## Lesson Summary
In this lesson, students will find and calculate the angle that light is transmitted through a holographic diffraction grating using trigonometry. After finding this angle, the students will build their own spectrographs in groups and research and design a ground or space-based mission using their creation. After the project is complete, student groups will present to the class on their trials, tribulations, and findings during this process.

## Prior Knowledge & Skills
- Basic understanding of trigonometry
- Basic understanding of electromagnetic spectrum
- Understanding of light and prisms
- Experience with angle measurements
- Experience with scientific investigation

## AAAS Science Benchmarks
**The Nature of Mathematics**
*Mathematics, Science, and Technology*
*Mathematical Inquiry*
**The Nature of Technology**
*Technology and Science*
*Design and Systems*
**The Mathematical World**
*Shapes*

## NSES Science Standards
**Science and Technology:** Understandings about Science and Technology

## NCTM Mathematics Standards
- **Geometry:** Analyze characteristics and properties of two- and three-dimensional geometric shapes and develop mathematical arguments about geometric relationships. Use Visualization, spatial reasoning, and geometric modeling to solve problems.
- **Algebra:** Understand patterns, relations, and functions. Use mathematical models to represent and understand quantitative relationships.

## Colorado State Standards
- Mathematics Standards 3, 4
- Science Standard 1, 4, 5

## Suggested background reading
*Light*

**Teaching Time**: Long-term project, 60 min/week, 3-5 weeks

## Materials
Each group needs:
- 1 Holographic diffraction grating (1000 lines/mm or 25,400 grooves/in)
- Scientific calculator
- Protractor or angle ruler
- Ruler
- Graph paper
- Butcher-block paper
- Copies of the directions, questions, and homework pages
To Share with Class:
- 4-5 large sheets of black foam core board
- 1 red and/or green laser pointer
- 1 white light source (incandescent light bulb, not fluorescent)
- Copies of *Astronomy Today* or *Sky and Telescope* magazine
- Computers for Internet research
Have readily available if needed:
- Exact-o Knives
- Scissors
- Masking tape
- Duct tape
- Black paint

## Advanced Planning
**Preparation Time**: 15 minutes
1. Print out student handout
2. Gather materials

## Why Do We Care?
Spectrographs are used to study atmospheres and surfaces of stars, planets and even components of other galaxies, and can be used in ground-based or space-based missions depending on the desired wavelength of study. To create a spectrograph, engineers must carefully measure out and compute all angles. Engineers use a combination of ray-trace computer programs, testing, and careful analysis using computation in order to determine the correct path the light will take in the spectrograph. A slight miscalculation will make the spectrograph useless, so it is crucial to compute these angles and then test them to make sure they are accurate before building a case to enclose the spectrograph.

**Group Size**  4

**Expendable Cost per Group**  $20

**Pre-Requisite Knowledge**
Students should have an understanding of trigonometry. They should also have an understanding of the nature of light and prisms.  They should complete "Building a Fancy Spectrograph" before attempting this activity.

**Learning Objectives**
After the lesson, students should be able to:
- Explain how a diffraction grating works.
- Define "wavelength"
- Explain the design process
- Describe sources of error

Notes on materials:
Student groups will make a materials list.  Encourage students to use materials they find around the house or school as well as materials that can be purchased.
Holographic diffraction gratings can be purchased in sheets or on card-mounted slides (Prices are from 2007) from:

Edmund Scientifics
http://scientificsonline.com/search.asp?t=ss&ss=diffraction+grating&x=0&y=0
A set of 2 12" x 6" sheets with 12,700 grooves/in. costs $7.95
A set of 15 2" x 2" card mounted slides with 12,700 Grooves/in. costs $9.95
A set of 80 2" x 2" card mounted slides with 12,700 Grooves/in. costs $39.95

Rainbow Symphony Store
http://store.rainbowsymphonystore.com
A set of 10 12" x 6" linear sheets with 500 Line/mm. costs $25.00
A set of 50 2" x 2" linear calibrated card mounted slides with 500 Line/mm. costs $20.00
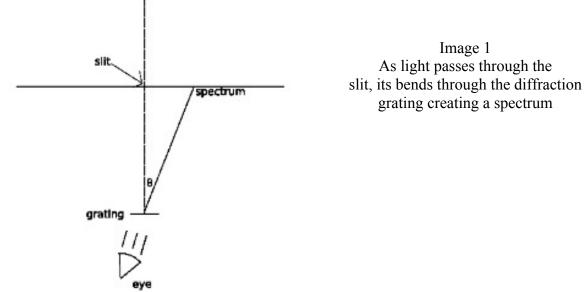A set of 100 2" x 2" linear calibrated card mounted slides with 500 Line/mm. costs $35.00

**Introduction / Motivation**

You may have heard about scientists and engineers discovering the components of the atmosphere or surface of a far-off planet, star, comet, or other astronomical body.  How can they know what the molecules and atoms of these bodies are without actually physically traveling to them?  Sometimes, they send a spaceship to the object or use spacecraft orbiting the Earth, and sometimes they can figure this out using instruments on the ground.  In all cases, they use spectrographs to measure the atomic and molecular constituents.

