Technology Enabled Science Teaching: Software Framework for Electromagnetism

by

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Bachelor of Engineering in Computer and Communication Engineering, American University of Beirut, 2000

Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

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Abstract

The complex and abstract nature of science makes the subject difficult to understand [3] Facility in solving standard quantitative problems is the criterion most often used in science instruction as a measure of students' mastery of the subject. As course grades attest, many students who complete a typical introductory course can solve such problems satisfactorily. However, they are often dependent on formulas that they are unable to apply to situations not previously memorized. Qualitative information that is presented to the students makes them understand the concepts. It has been shown that an emphasis on concept development does not detract from, and may even improve, the ability of students to solve quantitative problems [24].

We have chosen to study physics teaching, and for our case, electromagnetism as taught to MIT undergraduates. Conceptual tests have shown that students have trouble understanding concepts because of the mathematical complexity that underlies physical phenomena [34]. We present the research conducted in designing simulations of the physical interactions between electromagnetic (E&M) objects. These simulations present to the students a way to interact with physical objects, be active in the classroom, and get a qualitative understanding of the subject matter. They enable students to visualize the field lines between the objects, which are invisible in practice. The dynamic motion of these objects is also incorporated. The user can change the parameters of a simulation and that of the electromagnetic objects, observe the resulting changes, and thereby get a better qualitative conceptual understanding of the underlying physics.

The two- and three-dimensional simulations are a part of a software framework designed in order to make new simulations' development an easy task for non-programmers and teachers. The framework can also be easily extended to accommodate new features, objects, and integration methods for field lines' and objects' dynamics computations.

Thesis Supervisor: Steven Lerman
Title: Professor of Civil and Environmental Engineering

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I would like to thank John Belcher, physics professor and Principle Investigator of the Technology Enabled Active Learning (TEAL) project, for his supervision of my research work, his help in explaining electromagnetism, as well as his great feedback on the simulations development. It was under his leadership that I was able to grow intellectually at MIT.

Andrew McKinney, researcher at the Center for Educational Computing Initiatives and project manager of TEAL, gave me advice on putting better focus in my work, which helped me deliver several motivational discussions to communicate properly what I was trying to solve, and ultimately understand better the problems I was solving.

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Several of my family members have moved to the Boston area or have been visiting quite regularly. My cousins in the United States, Canada, Belgium, South Africa, Saudi Arabia, Spain, Ireland and Lebanon have been and are always tons of fun and

plenty encouraging.

Let me also mention friends, Lebanese, American and international. You made my stay at MIT entertaining and shared your energy, wit, jokes, etc. I would like to mention my lab mates here and gone Anup, Charuleka, Pierre, Steve, Ying and Jed. For that I thank you all and I'd like to mention also: Bassam, Issam, Karim, Sanjit, Ivan, my lifelong friends Paul and Colette, Carla, Fernando and Charbel for reminding me of long-lasting friendship.

The Lebanese Club at MIT was a great experience for me. It helped me understand that my point of view was not the correct one all the time. I learnt things about my country that I had never known because I was on "the other side". The frequent and sometimes heated discussions that I had with Jad Karam, Mahdi Mattar and Louay Bazzi were eye-opening experiences that gave me a great deal of knowledge. The club has helped understand the differences in attitudes between the younger and older generations of Lebanese students at MIT. A feeling of helplessness and defeat characterizes the younger generation while the older ones have the boiling blood of revolutionaries. I therefore wanted to give a good push to the younger generation by bringing them together and creating closer bonds.

It has been about a month that I have not been back to my country, Lebanon, after two years of absence. Although I miss it quite a bit, I also feel torn between my allegiance to my hometown Beirut and the new town that has embraced me and helped me thrive: Boston. Beirut and Boston will always represent what I like and dislike most in the world. They carry in their hearts the best and the worst days of my life and for that, I love you both.

To Josephine, Ronald, Richard

I LOVE YOU!

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Chapter 1

Introduction

1.1 Overview

“If computer screens simply provide us with a stream of information, verbal or pictorial, students can receive it just as passively as they can listen to lectures. Technology has the power to improve education only to the extent that it induces the student’s continuous mental activity by presenting tasks that require thoughtful responses” said Dr Herbert Simon of Carnegie Mellon University [15].

Our focus is on science subjects in which the topics covered are hard to conceptualize. To explain the different physical sciences, teachers often give a set of mathematical formulae. These equations are sometimes difficult for students to understand, and coupled equations even harder to solve. In this thesis, we focus our research on electromagnetism taught at MIT to freshmen.

Introductory physics is a fundamental underpinning of a technical education, but the material is difficult for students to master. It is a subject in which mathematical complexity can quickly overwhelm physical intuition. Therefore, a reform of physics education at MIT, which is designed to help students understand conceptual models of physical phenomena, was undertaken. This reform is centered on an “active learning” approach [3],[5].

Used appropriately, educational technology has the potential to support meaningful learning and to enable the presentation of spatial images to portray relationships among complex ideas. The options educational technology offers have stimulated us to envision computer-based visualization as a prime aid for science teaching. The Technology Enabled Active Learning (TEAL) Project at MIT involves media-rich software for simulation and visualization in a freshmen physics course to help students in the conceptualization of phenomena and processes. Introductory undergraduate physics courses are fundamental underpinnings of any science and engineering education. The assessment of the project includes examining students' conceptual understanding before and after studying electromagnetism in a media-rich environment and investigating the effect of this environment on students' preferences regarding the various teaching methods.

Teaching freshmen courses in a large lecture hall with over 300 students listening to an instructor (as excellent as he or she is) is based on the assumption that the instructor can pour out knowledge from her vast knowledge base into the thirsty minds of students. However, interaction is a key element to learning. It can be real or simulated [22]. The research reported here was on the best uses of physics simulations that enable the student to interact with electromagnetic objects in an environment suitable for the student to visually understand physical phenomena.

This thesis presents the TEAL project, its added value compared to previous ventures and the simulations design applied to the TEAL project. It then explains the structure of the software framework that these simulations are part of, and the benefits and limitations of that framework. We then conclude with future directions that can be taken to enhance the simulations research and to make science teaching more efficient.

1.2 The TEAL Project

1.2.1 Description of TEAL

The TEAL project is revamping the way introductory physics classes are taught at MIT. Physics is an experimental science, but many of the introductory level classes taught at MIT involve no hands-on laboratories. Modeled after the Studio Physics format instituted by Professor Jack Wilson at Rensselaer Polytechnic Institute in 1994, the TEAL format combines lecture, recitation, and hands-on laboratory experiments into one classroom experience which, in this case, even means revamping the classroom itself. In addition, animations and simulations are incorporated into course materials to help students visualize and understand fields, the complex interactions inherent in electromagnetism. The goal of TEAL is to engage students more fully and help spark students' fascination with the subject matter. The 8.02 class (electricity and magnetism) is the pilot of the new TEAL format. The objectives of the TEAL/Studio project are to:

- Create an engaging and technologically enabled active learning environment
- Move away from a passive lecture/recitation format
- Increase students' conceptual understanding of the nature and dynamics of electromagnetic fields and phenomena
- Foster students' visualization skills.

1.2.2 Studio Physics

The TEAL/Studio Project is aimed at serving as a model for undergraduate science courses for large groups. The TEAL/Studio environment is a merger of lecture, recitations, and hands-on laboratory experience into a technologically and collaboratively rich experience. The project is scheduled to take five years to reach full implementation. The first prototype implementation of TEAL/Studio took place in freshman electromagnetism in the fall term of 2000. Engaging 3D animations and 2D and 3D simulations of the phenomena under study complement the laboratory experiments that students carry out as a part of the course [7].

TEAL also takes advantage of an automated system, called WebAssign, for submission and electronic grading of problem sets. This system gives the instructor access to a summary of how the students did on an assignment immediately after the submission deadline, allowing the instructor to tailor the next class to the particular needs of the current students. This gives the instructor the freedom to cover material that is more sophisticated, rather than spending time covering definitions and elementary concepts.

1.2.3 The Classroom

The studio physics classroom is designed for moving between lecture, experiment, and discussion portions of the class. It consists of 11 round tables that seat 9 students each. In the center of the room is the instructor's station used to present material that can then be projected on eight projection screens located around the perimeter of the room. Also located along the perimeter of the room are numerous whiteboards available for impromptu discussions and presentations by both staff and students. On each table are three laptops, provided for the students to work in teams of three on experiments and problems assigned in class.

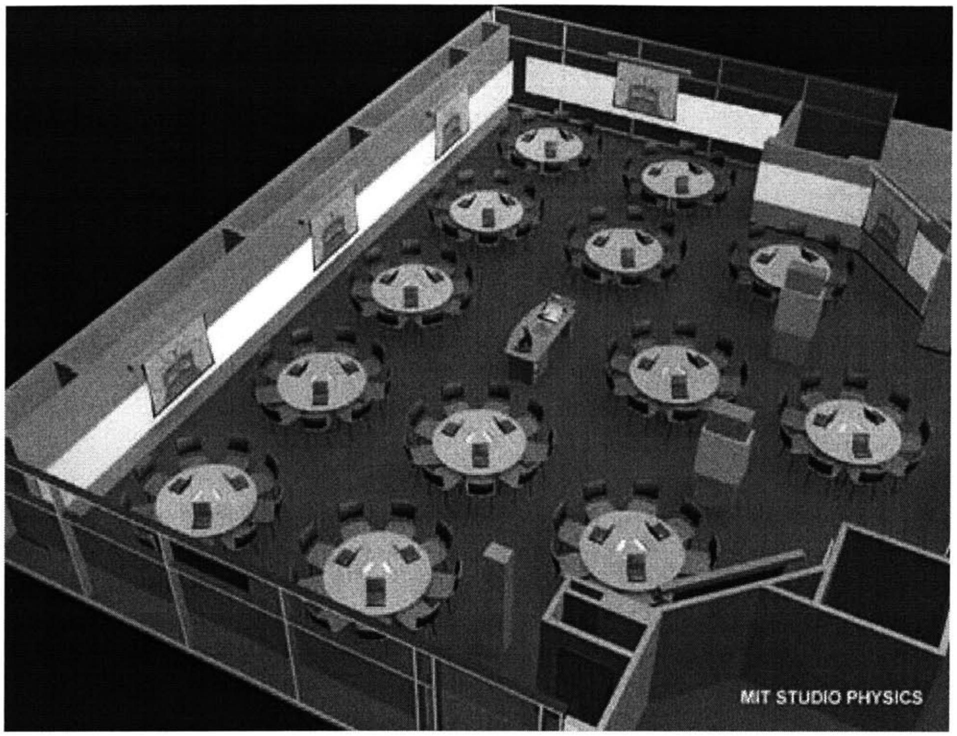

Figure 1: Artist's Conception of the Studio Space

1.2.4 Visualization

In moving to the Studio Physics format, TEAL is benefiting from the experience of many institutions outside of MIT that have pioneered that format. The research component of TEAL is adapting this format to fit the capabilities of the MIT student body and the extensive coverage of the MIT physics curriculum. In the course on electromagnetism, the research focus is evaluating the effectiveness of using modern visualization techniques to help students understand fields and their effects. Animations allow the student to gain insight into the way in which fields transmit forces, by watching how the motions of material objects evolve in time in response to those forces. Research simulations created as Java applets provide more interactive demonstration of concepts that allow students to enter their own data, and then observe and interpret the results.

1.2.5 Comparison of TEAL with Previous Efforts

Previous studio-style physics teaching was implemented at other universities. TEAL collaborated with the RPI and NCSU physics departments to make the format a successful one, and to foster active students' learning.

1.2.5.1 Comparison with Rensselaer Polytechnic Institute

At RPI, the lecture, recitation and hands-on experiments take place in the same classroom, where students feel comfortable having to deal with one sole environment. TEAL has collaborated with RPI to get ideas on how to make sure that the implementation at MIT would be a success.

