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# *The MIT TEAL Simulations and Visualizations in Electromagnetism*

Abstract: The Technology Enabled Active Learning (TEAL) Project at MIT has developed a range of 3D visualizations and simulations to foster intuition about electromagnetic fields and phenomena. In this talk we discuss the software approaches used to create these simulations, including Java 3D applets for interactive visualization, passive animations created with 3ds max, and the Dynamic Line Integral Convolution (DLIC) method for constructing time dependent representations of the electromagnetic field at close to the resolution of the computer display (Sundquist, 2003).

## Introduction

Over the last eight years, the MIT Physics Department has introduced major changes in the way that introductory physics is taught at the Institute, through the Technology Enhanced Active Learning (TEAL) Project (see Figure 1). The TEAL Project was under Departmental guidance and was an outgrowth of initiatives sponsored by the MIT Council on Educational Technology. The courses involved are the various flavors of 8.01 (mechanics) and 8.02 (electricity and magnetism). The new format is a merger of lecture, recitations, and hands-on laboratory experience into a technologically and collaboratively rich experience for incoming freshmen, and is described and assessed in Dori and Belcher (2005). We are not the first to teach in this format. "Studio Physics" loosely denotes a format instituted in 1994 at Rennesaeler Polytechnic Institute by Jack Wilson. This pedagogy has been modified and elaborated on at a number of other universities, notably in the North Carolina State University *Scale-Up* program. We have expanded on the work of others by adding a component centered on active and passive visualizations of electromagnetic phenomena, supported in part by grants from NSF. In this paper we will discuss those visualizations, which are open source under a liberal license (see http://web.mit.edu/viz/soft/ ). You can find the visualizations discussed in this paper and many others by going to the link below.

http://web.mit.edu/8.02t/www/802TEAL3D/teal_tour.htm

Our contention is that using visualizations helps students in understanding electromagnetic fields because in this way we can make the normally unseen seen. Moreover, when animated, the dynamical effects of fields can be understood by analogy with rubber bands and strings. The insight connecting field shape to dynamics is due to Faraday, the father of the concept of fields. Making the fields visible and animated and using the analogy of rubber bands and strings gives insight into the reasons that fields have the effects that they do.

