Computer-Based Electromagnetic Education

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Abstract— **Computers provide an exciting opportunity for boosting electromagnetic education and corporate training. Animated graphics of the wave propagation phenomenon, visualization of the abstract and highly mathematical subjects, one-on-one and self-paced tutoring, and the ability to mimic often unavailable and expensive laboratory experiments are among the often-cited benefits of a computer-based electromagnetic education. The activities of the NSF/IEEE Center for Computer Applications in Electromagnetic Education (CAEME) is reviewed here. This Center was established to stimulate and accelerate the use of computers and software tools in electromagnetic (EM) education. A reflection of the extensive software package developed and distributed by the CAEME Center is described, and examples of the developed software are presented. To help integrate available EM software in classroom teaching and corporate training, CAEME developed four multimedia lessons for instruction. These interactive media lessons integrate and allow individuals to interactively manipulate information from multimedia sources such as video, software, and animated graphics and also include instructional information such as quizzes and tutorials to help evaluate the students' performance. Features of these lessons are presented, and future developments in the Center's activities are discussed.**

I. Introduction

THE use of computers and software tools in science and engineering education is no longer an opportunity but a necessity that may help address some of the challenges facing education in the 1990's and beyond. With congested curricula, there is a serious need to effectively and quickly teach abstract and highly mathematical subjects, and with the prohibitively expensive modern laboratories, the use of computers and software simulation tools is becoming an integral part of modern curriculum development. For example, well-structured software tools may provide adequate visualization capabilities that may help communicate abstract subjects and present dynamic phenomena such as wave propagation, reflections, and interferences. Furthermore, computers provide one-on-one tutoring for subjects that require long learning time and may help in simulating open-ended problems that mimic laboratory experiments. Computers may also provide the ability to simulate practical engineering design exercises that motivate students and stimulate discussion of exciting engineering applications.

Many educators are aware of the challenges and opportunities presented with the proliferation of computers on university campuses. New courses have been developed, software and computer-generated movies have been created [1], and some efforts have been initiated to develop a computer-based curriculum in electromagnetics (EM). However, many of these activities are hindered by the lack of effective distribution mechanisms to facilitate sharing and minimize duplication, and by the nonexistence of standards for software development and preparation of documentation.

The National Science Foundation/Institute of Electrical and Electronics Engineers (NSF/IEEE) Center for Computer Applications in Electromagnetic Education (CAEME) was established as a result of a grant from NSF to IEEE on behalf of the Antennas and Propagation Society. Other organizations, including the Microwave Theory and Techniques Society, now also participate. CAEME's objective is to stimulate and accelerate the use of computers and software tools to help boost electromagnetic education. Electromagnetics is often perceived as an abstract, highly mathematical, and difficult subject to comprehend. Computer visualization and animation capabilities, therefore, are expected to be of significant value in teaching electromagnetics. The CAEME Center is expected to play a leadership role not only in the development and distribution of software but also in providing a focus for future software development and avenues for software integration in classroom teaching. CAEME proceeded to achieve its objects by

1. publishing a catalog of available EM educational software,
2. providing seed money from NSF funding to help develop new software for EM education,
3. holding workshops and special sessions in conjunction with international symposia on "Innovative Applications of Computers in Electromagnetic Education,"
4. serving as a focus for distribution of its software and video products using the National Electrical Engineering Department Heads Association (NEEDHA) mailing list, and
5. initiating a strong fundraising effort so that the Center will continue to be active and self-supporting after the three years of NSF funding.

This paper summarizes the activities of the CAEME Center and describes examples of its software development projects. Reflections on the *CAEME Software Book*, vol. I [2], [3] are highlighted and future software development projects are listed.

As instructors continue to integrate computers and software tools in classroom teaching, more and more of the limitations of using this technology in education are being realized. For example, it is not clear whether students will effectively and independently be able to understand basic phenomena from the numeric or graphic representations of the output

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of simulations. Also, avenues for the effective integration of simulation, demonstration, and computer-based homework assignments and tests in and outside of a typical classroom teaching procedure are not clearly defined. Many courses need to be restructured, and even the role of the university professor needs to be redefined to fit the era of a computer-based curriculum.

Fortunately, this uncertainty in understanding the role of computers and software tools in engineering education has coincided with rapid growth in the area of multimedia presentations [4], [5]. Interactive video applications integrate the visual power of video, interactivity of software, and an ability to structure educational lessons that include tutorials, quizzes, and maintenance of scores for the instructor's use. To help integrate software in EM education, CAEME developed four multimedia lessons in electromagnetics. The features of these lessons are also described in this paper. It is shown that the use of multimedia technology will make teaching electromagnetics fun, visual, effective, and, most importantly, independently understandable by students.

TABLE I
EM SOFTWARE DEVELOPMENT PROJECTS FUNDED BY CAEME IN 1990

Project	Principal Investigator	Institution
1. MacEM	K. Lonngren	Univ. of Iowa
2. Lienard-Wiechert Field Generator and Hypercard Tutorial for Visual EM	R. Cole	Univ. of Calif., Davis
3. Preparation of Computer-Aided Instructional Materials for Teaching Undergraduate EM: Integral Equations and Numerical Solution Methods	C. Butler and D. Wilton	Clemson Univ. Univ. of Houston
4. An Interactive Software Package for Teaching a Course on Computational EM	M. Iskander and O. Andrade	Univ. of Utah
5. An Interactive Menu-Driven Software Package to Solve Static, Sinusoidal Steady-State, and Transient 2D EM Problems	J. Lebaric	Rose-Hulman
6. Simulator for Signal Propagation on General Multiconductor Transmission Lines	L. Carin	Polytechnic Univ.
7. Electromagnetic Waves: A Software Package	W. Stutzman	Virginia Polytech. Inst.
8. Nuline: A Time- and Frequency-Domain Transmission Line Analysis Program	F. Tesche	Tesche Associates
9. Computer-Aided Instruction for Theory and Design of Linear Antenna Arrays	S. Blank and S. Wang	New York Inst. of Technology
10. Analysis of TE and TM Modes in Arbitrarily Shaped Waveguide Structures Using Finite-Difference and Conjugate-Gradient Method	T. Sarkar	Syracuse Univ.
11. 3D: A Software Package Providing Three-Dimensional Antenna and EM Field Displays on Personal Computers	J. McKeeman	Virginia Polytech. Inst.
12. Analysis and Visualization of EM Fields in Cylindrical Waveguides	A. Elsherbeni	Univ. of Mississippi

II. The CAEME Center—Organizational Structure and Summary of Activities

A. Organizational Structure of CAEME

The NSF grant was made to and is managed by the Executive Office of IEEE on behalf of the Antennas and Propagation Society, which arranged for the preparation of the CAEME proposal. Having CAEME under the umbrella of IEEE provides a broad base for participation by professional societies, universities, and corporate sponsorship by industry [3].

The CAEME activities, however, are controlled by a policy board that includes representatives from IEEE, NSF, participating professional societies, sponsoring companies, and the CAEME director. The policy board meets twice per year to monitor the CAEME budget and activities, and to approve funding for new software development projects at various institutions. Policies regarding international participation, copyrights, and licensing of the CAEME books are discussed and approved by the policy board. The policy board also decided to establish a group of technical advisors chaired by Professor Robert E. Collin of Case Western Reserve University to assist in evaluating CAEME's technical activities and products. During the three-year NSF funding, the policy board is chaired by the president of the Antennas and Propagation Society.

B. Summary of CAEME Activities

During the three-year NSF funding, CAEME focused its activities on creating software suitable for undergraduate EM education. To date, CAEME has available or has under subcontract software development projects that cover all aspects of an introductory course in electromagnetics. Although it was not part of the original NSF proposal, CAEME has recently devoted significant efforts to help promote the use of computers and software tools in classroom teaching. Specific examples of this activity include the creation of four multimedia lessons on introduction EM and the publication of a new journal [6] that deals with various aspects of computer applications in engineering education. The following is a summary of CAEME activities:

1) Published a catalog of available software for EM education. The catalog lists various software packages, their availability, cost, and an example of their use. Copies of this catalog are available from the CAEME Center.

