WebTOP: 3D Interactive Optics on the Web

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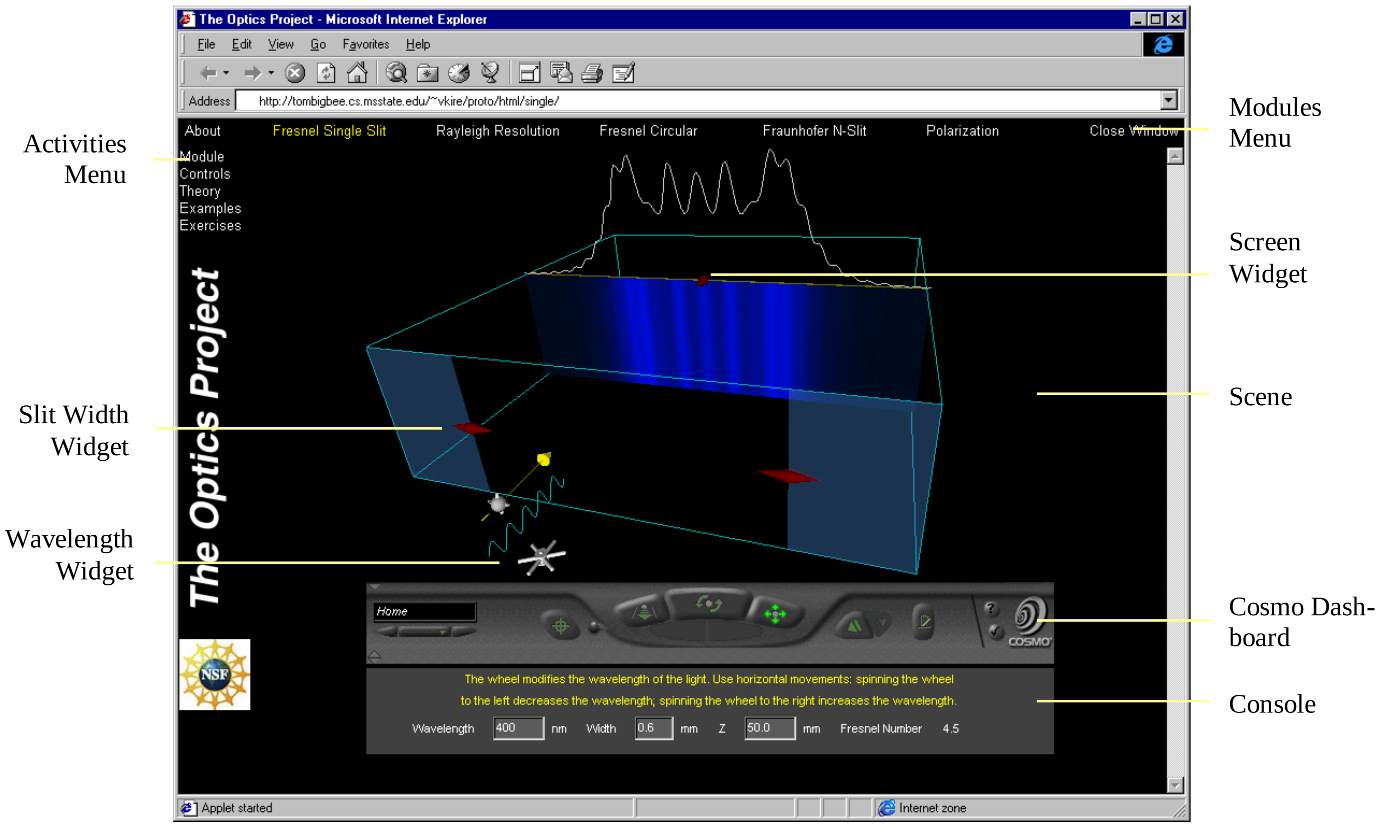

Figure 1. Overview of WebTOP: The Fresnel Single Slit module at work.

