Rainbow Science

Target Grades: Middle and High School

Time Required: 120 minutes

Background Information for Teachers and Students

Rainbows are fascinating phenomena that occur due to the interaction of sunlight and water droplets suspended in the air. While students are generally somewhat familiar with the separation of white light into its component colors by prisms, they are less familiar with the geometry involved in refraction and reflection of light as it impinges on the boundary between two media (in this case, air and water). This lesson plan is an investigation into the geometry requirements that enable us to see rainbows.

Lesson Objective

Students will investigate the geometry of rainbow production by performing laboratory investigations using simple equipment. They will benefit most from these experiments if they first understand vocabulary terms such as *refract*, *reflect*, *normal*, and *medium*. Prior knowledge that light travels in a straight line in a given medium is helpful, although they will observe this using the lasers. Students should be able to measure angles using a protractor, and should understand the basic geometry of a circle, including terms such as center, radius and diameter.

The activities in this lesson plan will illustrate to students that scientists investigate natural phenomena by using appropriate models. Students should be prompted to think about ways the models used in this lesson serve as good representations for rainbow production, and what the limitations of the models might be. Mathematical understanding of the Law of Reflection or Snell's Law of Refraction is not required, although high school students who have been introduced to Snell's Law can perform calculations to determine refractive indices of glass, acrylic, and water, based on the data collected. High school teachers can consider adding a calculation component to the lesson.

The activities described below in the **Instructional Process** section are designed to help students discover for themselves how the primary rainbow is produced. An extension into the production of the secondary rainbow, the dark space between rainbows, and the dark and light interference bands sometimes seen accompanying rainbows, will also be presented during the *Science Saturdays* session. Advanced students in high school physics will likely be able to understand and subsequently explain the extension activities. Students in more elementary courses should be able to explain the production of the primary rainbow, and will probably be fascinated by the extension even if it is beyond their current ability to explain.

