LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
— LIGO —
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Interference Concepts in the LIGO Science Education Center (SEC)

Amber L. Stuver

Distribution of this document:
LIGO Science Education Center,
LIGO Scientific Collaboration

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189

http://www.ligo.caltech.edu/

INTRODUCTION:

This document discusses interference, the different types of interference and the ways to demonstrate interference at the SEC. Each major concept (direct interference, thin-film interference and diffraction) is introduced and then followed by descriptions of demonstrations (in classroom, exhibit or other) that illustrate the concept. The each demonstration description contains an overview of the activity/exhibit and more depth on the details of the concept.

Interference (Direct)

Concept Introduction

The focus on this unit is *interference*. This was discussed in "Giant Slinky: Quantitative Exhibit Activity" (LIGO-T080203). Here, it is assumed here that one is familiar with wave concepts, but let's review the concept of interference so that we can expand on this:

Interference occurs when two waves overlap each other. In the "Giant Slinky," these waves are caused by the newly produced waves traveling towards one end of the Slinky and older waves that have been reflected back to the other end. When these two waves overlap, they add up to make larger and smaller amplitude waves.

- *Constructive interference* occurs when two peaks (maxima) of a wave (or two valleys/minima) overlap and add together to create a larger wave than either of the original waves.
- *Destructive interference* occurs when a peak (maximum) and a valley (minimum) overlap and add to either partially or completely cancel out the waves.

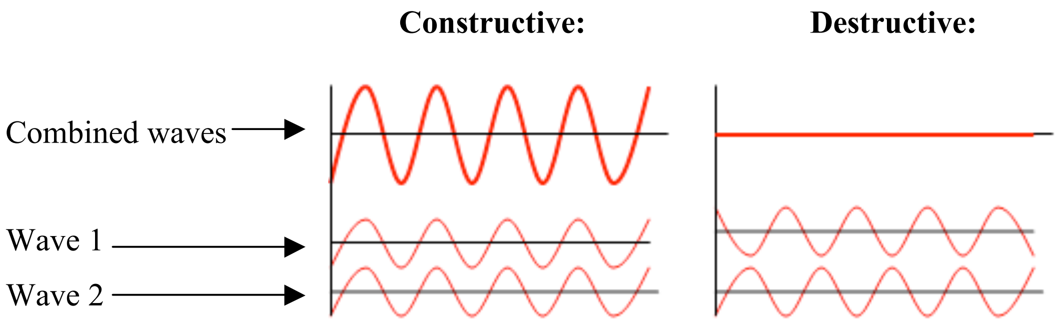


Exhibit: **Giant Slinky**

SEE "GIANT SLINKY: QUANTATITIVE EXHIBIT ACTIVITY" (LIGO-T080203)

Exhibit: **Interferometer**

This exhibit illustrates how LIGO uses the direct interference of two different waves (one from each arm of the **L**) combining to produce an interference pattern. The dark fringes are areas of destructive interference and the bright fringes are areas of constructive interference. The effect of air in the arms on the fringes can be seen by pumping the air out of (or letting it back into) one arm and the effect of vibrations in the environment can be seen on the fringes by tapping the top of the table.

Thin-film Interference Patterns

Concept Introduction

There are different ways to produce interference patterns. One of the most visually appealing ways is to produce spectra from thin films (much like the colors you see in an oil slick in a parking lot or the colors you see on the surface of a bubble). However, it is very important to note that these spectra are NOT RAINBOWS! Rainbows are produced when light bends (*refracts*) in different materials (like rain droplets) and separates the colors from one another and is NOT an INTERFERENCE EFFECT!

Classroom activity: **Permanent Oil Slicks**

This activity will take approximately 30 minutes.

Materials

For every table/group:

Pan about 2/3 filled with clear tap water, crayons (for writing names on paper), paper towels, bottle of clear nail polish, and several sheets of black construction paper for each participant.

Other:

Colored paper, colored nail polish, vinegar, clear & colorless beverage (like ginger ale), hot tap water, colored (RGB) light filters, food coloring, more paper towels, and nail polish remover

I. Introduction
  a. Ask who remembers what 'LIGO' stands for.
    i. Stress the word interference and how this is central to the operation of the detector and how LIGO looks for gravitational waves.
      1. For now, just commenting on how interference is the result of combining waves like light is sufficient.
  b. Draw on the student's experience with oil slicks on puddles and in parking lots.
    i. What did they see? Students will often refer to the 'rainbow' they saw in the slick. This is a good time to tell them that while they saw all of the colors in the rainbow, this was **not** a rainbow. But, the difference between a rainbow and what they see in an oil slick will be discussed later (see IV.c).
  c. Tell the students that they are going to be scientists today and make a permanent oil slick with clear nail polish.

