Session 3632

A New Approach in Teaching Electromagnetism: How to Teach EM to All Levels from Freshman to Graduate and Advanced-Level Students

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1. Introduction

1.1. Historical perspective

James Clerk Maxwell provided a unified field formulation of electromagnetism in 1873 with his famous "Treatise on Electricity and Magnetism."[1] From the beginning he explained the field was made of a set of observed phenomena, fundamental concepts governing electromagnetism (EM), and mathematical formulations to help the patron utilize and manipulate the concepts in order to explain observed phenomena. Consequently, the mathematical nature of electromagnetism has been an inseparable part of the subject from the beginning. It should be noted that Maxwell himself spends considerable effort in his treatise clearly describing fundamental concepts, observed phenomena, and measurements rather than explaining the detail of the mathematics (which used to be the calculus of quaternion). Then in the first part of the 20th century, Oliver Heaviside and Heinrich Hertz,[2] in a practical attempt to make the field more applicable and powerful, introduced the modern vector calculus-based presentation of electromagnetism; however, the basic approach to teaching electromagnetism has remained fundamentally the same. The field is still broken into three major entities, which are the observed phenomena, concepts summarized in Maxwell's equations and the Lorentz force equation, and the mathematical formulation of these concepts. Despite the subject being highly conceptual and phenomenological in nature, during most of the 20th century EM has been taught with heavy emphasis on the mathematics and fundamental constructs, with a more or less anecdotal approach to the observed phenomena and practical side. It is for this reason that we suggest a new approach to teaching electromagnetism in which the emphasis of concepts and phenomena is strengthened in an attempt to increase the understanding of a typical electrical engineering student.

1.2. The method of teaching EM in history and the present

In general, presenting and understanding the mathematical constructs of EM is a major task for most engineering students. In fact, even the simplified mathematical approach that assumes perfect plane waves and idealized systems (without any outside interference or external forces)[3] involves specialized manipulations that are not trivial for most students of EM. Now adding to this the observed phenomena, the level of complexity of learning is considerably compounded. Many tools have since been developed to help both researchers and students understand the subject, apply them to complicated geometries, and visualize the electromagnetic phenomena for specialized specifications. Perhaps the most interesting tools have been the computer-aided programs to visualize the fields and to solve realistic problems numerically.

Consequently, a quick review of the development of electromagnetism reveals that our fundamental approach to teaching the subject has not fundamentally changed since the days of Maxwell. With the addition of vector calculus, the subject is approached more clearly with logical mathematical manipulations; however, with this addition the level of mathematics was raised considerably. As a result, most electromagnetic classes have become heavily involved with mathematical approaches and proofs, leaving understanding behind. Currently, electromagnetism in electrical engineering is considered to be the most difficult class that any undergraduate can take. Despite the fact that it is the most fundamental knowledge base that originally created the field of electrical engineering, students believe that it is a non-practical, mathematically saturated, and abstract subject. Unfortunately, very few students either know enough about the field to enjoy it or see the importance of the subject in their everyday lives as professional engineers. At the same time, most of the new computer-based packages are designed to help only advanced users and not the introductory or intermediate users who could greatly benefit from such tools.

1.3. The current problems

Today, due to the rapid development of the field, higher-speed electronics, and optical systems, there is a definite need for electrical, computer, and system engineers to be familiar with the fundamental concepts of EM. Based on this new demand, the authors feel that it is a great time to revise our approach to teaching electromagnetism. The question then is how can this be done effectively? In this paper we propose a fresh approach for teaching the subject of EM. This approach focuses on the teaching of the governing physics of electromagnetism and decouples the advanced mathematics from the physics of the subject.

We believe by doing so the instructor will spend more time with the concepts in EM. Then, depending on the level of the students, one can utilize the currently available tools such as Mathematica and MATLAB to help students learn the mathematical manipulations as well as the computational part of the field. This will allow students to learn by discovering and inquiring in a non-threatening learning environment. We believe that in this environment the student will be able to thrive in a subject that has long been dreaded.

1.4. Brief idea of solution

By decoupling mathematics from the physics of EM, lectures can be more focused on conveying to students the conceptual nature of EM and give them a good understanding of the field. It is the hope of the authors that this strong conceptual footing will aid students later in problem solving and physically realizable phenomena. It is generally the lack of EM understanding that makes it so abstract and causes the mathematics to appear difficult. By allowing students to learn by discovery in a non-threatening environment, we believe that students will become better long-term engineers and life long learners.

