Using 3D Animation In Teaching Introductory Electromagnetism

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Introduction

"In order ... to appreciate the requirements of the science [of electromagnetism], the student must make himself familiar with a considerable body of most intricate mathematics, the mere retention of which in the memory materially interferes with further progress."

James Clerk Maxwell[3]

Classical electromagnetism is a fundamental underpinning of a technical education, but one of the most difficult subjects for students to master. It is also a subject in which mathematical complexity quickly overwhelms physical intuition. With the aid of animation, we are developing a treatment of electromagnetism designed to help students develop intuition about the dynamics of electromagnetic phenomena, in a manner independent of advanced mathematics.

Laurillard[2] cites two key criteria for selecting subjects in the college curriculum for this kind of treatment. To justify the extensive resources required for technological development, the subject must be: widely taught and widely acknowledged to present difficulties for students. In the standard science and engineering curriculum, classical electromagnetism satisfies both of these criteria. It is widely taught and also widely misunderstood. Why is this? It is because students have few pre-existing models for electromagnetic phenomena or of the concept of fields. Since much of our learning is done by analogy,[5] students have a hard time constructing conceptual models of the material they are trying to absorb. The standard textual approach to teaching this subject does little to help students establish such conceptual models, because a purely textual approach does little to connect the dynamics of electromagnetic fields to the student's everyday experience.

However, there is a way to make that connection for many situations in electromagnetism — an approach that has been known since the time of Michael Faraday, the inventor of field theory. Faraday was also the first to understand that the shape of field lines is a remarkable guide to their dynamics — a guide that does not require use of advanced mathematics to understand. By trial and error, Faraday deduced that field lines exert a pull parallel and a push perpendicular to themselves. Knowing the shape of field lines from his experiments, he was able to understand the dynamical effects of the fields based on simple analogies to ropes and strings, without recourse to advanced mathematics. It is this Faraday approach that we are pursuing, with the goal of helping students gain intuition about electromagnetic dynamics. Our means to achieve that goal is animation.

The following question arises immediately: If animation is an effective way to develop student intuition, why is it almost never used in introductory courses in electromagnetism? The answer is that this method is of only modest use if the field lines are displayed as static images. However, the power of the method increases dramatically if the field lines are animated. The mind has an enormous capacity to integrate time-changing visual information into a coherent dynamical whole — a capability that evolved because it is fundamental to survival. With animation, one can appreciate the effects of the stresses transmitted by fields in an immediate and visceral way, by watching how things evolve in time in response to these stresses.

Animation has not been used to display electromagnetic fields in the past (with notable exceptions) due to the twin difficulties of producing such animations and then delivering them to the student in an easily accessible manner. The enormous increase in computing power over the last decade, and the advent of the World Wide Web, has made both production and delivery of animations, integrated into textual development, an increasingly viable proposition. We are taking advantage of these technologies to implement Faraday's insights, using video clips to display actual experiments, as well as producing computer visualizations and animations of the electromagnetic field lines in those experiments. These visualizations of the field lines make the unseen seen, so that students can come to an understanding of what is happening dynamically, via analogies to familiar concepts.

Examples of Visualizations

"To understand this point, we have to consider that a [compass] needle vibrates by gathering upon itself, because of its magnetic condition and polarity, a certain amount of the lines of force, which would otherwise traverse the space about it."

Michael Faraday[1]

"It therefore appears that the stress in the axis of a line of magnetic force is a tension, like that of a rope."

James Clerk Maxwell[4]

Contrast the usual way of explaining the torque on a compass needle in a background magnetic field with Faraday's approach to understanding the same phenomenon. In the standard explanation, we appeal to the notion of atomic currents in the needle, circulating in a plane transverse to its dipole axis. We then consider the torque on such a current loop. We usually take a rectangular loop of wire carrying current i in a background field **B**. We look at the various forces on the sides of the rectangular loop to deduce the net torque on the rectangular loop, which tends to align the compass along the background field. The advantage of this procedure is that it yields a quantitative calculation of the torque. The disadvantage is that the explanation requires several relatively abstract steps, which most students cannot reproduce in any coherent fashion. Thus, although they memorize the result, students subsequently have little intuitive feel for why it should be so.