At RPI, the focus is on analytic problems, while TEAL focuses on conceptual problems. Focusing on conceptual understanding makes sure that the students are able to understand qualitatively the underlying physics. Solving problems does not help the students understand the concepts; instead, it draws their attention on solving mathematical problems rather than conceptually thinking about what they are trying to solve.

The simulations developed at RPI focus on numerical values that the student exports to a Microsoft Excel sheet for subsequent analysis. According to the physics teachers at RPI, when dealing with formulas and problems that are not too involved, spreadsheets can be an invaluable tool for learning physics. Spreadsheets allow the student to see all of the data at once, allowing for an easier spotting of trends in the data, and take away the tedium of numerous calculations. The simulations in TEAL rather focus on the qualitative information that can be provided to the student. They are a means to help students visualize and understand fields and the complex interactions inherent in electromagnetism.

1.2.5.2 Comparison with North Carolina State University (NCSU)

TEAL first used the NCSU studio physics model to get ideas and build on them. The core of TEAL is based on the NCSU model where they fold together lecture and lab with multiple instructors to provide an effective, yet economical, approach. Students are grouped in three, each group using a laptop to encourage interaction among the students.

The focus of the NCSU is more on the classroom setting, which TEAL built its model upon. TEAL was therefore free to focus more on the content delivered and to create a visually attractive environment using laptops and technology for hands-on experiments and simulations.

At NCSU, simulations are seldom used and the focus is rather on hands-on experiments. As an example, spreadsheets are used at NCSU to visualize surface potentials, and the student has to manually change parameters to observe a change in the plotted graphs.

Simulations provide a powerful tool to visualize the unseen, easily change the physics objects' properties and observe the resulting effects. TEAL takes full advantage of the simulations' power to design and develop a set of 2D and 3D visualizations. Collectively, the simulations developed by TEAL follow the entire semester curriculum.

1.3 Motivation of research in TEAL

The research work conducted as part of TEAL was motivated by many factors. These stemmed mainly from the weaknesses of traditional lectures in the traditional classroom and lab setting. Below we explore the areas of desktop experiments, traditional teaching and mathematical difficulties.

1.3.1 Limited Scope of Desktop Experiments

Experiments are a useful tool for the student to understand physical behavior, and see the actual physics in application. Conducting experiments is a way to focus more on the concepts behind the mathematics that the traditional lecture tries to explain. The student can "see" the electromagnetic objects and their interactions. Nevertheless, some experiments cannot be easily realized because of the existence of extraneous forces such as gravity that cannot be overcome, or because some phenomena we want to show are invisible such as field or force lines.

- Extraneous forces are difficult to overcome: Lab experiments are not always easy to setup and conduct. Some experiments explore the dynamics of objects in three-dimensional space. If, for example, one wants to put a charge inside the field of the magnetic dipole, and lets it move freely in order to observe its dynamics, the experiment is difficult to actually have in reality since the charge will be traveling in three-dimensional space and the magnet should be held floating in the air without a stand to sit on. Effects of gravity are not always desirable, and removing this parameter can be achieved only with great difficulty. Figure 2 shows a simulation snapshot that visually explains the above-mentioned experiment.

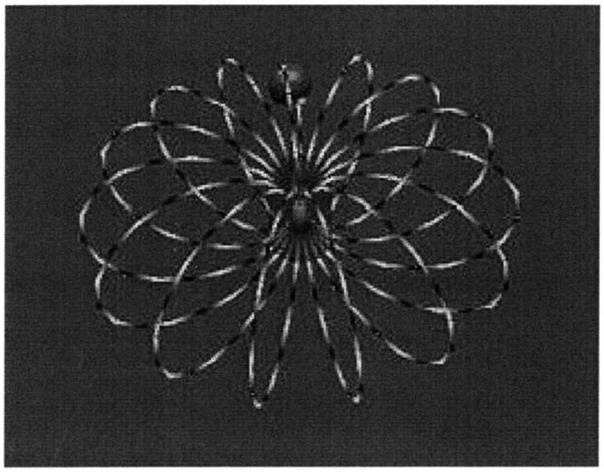

Figure 2: Charge (ball-shape) in the field of a magnet (cylinder-shape)

- Invisible phenomena are only assumed to exist: Invisible phenomena like the interaction between particles at microscopic levels, electromagnetic fields that exist between objects, are difficult for the students to imagine. Students are asked to imagine the existence of these fields rather than actually see them.

1.3.2 Traditional Teaching and Technology

Traditional teaching in the traditional classroom has made poor use of technology with only videos and slide shows being the main visually appealing and exciting applications used. Computer power has been for the most part ignored in teaching, even though it can provide a way for the student to be more active in the classroom rather than passively receive the information delivered by the teacher. It can also assist lab experiments in calculating and plotting parameters such as current and voltage when it is plugged into the experiment. Simulations are also a powerful tool that the computer can achieve by providing a quasi real-time depiction of phenomena plus the added details that we are interested in such as invisible phenomena and microscopic interactions.

1.3.3 Mathematical Difficulties

Lectures give a mathematical explanation

In physics, traditional lectures focus on the mathematics of idealized systems, the equations that explain the science, and how from derivations of the equations one can show that the science is correct. By solving a coupled set of equations, for example, we can see that the trajectory of a projectile is a parabola. How did we learn it? By starting with the acceleration of the gravity and then integrating twice. If we had a simulation with the vectors of accelerations and velocities and their sums following the projectile during the motion, we could have seen how these change over time, and how they end up drawing a parabola.

Similarly, in electromagnetism, mathematical equations tell us that the field existing between a charge and another will drive motion of these two relative to each other. The grasp of the meaning of these equations can be obtained by actually seeing two charges in motion, and observing their behavior. Mathematical equations give us a clear answer that we can be certain of within the simplifying assumptions of the system they model, but that does not easily relate to reality. Problem solving focuses on the abstract realm, but often does not convey concepts in the form of qualitative information.

Mathematical equations are sometimes complex

Solving equations is sometimes complex. Having coupled equations to solve focuses the student on solving a mathematical problem, and forgetting how to relate back to the physics concepts that were the primary goal. Concepts are not easy to grasp, and visualizations, simulations and conceptual questions aid the student in understanding them. Computer simulations have the potential to expand the range and nature of student experiences and, if properly designed and used, will expand their understanding of physics.

Chapter 2

Technology Background

A brief introduction to the various technologies used in developing the software is presented here.

2.1 Java

Java was used for the development of the simulations. It was an attractive solution for its portability across different platforms and imaging capabilities. It also allows the development of user interfaces rapidly. Below is a brief description of Java, and a taste of its benefits and limitations.

Introduced by Sun Microsystems, Java was the first programming language that was not tied to any particular operating system or microprocessor. Applications written in Java will run anywhere, eliminating one of the biggest headaches for computer users: incompatibility between operating system and versions of operating systems. Java started in 1990 when a team of Sun researchers developed technology for the convergence of digitally controlled consumer devices and computers.

Java is directly derived from C++ and was designed with many goals in mind. Its designers wanted a new language that was familiar, simple, object-oriented, platform independent, high-performance, multi-threaded, robust and secure. To this end, a number of more complicated features of C++ such as pointers, multiple inheritance and operator overloading were omitted from Java. Java is a language of the 1990's and quickly gained fame as the language of the Internet. It was recognized that a language for the Internet would present immense security worries. Users would not want to download executable programs to their local machines if these routines had the potential to wreck their local working environments. The creators of Java built into the language mechanisms that prevent remotely loaded routines from taking control of the machine they run on, particularly when using Java applets.

2.2 Java Applets

The simulations developed are Java applets that do not present serious security threats when downloaded from the network and run on the client machine. They are also relatively small in size, and therefore attractive to be downloaded to the client end.

A Java applet is a Java program that is cross-platform compatible and can be embedded in the HTML[1] of a Web page. An applet may be downloaded over a network connection

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[1] Hypertext Markup Language

and run on a local machine via a Java-enabled browser. Web browsers that are equipped with Java virtual machines can run an applet to perform interactive graphics, games, calculators, etc. Applets can add sophisticated support for Web pages, far beyond other programming such as DHTML[2] or JavaScript. Applets provide a means of doing client side data manipulation under the HTTP[3] protocol. Unlike complete applications, applets cannot be executed directly from the operating system. A well-designed applet can be invoked from many different applications.

Applets differ from applications in that they are more secure -- they cannot access certain resources on the connection to the computer from which the applet was sent (local computer, such as hard drives, modems, and printers). Applets can in some cases slow page loading to a crawl, and just plain crash non-compatible browsers.

2.3 Java3D

A number of simulations were developed in three dimensions for the greater sense of reality they would present, and the extra information they would contain and the need for students to look at the objects and field lines from different angles. Plane cuts could have allowed these different two-dimensional views, but one could not, in that fashion, provide a complete picture of the other planes. Java presented an easy solution through the use of the Java3D package.

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[2] Dynamic HTML

[3] Hypertext Transfer Protocol

As a part of the Java Mediaproduct family, the Java3D Application Programming Interface (API) is used for writing stand-alone three-dimensional graphics applications or Web-based three-dimensional (3D) applets. It gives developers high-level constructs for creating and manipulating 3D geometry and tools for constructing the structures used in rendering that geometry. With Java3D API constructs, application developers can describe very large virtual worlds, which, in turn, are efficiently rendered by the Java3D API.

The Java3D API specification is the result of a joint collaboration between Silicon Graphics, Inc., Intel Corporation, Apple Computer, Inc., and Sun Microsystems, Inc. All had advanced, retained mode APIs under active internal development, and were looking at developing a single, compatible, cross-platform API using Java technology.

The Java3D API draws its ideas from the considerable expertise of the participating companies, from existing graphics APIs, and from new technologies. The Java3D API's low-level graphics constructs synthesize the best ideas found in low-level APIs such as Direct3D API's (http://www.direct3d.net/), OpenGL (http://www.opengl.org/), QuickDraw3D (http://www.apple.com/quicktime/), and XGL (http://www.xglspec.org/). Similarly, the Java3D API's higher-level constructs leverage the best ideas found in several modern scene graph-based systems. This API also introduces some concepts not commonly considered part of the graphics environment, such as three-dimensional spatial sound to provide a more immersing experience for the user.

2.4 XML

The simulations developed are all part of one software framework. The creation of a simulation starts with reading a configuration file, written in XML (Extensible Markup Language). XML (http://www.w3.org/XML/) was chosen because it is human readable, easy to write, and can present the non-programmer with an attractive way to develop a new simulation by simply looking at an example. Further explanation of how XML was incorporated in the framework can be found in sections 4.1.4 and 4.2.1. In this section, we present an overview of XML.

Extensible Markup Language (XML for short) is a new language derived from Standard Generalized Markup Language (SGML) designed to make information self-describing. This simple sounding change in how computers communicate and exchange data has the potential to extend the Internet beyond information delivery to many other kinds of human activity. Since XML's specification was completed in the early 1998 by the World Wide Web Consortium (W3C), the standard has spread through science and into industries ranging from manufacturing to medicine. This enthusiastic response is fueled by a hope that XML will solve one of the Web's biggest problems: although every kind of information is available online it can be extremely difficult to find the information one needs. The problem arises from the nature of the Web's main language, HTML (shorthand for Hyper Text Markup Language). Although HTML is the most successful electronic publishing language ever invented, it is superficial. In essence it describes how a Web browser should arrange text, images and widgets on a page. HTML's concern with appearance makes it a relatively simple language to learn, but this simplicity also has its costs. XML makes it possible, despite the use of incompatible computer systems, to create a data format that all can read and write. Unlike most computer data formats, XML markup also makes sense to humans, because it contains nothing more than ordinary text.