1.5. What we see in the paper

In this paper we first introduce the traditional ways of teaching and presenting EM to the students and discuss the strengths and weaknesses of the traditional method as well as why we propose to change it. Then the proposed new method is introduced and discussed. This is followed by a typical lecture using the proposed method where the highlights and general approach of the lecture are discussed together with some of the MATLAB/Mathematica tools and units. Finally the premise of the new methods, issues, and concerns are discussed, followed by concluding remarks and future work.

2. Traditional Approaches

2.1. The general premise

Traditionally, introductory EM course goals are to teach concepts and basic mathematical formulation in order for students to see the importance and application of the laws of EM and provide the background necessary for an advanced study of the subject. In this manner, the students should be able to explain the concepts behind Maxwell's equations and apply them to simplified situations. These EM courses are also designed with the purposes of teaching students how to utilize models based on physical concepts in order to solve realistic problems and of giving students the ability to examine results, answers, and expected outcomes based on fundamental concepts. In this way students should learn how to apply their basic knowledge to more realistic applications in a way that they may be able to engage in research or industrial applications. Students who know the fundamental concepts and are able to demonstrate their knowledge in simplified applications are considered successful EM students. Figure 1 depicts the major premise of the traditional approach to EM training.

2.2. Pros and cons

A course based on these goals gives students a great and highly mathematical, conceptual, and theoretical background to the subject. Students also get to examine generalized models and consider the application of these models in the solutions to more complex problems. The goals set forth also provide students with a sense of the strength of the field and the essence of the true historical development of EM. Perhaps the most important outcome of typical EM classes is to show students that by utilizing abstract concepts with the right mathematical tools one is able to examine, explain, and formulate practical applications. However, this notion is usually only communicated in the more advanced-level classes.

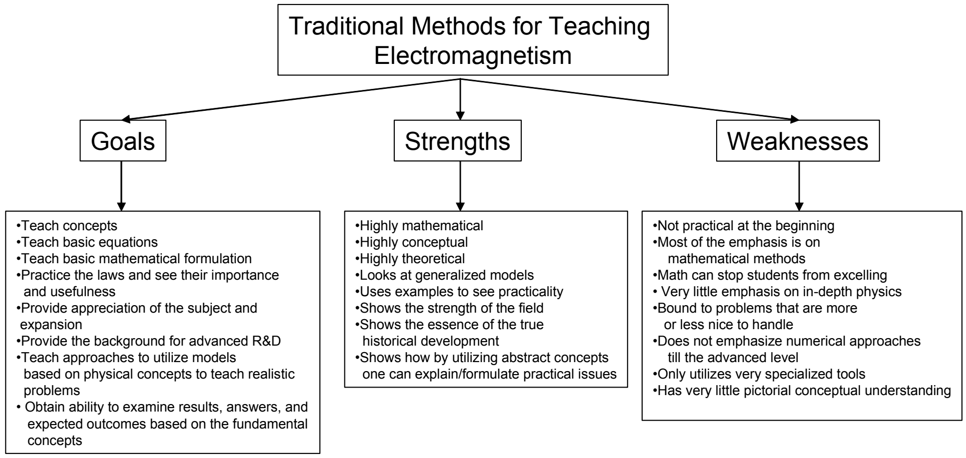


Figure 1. The traditional approach of an EM education.

2.3. Why is there a need to change?

While students acquire many valuable and important skills based on the goals of a classic EM course, the manner in which a classic EM course is taught does not fulfill these goals completely. One weakness in the classical teaching approach is its abstract nature without many practical considerations to begin with. This can often detract from a typical engineering student's desire to learn the fundamental concepts needed to understand practical issues and in many cases pushes a generally good, practical, and enthusiastic student to the back of the pack. Additionally, traditional courses in EM tend to put an extreme amount of attention on mathematics instead of in-depth physical understanding of electromagnetic fields, their manifestations, and their applications. It is rare even for some of the experienced instructors to have a practical picture in their mind of what is happening in many complicated problems. So, in order to get to the answer, one needs to lean heavily on the mathematics. We have seen in many cases that the mathematical presentations stop very bright and practically oriented students from excelling, even if the student has an amazing conceptual understanding of the subject. Due to the mathematical formulations used, problems are generally constrained to be fairly nice to handle with closed form solutions in most cases, and little or no attention is paid to numerical approaches until advanced-level courses. This emphasis on mathematical formulation over conceptual understanding is the essence of the EM teaching methodologies in most of the 20th century. Consequently, EM has become a very difficult and unimpressive subject to many of today's engineering students.

