

Applets for Interactive Exploration of Electric and Magnetic Fields

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Abstract

The World-Wide Web and Java-equipped browsers enable us to create interactive hypermedia class materials and to distribute them easily to a studio class. One use of Java applets is for the visualization and exploration of electric and magnetic fields.

1 Background and Rationale

The World-Wide Web, with the addition of the Java language, provides a simple and portable way to create and distribute interactive hypermedia learning material. This combination of technologies has many advantages.

It had previously been the case that in any computerized classroom, such as a studio classroom[1], each computer had its own copy of the courseware. Any revision to this courseware required the changed files to be propagated to every computer that would use them. This made it inconvenient to keep all copies of the courseware up to date. The World-Wide Web provides a way to remedy this problem.[2, 3] Only one copy of a file needs to exist, and it may in fact be kept on a server far from the classroom where it is used. This way, when a file is revised, only the copy on the server must be replaced. The students view the class materials using a Web browser such as Netscape Communicator or Microsoft Internet Explorer, both of which are freely available.

Unfortunately, the Web brings its own problems to the classroom. One of these is the lack of support for mathematical equations. The HyperText Markup Language (HTML), the standard markup language used on the Web, has no built-in support for mathematics.[4] This can be solved, though not entirely satisfactorily, by rendering equations into bitmap images, by using an

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equation-drawing applet like WebEQ[5], or by using a “plug-in” like IBM’s techexplorer[6]. Simple expressions can even be typeset in the HTML with an italic font and images of the Greek characters. None of these is a good, portable, long-term solution, but they do work, and there is hope that in the reasonably near future, a usable and comprehensive standard will be adopted.

The other, more profound limitation has been the inability of a web page to be interactive. It is not particularly useful for a student to merely be able to read text on a computer; the textbook is much more nearly complete and easier to refer to. The computer should offer *interactivity*, but until 1997, HTML and the Web browsers that used it allowed only text (that is, *hypertext*) and images.

Other multimedia presentation formats (like ToolBook, in which CUPLE is written) allow the author to include in a page a simulation or non-static illustration that the student can interact with. Typically, the student can move objects or change settings and watch the change in the physical system being modeled. This interactive behavior was not possible in documents written in HTML, although there was a limited ability to show animation.

The advent of the Java language[7], which is platform-independent and freely available for education, added interactivity to the page, while still using the advantages of the World-Wide Web.[8] The HTML standard, and most browsers now, allow an author to embed into a web page a type of Java program called an *applet*. An applet runs under tighter security conditions than a free-standing program (an *application*), but otherwise, it can do anything that an application can do. In particular, an applet can serve as an interactive illustration in a web page of courseware. The tighter security usually has little or no effect on interactive illustrations. I have developed several such applets for Physics II, Rensselaer’s first- or second-year course in electricity and magnetism, and they are available from the Project Links[9] website at <http://links.math.rpi.edu/devmodules/electromagnetism/>. The applets are also suitable for a higher-level electricity and magnetism class, and those applets concerned with fields can also be used in a class on vector calculus.

2 Field Explorers

The Electric and Magnetic Field Explorer applets (“Field Explorers” or “field applets”) used in Rensselaer’s Physics II course illustrate the advantages of the HTML/Java approach. The Field Explorers are a set of two similar applets that let a student investigate properties of electric and magnetic fields. The screen represents a plane in space with field sources embedded in or running through it. Often the sources are infinitely long and perpendicular to the plane, and are seen as cross sections, as represented in figure 1. At present the sources cannot be moved or reconfigured. The sources are configured in the HTML file, as is the behavior of the applet as a whole.

Figure 2 is an example of a field applet embedded in the HTML text of a web page. All applets begin with an `<applet>` tag with several attributes. The `codebase` gives the location on the server of the Java class bytecode files or of the