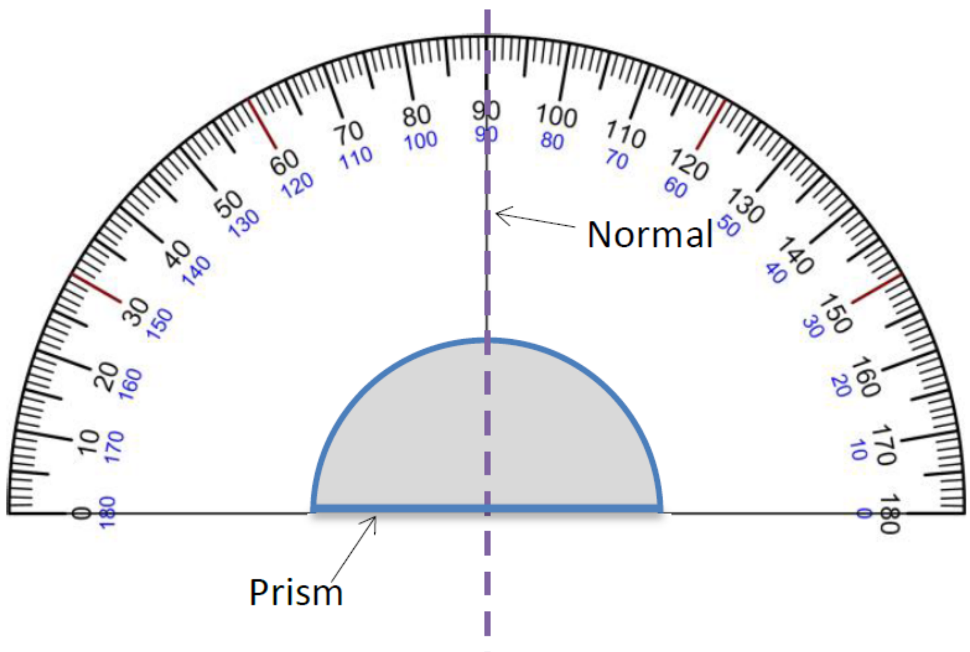
Instructional Process

Activity 1: Determination of Critical Angle

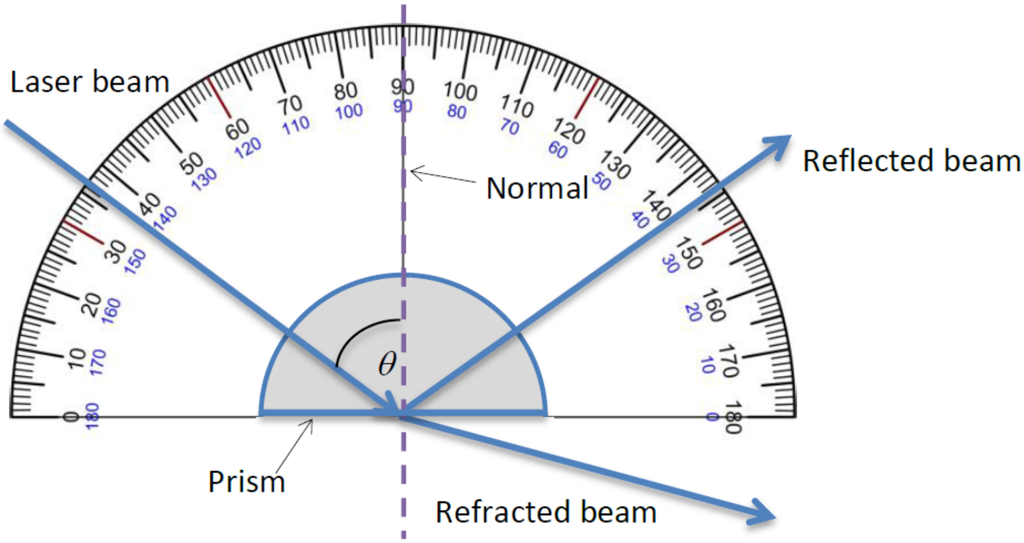
Materials needed:

- Low power red or green lasers (5mW or less)
- Protractor images printed on plain paper
- Semicircular prisms (glass and/or acrylic)

Students in small groups are given protractors printed on white paper, upon which they sketch a normal (perpendicular) to the flat side of the protractor. They then place a semicircular prism of a transparent material on the protractor as shown below.



The students then shine a laser through the material such that the beam is directed along a radius. For smaller angles q, they will see both refraction and reflection of the laser, as shown below.



The students move the laser, maintaining the beam along a radius. They will find that for large values of *q*, 100% of the light will be reflected off of the flat surface of the semicircle, and the refracted beam completely disappears. The smallest angle *q* at which total reflection occurs is called the critical angle of incidence.

The critical angle found by each student team is recorded electronically by typing the results into a Google document that is displayed in the auditorium for all to see. Students repeat the experiment for two different transparent materials, glass and acrylic, to find the critical angle for each material.

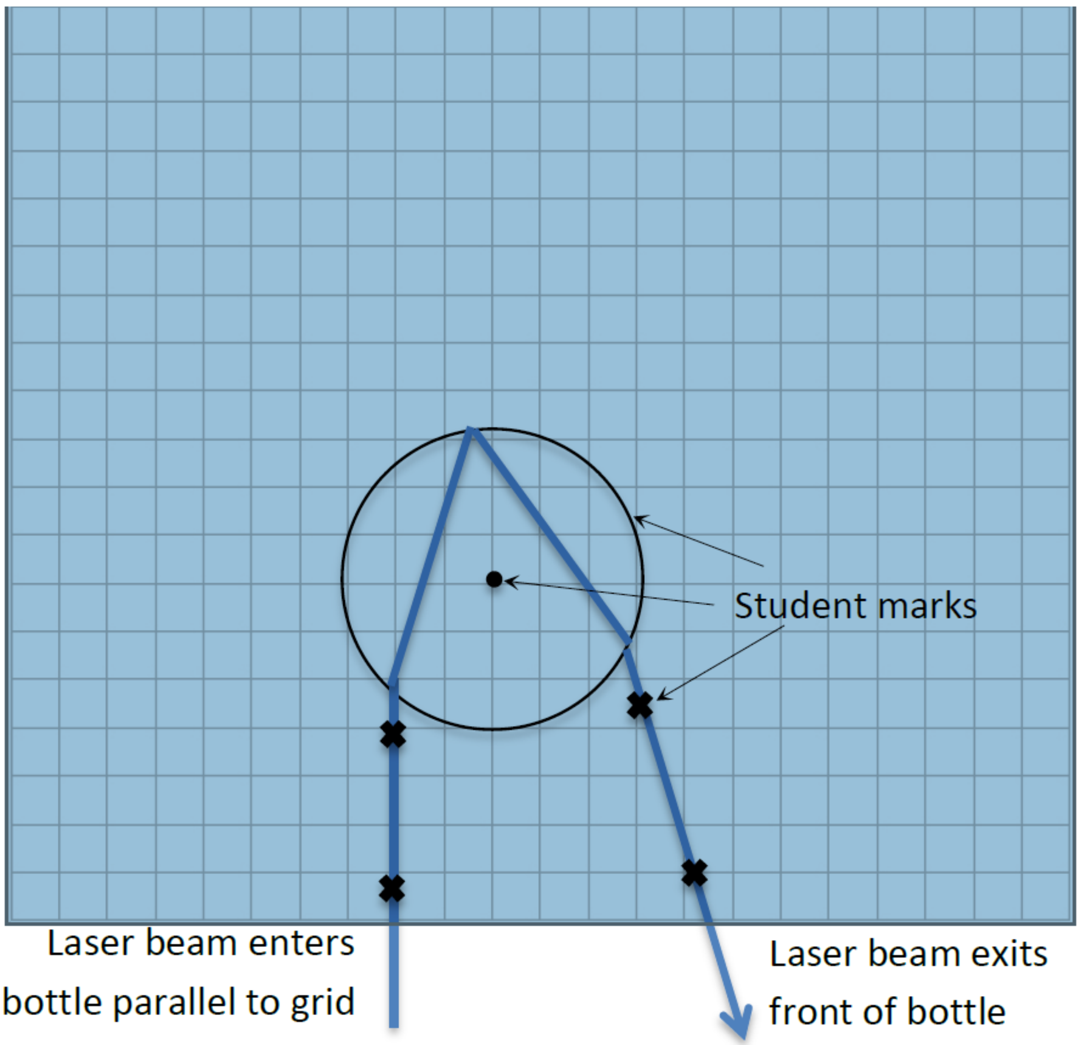
Activity 2: Determination of the Rainbow Angle