Abstract

The Optics Project (TOP) is a 3D interactive computer graphics system that visualizes optical phenomena. The primary motivation for creating TOP was to develop an educational aide for the student studying undergraduate optics. TOP runs on SGI workstations and PC computers. We have developed a Web-based version of the system that encompasses a physical simulation, an overview of the theory involved, a showcase of examples, and a set of suggested exercises. The actual simulation is implemented using VRML, Java, and the External Authoring Interface. This work is significant in that it represents, to our knowledge, the first complete 3D interactive optics system on the Web.

Keywords: Computer graphics, optics, education, simulations, VRML, Java, EAI.

1. Introduction

Each of us has images, vivid images, which are stored in our memories and can be recalled with a single phrase. For physicists, optical engineers, and optics students, phrases such as “the ray diagram for a thin lens” or “reflection and refraction at a planar interface” immediately bring the corresponding images to mind. These images are extremely important to us, because they often serve as the starting point when we begin to solve an optics problem or to explain an optical concept to a student.

In 1994 The Optics Project (TOP) [2, 4] was begun at Mississippi State University, in the Engineering Research Center for Computational Field Simulation. The motivating idea behind TOP was to provide students and educators with better images to work with. In particular, TOP is a 3D interactive computer graphics system that provides the user with computer simulations of optical phenomena which are: (a) interactive, (b) 3D, and (c) animated (for those phenomena for which animation is appropriate).

TOP was originally designed to run on SGI workstations and PC’s and was implemented using Open Inventor [12]. With the incredible growth of the Internet and the Web, we decided to create a Web-based TOP (WebTOP) that would utilize three important advantages of the Web platform: ubiquity (through the availability of cross-platform browsers), seamless integration with text and images into a versatile tutorial, and collaboration capabilities.

WebTOP is implemented using VRML 97, Java, and the External Authoring Interface (EAI) [9]. The system currently consists of 5 different submodules that visualize a variety of optical phenomena. We will be working for the next two years to port all the TOP modules to the Web.

2. Related Work

There are many Web-based simulations of various physical phenomena. However, only some of them are related to optics [6, 10]. Most of these applets present individual attempts at simulating a particular optical phenomenon. Other applets are part of a larger set but have limited scope and provide only partial interactivity. For example, Physlets [3] represents a set of Java applets that provide physics students with tools to solve specific problems. Similarly, The Virtual Physics Laboratory [1] provides a set of applets with a section on optics including some simple 2D Java applets. The applets developed through the CPU Project [5] enable students to simulate laboratory settings. They provide realistic renditions of optical phenomena and a platform for simulating situations that are difficult to duplicate in laboratory settings. Although many of the problems in optics naturally lend themselves to a 3D implementation, most of these applets use 2D diagrams or 2D cross-sections to depict the output of a given simulation. This closely follows the tradition of using 2D diagrams in optics textbooks. Those applets that use some form of a 3D implementation allow restricted interactivity and stop short from providing a fully integrated direct-manipulation-based immersive system.

To our knowledge, Web TOP is the only interactive 3D Web based system for learning optics at the current time. The closest related system is the VRML Gallery of Electromagnetism [11]. However, this system does not cover any optical topics, and it only consists of a set of static VRML worlds.

WebTOP builds upon work previously done on TOP. We now briefly describe TOP and each of its modules. Upon completion, WebTOP will contain all of these modules.

TOP is comprised of seven modules. The Wave Simulation module simulates waves in a ripple tank. The user can insert several monochromatic point sources or line sources, and can interactively vary the properties of each source. The Reflection and Refraction module simulates the incident, reflected, and refracted electric field vectors for the case in which a monochromatic plane wave is incident upon a planar interface which separates two homogeneous media. The user controls the properties of the incident field and the indices of refraction of the two media. The Geometrical Optics module simulates the behavior of light as it passes through lenses and stops on an optical bench. In the Polarization module the propagation of a monochromatic completely polarized plane wave of light and the effect of various optical elements (polarizers and wave plates) on the corresponding electric field vector are simulated. The user controls the optical properties of the incident field, and the type, location, and characteristics of the optical elements being used.