2) Organized several workshops and special sessions in conjunction with the IEEE AP-S International Symposium, the IEEE MTT-S Microwave Symposium, the Applied Computational Electromagnetic Society (ACES) Conference, the Progress in Electromagnetic Research Symposium (PIERS), and the American Society of Engineering Education (ASEE) Conference. During the first two years of CAEME operation, the workshops were focused on describing the features and training the participants on the use of available software tools, particularly those developed by CAEME faculty. More recently, CAEME used these opportunities to discuss ways and means of promoting the integration of software tools in EM education.

3) Funding of software development projects. In three years of operation, CAEME funded 27 software development projects at 18 universities. Tables I, II, and III list the CAEME projects. In addition, colleagues from MIT [7], Georgia Tech [18], the Naval Postgraduate School [9], and the Lockheed Corporation [10] participated in CAEME projects at no cost. It is truly remarkable to see educators from universities across the country collaborate and participate in this unique effort that will certainly have a lasting impact on EM education.

4) Published the first software book in September 1991. Copies of the book were distributed to over 300 universities

TABLE II
EM SOFTWARE DEVELOPMENT PROJECTS FUNDED BY CAEME IN 1991

Project	Principal Investigator	Institution
1. 2-D Static and Dynamic Software	J. Lebaric	Rose-Hulman
2. Analysis and Visualization of EM Waves Inside Waveguides and Cavities	A. Elsherbeni	Univ. of Mississippi
3. An Array Antenna Pattern Program	W. Stutzman	Virginia Polytech. Inst.
4. Simulation of EM Phenomena Using Field Line Animation	P. Visscher	Univ. of Alabama
5. Field Generator for Electromagnetic Scattering	R. Cole	Univ. of Calif., Davis
6. Computer Graphics Aided Teaching and Learning Tools for Antennas	S. Chakrabarti	Univ. of Kansas
7. Antenna Pattern Visualizating using Personal Computers	A. Gasiewski	Georgia Institute of Technology
8. Development of an Interactive Video Educational Software Using QUEST	M. Iskander	Univ. of Utah

TABLE III
EM SOFTWARE DEVELOPMENT PROJECTS FUNDED BY CAEME IN 1992

Project	Principal Investigator	Institution
1. Interactive Exercises for Visual Electromagnetics	R. Cole	Univ. of Calif., Davis
2. Development of a PC-Based Simulation of Electromagnetic Wave Propagation	T. Kao	Loyola-Marymount Univ.
3. Radiation Characteristics of Phased Array Antennas and Mutual Coupling of Microstrip Antennas	A. Kishk	Univ. of Mississippi
4. Application of the Finite Element Method for Quasi-Static and Dynamic Analysis of 2D Arbitrarily Shaped Inhomogeneous Anisotropic Multiconductor and Multidielectric Waveguiding Structures Utilizing the Classical Elements and Edge Elements	M. Salazar-Palma	Polytech. Univ. of Madrid
5. Reflector Antenna Analysis Software: An Educational Approach	Y. Rahmat-Samii	Univ. of Calif., Los Angeles
6. Analysis and Design of Antenna Arrays	A. Elsherbeni	Univ. of Mississippi
7. Use of Matlab to Solve EM Problems	J. Lebaric	Rose-Hulman
8. Development of Interactive Video Lessons	M. Iskander	Univ. of Utah

in the United States and 27 foreign countries. In many cases, universities paid a $500 two-year membership fee to join the CAEME Center, while in a few others, single copies were provided to individual faculty members at cost (\$150). A more detailed description of the features of the CAEME book will be given in following sections.

5) To help promote the integration of software tools in classroom teaching, CAEME developed four multimedia lessons. These lessons combine multimedia information from simulation, video, and animated graphics with instructional information such as tutorials and quizzes. Features of these multimedia lessons will be described in more detail in Section V.

6) As CAEME intends to continue to be active and self-supporting after the three years of NSF funding, an important aspect of its activities was to raise funds from corporate sponsors and charge a membership fee to participating professional societies. To date, CAEME has corporate sponsorship from Hewlett-Packard, Texas Instruments, Lockheed Corporation, Andrew Corporation, Motorola and Hughes Aircraft. Participating professional societies include IEEE AP-S (host), IEEE MTT-S, IEEE EMC-S, and ACES. More than $200,000 has been raised thus far, which is sufficient to support CAEME for two years after the NSF funding. This is based on the present level of activities, but clearly more funds are needed to adequately address CAEME's expanded activities in areas such as the development of multimedia lessons and the use of CD-ROM technology to distribute CAEME products.

III. *CAEME SOFTWARE BOOK*, VOL I

As a result of the software developed using CAEME seed funding in 1990, as well as because of other software and videos contributed to the Center, the first CAEME software book was published in 1991 after only 18 months of the Center's operation [2]. The book contains sixteen chapters, fifteen $3\frac{1}{2}$ inch diskettes, and two VHS videos. Fifteen chapters are associated with the developed software and the other discusses the experimental demonstrations for teaching electromagnetic fields and energy [11].

A. Reflections on the CAEME Software Book

Examination of the contents in Table IV shows that the book provides broad and comprehensive coverage of an introductory course in electromagnetics. It includes both tutorial and simulation software in topics such as vector algebra, Maxwell's equations, electro- and magnetostatics, transient and sinusoidal steady-state analysis of transmission lines, display of field configurations associated with modes in waveguides of regular cross sections, analysis of wire antennas, and an introduction to numerical techniques, including the finite-difference time-domain method and the method of moments. Specific examples of the software are discussed later, but it may be worth mentioning that all the software packages are interactive and menu driven, and provide both simulation and visualization capabilities. It is believed that an easy-to-use I/O interface is crucial to the successful use of software in teaching and corporate training.

B. Examples of Software Packages

Examples of the software packages available in the first CAEME book are available in several publications [3], [7], [12], [13]. In this paper, focus is placed on software packages that address issues of interest to the MTT community.

1. Simulation of Electromagnetic Phenomena Using a Finite-Difference Time-Domain (FDTD) Technique: This is a 2D FDTD program with movie-making capabilities [7]. The electric- and magnetic-field results are solved as a function of time and stored solutions of scattering or radiation fields are then visualized in a movie format. Dielectric, magnetic, or conducting materials may be used to construct the object of interest. Sinusoidal or Gaussian beam plane waves, or line sources may be used as excitation sources. Both TE and TM polarizations are analyzed. In addition to the capability of animating the propagation of the EM fields, radiation and scattering patterns can be generated. An example of an animated series which shows the focusing action of a dielectric lens when excited by a sinusoidal plane wave is shown in Fig. 1. The software operates on IBM 386-type PC's and requires a math coprocessor.