The unifying power of XML comes from a few well-chosen rules. One is that tags almost always come in pairs. Like parentheses, they surround the text to which they apply. And like quotation marks, tag pairs can be nested inside one another to multiple levels. The nesting rule automatically forces certain simplicity on every XML document, which takes the structure of a tree. Each element in the document represents a parent, child or sibling of another element; relationships are unambiguous. Trees cannot represent every kind of information, but they can represent most kinds which we need computers to understand.

Chapter 3

Simulations

3.1 Research Goals

The simulations that were designed as part of TEAL were created in order to make the task of learning more interesting and more effective. Students are used to sitting in a traditional classroom and listening to the explanation of the teacher, with only occasional questions from the teacher or the student that provide interactivity during class time. Laboratory experiments are a way to make the students more active. These hands-on experiments help the student get a better feel for the abstract explanations given in class by providing actual physical components to the students. Nevertheless, not all experiments are possible, be it simply because it is very hard to get rid of some surrounding phenomena such as gravity, or because some phenomena such as field lines in electromagnetism or forces in mechanics are invisible.

On another hand, traditional teaching has mainly focused on problem solving tasks and “plug-and-chug” exercises. In our work, we focus on improving students’ conceptual understanding, and present qualitative information to students rather than quantitative problems. Qualitative information can be presented through visualizations and simulations.

The simulations were designed to make learning more appealing. They relate to real-life situations by having the objects' properties in the simulations similar to the ones in real electromagnetic objects. The simulations all have the same look-and-feel in order for the student to be able to use the same simulations' environment throughout the semester. We explore below the research goals in detail.

3.1.1 Complement Laboratory Experiments

Traditional science lectures present the concepts to the students, and explain difficult ones through equations that quantify those concepts. Laboratory experiments give the student a more hands-on experience with the concepts learnt in class. Nevertheless, not all experiments are possible to conduct. Gravity for example is a factor that cannot be practically eliminated; some explanations of concepts need to remove this component in order to be easily understood.

Some other phenomena, such as field lines in electromagnetism, forces in mechanics and chemical reactions at the molecular level, are invisible. By designing simulations, the limitations of the desktop experiments can be overcome, whereby constraining factors can be eliminated by one click of the mouse, and invisible phenomena can be easily visualized through line drawings, vector representations and visual illustrations.

3.1.2 Improve Conceptual Understanding

We focus on improving the conceptual understanding of the students by:

- Presenting visual understanding of interactions between objects that are not evident from equations: The simulations have the ability to show the students the interactions among objects and the unseen phenomena. Equations explain the concepts but do not make evident phenomena such as the actual charge distributions, field lines, equipotentials and dynamics. Once the students visualize these aspects, they can more easily understand the complexity of the equations presented in class.

- Interactively demonstrating concepts: All the simulations should be interactive. This makes the students more interested in spending time changing parameters in the simulation and observing the corresponding behavior. Moreover, the students are given control over the parameters of the physical objects. They can also choose to show or hide invisible phenomena such as field lines, or choose the visualization that is most suitable for the simulation such as the texture for the field lines. By texture, we mean the way we draw the field lines: they can either be continuous lines, made up of vectors with direction and intensity, filling the whole surrounding space, or drawn at specified points only.

- Asking conceptual questions: While the student interacts with the simulations we display conceptual questions related to them. This makes sure the student comprehends the theory that the simulation is trying to explain. We will explore this area more in section 5.5.

3.1.3 Provide a Comfortable Learning Environment

Another goal of the simulations is to provide an easy environment for students to deal with. The students are naturally driven to spend more time interacting with the simulations until they can relate the simulated objects and environment to reality.

Simulation objects have the same properties as their physical counterparts: Electromagnetic objects have sizes, magnetic moments, charges, mass, current, etc.... The students therefore deal with parameters they are used to in desktop experiments, but with the added facility that these parameters can be changed very easily. By typing in a new value, or just by moving the pointer of a slider, one can change any of the parameters.

Students deal with a common user interface: The simulations follow a common graphical user interface (GUI) in order for the student to be acquainted with the environment instead of coping with a new environment for each animation.

3.2 Simulations in Physics Instruction

In this section, we present the work done by previous and concurrent physics teaching efforts, and then present our work followed by examples and the challenges that we faced. A clarification is needed here to distinguish between simulation and visualization. Simulations are applications that one can interact with. We mention a few examples such as changing the simulation's parameters, watching it from different angles, grabbing objects and changing their locations. In contrast, visualizations are just static images and videos that the user cannot modify.

3.2.1 Previous Work

Previous efforts to create physics simulations for educational purposes have been conducted at several universities. We split previous simulations into static and dynamic ones.

Static simulations are simulations where objects do not have dynamics equations that drive them. Dragging objects from one position to another is their sole displacement. Colorado University and Georgia Tech have worked in this area and their simulations were interactive. One can change the parameters of the E&M objects and drag them around. These simulations are attractive and have good functionality but they are limited by their intrinsic static nature. Below are two snapshots of their work. Figure 3 shows a positive charge and a negative one. The smaller circles are points where the electric field is measured. The vectors drawn are the sum of the electric fields generated by the two charges. One can click on the point charges, drag them to new positions, and observe the change in the vectors at the different points. Figure 4 shows the relations between electric field, magnetic field and wave vector when electromagnetic waves propagate through space.

Figure 3: Colorado State University: Charges and Fields

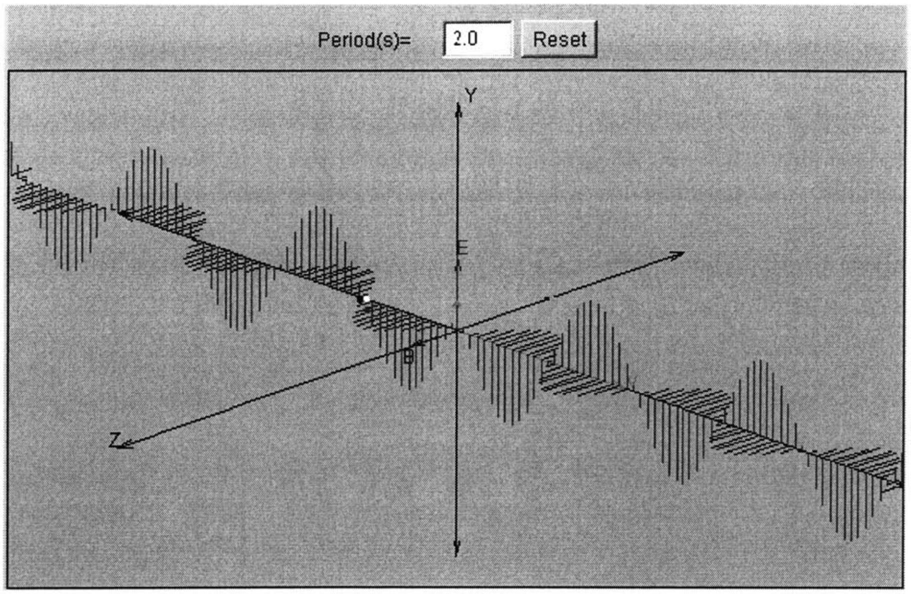

Figure 4: Georgia Tech: Propagation of Electromagnetic Wave

Dynamics simulations involve having more than one electromagnetic object, and solving dynamics equations when one or more of these objects are free to move. This kind of simulations was developed at several universities. We particularly focus here on RPI and Syracuse. Although these simulations are attractive and give insight into how the electromagnetic objects interact, they are not as interactive as one would wish, and therefore are considered more as visualizations. In this case, the student is passive, and this defeats one of TEAL's objectives, that is to make the student active in class. Syracuse has an extensive number of simulations built in VRML[4]. RPI has a limited set of simulations that are not interactive but can give an idea about the theory behind the dynamics.

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[4] Virtual Reality Modeling Language: http://www.web3d.org/vrml/vrml.htm

At these universities and others that we did not mention, the simulations did not cover the entire curriculum of the class. There were only few simulations that the teachers found useful or practical to have. They were therefore not exhaustive of the syllabus followed in class.

One major issue in electromagnetism is the field lines drawn around and between electromagnetic objects and how the drawing is done. Each of the previous ventures focused on one texture used to represent fields that was followed in all the simulations. In this context, texture refers to the way field lines are to be represented (dotted lines, vectors at different points of the line, lines filling the whole surrounding space or just a few lines drawn). This is an expected behavior when the same teacher is teaching the class, but different teachers have different preferences for representing field lines. Some prefer dotted field lines, others ones formed of small vectors, and others prefer the usage of continuous lines. These textures give different viewpoints to the fields. They are all useful, but some are more informative than others, depending on the simulation. We will show in our simulations how different simulations require different textures to best illustrate the key concepts students need to learn.

3.2.2 Simulations Achievements

The simulations that we designed followed the curriculum of the electromagnetism class taught at MIT.

- These simulations were designed in two-dimensional and three-dimensional space according to the needs of each simulation. If a two-dimensional simulation was sufficient to explain a certain concept, then we did not bother to go to the third dimension, therefore sparing the student unnecessary complexity. This brought an added value to previously designed simulations where only two-dimensional simulations existed. We used Java3D to have good graphics resolution and speed of simulation.

- Each simulation explained a new concept or law (Faraday's Law, Coulomb's Law, Lorentz's equations, Maxwell's equations, etc...) so that the entire syllabus was covered, in contrast to other physics efforts at other universities where only a limited number of simulations were created.

- Each simulation shows field lines the way we judged most useful to that particular simulation. Some are drawn as dotted lines; others are formed of vectors at different locations along the line. For the three-dimensional simulations, we draw a few field lines surrounding the E&M objects. These simulations would not be very informative if field lines were drawn at every point in the surrounding space because that would hinder visualizing the objects themselves, even if the field lines were made semi-transparent. Instead, a few lines are enough for three-dimensional simulations. We discuss this further below.

- All simulations are interactive in the sense that all the parameters of the simulations can be changed.

- An easy look-an-feel made it simple for students to have everything they were able to manipulate easily accessible. For example, students can easily alter the charge of a point, whether to display field lines, change grid spacing, etc.

- Numerical methods for integration of differential equations were properly chosen in order to accurately draw the field lines and calculate the objects' dynamics. Different integration schemes were used, and one could choose between Euler, Runge Kutta and stepped Runge Kutta. Euler's method is the fastest but least accurate. When one uses Runge Kutta, further details can be visualized and more accurate calculations result. In particular, when we want the magnetic field lines to follow their loop path and close down on themselves, Euler is not guaranteed to achieve that, and instead the simulated field lines would diverge and go to infinity.

- Sound was added to some simulations where necessary. For example, a magnet falling inside a ring of current had attractive graphics (see Figure 7) and an ammeter to measure the current inside the ring, but a more impressive way to do it was to add sound that was proportional to the square of the current in the ring. This feature does not exist in previous or concurrent efforts in physics simulations.

Line Integral Convolution

Line Integral Convolution (LIC) is another area that was explored for the illustration of the field lines. It is an elegant method for creating textures that embed the directional information of vector fields. It can be regarded as an image processing algorithm, which is fed by an input image and some vector field, and produces an output image, which embeds directional information about the vector field into the original image. This technique shows the field lines at every point in the simulation area in a two-dimensional world, and gives more information (such as field lines'singularities), which can be missed by drawing just a few field lines in a three-dimensional environment. This visualization is not practical to use while the simulation is running because of the extensive mathematical calculations needed to create it. The integral calculated for each line is:

$$I(\vec{x}_0) = \int_{s_0-L}^{s_0+L} k(s-s_0) \cdot T(\vec{\sigma}(s)) \cdot ds \tag{3.1}$$

In this expression, $I(\vec{x}_0)$ denotes the canvas pixel intensity at the seed point position $\vec{x}_0$, where s_0 is the arc distance from $\vec{x}_0$. Here, s_0 is equal to zero. L is the arc distance. Field lines are usually denoted by the Greek letter σ and they are parameterized by arc length *s*. *k* represents a filter kernel that is normalized to unity in order to conserve a range of intensities between 0 and 1. To denote our input image, we identify it with a texture and use a scalar field notation: $T(\vec{x})$. Figure 5 shows a circular and turbulent field textures created by LIC.