The Interference module is comprised of two separate submodules: (a) Michelson Interferometer and (b) Fabry-Perot Interferometer. In both cases, the user can manipulate all the controls of the interferometer and vary the wavelength of the incident light. The Fraunhofer Diffraction module is comprised of four separate submodules: (a) Single Slit, (b) N Slit, (c) Diffraction Grating, and (d) Rayleigh Resolution Criterion. The Fresnel Diffraction module is comprised of three separate submodules: (a) Fresnel Single Slit, (b) Fresnel Double Slit, and (c) Fresnel Circular. In these modules either a monochromatic plane wave or the light from a monochromatic point source is incident upon an aperture (or set of apertures) and the corresponding intensity pattern is viewed on an observation screen. The user can vary the properties of the sources or incident fields, the locations and sizes of the apertures, and the location of the observation screen.

3. WebTOP

Currently WebTOP has five submodules from three different areas of optics:

- Fresnel Diffraction – Single Slit
- Fresnel Diffraction – Circular Aperture
- Fraunhofer Diffraction – Rayleigh Resolution Criterion
- Fraunhofer Diffraction – N-Slit
- Polarization

3.1. User Interface

The WebTOP user interface for each module has five basic parts: the Modules Menu, the Scene, the Dashboard of the VRML browser, the Module Console, and the Activities Menu (see Figure 1).

3.1.1. The Modules Menu

The Modules Menu is located at the top of the window. It allows the user to change to a different module by simply clicking on the module's name.

3.1.2. The Scene

The Scene is the interactive 3D simulation itself and occupies the largest part of the Web page. It usually consists of a variety of optical elements whose parameters can be modified using direct manipulation. For example, in the Fresnel Single Slit module (see Figure 1) the scene consists of a single slit aperture, an observation screen, and four widgets that allow the user to change the parameters of the simulation. This module is simulating a monochromatic plane wave of light normally incident upon a single slit aperture. The observed intensity pattern is displayed on the observation screen, and is plotted (see the white curve) above the observation screen. The user can vary the following parameters: (a) the wavelength of the light, (b) the width of the slit, and (c) the distance, call it z, from the plane containing the slit to the observation plane. Each of these parameters can be modified using custom-provided widgets: for the wavelength it is the white wheel in front of the slit, for the slit width it is either of the two red cones located on the edges of the slit, and for z it is the red cone on the top of the observation screen.

Suppose the user wants to change z. Once she moves the mouse over the red cone widget, the Module Console displays a short message that explains the purpose of the widget. The user then uses the widget to place the observation screen to the desired position. Similar comments apply to the two other types of widgets.

3.1.3. The Module Console

The Module Console is at the bottom of the window (see Figure 1). The purpose of the Module Console is to inform the user of the current parameter values and to provide another method for changing them. For example, in Figure 1, the first three parameters shown on the Console are the wavelength of the light, the width of the slit, and the distance from the aperture plane to the observation screen. If the user uses a widget, the new value of the parameter appears in the corresponding box. Alternatively, one can type the parameter value in the box, if one so desires. The last value shown on the Console is the Fresnel number which depends on all three parameters. The Fresnel number is an example of a dependent parameter that the user cannot control. Its value is updated whenever the value of any one of the other three is changed.

3.1.4. The Activities Menu

The Activities Menu is in the upper left-hand corner of the screen. It lists the five activities available in WebTOP. These will be discussed in the next section.

3.2. WebTOP Activities

Let us now take a look at the activities available for each module.

3.2.1. Module

This is just the simulation itself, as pictured in Figure 1. As an example of the kinds of things that can be done, consider Figure 2. This is a set of four images from the Rayleigh Resolution submodule of the Fraunhofer diffraction module. In each figure, monochromatic light from two distant point sources is incident upon a lens. Each of the two gray bars represents the chief ray from its respective source. The light passes through the lens and is imaged on the observation screen, which lies in the back focal plane of the lens. The two images are not point images due to the diffraction which takes place when the light passes through the lens; they are circular diffraction patterns. In this submodule the user can vary: (a) the angle between the two sources, (b) the wavelength of the light, (c) the diameter of the lens and (d) the focal length of the lens.

