

Instructional Software for Visualizing Optical Phenomena

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Abstract

We describe a multidisciplinary effort for creating interactive 3D graphical modules for visualizing optical phenomena. These modules are designed for use in an upper-level undergraduate course. The modules are developed in Open Inventor, which allows them to run under both Unix and Windows. The work is significant in that it applies contemporary interactive 3D visualization techniques to instructional courseware, which represents a considerable advance compared to the current state of the practice.

1. Introduction

Optics developed as a scientific field primarily through the experiments of Isaac Newton (who considered light as particles) and Christiaan Huygens (who considered light as waves) in the late seventeenth century. The theoretical basis of classical optics was developed in the nineteenth century by Thomas Young, Augustin Fresnel, and James Clerk Maxwell. More recently, the invention of the laser has promoted research in optics since the 1960's. Fiber optics and quantum optics also drive optics research in the 1990's. Improving understanding of optics is consequently a significant educational goal.

Each year at colleges and universities nationwide, some 10,000 students take a course on optics, typically through a department of physics. The method of instruction has changed very little in the past 40 years, and many of the textbook illustrations have remained essentially the same over this time. In particular, the illustrations rely heavily on line drawings and 2D graphs. Certain key concepts in the study of optics possess fundamentally 3D aspects, which are typically demonstrated in a classroom laboratory. The lab equipment may include light sources, apertures, lenses, and polarizing filters. The 2-dimensional diagrams in a textbook may illustrate invisible but important features of light (such as the electric field vector at a given point as a function of time), whereas the laboratory reveals 3-dimensional visible features of light (like focus and interference that vary according to position).

There are several existing computer-assisted instructional modules designed to support the teaching of optics by visualizing optical phenomena. These systems are primarily 2D and use line drawings similar to the ones found in traditional textbooks. Some of these software systems are semi-interactive: a student types in different values for various parameters, and the system recalculates the display in response. Because these systems are designed for personal computers, interactive 3D visualization has not yet been a significant design-objective.

At 19 institutions nationwide that conduct research in the field of physics education, we have found 12 software systems that are currently being designed for or used in physics classes. Only one of them ("CUPS," <http://physics.gmu.edu/~cups>, [CUPS]) includes modules specifically designed to teach waves and optics. The remaining systems target other aspects of physics, especially mechanics. Several publishers offer commercial products designed

for instruction in optics, with prices ranging from US\$ 20 to US\$ 70. The Optical Society of America offers instructional software for the Apple Macintosh [OSA]. These systems (some of which are illustrated in Figure 1) have already been deployed at high schools, colleges, and universities and have experienced success even without the benefit of 3D visualization.

2. The Optics Project

The Optics Project serves to amplify lessons learned in class by providing interactive demonstrations both inside and outside of class. This section gives an overview of the project and describes the workings of two of the modules.

2.1 Overview of TOP

In 1994, work first began on The Optics Project (TOP) at Mississippi State University. This multidisciplinary effort has involved students and faculty from three Departments (Physics and Astronomy, Computer Science, and Electrical and Computer Engineering), constructing stand-alone modules to complement a standard undergraduate course in optics. The first software modules were implemented using OpenGL; Open Inventor has now become our graphics library of choice for developing new modules and updating old ones.

Each module is designed to be (1) interactive, (2) dynamic whenever animation is appropriate, and (3) three-dimensional. We identified eight fundamental topics that would lend themselves to interactive 3D visualization. These are summarized below.

- 1 Wave Simulation** - Plane waves, cylindrical waves, and spherical waves
- 2 Reflection and Refraction** - Vectorial treatment of monochromatic plane waves incident upon a planar interface. Total internal reflection, critical angle, Brewster's angle.
- 3 Geometrical Optics** - Systems of thin lenses. Stops apertures and pupils. Optical instruments.
- 4 Polarization** - Different kinds of polarization, action of polarization elements.
- 5 Interference** - Two slits, N slits, Michelson interferometer, and thin film interference.
- 6 Fraunhofer Diffraction** - Single slit, multiple slit, diffraction grating, circular aperture, Rayleigh resolution criterion.
- 7 Fresnel Diffraction** - Single slit, transition to Fraunhofer, circular aperture, double slit.
- 8 Coherence** - Temporal and spatial coherence.