In contrast, consider how Faraday explained the torque on a compass needle, and thus its oscillations. First, he used his intuition about the shape of field lines based on his experiments with magnets and iron filings. He then appealed to the concept of a pull along the field line to infer the dynamical effects associated with that field configuration. In the case of the compass needle in a background constant field, he drew a field configuration for the sum of the magnetic field of a dipole whose dipole vector makes an angle to the vertical, plus that of a constant vertical field. Faraday then understood the oscillation as due to the tension in the field lines pulling the needle into alignment with the background field, with the needle then overshooting.

An animation of this behavior makes the oscillation seem natural and intuitive. We argue that both of the above explanations should be provided to the student. The first is quantitative and appeals to students who are analytical in their thinking. The second is qualitative (although it can be made quantitative) and much more intuitive, and it is comprehensible to students of all persuasions, because it can be understood by analogy to concepts they already have. Our contention is that one year after taking a course in electromagnetism, average students will not remember the details of the first explanation. However, if they have "seen" the second, they will continue to have a mental model as to why compasses "work" this way.

The Falling Magnet Experiment

One of the main thrusts of our effort is to make the unseen seen, to use the power of sophisticated 3D animation to show the student "actual" phenomena, with the ability to add to that visualization things that we cannot ordinarily see. As an example of this, consider an experiment, and then a virtual recreation of that experiment.

A magnet falls in a Plexiglas tube through a conducting copper ring. When the magnet approaches the ring from above, eddy currents are set up so as to prevent an increase in the flux through the ring, and the magnet undergoes a clear deceleration. Figure 1 is a frame from a 3D animation of this motion. As the magnet moves toward the ring from above, it is repelled by currents induced in the ring. In the animation, the field is compressed as the magnet falls toward the ring, and the slowing down is naturally interpreted by the mind's eye as a deceleration due to an upward push due to the compression of the field. When the magnet falls through the ring and is below it, the eddy currents reverse direction so as to now prevent a decrease in the flux through the ring, and the magnet is again decelerated. In the animation, the field is now stretched out as the magnet falls away from the ring, and the slowing down is naturally interpreted by the mind's eye as a deceleration due to the upward pull of the stretched field lines. This overall animation is a good example of our approach. The visual treatment does not replace the traditional explanation, but complements and expands on it, and in a way that makes "intuitive" sense to the student.

Magnet Being Pulled Away From A Coil Of Wire.

Let us consider a final example of our approach. Consider an experiment in which a magnet is moved along the axis of a coil of wire. Initially, the magnet is at rest close to the coil, and then is pulled away from the coil at constant speed and brought to rest farther away from the coil. As the magnet is pulled away from the coil, an ammeter registers current in the coil in a direction such as to try to prevent the decrease of flux through the coil. The sense of that current is such that the coil and the magnet are attracted (the agent moving the magnet must do work to pull the magnet away from the coil).

Now consider a computer visualization of this process. Figure 2 is one frame of an animation of this process, at an instant of time just before the magnet comes to rest. The field lines have a hard time "getting through" the coil, since the sense of the current in the coil is such as to try to keep the number of field lines threading the coil from decreasing. Thus the field lines get "hung up" on the coil as they try to move through it. The intuitive sense that one gets in

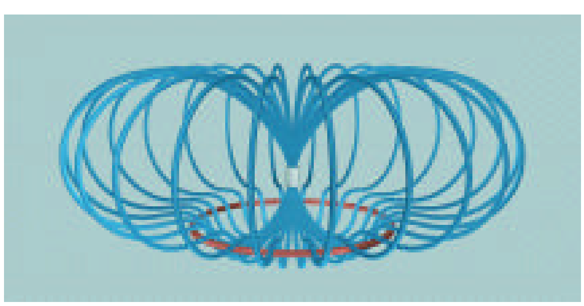

Figure 1: The magnetic field lines of a magnet falling under gravity through a conducting non-magnetic ring (for example, a ring made of copper). The field lines shown are those of the total magnetic field (the dipole field of the magnet plus the magnetic field due to the eddy currents generated in the ring, which are, in a sense, such as to try to keep the flux through the ring constant).