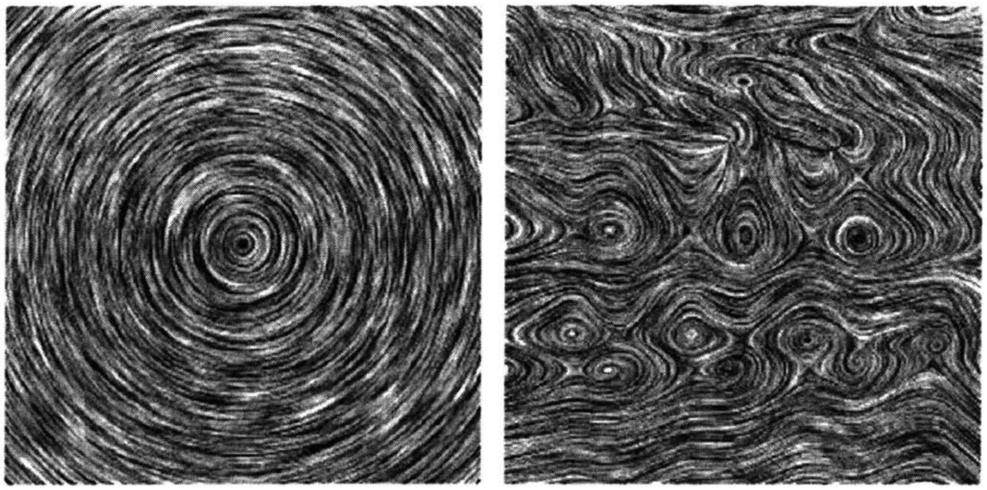


Figure 5: Sample textures created by LIC

3.2.3 Examples

We first show the added value that the simulations can bring to the laboratory experiments. Below in Figure 6, we see a single frame from a video clip of a magnet falling through a ring of current. In the actual video, the dynamics are very apparent, but the invisible field lines are hard for the student to imagine. Figure 7 presents the simulation applet created that shows the field lines at every point surrounding the electromagnetic objects. This brings added value to the experiments by showing invisible phenomena. As the magnet falls under gravity, the magnetic flux through the ring changes. This change in flux through the ring leads to an *emf* (electromagnetic force) in the ring and a resultant eddy current that can be computed via Faraday's Law. The sense of the current is to try to keep things from changing, that is, to set up a force on the magnet which impedes its fall with an upward force. The sense of the current is always such as to try to keep the magnetic flux through the loop from changing, which results in the field lines getting "hung up" as they try to pass through the ring.

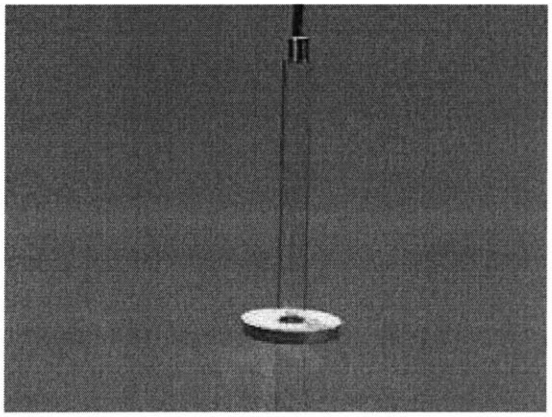


Figure 6: Lab experiment of Falling Magnet

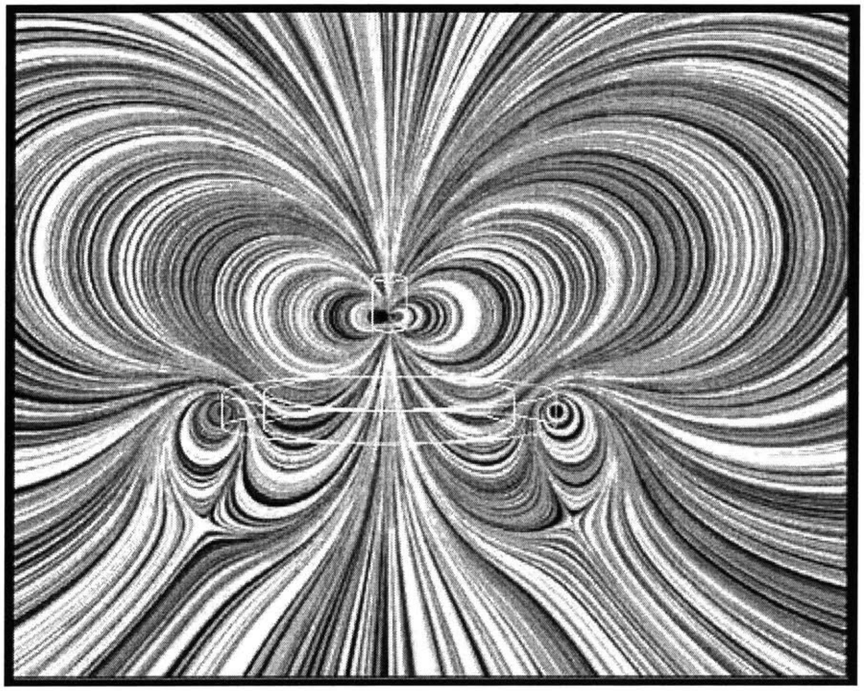
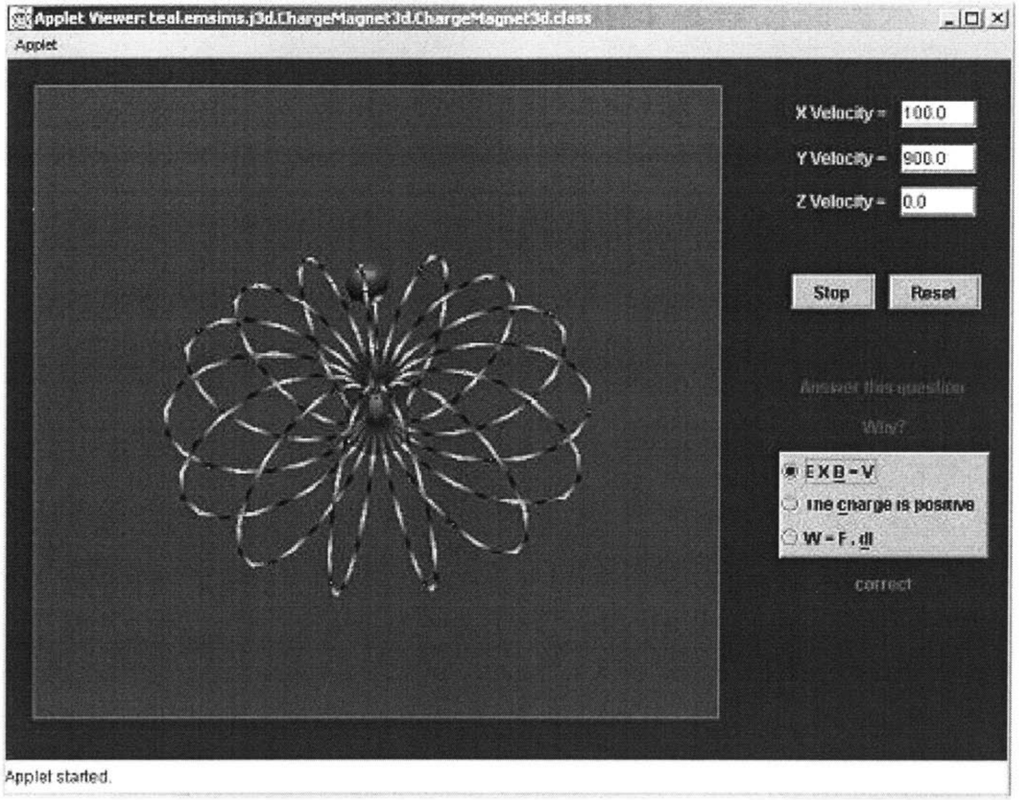


Figure 7: Falling Magnet with Field Lines

Figure 8 is a screen shot of a simulation applet. It shows a point charge inside the field of a magnetic dipole. This charge rotates around the charge in a way according to a coupled set of motion equations. The charge starts with an initial velocity and is trapped in the field of the magnet. This experiment is not possible to conduct in a laboratory setting due to the presence of gravity. The particle in a magnetic field will gyrate around magnetic field lines in a constant magnetic field, and it will do the same thing in an inhomogeneous magnetic field if the field is strong enough. However, there exists a variety of other motions in an inhomogeneous magnetic field, as this applet illustrates. The motion shown in the simulation mimics the motion of charges in the Van Allen radiation belts of the Earth.

In this simulation, the numerical integration scheme (Runge Kutta in this case) was chosen in order to have a good compromise between level of detail and speed of the simulation. Euler's method gives less detail and is faster than the detailed Runge Kutta scheme that makes the simulations run slower.



X Velocity = 100.0

Y Velocity = 900.0

Z Velocity = 0.0

Answer this question

Why?

● E X B = V

○ The charge is positive

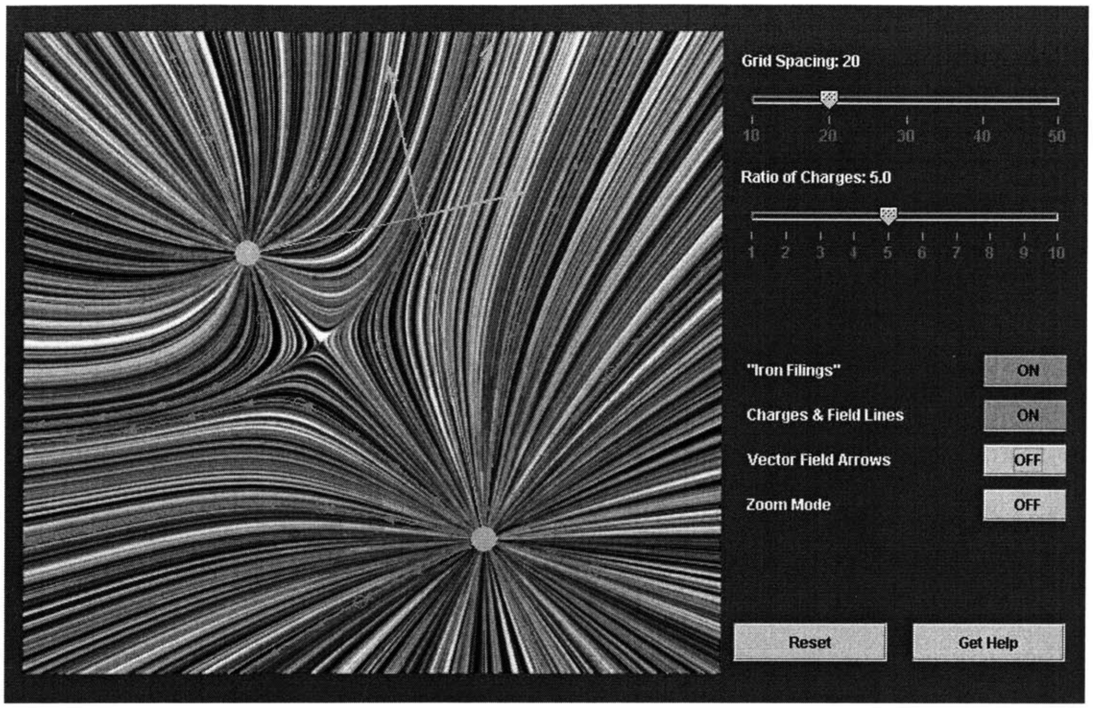
○ W = F . dl

correct

Applet started.