# Designing a Spectroscopy Mission

A spectrograph is a device that bends incoming light to form a spectrum. The first spectrographs used photographic paper, which is paper that is coated with light-sensitive chemicals. Today, most spectrographs use what is called a Charge-coupled device or CCD camera.

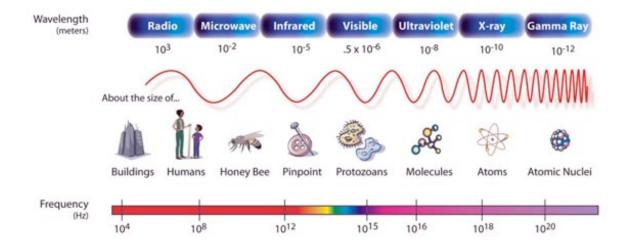Here is a diagram of how a simple spectrograph works:

slit

spectrum

θ

grating

eye

Image 1
As light passes through the slit, its bends through the diffraction grating creating a spectrum
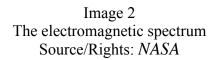
The light passes through the slit. It then makes its way to the Holographic diffraction grating. Once the light reaches the grating, it will bend at a certain angle represented by the Greek letter Theta ($\theta$). This angle is different for every wavelength. What this means is that light hitting the diffraction grating will diffract onto a surface (or within your eye), and the position of the color is dependent on the color itself!  For example, green diffracts through the grating at a different angle than violet, etc. The color that diffracts at the biggest angle is red, and the color that has the smallest angle is violet.

Light travels in waves.  Wavelength is the distance between one peak or crest of a wave of light and the next corresponding peak or crest. Wavelength is a measure of distance and is generally shown in units of micrometers, nanometers, millimeters, centimeters, and meters. As you can see from the graph, every color of light has a different wavelength. This is why we are able to see a spectrum. You can also see that there are many different types of light that we cannot see, like X-rays or radio waves.

Image 2
The electromagnetic spectrum
Source/Rights: *NASA*

A diffraction grating is a surface with a series of evenly spaced grooves on it.  When light hits the surface it diffracts, or bends, around the grooves at a certain angle dependent upon its wavelength. Today, we will be using holographic diffraction gratings.  Basically, it's a thin piece of film with a hologram of the grooves printed onto it.

The grating that will be used for this experiment has 1000 lines/mm. This means there are 1000 parallel grooves in every 1 mm of the surface. In a spectrograph, if you are looking through the holographic grating toward the light source, the image appears at that angle in front of your eye.
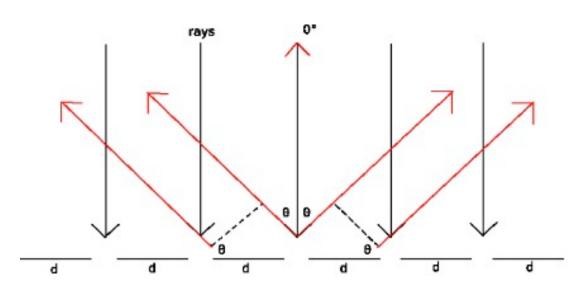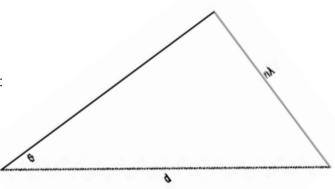
Image 3
As light travels through the slit, it transmits through the diffraction
grating at different angles θ.

The distance between the grooves is 'd'. If there are 1000 grooves per millimeter, and we want to
know the distance between the grooves, we divide the length (1 mm) by the number of grooves
(1000). This can be represented by the equation:

$$d = 1/N$$

where N = the number of grooves per unit length (in this case, millimeters)

From the diagram above, we see 'd' is the grating spacing, and 'θ' is the angle of diffraction. The
dotted line represents one complete wavelength, λ. Knowing this allows us to map out where our
spectrum will be located in our spectrograph.

Image 4: A triangle showing the angle
At which the spectrum will appear. We
Find the angle theta by using the equation:
$$n\lambda = d \times \sin(\theta)$$

We want to find λ, so using simple trigonometry we can see that:

$$\sin(\Theta) = \frac{n\lambda}{d}$$

Where n is the order number.  In this experiment, we will use n = 1.