Many experienced educators would argue that the most fundamental knowledge base that is required for EM is the conceptual understanding, which is based on physical aspects of the field. The mathematical formulation should help enhance our capabilities of utilizing the concepts and should not be treated as the concept. This is certainly the treatment that is followed in the famous "Feynman Lectures on Physics."[3] The first and utmost item is the understanding of the physics and then the utilization of the mathematics to help solve more advanced problems.

3. The Proposed Approach

3.1. What is the basic idea (lecture and discovery introduced here)?

The new approach to teaching EM is just that—a new approach to teaching. The goals remain the same, but the method by which these goals are conveyed is different. According to our experience gathered by enrolling in an array of EM classes in physics and engineering disciplines, the required mathematics for advanced EM is much more digestible after the student knows the fundamental physics, units, and concepts that govern EM theory. Take a ring thrower for example—by playing with it and even trying to build it, one has a keener sense of understanding and using the required mathematics for Faraday's law. Indeed the most difficult aspects of EM training are understanding the concepts and ideas and communicating the concepts with words to explain theories such as flux, electric field, inductance, etc. Some of the modern education theories also emphasize the usage of the common language as one of the fundamental means of learning.[4]

In recent years there have been some noteworthy attempts to present new approaches to EM education, and in many of them the concepts of utilizing the numerical packages such as MATLAB, CAD systems, and other visualization systems and numerical tools have been proposed.[5-15] In this paper we try to present an approach to modularize the entire teaching concept and provide a unified platform that can be utilized, augmented, and detailed for all student levels from introductory to advanced students. Figure 2 depicts the general idea of the proposed approach.

Here we see that the mathematics is decoupled from physical understanding. Especially for engineering students, this approach will provide a valuable practical extension. We can teach the students more practical issues as well as instrumentation and measurement issues, which can help the typical engineering students see the purpose of the mathematics that are involved. In the same way, students will also be able to see the importance of EM in their professional and everyday lives. Consequently, students will be motivated and interested in EM before receiving the mathematical constructs needed to solve classical EM problems.

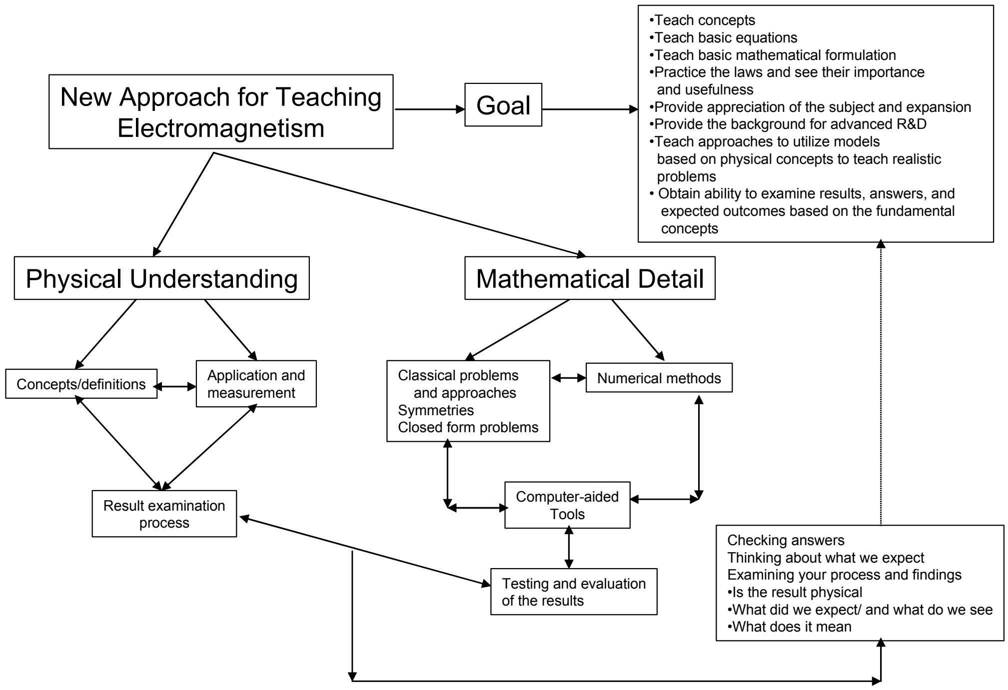


Figure 2. A proposed approach for teaching electromagnetics to students of all levels.