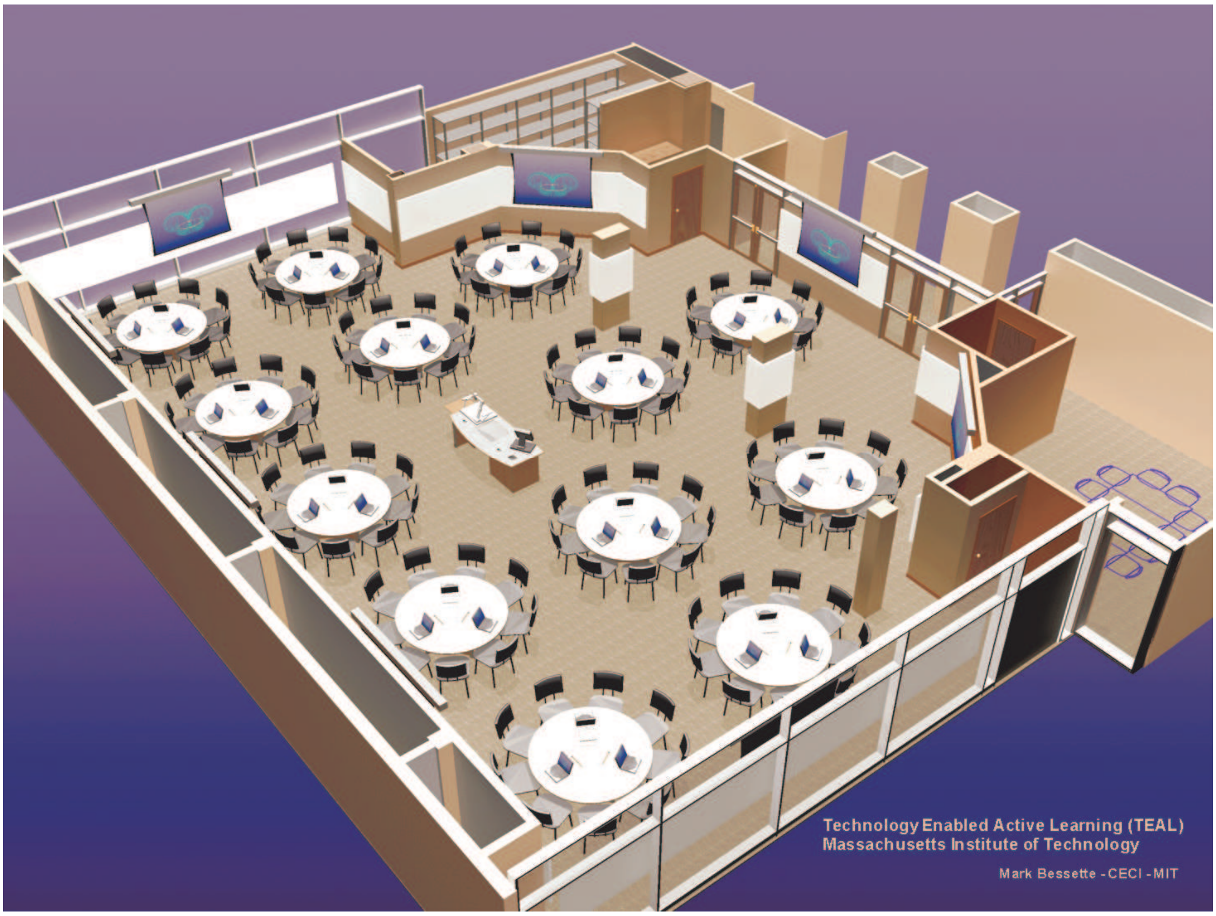


Figure 1: The D'Arbeloff Active Learning Classroom at MIT.

Dynamic Line Integral Convolution (DLIC)

We first discuss a novel technique for visualizing fields which was developed at MIT in the course of the TEAL Project. The visualization of time dependent vector fields is a central problem in scientific visualization. There have been two advances in computer graphics since 1993 which have fundamentally changed the way that vector fields can be visualized in two dimensions. The first of these was the introduction of the Line Integral Convolution (LIC) method for showing the structure of vector fields at a resolution near that of the display, using textures generated by convolving the vector field with a grid of pixels of random brightness [Cabral and Leedom, 1993]. The second was the introduction of a method for the animation of a LIC using a second velocity field to evolve the underlying grid of random pixels used to generate the LIC [Sundquist, 2003]. This latter method, called Dynamic Line Integral Convolution (DLIC), produces an animated sequence of images of the first field such that the time dependence of that field is evident from frame to frame by the inter-frame coherence in the LIC texture pattern.

In a paper to be submitted to the American Journal of Physics, Belcher and Koleci [2007] discuss at a heuristic level how these two algorithms work, and why they are effective learning tools for electromagnetism. The motivation for this paper is to make the LIC and DLIC methods and their educational impact more widely known to the physics community.

The LIC method uses correlations in a texture pattern to show the spatial structure of a vector field. To explain heuristically how the LIC algorithm works, we first consider a constant field. Given a square array of *NxN* pixels of random brightness, we want to generate a textured array of the same dimension, where the texture pattern indicates the direction of the constant field, to within a sign. To do this, we process our *NxN* random array pixel by pixel to produce the new texture array, as follows. At any pixel 1 (see Figure 2), we average the brightness of the pixels along a line centered on pixel 1 and in the direction of the local field, for n pixels, $n << N$, and put this value in our new texture array at the same location as pixel 1 was in the initial array.