    - i. It is important to make sure that the audience knows that they are not being 'humored' when we call them scientists – *anyone* who performs experiments to investigate the world is a scientist.

- II. Experimental Design
  - a. Perform a **control** test.
    - i. Materials: clear polish, pan with tap water in it, black construction paper, paper towels
    - ii. Method:
      1. Put your name on the paper (just to claim later).
      2. Submerge the paper completely in the water.
      3. Let a <u>single</u> drop of polish fall on top of the water.
      4. Grasping a corner of the paper, pull the paper up and towards the film in order to catch the slick on the paper.
      5. Place the wet paper on a paper towel.
    - iii. Observe: Ask the students what they see. Again, they may mention a rainbow. Quickly stress the difference and then call the colors they see a *spectrum* and/or refer to these colors as an ***interference pattern***. Again, this will be discussed in more depth later (see IV.c).
  - b. Perform the experimental tests.
    - i. A scientist's goal is to learn about the world and to do that, they make an initial observation then ask, "What if?". What if just one thing was changed? How would the results change?
      1. Suggesting how the results will change before the experiment is performed is called making a **hypothesis**. It is important to stress that there are no 'right' or 'wrong' hypotheses. The whole point is to investigate something. While a hypothesis may be proven not to correspond to the experimental results, the important part is that the true result is given by the experiment and new knowledge is gained.
    - ii. Ask the students what one thing they would like to change. Common variables are:
      1. Paper (color)
      2. Polish (color)
      3. Water
         - a. Color
         - b. Temperature
         - c. Chemistry (use vinegar or soda pop)
      4. Light (this is best tested last since this makes a good bridge to the observation portion of the experiment)
         - a. On/off
         - b. Color
    - iii. Perform the new experiments with a *single* change in variables. Making only a single change from the control is an important part of the scientific method. This can be done by having all of the groups perform the same experiment or by letting the different groups each

perform a different experiment and then share their observations during the observation portion.

III. Observations
  a. *Always compare each experiment to the control test!*
  b. Common observations:
    i. Colored paper:
      1. The pattern may not be very evident – instead, the pattern is dominated by the color of the paper (black paper was chosen for the control since black is the absence of color in light).
    ii. Colored polish:
      1. There is little to no pattern. (There is often a bit of pigment at the center of the pattern surrounded by a slight pattern.)
    iii. Water
      1. Colored water
        a. There is no significant difference from the clear water control test.
      2. Hot water or vinegar water
        a. There is a more spectacular pattern.
    iv. Light
      1. On/off
        a. When there is no light, there is no pattern.
      2. Color (red/green/blue [primary colors of light] filters)
        a. When a single color of light is on, only that color appears in the pattern. When two colors of light are on, both colors and their combination are visible. When all three primary colors of light are on, the all the colors in the pattern can be seen.

IV. Explanation
  a. The fingernail polish forms a thin film.
    i. The film is thickest in the middle and thinnest at the edges.
    ii. The edge is about one molecule of polish thick.
    iii. "Thin" is with respect to the wavelength of visible light.
  b. Reflection
    i. Some of the light is reflected from the top surface of the film and some of the light is reflected from the back surface of the film. Depending on how thick the film is compared to the wavelength of light, when the reflected light recombines the two waves will not be *"in sync"* (in physics this is called *"in phase"*) and will recombine or *interfere* in different ways.
  c. Interference – the colors are seen in areas where the thickness of the film allows for the constructive interference of only that color (wavelength) of light.
    i. **Constructive**
      1. When the *crest* (maximum, peak) of one wave lines up with the crest of another, the waves add up to produce a wave

with a large *amplitude* (height of the wave crest) than either of the original waves had. (1+1=2)

    ii. **Destructive**
        1. When the crest of one wave lines up with the *trough* (minimum, valley) of another, the waves add up to produce a wave with smaller amplitude than the original waves. If the original waves each had the same amplitude, the waves will be completely destructively interfered resulting in no resulting wave (zero amplitude). (1-1=0)