3.2. Pros and cons

In doing this, the introduction of the traditional mathematics will come later, but the mathematics and the most important mathematical concepts will not be eliminated. The goal of this form of teaching is to eliminate the need for students to have to learn mathematical tricks and spend lots of time solving integral/differential equations. Students can then utilize mathematical packages in order to solve these types of equations. Instead, this form of teaching will then make students think critically as to how to utilize their fundamental understanding to solve problems conceptually on paper and then use the computer to perform the more rigorous calculations. In this way, students learn the concepts and not just mathematics. For example, instead of teaching the student the detail, derivation of the curl and divergence, and asking them to do many problems by hand to master these operations, we would explain the operations, show them the derivation, but ask them to use the tools and see what the operations of curl and divergence do to some of the typical fields that are used in electromagnetics. Students then become familiar with the result of what these operations do and hence understand the meaning of these operations but do not become obsessed with how to perform them.

EM classes could then be broken up into lecture and practice-discovery sessions. During the lecture, concepts would be discussed and problem-solving skills addressed. The instructor would then be able to spend more time with the fundamentals, applications, and particular details of the subject. In the practice-discovery sessions, the student would then become familiar with current mathematical packages and see electromagnetics first hand through demonstration and measurement.

3.2. The concept of lecture and discovery session

This is indeed replacing the traditional recitation section. In traditional recitation sections, the emphasis is to show examples and answer one-to-one questions. In practice-discovery sessions, we will do examples and answer questions; however, the purpose of the class is to promote the concepts, which reemphasizes the issues covered in the lecture by specific demonstration, letting students participate, do, and even create their own demonstrations, as well as showing them how to work with tools such as Mathematica, Matlab, Pspice etc. It is important for the students to know what we are looking for with these packages and how they can become a part of the students' toolsets for their whole carriers.

In the practice-discovery sessions, most attention would be spent teaching students how to use computer-based tools in order to solve problems. Mathematical packages for functions such as Div, Curl, Grad, etc. would be provided to the students who would then use these packages in order to solve simple EM problems at first. This computational part of the lab could then be expanded so students could use finite-element or finite-difference algorithms in order to solve EM problems with no closed form solutions. This computational section would help in easing the mathematical nature of classical EM courses as well as better preparing students for higher-level classes in EM and other computational courses. It should be noted that typical flux problems can be set up, examined, the answers tested, units analyzed, and solutions plotted easily.

4. A Typical Lecture

4.1. The lecture and discovery session concepts

A typical lecture would begin with the introduction of a new concept. Its historical discovery and importance would be noted first, giving students a sense of the accomplishment and an idea of how things are discovered. The concept would then be explained in words, when possible using a visual model, so the students could have a foundation of what is being presented to them. A derivation, if applicable, would then be carried out to show students the formulation of the result to better help their understanding; however, students would do no derivations at the early stages. It would then be necessary to explain where the topic of the day could be useful in everyday life and applications. Finally, to conclude, a discussion and example of how to apply the concept mathematically would be carried out without emphasizing heavy mathematical detail. The rigorous mathematics would be left to the practice-discovery portion of the class. In this way, students would learn and know how to apply EM concepts to different situations without having to contribute large amounts of time to work through the mathematics. Problems would still be assigned in class, but those where complex integrals or extremely heavy computation are needed would be left to the practice-discovery session.

In the practice-discovery session, concepts from the lecture would be used to solve more complex problems. In certain cases, such as the beginning of such a course, general computer functions and tools would be addressed. The laboratory would then mainly consist of a set of problems for students to solve along with an out-of-class assignment. Mathematical packages such as MATLAB and Mathematica could then be used to solve problems such as Gauss' law and boundary value problems. Other cadence-type programs could also be used in conjunction to look at transmission-line problems and magnetic circuits. In this manner, students would learn how to be problem solvers instead of allowing their doubts in mathematics to hinder their thinking process. They would also be exposed to high-level computation and simulation packages necessary for research and professional careers.

In addition to the computational part of the practice-discovery sessions, a demonstration or measurement would be added to each meeting. These demonstrations would be used to either illustrate a concept visually or to show how quantities are physically measured. Many students often complain that EM is not really applicable to their hands-on, everyday experiences as engineers. Many say this because they cannot visualize the things they are doing in class. In fact, it is not easy to see an EM wave. The purpose of these demonstrations and measurements is to give a "real world" feeling to fundamental EM concepts. This also helps the conceptual learning because instead of always being given a wave or charge distribution to start with, the student see how these starting conditions were or can be determined through measurement.