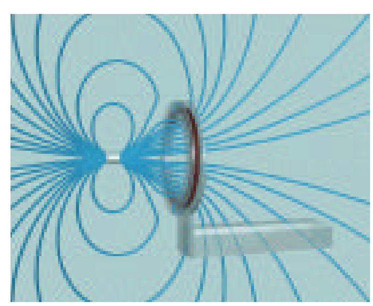

Figure 2: The magnetic field lines of a magnet being pulled away from a coil of copper wire. The field lines shown are those of the total magnetic field, (the dipole field of the magnet plus the magnetic field due to the eddy currents generated in the coil). We show many field lines in latitude, instead of only one field line in latitude, as in Figure 1. The field is symmetric about the axis of the coil.

watching this animation is that the agent moving the magnet must do work to pull the field lines "through" the coil. We emphasize that these animations are based on quantitative calculations. These are not cartoons.

Moving Field Lines

The concept of moving field lines is unfamiliar to many professional scientists and engineers. Since this concept is central to our approach, we discuss it here, for the benefit of that audience.

The magnetic field lines above are defined in the usual way: a field line is everywhere tangent to the local field. We make no attempt to have the density of field lines correspond to field strength (this is impossible in 2D projections of 3D fields in any case.[7] How do we define the motion of magnetic field lines in the above animations? Consider the following thought experiment.

We have a solenoid carrying current provided by the emf of a battery. The axis of the solenoid is vertical. We place the entire apparatus on a cart and move the cart horizontally at a constant velocity **V** as seen in the laboratory ($V<<c$). We intuit that the magnetic field lines associated with the currents in the solenoid should move with their source. How do we make this intuition quantitative? First, we realize that in the laboratory frame there will be a "motional" electric field **E** = -**V** x **B**. We then imagine placing a low-energy test electric charge in the magnetic field of the solenoid. The charge will gyrate about the field, and the center of gyration will move in the laboratory frame because **E** x **B** drifts in the -**V** x **B** electric field. This drift velocity is just **V**. That is, the test electric charge "hugs" the "moving" field line, moving at the velocity our intuition expects.

In the more general case (for example, two sources of field moving at different velocities), the motion we show in our magnetostatic computer visualizations has the same physical basis. It is the drift motion we would observe for hypothetical low-energy test electric charges initially spread along the various magnetic field lines, drifting in the electric field that arises because of the time-changing magnetic field via Faraday's Law.

Summary

"...a simple precis is that these improvements are attempting to nurture a sense of wonder among students about the natural world, and to maintain students'active curiosity about this world while equipping them with tools to explore it and to learn."

Shaping The Future: New Expectations for Undergraduate Education in SMET[6]

Let us return to the objectives of our approach. One of our primary aims, an aim that is fulfilled if we are careful in what we present, is to engender a sense of wonder in the student. The 3D visualizations that we have created and plan to create are visually compelling. They engage the student's imagination because they show the world in a photo-realistic way, including representations of phenomena that heretofore could only be seen in the mind's eye. In large lecture courses in the freshman year, one of the purposes is to inspire students to invest the time to pursue quantitative mastery of the subject outside of lecture. Our extension of the pedagogy in this subject will be successful in large degree as long as it arouses interest and excitement by engendering a sense of wonder.

Beyond engendering a basic sense of wonder, what is the central student learning need that we are trying to meet? It is this: Students need an enormous amount of help in understanding the nature of fields. The central learning objective of introductory courses in electromagnetism is to help students understand how fields are generated, how they mediate the interaction of material objects, and how they propagate. Our contention is that in the standard pedagogy, this learning objective is not well fulfilled. Our approach to help remedy this deficiency is to give the fields a more prominent role in the pedagogy, by literally making them more visible. They are thereby made more understandable dynamically, based on students'pre-existing models of the behavior of strings and rubber bands.

The use of animated visual displays of field lines has many advantages. They continually remind the student that it is the field that mediates interactions between material objects — that the field has as much "reality" as the objects themselves. By stressing the pushes and pulls transmitted by the fields, we stress the importance of the fields themselves as the mediator of interactions. Ultimately, animations allow students to understand intuitively what is happening dynamically simply by looking at the shape of the field lines, once the eye and the mind are trained to this purpose. It is this intuition that we seek to develop.

Acknowledgements

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