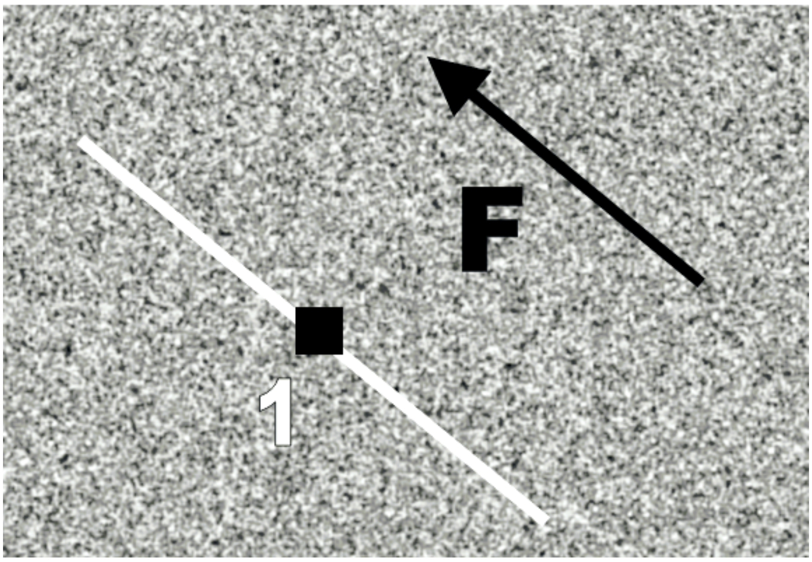


Figure 2: To produce a LIC image for the constant field **F**, we take each pixel in a random pattern, for example, pixel 1, and average the brightness of the n pixels lying along a line parallel to F centered on pixel 1, as indicated by the while line.

We now move to an adjacent new pixel and repeat this same process again (Figure 3). If we move parallel to the field to get to the new pixel, say pixel 2 in Figure 3, then the resulting average that we obtain at pixel 2 is almost the same as the average for pixel 1, because most of the pixels are the same. So the calculated brightness at pixel 2 is highly correlated with the brightness of pixel 1. If on the other hand we move perpendicular to the field to get to the new pixel, say pixel 3 in Figure 3, the resulting average is not correlated at all with the average at pixel 1, because none of the pixels whose brightness is being averaged are the same. This process produces a new array which has correlations in brightness (or darkness) along the field direction. Another way of saying this is that we have produced a texture pattern where the streaks in the texture are parallel to the field direction, as shown in Figure 4.

Now consider the LIC procedure for a field that varies in space. If we simply follow the procedure described above and average the brightness of pixels along straight lines in space, where the direction of the straight line is determined by the local direction of the field at (for example) pixel 1, we would get a visual representation of the field but it would be inaccurate, because we would be assuming that the local streamline can be reasonably approximated by a straight line along the entire n pixel averaging length. For locations where the local radius of curvature of a given field line is large compared to the n pixel length of the averaging line, this assumption is valid. However, if the local radius of curvature is comparable to or smaller than the length of n pixels along the averaging line, this assumption is no longer valid, and correlations in the texture pattern so generated will no longer show the details of structure of the field at this scale.

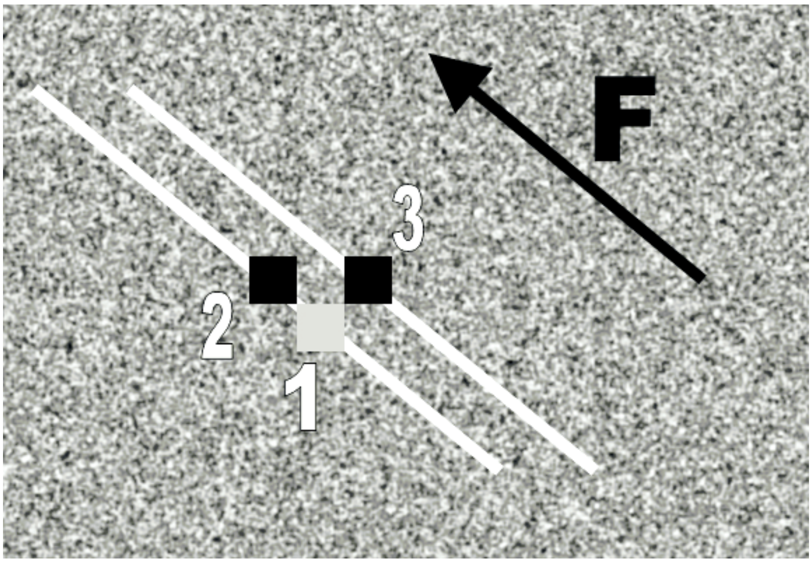


Figure 3: We calculate the brightness at pixels 2 and 3 by averaging over the brightness of the n pixels lying along the lines parallel to **F** centered on pixels 2 and 3, as indicated by the two white lines.

