Teacher's Preparatory Guide

Lines on Paper

Overview: In this lab, students will learn how scientists use a process called *X-ray diffraction* to figure out the structure of things that are too small to see such as atoms, molecules, and crystal structures. X-ray diffraction is a tool used to investigate the structure of matter and is commonly used to study certain nanostructures. This lab will help students understand how light is bent into different directions as it interacts with small objects, especially those on the nanoscale (1-100nm). Students will create and explore their own diffraction gratings, and then predict the structural shape of a tiny diffraction grating that cannot be seen to the naked eye—similar to how scientists determine the structure of crystal lattices, or DNA.

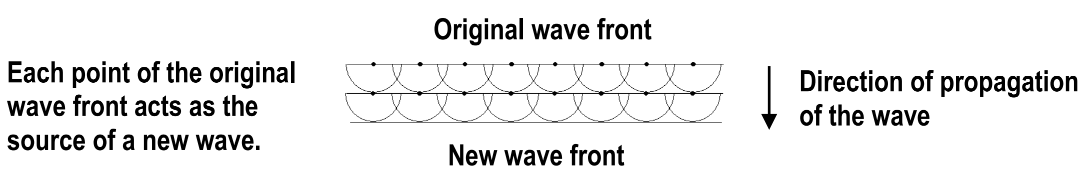
Purpose: These labs are designed to help students understand diffraction, how a grating diffracts light, and how this method can be used to determine nanoscale structure.

Time Required: This series of labs requires four 55-minute periods; *optional:* reducing time required by omitting one or more sections (see *Teaching Strategies*).

Level: High school Physics and Chemistry

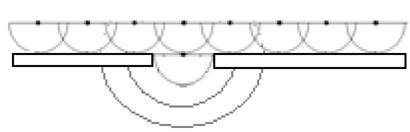
Big Idea: Structure of Matter, Tools and Instrumentation, and Quantum Effects

Teacher Background: Light can be bent in three different ways: reflection, refraction, and diffraction. This lab focuses on *diffraction,* which is the bending of a wave around the edges of an object. Diffraction explains the fact that you can hear people talking even though they are around a corner from you. Huygens' principle describes diffraction as "every point on a wave-front may be considered a source of secondary spherical wavelets which spread out in the forward direction at the speed of light[1]."



Huygens' Principle

When a wave interacts with a small enough hole (ideally, less than or equal to the wavelength of the wave) only a single point on the wave front passes through. We might predict that the wave would continue in a straight line through the width of the hole, but Huygens' Principle tells us that the single point on the wave front acts as a new source and will create a new spherical wave emanating from the hole.



Wave passing through a slit.

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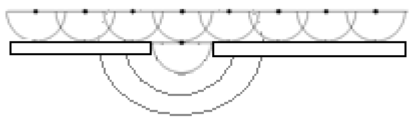
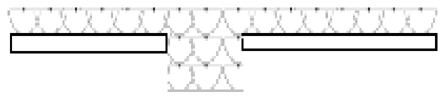
NNIN Document: NNIN-1345
Rev 08/2013

Some students get confused about this, because they forget to consider the wavelength of the wave. For example, sound diffracts when it enters a room from a doorway, so that it fills most of the room. Light, on the other hand, does not diffract significantly when entering through a doorway. The difference is that the doorway is smaller than the wavelength of the sound, but is much larger than the wavelength of light. Therefore, only one portion of the sound wave front enters the room where as many portions of the light wave front enter the room. The many light wave sources interfere with each other inside the room in such a way that there is destructive interference in any direction but a straight line. The light does not noticeably diffract through the opening. Observant students may recall that bass travels through a building better than treble does, which is due to its longer wavelength and, consequently, greater diffraction.

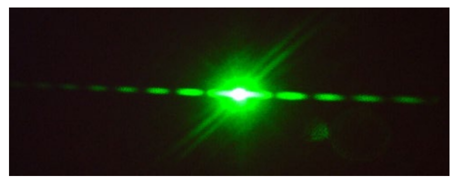


Sound passing through a slit.



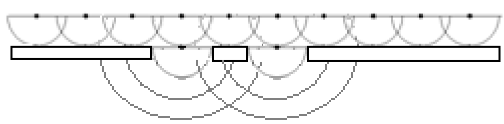
Light passing through a slit.