V. Summary
  a. "You were scientists today!"
  b. Made hypotheses
  c. Undertook an experiment
  d. Made observations
  e. Shared with others

VI. Completion
  a. Put patterns on side shelf until the students are ready to claim them to take them with them (or, if they do not want to keep their pattern, they can be thrown away).
  b. General clean up

Exhibit: **Soap Film Painting**

This exhibit also produces spectra through thin film interference. To make a film (sheet) of bubble solution, make sure that the lower bar is in the bubble solution and that there is a coating of bubble solution on the side wires (not the central rope) that support the bar, and then pull slowly on the central rope.

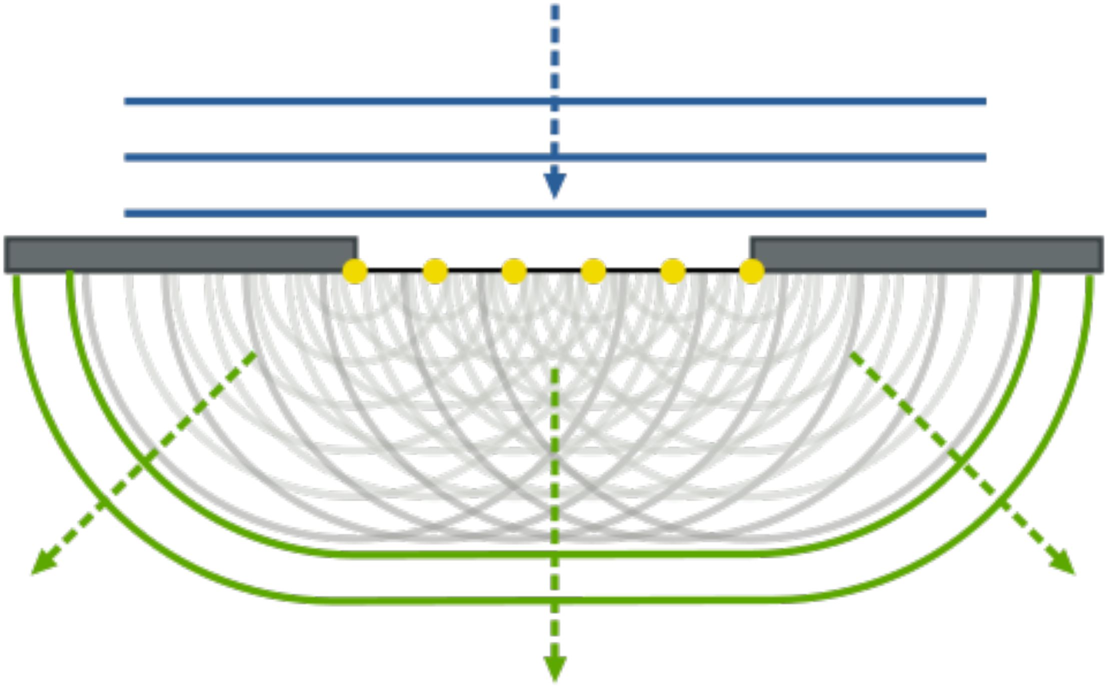
As the bar elevates, a flat sheet of bubble solution is created. With the lights on the white wall on and viewing the film facing the black wall behind the exhibit, the spectra produced by thin film interference will be evident.

You will easily see the solutions streaming towards the ground due to the effects of gravity. As the solution is being pulled downward, the sheet is getting progressively <u>thicker near the bottom and thinner near the top</u>. Once the top of the film becomes much thicker than the wavelength of light, you will notice that there is no color in that part of the film. This is because there is so little change in *phase* that the light being reflected from the front and back of the film interfere (recombine) constructively – the two waves are still almost perfectly "in sync."

Diffraction Interference Patterns

Concept Introduction

Diffraction is the effect of light bending as it passes through slits or around edges. Every point on a wave can be thought of as the source for new waves. This is called *Huygens Principle*. As shown in the illustration below, a plane (flat) wave is incident on a slit. The points within the slit will represent the sources of new wave we will consider.



Waves "want" to travel in all directions producing circular waves. All of these new waves will interfere to produce the resulting waves passing though the slit. This results in a new planar wave shape for the central portion of the wave emerging from the slit and a circular wave shape from the edges of the emerging wave.