Figure 8: Point Charge and Magnet

In Figure 9, we see a complete example of how the textures can be drawn. We see equipotentials (lines formed of small vectors) that were obtained by clicking on any point on these lines. The arrows on these lines show the vectors that form these lines. The direction of the vectors is also very important to indicate where these field lines originated at, and which direction they are pointing to.



Grid Spacing: 20

Ratio of Charges: 5.0

"Iron Filings" ON

Charges & Field Lines ON

Vector Field Arrows OFF

Zoom Mode OFF

Figure 9: A snapshot of a simulation with LIC texture

Figure 10 shows the feature of zooming into a specific area. This feature is very useful to carefully observe the zeros or singularities as we see in the figures below. This adds a great amount of detail, and the student can therefore have clearer pictures of where the electromagnetic field becomes null or disappears (dark intersection of lines in the zoomed picture).

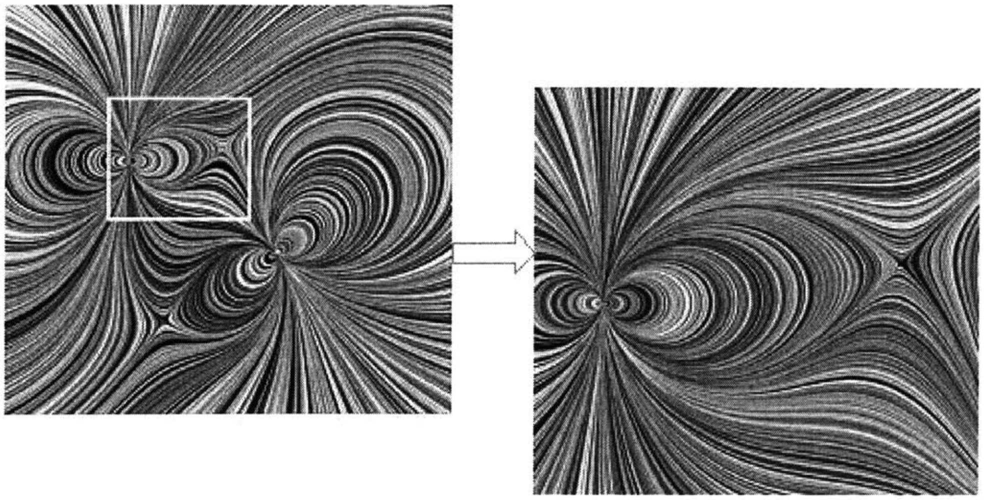


Figure 10: Illustrating zooming

3.2.4 Challenges

In designing and implementing these simulations, several challenges were overcome. They mainly stem from an understanding of physical phenomena, designing an effective educational tool and, last but not least, dealing with technical challenges associated with implementing the software.

Thorough Understanding of the Physical Phenomena

In order to write an efficient simulation that would run as desired, the physics and electromagnetism concepts had to be first thoroughly understood. Several mathematical formulas underlie the physics, and these need to be well understood to be able to find numerical solutions for them and implement them. Analog quantities and calculations are to be quantized and digitized to have accurate numerical solutions to the underlying equations.

Educational Effectiveness

We started with goals in mind of stimulating the student's interest and creating a tool that brings proper understanding of the concepts. We were therefore bound to design attractive simulations that we refined according to a few rounds of student feedback. We took into account their comments, observed their behavior, and were able to develop an effective tool that would offer an easy-to-use interface, with defined separations between controls of E&M objects and the parameters of the simulation. For example, at first, students wanted to be able to add point charges during the simulation. We therefore added that functionality to the framework. Another example that is relevant to the GUI is the ease of use. Students had difficulty finding the appropriate buttons and sliders. We agreed therefore on having all the simulation controls on the right side of the applet window. After this change, students did not complain and were more comfortable with the simulations.

The number of parameters that we can let the student change are numerous; consequently, a careful choice of parameters was studied to bring the students the needed educational value: a balance was struck between the number of controls, their functionality, and the parameters that play a role in understanding the concept presented.

Figure 9 shows us a well-balanced graphical user interface that most of the students felt comfortable dealing with.

Technical Challenges

A great amount of know-how of Java3D helped us make the most out of three-dimensional vectors in the VecMath package, which is incorporated in the Java3D package. The Sound3D package was able to provide a realistic three-dimensional surrounding sound to the student.

Earlier versions of the software were implemented using the classic AWT library of Java. This library was not well suited for graphics, especially when dealing with animations. The Swing package used in subsequent versions provided us with built-in buffered images that did not have any flickering.

The speed of the simulations was a challenge since we were dealing with students who had different computer processor speeds. Therefore, the code was optimized to minimize the number of calculations that were required in order to have approximately the same animation speed on all the computers. The agreed-upon speed was chosen to keep the students' interest high.

Furthermore, the code structure was refined over time to make new simulations easy to develop by people that would join our group, and who were not involved in the cycles we went through. In addition, the maintenance of the software was not costly, due to a good design from the start. Changing an integration scheme for the entire set of simulations would not have to be fixed in all the simulations for example, but instead in one place only. This brings us to the next chapter that explains about the structure of the software that made all this possible, and that made the creation of new simulations an easy task for non-programmers to achieve.

3.3 Value of Accomplishments

The simulations that were part of the work in TEAL had many benefits educationally and on the software practice point of view.

3.3.1 Students' Feedback

An assessment of TEAL's benefits was conducted by Yehudit Dori [11], and we mention here some of the feedback from the students.

Student A: *"This is my third time around trying to take 8.02 and I will honestly say that in order for me to grasp the concepts of 8.02 I NEEDED to "see" them in action as clearly as possible. However, I can't just understand it by following the steps of the protocol, anyone can do that, the oral explanations of what was going on helped put it all together in my mind."*

Student B (Fall 2001): *"Desktop experiments help to really grasp the conceptual background of various problems while integrating calculations and quantitative analysis. Visualizations and conceptual questions also help to explain what is really happening behind all the numbers."*

In Fall 2001, the end-term survey the question had the question: "Would you recommend this course to a fellow student?" and the answers are listed in Table 1. The majority of students indicated they would recommend the TEAL course to fellow students without any reservation.

Table 1: Student Recommendations

Answer	**Type Frequency**	**Examples**
Yes	45%	
Yes, with explanation	26%	*Yes. The interactivity makes it much more interesting and easy to learn when compared to traditional lecture style. Definitely. My impression of 8.02T is that it conveys the concepts of electricity and magnetism in a much more visual and hands-on way than the standard 8.02 class.*
Maybe, yes but...	22%	*I would recommend it to any student who is not planning on majoring in course 8, or who doesn't need to take more advanced physics classes. I feel like 8.02T was a good class for non-physics majors because it was interesting, and the pace was good.*
No	4%	
No, with explanation	3%	*No. I was looking for a more complicated physics class. I wanted more conceptual work, and in-depth approach.*

3.3.2 Students' Performance

The assessment on TEAL divided the students' proficiency into three academic levels by assigning an equal number of students to each group [11]. The students were asked conceptual questions, and we have below the scores out of 100 for the three levels of students. We can see that all levels of students improved their conceptual understanding (see Figure 11). The net gain of the low-achieving students was the highest because their starting point was the lowest, so they had the most room for improvement.

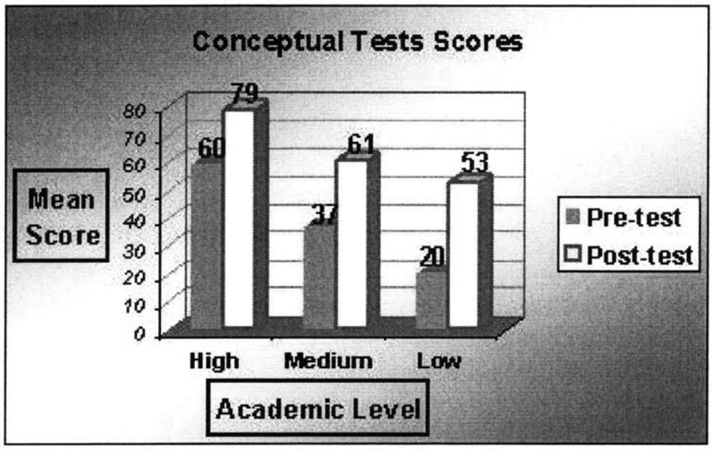


Figure 11: Conceptual Tests Scores

However, the relative improvement measure, defined as follows, was examined:

$$\langle g \rangle = \frac{\%Correct_{post-test} - \%Correct_{pre-test}}{100 - \%Correct_{pre-test}} \tag{3.2}$$

The high achievers' relative improvement was significantly higher than each of the intermediate and low achiever groups (see Table 2). Overall, all the students improved their conceptual understanding scores, but differently. This may be due to the way information was delivered to them.

Table 2: Relative Improvement of Conceptual Understanding

	N	$\langle g \rangle$
Entire Population	176	0.44±0.24
High	43	0.55
Intermediate	64	0.38
Low	69	0.42

The students received the same information and quizzes without taking into account their level of proficiency, and this may be one of the major reasons they benefited differently. We will explore this topic more in detail in Chapter 5, where we explain ways of delivering the information according to the level of proficiency of the student.

Chapter 4

Software Framework

4.1.1 Framework Motivation

TEAL requires a large number of computer simulations that collectively span the curriculum. Nevertheless, this curriculum may change over time. We cannot guarantee that the set of simulations that we create at the present time will still be useful in a few years. We therefore had to come up with a way to make creating new simulations an easy task.

Furthermore, a number of teachers will teach the class in subsequent semesters, and each has preferences for which simulations to use or not, modify existing ones, or create new ones that they feel are useful.

These reasons were the drivers to come up with a set of requirements while designing our simulations and the software framework that these simulations would be part of. The prominent requirements were:

- Interactive animations and configurable parameters: The student should be able to dynamically alter the state of the different electromagnetic objects in the simulation and even add and remove electromagnetic objects dynamically.

- Modular architecture in order to make it possible for developers to reuse software components in multiple simulations. Different modules communicate with each other through well-defined interfaces.

- Consistent and extensible method for incorporating the physics into the simulations in order for new developers to be able to add new features they find necessary. If the existing components do not provide the required functionality, new implementations can be written and plugged in, as long as they conform to the interface used to communicate with other components.

- Easy and convenient API to manage objects that have to be rendered on the screen.

- Virtual instrumentation for drawing graphs representing the variation of different parameters of the simulation. This requirement was set in order to simulate the desktop experiments and to have the same measurements available that the student is used to when doing hands-on experiments.

4.1.2 Important Components/Classes and Interfaces

The following are the main components in any simulation.

EMObject

All the physical and electromagnetic properties of objects like PointCharge, ElectricDipole, etc... are abstracted into a base class called EMObject. The different electromagnetic objects are represented by concrete implementations of this base class.

EMObjectHandler

EMObjectHandler is a class used to model the physical and electromagnetic behavior of an electromagnetic object. Different EMObjectHandlers are developed for each electromagnetic object each modeling the respective behavior of their corresponding physical object. In its simplest form, the EMObjectHandler for a PointCharge models the dynamics of a PointCharge by calculating the force acting on the PointCharge using the equation:

$$\mathbf{F} = q\,(\mathbf{E} + v \times \mathbf{B}) \qquad (3.2)$$

Where: **F** is the Lorentz force exerted on a test point charge (in Newtons), q is the charge (in Coulombs), **E** is the electric field (in Newtons/coulombs), ***v*** is the velocity (in m/sec), and **B** is the magnetic field (in Newtons/Amp).