Things get really interesting when we add multiple slits. In 1801, Thomas Young performed an experiment where he passed light through two slits onto a film. You might expect that the light would pass straight through each slit and create a line of brightness on the film. That is not what happened. The light created a series of evenly spaced lines with decreasing brightness as shown in the image at right.



Interference pattern

In other words, as light passed through the slits, each slit became a new point source for the wave front. The waves from each of the sources interfered with each other. When light from both sources travelled the same distance, they arrived in phase, creating a bright spot on the wall. Because of the conservation of energy, the spots of light appear less bright the further away they are from the slit. Elsewhere, the light waves arrived 180° out of phase, destructively interfering with each other so that no light appears on the wall. This result is seen with any series of evenly spaced slits.



Wave passing through two slits

This only works with very narrow slits, because of light's tiny wavelength. Also, understand that Huygens' principle assumes that light always behaves as a wave. This is not accurate, because light also behaves as a particle at times (see NanoHub animation in resource section). Nevertheless, Huygens' principle is a good place to start and is sufficient for a high school level. If you desire to introduce some of the complexity, check the "Dr. Quantum" video listed in the *Resources* section as well as simulations at PhET and NanoHub.

In real scientific explorations, there is more to diffraction than vertical slits. In actual X-ray diffraction studies, scientists use interference patterns created when X-rays diffract through a material to learn about that material. The different patterns can tell them about the spacing between the layers in the material, or the positions of atoms in the material. This is information that nanoscale researchers need to understand the structure of materials. Just like in the slits, any

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repeating pattern in the material, be it in the x, y, or z directions, will create a corresponding distinctive interference pattern. Also, the closer the layers are together, the wider the spacing on the interference pattern. For example, the double helical structure of DNA was verified by studying the way DNA diffracted X-rays (See video of this discovery at: http://www.youtube.com/watch?v=u7RrXAjuNRk) . Your students will look at the way in which light diffracts through a variety of patterns in the same way that a scientist looks at X-ray diffraction data.

How is this related to nanoscale science and engineering? First, one must remember that the wavelength of X-rays is on the nanoscale (.01nm – 10nm). This makes X-Ray diffraction an important tool for probing and understanding the structure of nano-materials. Researchers need to have tools to investigate and measure nanoscale materials that are too small to see with optical microscopes (they are below the range of visible light). X-ray diffraction is a tool used to investigate the structure of matter at the nanoscale. This method is widely used, is non-destructive, and can provide detailed information about the chemical composition and crystallographic structure of natural and man-made materials.

Sources

1. Fitzpatrick, Richard. "Huygens' principle." (accessed August, 2011) http://farside.ph.utexas.edu/teaching/302l/lectures/node150.html

Materials for the creation of each black box; make one per student group

- pizza box
- marker
- pair of scissors
- craft knife
- laser printer gratings (from templates provided in the lab)
- transparency paper
- *optional*: commercial diffraction grating slides or film (Educational Innovations Item #PG-400 or PG-415, $6.75 or $17.85 at http://www.teachersource.com)
- 8½ x 11 in. piece of white paper
- ~ 20 cm. of masking tape
- Optional digital camera

Materials per group of 3 students

- black box
- laser pointer
- wood block, ring stand, or some other material for mounting the laser pointer 3 cm off the tabletop
- 1– 4 sheets of graph paper
- 10 cm of masking tape
- 2 manila folders
- small laser printer grating
- sheet of laser printer gratings
- one cubic inch piece of modeling clay of block of wood
- laser printer transparency
- meter stick or ruler
- optional breen laser pointer

Advance Preparation: Gather some extra large pizza boxes. Laser pointers can be purchased from www.amazon.com for about $3-5 each or your local office supply store. All other items can be found at an office supply store or a craft store.

1. ***Prepare your classroom to be dark.*** This activity requires dim light. If your classroom has a lot of stray light from the outside, close the blinds. If you do not have blinds in your classroom, you may need to hang dark cloth onto the windows to darken the classroom.

