Interactive Software for Undergraduate Electromagnetics

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Abstract—To demonstrate the relationship between physical reality and the equations used in electromagnetics, we have created interactive software using Mathematica with its “notebook” capability. This software is composed of different notebooks, each covering a specific topic, which are collectively called EM Notebooks. The notebooks are used in a workstation laboratory of 12 NeXT® computers in conjunction with our two required junior-level courses in electromagnetics. Each notebook consists of text, equations, and graphics. The equations are actually Mathematica commands which are used to evaluate electromagnetic formulas found in a typical undergraduate electromagnetics textbook. Equation parameters can be changed by a student permitting examination of an unlimited number of examples. In addition, much of the graphics can be animated. The animations provide a pedagogic tool unavailable in traditional textbooks; they have proven valuable in illustrating dynamic processes and parametric dependence in a function. EM Notebooks are not restricted to NeXT workstations; however, they must be used on a computer that runs Mathematica with the notebook facility.

1. INTRODUCTION

The study of electromagnetics is required in most electrical engineering undergraduate curricula, usually in the junior year. However, many students would not study electromagnetics if given a choice. They question its relevance since interesting, “real-world” problems are difficult to cover in an introductory course. They also complain that electromagnetics is too theoretical and abstract, that it is simply another mathematics course filled with a jumble of dry, uninteresting, and confusing equations. A minority of undergraduates has the sophistication and motivation to understand the correspondence between the equations and the physical phenomena they describe.

A number of researchers have suggested the use of computers to assist in teaching electromagnetics [1]–[7]. In fact, the National Science Foundation has sponsored development of software specifically for teaching electromagnetics, and the results, compiled in the NSF/IEEE Computer Applications in Electromagnetics Education (CAEME) Software Book [8].

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1Mathematica is a registered trademark of Wolfram Research, Inc., 100 Trade Center Dr., Champaign, IL 61820–7237.
2NeXT is a registered trademark of NeXT Computer, Inc., 900 Chesapeake Dr., Redwood City, CA 94063.

have been enthusiastically received by many universities, We have attempted to make our required, junior-level electromagnetics courses more accessible to students by creating

Fig. 1. (a) Electric potential in a plane containing a dipole along the z axis. (b) Magnitude of the electric potential evaluated on a spherical surface centered at the origin for an octupole centered at the origin.
ScalarFields (Electric Potential)

Introduction

Surface Plots

Introduction

Monopole

Dipole

Quadrupole

Contour and Density Plots

Parametric Plots (Spherical Coordinates)

Initialization Cells

Fig. 2. (a) View upon opening the section Surface Plots in the ScalarField notebook. (b) Partial view upon opening the Quadrupole subsection.

Interactive software that combines text, equations, and graphics in an "on-line" textbook called EM Notebooks. Unlike ordinary textbooks, many of the figures can be animated. This allows a student to visualize such phenomena as the propagation of a plane wave as a function of time and position, the change in the direction of the electric field of a circularly-polarized wave, and how the intersection of constant coordinate surfaces determines a unique point in space for different coordinate systems. EM Notebooks also remove the inherent limitations of traditional textbook examples. Students have the freedom to change the values of the equation variables and, thus, can investigate an unlimited number of examples; this allows them to discover the physical effects of parameter changes. In essence, EM Notebooks provide a laboratory for the equations of electromagnetics.

The notebooks are run in an undergraduate workstation laboratory comprising twelve Next workstations. They are used in conjunction with two, three-semester-credit electromagnetics courses. The first course covers electrodynamics, magnetostatics, Maxwell's equations, and an introduction to plane waves. The second course covers plane wave propagation, transmission lines, waveguides, fiber optics, and antennas. Both courses are offered during the Fall and Spring semesters and in recent years have had combined enrollments between 90 and 125 per semester.

II. EM Notebooks

Mathematica is a powerful software package that can perform symbolic and numerical calculations. It also provides a rich programming environment in which modeling and analysis are made quite simple. For example, the electric potential about a point charge $q$ in free space is given by

$$V(q, r) = \frac{q}{4\pi\epsilon_0 r},$$

where $r$ is the distance from the charge to the observation point. In Mathematica this function can be written as follows:

$$\text{Epsilon0} = 8.8537 \times 10^{-12};$$

$$\text{Potential}[q, r] := \frac{q}{4 \pi \text{Epsilon0} r} \quad (1)$$

If a student were to enter Potential[2, 1], Mathematica would return the electric potential $1$ m from a $2 \text{C}$ charge. Of course, this is not very interesting itself, but a student can use this function as a building block to create a function that gives the electric potential about an arbitrary system of point charges. The notebook we have written on scalar fields, called ScalarFields, uses building blocks such as this to demonstrate a number of concepts in electromagnetics. For example, Potential is used to construct a function that provides the potential about a dipole, appropriately named Dipole. This function is then used to display the potential about a dipole in several ways. The following statements produce the output shown in Fig. 1(a).