Let λ be the wavelength of the light, D be the diameter of the lens, and θ be the angular separation of the sources, i.e., the angle between the two gray bars. According to the Rayleigh resolution criterion, the two images are resolved if and only if θ is greater than or equal to

$$\theta_{\min} = \frac{1.22\lambda}{D} . \qquad (1)$$

In Figure 2 (a), θ is twice as big as θ_{min} and the stars are resolved. In Figure 2 (b), θ has been decreased until it is equal to θ_{min} , and the two stars are barely resolved. In Figure 2 (c), θ is half as big as θ_{min} and the stars are not resolved. In Figure 2(d), the θ and the diameter of the lens are the same as they were in Figure 2(b), but the wavelength has been decreased from 550 nm to 450 nm. Upon comparing (d) to (b), we see that in the latter the resolution is better, because θ_{min} is larger.

3.2.2. Controls

The Controls section contains documentation that explains: (a) how to use the VRML browser and (b) how to change the parameter values by using the Module Console.

3.2.3. Theory

When the user clicks on Theory in the activities menu, she is linked to an HTML document which contains the theory relevant to the current module. These are the relevant sections of lecture notes from the junior/senior undergraduate optics course taught at Mississippi State University. For example, in the Fresnel Diffraction, Circular Aperture submodule the theory section has sections on the relevant diffraction integral, the on-axis intensity and the Fresnel number, Fresnel zones, and the full intensity pattern. It is suggested that the user read this material before interacting with the module, but this is not mandatory.

3.2.4. Examples

When the user clicks on Examples in the Activities menu, she is linked to an HTML page that offers the opportunity to view any of several previously recorded WebTOP sessions. When the user clicks on one of the choices, the session is replayed in the Scene part of the window. These example sessions are very helpful to a new user because it gives her a feel for what can be done with the module. They also help the instructor to provide illustrations of particular phenomena.

It is important to note that these previously recorded sessions are not just “movies.” They are fully 3D in the sense that the user can use all the VRML browser commands (Rotate, Pan, Zoom, etc.) to change the way the scene is being viewed. The user can even change the parameters while the example is running.

3.2.5. Exercises

When the user clicks on Exercises in the Activities module, she is linked to an HTML page with a list of exercises she can try. These are inquiry-based exercises in that the user is asked to interact with the software, observe how the simulation changes, and then come up with an explanation for what is happening. The following is one of the exercises from the Fresnel Diffraction Circular Aperture submodule.

> Exercise 6: Changing z, the distance from the aperture plane to the observation plane: odd Fresnel numbers.
>
> Set the wavelength of the light to be 500 nm and the diameter of the aperture to be 1.0 mm.
>
> (a) Use the red cone widget on the top of the observation screen to make the position of the screen such that the Fresnel number is 5.0. Starting at one edge of the intensity pattern and proceeding across it through the origin to the other edge, how many "major" maxima do you encounter?
>
> (b) Use the red cone widget on the top of the observation screen to make the position of the screen such that the Fresnel number is 7.0. Starting at one edge of the intensity pat-

tern and proceeding across it through the origin to the other edge, how many "major" maxima do you encounter?

(c) What rule of thumb can be deduced from the results seen in (a) and (b) above, as regards the number of major maxima seen across the intensity pattern when the Fresnel number is odd? Use Fresnel zones to explain why this is happening.

Figs. 3 (a) and (b) show, respectively, the diffraction patterns when the Fresnel numbers are five and four.

4. Implementation

The modules are implemented by separating the geometry and the behavior in two distinct entities. The static geometry (such as apertures, observation screens, and widget geometry) is stored in VRML world files. The simulation output and the dynamic geometry are generated on-the-fly by *behavior components* that drive the simulation. The behavior components are implemented in Java and communicate with the VRML world files through the EAI. As an example of dynamically-generated geometry, consider the aperture in the Fresnel Diffraction – Circular Aperture submodule (see Figure 3). The geometry is dynamically calculated based on the current diameter of the circular aperture.

The above design closely follows the one of the Open Inventor implementation of the modules [2] where the geometry was stored in Inventor files and the behavior was implemented through the use of custom-written Inventor engines and nodekits [14].