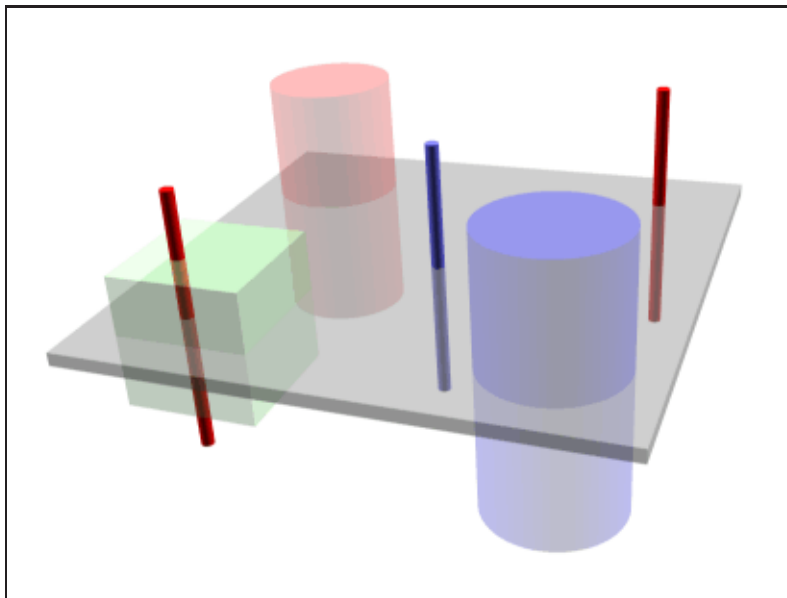


Figure 1: Field Explorer’s infinitely long sources

Zip or Jar (Java archive) file containing the class files. The `code` gives the name of the applet class; in this case the applet is an Electric Field Explorer applet (see section 2), the Java class’s name is *links.applet.fieldapplet.ElectricFieldApplet*, and it will be in *links/applet/fieldapplet/ElectricFieldApplet.class* in the archive file or in the code base directory. The `archive` gives the name of the archive file that contains the class files and images. An archive is not necessary, but it is desirable because there are over two dozen class files used by this applet. The `height` and `width` are the pixel size of the applet on the page.

The `<param>` tags are used to pass parameter strings to the applet. Their interpretations are applet-specific; the parameters for the Field Explorer applet will be explained below in section 2. The text that is not part of any tag (“...Complain vociferously...”) will be printed by a browser that does not understand the `<applet>` tag. Such browsers are useless for these modules (and indeed all of Project Links) but they are no longer common. The text will be ignored by a browser that can run the applet. Finally, the applet text concludes with the ending `</applet>` tag.

Each source is an object which, when given a point in the plane, can calculate its own contribution to the field at that point, as well as the field’s potential, if any, and its curl and divergence. The applet then finds the net field (or curl, ...) at a point by adding up all the sources’ contributions. The sources on lines 5–9 of figure 2 are sources of electric field; line 2 says that this is an electric field applet. There may be up to ten sources (`source0` through `source9`) listed. This restriction to ten sources is arbitrary but not particularly onerous

```

1  <applet codebase="../../../code/"
    Where the Java class files are located
2  code="links.applet.fieldapplet.ElectricFieldApplet.class"
    The name of the applet class
3  archive="fieldapplet.jar"
    The name of an archive containing all the class files
4  width="400" height="300">
    The size of the applet on the HTML page
5  <param name="source0" value="Linecharge, 50, 230, 1">
    This source is a line charge at  $x = 50$ ,  $y = 230$  with  $\lambda = 1$ .
6  <param name="source1" value="Linecharge, 350, 50, 2">
7  <param name="source2" value="Linecharge, 200, 150, -1">
8  <param name="source3" value="CylinderCharge, 50, 50, 2, 40">
    This source is a uniformly charged cylinder,
    centered at  $x = 50$ ,  $y = 50$ , with  $\lambda = 2$  and  $R = 40$ .
9  <param name="source4" value="CylinderCharge, 350, 230, -1, 40">
10 <param name="showsources" value="true">
    Should the applet display the field sources?
11 <param name="loops" value="true">
    Should the student be able to perform loop integrals?
12 <param name="surfaces" value="true">
    Should the student be able to perform surface integrals?
13 <param name="curlmeter" value="true">
    Should the student be able to use the curl meter?
14 <param name="divmeter" value="true">
    Should the student be able to use the divergence meter?
15 <param name="fieldlines" value="true">
    Should the student be able to draw field lines?
16 <param name="equipotentials" value="true">
    Should the student be able to draw equipotential lines?
17 Your browser doesn't support Java. Complain vociferously.
    This will be printed if the browser doesn't support Java.
18 </applet>

```

Figure 2: HTML text for a field applet.