The modules allow a student to visualize effects that either (1) cannot easily be made visible or (2) cannot be controlled very well in a physical laboratory experiment. As an example of an important but invisible feature of optics, consider the dynamic evolution of the electric field vector as it reflects off a surface or transmits through a medium. The vector can easily be made visible in a graphics system

Properties of lenses

Lenses are characterized by their focal length. The focal length is given by the lens maker's formula:

$$\frac{1}{f}(\lambda) = [n(\lambda) - 1] \left[\frac{1}{R_1} - \frac{1}{R_2} \right]$$
 where f is the focal length, n is refractive index, and R_1 and R_2 are the radii of curvature of the two surfaces of the lens.

Illustration of lens properties:

object at: f produces image at: infinity
 infinity f
 $2f$ $2f$

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Wave Interference

Please use Netscape Navigator 2.02 or Microsoft Internet Explorer 3.0 !
 This applet can't run on Netscape Navigator 3.0.

Animation of Interference Pattern Formed by Two Points Sources

Figure 1. Examples of current educational software that supports the teaching of optics. Top left: Static HTML document with images (Brian M. Tissue, www.scimedia.com/chem-ed/optics/lenses.htm). Top right: Macintosh application with 2D line drawings [RONEN]. Bottom left: PC application with 2D graphs [CUPS]. Bottom right: Java animation of pre-computed height field (Sadahisa Kamikawa, www.bekkoame.or.jp/~kamikawa/wave/wave_e.htm).

by drawing an arrow. As an example of an important parameter to control in a laboratory exercise, consider the effect of changing the angle of incidence of a beam of light on the reflected beam's intensity. The student adjusts a mirror to the proper angle, re-aligns the beam, and then locks down the mirror mount. Fifteen seconds may elapse during the change of this single parameter (one physicist said that such tedium "turned me into a theoretical physicist instead of an experimental one!"). By comparison, selecting a 3D widget to adjust the angle in a graphical version of the exercise is almost instant.

2.2 Fresnel Diffraction Module

Module 7, "Fresnel Diffraction," is used to visualize the behavior of light that passes through an aperture. Figure 4 shows a sample image produced by the module. Fresnel diffraction occurs when a beam of light passes through an aperture, exhibiting patterns of varying intensity when it illuminates an observation screen on the other side. The beam's behavior far beyond the aperture is called Fraunhofer diffraction; the behavior near to the aperture is called Fresnel diffraction. Monochromatic light that passes through a small circular aperture creates concentric bright and dark rings on a flat plane placed slightly beyond the aperture. Monochromatic light passing through a thin rectangular slit produces a series of bright

and dark bands. In the case of a vertical slit, the light's intensity $I(x, y, \lambda, w)$ is a scalar function of the distance y from the slit, the spanwise distance x , the wavelength λ , and the width w of the slit.

While a user interactively varies the parameters, the module recalculates and displays the surface of $I(x, y, \lambda, w)$ defined implicitly by $\lambda = \text{constant}$ and $w = \text{constant}$ and parametrically by distances x and y : a surface in (x, y, I) space. We display the aperture as a 3D object; a 3D widget allows the user to modify the width-parameter directly (with immediate visual feedback). Another 3D widget controls the wavelength of the monochromatic light source; the color of the intensity function provides visual feedback.

By combining the Fresnel and Fraunhofer zones in a single view, this module displays a wide range of diffraction patterns. A 1994 article shows the intensity in this same range for a planar slice through the center of a circular slit [FORBES]; we have found no similar illustration in any textbook, however.

As the computational grid approaches $y = 0$ from above, the Fresnel approximation to the intensity function becomes inaccurate and the oscillations it predicts become arbitrarily close together. In order to resolve the surface features of the height field (within some small distance of the aperture), we vary the grid spacing according to

