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Visualizing Electricity and Magnetism: The Collaborative Development of a Multimedia Text

Jennifer A. George-Palilonis, Ball State University, USA
John Belcher, Massachusetts Institute of Technology, USA

Abstract: Visualization has proven to be a powerful tool that enables both concrete and abstract representations of concepts that are often difficult to teach and learn. Likewise, multimedia storytelling has emerged as an equally powerful tool for combining rich media with nonlinear presentations of complex content. The authors of this paper, from two very different fields of study (physics and visual journalism) have collaborated to develop of an interactive, multimedia teaching and learning tool for physics. This tool combines visual storytelling, animation, graphic design, and nonlinear presentation to create a digital visualization of electricity and magnetism. Based on a number of 3D animations, interactive applets, and videos focused on field theory, scalar and vector fields, electrostatics, magnetostatics, Faraday's Law, and light, the module allows students to visualize concepts that are normally invisible to the naked eye. Additionally, the nonlinear design of the module allows students to explore and experience content in rich, interactive formats. Naturally, this project raises a number of possibilities for discussion about the future of the educational text and research related to teaching and learning with multimedia. This paper will first provide insight into how this particular text represents innovation for both physics and multimedia storytelling pedagogy by transforming how we teach the foundations of electricity and magnetism from a traditional, equation-based system to a visualization-based, multimedia experience. We'll also share how we collaborated and discuss possibilities for future research and development related to this module.

Keywords: Multimedia, Interactive Text, Nonlinear Storytelling, Physics, Visual Communication, Animation, Graphic Design, Visualization

Introduction

EDUCATIONAL TECHNOLOGY IS evolving rapidly, in part because tools for creating rich multimedia presentations have become more accessible to classroom instructors. Just as important, there has also been a rapid growth in the capability of those instructors to widely disseminate the presentations they develop via the Internet. The digital age has thus greatly enhanced the potential for visualization technologies to enhance learning. Digital learning is quickly taking center stage in discussions related to both the future of education in general and, more specifically, the future of all types of teaching and learning tools, from the textbook to the classroom itself. Likewise, the form multimedia presentations take–that is, their design, navigation, and interactive features–has become a vital consideration for instructors and developers as they attempt to translate educational content from traditional to new media formats. And, perhaps most exciting, the development and use of digital media in education create new avenues for meaningful storytelling through multimedia and cross-disciplinary collaboration among educators who hold different stakes in the multimedia equation.

In the present paper we present a case study of a multimedia piece, "Visualizing Electricity & Magnetism" which exemplifies many of the ideas mentioned above. This piece grew from two separate efforts. The first effort was the development of visualizations for the Technology-Enabled Active Learning (TEAL) Visualization Project at MIT. Based on the premise that visualization "can support meaningful learning by enabling the presentation of spatial and dynamic images, which portray relationships among complex concepts," (Dori & Belcher, 2004), the TEAL Visualization Project developed more than one hundred visualizations used to teach electromagnetism in freshman courses at MIT. A combination of desktop experiments and interactive Java3D simulations that are virtual versions of those experiments help to make the unseen seen by showing electric and magnetic field lines.

The second effort was a Ball State University project focused on digital publishing models. The thrust of this project was to address a number of important questions related to the design, development, and distribution of multimedia texts, as well as to explore how storytelling changes when educational content takes digital media forms (George-Palilonis & King, 2007). The Ball State Digital Publishing Project (DPP) has included the creation of numerous multimedia e-text prototypes based on a number of different topics, including biology, biomechanics, and graphic design. Those prototypes have been used

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in research that addresses variables that affect students' approval and enjoyment of a multimedia text as a learning tool (George-Palilonis & Filak, 2008), blended learning in the visual journalism classroom (George-Palilonis & Filak, studies in progress), and how learning outcomes compare between multimedia teaching and learning tools and their traditional counterparts (George-Palilonis & Filak, studies in progress). At its core, the DPP lays the foundation for "building, testing, and researching a variety of new book models, so that we can both speak from a position of authority on best practices in multimedia and digital publishing" (George-Palilonis & King, 2007).

These two projects came together through the intermediary of Professor Henry Jenkins of MIT. In spite of the vastly differing backgrounds and fields of the two authors involved in this joint project, they have a shared belief in the power of visualization to enhance learning. "Visualizing Electricity & Magnetism" is an e-text module built to harness the power of interactive media. The basic approach is to determine whether we can transform how the foundations of electricity and magnetism are taught, from a focus on a traditional, equation-based system to a system which also includes as a central component a visualization-based, multimedia experience. The module represents innovation for both physics and multimedia storytelling pedagogy by combining visual storytelling, animation, graphic design, and nonlinear presentation to offer students a more tangible, tactile experience to explain what is normally invisible to the naked eye.