in practice. The first “word” in the **value** of a **source** gives the type of source (see tables 1 and 2 for lists of available sources), and the succeeding numbers are interpreted as follows: the first two numbers are the x and y position of the source or its center, measured in pixels rightward and downward from the upper left corner. The third number is the “strength” of the source. This may be interpreted as the total charge, the charge per unit length, or the current—whichever is appropriate. The fourth number, if present, is the radius of an extended cylindrical or spherical source. There are a few “oddball” sources available but not listed that don’t conform to this scheme, but only one is ever used in these modules. Sources are drawn onscreen as specified in tables 1 and 2 unless the applet parameter **showsources** (figure 2, line 10) is set to **false**. A source will not appear if it is located outside the applet’s screen area. It is still being “drawn”, though, but outside the applet space, and still has an associated field.

Sources use a red/blue color scheme to indicate polarity; red indicates “positive” for static electric charges and “out of the page” for currents and Faraday solenoids, and blue represents “negative” or “into the page”. A Faraday solenoid is dark red (maroon) if its magnetic flux is increasing out of the page, and dark blue otherwise.

Source type	Description	Drawn as
PointCharge	Point charge	Ball image
SphereCharge	Uniformly charged sphere	Circle
ShellCharge	Uniformly charged spherical shell	Circle
LineCharge	Infinite uniform line of charge	+ or –
CylinderCharge	Infinite uniformly charged cylinder	Circle
FaradaySolenoid	Solenoid with time-varying field	Dark Circle

Table 1: Sources of electric field

Source type	Description	Drawn as
ThinWire	Infinite, zero-width current	\odot or \otimes
FatWire	Non-zero-width current	Circle
DisplacementCurrent	Capacitor with time-varying field	Light Circle


Table 2: Sources of magnetic field

Whenever the mouse pointer is moved, the applet prints the pointer’s location in the status line of the browser. This position, like the positions of sources, is measured in pixels from the upper left corner. Many of the questions in the exercises ask for the location of some feature such as a source or a place where the field vanishes. There is no way (or need) to disable this behavior.

The electric and magnetic field explorers have a common visual behavior because they are both derived from a common parent. As the student moves

the mouse pointer around, the applet draws an arrow based at the pointer's location; the arrow points in the direction of the field and its length is indicative of the field's strength. The length is not proportional to the field's strength, but it is at least a monotonic function of the strength. (See figure 3.) The infinitely-long sources have fields whose strengths decrease with distance as $1/r$, and the arrow behaves well if its length is proportional to $\arctan \sqrt{f}$, where f is the field strength. When all the sources are point charges, and the field contributions decrease as $1/r^2$, the arrow's length should be proportional to $\arctan \sqrt[3]{f}$.

The student can explore field properties by pressing the mouse buttons, perhaps simultaneously with the keyboard modifier keys (Shift, Control, Alt, and Meta) and by pressing some of the keyboard letter keys. The field applets are capable of using every possible mouse button/modifier combination, but fortunately for the student, no assignment has more than a few related combinations enabled. In addition, a help page lists and explains all of the combinations. Most of the applets' capabilities can be enabled and disabled with parameters in the HTML code. In this way, an applet can be customized so that the students cannot accidentally do anything that they are not yet ready to understand.

When the student presses and holds the proper combination of mouse buttons and modifier keys (Control-Right), the field arrow is replaced by a "curlmeter" which measures and prints the curl of the field¹. Releasing the button changes the indicator back to the arrow. In every case, the curl vector is either zero or is directed into or out of the applet plane. The curl is therefore described by a scalar which is positive for curl directed out of the page and negative for curl directed into the page. The curlmeter looks like this:  and represents four identical positive charges at the ends of a cross connected to a torsion spring. One arm of the cross is its pointer and is thicker than the other arms and also colored red. The greater the field's curl, the more the curlmeter is deflected from its unrotated position. The amount of deflection is a logarithmic function of the curl, suitably constrained, so that when the curl is zero the curlmeter points to twelve o'clock, and when the curl is large the curlmeter is "pinned" at six o'clock. The direction of the deflection is clockwise for negative curl and counterclockwise for positive curl. The illustration (eleven o'clock) thus corresponds to a small positive curl. Use of the curlmeter is not allowed if the applet parameter `curlmeter` (figure 2, line 13) is set to `false`.