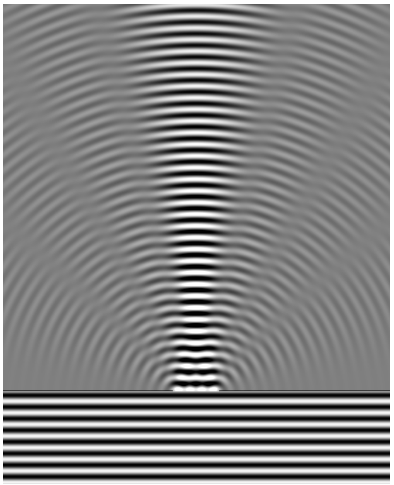
This <u>diffraction</u> effect can then produce interference patterns.

Exhibit: **Interference**

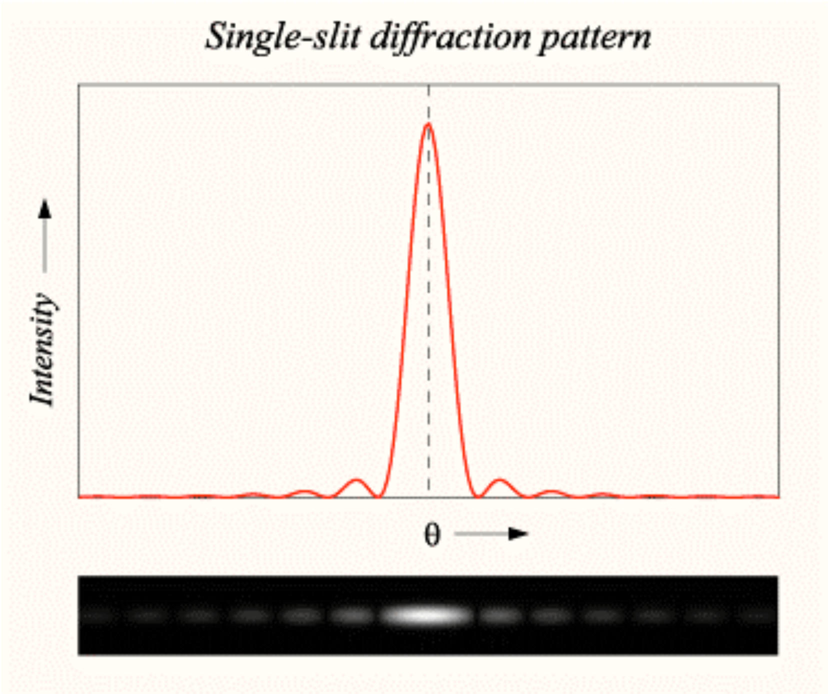
This exhibits illustrates diffraction interference patterns coming from single and double slits of varying widths that are *close to the wavelength of light*.

First, play with the exhibit. Notice that the light source is a laser of a single color (red). That is important for diffraction interference patterns here to be well defined. However, diffraction can be used with light of mixed color (like white light) to produce an interference pattern that separates the colors of light from each other. This is called a diffraction grating and is used in the spectrometers that accompany the "Gas Lamp" exhibit.