Today, working in a group, you will begin to build a spectrograph for a mission you design.  Over the next few weeks, you will conduct research about the mission you would like to do and build a spectrograph using materials I provide as well as any additional materials you request after discussing your plan with me.  The mission can either be something you imagine, like sending your spectrograph to another planet, or something you could actually do while on the ground.  Remember, you are constrained by the wavelengths the diffraction grating is capable of producing, so you will be limited by the diffraction grating I give you today.  You are also limited by what your eye is capable of seeing!

**Vocabulary / Definitions**

| | |
|---|---|
| Wavelength | the distance between one peak or crest of a wave of light and the next corresponding peak or crest |
| Spectrum (plural:  spectra) | The pattern light produces as can be seen through a spectrograph |
| Spectrograph (also Spectroscope) | A tool that allows the components of light to be seen easily with the eye. |
| Diffraction | When light bends, as through a prism or diffraction grating. |
| Diffraction Grating | Usually a piece of film designed to act like a prism. |

**Procedure:**
**Background**

*Establishing θ*

The holographic diffraction grating used in this experiment has 1000 grooves/mm. With this number of grooves, the students will only be able to view light with wavelengths between 400 nm and 700 nm, or the visible portion of the spectrum, which also happens to be the limits of the human eye.  The students will calculate the grating spacing, which is the equation:

$$d = 1/N \qquad\qquad (eq. 1)$$

where 'd' is the grating spacing, and 'N' is the number of grooves per unit length. In this case, d = 0.001 mm. At this point, they will need to convert this to nanometers (nm). One meter is equal to 1 x $10^9$ nm OR you can calculate this by knowing that one millimeter is equal to 1 x $10^6$ nm. This gives you:

$$0.001\text{mm} \times \frac{1\text{x}10^6 \text{ nm}}{1\text{mm}} = 1000\text{nm}$$

The grating has a spacing of 1000nm. This means that the distance between each groove is 1000nm.

To solve for either wavelength of angles, use the equation:

$$\sin(\Theta) = \frac{n\lambda}{d} \qquad\qquad \text{(eq. 2)}$$

Where 'n' is the order number, '$\lambda$' is the wavelength of light, and '$\theta$' is the diffraction angle (angle to any specific color from the center of the grating). Since the students have already calculated 'd' in nanometers, the wavelength will also be in nanometers. The grating produces multiple images of the spectrum because of the properties of light, and each image is given a different order number. On one side, the spectrum is labeled with positive numbers and the other with negative numbers. For the purposes of this lab, we will state that the order number 'n' is equal to one to simplify the concept.

Students can choose a specific wavelength and compute the angle using the above equation. Solving for θ:

$$\Theta = \sin^{-1}\left(\frac{n\lambda}{d}\right) \qquad\qquad \text{(eq. 3)}$$

It is a good idea for the students to pick one color as their central wavelength. The light corresponding with the color green, 550 nm, is often a good choice (see table 1). Really, students can compute the angle to any wavelength. If they are very ambitious, they can create a fairly accurate scale for the spectrograph.

Once students know the appropriate angles associated with the grating, they can begin to establish what shape will best fit the spectrograph. They will want to make sure the spectrum appears on a flat surface, making a triangularly shaped box the best option. The box requires a slit that lets in light that will need to be placed opposite the grating, as in "Building a Fancy Spectrograph." The distance from the slit to the grating is not very important, but the angles to the edges of the spectrum are what will establish the shape of the box used.

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*Alternative Methods for Establishing θ*

There are actually a few experimental methods for determining θ for a specific wavelength. Students could shine a flashlight through the grating, directly measuring the angle of diffraction of light as described in "Engineering a Spectrograph" for several colors (see activity for details). Once they have these angles, they can compute each corresponding wavelength by solving for λ in eq. 2. Unfortunately, even with a focused flashlight, the beam is fairly diffuse, which may skew measurements.

Alternatively, a more accurate method uses a laser pointer. Shine a laser pointer through the grating to measure the angle of diffraction and solve for λ. The grating produces three laser dots (spectral orders: 1, 0, -1). Students will need to ignore the one in the middle (the zero order) and measure the angle to one of the laser dots that appears at an angle to the center of the grating as in figure 5. Typically, the wavelength of the laser is printed on it, and the students can compare the actual wavelength with the calculated one. Because we are using cheap gratings, the calculated and actual values might differ. This could lead into a discussion of accuracy and quality in engineering. The drawback to the laser pointer method is that only one color can be measured, but it will give an idea of where the color will appear in the spectrograph. With both of these methods, make sure the grating and light source aren't shifting position during the measurement by using a stand (see activity "Engineering a Spectrograph" for cheap suggestions).