2. Transmission Line Simulators: There are two software packages for transmission-line analysis. The first [14] is suitable for determining the time-domain or sinusoidal steady-state response of a single-conductor transmission line over

TABLE IV
CONTENTS OF THE FIRST CAEME SOFTWARE BOOK

A. Software for Fundamentals of Electromagnetics

Chapter 1 -- Fields & Operators; M. Lapidus, Lascaux Graphics
Chapter 2 -- Elements of Engineering Electromagnetics; N. N. Rao, University of Illinois
Chapter 3 -- ElectroCard and SilverHammer: Teaching Fundamentals of Electromagnetics; R. Cole, D. Krull, M. Sweitzer, S. Finch, and T. Palmer, University of California, Davis
Chapter 4 -- MacEM; K. E. Lonngren and W. B. Lim, University of Iowa
Chapter 5 -- Electromagnetic Waves -- A Video Tutor Graphics Package; W. L. Stutzman and A. B. Garrett with code modifications by M. Cerny, Virginia Polytechnic Institute and State University
Chapter 6 -- Electromagnetic Software for Solving Static and Dynamic 2-D Field Problems on a Personal Computer; M. Melton, J. Engel, and J. Lebaric, Rose-Hulman Institute of Technology
Chapter 7 -- Experimental Demonstrations for Teaching Electromagnetic Fields and Energy; M. Zahn, J. R. Melcher, and H. A. Haus, Massachusetts Institute of Technology

B. Software for Transmission Lines

Chapter 8 -- Nuline Transmission Line Analysis Program; F. M. Tesche, Tesche Associates, Dallas, Texas
Chapter 9 -- Polylines: A Multiconductor Transmission Line Simulator; L. Carin, M. Giordono, and J. Beninati, Polytechnic University of New York

C. Software for Waveguides

Chapter 10 -- Mapping of Vector Fields Inside Waveguides; A. Z. Elsherbeni, D. Kajfez, and J. A. Hawes, University of Mississippi
Chapter 11 -- Analysis of Waveguides Using the Conjugate Gradient Method; V. Narayanan and T. K. Sarkar, Syracuse University

D. Software for Antennas and Radiation

Chapter 12 -- Computer-Aided Instruction for Linear Antenna Array Theory and Design; S. J. Blank and S. L. Wang, New York Institute of Technology
Chapter 13 -- An Interactive Graphics Tool for Displaying Three-Dimensional Equations; J. C. McKeeman, G. M. Ruhlmann, and M. A. Colbert, Virginia Polytechnic Institute and State University
Chapter 14 -- "Mininec," Containing Mininec 3.13 and Graps 2.0; R. W. Adler, naval Postgraduate School

E. Software for Numerical Techniques

Chapter 15 -- Computational Electromagnetics -- Software for an Introductory Course; M. F. Iskander and O. M. Andrade, University of Utah
Chapter 16 -- Simulation of Electromagnetic Phenomena Using a Finite Difference-Time Domain Technique; K. Li, M. A. Tassoudji, R. T. Shin, and J. A. Kong, Massachusetts Institute of Technology

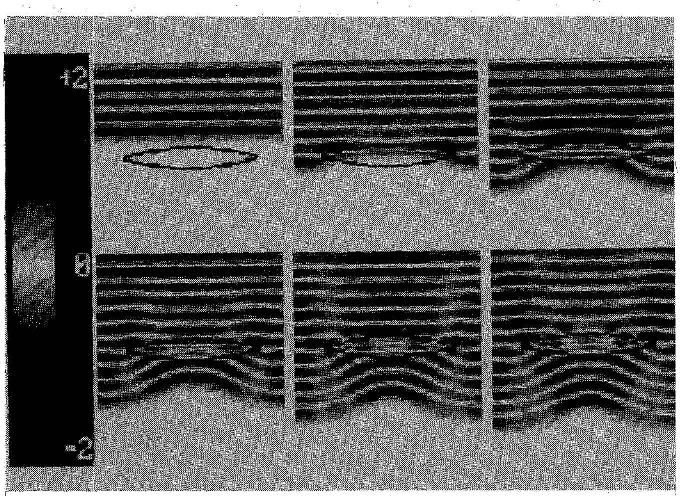


Fig. 1. A series of photographs that illustrates the focusing action of a dielectric lens ($\varepsilon_r = 4$) when excited by a sinusoidal plane wave. The series starts at the top left-hand corner, continue from left to right, and ends at the lower right-hand corner.

a perfectly conducting or a lossy return ground plane. Each end of the line may be terminated by a general series R, L, C impedance, and excitation may be lumped voltage source, current source, or an incident plane wave. This software

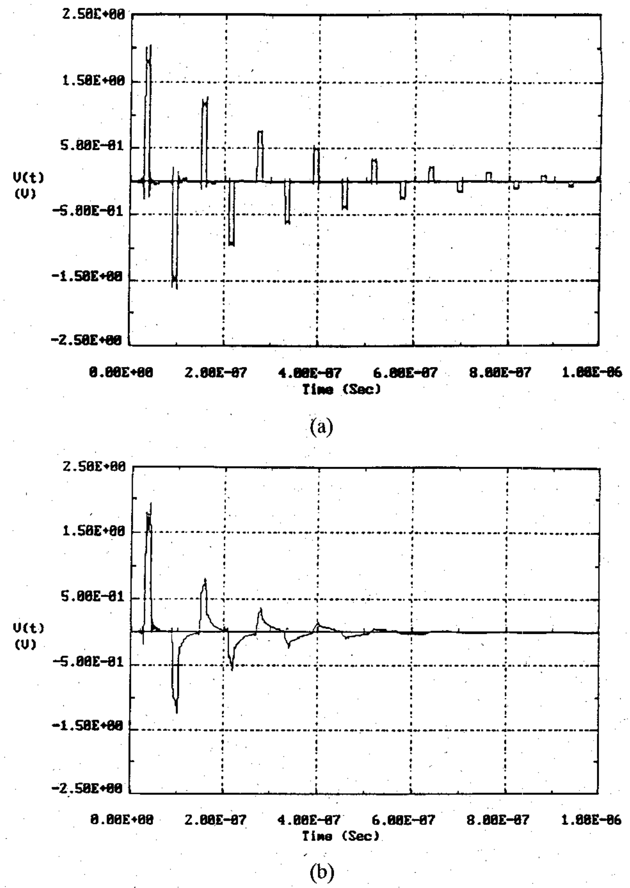


Fig. 2. Illustration of the transient analysis capabilities of the Nuline software package [14]. The total voltage is at an open-circuit load. (a) Perfectly conducting plane case. (b) Lossy ground return plane cases.

package is menu driven and easy to use. It also has an attractive graphics package for plotting the output results. Figure 2 shows the output voltage versus time at an open-circuit load for both perfectly conducting and lossy ground planes. The pulse distortion as a result of the losses on the ground plane is clearly demonstrated in Fig. 2(b).

The other transmission-line analysis software package is Polylines [15]. This software provides a frequency-dependent analysis of a signal propagating on single or coupled transmission lines. Parameters such as the characteristic impedance, effective dielectric constant, phase velocity, and cross talk as a function of frequency are typical outputs of this program. Figure 3 shows the variation of the characteristic impedance of a microstripline as a function of frequency, while Fig. 4 shows a comparison of the output voltage versus time when dispersion is not taken (Fig. 4(a)) and is taken (Fig. 4(b)) into account. The above results show both the frequency and time domain capabilities of Polylines [15].

3. Electric- and Magnetic-Field Vectors in Cylindrical Waveguides: This software package [16] calculates and plots the electric- and magnetic-field vectors associated with the various TE and TM modes in cylindrical waveguides. The program is based on analytical expressions for fields in waveguides of cross sections shown in Fig. 5. Figure 6 shows an example of plot of the electric- and magnetic-field vectors. A newer version of this software that provides color display of the

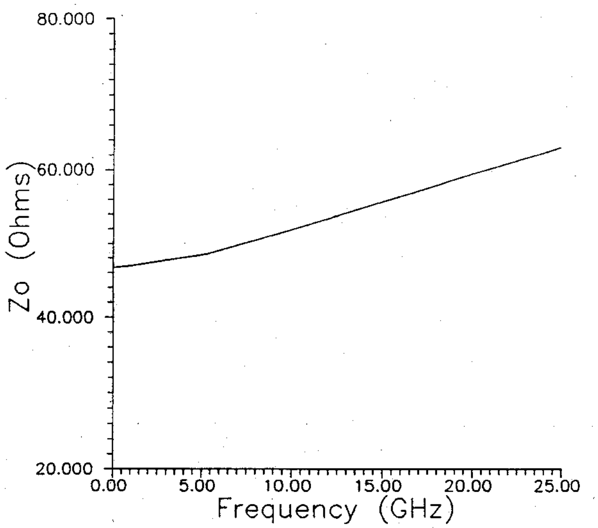


Fig. 3. Characteristic impedance of a microstripline as a function of frequency. Line width = 1 mm, dielectric thickness = 1 mm, box height = 10 mm, and dielectric constant = 10.

electric and magnetic field vectors in cavities will be published soon by CAEME.