In short, EMObjectHandler encapsulates the electromagnetic behavior of an EMObject. There could be various reasons for developing different EMObjectHandlers for the same EMObject. For example, if only one degree of freedom is active for a simulation, we want to use a handler that takes this into account instead of using a generic three degrees of freedom handler, for performance reasons. Different simulations may emphasize different physical principles, making it necessary to associate a different behavior to the EMObject. This is achieved by using a different EMObjectHandler for the EMObject in different simulations.

Force Model

This is an interface that encapsulates the necessary properties of physical forces like friction, gravity, etc… By creating new implementations of this interface, different forces can be simulated.

ImpulseModel

All the necessary properties of any object, which exerts an impulse on the EMObjects in the simulation, are encapsulated in this interface. A simple example is the boundary of the simulation area. Whenever an EMObject hits the boundary, it gets reflected back so that the object never leaves the simulation area. This is very easily modeled as an impulse being exerted on the EMObject whenever it reaches the boundary. Another place where impulses could be used is when there are collisions between EMObjects.

SimulationModel

This is the central control of the simulation. All the EMObjects that are added to the simulation register themselves with the SimulationModel. For every simulation step, the simulation model updates the different EMObjects accordingly.

Drawable

This is an interface to be implemented by all objects that have to be rendered on the screen. Whenever a new object that has to be rendered on the screen is added to the simulation, if it implements this interface, it is registered with the simulation to be rendered at the end of every simulation step.

FieldLine

Electromagnetic field lines are an excellent way to depict the variation of electric and magnetic fields as the simulation progresses. Every EMObject for which the field lines have to be drawn has a FieldLine object associated with it. Points relative to the EMObject can be specified through which the field lines will be drawn. Since the field lines have to be rendered as part of the simulation, FieldLine implements the Drawable interface.

SimulationApplet

This is the class that actually starts the simulation and acts as a container for the simulation. This class features a thread that is used to control the progress of the simulation. This thread is used to trigger each subsequent step of the simulation.

SimulationPanel

This is the panel where the entire simulation-related rendering occurs. This panel maintains a list of all the objects that need to be rendered onto the screen. At the end of every simulation step, all these objects are redrawn on the screen. This object is also in charge of generating and propagating events at the end of every simulation cycle. Objects interested in these events must register themselves with the SimulationPanel.

GraphPanel

This class acts as a panel for the different graphs to be drawn. This is also the panel where the actual graphs are displayed. Different graphs that have to be displayed register themselves with the GraphPanel. After every simulation cycle, all the graphs are updated, keeping them up-to-date with the simulation.

Graph

This class encapsulates the different properties of a graph. It provides the GraphPanel with points through which the graph are to be drawn.

SidePanel

Different simulations may have different GUI requirements. For example, some simulations may want to display the constantly varying parameter values for the different EMObjects. Other simulations may want to plot and display different graphs relevant to the simulation or add some controls (example: buttons to add and remove EMObjects). The SidePanel acts as a container for all the simulation-specific GUI components.

ConfigurationFile

The configuration file is an XML file that contains information regarding the simulation setup and initialization. At the start of a simulation, this file is parsed and the simulation environment is setup and initialized with default objects, as specified in the configuration file.

Factory Classes

Factory classes are used to parse the XML configuration file and then create simulation objects according to the properties read from the configuration file. Every simulation object whose properties can be set in the XML file induces the creation of a Factory class first, which then will create the appropriate object. Some of the important factory classes used are listed here.

- **SimulationFactory:** This class is responsible for reading the simulation's configuration file and then setting up the simulation. It is also responsible for initializing the simulation with parameters read from the configuration field. It uses various other helper classes to assist in the process.

- **EMObjectFactory:** This class is used by the SimulationFactory to create EMObjects that will be added to the simulation. Some of the other tasks that are performed by this class are: initializing the created EMObjects with default values read from the configuration file; setting the EMObjectHandler for the EMObject;

and setting the FieldLines for the EMObject created. New EMObjectFactories can be easily developed to have custom creation of EMObjects.

- **FieldLinesFactory:** This class is used by the EMObjectFactory to set the field lines that have to be drawn for the EMObjects created by the EMObjectFactory.

4.1.3 Simulation Tasks

In this section, we explain the creation of EMObjects, the rendering of different objects on the screen and how these processes fit together.

EMObjects Creation

The creation of new EMObjects is handled by the EMObjectFactories. These factories are created during the setup of the simulation. After these factories are created, they are registered with the SimulationModel for later use in the simulation. One can create new EMObjects either at initialization or dynamically during the simulation. In the first case, the XML file contains the information about the EMObject to be created. In the latter case, the user is prompted to enter values like mass, velocity and physical properties before the object is added to the simulation.

Rendering of Objects

SimulationPanel is the area where the entire simulation-related rendering occurs. The objects that are to be rendered implement the Drawable interface. The objects know how to render themselves on the screen. The SimulationPanel maintains a list of objects that are to be rendered, so when a new object which implements the Drawable interface is added to the simulation, it is registered with SimulationPanel, and the SimulationPanel renders this object on the screen.

Drawing Graphs

GraphPanel is the region where all the graphs for the simulation are drawn. Every simulation that wants to display graphs should have the GraphPanel as one of its components. Individual graphs can then register themselves with the GraphPanel.

Simulation Physics

The physics of the simulation are separate from other aspects of the simulation. The SimulationModel achieves this goal by having all the EMObjects to be simulated registered with the SimulationModel. At every simulation step, the SimulationModel computes the next state for all the registered EMObjects.

The simulations are mainly solvers for the differential equations that model the underlying physics. Depending on the complexity of the equations and the interdependence of the properties of different EMObjects, it may or may not be possible to dynamically add or remove EMObjects to and from the simulation. As an example, consider the interaction of point charges. Their behavior is purely a function of the total electric field due to all the EMObjects. The point charge only needs to know the ElectricField contribution of other EMObjects. Hence, in this simulation it is possible to add and remove point charges dynamically. In contrast, consider the interaction of two electric dipoles. To solve the equations of motion, we have chosen to rely on the conservation of linear and angular momentum, which very closely couples the two electric dipoles together. The moment a new electric dipole is added to the simulation, the equations to be solved using this approach change drastically, making it impossible to add and remove EMObjects dynamically unless certain approximations are made. There are therefore two types of SimulationModels: one that allows us to add and remove EMObjects dynamically, and one that does not let us change the number of EMObjects in the simulation.

4.1.4 Simulation Setup

The first step in any of the simulations is the setup according to the configuration file (see Figure 12). First, the SimulationPanel class for the simulation is read from the configuration file, and then an instance of it is created and initialized. Some of the properties that can be set are size of the panel and color of the background.

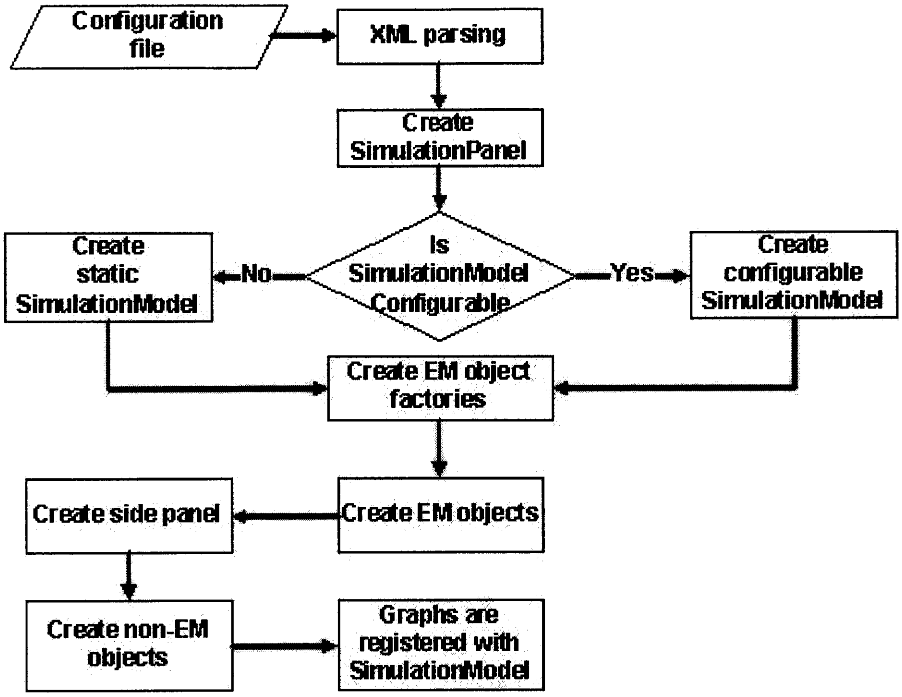


Figure 12: Simulation Setup

According to whether we want the simulation to let the user add objects during the simulation or not, we create either a static SimulationModel or a configurable one.

Next, the EMObject properties for the simulation are read from the configuration file. During this process, the different EMObjects that are allowed in the simulation are read in and appropriate EMObjectFactories are created for them. These EMObjectFactories are then registered with the SimulationModel, and they create the actual EMObjects.

After this, the controls are created inside the SidePanel. The Graphs node is processed to register the appropriate graphs with a GraphPanel, if the simulation supports graphs. This completes the initialization of the simulation.

4.1.5 Simulation Lifecycle

The SimulationApplet is the starting point of any simulation. After the simulation is ready to start, the thread is started. It periodically advances the simulation through time steps (See Figure 13). The trigger for new computations depends on time, and the lifecycle is therefore "Time Dependent". The objects that want to be updated are updated at the same time when the graphs are updated since the calculation for these values has already occurred when the EMObjects are advanced to the next step.

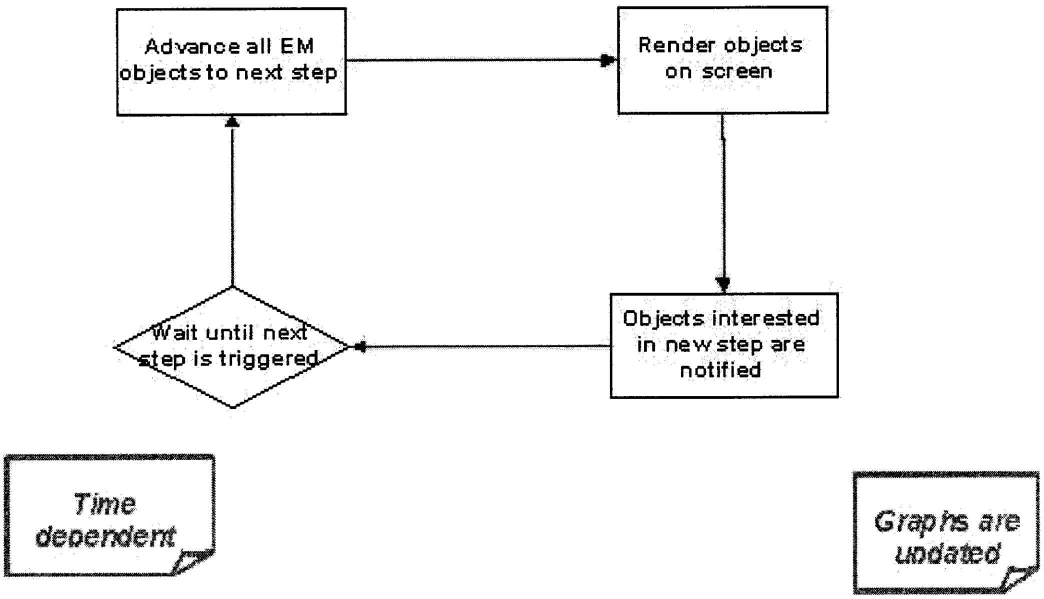


Figure 13: Simulation Lifecycle

The simulation can be controlled by the different controls added to the SidePanel. As the simulation progresses, all the different listeners for events or updates are notified when appropriate events occur. The simulation now proceeds until the user stops it or until a certain number of simulation steps have been completed.