The WebTOP modules use a variety of behavior components of one of the following three types: (a) a mathematical component that performs the actual simulation, (b) a widget coordination component that encompasses complex multi-part widgets and ensures a one-to-one mapping between the simulation parameters and the widgets in the scene, (c) a console component that displays messages for the user, displays the current simulation parameter values, and allows the user to type in new ones.

The mathematical engine component receives input values from the widgets or the text fields and computes either a low-resolution or a high-resolution simulation output.

The widget coordination component ensures that a given widget corresponds to the actual value used in the simulation. It also coordinates the motion of the different parts of a complex multi-part widget that are affected by a change in one of the simulation parameters. For example, in the Fraunhofer N-Slit module (see Figure 4), the widgets that are responsible for changing the width of each slit and the distance between consecutive slits are co-dependent parts of a complex widget. Whenever the width widget moves, the distance widget needs to move correspondingly. Since the movement is a function of the number of slits, this coordination cannot be achieved by a simple creation of VRML routes. Instead, the widget coordination component uses the functions *d(N, width, distance)* and *w(N, width, distance)* to compute the new position of the distance and width widgets respectively. The new positions are then funneled through the EAI and propagated to the affected widgets. The widgets themselves are instances of VRML prototypes with well-defined input and output events, and use standard VRML sensors augmented with custom-generated geometry and constraints.

The console is a Java AWT Panel that serves as a placeholder for various 2D widgets that either display information on the simulation activities, or provide additional control over the simulation parameters. For example, the console in the Polarization module (see Figure 5) sports radio buttons that enable the user to choose between polarized and unpolarized light. Further, it contains different buttons that let the user add or remove polarizers and wave plates, and turn on or off different visualization components. Finally, the text fields provide the user with an additional capability for discretely controlling the values of specific simulation parameters.

Note that the widgets provide capabilities for direct manipulation typical of immersive environment. They empower the user with a natural and intuitive interface that allows them to effectively control certain simulation parameters. This is especially important for understanding certain optical phenomena where the continuity in the change of a parameter can bring additional insight to the student. Consider the Rayleigh Resolution Criterion module (see Figure 2) where the user can use the “pole” widgets to interactively modify the separation angle of the rays inducing the diffraction. The continuous change of the angle through the use of the “pole” widgets allow the student to see the transition between the resolved and the unresolved case. Similarly, the user can use the "wheel" widget to continuously manipulate the wavelength of the incident light sources.

In most of the modules, WebTOP uses dynamic resolution to maintain interactive frame rates. This feature is especially crucial in those modules that are computationally intensive. Once the user starts moving a widget, the module automatically lowers the sampling rate. When the widget is released, the module recomputes the simulation output at a higher sampling rate.

5. Results

TOP has been used to help teach junior/senior level optics courses at: (a) Mississippi State University (MSU) in the Spring semesters of 1997 and 1998, (b) the University of North Carolina at Chapel Hill (UNC-CH) in the Spring semesters of 1998 and 1999, and (c) North Carolina A&T State University (NCA&T) in the Spring semester of 1999. It will be used to help teach the junior/senior level optics courses at all three institutions in the Spring semester of 2000.

At MSU TOP was used in three different ways. First, this class was taught in a video classroom, and TOP was used to present material to the class. The second way that TOP was used in this class was that the students were required to use it to solve some homework problems. The third way TOP was used in the students’ class projects. The class was divided up into two person teams, and each team was required to use TOP to make a two to three minute video tape or QuickTime movie of a simulation of an optical phenomenon of their choice.

At UNC-CH the students used four modules outside of class to do detailed assignments provided by their professor [8]. The professor also had the students complete a very thorough evaluation form on TOP. The students’ responses were very positive, as had also been the case with the student evaluations done at MSU. It was determined that TOP had helped the students with concepts, in that they answered qualitative test questions noticeably better than previous classes had.

At NCA&T in the Spring of 1999, three TOP modules and three WebTOP submodules were used by the professor [7] in a computer lab to demonstrate concepts, and the students worked with the modules on their own outside of class.

