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|  | Spy Spotting ScopeTeacher Edition |
| **Subject(s)/Course(s):** Physical Science | **Grade Level:** High School | **Duration:** One 80 minute block |
| **Lesson Synopsis/Narrative:** Students will learn about how convex and concave lenses form real and virtual images. Students will learn how they can be paired to magnify images to create a spotting scope. |
| **Prior Knowledge:**Snells law and the Rochester Cloak with ray diagrams should be taught first. It would be advantageous if they knew the vocabulary words and real vs virtual images first. |
| **Background information:**Spotting scopes area class of small portable telescopes that are optimized for observation of terrestrial objects. They are commonly used for hunting, marksman sports, surveillance, and other naturalist activities when the application requires more magnification than a pair of binoculars. |
| **Challenging Question or Problem:** How can we create a spotting scope to spy on small objects across the room? **Open Question:** What is the minimum spy spotting scope focal length required to optically resolve the license plate on an oncoming car that is 1,000 meters away using the image sensor on your cell phone. (camera without the lens) |
| **Phenomenon and Manufacturing Application:** Optimax or QED Optics. Any optics company that manufactures lenses for spotting scope applications. |
| **Examples (in action):**U.S. Army Spc. Zachary Dixson, with the 173rd Airborne Brigade Combat Team uses a spotting scope to watch for simulated enemy combatants during an exercise at the Joint Multinational Readiness Center in Hohenfels, Germany, on March 21, 2012. *Defense.gov News Photo 120321-A-ML570-006 Author Sgt. Eric M. Garland II, U.S. Army* | **Vocabulary:**LensConvexFocal pointFocal lengthPrincipal axisReal imageVirtual imageObjectiveEyepiece |
| **State and National Standards & 21st Century Skills:**HS-PS4-6: Use mathematical models to determine relationships among the size and location of images, size and location of objects, and focal lengths of lenses and mirrors. Emphasis should be on analyzing ray diagrams to determine image size and location. Assessment Boundary: Assessment is limited to analysis of plane, convex, and concave mirrors, and biconvex and biconcave lenses. |
| **Science and Engineering Practices**Using Mathematics and Computational Thinking* Use mathematical representations of phenomena or design solutions to describe and/or support claims and/or explanations. (HS-PS4-1),(HS-PS4-6)
 | **Disciplinary Core Ideas**PS4.A: Wave Properties* (NYSED) The location and size of an image (real or virtual) are related to the location and size of an object and the focal distance for biconvex and biconcave lenses. (HS-PS4-6)
 | **Crosscutting Concepts**Patterns * Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena. (HS-PS4-6)
* Mathematical representations can be used to identify certain patterns. (HSPS4-6)
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| **Learning Targets:**1. Students will be able to explain how convex lenses in an optical assembly can be used to magnify the image of objects.
2. Students will draw ray diagrams for convex and concave lenses.
3. Students will determine the relative size and location of an image as it goes through the optical assembly by analyzing the ray diagram.
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| **Materials and Equipment Per Group:**1, 50mm, f=50mm convex lens1, 50mm, f=100mm convex lens1, 50mm, f=100mm concave lens1, 50mm, f=200mm concave lens1, 50mm, f=200mm convex lens1, 50mm, f=300mm convex lens1, 50mm, f=300mm concave lens1, 50mm, f=500mm convex lens1 optical tube assembly2 laser blox (color ultimately does not matter but red and green is safer)Fog Machine (only if the activity is performed outside or in a room with heat detectors. DO NOT use fog machine in a room with smoke detectors). |
| **Materials not provided in kit, preparation/time:**1, metric rulerBlank paperPoster paper or receipt paperMarkers |
| **Safety:**NEVER point the spotting scope towards the sun, never look at the sun with the spotting scope. Doing so can cause burns, permanent eye damage, or property damage. Lasers are light sources that can permanently damage the eye. They are not toys. If you stare into a laser beam for a period of time, permanent and irreparable damage to the eye can occur. The Laser Blox set provided in the kit is a Class IIIR laser product. At this power rating the human eye blink reflex will prevent any permanent eye damage. To reduce the chance of eye injury, do not completely darken the room as to prevent complete pupil dilation.Laser safety posters should be posted around the classroom when they are in use. Information about laser classifications and safety:<http://www.lasersafetyfacts.com/laserclasses.html> |
| Procedure and Prompts:

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| Teacher Does and Says | Student Does and Says |
| **Introduction:**  |
| Students read the article and answer the questions based on the text. | The history of telescopes article1. What was Lippershey’s specific contribution to the invention of the telescope?