After the students have seen some of the effects of the mathematical treatment and practice-discovery sessions to experience and visualize flux calculations, the lectures can introduce more steps containing rigorous mathematics. It should be noted that in the more advanced classes the level of questioning, detail of the methodology, more complicated transformations, lossy and non-ideal cases, anisotropy media, realistic numerical applications, creation of new computer-aided operations, visualization, as well as advanced animations and wave propagation modeling can all fit into the category of what is necessary to do as the student becomes more advanced. At the introductory level, the students use the given tools and commands to see, feel, explore, and visualize; and as they become more advanced they can question the tools, look at more complicated tool development capabilities, and work with multiple tool platforms to enhance their knowledge. These have always been some of the most important goals for advanced courses, but they usually take some time to start up. By exposing students to a higher conceptual and computer-based course, the advanced student is better prepared to begin these activities.

4.2. What a typical lecture looks like

The following is a typical lecture for a 1.5-hour class. The lecture notes indicate the key points and ideas. The notes also identify how the concepts can be expanded for the introductory and advanced-level classes. It can be seen that while the concepts are the same, the depth and mathematical sophistication varies greatly between the different levels. At the very introductory level, terminology is mostly used along with general graphs. The advanced level indeed looks like current advanced-level classes. At the advanced level, the treatment of mathematical sophistication is more advanced using numerical techniques to look at non-ideal systems.

1. **Start the lecture with a discussion:** How do we know if there is an electric field in a region of space?

    Intro. level: *Think about what you know from physics.*

Relate Electric field and electric potential.

<u>*Adv. level:*</u> *Work with concept of E field and definition of unit charge, and relate that to force, measurement of force, measurement of potential, etc.*

2. **The Lorentz force**
   A significant law
   An equation to remember
   A basis for definitions of E and B

$$\vec{F} = q(\vec{E} + \vec{v}x\vec{B})$$

E is electric field intensity in V/m.

- It is defined as the force per unit charge.

B is the magnetic flux density in Tesla=Wb/m^2.

- One can see that it defines the force per unit charge, which is moving in unit velocity perpendicular to the field

<u>*Intro level:*</u> *Units SI*

<u>*Adv. Level:*</u>
- o *Does magnetic field do any real work according to Lorentz force equation?*
- o *Unites in EM SI, MKS, CGS, Georgian*

3. **Maxwell's equations in integral form in words**
   - The flux of electric field intensity (E) through any closed surface = the net charge inside the closed surface /ε_0
   - The flux of magnetic flux density (B) through any closed surface = 0.
   - Circulation of electric field intensity (E) around any close path C = time rate change of the magnetic flux through a surface that has C as the edge.
   - Circulation of magnetic flux density (B) around a close path C = (flux of electric current through a surface that has C as the edge)m + (time rate change of the electric flux through the surface S, which as C as the edge) ε_0.

<u>*Demonstration: Ring thrower and class explanation*</u>

<u>*Intro level:*</u> *Provide 3D picture of these.*

<u>*Adv. level:*</u> *Provide integral, forms and discuss linear, homogeneous, and isotropic issues in integral form.*

Discussion: VLSI and electronic design, as the speed goes up, the wavelength of the EM phenomena reduces and one can see that at high speeds there is EM interaction, compatibility, and immunity to worry about.

<u>*Adv level:*</u> *Discuss connectors, conductors, and PCB level lines; add circuit elements and discuss the reactions.*

4. **Maxwell's contribution is in red.** At first glance it does not seem to be much, but that small term changes the nature of these equations. With his contribution, Faraday and Ampere's laws show coupled wave equation characteristics.

5. **Before Maxwell**: Faraday-Ampere are coupled diffusion equations.
   After Maxwell: Faraday-Ampere are coupled wave equations
   <u>Intro. level:</u> Discuss wave equation and wave phenomena
   <u>*Adv. level:*</u> *Discuss wave and diffusion, the relationships, compare and contrast*

6. **Definition of flux and circulation**

   The equations are in general two groups.

   Group 1: The flux laws dealing with net flux through closed surfaces.

   Group 2: The circulation equations dealing with circulation along a closed path that are related to the flux through surfaces with closed paths as the edge.

   How are they defined (typical fields for flux and circulation are discussed and demonstrated)?

   <u>*Adv. level:*</u> *Relate to some mechanical systems with mass flow, etc.*

7. **Flux**

   Flux of a vector is defined as how much of the vector is going through a given surface. It is usually defined with respect to a given surface. How much of a field goes into the surface? That means (will be demonstrated by pictures) to find how much is perpendicular through the surface.