4. Numerical Techniques in Electromagnetics: This software package was developed by the group at the University of Utah and includes software suitable for an introductory course on numerical techniques in electromagnetics [17]. Both the finite-difference and the method of moments solution procedures are described. Examples of the finite-difference programs include calculation of characteristic impedance of strip and microstrip lines, the first TE and TM modes in ridged waveguides, and the junction capacitance of two coaxial cables. The first two examples are based on finite-difference solutions in Cartesian coordinates, while the junction example is based on solution of Laplace's equation in the cylindrical coordinate system. Method of moments programs, on the other hand, include calculation of charge distribution on wires raised to specified voltages, the capacitance of a parallel-plate capacitor (including fringing effects), and the TM polarization, 2D scattering from an inhomogeneous dielectric cylinder of arbitrary cross section. Figure 7 shows the geometry of a parallel-plate capacitor for the method of moments calculations and the results of C/C_0 versus the spacing between the plates. C_0 is based on the geometry of the capacitor and neglects the fringing effects. Figure 7 demonstrates that neglecting the fringing capacitance may make values of C_0 in error by as much as 300 percent.

The above examples are just samples of the software available in the first CAEME book. Additional features are being discussed in other journal and magazine articles.

IV. Integration of Software in Curriculum and Classroom Teaching

With the availability of a significant amount of software for EM education from CAEME and other commercial sources, it is important to assess the effectiveness of these new tools in classroom teaching and develop procedures that promote their effective use in education. Routine classroom teaching

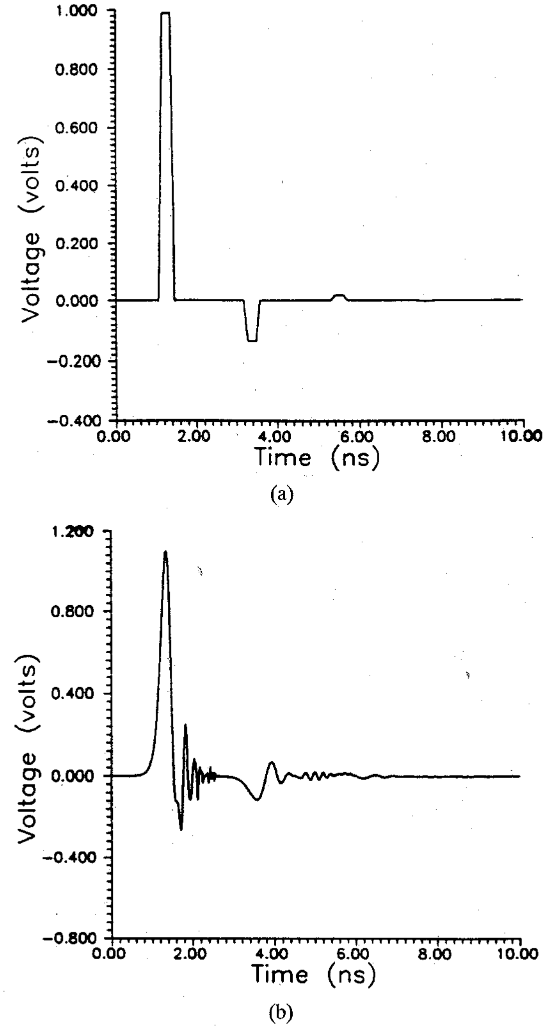


Fig. 4. Voltage at the output port of line T line of Fig. 3. The line is assumed to be terminated by a 50- Ω resistor in series with a diode. The default SPICE model is used for the diode. A 1-V voltage source in series with a 50- Ω resistor was placed at the input end of the T line. The line parameters at 1 GHz were used in these calculations. (a) Output voltage when dispersion is neglected. (b) Output voltage when dispersion is taken into account [15].

is significantly different from computer-based instruction and concerted efforts must focus on developing new teaching techniques.

The CAEME Center addressed these new challenges by expanding its activities to include the following new tasks:

1) Develop educational tools to help the integration of software in classroom teaching. This includes new homework assignments, open-ended design problems, and simulation of EM-based practical applications such as xerography, optical fibers, Doppler radar, etc. These applications may be used in stimulating students' interest in and out of classroom teaching.

2) Focus some of the workshop activities on discussing the issue of effective integration of computers and software tools in teaching.

A workshop that addressed this issue has already been held in August 1992 in Salt Lake City, Utah. Throughout the presentations and discussion sessions, it was clear that educators agree that computer use in education is a necessity. It provides a unique opportunity to boost engineering

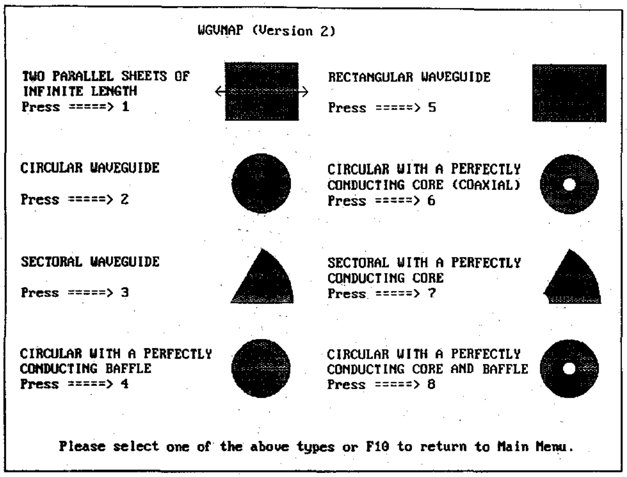


Fig. 5. Cross sections of cylindrical waveguides that may be analyzed using WGVMAP [16].

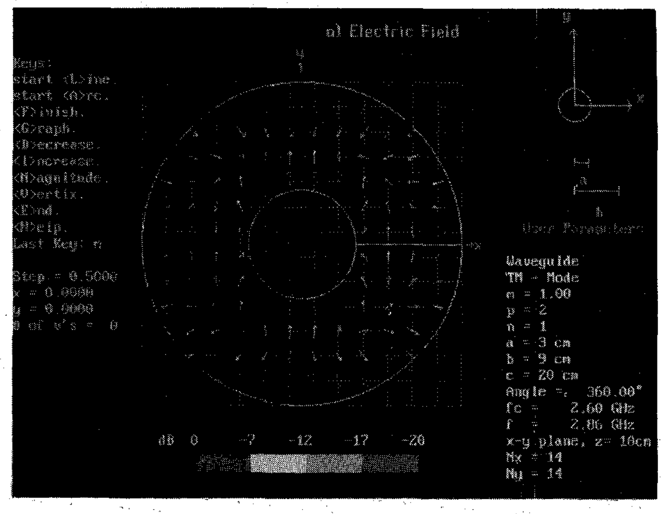
education. As educators continue to use computers in their teaching, however, they discover some limitations of this technology. Among the problems often cited is the congested curricula. A standard teaching procedure is based on text materials and laboratory instruction. With the introduction of computers, however, discussion of software and its uses and capabilities replaces some of the standard textbook and laboratory instructions. It is not clear how much of the standard instruction should be replaced by computer- and software-related instruction, and procedures to ensure the students' self-study of the deleted portions of the standard instruction must be developed and enforced, and their effectiveness be carefully evaluated.

Furthermore, it is not clear whether students would independently understand physical principles and mathematical procedures underlying the often-attractive graphical representation of simulation results. Tutorials describing the advantages and limitations of adopted solution procedures and quiz sessions must accompany routinely developed simulation software. Finally, the role of instructors in this era of computer-based instruction must be carefully defined. It is suggested that with the one-on-one tutoring capability of well-structured computer-based lessons, instructors may need to focus on difficult topics and leave routine ones to self-study by students.