2. How did the earliest telescopes work?
3. How did Galileo change the course of history with the telescope?
4. What are some important discoveries that telescopes have aided in the past century?
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| **Part A: Review Convex Lenses** |
| Reinforce laser safety and the rules of the classroom when using lasers. Make sure all lasers are pointed below chest level at all times and that students do no play with them.Distribute a 50mm and 200mm focal length convex lens, two lasers, a piece of paper, and a ruler to each group. If you are in a room that uses heat detectors instead of smoke detectors (usually chemistry rooms), you can have the students use the fog machine to observe the incident and refracting light. Prompt the students to use the longer focal length lenses first. | First Lens:Using the two lasers stacked on top of each other and one convex lens, place the lens in the tube holder and aligning the lasers to the principle axis, turn the lasers on and investigate how the light bends when it passes through the lens.Place your finger or a small piece of paper in the path of the laser after it refracts through the lens. Move it close to the lens and then away. Using the ruler, verify what the focal length of the lens is by using your observations. |
| Optional |
| Students should determine that the light rays are NOT refracted when the ray passes directly through the center of the lens. This will be useful when determining the location of an image that passes through a lens.Ray diagrams are useful tools to determine the path that the light takes when it refracts through the lens. It can also help determine the location and size of an image. | Draw the path of the laser as it refracts through the lens using the attached sheet. This is known as a ray diagram. |
| Guide students on how they might create a scale drawing of the image using the focal length of the convex lens. Example:Ask the students if the image is real or virtual and why.To determine image distance the students can use trig, measure directly, or use the lens equation. The relationship between the focal length (f), object distance (do), and image distance (di) is $\frac{1}{f}=\frac{1}{d\_{o}}+\frac{1}{d\_{i}}$For this example the image distance (di) should be 75mm.To determine the image height the students can use trig, measure directly, or use the magnification equation. The magnification (M) equation is the ratio of the image distance (di) to the object distance (do) as well as the ratio of the image height (hi) to the object height (ho). $M=\frac{h\_{i}}{h\_{o}}=-\frac{d\_{i}}{d\_{o}}$ For this example the image height (hi) should be 7.5mm.<http://www.physicsclassroom.com/class/refrn/Lesson-5/The-Mathematics-of-Lenses><http://www.rocketmime.com/astronomy/Telescope/Magnification.html> | **Images from Lenses:** Lenses bend the light to manipulate an image. Convex lenses can form real or virtual images. We will first explore how real images are formed with theses lenses.Real images are formed when the object that is creating the image is further from the lens than the focal point of the lens. Locating images through ray tracing.We can locate the image of an object as it pertains to the lens by following three rules (see figure 1 below)1. A ray coming from the image that is parallel to the principle axis of the lens will pass through the focal point on the opposite side of the lens (see ray 1 in figure 1).
2. A ray coming from the image that passes through the focal point on the same side of the lens will emerge from the lens parallel to the principle axis (see ray 2 in figure 1).
3. A ray coming from the image that passes through the center of the lens will not experience any change in direction (see ray 3 in figure 1).