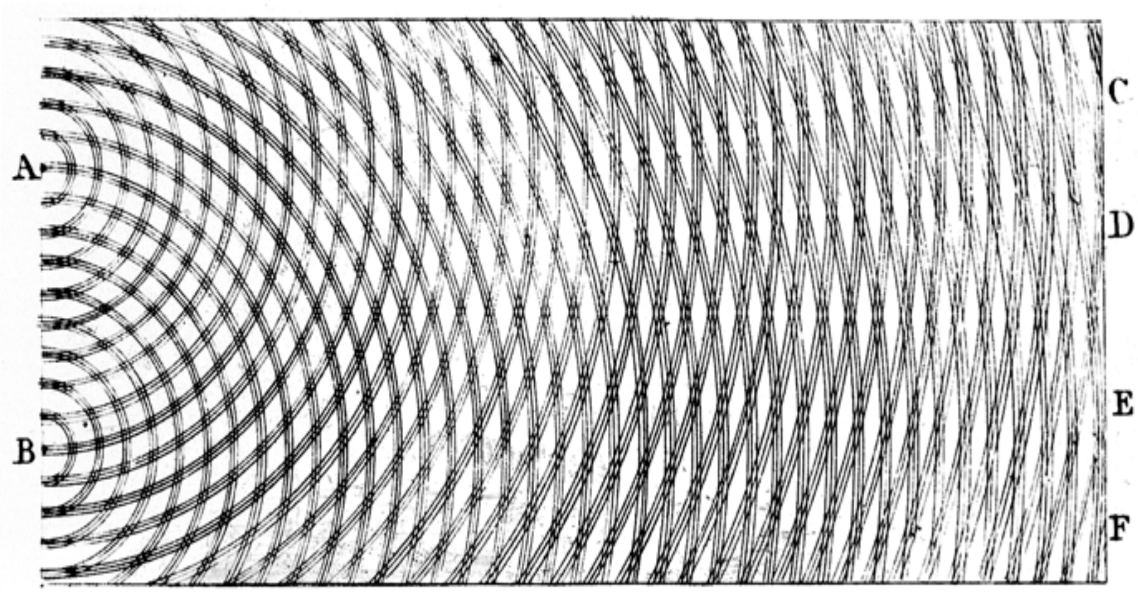
Now, pull the handle up so that it is at position **B**. This is a single slit. While you cannot see the interference pattern until it hits the screen at the end of the table, an illustration of how the wave-fronts are interfering along the path is shown to the right:



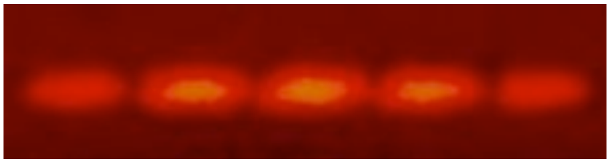
The radial "fuzzy" lines that project from the edges of the slit are areas where destructive interference is taking place. When the light is projected on a flat screen, these areas of destructive interference will appear as dark spots while the other areas of constructive interference will appear as bright spots. This is shown in the illustration below. The top plot is the intensity of the light corresponding to the brightness of the pattern in the picture directly below the plot. Notice that the central maximum (bright spot) is twice as wide as the other maxima and that the minima (dark spots) are evenly spaced around the central maxima.



Now push the handle down to position **A** (and make sure that there is a pattern projected on the screen). This diffraction interference pattern that you see now is the result of diffraction through a double slit (two slits). The interference of the waves along the path between the slits and the screen is shown below:



Here, A and B (different from the **A** and **B** positions of the handle on the exhibit) are the slits and C, D, E and F are points on the screen corresponding to the minima of the pattern. An actual pattern is shown below:



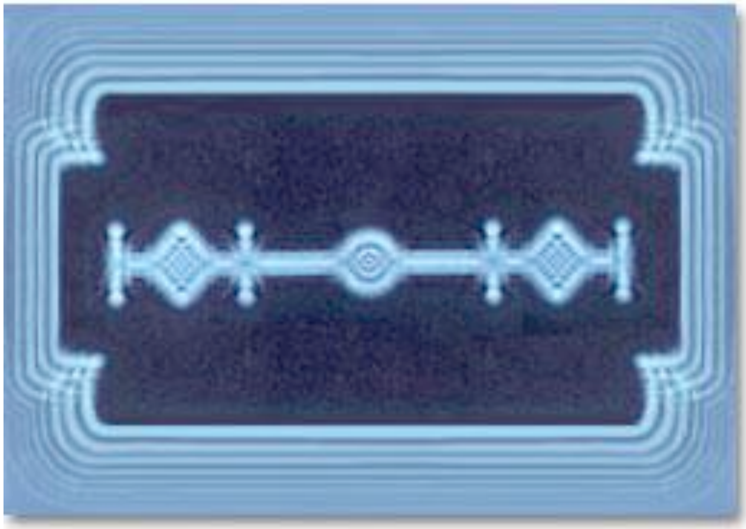
Notice here that the width of the central maximum is the same as the other maxima. This is one of the primary ways to identify if a diffraction interference pattern was produced by a single or double slit.

Now, pull the handle up a little and notice how the spacing of the minima and the width of the maxima change. As you pull up on the handle, the <u>width of the slits used to make the pattern is increasing,</u> producing a pattern with <u>decreasing maxima width and spacing between minima</u>.