Materials needed:

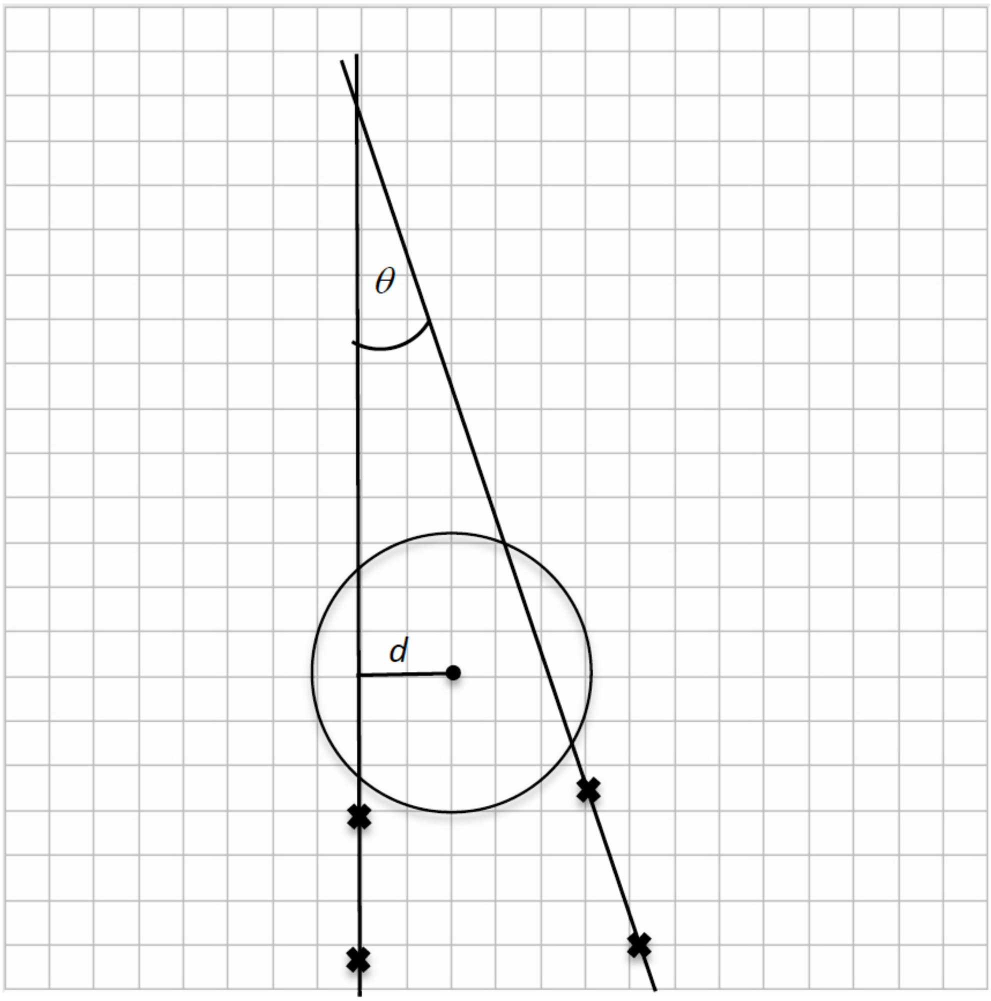
- Low power red or green lasers (5mW or less)
- Protractors
- Graph paper
- Cylindrical bottles
- Rulers