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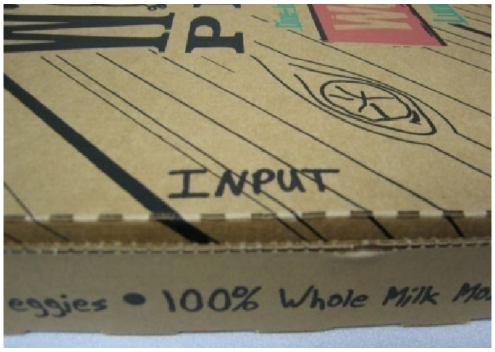
NNIN Document: NNIN-1345

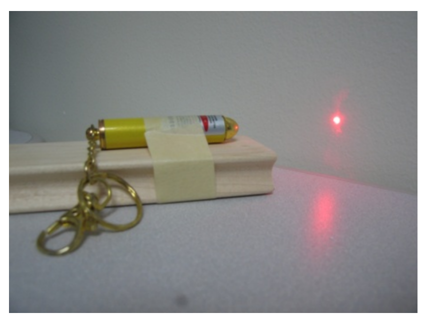
Rev :08/2013

2. ***Print diffraction gratings.*** Print the diffraction gratings (templates are provided in this lab) onto transparency paper. Each student group will need one section of 3 gratings from *Student Gratings 1*.
3. ***Reserve space in the computer lab.*** The students will need access to their own computers on day 3 of the lab.
4. ***Make a black box for each student group (Steps a-i).*** Below are step-by-step instructions:
   a. Label one side of the pizza box "input" and the opposite side "output." Do not label the side with the hinge or the side opposite of the hinge.



   b. Cut the tabs off the output and input sides of the box.

   c. Mount a laser pointer on top of a wooden block or piece of clay approximately 3 cm tall. You can use any object so long as the laser pointer can be held at a height not greater than the height of the box. Attach the laser pointer with tape, so that the beam remains on.



   d. Double check that the beam hits the side of the pizza box when resting on a table.

   e. Mark the input side of the box with a dot where the laser hits the box. Move the laser pointer along the box and mark several more dots where the beam appears.

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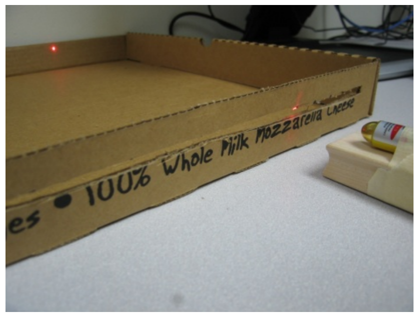
f. Use a craft knife to cut a slot in the input side of the box that the laser beam can shine through. The slot should be only tall enough to let the laser shine through easily, and end about 2 cm from each side of the box. Open the lid and verify that the beam lands on the output side of the box.



g. Cut off the output side of the box.

h. Tape gratings inside the box to create the patterns in the laser beam, by either:
- printing gratings onto a laser printer transparency using the template in this lab, and taping them as close to the input side as possible (to make the patterns more visible)
- *optional:* using commercial grating slides to create a flat interference pattern and taping them no more than 2 cm from the output side of the box (due to the wide interference pattern)
- *optional:* cutting commercial grating film into squares, orienting them at a 45° angle to each other and taping them no more than 2 cm from the output side of the box (due to the wide interference pattern)

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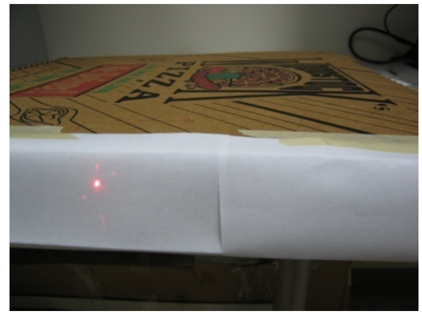

i. Cut a piece of white paper in half lengthwise, and tape it to cover the output side so that students cannot see inside. The patterns will be visible, and the laser beam will not travel through the paper. Do not overlap the paper any more than necessary. Check that the laser beam shines onto the gratings (from the input side) and creates a noticeable pattern on the output side.