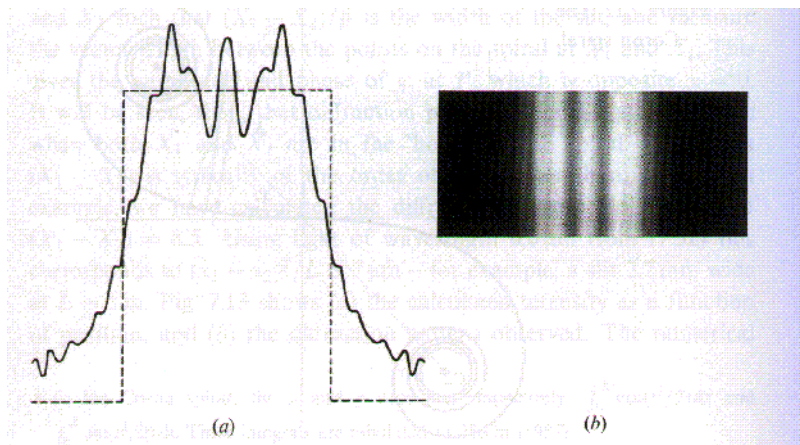
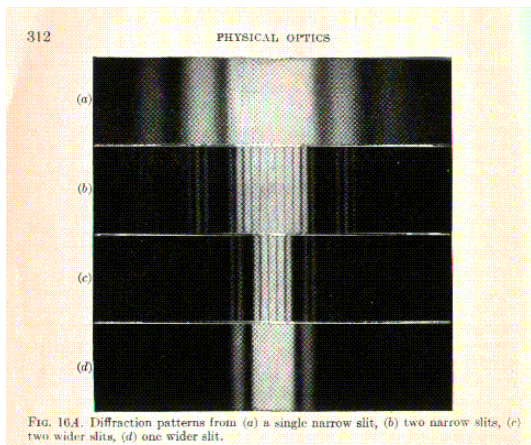


Figure 2. Many textbook illustrations of optical phenomena have remained essentially the same for decades. Left: diffraction through single and double slits as projected on an observation screen [JENKINS]. Right: Diffraction pattern through a single slit, shown as a cross-section of a height function and as an image on an observation screen [LIPSON].

$$y = a_1 \exp(-b_1 \bar{y}) \quad \text{and} \quad x = a_2 \exp(-b_2 |\bar{x}|)$$

where \bar{x} and \bar{y} are normalized to the interval $[0, 1]$, a_1 and b_1 are constants, and a_2 and b_2 are linear functions of y . The resulting grid resolves small features directly in front of the slit and makes a better fit to the spreading hills and valleys of the height function than does a perfectly rectangular mesh. The non-uniform distribution of grid points is shown in Figure 3.

This module also includes audio feedback to indicate the parameter values of the width of the slit. When the width is 0.25 millimeters, the application catenates the audio elements “zero” “point” “two” “five” together. We also use “earcons” to indicate when a dragger has reached the limit of its extent, such as when the aperture width reaches zero.

2.3 Geometrical Optics

Module 3, “Geometrical Optics,” simulates the behavior of light passing through optical elements such as stops and lenses (Figure 4). A user can interactively vary the placement and the focal point of each lens. Points on a 3D object serve as sources of rays which are traced through the optical elements. Each of the point source emits a number of rays (*e.g.* 1000) at random angles, forming a cone-shaped distribution that covers the area of the first optical ele-

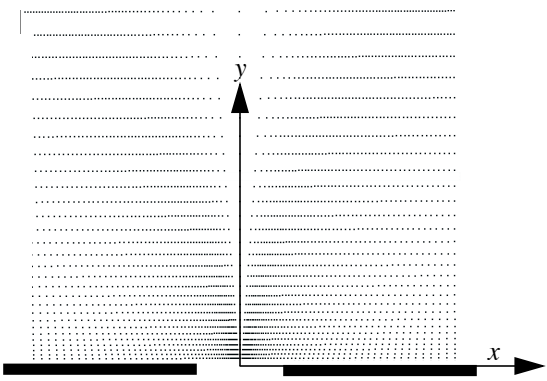


Figure 3. A curvilinear grid offers a better match to the shape of the height function than does a uniform grid.

ment. When the 3D object is non-planar (*e.g.*, a teapot), the front-most stop aperture can be shrunk to yield a greater depth of field.

A ray is discarded if it misses the optical elements or the hole of a stop. The rays are accumulated as translucent dots on the observation screen (using additive blending). These overlap to produce an image that blurs out of focus when the screen is moved from the focal plane.

2.4 Implementation and Performance

Open Inventor allows us to separate the underlying structural elements of a scene from the behavioral elements of the scene. The structural elements – the geometry – are contained in an Inventor-formatted text file. The behavioral elements are contained in shared binary objects. Open Inventor provides a mechanism for dynamic simplification of geometry. When draggers are moved, the height field is repeatedly recalculated by an engine (which is a time-consuming operation). To preserve a steady frame rate, we reduce the geometric complexity of the mesh whenever a dragger is moved so that a coarser mesh is recalculated and displayed. We also take advantage of Open Inventor’s ability to vary the geometric complexity of a dragger according to its distance from the viewpoint.