   Student would need to practice with radial, circular, direct field.

   Think of other fields and their flux.

   Circulation

   If a field has circulation along a given path, that means the field will have net flow that adds together along the given path. One way to visualize it is to think of a field as a fluid. If there is circulation for a given path, that means that if the path was replaced by flexible pipe there would be flow in a direction in the pipe.

   Students need to visualize circulation and how it works, how radial and constant fields have circulation, etc.

   <u>*Intro. level:*</u> *See pictorial ideas, what these mean, use MATLAB functions and given fields*

   <u>*Adv. level:*</u> *Look into the way these functions are written and see numerical computations of the integral forms*

8. **Is circulation path dependent?** Yes, of course it is. Class discussion at the two levels. With pictorial examples with MATLAB.

9. **Infinitesimal (differential) view of circulation and flux**

   Discuss flux and circulation as addition of small contributions so that it is the net of all area patches of field along the small part of the path. Show them the integral forms and how helpful it is to use mathematical terminology.

10. **Div (point flux) and curl (point circulation)**

    This should follow by the definition of div and curl and how they are related to the flux and circulation. Examples can be provided with different fields.

11. **What did Maxwell know?** Reading from Maxwell and his definitions of the calculus of quaternian.

12. **How did the new EM come about? Who is responsible for the new formulation?**

Discussion and introduction of Heaviside and Hetz formulation and how the new vector forms came about.
At this point we will show Maxwell's equations before the new formulation, the way Maxwell did them, and the same equations with the new formulation. Students would see and agree that the new form is more compact, easier to use, and a more advanced presentation.

Adv. level:

- *Read the original Hertz and Heaviside ideas and papers and see the development of the modern vector formulation. Compare and contrast the form in the early part of the 20^{th} century and now.*
- *Also look at some of the developments in Einstein's famous paper that introduced special theory of relativity.*

13. **Final thought for the day**

Intro. level: *Can a field have both point circulation and divergence at the same point? Why and why not?*

Adv. level: *Review of the units SI, MKS, CGS, and Georgian and discuss why were each popular.*

4.3 What kinds of examples would we see in a discovery session

A typical discovery session would last about 2 hours and cover closely the concepts discussed in the lecture with more emphasis on the mathematical concepts and visualization. Here we show a few examples for the above lecture plan. It should be noted that the following is for the introductory level discovery session.

1. Determine the vector field of the following fields and discuss their circulation properties.

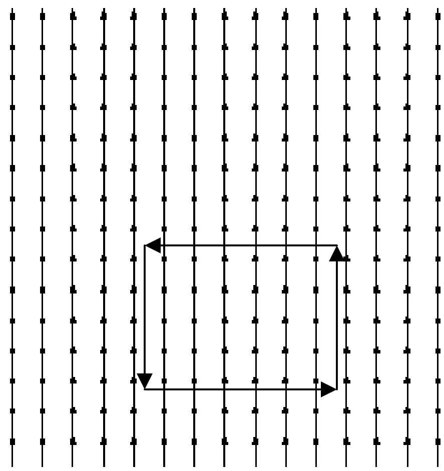
$$\vec{F}a = \vec{a}_y .$$

The following is a plot of the vector field rendered by Mathematica. Once the students define the vectors the way we have indicated, they can use curl and div operations on the defined vector fields.

```
fa = {0, 1, 0}

{0, 1, 0}

PlotVectorField[{0, 1}, {x, -1, 1}, {y, -1, 1}]
```



```
- Graphics -
```

If we look along the path given by the arrows we see that for this field there is not circulation, which verifies the 0 curl.

2. Next we look at an x dependent field propagating in the y-direction given by

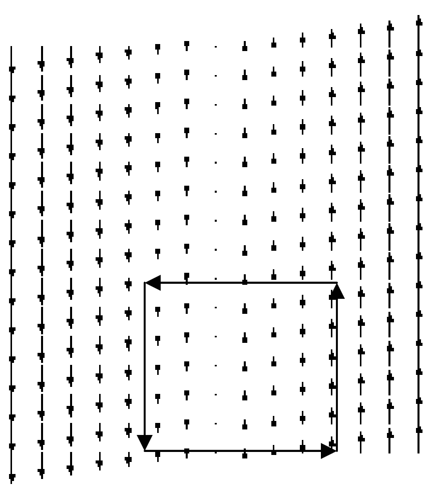
$$\vec{F}b = x\vec{a}_y .$$

The following is then a plot of this vector field.

```
fb = {0, x, 0}

{0, x, 0}

PlotVectorField[{0, x}, {x, -1, 1}, {y, -1, 1}]
```