Safety Information: Laser beams are highly destructive to the eye. Modifying a laser can be a fire hazard if infrared (IR) filters are damaged or removed. Tell students not to point the laser outside of the black box at any time. During the grating investigation, students should only point the laser toward the wall they are projecting the laser onto. Transparencies partially reflect, and will direct a laser beam back toward the laser operator. Make students aware of the reflected beam. Students often do not realize that the beam will be invisible in the air, and need to be very careful to always "catch" the beam. Show them how to stand a folder in a V-shape so that it catches that beam. Perform the experiment in dim light so that you can easily identify any lasers that are pointed where they should not be.

Suggested Instructional Procedure

Time	Activity
Day 1	**Black Box**
3 min	*Warm-Up:* Draw what happens to sound as it enters a room and compare it to what happens to light as it enters the room. Emphasize that we usually see light traveling in a straight path.
30 min	Have students investigate the black boxes with their laser and complete *Student Worksheet 1.* Do not allow students to move the box, or shine the laser outside of the box. Collect the lasers.
17 min	Have students share the observations and inferences they have made. Summarize the presentations and emphasize how strange it is to see the light bending/splitting. Give other examples of light bending, such as looking at a pen immersed in water or the star patterns observed around lights when you squint. Explain why this is different. Tell your students that the goal for the next few days will be to understand what is happening inside of the box.
5 min	*Clean up:* Collect boxes.
Day 2	**Grating Demonstrations**
3 min	Remind the students of the questions from the previous day.
5 min	Demonstrate what happens when the laser shines through a single slit and have your students predict what will happen when light shines through a double slit. Demonstrate both the double and multiple slits. *Optional:* Use a green laser to show that different wavelengths of light will create a different size of diffraction pattern.

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15 min	Student investigation of the *Student Gratings 1* transparency. Students complete *Student Worksheet 2*.
20 min	Explain *diffraction.* (Explained in detail in the *Teacher Background* section.)
5 min	Students write down questions they would like to investigate related to the gratings.
7 min	Show students some other kinds of gratings. Tell students that they will have a chance to make their own gratings. Students should brainstorm and draw (on paper) some designs for gratings that they would like to create on the computer.
Day 3	**Computer Lab (*optional*)**
20 min	Have students answer the *light* section of the PhET simulation of wave interference[R2] (in the *Resources* section).
5 min	Show how to make gratings small enough with minimum effort and time (instructions are in the *How to Make Your Own Gratings* handout) and distribute handout.
30 min	Students print a template that includes both the pre-designed gratings and the gratings they have designed. Have students paste their gratings into the empty spaces on the *Student Gratings 2* worksheet, and print that onto a transparency to test the next day.
Day 4	**Test Day**
5 min	Before you begin, show students 3 gratings. Have them draw what interference pattern they expect to see.
30 min	Students follow instructions on *Student Worksheet 3*. Test the diffraction gratings on the *Student Gratings 2* worksheet, including the ones that they have made for themselves. Students test their diffraction gratings and record what images they see. Students should draw the patterns they see from each grating, or you can have them take pictures of each of the patterns using their cell phones or digital camera.
10 min	Have students review their questions from Day 2 and summarize what they have learned.
10 min	Have the students describe the black box (from day 1) more completely. They can compare to the patterns they have seen from *Student Gratings 2* worksheet.

Teaching Strategies: This activity works best in groups of 3 students. Four students are too many for all of them to participate, and two students can be too small for effective idea generation. Students should work in the same groups throughout this series of labs.

It is a good idea for students to have some prior knowledge of how light behaves. If they know that light travels in straight paths, they'll be surprised when it fails to do so inside of the black box. Students should also have some experience with waves and their behavior. They should understand that light has *amplitude* and *wavelength*.

There is a way for students to determine the position of where the diffraction gratings are in the box. Students will use graph paper to make observations of the black box. It is labeled input and output and composed of square centimeters that create a scale model of the box. Smart students will be able to determine the position of the gratings by noting their edges and using different angles of the laser beam to triangulate their position. The pattern is not related to the distance between the laser and the grating; it is related to the distance between the grating and the output side of the box, which remains constant.