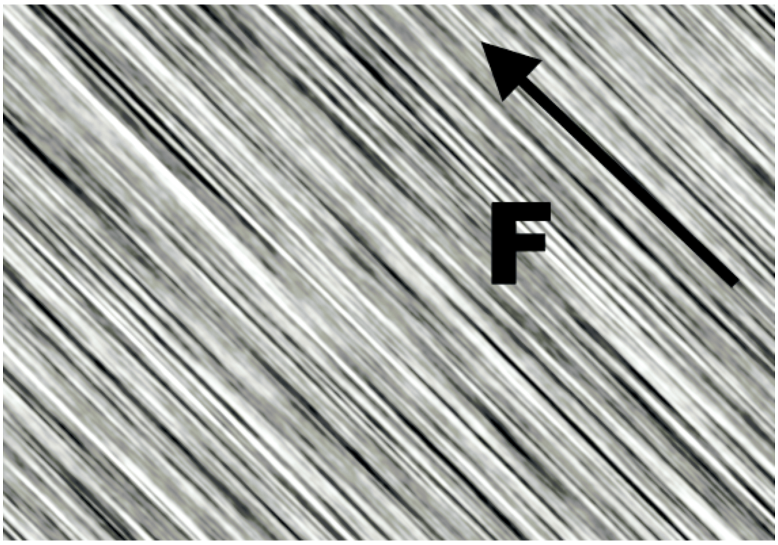


Figure 4: A LIC of a constant field, constructed in the manner described in the text.

To correct for this, the Cabral and Leedom LIC algorithm averages over n pixels along a line in space, but the averaging line is no longer a straight line, but the field line that passes through the point at which we are calculating the new texture value, for example pixel 1. That is, the texture pattern is convolved with the field structure along a line in space determined by the field lines, thus the name line integral convolution. This procedure retains the property that movement along the local field direction exhibits a high correlation in brightness values, but movement perpendicular to that direction exhibits little correlation, and this is true even in regions of high curvature.

Figure 5 shows a DLIC of the vector function $\mathbf{F}(x,y)=\sin^2(x)\,\hat{\mathbf{i}}-\cos^2(y)\,\hat{\mathbf{j}}$. Even relatively simple functions such as this can produce complex visual images. One of the attractions of this method of visualization is that it starts with a random pattern and then superimposes order on that pattern, but the underlying random character still persists in the image. This makes the image much less "sterile" than most computer generated images.