The location of the image is where all three of the rays converge. The size, orientation, and location of the image can be determined from this point (see the figure 1 below).In the area below, create a scale drawing that shows the location, size, and orientation of the image that is 1.5cm tall and 30cm away for the 200mm focal length convex lens (use the receipt paper if you need to). Figure 1: |
| **Constructing a Traditional Refracting Telescope** |
| Resources:On telescopes: <http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/teles.html>On microscopes: <http://hyperphysics.phy-astr.gsu.edu/HBase/geoopt/micros.html>Go over citations and appropriate websites for information with students.Distribute the f=300mm lens to each group.Students should discover:- The objective needs to be the lens with the longer focal length (300mm) and the eyepiece has the shorter focal length (50mm). - The distance between lenses is the sum of the focal lengths. (350mm) | Research the construction of a traditional refracting telescope. Determine which lens needs to be the objective, which lens needs to be the eyepiece, and how far apart to place them.What is the difference in optical design between a microscope and a telescope? |
| When using the telescope, the operator must be observing an object that is considered to be at infinity (usually greater than 20 feet) for it to be in focus. <https://en.wikipedia.org/wiki/Infinity_focus>NEVER point the spotting scope towards the sun, never look at the sun with the spotting scope. If you are not observing an object at infinity, instruct the students to make small adjustments with the position of the eyepiece with respect to the objective until the image is in focus.Students should research optical defects and distortions. Prompt students to click on each image defect and play with the java app that allows you to see the distortion in action. This will greatly aid in proper identification of the image distortions. <https://micro.magnet.fsu.edu/primer/anatomy/aberrationhome.html>Students should find that there is some chromatic distortion and significant geometric (specifically pincushion) distortion present. | Place the lenses in the optical tube assembly at the proper distances and assemble the tube by carefully placing the second half on top and securing it with the end stops. NEVER point the spotting scope towards the sun, never look at the sun with the spotting scope. Observe an object that is at infinite focus or far away. If the object is not in perfect focus you can make small adjustments with the position of the eyepiece with respect to the objective.Describe the image of the object, is it inverted, are there any optical defects or distortions, how large is the object?Investigate optical image aberrations to help answer the question: <https://micro.magnet.fsu.edu/primer/anatomy/aberrationhome.html> |
| At this point distribute the f=100mm convex lens, f=200mm convex lens, and f=500mm convex lens to each group.The students should discover that the magnification of the image increases when the focal length of the objective increases while keeping the eyepiece focal length the same. The magnification of the image decreases when the focal length of the eyepiece increases while keeping the objective focal length the same.The angular magnification of a telescope is the focal length of the objective divided by the focal length of the eyepiece =-fo/fe | Students change the objective and eyepiece lenses and record their results in the table provided. |
| Guide students on how they might create a scale drawing of the image using the focal length of the convex lens. Example: | Virtual images are formed when the object that is creating the image is closer to the lens than the focal point of the lens. Classical telescopes create virtual images.Locating images for the telescope through ray tracing.We can locate the image of an object through a telescope as it pertains to the lens by following two rules.1. A ray entering the lens parallel to the principle axis coming from the image passes through the focal point on the opposite side of the lens.
2. A ray coming from the image that passes through the center of the lens will not experience any change in direction.

The location of the image is where the two rays converge. The size, orientation, and location of the image can be determined from this point.In the area below, create a scale drawing that shows the location, size, and orientation of the image that is 1.5cm tall and 30cm away for the 200mm focal length objective and 50mm focal length eyepiece (use the receipt paper if you need to). |
| Answers to the questions:1. Virtual
2. Inverted
3. 4x’s Students can find their answer by measuring the size of the object and then the size of the image on their ray diagram or they can use the magnification equation for a telescope. The angular magnification of a telescope is the focal length of the objective divided by the focal length of the eyepiece =-fo/fe
 | Questions:1. Is the image real or virtual?
2. Is the image upright or inverted?
3. How many times larger is the image than the object? (show all work and/or reasoning for your solution.)
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| **Optional** |
| Students should realize that all they have to do is look through the other end of the tube to turn it into a microscope. For a microscope the students want the objective to be the lens with the shorter focal length and the eyepiece to be the lens with the longer focal length. | Addition:Use the optical assembly of the telescope just created as a microscope instead of a telescope. What did you have to do differently? |
| **Part B: Concave Lenses** |
| Reinforce laser safety and the rules of the classroom when using lasers. Make sure all lasers are pointed below chest level at all times and that students do no play with them.Distribute the 100 mm concave lens to each group. Do not tell them that it is 100 mm and see how close they are able to determine the focal length of the lens. If you are in a room that uses heat detectors instead of smoke detectors (usually chemistry rooms), you can have the students use the fog machine to observe the incident and refracting light. If the students get stuck on how to determine the focal length of the diverging lens you can prompt them to research the method. | First Concave Lens:Using the two lasers stacked on top of each other and one concave lens, place the lens in the tube holder and aligning the lasers to the principle axis, turn the lasers on and investigate how the light bends when it passes through the lens.Place your finger or a small piece of paper in the path of the laser after it refracts through the lens. Move it close to the lens and then away. Develop a way to determine the focal length of the diverging lens by plotting the path. |
| Correct students if they do not get that the focal length of the lens is 100mm.Students should determine that the light rays are NOT refracted when the ray passes directly through the center of the lens. This will be useful when determining the location of an image that passes through a lens.Ray diagrams are useful tools to determine the path that the light takes when it refracts through the lens. It can also help determine the location and size of an image. | Draw the path of the laser as it refracts through the lens. This is known as a ray diagram. |
| Guide students on how they might create a scale drawing of the image using the focal length of the concave lens. Example:Ask the students if the image is real or virtual and why. How this image differs from the images created by the convex lens.To determine image distance the students can use trig, measure directly, or use the lens equation. The relationship between the focal length (f), object distance (do), and image distance (di) is $\frac{1}{f}=\frac{1}{d\_{o}}+\frac{1}{d\_{i}}$For this example the focal length is negative and the found image distance (di) should be -60mm.To determine the image height the students can use trig, measure directly, or use the magnification equation. The magnification (M) equation is the ratio of the image distance (di) to the object distance (do) as well as the ratio of the image height (hi) to the object height (ho). $M=\frac{h\_{i}}{h\_{o}}=-\frac{d\_{i}}{d\_{o}}$ For this example the image height (hi) should be 6 mm. | **Images from Concave Lenses:** Unlike convex lenses, concave lenses form only virtual images as they bend the light away from a real focus (diverging lens). Locating images through ray tracing.We can locate the image of an object as it pertains to the lens by following three rules (see the figure below)1. A ray coming from the image that is parallel to the principle axis of the lens will pass through the focal point on the same side of the lens (see ray 1 in figure).