4.2 Framework Value

4.2.1 Benefits

The software framework brought significant contribution to the developers and non-developers. The modularity of the software, and the consistent and extensible API used now make it easy for developers to add or modify the existing functionality without having to understand the existing code already implemented.

Furthermore, in order to create a new simulation based on the current framework, one only needs to write an XML file which is human readable, easy to write, and straightforward. The snippet of code below shows for example how it is possible to create a new PointCharge in just a few lines of XML code.

```
<emobject type =“PointCharge”>
<handler>teal.simulation.emworld.PointCharge</handler>
<fieldlines draw=“true”>
<symmetry x=“false” y=“false”/>
<step size=“5”/>
<point radius=“10” angle=“1.57”/>
</fieldlines>
</emobject>
```

This makes it feasible even for physics teachers to write a new simulation in minimal time without having to learn Java or understand how the software works. By looking at an example XML configuration file makes it straightforward to write a new simulation and start it right away.

4.2.2 Limitations

A few limitations to this software framework were mentioned briefly while explaining the simulations setup. Here we explain the two main limitations.

4.2.2.1 EMObject Addition Difficulty

When adding a new electromagnetic object to the simulation, this may create undesired complexities to the computations of the electric and magnetic fields and to the dynamics of the objects. We have therefore limited the functionality of adding new EMObjects instead of dealing with trying to solve very complex mathematical equations.

4.2.2.2 Textures Computation Complexity

We have seen in section 3.2.3 that different textures were used to illustrate the field lines. The main limitation is when we want to compute the field line at every point surrounding the simulation. The number of computations quickly becomes time consuming. We therefore freeze the simulation when we want to draw such field lines. The computations took on average around five seconds, and were therefore hindering a smooth continuation of the simulation.

Nevertheless, when computing only a few field lines such as in Figure 8, the simulation went on very smoothly since the number of computations was smaller, even though this simulation is in three-dimensional space. Therefore, we have a tradeoff between the speed of the computations and the level of detail desired. If zeros are not of interest to us, we can limit ourselves to a few field lines and have a real-time simulation.

Chapter 5

Future Work

The research work for this Master's thesis has a few directions that one can explore to enhance the existing framework. Some directions would be to:

- **Refine the user interface:** Asking the students where they feel uncomfortable and observing whether they are successful at finding the controls they need would enhance the graphical user interface.

- **Add drag-and-drop functionality:** The electromagnetic objects are not added to a simulation as drag-and-drop components. Instead of specifying manually in the XML file where we want the object to exist, an extension of the work would be to simplify the coupled mathematical equations in order for the drag- and-drop functionality to be efficient. As was discussed in section 4.1.3 and 4.2.2.1, adding a new object makes solving the equations that describe a simulation more complex.

- **Simplify algorithms for field lines:** The current algorithm for computing field lines calculates the direction of the field line at a point, travels a certain distance in that direction, and does the same at the new point. The points are then connected by line segments. This constrains us to having a considerable number of points in order to draw smooth field lines. Joining the points by splines would relieve us from that constraint. We can then have fewer points and fewer computations, making the simulations run faster.

The initial goal of the simulations was to make the student more active, complement the laboratory experiments, and help the students understand the concepts that the teacher is trying to convey in the classroom. We therefore want to make sure that the students understand the concepts related to the simulations that are presented to them in order to make sure that they are grasping the intent of the simulation.

The simulations require different levels of proficiency of the student. Instead of presenting the same simulations to all the students uniformly, we could make sure that the most appropriate simulation is suggested first, with the freedom for the student to explore other simulations at different levels of proficiency. We can do this by building a model of each student, with the model focused on categorizing the student's proficiency. The entity that can help us build such a model is called a 'tutoring agent'.

In this chapter, we present an area that is worth exploring in order to personalize the information presented to the students, rather than to consider that at a given time of the academic semester, all the students have a good grasp of all the previous concepts presented. The appropriate simulations can then be presented to the students for them to run.

5.1 Student Modeling Goals

In order to understand the level of proficiency of the student, we can build a student model. The goals of building a model fall under two main areas: delivering the appropriate information and adapting to the student.

5.1.1 Delivering the Appropriate Information

The learners, as mentioned above, do not all have the same grasp of the material provided in earlier sessions and simulations. They also fluctuate in their work intensity during the semester. Therefore, we cannot assume that any previous concepts explained were well understood by every student.

The simulations that we invite the students to run have different conceptual levels of difficulty that they are conveying. If the basics are not understood, more elaborate topics will not be. A useful student model would make inferences about the student's level of proficiency, and therefore suggest the appropriate simulation to run.

5.1.2 Adapting to the Student

Students show patterns of improvements throughout the semester. We can notice for example continuous improvement, a sporadic one, or other patterns. Trying to incorporate this information in the student model would help anticipate the coming improvements, and therefore allow us to present more or less complicated topics to the student.

In addition, students have different backgrounds depending on the classes they have taken previously and their personal knowledge. Having some background knowledge of the students would help us build a better model of them and start from that model rather than from scratch.

5.2 Tutoring Agents

After decades of work, programmers were able to build a computer system that beat the world chess champion. The question is whether it is possible to create an intelligent tutoring system that is better than the teacher in a given subject. Paul Goodman, director of the Institute for Strategic Development at Carnegie Mellon University, argues that this is indeed possible [15]. Tutoring agents are a special class of software agents aimed at teaching.

In order to understand software agents, let us understand their features [16]:

- One must be able to communicate with the agent. Both the human subject and the agent must speak the same language. Any agent that cannot understand what one wants to accomplish will be of little help.

- The agent must be able to act and suggest. Taking the analogy with a travel agent, a customer expects the agent to be able to book flights, hotels and rent cars. A travel advisor in contrast only advises which are the best flights, hotels and car rentals.

- An agent can do things without supervision. If a customer wants to book a complex trip through a travel agent, which requires one to be on the phone while all details were planned and finalized, it would take a considerable amount of time. Instead, the agent should be able to do its work without consuming the customer's time.

- A key ability of good agents is their experience. If a customer travels a lot, the travel agent should learn about this person's preferences. But further, the best agents learn how much, or how little, the customer wants them to do.

Although the tasks that software agents carry out seem fairly easy to visualize, the construction of the agents themselves is somewhat more problematic. Agent programs differ from most software mainly by what we can best describe as a sense of themselves as independent entities [23]. An agent should also be robust and adaptive [12], capable of learning from experience and responding to unforeseen situations with a repertoire of different methods. Finally, it should be autonomous so that it can sense the environment and act independently of it in order to be able to make progress towards its goal.

In an educational environment, a tutoring agent should observe the habits of the student, understanding her proficiency level, and suggest the information that would benefit the student most. If the agent notices a lack of understanding of fundamental concepts, it would suggest to the student to learn about them first before exploring more advanced topics.

The agent's activity can range from very active to passive, a simple observer [1]. This depends on how comfortable the student feels when dealing with the agent [20]. Some people like to work at their own pace, and explore resources without any help. An example would be the Microsoft Office "paper clip" agent that people either like or dislike.

5.3 Tutoring Agent Design

The difference in the levels of proficiency of students makes each of them a unique person to be targeted with specific information. The proposed design consists of an agent object that interacts with one student, learns from this student, and is therefore capable of building a model of that student.

In figure 14, we can see the agent as an intermediate level between the student and the student model. The student, by browsing the educational website, taking on-line quizzes, running educational simulations, provides information to the agent. The agent then processes this data, discards what is not relevant, such as spending too much time on a page because the student has left the workstation, and feeds the useful information into the student model. When the student wants to learn about a new topic, the agent analyzes the requirements for this topic to be learnt and the student's proficiency level based on the student model, and provides the customized information to the student.

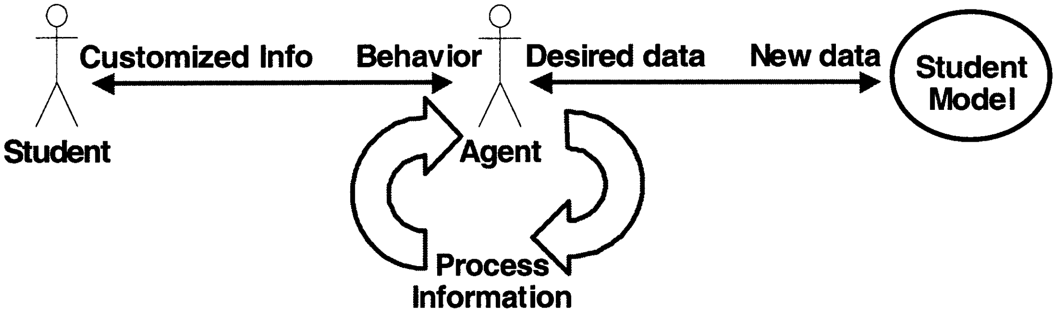


Figure 14: Student-Agent-Model Interaction

5.3.1 Design Areas

The agent keeps a record of the student every time the software is accessed. Previous information is not deleted. This allows the agent to follow the progress of the student [17]. If we are designing a website from which the simulations are delivered, a connection between the agent and a database about the student is crucial. A channel provides communication between the client, the agent, the server, and the database.

The system gives advice on which simulations to run first, or it can add some extra explanation of terms for which the student has not yet read the definition [10].

The agent has also the option to be shut down [13] . In that case, it ceases making suggestions; instead, it records the progress and the habits of the student 'silently'. These are stored, and used later on if the student changes her mind and wants the tutoring agent to interact with her again. The agent will in that case be prepared, have background information about the student, and be efficient at suggesting the appropriate simulations.

In addition, the student's level of proficiency is assessed by short quizzes and by recording the progress of the student. In the case of a website equipped with a search engine, the agent monitors words that are typed more frequently than others, and maps them into the existing database of technical words. If many occurrences of one topic occur, the agent identifies it, searches the database for related material, and presents this material to the student.

A good design to work on is collaboration between tutoring agents [19]. Since each tutoring agent is assigned to a student, they can share information on whether a particular set of simulations presented was more successful than others in the student's understanding of the concepts. This understanding can be measured by the answers to the conceptual questions in quizzes, short tests and dynamic questions that pop up during the simulation. This last measurement will be further explored in section 5.5.

5.3.2 Advantages Over Previous Work

Previous work has focused on a few areas discussed in section 5.3.1, therefore having some aspects of a fully functional agent. The advantage of our proposed approach is that we join all the proposed aspects of building a comprehensive student model, following the student's progress, making the agent privacy-enabled, and creating collaboration among different agents. Bringing all these aspects together provides a way for the student to get the information most relevant in a fast fashion. The collaboration of the tutoring agents makes the agents learn faster about 'their' students, and therefore able to deliver the proper information after a shorter period.

5.4 Student Model Design

The parameters of interest that help build the student model focus on the student's proficiency. We can measure that proficiency by observing the registration details, the quizzes results, and the student's progress.

5.4.1 Registration details

Before starting to have the agent build the student model, the learner is asked a series of questions that helps categorize the student to fit a certain proficiency level [25]. The questions focus on the background of the student, her familiarity with the material taught in class and her knowledge about a few basic concepts the class requires. For example, questions are asked about the student's mathematical background required in order to feel comfortable with some mathematical manipulations.

This questionnaire can be as trivial as a few questions that give us an idea about certain topics, or as advanced as a knowledge-based system where questions are dynamically generated, and help build a model of the student's proficiency with a certain level of confidence after each answer by the student. This questionnaire can be used as a starting point of the student's model building.

5.4.2 Quizzes

The quizzes can give us a reliable idea about the proficiency level of the student [4]. The criteria that can be observed are:

- The number of correct answers about a certain topic and the overall performance on the quizzes.

- The type of questions solved, in particular whether they were conceptual or quantitative.

- The difficulty of questions solved. This gives information on whether advanced topics are well understood.

- The speed with which questions are solved and answered is another indicator on the easiness to solve the problems, and therefore of the level of proficiency.