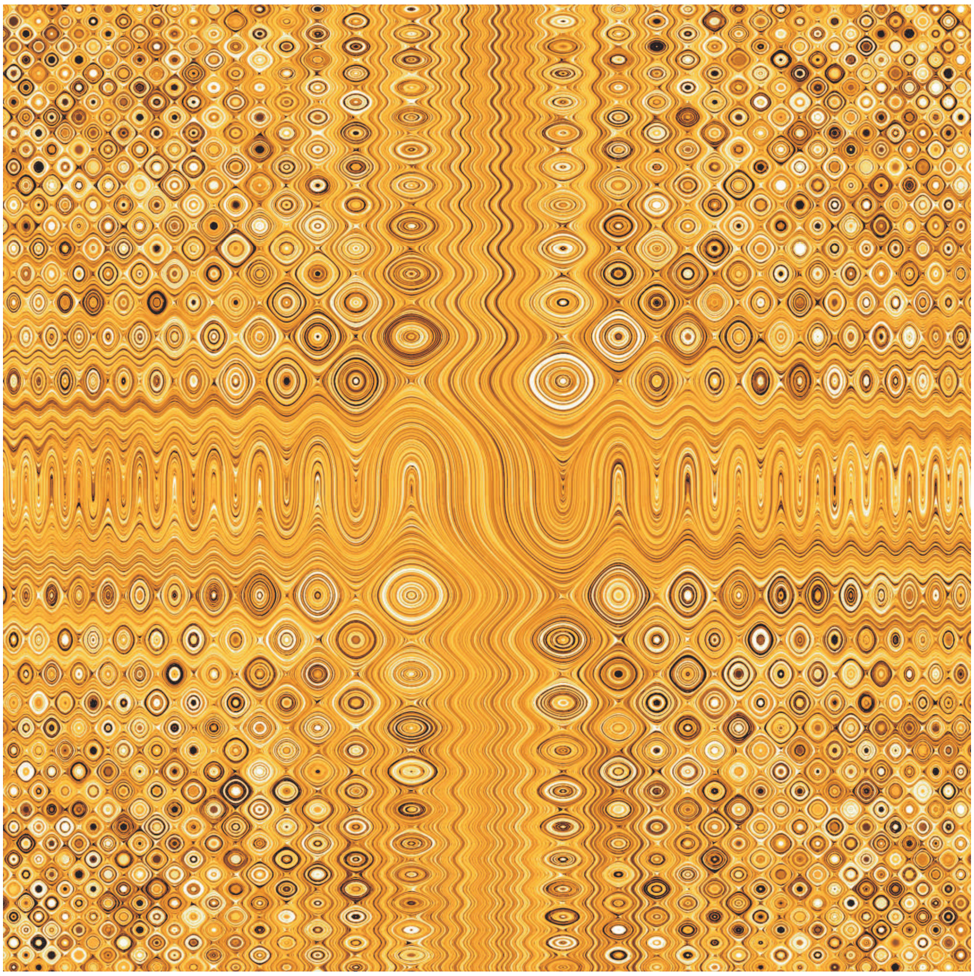

Figure 5. A LIC of a simple vector field.

Dynamic Line Integral Convolution (DLIC) extends the LIC algorithm to time-dependent fields. The vector field $\mathbf{F}(\boldsymbol{x},t)$ is allowed to vary arbitrarily over time, with the motion of its field lines described by a second velocity vector field, $\mathbf{D}(\boldsymbol{x},t)$. That is, at any time $t$ the field line of $\mathbf{F}(\boldsymbol{x},t)$ passing through $\boldsymbol{x}$ at time $t$ is displaced in space at time $t + dt$ to a new position $\boldsymbol{x} + \mathbf{D}(\boldsymbol{x},t)\,dt$.

The DLIC algorithm originated by Sundquist produces an animation by evolving the random texture input used in LIC in a manner prescribed by the velocity field **D**. That is, if $T(\boldsymbol{x},t)$ represents our random texture map, we evolve it with time according to

$$T\left(\mathbf{x},t+dt\right)=T\left(\mathbf{x}-\mathbf{D}\left(\mathbf{x},t\right)dt,t\right) \tag{1}$$

Intuitively, since the particles that produce the input texture advect according to the motion field **D**, the LIC convolution of the field lines of **F** with the texture from one frame to the next samples the same part of the texture pattern, since the texture particles and field lines move in concert. Thus, the streaks in the LIC of **F** appear to move from one frame to the next according to the motion field **D**. Each output image in the sequence will individually have the same properties as a static LIC rendering, but successive frames will have an inter-frame coherence that depicts the prescribed motion of the field lines.

We now give an example of the use of this technique in electromagnetism where the construction of a DLIC is of physical interest. A conducting ring with mass *m*, radius *a*, resistance *R* and self-inductance *L* is located on the *z*-axis above a stationary permanent magnet with a magnetic dipole moment vector that is vertical. The normal to the ring is along the vertical *z*-axis, and the ring is constrained to move along that axis. The ring is released from rest at $t = 0$, and falls under gravity toward the conducting ring. Eddy currents arise in the ring because of the changing magnetic flux as the magnet falls toward the ring, and the sense of these currents will be such as to slow the ring. The overall field configuration of the total magnetic field will be as shown in Figure 6. The solution for the motion of the ring involves the solution to three coupled ordinary differential equations for the *z*-coordinate of the falling ring, the current in the ring, and the *z*-coordinate of the velocity of the falling ring.

