect on the students' learning of concepts was achieved.

It is observed that computer visualization integrated with examples in the lecture enhanced students' ability to transfer the concepts from the abstract level to the concrete level, thereby, improving their conceptual understanding of electromagnetic phenomena. Computer aided visualization makes the study of electromagnetic fields more appealing.

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Biography

YEQIN HUANG received a Ph.D. in Electrical Engineering from the University of Nebraska in Lincoln. He is an Assistant Professor in the Department of Engineering and Technology at Western Carolina University. His research interests include antennas and electromagnetic waves. He is a senior member of IEEE and a member of ASEE.

ROBERT ADAMS received a Ph.D. in Electrical Engineering from the University of Alabama in Huntsville in 2004. He has been a faculty member in the Department of Engineering and Technology at Western Carolina University since 2003. His research interests include numerical solutions to biomedical applications of electromagnetics, 3D modeling and visualization, and digital image processing. He is a member of ASEE and a senior member of IEEE.

JAMES Z. ZHANG is an Associate Professor with the Department of Engineering and Technology at Western Carolina University. His research interests include communications and DSP techniques for information processing. Dr. Zhang is a senior member of IEEE and a member of ASEE.

KEN BURBANK is a Professor of Electrical Engineering and Department Head of Engineering and Technology at Western Carolina University. Dr. Burbank is active with IEEE, OSA, and TAC of ABET. He strives to bring practical engineering activities into the classroom. His current project is the testing of metamaterials at microwave frequencies.