There is also a divergence meter (Shift-Right), which looks like a black square with the word "div" in it. The divergence meter's sides bow inward and change

¹Different machines have mice with different numbers of buttons. A Macintosh mouse has one button, a PC mouse has two, and a Unix workstation mouse has three. Java handles this problem by pretending that every mouse has just one single button; for two- and three-button mice, it's the left button. Java interprets the right button, if any, as the single button plus the Meta key (Macintosh: Command key), and the middle button, if any, as the single button plus the Alt key (Macintosh: Option key). This allows an underequipped student to simulate a three-button mouse. By judiciously combining modifier keys and mouse buttons, the student can make the applet think he has simultaneously pressed both the right and middle buttons. In this case, the applet will then perform both actions. In this paper, I will assume a three-button mouse and refer to the left, middle, and right buttons. In a description of a button combination, the capitalized word "Left" means "the left button" and similarly.

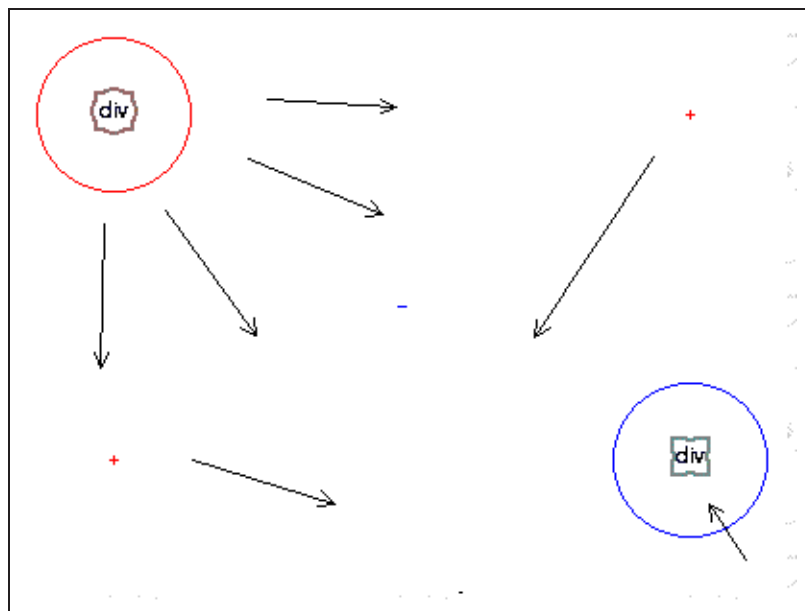


Figure 3: Field arrows and divergence meters. The applet contains infinite lines of charge and uniformly-charged infinite cylinders.

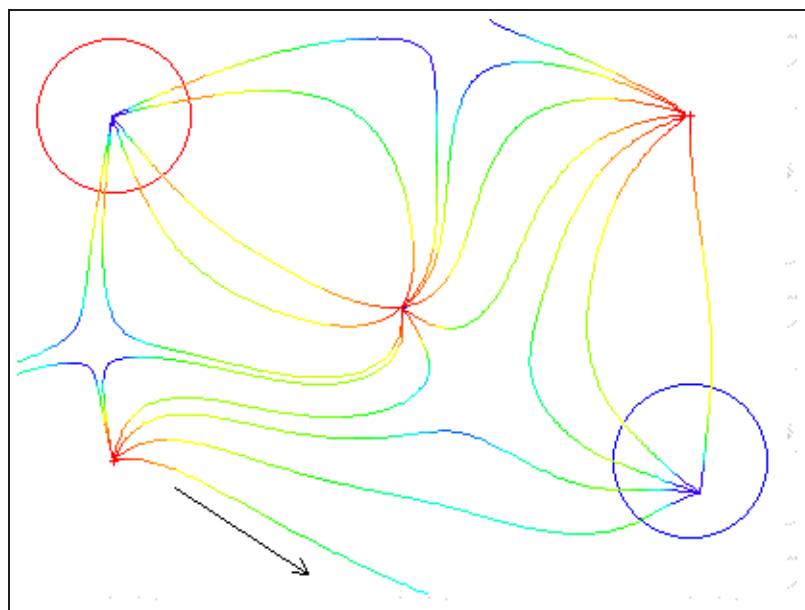



Figure 4: Electric field lines. The charge distribution is as in figure 3. The hue of a point on a field line indicates the strength of the electric field there.

color towards cyan for negative divergence and bow outward and redden for positive divergence: . (See figure 3.) The divergence meter is disabled if the parameter `divmeter` (figure 2, line 14) is set to `false`.