According to the scheme introduced by Belcher and Olbert [2003] the magnetic field lines in this case should evolve with a velocity field given by

$$\mathbf{D} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} \tag{2}$$

The physical interpretation of this velocity field is that it represents the guiding center motion of a set of low energy electric monopoles initially arranged along any given magnetic field line, as those monopoles drift in the time-dependent electric and magnetic fields. Using this definition has the advantage that the motion in the DLIC is locally in the direction of the electromagnetic energy flow vector.

Figure 6 shows one frame of a DLIC for the magnetic field of a conducting ring falling toward a stationary magnetic dipole. Regions of high curvature occur near the two zeroes just above the ring. The zeroes are distinguishable by the tilted X-like structure near them. For comparison we also draw four field lines in the figure. The full animation can be found on the web in links at the URL given above.

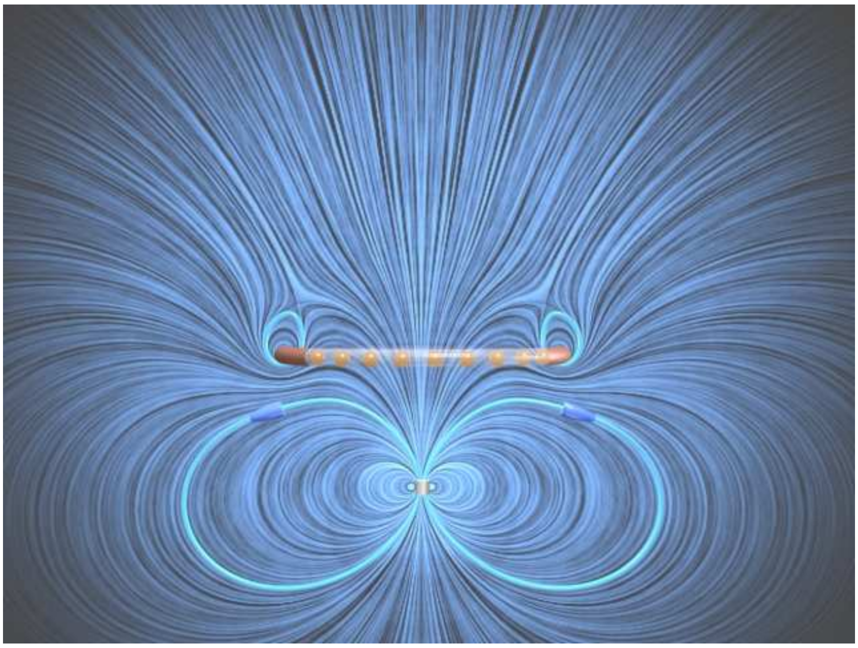

Figure 6: One frame of a DLIC for a Faraday's Law visualization. A conducting ring falls toward a stationary magnetic dipole, and eddy currents are induced in the ring.

## Java 3D Interactive Applications

In addition to many passive DLICs of electromagnetic phenomena similar to that in Figure 6, we have also developed a set of Java 3D interactive applets. Figure 7 is an example of one of these applications, modeled on the same physics as discussed for Figure 6. In this application the student has a choice of displaying the time dependent magnetic field in one of three different ways: (1) a field line representation, where a discrete set of curves are drawn which are everywhere parallel to the local field direction; (2) a vector field grid representation, where a set of icons on a fixed grid of spatial coordinates represents the field direction at a given grid point; (3) a LIC representation. The first two of these are computationally fast, and can be displayed in real time as the ring falls toward the magnet. The third is computationally slow, and essentially the student chooses a frame for which to draw the LIC and stops the real time execution of the application to display the LIC. In addition, the student can vary in real time various parameters associated with the physics of the problem, e.g. the resistance of the ring or the magnitude of the dipole moment of the magnet.