Related Literature

As noted above, digital learning and more specifically, technology-enabled visualizations have become increasingly appealing to numerous universities for a variety of reasons. As digital learning trends change the way we teach and learn, new teaching and learning tools are surfacing as viable means for content delivery, and many educators are beginning to experiment with developing and using them in the classroom. The driving force for this is not only the search for a way to deliver traditional content via digital means, but to also develop non-traditional digital content that has the potential to add value to the learning process in ways that are simply not possible with traditional media. Furthermore, as educators, researchers and policymakers continue to press for updated learning models that will move us out of the 1950s approach to education, many are speculating that electronic learning may be one of the best ways to meet the needs of a changing educational landscape (McCombs & Vakili, 2005).

Kelly (2005) notes that the heavy implementation of computer-based interfaces, such as games, simulations, and other interactive items, could provide students with a better learning environment and help them more fully enjoy the learning process. He notes that computer simulations could allow users to play with cell structure and chemical processes, thus giving them access to the material and allowing them to experiment with ideas and find solutions to complex problems. Simulations could give students a chance to engage in problem-solving activities by applying learned theoretical knowledge to practical problems. While he notes that research into the value of this type of education is sorely lacking, he states that research into this area would not be wasted. If findings can show positive results, these results "can be translated rapidly by individuals and companies into commercial products that can be used across the country by instructional institutions with innovative leaders."

The literature suggests that graphical displays and other visual images in education generally lead to positive learning outcomes for students. The integration of these types of teaching and learning tools is increasing in textbooks, presentations, and computer-driven course materials (Benson, 1997). Stokes (2001) asserts that we are approaching "a visualization movement in modern computing whereby complex computations are presented graphically, allowing for deeper insights as well as heightened abilities to communicate data and concepts. Visualization helps make sense of data that may have seemed previously unintelligible." Stokes also provides a detailed collection of sources for a wide range of exploration into the increasing role of visuals in teaching and learning.

A number of studies have already reported that visual teaching tools and strategies can often be more successful than traditional lectures and text-driven techniques. Notable studies have included the use of interactive graphics in mathematics courses (West, 1997); the affects of color vs. black and white graphics in learning activities (Kleinman & Dwyer, 1999); the levels of effectiveness of simple vs. complex graphics (Myatt & Carter, as cited in Heinich et. al., 1999); variations in types of still graphics used in instruction (Roshan & Dwyer, 1998); and comparisons of multimedia graphics to their text-driven equivalents in knowledge retention (Mayer, Bove, Bryman, Mars, and Tapangco, 1996). Mayer, et al. found that the multimedia model was more effective than the text-based model and that better learning is promoted with text-visual combinations than with text alone.

In that same vein, Chanlin (1998) explored how course exercises with no graphics, still graphics, or animated graphics influenced students with different prior knowledge levels. The study found that both still and animated graphics were better than text-only models for learning descriptive facts when students' prior knowledge was low on a particular topic. In addition, animated graphics were more effective when students' prior knowledge of the subject was high. This could suggest that more complex multimedia models are more successful in upper-level courses or courses that cover content students have come into contact with in previous courses. The study also found that animated graphics might even be distracting in certain situations. Yet, a subsequent study (Chanlin, 1999) found that the ability to interact with and control the pace of animated graphics enhanced learning.

Finally, courses that offer online content either partially or entirely make way for blended approaches to learning that combine face-to-face contact with instructors with multimedia teaching and learning tools (Bonk, et. al., 2005) and/or provide more options for course delivery. This consumer-centric approach is gaining popularity among universities seeking new innovations for attracting millennial students (Larkin & Belson, 2005) and for its capability to reach a much larger audience with a consistent message (Fearing & Riley, 2005). In fact, according to Neuhauser (2004), a number of surveys of higher education institutions have begun to point to a climate in which, "Online education has moved to the mainstream of higher education and may surpass all other course delivery methods in quality in the near future."

Neuhauser's assertion may still be a bit strong, even for these authors. In fact, a good portion of the research on hypermedia environments has shown that instructor-student relationships in face-to-face settings are still an extremely important part of the learning process. For this reason, blended learning as a pedagogical strategy has gained interest among researchers and educators who hope that offering students more and different ways of consuming material will better cater to different learning styles, make more efficient use of class time, and enliven courses (Osguthorpe & Graham, 2003).