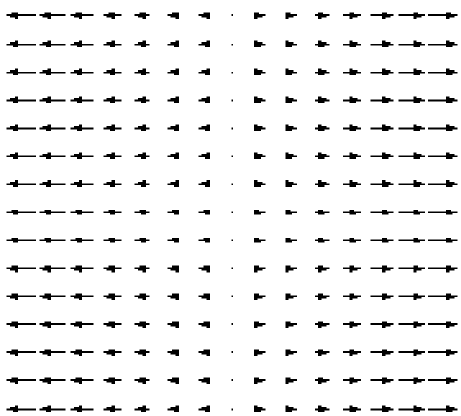


If we look along the path given in this figure we see a noticeable counterclockwise circulation of the field. Interestingly, the curl of this field is calculated as $\vec{a}_z$.

3. The next example looks at an x dependent field pointing in the x-direction and given by

$$\vec{F}c = x\vec{a}_x .$$

```
fc = {x, 0, 0}
{x, 0, 0}
PlotVectorField[{x, 0}, {x, -1, 1}, {y, -1, 1}]
```

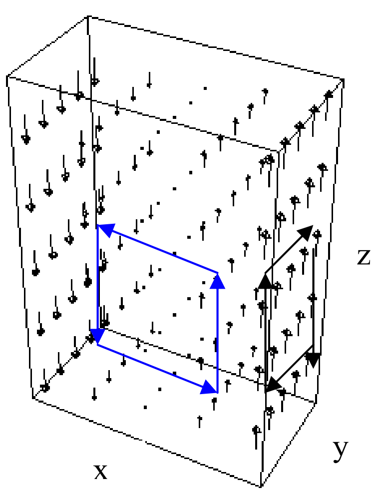


Here we see that the field diverges in both directions from zero. In this case, one can see that there is no point circulation, so there is no curl. However, there is a divergence of the field.

4. In the following example we look at another x dependent field pointing in the z-direction given by $\vec{V}a = 2x\vec{a}_z$.

The following is a 3-dimensional plot of the vector field.

```
In[8]:= Va = {0, 0, 2*x}
Out[8]= {0, 0, 2 x}
In[17]:= PlotVectorField3D[Va, {x, -2, 2}, {y, 0, 2}, {z, 0, 5},
   VectorHeads -> True, PlotPoints -> 5]
```



Here we see a circulation of the field along the blue path in the xz-plane, but no circulation along the black path in the yz-plane. This shows that the circulation of the field is indeed path dependent.

Finally there will also be demonstrations in order to give students a physical interpretation of the concepts seen in class. For this particular session a demonstration of the Lorentz force is done using a current carrying wire and magnet to exhibit the force felt by the current (which are also moving charges). In addition, the ring thrower demonstrated in class will be taken apart in the session. Consequently, the students will see how this device was constructed and what principles of EM were used to develop this device. In this way students gain a more practical view of EM and the principles.

In the advanced level discovery session, the students would be focusing on the detailed mathematical operations. Utilization of mathematical tools will be at the level of writing functions to do the curl, divergence, and other operation in different coordinate systems and utilizing the tool for better visualization. In addition, in the advanced discovery session students would be required to utilize the tools to set up known numerical models for examining special geometries. This session will also include demonstrations. We utilize microwave and antenna systems and measurements for demonstration tools. Students would see how a network analyzer would be used to see the matching, phase, and gain/loss effects. We also would show the students the principles and typical applications and utilization of time domain reflectometer.

4.4. The concept of lecture and discovery session

One of the most practical and interesting aspects of this approach is the fact that the tools can be interchanged as well. While many in microwave propagation need to visualize wave propagation with sources, boundary conditions, and lossy media, etc., those in microwave hardware and measurement need to utilize PSpice and other tools. The point is that it is no longer necessary to make EM students become mathematicians. Currently there are computer driven packages to aid in multiple types of calculations so that a mathematical background should no longer hinder creative and inventive electrical engineers. This also provides students with varying interests and useful skills for future endeavors.

5. The New Premise

5.1. What we are trying to do

We believe that this approach to teaching EM will give students a strong fundamental background of EM, create better problem solvers, and better prepare students for advanced EM courses. Students would have a more historical and applied perspective to the subject. Consequently, they would have a more in-depth appreciation of the concepts and applications. At the same time, the atmosphere in which EM is being taught to them will be less threatening and will promote a more questioning and discovery type learning. It is our belief that this type of learning will promote lifelong learning and create better prepared engineers.