For the Fresnel diffraction module (Figure 4), the light’s intensity is evaluated on an $n \times n$ grid and displayed as a height function. The intensity on the observation screen is evaluated on a $2 \times n$ grid. On an SGI Indigo2 High Impact system with an R4400 250Mhz processor, we can maintain interactivity up to $n = 100$, which is sufficient to resolve the main features of the intensity surface.

3 Conclusions and Future Work

The modules of The Optics Project (TOP) provide a user with a 3D visualization of optical phenomena, especially those phenomena that are difficult to see or to control in a physical experiment. Although 3D visualization has found wide application in research-and-development organizations, most educational software continues to rely on 2D illustrations or 3D line-drawings. TOP exploits the multi-platform availability of Open Inventor to investigate the effect of applying more current graphics and visualization techniques to modernize courseware in a particular subdiscipline of physics. This is the first serious attempt that we are aware of to

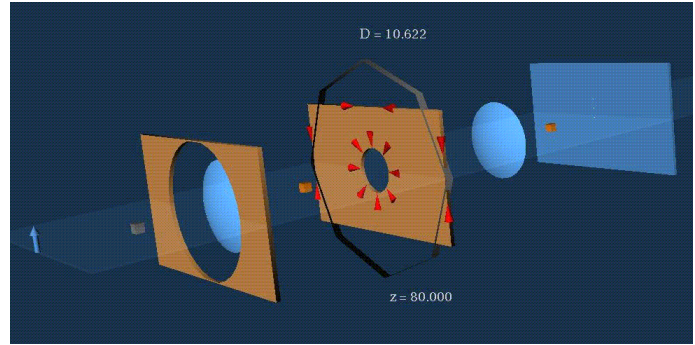
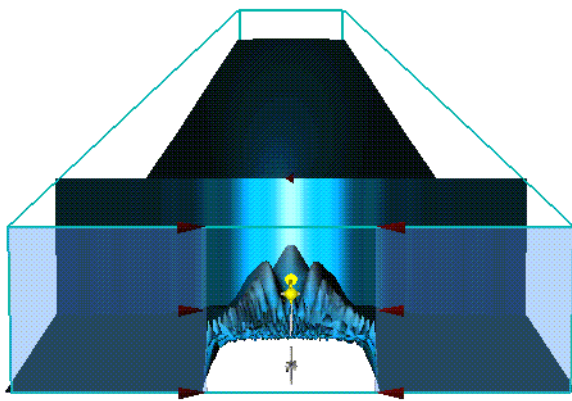


Figure 4. Left: diffraction module in operation. Blue light shines through a 1mm slit onto an observation screen (depth is compressed by a factor of 100). The intensity of the light is plotted as a height function whose central peak corresponds to maximum brightness at the observation screen. Right: geometric optics module. Distributions of rays at the source (on the left) are imaged onto the observation screen (on the right) after they pass through user-controllable optical elements.

build a suite of educational tools using interactive 3D visualization for an undergraduate course in optics.

In the spring of 1997, TOP was used for the first time in an actual optics class (Physics 4513/6513 at Mississippi State University). Students made comments such as the following.

Student1: Polarization was one of the concepts which seemed most unclear during my high school physics and even during my college physics sequence. I feel that I would still have had to invest more time trying to envision circular polarization and even linear polarization, had I not been able to watch an animated model.... After seeing more abstract concepts being animated I can easily envision them.

Student2: [TOP] is also ideal because of the animation and the ability to look from different directions. Most book diagrams are from the same points of view and can only be static.

To date, seven other colleges and universities have agreed to examine TOP for use in their junior/senior-level optics courses as well. We have also made arrangements to include an image from TOP in future editions of an undergraduate optics textbooks.

Within the physics community there is a lively debate about the role of computer simulations in the classroom. On the one hand, computer-aided instruction takes much of the drudgery out of the operation of physical devices in a lab. But on the other hand, there is concern that students may no longer be learning the proper professional lab techniques if they become familiar with simulation at the expense of experimentation. Would future physicists be less capable as a result of spending too little time directly experiencing physics? We expect that continued observation of (and feedback from) students will clarify the appropriate use of this visualization tool both in and out of the classroom.

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