6. Conclusions and Future Work

WebTOP represents a complete system for studying a variety of topics in optics. Upon completion, WebTOP will contain all of the TOP modules. Despite the already successful use of TOP and WebTOP in the classroom, we foresee that the final WebTOP systems will need to be thoroughly tested. Additionally, we plan to develop a laser module and add session loging capabilities. The latter will enable an instructor to record a demonstration of a particular optical phenomenon and make it available to the students for later use. Furthermore, WebTOP will feature collaboration capabilities that will allow an instructor to teach optics to students at remote sites. This will also allow the students to concurrently run a simulation and to collaborate on solving a particular problem. We already have implemented a version of WebTOP with limited collaboration [13] and plan to further expand on its capabilities.

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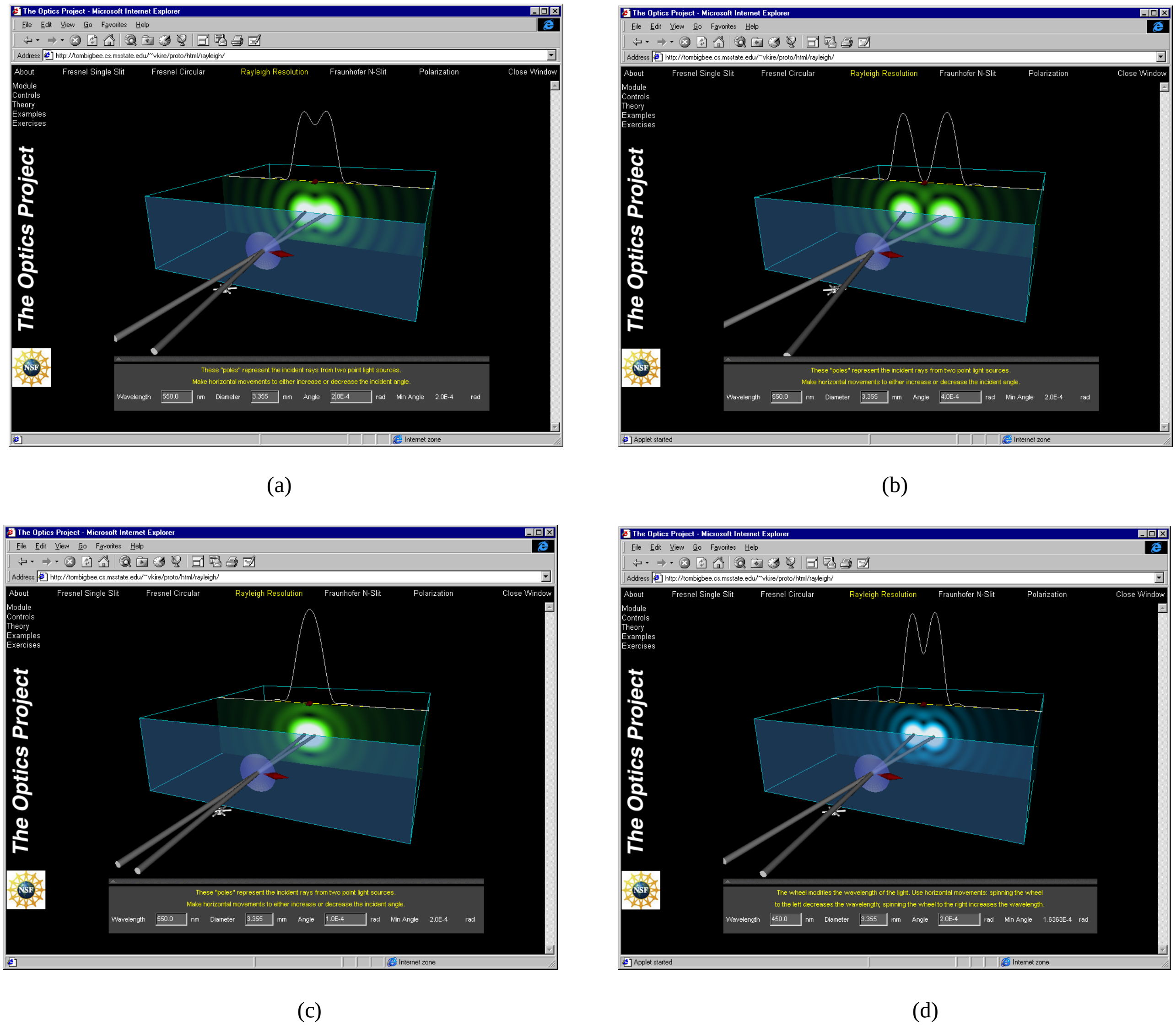