Table 1

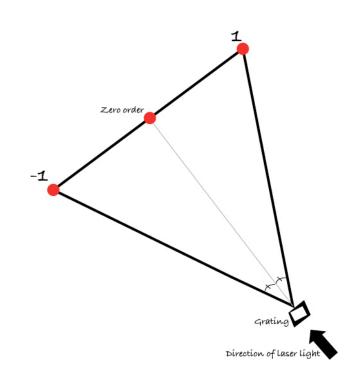| Wavelength (nm) | Angle (degrees) | Color |
|:---:|:---:|:---:|
| 380-400 | 22.3-23.6 | Violet |
| 495-570 | 29.7-34.8 | Green |
| 620-750 | 38.3-48.6 | Red |



Image 5:
The laser light through the grating produces three dots of orders (1, 0, -1). Find the angle to either the 1 n or -1 n order and compute the wavelength using the equation:
$$\lambda = d \times \sin(\theta)$$

**With the Students**

1. Hand out student instructions.
2. Assist with the calculation of the grating spacing, d.
3. Assist student groups with the calculation of the spectrum's position using equation 3.
4. Help students brainstorm spectrograph designs.

## Safety Issues

- Never have students look directly at the Sun, and advise students not to look at the Sun.

## Troubleshooting Tips

Colorblind and vision-impaired children will have difficulty with portions of this lab. Students with corrective lenses will not have difficulty. Colorblind students can be paired with a student to assist them with the activity.

Students may need assistance adjusting the position of the grating so that a continuous spectrum appears. The grating must be rotated $90^o$ if a continuous spectrum is not visible. Also, the slit should be visible through the grating. The slit should not have any light leaks or the spectrograph will not work properly.

Students may be confused that they see two spectra through the grating. The diffraction grating produces two spectra, and both are a complete spectrum of the source. Make sure the students choose one or the other, but not both.

## Assessment

**Pre-Lesson Assessment**

*Brainstorming*: Ask Students how they think spectrographs are made and why Engineers make spectrographs.

**Post-Activity Assessment**

Have the students present their designs, showing the math they use as well as how the spectrograph works. This may be a good opportunity for students to hone their PowerPoint presentation skills. Students should elaborate on the research they conducted and the mission the spectrograph will undertake.

## Owner

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**Student Instructions:**

**You and your team are NASA engineers. You have been asked to create an innovative spectrograph to conduct research in the visible region of the spectrum. Since your team knows a lot about spectroscopy, you help NASA identify the mission, establish and build a design, and present your mission and design at a national engineering conference. Consult the project manager (your teacher) with your plans before proceeding at each of the steps listed below.**

## Step 1: Establishing the mission

- You and your team will identify a problem related to solar system spectroscopy for the mission you will undertake. You can use current events, magazines, journals, and books for research. If you choose to use the Internet (which is a great place to search), please verify the sources with your teacher.

- Establish whether your mission is ground or space-based and why. What are the associated problems with ground and space-based missions?

## Step 2: Building your spectrograph

- You and your team will construct your own spectrograph using a grating that has 1000 grooves/mm. Determine the grating spacing using the equation:

$$d = 1/N \qquad \text{(eq. 1)}$$

Where 'd' is the grating spacing, and 'N' is the number of grooves per unit length. Convert 'd' into nanometers.

- Determine the location of the spectrum by establishing the angle between the grating and the spectrum and designing a box based on your calculations. Your team will determine the angle of the spectrograph optimized for viewing a spectrum by using equation 2 and solving for either wavelength or angle:

$$\text{(eq. 2)}$$

$$\sin(\Theta) = \frac{\lambda}{d}$$

Where 'λ' is the wavelength of light, and 'θ' is the diffraction angle (angle to any specific color from the center of the grating).

- You and your team will construct the spectrograph.  Some concepts to keep in mind:

   **Shape:**

   - What shape will make your spectrum lie on a flat surface?
   - What is the simplest design to build and look through?
   - Where will the light enter your spectrograph and where will the spectrum show up?

   **Size of spectrograph**:

   - How big does a spectrograph need to be to work?
   - Is there a limit to how big it could be?
   - Do you want a smaller spectrograph that is easy to take with you?
   - What is the best size to use for it to be useful and portable?
   - What are the size and weight restrictions of a space-based mission?

   **Placement of Parts:**

   - Where will you place your diffraction grating?
   - Where will the slit be placed?
   - Where will you spectrum be when you look into the spectrograph?
   - Is there anything you can do to make your spectrum easier to see?

## Step 3:  Mission and Design Analysis

Your team must determine whether your spectrograph could actually achieve the mission.  Consider the following questions:

- What are the limitations of your design and the grating?
- What aspects of the spectrograph would you need to change in order to make it work?
- What additional engineering would help to achieve the goal?

## Step 4:  Engineering Conference Presentations

You and your team will give the class a 10-minute presentation and answer questions from the classroom audience.  In the presentation, you will describe:

- Your mission
- Engineering you accomplished
- Problems you may have encountered
- Any other topics relevant to the project