As you continue to pull up on the handle, you will progress to a wide single slit. If you continue to <u>pull up on the handle to point **B**, the width of the single slit will decrease producing wider maxima</u>. You will also notice as you transition between a double slit to a single slit, that there will be a <u>combination pattern</u> (between the double slit pattern and the single slit pattern) on the screen.

Exhibit: **Long Path Diffraction**

Diffraction interference patterns can also be caused by light bending around the edges of objects. The "Long Path Diffraction" exhibit shows how such diffraction effects produce interference patterns that are very noticeable when the wavelength of light is long. The image below shows the diffraction interference pattern around a razor blade. (The image was not produced using the "Long Path Diffraction" exhibit, since we don't let children play with razor blades, but this is a good example of the interference effects that are illustrated with this exhibit.)



When the wavelength of light is short or when there are many wavelengths of light used to cast shadows, the effect of diffraction is not as apparent – but with VERY close inspection, *even the sharpest, most well defined shadows will have some blurring around the edges due to diffraction.*

Other Demonstrations of Diffraction Interference Patterns: **Spectrometer**

At the “Gas Lamp” exhibit, students are encouraged to use the spectrometers that are kept nearby to investigate exactly what colors are interfering together to produce the color of the lamp.

The spectrometer is an excellent example of the practical application of diffraction. When many very narrow slits are placed one after another, they form what is called a *diffraction grating*. This is going to cause many new waves (one from each slit) and produce many more interference points (compared to diffraction through a single or double slit). This will cause there to be different points along this path that will cause constructive interference for different wavelengths. In other words, if we were to project the interference pattern on a screen like in the “Interference” exhibit, the position of the bright spots (maxima) would move farther away from the central maximum as you move from red (long wavelength) light to blue (short wavelength) light. Now consider using white light (light made up of all wavelengths) on this grating. One should expect to see a full color spectrum on either side of the central point (which would be red).

The spectrometer uses a diffraction grating to separate the colors of light. Since these separated colors will only appear at fixed distances from the central point, the spectrometer can also be used to measure the wavelength of light – just like it does at the “Gas Lamp” exhibit.

Other Demonstrations of Diffraction Interference Patterns: **CDs and DVDs**

CDs and DVDs store data in the form of ones and zeros (just like all computers store data). Pressed discs (not ones made using a computer) have a fine series of depressions in a continuous spiral from the center to the edge of the disc on a metallic film laminated inside protective plastic sheets. When a laser (in a CD or DVD player) shines on that area of the disk, the light will be reflected back to a light detector if there is no depression present, and away from a detector if there is one present. The 1s and 0s that the computer then reads is a 1 is a reflection is detected and a 0 if it isn’t. The computer then knows how to interpret these ones and zeroes to produce sound or images.

This spiral of depressions also have the effect of producing a rough diffraction grating when the bottom of the disk (not the side with the label) is inspected with light. Interference spectra are visible and each area of color is where constructive interference for each color (wavelength) of light is present.

Image Credit:

- Page 2 (Constructive and Destructive Interference) image from: http://upload.wikimedia.org/wikipedia/commons/8/8a/Interference_of_two_waves.png retrieved on 15 April 2009.

- Page 7 (Huygen's Principle) image from: http://upload.wikimedia.org/wikipedia/commons/6/60/Refraction_on_an_aperture_-_Huygens-Fresnel_principle.svg retrieved on 16 April 2009.

- Page 8 (Single Slit) image from: http://en.wikipedia.org/wiki/File:Wave_Diffraction_4Lambda_Slit.png retrieved on 16 April 2009.

- Page 8 (Single Slit Plot/Pattern) image from: http://upload.wikimedia.org/wikipedia/commons/e/e1/Diffraction1.png retrieved on 16 April 2009.

- Page 9 (Young's Double Slit) image from: http://upload.wikimedia.org/wikipedia/commons/8/8a/Young_Diffraction.png retrieved on 16 April 2009.

- Page 9 (Double Slit Pattern) image from: http://upload.wikimedia.org/wikipedia/commons/4/46/Diffraction2vs5.jpg retrieved on 16 April 2009.

- Page 10 (Razor Diffraction Pattern) image from: http://www.astro.queensu.ca/~hanes/PHYS015-2007/Notes/DAH_Figs/Razor_Diffraction.jpg retrieved on 16 April 2009.