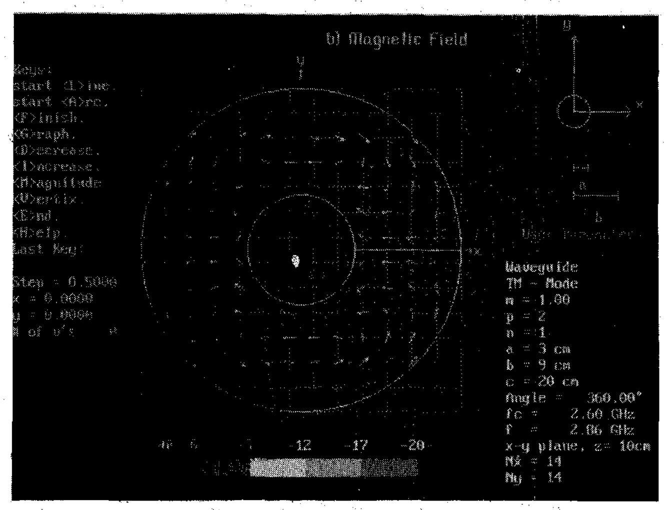
Many other timely topics were discussed during the Salt Lake City workshop, and a full proceedings will be published as a chapter in the *CAEME Software Book*, vol. II.

3) Use of interactive video and multimedia lessons in EM theory and applications. An interactive video lesson includes access to multimedia information from video, software, and animated graphics, and access to multimedia instruction including tutorials and quizzes. CAEME has already developed four interactive video lessons using the QUEST authoring software [18]. Main features of the developed lessons include

a. Access to and specific assignments from software packages in the *CAEME Software Book*, vol. I.
b. Access to all or part of the experimental or computer-generated videos distributed by CAEME. Portions of these videos have been transferred to two laser discs (30 minutes each), and specific frames of the video sections are accessed by QUEST through a videodisc player (e.g., Sony LDP 1450).
c. Animated graphics of various dynamic phenomena associated with the topic of the lesson. QUEST [5], [19], as well as other authoring systems, provides relatively easy to use capabilities for creating animated graphics so valuable to the effective explanation of the dynamic electromagnetic fields. Examples of some of the developed animated graphics are discussed in the following section.
d. Quiz sessions that help evaluate the students' understanding of key topics in the lesson, guide students through correct solution procedures, and suggest specific avenues (additional reading, software simulation, or video review) to help students in their understanding. In all cases, the multimedia lessons were structured such

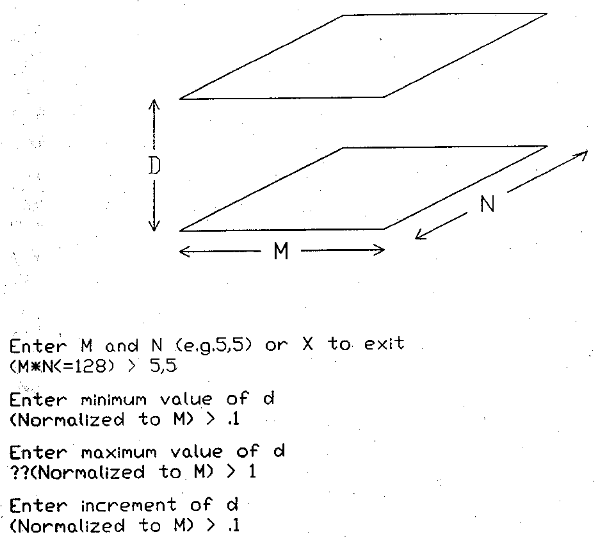


(a)

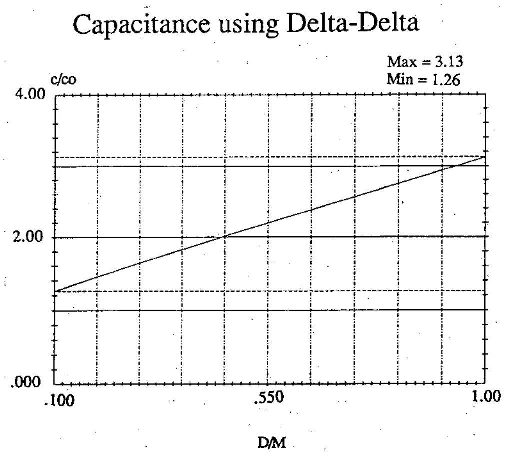


(b)

Fig. 6. An example of the WGVMAP resulting from electric and magnetic fields associated with the $TM_{11}(P = 2)$ in a circular waveguide with a perfectly conducting core and baffle. The radius of the center and outer conductors are 3 cm and 9 cm, respectively. The calculated cutoff frequency f_c = 2.6 GHz [16]. (a) Electric field. (b) Magnetic field.



(a)



(b)

Fig. 7. The parallel-plate capacitor example used to illustrate the method of moments solution procedure [17]. (a) Geometry of the parallel-plate capacitor. (b) The calculated capacitance C normalized with respect to $C_0 = \varepsilon_0 \mathrm{NM/D}$ to illustrate the fringing capacitance $(C - C_0)$ effect.

that results from the quiz sessions are reported to the instructor.

Features of the developed EM multimedia lessons are described in the next section.

V. Examples of Multimedia Lessons in Electromagnetics

In all the four multimedia lessons developed by CAEME thus far, the animation, access to video, simulation, and quiz features described above were implemented. In each of the following examples, however, we highlight one of these features.

A. Example 1: Electromagnetic Waves

The objective of this lesson is to introduce the student to basic propagation characteristics of traveling and standing waves. The main menu of the lesson is shown in Fig. 8, where it may

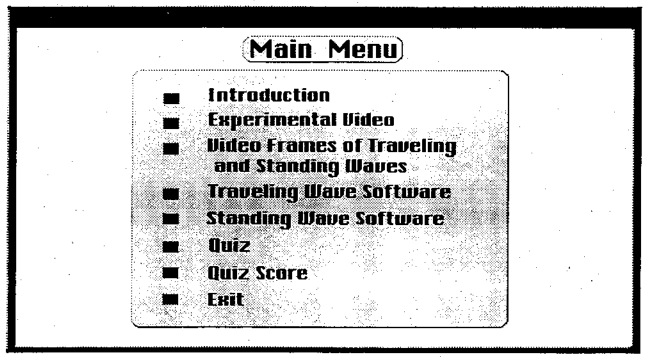


Fig. 8. Main menu of the multimedia lesson on electromagnetic waves. The lesson includes access to experimental video, two CAEME software packages [20], [21], animated graphics, and a quiz that consists of five questions.

be seen that the lesson provides access to video demonstrations on standing waves [11] and to two software packages from the CAEME book [20], [21]. It includes animated graphics and tutorials on some basic properties of traveling and standing waves and a quiz session.

We use this example to demonstrate the animated graphics and access to video features of a multimedia lesson.

Video Frames of Traveling and Standing Waves: When this option is selected from the main menu, the student is given the option of selecting and studying the topic of either traveling or standing waves. Let us briefly consider the content of each topic.

Traveling waves: In this section, the student is introduced to the basic propagation properties of a traveling wave and the relationship between the associated electric and magnetic fields. An example screen in this option is shown in Fig. 9, where the electric and magnetic fields associated with a plane wave propagating in air are demonstrated dynamically using a sequence of animated graphics. This dynamic and animated presentation of the propagation characteristics of wave makes the use of computers far superior to routine textbook static-type teaching. At the end of the traveling wave section of the lesson, it is suggested that the student access and perform independent simulations of some specified aspects of wave propagation using the CAEME software [20], [21].

Standing waves: Upon selecting the standing-wave option, the new menu of Fig. 10 is displayed. This menu is quite comprehensive. It allows the student to access a short section of video that experimentally demonstrates mechanical standing waves, a brief tutorial with animation on characteristics of standing waves, and additional captured small sections of the video on experimental demonstrations of standing electromagnetic waves. The video sections on mechanical waves and the electromagnetic waves are included in the video available with the CAEME book [11].