Figure 2 Fraunhofer Diffraction – Rayleigh Resolution.
(a) wavelength = 550 nm, diameter = 3.355 mm, angle = $4.0\text{x}10^{-4}$ rads. The images are resolved.
(b) wavelength = 550 nm, diameter = 3.355 mm, angle = $2.0\text{x}10^{-4}$ rads. The images are barely resolved.
(c) wavelength = 550 nm, diameter = 3.355 mm, angle = $1.0\text{x}10^{-4}$ rads. The images are not resolved.
(d) wavelength = 450 nm, diameter = 3.355 mm, angle = $4.0\text{x}10^{-4}$ rads. The images are resolved.

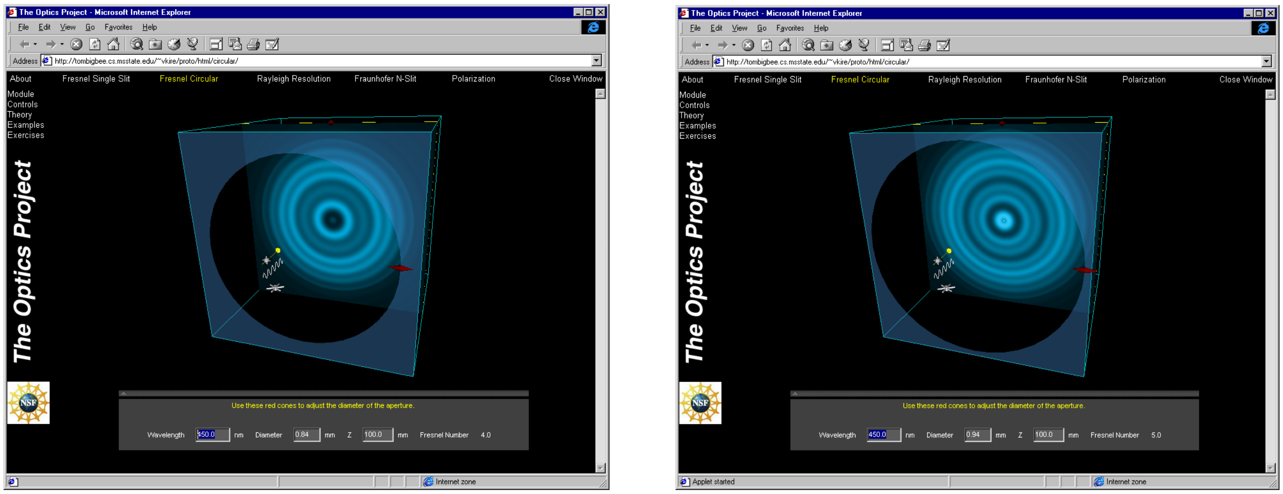

Figure 3 Fresnel Diffraction – Circular Aperture. (a) Fresnel number = 5, (b) Fresnel number = 4.