The indicators (field arrow, curlmeter, divergence meter) can be “dropped” to remain at a point by substituting the middle button for the right button. A field arrow is dropped with Shift-Control-Middle; for consistency, then, the combination Shift-Control-Right performs the useless action of “changing” the indicator from a field arrow to a field arrow. It is also possible to drop an array of indicators on a lattice covering the whole applet. The array-dropping actions are triggered by keyboard keys (A, C, and D respectively) rather than mouse buttons because the location of the mouse pointer is irrelevant. The collection of indicators, as well as anything else drawn on the screen, is erased with E, backspace, or delete.

A Right mouse click with no Shift or Control draws the field line through the mouse pointer’s location. Field lines are drawn with a rainbow of colors to indicate the field strength along the line. Red represents a strong field; yellow, green, and cyan represent progressively weaker fields, and the weakest fields are colored blue. (See figure 4.) The color-choosing algorithm is similar to the one that determines the length of the field arrow. The student can then move the pointer along the field line and see that the field arrow is always tangent to the field line. The applet calculates a field line by using a Runge-Kutta method to take short steps along the direction of the field. The step size of 0.3 pixel is large enough to allow the calculation to finish in a reasonably short time, but small enough not to accumulate inaccuracy. The calculation terminates when the line reaches a point on the applet boundary, a point where the field is zero, or a point within one pixel of its starting point. Field lines will not be drawn if the applet parameter `fieldlines` (figure 2, line 15) is set to `false`.

The applet calculates equipotential lines (Middle click) in a similar way. The equipotentials, when defined, are the integral curves of the “potential stream function”, which is always orthogonal to the electric field. The applet finds some multiple of the stream function by rotating the field by 90°; the magnitude may not be correct, but it is not relevant, because only the direction matters. The equipotentials are drawn in cyan, as shown in figure 5. Equipotentials will not be drawn if the applet parameter `equipotentials` (figure 2, line 16) is set to `false` or if the field does not admit a scalar potential.

The applet can also illustrate Maxwell’s laws in integral form for a two-dimensional source. By clicking and dragging the left mouse button, the student can create a circle (Control key) or a rectangle (no Control key) which will be either a closed loop (no Shift key) or the “footprint” of a closed surface whose height is one unit (Shift key). So, Control-Shift-Left drag creates a circular surface. Mnemonically, Shift is for surface and Control is for circle. If the student has chosen a loop, the applet will then calculate the contour integral of the field counterclockwise around the loop, and if the student has chosen a surface, the applet will calculate the two-dimensional analog of the surface integral of the field through the loop. In both cases the integral is calculated

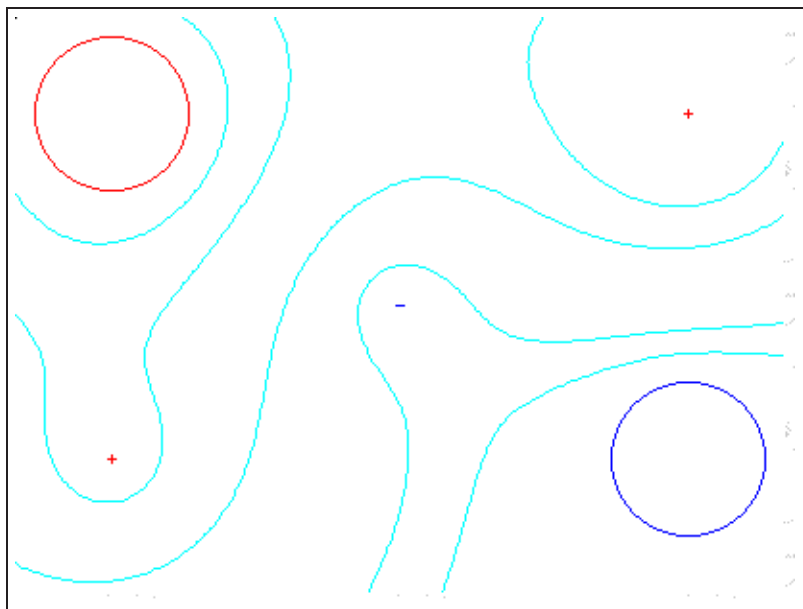


Figure 5: Equipotential lines for the same charge distribution as in figures 3 and 4.