Cylindrical bottles are filled with water. A drop of whole milk is added to each bottle to create a suspension capable of scattering laser light. Student teams place the bottles on graph paper, trace the outline of the bottom of the bottle, and mark the position of the center of the bottom of the bottle.

Students then shine laser light into the bottle such that the laser beam entering the bottle is parallel to the grid lines of the graph paper. They mark the path of the beam entering and exiting the bottle. An example of the light path of interest appears below, with representative student markings. Students may notice other light paths due to reflection and refraction, but since these do not contribute to the creation of the primary rainbow, they will not be marked.



Students then analyze their data by removing the bottle, drawing lines through the points they previously marked, and measuring the angle q between their entering and exiting beam. They also measure the shortest distance *d* between the entering beam and the center of the circle by measured along a grid line. An example appears below:



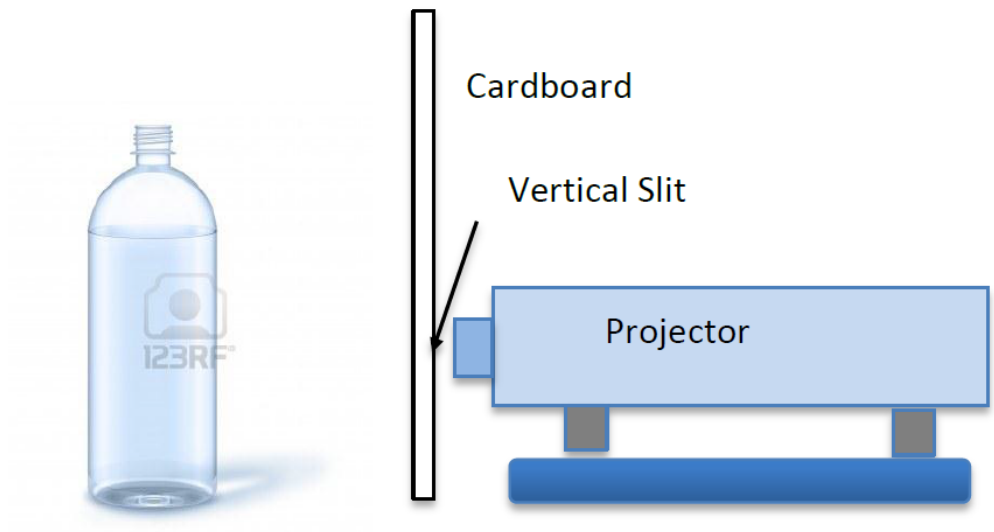
Students will repeat the measurement of θ for a range of values *d*. They will again enter their results into Google docs, and compiled results will be displayed in the auditorium.

Activity 3: Color Separation in Rainbows

- Materials needed:
- LCD projector (or alternatively, a bright white incandescent light)
- Cylindrical bottles filled with water
- Screen made of cardboard or foam board (approximately 2 feet tall and 3 feet wide) into which a vertical slit (approximately 3 inches tall and 1/8 inch wide) has been cut
- Some way to hold the screen vertically such that the projector beam shines through the slit in the cardboard.

The projector is set up to project a plain white light beam. One way to do this is to connect the projector to a computer displaying a white PowerPoint slide. If an incandescent light source is used, it must be quite bright.

To run the experiment, the room is darkened. The cardboard or foam board is placed in front of the projector beam so that the light shines through the slit. The water bottle is placed in front of the slit so the resulting narrow, vertical beam of white light shines through the bottle. The general arrangement of equipment is shown below:



Students adjust the position of the cardboard and bottle until they see a rainbow projected on the cardboard on the opposite side from the projector. Students are asked to observe the spectral ordering of the colors, as well as the characteristic curved shape of the rainbow.

Assessment/Follow-up

The results of the experiments performed by the students will be tallied and presented. For the purpose of formative assessment, students can then be asked to discuss the production of the primary rainbow, using evidence from their investigations. Below are some sample questions and student responses. Note that the responses given by different groups of students might prompt different lines of questioning and subsequent discussion.