$$\text{charge} = \text{Pi Epsilon0};$$

$$\text{location1} = \{0, 0, 1\}; \text{location2} = \{0, 0, -1\};$$

$$\text{Plot3D}[	ext{Dipole}[\text{charge}, \text{location1}, \text{location2}, \{y, -4, 4\}, \{z, -4, 4\}], \{y, -1, 1\}, \{z, -1, 1\}, \{\text{ClipFill} \rightarrow \text{None}, \text{Lighting} \rightarrow \text{True}, \text{PlotPoints} \rightarrow 31, \text{PlotRange} \rightarrow \{\text{Automatic, Automatic}, \{-2, 2\}\}, \text{BoxRatios} \rightarrow \{1, 1, 1\}, \text{AxesLabel} \rightarrow \{"y", "z", "v"\}, \text{PlotLabel} \rightarrow \text{"Fig. 3"}]$$

Similarly, one can use Potential to display the potential...
about an octupole as shown in Fig. 1(b). Notebook equations are explained so that a student understands how to change parameters, and he or she is given suggestions for changes to make and interesting examples to explore.

Despite the computational power of *Mathematica*, it is useful in an introductory electromagnetics course only if the student can be guided through the material in a clear, concise, and intuitive manner. Fortunately, the notebook facility allows a programmer to hierarchically structure text, equations, and graphics in an easy-to-understand way. Fig. 2(a) shows the view a user has of the ScalarFields notebook after the mouse has been used to open up the section *Surface Plots*. Successive subsections can, in turn, be opened to reveal greater and greater detail as in Fig. 2(b) where part of the *Quadrupole* subsection is shown. This layered structure allows the user to delve as deeply as he or she desires into a particular subject and also serves to organize information visually.

The animation capability of the *Mathematica* notebooks allows the user to examine changes in output as a function of a given variable such as time or position. We have taken advantage of this feature in a number of notebooks. For example, in the notebook *StandingTraveling* the student can examine the incident, reflected, and transmitted waves when a plane wave propagates from one medium to another. Typical output in this notebook is shown in Fig. 3 for a wave propagating from free space to water. When animated, the figure displays the oscillations of the nearly standing wave in free space and the exponential decay of the traveling wave in water. By changing the frequency a student gets an instantaneous, graphic illustration of the frequency dependence of the exponential decay.

In most textbooks the gradient operator is introduced as a rule for mapping a scalar field to a vector field. This approach tends to reduce the concept to an exercise in differentiation. In contrast, the *Gradient* notebook gives a visual display of the gradient operation. In Fig. 4(a) the surface plot shows the general shape of a two-dimensional scalar field, while in Fig. 4(b) the contour plot indicates the subtle dips and peaks in the same field. Figure 4(c) shows the gradient of the scalar field by projecting individual vectors in space onto the $x$-$y$ plane. Thus, a student sees that the gradient always points in the direction of the greatest increase in the scalar field.

To date, ten notebooks have been made available to our students and other notebooks are in different stages of development. Those currently available are:

1) *Introduction*  
   Introduction to *Mathematica* and *EM Notebooks*.

2) *CoordinateSystems*  
   Cartesian, cylindrical, and spherical coordinate systems.

3) *IntroVectors*  
   Unit vectors, position vectors, and field vectors in the different coordinate systems.
4) ScalarFields: Scalar fields explored using electric potential examples.
5) Gradient: Demonstration of the physical significance of the gradient of a field.
6) Divergence: Demonstration of the physical significance of the divergence of a field.
7) Curl: Demonstration of the physical significance of the curl of a field.
8) WavePropogation: Plane wave propagation in different materials.
9) StandingTraveling: Standing and traveling waves present when a wave is reflected from and transmitted into various materials.
10) Polarization: Linear, circular, and elliptical polarization.

The EM Notebooks are available to any interested party via anonymous ftp from emserv1.eecs.wsu.edu. The files are in the directory /pub/Notebooks. The README file in this directory gives an up-to-date description of the notebooks and further details about their contents.

III. SUMMARY AND FUTURE WORK

We have written interactive software to help students visualize the physics underlying the equations of electromagnetics. This software, composed of notebooks collectively known as EM Notebooks, uses Mathematica to combine text, equations, and graphics in a hierarchical structure. Equation parameters can be changed by the student user, allowing interactive experimentation, and much of the graphics can be animated to show a user such physical phenomena as how a propagating wave changes as a function of both time and position.

The notebooks are an ongoing project; much remains to be done. In the near future we intend to add notebooks on waveguides, transmission lines, antennas, the Lorentz force equation, and additional temporal and harmonic representations of fields.

REFERENCES


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