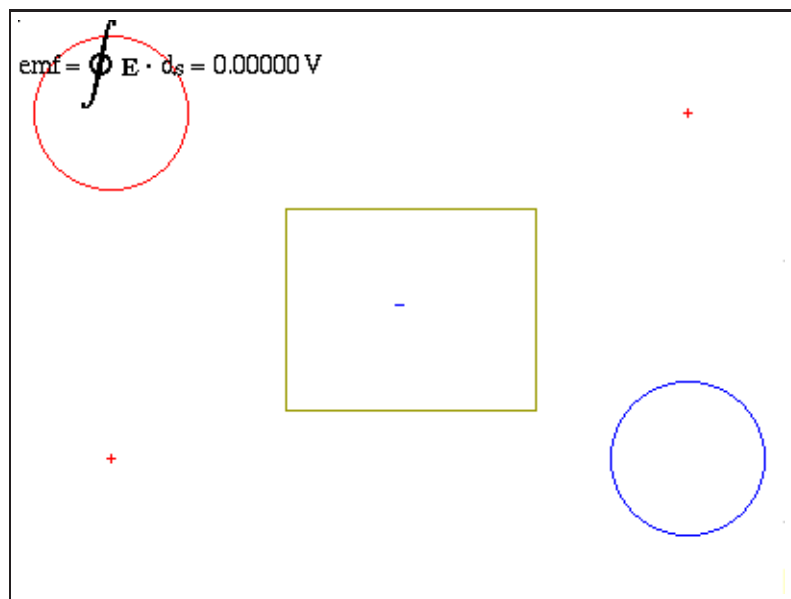


Figure 6: Circulation of the electric field (Faraday's Law).

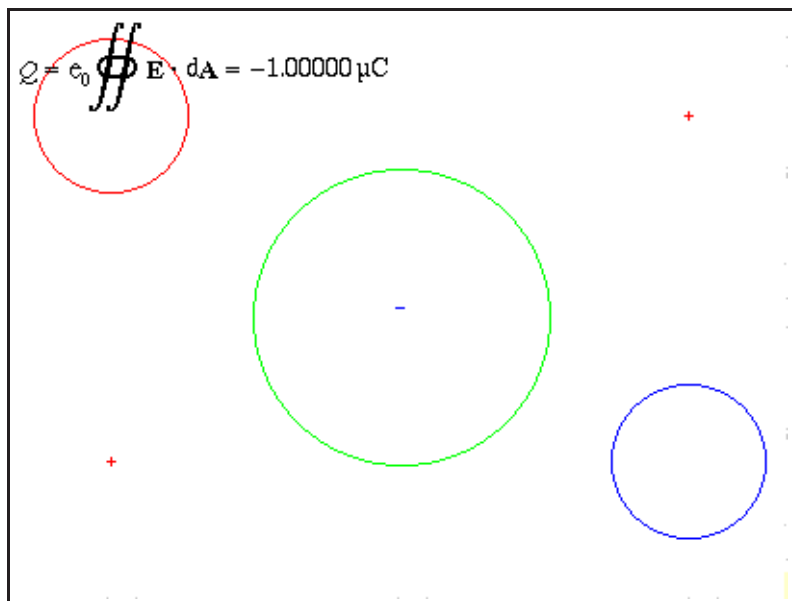


Figure 7: Flux of the electric field (Gauss's Law).