- What role does refraction play in rainbow production?
    - Light must enter the raindrop, and exit it again. This is refraction.
    - Different colors of light are refracted through slightly different angles. This separates the colors. The water droplets in a rainbow act as tiny prisms.
- Which of these did you demonstrate during your experiments with the laser?
    - Because we had just one color laser, we did not demonstrate the separation of colors.
    - We did demonstrate with the lasers that light bends when it refracts.

- In which of the experiments did you create an actual rainbow, and what was different about this experiment to enable this to happen?
  - In the experiment with the projector, we created a rainbow.
  - You must have white light to create a rainbow, and that is the only activity where white light was used.
- Could you use lasers to investigate separation of colors by refraction? If so, how?
  - Yes, but you would need to run the same experiment with different color lasers, and compare the results to see if the colors bend through different angles.
- Why is the sun always behind you and a misty rain in front of you when you see a rainbow in the sky?
  - The sun's rays refract into water droplets, reflect off the back surface of the drops, and refract back into the air toward you. You see the sunlight when it enters your eyes.
- What evidence is there that reflection involved?
  - If the light is coming from behind you, and you see it anyway, you must have reflection going on. The light returns back to you.
- What role does critical angle have in the production of a rainbow?
  - If you think very carefully you will see that the ray of light that just touches the outer edge of the drop will be reflected at the critical angle inside the drop.
- What are the limitations of the model you used in lab, and how might it affect the results you obtained?
  - Raindrops are a lot smaller than what we used, but this would not affect angle.
  - Water droplets are spheres, not cylinders. This means the model is accurate in one plane, but not others.
  - Water is in a bottle, and there is a container involved. Maybe this affects the angles.

Key Vocabulary

- **Electromagnetic radiation:** *Electromagnetic radiation* is the name we apply to a type of wave that can travel across space without requiring a medium through which to travel. The word "*electromagnetic*" refers to the interaction between electric and magnetic fields that creates this type of radiation. While electromagnetic radiation does not require a medium to travel from one point in space to another, it is capable of traveling through some physical media, although this typically affects its speed.
- **Light:** Visible *light* is a form of *electromagnetic radiation*. Unlike other forms of electromagnetic radiation, humans can see light.
- **Normal:** A *normal* is a line that is perpendicular to a surface at the point where it meets the surface. There is only one normal to a surface at any given point. Even a curved surface has a normal at each point on the surface. For example, each radius or diameter you can draw for a circle is *normal* to the circle where it meets the circle.

- **Reflection:** *Reflection* is the bouncing of light off of a surface back into the medium from which it came.
- **Refraction:** *Refraction* is movement of light from one medium into another. Generally, when light strikes a surface that is transparent or translucent, some of the light will be *refracted* and some will be *reflected*.
- **Refractive index:** When light *refracts*, it may change speed. This change in speed occurs at the boundary between the two media. The refractive index is a ratio of the speed of light in a vacuum to the speed of light in another medium. Hence $n = c/v$, where n is the refractive index of the material, c is the speed of light in a vacuum, and v is the speed of light in the material. The higher the refractive index, the slower light will move in the material.
- **Bending Relative to a Normal:** Typically, if light does not enter a medium along a normal to a surface, the light will bend as it refracts. If it slows down when it enters the medium, it will bend *toward the normal* at the boundary. If it speeds up when it enters a medium, it will *bend away from the normal*.
- **Angle of Incidence:** When light strikes a boundary between two media, the *angle of incidence* is the angle between the ray of light in the original medium and a normal to the boundary surface.
- **Angle of Reflection:** When light strikes a boundary between two media and reflects back into the original medium, the *angle of reflection* is the angle between the reflected ray of light and a normal to the boundary surface.
- **Law of Reflection:** The *Law of Reflection* states that the angle of reflection is always equal to the angle of incidence.
- **Angle of Refraction:** When light strikes a boundary between two media and refracts into the second medium, the *angle of refraction* is the angle between the refracted ray of light and a normal to the boundary surface. The angle of refraction depends upon the refractive indices of the two media and the angle of incidence.
- **Snell's Law:** Snell's Law mathematically describes the relationship between angles of incidence and refraction and the refractive indices of the media. In equation form, Snell's Law is written as $n_1 sin(q_1) = n_2 sin(q_2)$, where n_x is the refractive index of medium x, and qis the angle between the light ray and the normal in that medium.
- **Critical Angle:** When light strikes a boundary between two media and would speed up in second medium, it may have to bend so far away from the normal in the second medium that it cannot refract at all. In this circumstance, the all of the light will reflect back into the original medium. The smallest angle at which this occurs is called the critical angle.