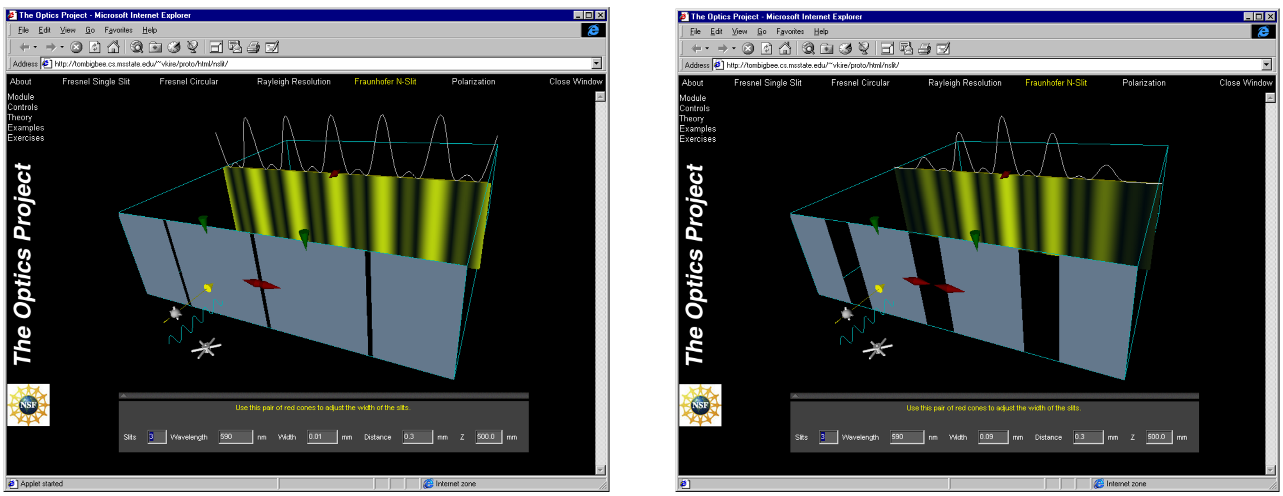

Figure 4 Fraunhofer Diffraction – N Slits. (a) narrow slits, (b) wide slits.

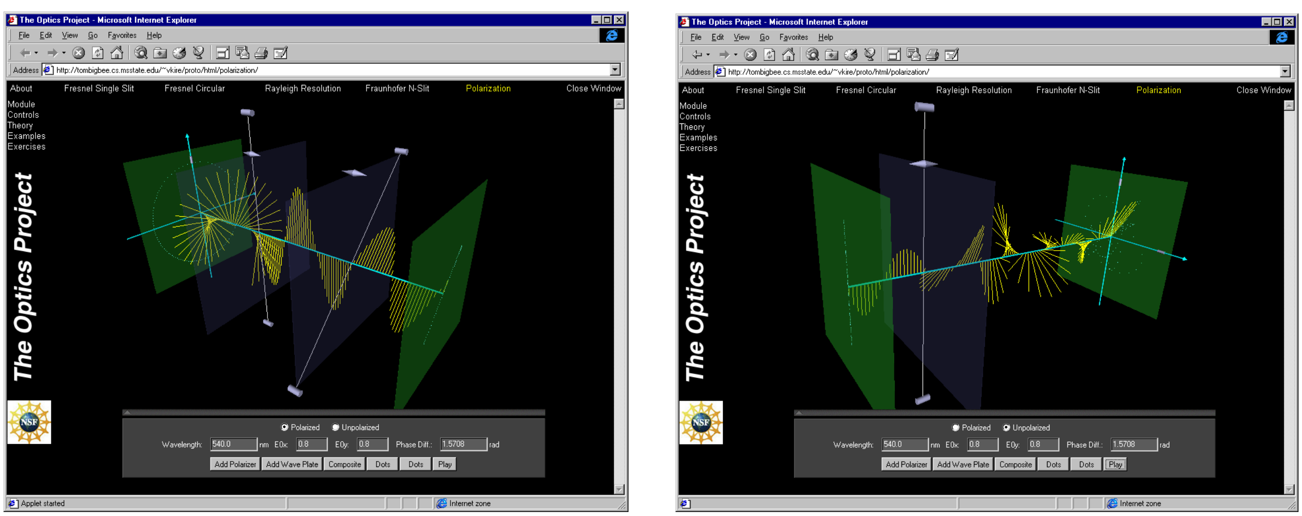

Figure 5 Polarization: (a) circularly polarized light, traveling from left to right, incident upon a linear polarizer, (b) unpolarized light, traveling from right to left, incident upon a linear polarizer.