When the "Electromagnetic Standing Waves" option from the menu of Fig. 10 is selected, the student will be briefly introduced to a tutorial on the cause and propagation properties of standing waves. An animation that demonstrates the interference between two waves of equal magnitude, of the same frequency, and propagating in opposite directions is included

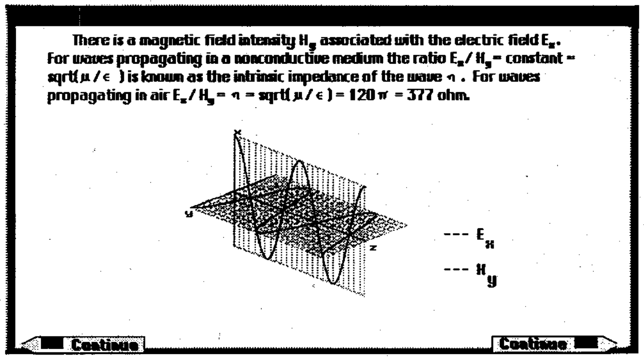


Fig. 9. An example that demonstrates the animated graphics capabilities of the "electromagnetic wave" multimedia lesson. The figure shows in phase sinusoidal electric and magnetic fields. These fields are perpendicular to each other and to the direction of propagation (z).

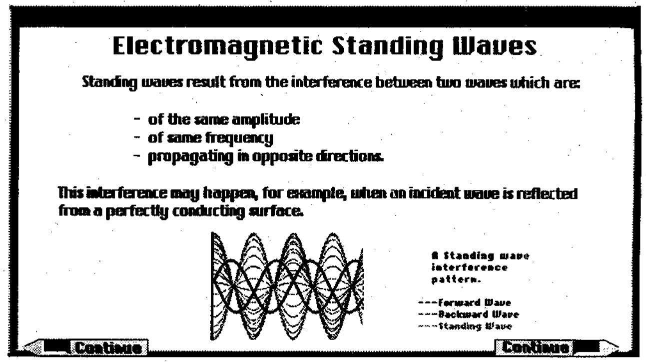


Fig. 11. Dynamic illustration of the concept of standing waves. Two sinusoidal plane waves of the same frequency and propagating in opposite directions (green and purple curves) interfere to produce the resulting standing wave (white curve).

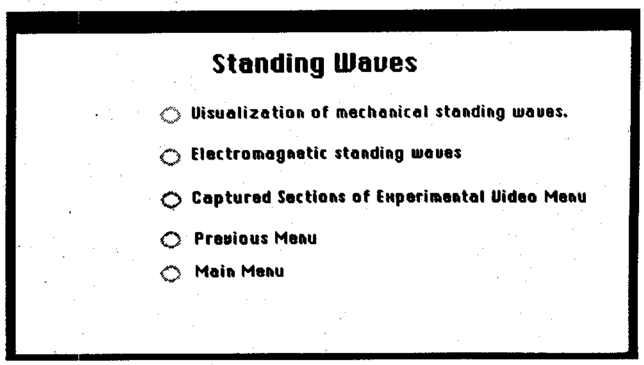


Fig. 10. The standing waves menu. It includes a comprehensive review and demonstrations of some fundamental characteristics of standing waves. In addition to various segments of videos and animated graphics, it accesses tutorial information and instructions.

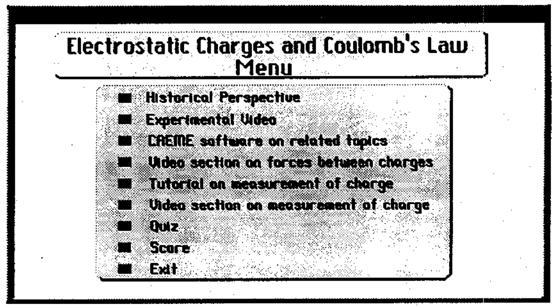


Fig. 12. Main menu of the multimedia lesson on electrostatic charges and Coulomb's law.

in this section (see Fig. 11). The basic properties of a standing wave are also summarized. Aspects such as distances between successive nulls in electric and magnetic fields and locations of nulls from short- and open-circuit terminations of TEM lines are discussed. Once again, the animated graphics illustrating the interference between two waves and the visualization of the characteristics of the resulting standing wave provide excellent demonstrations of the advantages of using computers to teach dynamic electromagnetic fields.

B. Example 2: Electrostatic Charges and Coulomb's Law

The purpose of this lesson is to review basic concepts concerning interactions between charged particles. To accomplish this, the student views a video presentation on the measurement of charge and an experimental verification of Coulomb's law. The main menu of the lesson is shown in Fig. 12. This lesson provides access to a section of the video on experimental demonstrations for teaching electromagnetic fields and energy [11], to CAEME simulation software relevant to the lesson's topic [12], [21], [22], and also to tutorials on electrostatic charges, their forces, and techniques for their measurement.

Besides the access to sections of the video on Coulomb's law and measurement of electrostatic charges, the lesson provides an attractive computer-based quiz session. This includes animated graphic features wherever appropriate and also interactive remediation for helping and guiding the student in solving the quiz problems. For example, in quiz problem number 3, the student is asked to determine the angle between an electrostatic charge Q and an infinitely large plane charged with a charge density ρ_s. If the student clicks on the wrong answer, the program will first advise the student that the answer is incorrect and then will proceed to provide guidance through one aspect of the required analysis. For example, in this case, the student will be asked to calculate the electric field associated with the infinitely large plane charged with a charge density ρ_s. It will be pointed out that Gauss' law for the electric field needs to be used and a Gaussian surface that takes advantage of the symmetry consideration and the resulting direction of the electric field needs to be established [23]. The student's selection of the appropriate direction of the electric field resulting from an infinitely large charged plane is indicated by clicking on the appropriate option as shown in Fig. 13. If a wrong selection is made, the student will be guided so as to recognize aspects of the symmetry consideration and then led to the selection of an appropriate Gaussian surface as shown in Fig. 14. The student will then be asked to attempt a second answer to the quiz. If the answer is still incorrect, a second level of remediation will be given. In particular, the analysis concerning balancing the electric and gravitational forces on the suspending string should lead the student to identify the correct answer to the quiz.

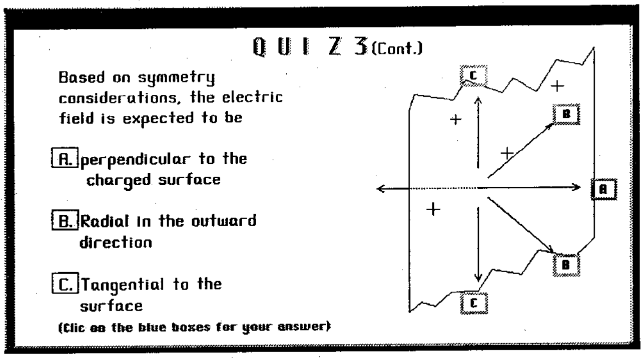


Fig. 13. A display of a multiple-choice question intended to help students identify the correct direction of the electric field associated with an infinitely large charged plane.

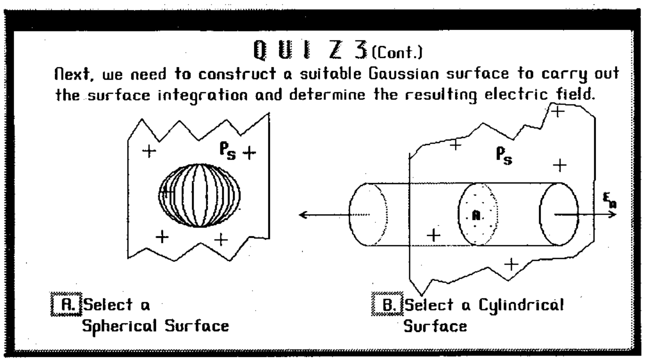


Fig. 14. A schematic demonstrating an incorrect and a correct option of selecting a Gaussian surface for evaluating the electric field associated with an infinitely large plane charged with a charge density ρ_s. If a wrong answer is selected, the student is advised to select option B to take advantage of simplifications when integrating the electric field E_n over the closed surface. (a) Incorrect option. (b) Correct option.