A number of studies have also addressed some possible negative outcomes of introducing large quantities of key course content in hypermedia formats, including disorientation that can result from nonlinear navigation schemes (Eveland & Dunwoody, 2001; McDonald & Stevenson, 1996) and negative affects on a user's perception of coherence (Sundar, 2000). Likewise, a number of studies have asserted that as disorientation related to nonlinear hypermedia increases, learning is likely to suffer (Beasley & Waugh, 1995; Tripp & Roby, 1990). And in some cases, although multimedia teaching strategies were found to yield some benefits, those benefits do not fall evenly on all students. In a study that compared two versions of a psychology course, one that included multimedia content in lectures such as photos and video clips and one that did not (Smith & Woody, 2000), the divide between visual, verbal, and kinesthetic learners was apparent, and a correlation was noticed between those who prefer visual examples in learning and those who performed well in the multimedia version of the course.

It's safe to say that although a substantial amount of work is being done in these areas in the way of development and research, the use and study of multimedia for teaching and learning are in their early stages, at best. And even more specifically, we must acknowledge that outcomes of development and implementation will certainly vary among disciplines. For example some fields, such as the sciences–in particular chemistry and biology–are ripe with possibilities where animation and visualization are concerned. Thus, all of the existing research as well as any new forays into this field will continue to address different perspectives to inform the greater body of knowledge and establish a foundation for future pedagogical strategies. The sections that follow offer a case study of the design and implementation of one such tool.

Transforming How we Teach and Learn

Beginning in Spring 2007, the present authors began a collaboration to create a more cohesive home for TEAL project visualizations related to electricity and magnetism. Two critical features that could offer students more context and control over their learning experience were missing: storyline and formal structure. In other words, we aspired to develop a design format that would provide a more formal path control as students explore content related to a single, yet broad concept. And we hoped that by providing a more engaging storyline for students as they navigate the information, a better sense of coherence and connection would be established. The result is an interactive, multimedia teaching and learning tool for physics that combines visual storytelling, animation, graphic design, and nonlinear functionality. Based on a number of 3D animations, interactive applets, and videos focused on field theory, scalar and vector fields, electrostatics, magnetostatics, Faraday's Law, and light, the module essentially allows students to visualize concepts that are invisible to the naked eye and understand the relationships among these different subtopics. The following discussion offers some insight into the most significant features in the module and shows how storyline and structure will build on the already innovative nature of the visualizations that are at the heart of the presentation.

Content: 2D/3D Animations, Videos, Interactive Simulations

> *In order therefore 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 [1855]

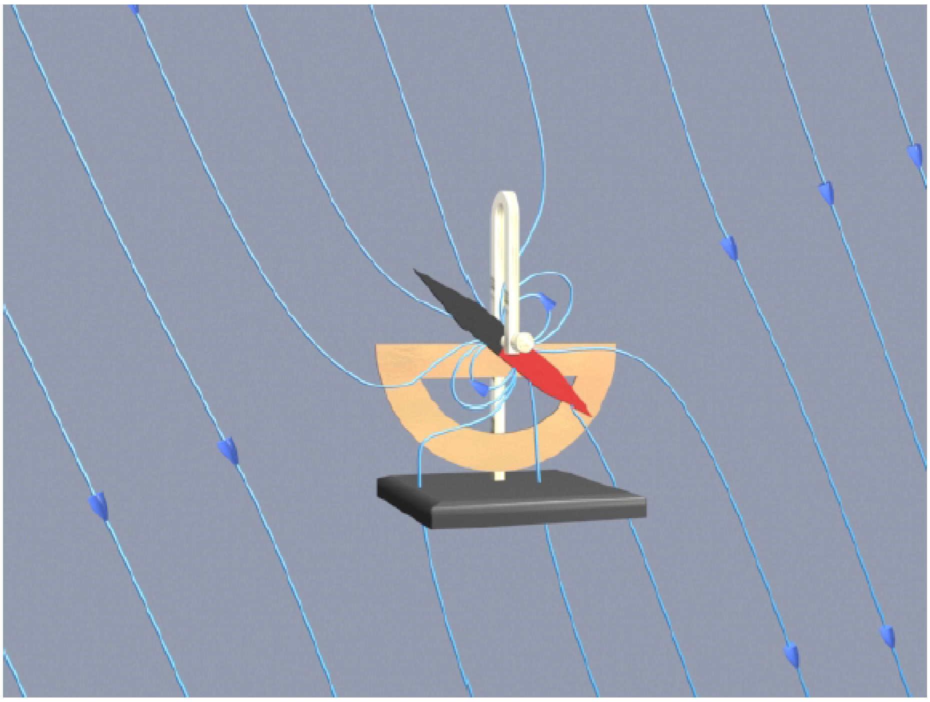
Classical electromagnetism is a fundamental underpinning of a technical education, but one of the most difficult subjects for students to master. It is a subject in which mathematical complexity quickly overwhelms physical intuition. The simulations and animation in the TEAL Visualization Project were designed to help students develop intuition about, and conceptual models of, the dynamics of electromagnetic phenomena in a manner independent of advanced mathematics. Laurillard (1993) cites two key criteria for selecting subjects in the university curriculum for this kind of multimedia treatment. To justify the extensive resources technological development requires, the subject must be: (1) widely taught; and (2) widely acknowledged to present difficulties for students. In the standard science/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 of electromagnetic phenomena or of the concept of fields. Since much of our learning is done by analogy (Redish, 1996), students have a hard time constructing conceptual models of the material they are trying to absorb. The standard textual approach that uses equations to teach this subject does little to help students establish such conceptual models, because a purely textual/mathematical approach does little to connect the dynamics of electromagnetic fields to the student's everyday experience.