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Options to modify the lesson: The lesson can be modified to take more or less time. At a minimum, students should test various gratings and use them to determine the contents of a black box. Creating their own gratings will significantly increase the students' interest in the subject, but this can be omitted to save time or to simplify the lesson.

Once students achieve a strong conceptual understanding, they can use the commercial gratings to investigate the mathematical relationships involved. Once students know these relationships, they can use that information to make even more detailed predictions about the contents of the boxes. The idea of color separation can be introduced by either projecting white light through a pinhole and into a grating or by simply looking through a commercial grating at an LED or other small light source.

You can also try other colors of laser lights such as blue, violet, or green to explore the differences in light sources in comparison to the laser used in the activity.

Enhancing Understanding: The students should be able to identify a few different patterns related to the gratings:

1. Students should notice that a narrower distance between gratings will create a wider interference pattern. The converse is also true—a wider distance between gratings will create a narrower interference pattern. This explains why we do not see interference patterns when observing light on a macro scale. Emphasize that the size of the slit required for diffraction is determined by the wavelength of the light traveling through the slit.
2. Students should also notice that an interference pattern is created perpendicular to the direction of the slit. Furthermore, interference patterns can be created in multiple planes by more complex shapes. This realization is the key to correctly characterizing the gratings inside of the black box. Also, it is directly analogous to the process of X-ray diffraction. With X-ray diffraction, X-rays are diffracted by the crystal lattice of a material. The interference pattern created is used to understand the spacing and orientation of the atoms in the material – the nanoscale.
3. Students should be able to explain that the pattern is due to interference between the light traveling out of each slit. Be careful, some students will assume that they are simply seeing the shadow of the lines projected on the wall. The best way to contradict that idea is to remind them of the findings from the double-slit experiment.

Review the findings with students:

- Smaller slits create a bigger interference pattern.
- The interference pattern is perpendicular to the slits.

Going Further: Students who have a good grasp of the content of the lab can be further challenged with these questions:

1. Red lasers have a longer wavelength than green lasers. How will the interference pattern from the red laser compare to the interference pattern from the green laser? *The red laser will have a wider interference pattern, because the slits will be smaller relative to its wavelength.*
2. Ordinary light microscopes cannot see anything that is smaller than the wavelength of visible light. How does diffraction help you to understand this limitation? *When light passes around*

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very small objects, it diffracts around the edges. This causes the viewer to see an interference pattern rather than a true image of the object. The smaller the object is, the larger the interference pattern will be.

3. In order to see an object that is smaller than the wavelength of visible light, what would you need to do? *You need to use something with an even shorter wavelength. That is why both X-rays (.01-10nm) and electrons are used to view the smallest objects.*

Assessment: At the end of this unit, students should be able to do 3 things:

1. explain that diffraction occurs due to interference between light waves
2. explain the relationship between the spacing of the diffraction grating and the interference pattern created
3. use their observations of different grating patterns to make an inference about the objects contained in the black box

Assess these things by having students create a PowerPoint presentation about what they have done. The presentation should include three sections: their findings from the experiment, an explanation of diffraction, and their conclusions about the black box.

Resources

1. YouTube. "Dr. Quantum – Double Slit Experiment." (accessed August, 2011) http://www.youtube.com/watch?v=Q1YqgPAtzho
2. YouTube has a variety of videos on diffraction and interference that can be accessed by searching key words.
3. PhET. "Wave Interference." (an interactive simulation) (accessed August, 2011) http://phet.colorado.edu/en/simulation/wave-interference
4. Davidson, Michael W. "Thomas Young's Double Slit Experiment." (an interactive Java tutorial) (accessed August, 2011) http://micro.magnet.fsu.edu/primer/java/interference/doubleslit/
5. Pumper, A., Swanson, B., Neubert, J., Widstrand, C., Elis, A. "X-Ray Diffraction and Scanning Probe Microscopy." (accessed August, 2011) https://mrsec.wisc.edu/Edetc/modules/HighSchool/xray/
6. PhET simulations http://phet.colorado.edu/
7. NanoHub Particle Wave Duality Animation https://nanohub.org/resources/4916

Next Generation Science Standards

- HS-PS4-3. Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than another.
- HS-PS2-6. Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.
    - See Crosscutting Concept Structure and Function

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Rev :08/2013