Safety and Cleanup Required

Because lasers are used in Activity 1 and 2 of this lesson, care must be taken to insure safety. Students must be adequately supervised, and should not be allowed to handle the lasers without direct adult engagement. Laser safety rules (not waving the laser around, not shining it into eyes) should be explicitly addressed before the experiments are performed.

After the investigations are complete, students should return all materials.

Alignment with TN Science and Math Standards

Elementary School

As early as fourth grade, students consider light traveling through materials *(GLE 0407.10.2, SPI 0407.10.2, and check for understanding 0407.10.2)*

Grade Level Expectations	Checks for Understanding	State Performance Indicators
GLE 0407.10.1 Distinguish among heat, radiant, and chemical forms of energy. **GLE 0407.10.2** Investigate how light travels and is influenced by different types of materials and surfaces.	✓**0407.10.1** Design an investigation to demonstrate how different forms of energy release heat or light. ✓**0407.10.2** Design an experiment to investigate how different surfaces determine if light is reflected, refracted, or absorbed ✓**0407.10.3** Gather and organize information about a variety of materials to categorize them as translucent, transparent, or opaque.	**SPI 0407.10.1** Identify different forms of energy, such as heat, light, and chemical. **SPI 0407.10.2** Determine which surfaces reflect, refract, or absorb light. **SPI 0407.10.3** Determine whether a material is transparent, translucent, or opaque.

Middle School

Students should be able to apply prior knowledge about reflection and refraction as they perform inquiry-based laboratory investigations. The emphasis is experimentation, observation, and data recording. Students are becoming familiar with making claims from evidence. *(GLE 0607.Inq.2, 0607.Inq.3, 0607.Inq.5, SPI 0607.Inq.4, and check for understanding 0607.Inq.3)*

Grade 6 : Embedded Inquiry		
Conceptual Strand *Understandings about scientific inquiry and the ability to conduct inquiry are essential for living in the 21st century.*		
Guiding Question *What tools, skills, knowledge, and dispositions are needed to conduct scientific inquiry?*		
Grade Level Expectations	**Checks for Understanding**	**State Performance Indicators**
GLE 0607.Inq.1 Design and conduct open-ended scientific investigations. **GLE 0607.Inq.2** Use appropriate tools and techniques to gather, organize, analyze, and interpret data. **GLE 0607.Inq.3** Synthesize information to determine cause and effect relationships between evidence and explanations. **GLE 0607.Inq.4** Recognize possible sources of bias and error, alternative explanations, and questions for further exploration. **GLE 0607.Inq.5** Communicate scientific understanding using descriptions, explanations, and models.	✓**0607.Inq.1** Design and conduct an open-ended scientific investigation to answer a question that includes a control and appropriate variables. ✓**0607.Inq.2** Identify tools and techniques needed to gather, organize, analyze, and interpret data collected from a moderately complex scientific investigation. ✓**0607.Inq.3** Use evidence from a dataset to determine cause and effect relationships that explain a phenomenon. ✓**0607.Inq.4** Review an experimental design to determine possible sources of bias or error, state alternative explanations, and identify questions	**SPI 0607.Inq.1** Design a simple experimental procedure with an identified control and appropriate variables. **SPI 0607.Inq.2** Select tools and procedures needed to conduct a moderately complex experiment. **SPI 0607.Inq.3** Interpret and translate data in a table, graph, or diagram. **SPI 0607.Inq.4** Draw a conclusion that establishes a cause and effect relationship supported by evidence. **SPI 0607.Inq.5** Identify a faulty interpretation of data that is due to bias or experimental error.

High School

High school physics courses address optics phenomena. Some sample high school standards addressed by this investigation include:

Physics:

CLE 3231.4.3 Explore the optics of lenses.
CLE 3231.4.4 Analyze the optics of mirrors.
SPI.3231.4.3 Solve problems related to Snell's Law.
SPI.3231.4.6 Using light ray diagrams, identify the path of light using a convex lens, a concave lens, a plane mirror, a concave mirror and a convex mirror.

Physical World Concepts:

CLE 3237.3.8 Explore the optical principles of mirrors and lenses.
CFU 3237.3.12 Investigate reflection, refraction, diffraction, and interference of light waves.