The TEAL Visualization Project was predicated on the fact that indeed there is a way to make that connection to everyday experience for many situations in electromagnetism--an approach that has been known since the time of Faraday. Michael Faraday invented field theory. He 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 the use of advanced mathematics to understand. By trial and error, Faraday deduced that field lines exert isotropic pressures but also tensions parallel to themselves. Knowing the shape of field lines from his experiments, Faraday was able to understand the dynamic effects of the fields based on simple analogies to ropes and strings. It is this approach of Faraday's that the TEAL Visualization Project pursued, with the goal of helping students gain intuition about electromagnetic dynamics. It is crucial to this approach that at least some subset of the multimedia material produced be animated. The mind has an enormous capacity to integrate time-changing visual information into a coherent dynamic whole--a capability that evolved because it is fundamental to survival. With animation, the student 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.*

The best way to understand the point we are making is to contrast the traditional way of explaining the torque on a compass needle in a background 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, and look at the various $i\,dl \times B$ forces on the loop to deduce the net torque on the loop. 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 tension along the field line to deduce the dynamical effects associated with that field configuration. In the case of the compass needle in a background constant field, he drew the field configuration shown below.



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. The image above is one frame of an animation of a compass "dip needle" oscillating in a background field. 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. This hypothesis is at the heart of the TEAL Visualization Project.

Storyline

Even though the TEAL Project created more than one hundred visualizations with the above goals in mind, there was one critical feature missing: a storyline independent of the mathematical and textual development. The TEAL visualizations were linked from a traditional textual treatment of electromagnetism, but only in the context of an equation-heavy development. In the present effort, we aspired to embed the visualizations in a design format that would provide a storyline with a formal path control as students explore content related to a single, yet broad concept. And we hoped that by providing a more engaging storyline for students as they navigate the information, a better sense of coherence and connection would be established.

Nonlinear Path Control

One key to truly harnessing the power of the Web, particularly for educational texts that present a variety of "chapters" comprised of a number of subtopics, is acknowledging the potential for nonlinear path control. This navigational technique is most common in *instructive*, *narrative,* and *simulative* graphics packages like the ones used in this module. Effective *instructive* graphics explain how to do something or how something occurs in a step-by-step format. *Narrative* graphics combine interesting audio voiceover with graphic depth and rich animation. And a *simulative* is usually a representation of some kind of real-word experience. *Simulative* graphics are generally the most immersive because they imitate a real experience as closely as possible (Nichani & Rajamanickam, 2003). Packaged together in a stylized format with explanatory text, these elements comprise an explorative module that allows the student to discover content in a nonlinear fashion.

This strategy was employed for "Visualizing Electricity & Magnetism" with the assumption that successful implementation and design of a nonlinear text could also enhance learning and student enjoyment of the experience because it gives the user more control over the order in which content is encountered and the pacing of the overall experience.

Based on an active learning approach to teaching with multimedia, this approach has been substantiated in a number of fields, including political science (Selzer, 2008), information technology (Wang, et. al., 2005), and nursing (Hodson, et. al., 1988), to name a few. Furthermore, George-Palilonis and Filak (2008) found that students reported nonlinear path control enhanced their enjoyment and engagement with, as well as their sense of learning from a graphically driven e-text focused on photosynthesis.