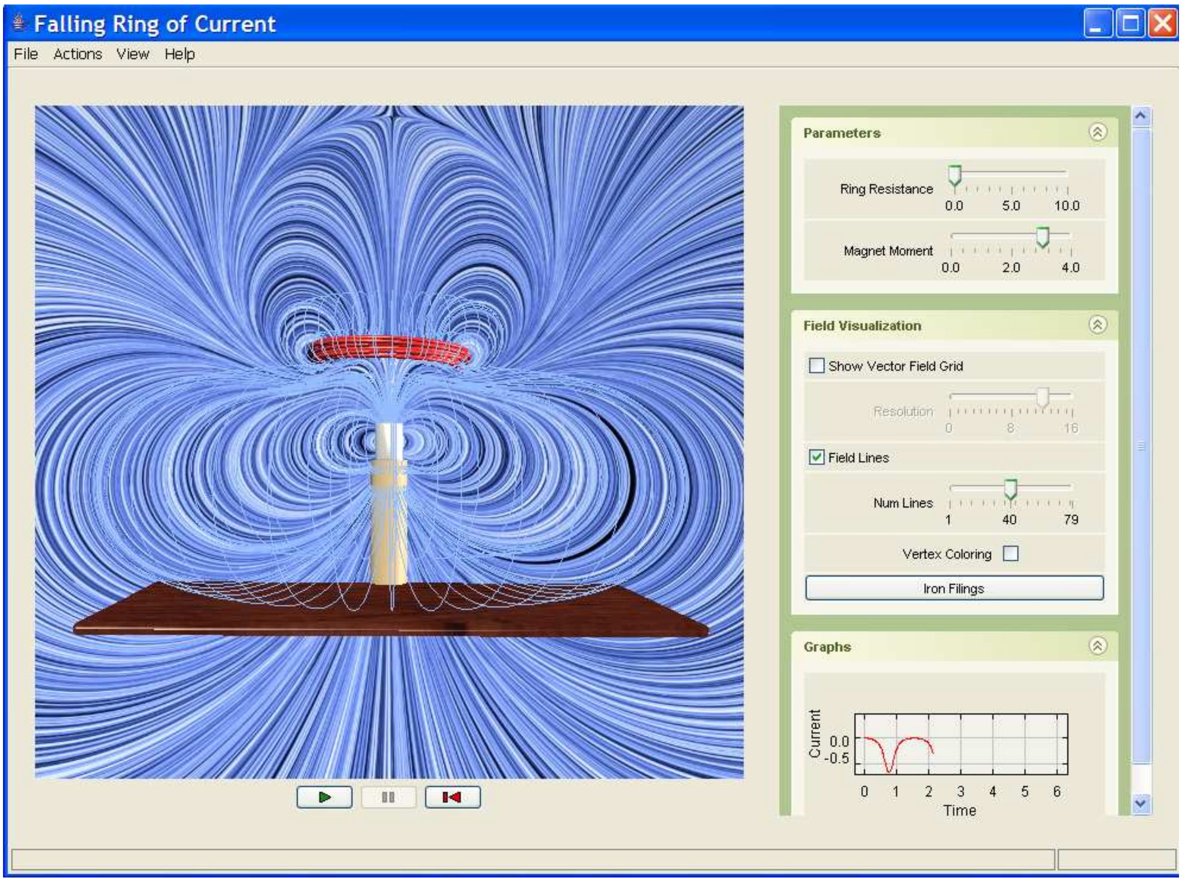


Figure 7: An interactive Java 3D application for the falling ring.

## Pedagogical Usefulness

Visualizations and simulations are powerful tools for illustrating physical processes and making sense of the relationship between different physical quantities. Via visualizations, scenarios that are otherwise too difficult to be carried out experimentally can be explored, and processes that are not normally visible can be presented in a variety of ways. In addition to helping students grasp and understand abstract concepts, visualizations often excite learning interest with their visual richness.

Although visualizations are stimulating, they often do not correspond to what students would observe in the real world. How important is the gap between the simulated situation and the real world counterpart? More importantly, do students truly understand what they see, and do they take away from the visualizations and simulations the message that the designers intended to convey? The central questions that we are currently investigating are: (1) how effective are visualizations in conveying key ideas; and (2) what are the essential elements of a visualization and the way in which it is delivered that maximize its effectiveness. Our firm belief is that our visualizations need to be embedded in a "Guided Inquiry" framework, and that simply providing accessibility and the opportunity for exploration is not sufficient for effective student learning. The real question at this point is how to embed visualizations effectively in curricula material.

## Acknowledgements

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