5.4.3 Progress

The progress of the students can be observed by comparing the existing model with current answers to quizzes [9]. This helps get a refined model of the students due to changes in their behavior. Giving a greater weight to the more recent findings, and decreasing previous findings weights with the passage of time can achieve this refined student model.

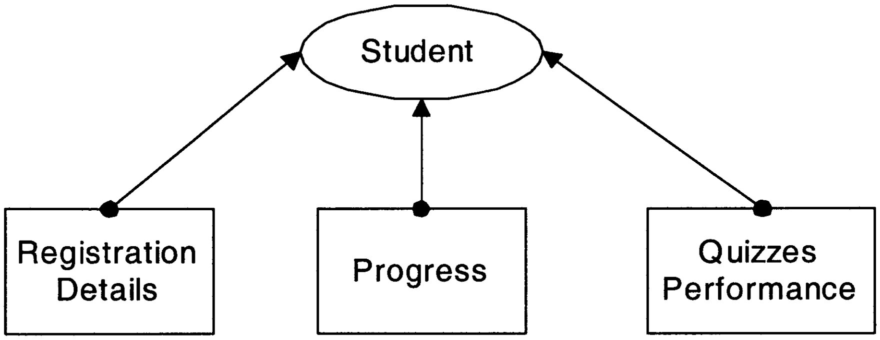


Figure 15: Student Model Parameters

Figure 15 shows the elements that contribute to the student model. Registration details are asked at the beginning of the semester in order to get information on the background and the level of the student. Progress measures the speed with which the student advances during the semester. Performance in quizzes is an important measure that helps understand the weaknesses of the student and therefore of the topics that should be further explored.

5.5 Example

We worked on a preliminary approach in that area by designing a mechanism that can ask questions during a running simulation. While the student is running the simulation, conceptual questions are asked in a dynamic fashion taking into account the student's previous answers, and therefore tailoring the next question's difficulty level to the level of proficiency of the user (see example incorporated in Figure 8).

5.5.1 Dynamic Questions Design

We implemented a basic design of adaptation to the students. It consists of a dynamic questionnaire that takes into account the students' previous answers in order to ask subsequent questions. This design was implemented to work alongside the simulations that we explored in Chapter 3. While the students are running the Java applets, they tend to 'play' with the applets as if they were games, without thinking about the concepts that are presented. One way to make the students active is to make them answer conceptual questions, which requires some deeper thinking. During the course of the animation, questions will pop-up randomly, and will tackle a certain aspect of the physics behind the current applet. This will make the student remember the concepts, which will be concretized in the animation.

The animation will be stopped when the question is asked. A set of answers will be given to choose from, and they can try all the answers out until they get the right one. Then, they will be invited to modify any parameters in the animation to concretize their answers.

The answers given to the question will be recorded, and an answer will be counted incorrect or correct depending on the first answer given. Three levels of questions will be prepared:

- Easy (E)

- Medium (M)
- Hard (H)

The path sequence of the questions would enable each student to tackle a different set of questions according to the individual grasp of the material and the concepts.

The first question starts with a medium level, and according to the answer (right or wrong), the next question is asked. To go to another level of questions, the student has to get two consecutive wrong or right answers. The path structure is the following:

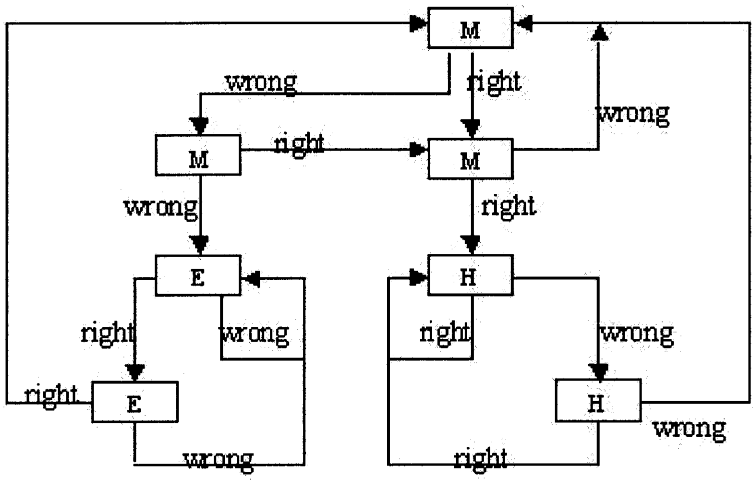


Figure 16: Path of Dynamic Questions

5.5.2 Examples of Conceptual Questions

We mentioned conceptual questions in different parts of the thesis. These are some examples of how the conceptual questions would look like. Note that they are qualitative in nature and drive the student to think about the material explained in class.

Question 1: The magnetic field lines shown are distorted when the electric charge is near them. This happens because:

1. The field lines of the magnet get caught on the charge when it moves past them.
2. The magnetic field lines shown represent the total field and the magnetic field of the charge is largest close to the charge.
3. The magnetic field lines of the magnet are attracted to the electric charge because of Coulomb's Law.

Question 2: If you double the speed of the charge in the x-direction or y-direction, what will happen to the radius of the small circle around which the charge rapidly moves?

1. It will increase
2. It will decrease
3. It will stay the same.

Question 3: The charge moves in small circles around the field, but it also moves slowly around in the equatorial plane of the magnet. Why does this happen?

1. When the charge moves closer to (further from) the magnet the field strength goes up (down) and the small circular orbit becomes smaller (larger) in radius. The combination of these two effects causes a drift in longitude about the magnet.
2. When the charge moves closer to (further from) the magnet the field strength goes up (down) and the small circular orbit becomes larger (smaller) in radius. The combination of these two effects causes a drift in longitude about the magnet.
3. When the charge moves closer to (further from) the magnet the speed of the charge goes up (down). The combination of these two effects causes a drift in longitude about the magnet.

5.6 Conclusion

This thesis presented a framework for electromagnetism simulations, the benefits these simulations bring to conceptual understanding and their practicality and appeal for the students. We hope the simulations were beneficial to the students, and that they will be able to still remember electromagnetism concepts in a few years.

We also presented a direction of future research in which a tutoring agent presents the appropriate simulations according to the student's proficiency level, instead of following the curriculum of the class without consideration of the student's understanding of previous basic concepts.

References

[1] André, E., Rist, T., and Müller, J., Integrating reactive and scripted behaviors in life-like presentation agents. In K.P. Sycara and M. Wooldridge (Eds.), *Proceedings of the Second Int'l Conf. on Autonomous Agents*, pp. 261-268, 1998.

[2] Athabasca University: Internet undergraduate courses. URL at http://www.athabascau.ca/main/procrs.htm.

[3] Beaty, W.J., "Popular Culture, K-6 Textbooks and "Science myths"", 1996.

[4] Beck, J. and Woolf, B., "Using a Learning Agent with a Student Model", *Intelligent Tutoring Systems*, 6-15, 1998.

[5] Belcher, J., "Project Proposal of TEAL", URL: http://caes.mit.edu/research/teal/.

[6] Belcher, J., "Studio Physics at MIT", *Physics News Letter Article*, 2001.

[7] Belcher, J., Olbert, S. and Bessette, M., "The Physics Of Using Field Line Animation In The Teaching Off Electromagnetism", *American Association Of Physics Teachers Meeting* January, 1999.

[8] Bigelow, J.D., "Developing in Internet section of a management course: Transporting learning premises across media", *World Conference of the Web Society Proceedings, AACE*, pp. 13-20, 1996.

[9] Brusilovsky, P., "Methods and Techniques of Adaptive Hypermedia", *User Modeling and User-Adapted Interaction* 6, 87-129, 1996.

[10] De Bra, P.M.E., "Teaching hypertext and hypermedia through the Web", *World Conference of the Web Society Proceedings, AACE,* 130-135, 1996.

[11] Dori, Y. and Belcher, J., "Assessing the Effect of TEAL Project on Students' Understanding of Physics Concepts", http://web.mit.edu/jbelcher/www/iCampus/TEALAssessmentFeb2002.pdf, not yet published.

[12] Eliot, C., and Woolf, B.P., "An adaptive student centered curriculum for an intelligent training system", *User Modeling and User-Adapted Interaction*, 5:67-86, 1995.

[13] Foner, L., "Clustering and Information Sharing in an Ecology of Cooperating Agents", *Proceedings of 1995 Conference on Computers, Freedom, and Privacy*, March 1995.

[14] Frost, R. and Cutkosky, M. R., "Design for Manufacturability via Agent Interaction," paper no. 96-DETC/DFM-1302, *Proc. 1996 ASME Computers in Engineering Conf.,* ASME, New York, pp. 1-8, 1996.

[15] Goodman, P., "Technology Enhanced Learning: Opportunities for Change", August 2001.

[16] Hendler, J., "Is There an Intelligent Agent in Your Future?" *Nature © Macmillan*, March 1999.

[17] Johnson, W L & Shaw, E., "Using Agents to Overcome Deficiencies in Web-Based Courseware", *IJCAI-97 Animated Interface Agents Workshop* 1997.

[18] Johnson, W. L., Rickel, J., Stiles, R., and Munro A., "Integrating pedagogical agents into virtual environments", *Presence* 7(5), 1998.

[19] Lashkari, Y., Metral, M., Maes, P., "Collaborative Interface Agents", *AAAI 1994,* 444-449, 1994.

[20] Lester, J.C., Converse, S.A., Kahler, S.E., Barlow, S.T., Stone, B.A., and Bhogal, R.S., "The persona effect: Affective impact of animated pedagogical agents", *Proceedings of CHI '97*, pp. 359-366. ACM Press, 1997.

[21] Lieberman, H., Van Dyke, N.H. and Vivacqua A., "Let's Browse: A Collaborative Web Browsing Agent," *IUI'99*, 1999.

[22] Linturi, R., "Network Society has new tools for learning, but it also redefines what learning means", Enabling network-based learning, *Enable99*, 1999.

[23] Maes, P., "Intelligent Software: Programs That Can Act Independently Will Ease the Burdens that Computers Put on People". *Scientific American* 273 (3): 84-86, 1995.

[24] McDermott, L., "Research in Physics Education", *The American Physical Society*, 1998.

[25] Mitrovic, A., "INSTRUCT: Modeling Students by Asking Questions", *User Modeling and User-Adapted Interaction*, Vol. 6, No. 4, pp. 273-302, 1996.

[26] Nakhleh, M.B. and Mitchell, R.C., "Concept learning versus problem solving", *Journal of Chemical Education*, 70(3), 190-192, 1993.

[27] Niemzcick, S., "Using Markov Models to Classify Usage Patterns in Courseware", not yet published.

[28] Nurrenbern, S. C. and Pickering, M., "Concept learning versus problem solving: Is there a difference?" *Journal of Chemical Education*, 64(6), 508 – 510, 1987.

[29] Pickering, M., "Further studies on concept learning versus problem solving: Is there a difference?" *Journal of Chemical Education*, 67, 254-255, 1990.

[30] Rakel: Rakel's online textbook of medicine: http://www.usc.edu/hsc/medicine/family_med/textbook

[31] Rhodes, B. and Maes, P., "Just-in-time information retrieval agents", *IBM Systems Journal special issue on the MIT Media Laboratory*, Vol. 39, Nos. 3 and 4, pp. 685-704, 2000.

[32] Ritter, S., du Boulay, B.. and Mizoguchi, R.., "Communication, cooperation, and competition among multiple tutor agents", *Artificial Intelligence in Education*, 31-38, 1997.

[33] Shaw, E., Johnson, W. E., and Ganeshan, R., "Pedagogical Agents on the Web". *Proceedings of the AI-ED Workshop on Pedagogical Agents*, pp. 48-55, Kobe, Japan, 1997.

[34] Yehudit Dori, John Belcher, "Assessing the Technology Enabled Active Learning Project", not yet published.