2. A ray coming from the image that passes through the focal point on the opposite side of the lens will be parallel to the principle axis on the same side of the lens as the image (see ray 2 in figure).
3. A ray coming from the image that passes through the center of the lens will not experience any change in direction (see ray 3 in figure).

The location of the image is where all three of the rays converge. The size, orientation, and location of the image can be determined from this point (see the figure below).In the area below, create a scale drawing that shows the location, size, and orientation of the image that is 1.5cm tall and 15cm away for the \_\_\_\_mm focal length concave lens (use the receipt paper if you need to).Example: |
| **Constructing a Galilean Refracting Telescope** |
| Resources:On telescopes: <http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/teles.html>Students will use the 300mm convex lens and the 100mm concave lens that they have.Students should discover:- The objective needs to be the convex lens with the longer focal length and the eyepiece has to be the concave lens with the shorter focal length. - The distance between lenses is the subtraction of the focal lengths.  | Constructing a Galilean refracting telescope:Research the construction of a Galilean refracting telescope. Determine which lens needs to be the objective, which lens needs to be the eyepiece, and how far apart to place them.What is the difference in optical design between a traditional telescope and a Galilean telescope? |
| When using the telescope, the operator must be observing an object that is considered to be at infinity (usually greater than 20 feet) for it to be in focus. <https://en.wikipedia.org/wiki/Infinity_focus>NEVER point the spotting scope towards the sun, never look at the sun with the spotting scope. If you are not observing an object at infinity, instruct the students to make small adjustments with the position of the eyepiece with respect to the objective until the image is in focus.Students should research optical defects and distortions. Prompt students to click on each image defect and play with the java app that allows you to see the distortion in action. This will greatly aid in proper identification of the image distortions. <https://micro.magnet.fsu.edu/primer/anatomy/aberrationhome.html>Students should find that there is some chromatic distortion and significant geometric (specifically pincushion) distortion present.The angular magnification of a telescope is the focal length of the objective divided by the focal length of the eyepiece =-fo/feIn this example the magnification is 3x’s | Place the lenses in the optical tube assembly at the proper distances and assemble the tube by carefully placing the second half on top and securing it with the end stops. Observe an object that is at infinite focus or far away. If the object is not in perfect focus you can make small adjustments with the position of the eyepiece with respect to the objective.NEVER point the spotting scope towards the sun, never look at the sun with the spotting scope. Describe the image of the object, is it inverted, are there any optical defects or distortions, how large is the object?Investigate optical image aberrations to help answer the question: <https://micro.magnet.fsu.edu/primer/anatomy/aberrationhome.html>Is the image upright or inverted?How many times larger is the image than the object (what is the magnification of the image)? Show all work and/or reasoning for your solution below. |
| Distribute the remaining concave lenses. The 200mm concave lens and 300mm concave lens.The students should discover that the magnification of the image increases when the focal length of the objective increases while keeping the eyepiece focal length the same. The magnification of the image decreases when the focal length of the eyepiece increases while keeping the objective focal length the same.The angular magnification of a telescope is the focal length of the objective divided by the focal length of the eyepiece =-fo/fe | Students change the objective and eyepiece lenses and record their results in the table provided. |
| **Open Question:** What is the minimum objective focal length required to optically resolve the license plate on an oncoming car that 1,000 meters away using the image sensor on your cell phone at prime focus. (camera without the lens) |