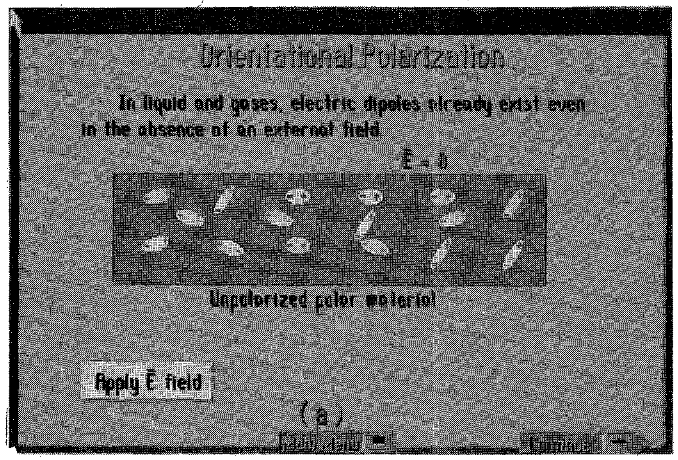
It should be emphasized that through this example, we attempted to demonstrate the integration of the visualization, animation, and interactive features of the multimedia lesson. The inclusion of sections of video help visualize experimental aspects of measuring charges, while access to CAEME software and interactive guidance of the student through the quiz session clearly distinguish multimedia lessons from classical static or textbook-type teaching.

C. Example 3: Dielectric and Conducting Materials

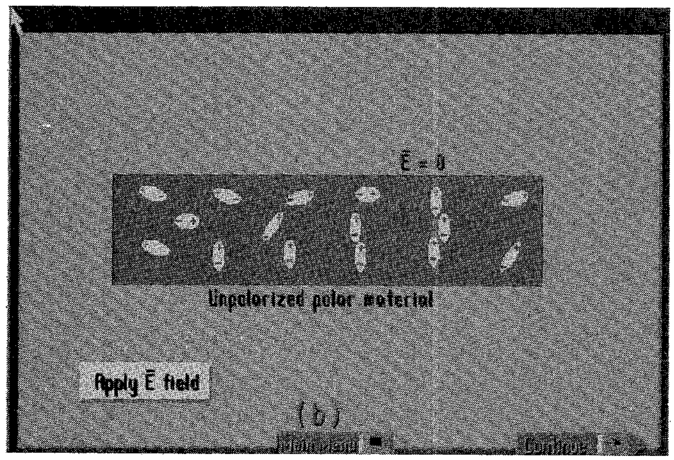
The objective of this lesson is to review the conducting and dielectric properties of materials, describe various polarization mechanisms, and quantify the conduction and polarization currents as well as the polarization charge that results from the interaction of materials with an externally applied electric field. The main menu of this lesson includes traditional features such as those shown earlier in Figs. 8 and 12.

This lesson, however, has additional attractive features. These include interactive animation, specific software assignments, and a hypertext-type tutorial whereby key words are highlighted and additional explanations are available to students upon request.

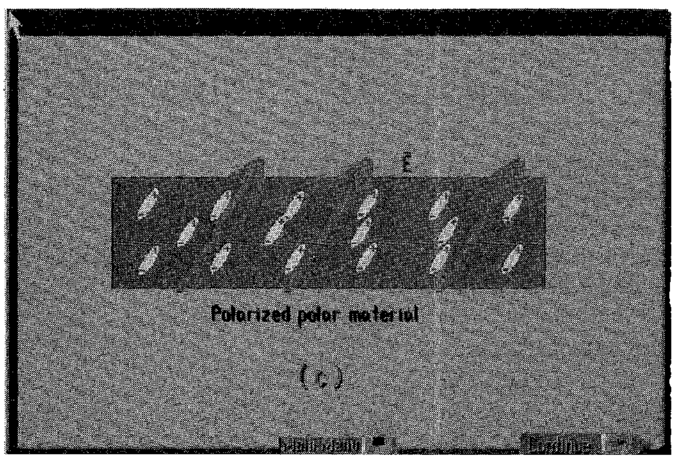
Regarding the interactive animation feature, let us consider the explanation of the various polarization mechanisms. In the lesson, it is initially stated that there are three main polarization mechanisms in pure substances, and a menu is provided to access an explanation of each of these mechanisms. Upon access of the electronic polarization option, for example, the student is shown a classical atomic model of a positively charged nucleus surrounded by a cloud of orbiting electrons.



(a)

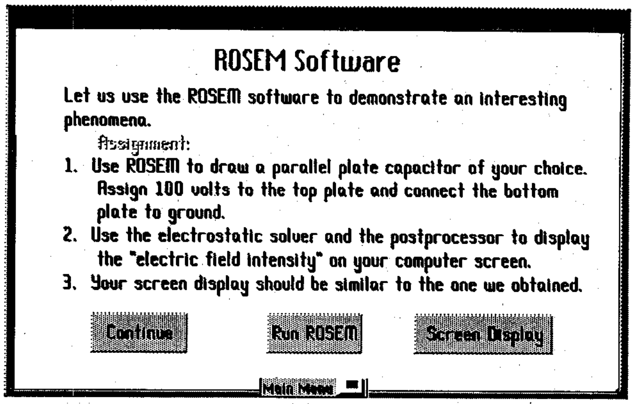


(b)

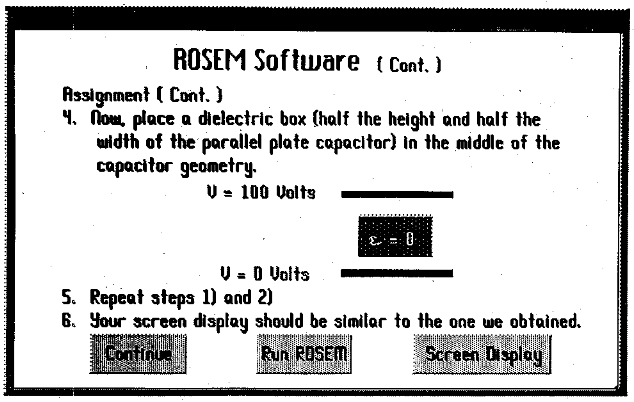


(c)

Fig. 15. A series of stills that illustrates the concept of orientational polarization. (a) and (b) Random orientation of permanent electric dipoles and their continuous motion in the absence of an external electric field. (c) Alignment of the permanent electric dipoles in the direction of the external electric field.



(a)



(b)

Fig. 16. An example of software assignment that helps guide students through simulation using CAEME software (e.g., ROSEM [24]). (a) Simulation example of an electric field in a parallel-plate capacitor. (b) Simulation of the electric-field intensity in part (a) when a dielectric slab is inserted between the plates.

The student is then asked to apply an external electric field by clicking the mouse and watching the shifts in the centers of the positive and negative charges in opposite directions, thus creating an electric dipole. In the orientational polarization case, a color graph of a section of material is shown and the permanent electric dipoles are displayed in random motion under the influence of their thermal energy. When the student applies an external E-field, he/she watches, in real time, the alignment of these dipoles in the direction of the E-field. Figure 15 shows stills that illustrate this process.

The other feature of this lesson is providing students with specific assignments to use CAEME software. Figure 16 shows a simulation example that will help students understand the reduction of the electric-field strength inside a dielectric material as a result of the material's polarization. The assignment provides access to the ROSEM software [24] and shows the student the expected result from the simulation "screen display." After performing the simulation, the student is asked to interactively explain the obtained results. Depending on the answer, the student may either be asked to carefully compare the results as shown in Fig. 17 or be guided through a detailed, often graphical explanation of the expected answer. This discussion provides an example of specific simulation assignments that may help guide students through an understanding of a physical phenomenon.