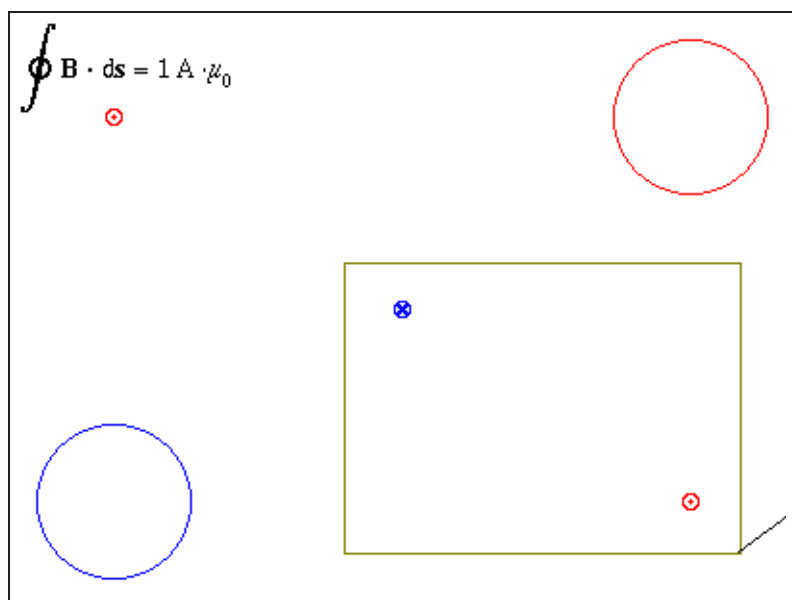


Figure 8: Circulation of the magnetic field (Ampere's Law). Here the sources are thin and thick wires.

using Simpson’s rule with a step size of half a pixel. The applet then displays the resulting circulation or flux with an appropriate integral sign and equation in the upper left corner. See figures 6, 7, and 8. Loops and surfaces are enabled or disabled with the `loops` and `surfaces` parameters. (See figure 2, lines 11 and 12.)

3 Class Use

The web pages developed by Project Links[9] at Rensselaer are organized into “modules”; a module contains several pages about a single topic, and represents about one class’s worth of instructional material. Many of the pages contain applets in addition to explanatory text and questions to guide the student. The Electricity and Magnetism modules roughly correspond in scope, but certainly not in depth, to the chapters of a textbook.

3.1 Electric Field Module

I will use the Electric Field module as an illustration of the use of the field applets. The applets are used for both simple examples and complicated exercises.

3.1.1 Examples

After the students have had a mini-lecture and some discussion of electric field, they work through a Web page of examples. This features a series of field applets with simple charge configurations. These examples should help the student realize that

- The electric field generally becomes weaker as the distance from the sources increases.
- Electric field lines terminate at charges or go off to infinity.
- In symmetrical situations, there are points where the field’s direction is particularly easy to determine.

The examples begin with single charges (figure 9). The student should observe that the field and the field lines are radial. Other simple examples have two or four point charges.

3.1.2 Hidden Charges Exercise

Once the students are familiar with the behavior of the electric field, they are asked to perform an in-class exercise on finding hidden charges. The students work in groups of about four, and they are asked to find the location, sign, and (qualitatively) relative magnitudes of some invisible point charges in the applet space. Here the applet parameters `showsources` and `fieldlines` are set

to **false**; allowing visible field lines would make it much too easy to find the charges. It is still possible to drop field arrows.

The students are asked to hand in answers to the following questions:

1. How many charges are in the rectangular area? (*Two.*)
2. Give the coordinates and sign of each charge. (*Both positive.*)
3. At how many points in the area is the electric field equal to zero? (*One. Look for the smallest arrows.*)
4. Give the coordinates of those points where $\mathbf{E} = 0$.
5. Rank the charges according to their charges, most positive first. (The location of the points where $\mathbf{E} = 0$ should help here.) (*The charge in the lower right has the largest magnitude.*)

These questions direct the students' attention to specific features of the field and guide them to discover properties such as the principle of superposition.

3.2 Other Modules

The field applets also appear in modules on electric potential, Gauss's Law, Faraday's Law, magnetic fields, Ampere's Law, and Maxwell's Equations. In every case, the applets are configured appropriately for the subject matter; for example, in the Gauss's Law module, some of the sources are uniformly charged cylinders, and the students can use the divergence meter and draw (two-dimensional) Gaussian surfaces, and in the Faraday's Law module, the sources are solenoids with linearly-time-varying magnetic flux, and the students can use the curlmeter and draw loops.

Other electromagnetism modules contain applets that model capacitors and resistors, graph the voltages in *LRC* circuits, and illustrate some principles of optics. The modules are available at

<http://links.math.rpi.edu/devmodules/electromagnetism/>.