In addition, this method does help students who perform greatly in the traditional classes and get top grades; however, in more standard tests such as the GRE or some of the company entrance tests they do not perform as well. Our experience shows that in most cases such students have great capabilities in mathematical rigor; however, they do not have enough practice in thinking systematically from the fundamentals and therefore building their knowledge logically. With the proposed model, from the first day the concepts are emphasized, and as the students become more advanced, the same fundamentals are reemphasized together with the traditional basics. Our experience shows that the students will have a better appreciation for the mathematics and will do better in conceptual tests.

5.2. Why do we think this is going to be a better approach?

This approach covers the fundamental concepts from the earliest level of EM and builds on top of the concepts. The new approach is like painting a whole picture first with very basic highlights and then adding the detail. As the level of sophistication increases, the level of detail under the concepts also increases. In this way we are constantly adding to what students already know. The novice student learns about what EM is all about and the major areas that EM entails, while the advanced student learns about special cases and other factors contributing to basic EM.

Many mathematical tools, concepts, and approaches are really special applications of the major concepts of EM. There are historical reasons for them to be developed and this method will put into perspective the importance of these mathematical applications of EM.

5.3. What type of reaction is expected?

First of all, the subject will be more applicable to other fields so we will see more students with more diverse backgrounds interested in the subject. No longer will EM be a subject that is avoided but a necessary knowledge base for other electrical engineering classes. Due to the emphasis on using computational software, students will become familiar with numerical and mathematical tools and will be able to use them for their careers in engineering as well as other classes. Finally, because of the freedom in learning and variety of examples and learning opportunities, we will see more conceptual thinking rather than manipulation to get the answers. All in all, we believe students will become more satisfied with their EM education and become better engineers for it.

5.4. General areas of concern

Many instructors and programs are not comfortable with this method of teaching and, if not done right, with a large-scale perspective it will not be very useful. Most instructors confuse mathematical rigor with mathematical/physical understanding. Consequently, one may not cover the definitions of curl, div, etc., due to the possible mathematical rigor. In this program, the concepts of mathematics will be covered but the details that are confusing and threatening to most students will be spelled out to give students a better conceptual understanding and provide practical reasons for the methods to be learned.

In many programs, the authors fear the use of MATLAB and Mathematica is to create courses that are solely based on tricks with the tools and to show the students all the great, cool ways of using those programs. The line between the correct use that emphasizes concepts, visualization, and understanding of the field as opposed to methods, function lists, and ways to advance

MATLAB or Mathematica programming is very fine. Methods of programming may be used in very advanced classes but should be avoided in the introductory classes. The purpose is to provide the students with a more interesting, integrated, and creative environment to enhance their thinking and visualization and enable them to freely engage in the process of inquiry, discovery, examination, and enhancement of their knowledge base. It is this ability to become a motivated free thinker that gives students the tools to become lifelong learners, which in turn produces better long-term engineers. This ultimate goal of producing better long-term results necessitates a change in teaching strategies.

Finally, it is clear that the same method can be applied to provide the right conceptual understanding for students who are not interested in the mathematics of the subject and only require a general conceptual understanding of the subject and related applications such as industrial managers, product designers, and testers. These applications will never require any field or flux type calculations but will require the general conceptual knowledge to make educated decisions about electromagnetic problems and equipment. Having an introductory course that stresses this conceptual importance will greatly help electrical engineers who may not have a career in EM but who will need to be able to understand electromagnetic concepts in order to be effective in an industrial occupation.

6. Conclusion

In this paper we propose a new approach for teaching a mathematical field such as electromagnetics to engineering students. Perhaps, utilizing this approach, one can truly follow the more creative approaches in the traditional EM classes that have been presented by Feynman,[3] Shin and Kong,[16] Cheng,[17] and others. These books first attempt to cover Maxwell's equations and give the student a taste of the whole picture, then work on the detail and more traditional aspects of EM such as electrostatics and electromagnetics. Traditionally, this method is not favored since the mathematics required for the generalized Maxwell's equations are more complicated than for static cases; this causes students to have major hurdles to overcome before they can treat Maxwell's equations. In the new approach, these major hurdles are quickly overcome by the use of mathematical packages to treat complicated mathematics, thereby allowing us to follow a more creative approach to teaching EM.

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