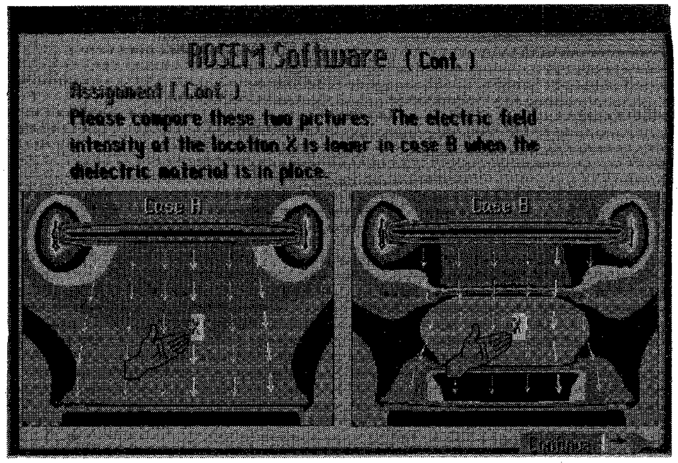


Fig. 17. Electric-field intensity in the region between the plates of a parallel-plate capacitor. Case A is for the air-filled capacitor, while case B is for when the dielectric slab of $\varepsilon_r = 8$ is inserted in a central subregion between the plates.

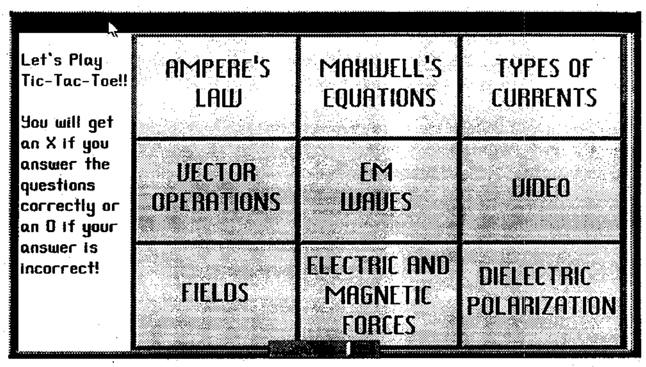


Fig. 18. Main menu of the Tic-Tac-Toe interactive video lesson. This is a review lesson on some basic concepts in introductory electromagnetics.

D. Example 4: Tic-Tac-Toe Review Test in Electromagnetics

The purpose of this multimedia application is to provide a review test of several basic concepts routinely covered in an introductory course in electromagnetics. As the student accesses the application and enters his/her name, the overall Tic-Tac-Toe board shown in Fig. 18 appears on the screen. Topics such as vector algebra, fields, Maxwell's equations, EM waves, and dielectric polarization are covered. It may also be noted that the question board includes a video category in which the student is shown a short section of a video and then asked to answer a question. In addition to the fun nature of this lesson, [25] many of the questions include animation; this emphasizes an additional advantage of having this Tic-Tac-Toe game played on a computer. The arrangement of the categories is randomized after each question to avoid a fixed arrangement of the topics.

In designing this review test, each question category was divided into subcategories, each of which includes several questions. For example, the category on Maxwell's equations includes subcategories on general aspects of these equations, Ampere's Law, Gauss' Law, and Faraday's Law. Also, the category on vector operations includes subcategories on vector

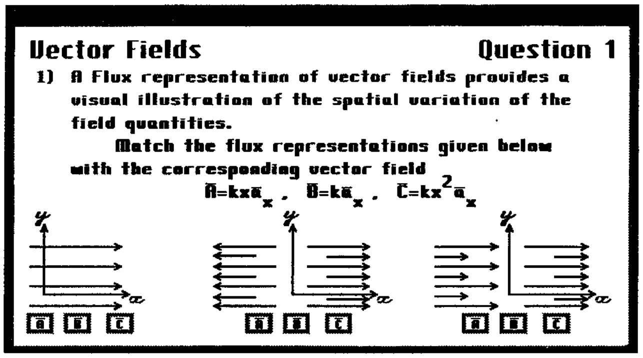


Fig. 19. An illustration of the type of questions included in the Tic-Tac-Toe review lesson. Flux representations of vector fields are sketched and the student is asked to match the flux representation with the appropriate expression of the vector field.

algebra, integral operations, and differential operations. An example of the questions in the vector differential operation subcategory is shown in Fig. 19, in which the student is asked to identify the relationship between the differential vector operations and the flux representations of some vector fields. It is difficult to demonstrate in this paper some of the dynamic, animation, and interactive aspects of these questions, but it suffices to indicate that students find this lesson fun, exciting, and most important, instructionally useful and certainly helpful in solidifying their understanding.

VI. Discussion and Conclusions

The grant from the National Science Foundation for establishing CAEME provided the electromagnetic community with a unique opportunity to align EM and microwave education with the 1990's. Software packages that provide broad coverage of all topics in an introductory course in electromagnetics were developed, and efforts are underway to develop additional software for volumes II and III of the CAEME books and to further explore avenues to promote integration of computers and software tools in classroom teaching. Besides the software developments, the mere existence of the CAEME Center and its widespread activities increased awareness of problems facing electromagnetic education, helped faculty share possible solutions, and provided avenues to effectively disseminate available software and other related information.

In addition to illustrating some features of the developed software, examples of multimedia lessons developed to help integrate CAEME software in teaching were described. It is shown that authoring software such as QUEST is available, and opportunities to develop lessons that combine multimedia information from video, software, and animated graphics with multimedia instruction, including tutorials and quizzes, are not only feasible but also affordable. Software and hardware requirements for developing such lessons may be purchased at an estimated cost of less than $3,000 (excluding the 386 computer). Based on instructor and student comments on these lessons, it is generally believed that multimedia applications will play a significant role in the future integration of computers and software tools in classroom teaching. Future developments in the CD-ROM and digitized-video technologies will significantly help in the distribution of these highly interactive and visual lessons. As a matter of fact, CAEME software is now available on CD ROM. Furthermore, CAEME received a grant from the State of Utah Centers of Excellence Program to develop multimedia lessons for pre-college physics and calculus courses.

As CAEME continues to proceed with its activities, faculty and institutions are encouraged to join in and seize this opportunity to help boost EM education. With the publication of the new journal, *Computer Applications in Engineering Education* [6], faculty now have an exciting opportunity to publish their work and share their software in a peer-reviewed, multidisciplinary journal. CAEME will also continue to organize special sessions and workshops to help faculty present new developments, exchange ideas, express concerns, and share successes. CAEME intends to provide additional seed funds so that its faculty can continue their work on new software development projects. To this end, corporate support and participation by participation by professional EM societies is crucial. Based on the present level of support, CAEME's future is bright.

Acknowledgment

The CAEME Center, its activities, and the software in the first book have all resulted from remarkable collaboration between participating faculty and outstanding commitment by their institutions. Some of the software packages were prepared by faculty who received CAEME grants, while others were contributed by faculty and institutions interested in and supportive of the CAEME effort. To all CAEME faculty members whose names appear in the CAEME book, congratulations on a successful effort, and I am indebted to you for your outstanding contribution.

I am also grateful to members of the policy board for their vision of the CAEME mission and for their remarkable efforts that made the Center a success. Members of the board who helped establish CAEME include Irene C. Peden, David Chang, Zvonko Fazarinc, Robert E. Collin, Gary Wojcik, Warren Stutzman, Barry Perlman, Clayton Paul, Peter Lewis, Rudy Stampfl, Hal Kimrey, Philip Green, and Vaughn Cable.

I am also indebted to colleagues from John Wiley & Sons, Inc., who supported the publication of the new journal, *Computer Applications in Engineering Education.* Now that engineering faculty can publish and be recognized for this work in this area, the future of a "computer-based engineering curriculum" is certainly bright.

I would like to thank our corporate sponsors Hewlett-Packard, Motorola, Lockheed, Texas Instruments, and Andrew Corporation, for their kind support. Equally appreciated is the remarkable support the Center receives from the Electrical Engineering Department at the University of Utah and the CAEME staff. In particular, I am grateful to Holly Cox, Doris Marx, Octavio Andrade, Joe Breen III, and Paul Cherry, who generously supported CAEME development every step of the way. The professional commitment and outstanding work by Tom Reed is wholeheartedly appreciated.

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