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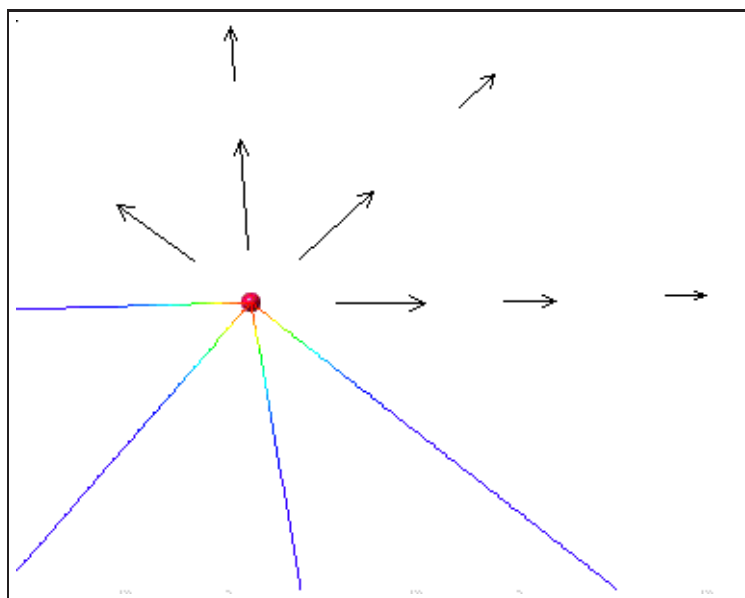


Figure 9: Single positive charge.

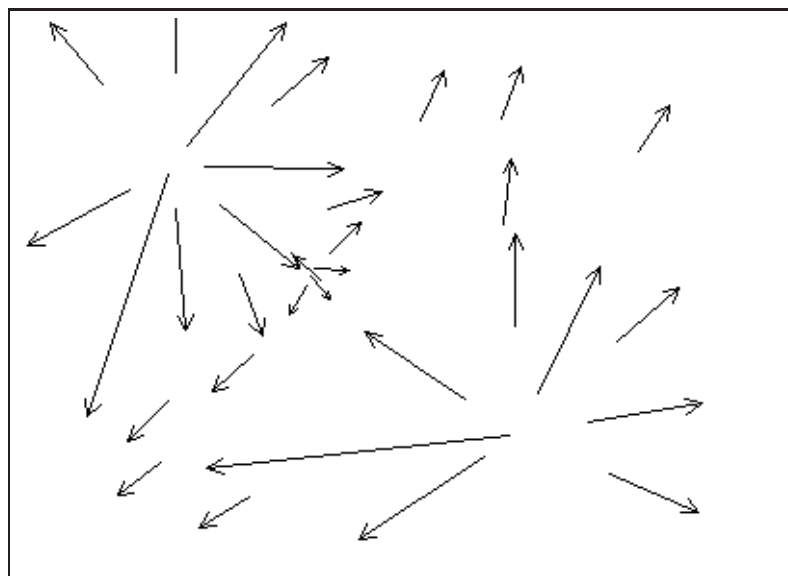


Figure 10: Hidden charges exposed.

References

- [1] Jack M. Wilson, “The CUPLE Physics Studio”, *Physics Teacher* **32**, 518–523 (1994).
- [2] Gregor M. Novak and Evelyn T. Patterson, “World Wide Web Technology As a New Teaching And Learning Environment”, *International Journal of Modern Physics C* **8**, 19-39 (1997).
- [3] G. D. Bothun and S. D. Kevan, “Networked Physics in Undergraduate Instruction”, *Computers in Physics* **10**, 318–324 (1996).
- [4] The World-Wide Web Consortium has issued a recommendation on an HTML extension called MathML. See <http://www.w3.org/Math/> (current on April 2, 1999).
- [5] WebEQ from Geometry Technologies, Inc. is available at <http://www.webeq.com/> (current on April 2, 1999).
- [6] The IBM techexplorer website is <http://www.software.ibm.com/techexplorer> (current on April 2, 1999).
- [7] Among the many good references about the Java language are *Java in a Nutshell* by David Flanagan (Cambridge, MA: O’Reilly and Associates, 1997) and Sun’s Java web site at <http://java.sun.com>.
- [8] Wolfgang Christian, “Physlets: Java Programming for Physics Education”, *AAPT Announcer* **27**, 90 (1997). Contributed talk to the AAPT Summer 1997 Meeting. The online version is at <http://WebPhysics.Davidson.Edu/WebTalks/JavaTalk/Welcome.htm> (current on April 2, 1999).
- [9] William E. Boyce, John B. Brunski, Michael M. Chen, Kevin Craig, James A. Fairweather, Joseph W. Haus, Joseph Porter, and William L. Siegmman, “Interactive Multimedia Modules in Mathematics, Engineering, and Science”, *Computers in Physics* **11**, 151–156 (1997). An introduction to [Project Links](#).