| <https://www.ephotozine.com/article/complete-guide-to-image-sensor-pixel-size-29652#Smartphone>To solve this problem the students will need to use the lens equation as well as the magnification equation (previously introduced in this lesson). The relationship between the focal length (f), object distance (do), and image distance (di) is $\frac{1}{f}=\frac{1}{d\_{o}}+\frac{1}{d\_{i}}$The magnification (M) equation is the ratio of the image distance (di) to the object distance (do) as well as the ratio of the image height (hi) to the object height (ho). $M=\frac{h\_{i}}{h\_{o}}=-\frac{d\_{i}}{d\_{o}}$ Introduce students to resources that will help them understand the problem. Having students read the Analog and Digital Data article will help them understand digital imaging.Begin by asking students to think of all of the variables that they need to know. They should write down, come to the conclusion that they need:* Size of the writing on the license plate (specifically thickness)
* The size of each pixel on the image sensor

Students can physically measure the size of the writing on the license plate. For a NYS license plate they should measure that the thickness of the line that makes up the license number is around 0.5cm. The size of each pixel on the image sensor requires them to look information up. Occasionally they will only find information related to the physical size of the image sensor and the number of pixels on the detector. <https://www.ephotozine.com/article/complete-guide-to-image-sensor-pixel-size-29652#Smartphone>**Example:** The iPhone 6S has a 12 Megapixel camera with sensor dimensions of 4.8mm x 3.6mm . Students can find the dimensions of each pixel by dividing the area of the detector by the number of pixels. Area of detector $4.8mm x 3.6mm=17.88mm^{2}$ Area of a pixel $=\frac{17.88mm^{2}}{12,000,000 pixels}=1.44x10^{-6}\frac{mm^{2}}{pixel}$Dimension of each pixel (they are square) = $\sqrt{1.44x10^{-6}\frac{mm^{2}}{pixel}}=0.0012mm$ Known variables:$d\_{o}=1x10^{6}mm$ (distance to object)$h\_{o}=5mm$ (height of the object, in this case the width of a line on the license plate)$h\_{i}=0.0012mm$ (height of the image on the sensor, which is one pixel)Unknown Variables:$f$ (focal length of lens)$d\_{i}$ (distance from lens to image). Using $\frac{1}{f}=\frac{1}{d\_{o}}+\frac{1}{d\_{i}}$ and $\frac{h\_{i}}{h\_{o}}=-\frac{d\_{i}}{d\_{o}}$ , the students are looking for the focal length of the lens $f$. Students should recognize that they have to solve by substitution of simultaneous equations to find $f$. The equation the students should get is: $\frac{1}{f}=\frac{1}{d\_{o}}-\frac{h\_{o}}{h\_{i}d\_{o}}$ Finally plugging in the known values and solving for $f=240mm$ Have students choose a lens that is equal to or longer than the focal length that they got. Place the lens in the optical tube assembly at the proper distance from an end stop (they will have to measure the distance from the tube to the outside end of the stop) and assemble the tube by carefully placing the second half on top and securing it with the end stops. Place a piece of tissue paper over the end and point the lens in the direction of something far away and bright (never point it directly at the sun). Students should observe the image projected onto the tissue paper. | The objective lens on a telescope creates a real image, just like how a camera lens creates a real image on a film (or a CCD/CMOS sensor using current technology). If you place your eye where this real image is, at the prime focus or objective focus of a telescope, you will not see an image. The reason why is because your eye is another optical system trying to create a real image. Your eye focuses an image onto an area on the back of your eye called the retina (see diagram below). It cannot focus a real image created by objective lens. Your eye requires a virtual image to focus a real image on the retina. The eyepiece creates a virtual image that your eye can focus into a real image.File:Accommodation (PSF).svgC:\Users\sthorndi\AppData\Local\Microsoft\Windows\INetCache\Content.Word\Classical Telescope.jpgOnce you have solved for the minimum focal length, choose a lens that satisfies the minimum focal length requirement. Place the lens in the optical tube assembly at the proper distance from an end stop and assemble the tube by carefully placing the second half on top and securing it with the end stops. Place a piece of tissue paper over the end and point the lens in the direction of something far away and bright (never point it directly at the sun). What do you see on the tissue paper? Why? |

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