It's worth noting that all of these features work together to tell the story of electricity and magnetism in a rich, multilayered fashion. In essence, lines between content, design, functionality, and structure blur as each depends on the others to offer the richest possible learning experience. "Visualizing Electricity & Magnetism" can be viewed at http://web.mit.edu/viz/EM/flash/E&M_Master/____LAUNCH.html and will be used in physics courses at MIT during the 2008-09 academic year. The module has also been presented at the American Association of Physics Teachers and Course, Curriculum, and Laboratory Improvement conferences (Summer 2008).

Collaborating Across Disciplines…and Distances

It is also worth spending a moment or two discussing how exciting the collaborative process can be, especially when authors come from different backgrounds and areas of expertise. At first glance, the authors of "Visualizing Electricity & Magnetism," made for a pretty unlikely pair. What could a rocket scientist and a journalist have in common? But, this collaboration also might be a great example of the doors that can open for educators when we step outside the silos that often confine us in higher education. Furthermore, although traditional textbook authoring is relatively clean and clear, it's fairly unlikely that a single individual would have expertise in a specific field like physics, as well as the technical expertise and design skills to "write" a single multimedia text. Thus, collaboration is nearly a necessity when considering the development of these types of materials. And if breaking down academic silos isn't daunting enough, so too are the challenges that arise when collaborators must work long-distance.

After one face-to-face meeting during which the authors discussed their philosophical approaches and spent an afternoon building two lesson sequences in Flash for charging by induction and Faraday's Law, all remaining development was done from a distance. The physicist would embed the content and storyline he imagined for a particular topic in a Power Point presentation with appropriate graphics and links to visualizations. The journalist would then use that Power Point as a guide and embed the content in a *Flash* framework with structure and functionality similar to that suggested by the physicist, with additions and suggestions for a clearer story line. They would then iterate the content until they arrived at a presentation they were both satisfied with, and then proceed to the next topic. The process converged within a few iterations, even though the authors never sat down for a face-to-face meeting throughout the entire development. Most communication was via email, except for a few telephone conversations to set overall direction. This was a remarkably easy process which produced a e-text that both authors take pride in.

Future Research & Development

In some ways, future research and development for interactive multimedia texts is limitless. At its heart, the most exciting thing about multimedia storytelling is that the ways in which content comes together are limited only by the topic at hand and the individuals creating a text. In other words, there is really in infinite range of possibilities for how animations, information graphics, real video, audio, still images, text, etc., can be combined to tell an educational story.

In the shorter term, we are assessing the full suite of visualizations in "Visualizing Electricity & Magnetism," through classroom use. And we plan to continue building more multimedia teaching and learning tools, including virtual labs that allow students to conduct virtual experiments or study visualizations before making scientific observations about those experiences. Likewise, the future will most certainly hold research studies that attempt to gauge the effectiveness of the module both through the study of learning outcomes and students' enjoyment of and engagement with the module. We feel that this text is just the beginning of a much more extensive set of similar products that will make the concepts of electromagnetic field theory much more accessible, both to students in introductory university courses and to the general public at large.

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About the Authors

Jennifer A. George-Palilonis
Prof. Jennifer George-Palilonis teaches courses in graphics reporting, multimedia storytelling and media convergence. She began her career as a news designer for the Detroit Free Press in 1996. She went on to be the Deputy News Design Director at the Chicago Sun-Times in 1999. She has been teaching since 2001 and has spoken at more than 30 conferences and seminars. Her research interests include visual rhetoric, multimedia storytelling, media convergence and digital publishing. She has a Masters Degree from Ball State in Composition and Rhetoric and a Bachelor's in Journalism. She is also the author of two books, *A Practical Guide to Graphics Reporting* (Focal Press 2006) and *Design Interactive* an electronic textbook on basic design principles.

John Belcher
Prof. John Belcher has taught electromagnetism at all levels at the Massachusetts Institute of Technology, from graduate courses to introductory first year physics courses. He is interested in visualization and was the lead in developing many physics visualizations that can be found at http://web.mit.edu/8.02t/www/802TEAL3D/. Professor Belcher's research interests are in the areas of space plasma physics, outer planet magnetospheres, solar wind in the outer heliosphere, and astrophysical plasmas. He was the principal investigator on the Voyager Plasma Science Experiment during the Voyager Nepture Encounter—the end of the Grand Tour. He is now a co-investigator on the Plasma Science Experiment on board the Voyager Interstellar Mission.

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