Geometrical Optics (Remote Lab)

So far this quarter, we have treated light as a wave. While that treatment is always correct, there are cases – namely when the wavelength of the light is much smaller than the optical component it is traveling through – when it is possible to simplify our life and treat light as if it travels in a direct, straight line. Treating light as such lines, called rays, is known as geometrical optics (as opposed to wave optics), and we will explore some of the phenomena of geometrical optics in today's lab.

Motivation

If you ask the average person on the street what they think of if they hear the word "optics," you will likely hear many different answers; they might mention light or camera lenses or just "seeing" in general. Indeed, the study of optics is often used to help humans "see" better – be it through zoom lenses on your phone's camera, the mirror you use in your bathroom each morning, a microscope studying amoeba in a biology lab, or one of the many telescopes pointed deep into space right now.

For today's video, we'll look at a particular optical setup known as Schlieren imaging. This is a great topic to start us off because it involves several of the geometrical optics features we'll study in more depth below (as well as a few phenomena you've already seen this quarter) including wave speed, refraction, lenses, and mirrors.

The video goes pretty fast, so we screengrabbed the most important part (shown in Fig. 1) and we'll break it down. Look at the image of the candle on the camera and match up the three distinct features to their causes.

- The stem of the candle is black because the candle itself blocks the light from the candle. Nothing fancy here... this is just the normal candle shadow.
- The light passing to the sides of or well above the candle travels in straight lines and is focused into the camera. Again, nothing fancy here... the light travels in straight lines and ends up right where we expect it to.
- Finally, the light passing right over the top of the burning candle travels through warmer air than all the rest of the light rays. Because the index of refraction of warm air slightly different from the index of the rest of the air, the light is bent when it passes through that part. Now, instead of being focused to where the other rays are focused, its focal point is offset and it is blocked by the barrier. Therefore, it too creates a sort-of shadow on the image...one that changes and moves as the air above the camera changes in temperature and density.
This slight bending of light is always happening, but it's so tiny that our eyes don't notice it. It is only with the particular Schlieren optics setup – a point source of light (so we have very direct, bright rays), a long path length (to exaggerate the bending), and the barrier (to cause the new shadows from the bent light) – that we can “see” the effect at all.

If you want to see some other videos that show off the cool videos you can make with a Schlieren setup, check out the videos from Veritasium, Smarter Every Day and the Harvard Natural Sciences Lecture Demonstrations Team.

Experimental procedure

Uncertainties

A quick note on uncertainties. This week’s lab is mostly qualitative. There are many numbers involved, but you aren't making many direct measurements or performing many calculations. As a result, there isn't a need for rigorous uncertainties; when you do compare numbers they will usually be either very close or very far apart and so it will be obvious at a glance whether the numbers are “the same” or not.

So, let's just be clear at the outset; there's no need to keep track of uncertainties this week.

Lab report template

Click the link below to access the template for this week’s lab.

Simulation: Light reflection and refraction

Theory

When light strikes a plane mirror and reflects from its surface, the angle of reflection, $\theta_r$, is equal to the angle of incidence, $\theta_i$, both angles being measured from the normal to the mirror surface:

$$\theta_i = \theta_r$$  (1)
When light passes from one transparent medium into another, the light will change speed at the interface between the two media. This change in speed is accompanied by a change in direction or refraction of the light. The angle through which the light changes direction depends on the angle of incidence at which the light strikes the surface and a characteristic of the media at the interface. This characteristic is known as the index of refraction, \( n \), which is defined as

\[
\frac{\nu_{\text{vacuum}}}{\nu_{\text{medium}}}, \quad (2)
\]

where \( \nu_{\text{vacuum}} \) is the speed of light in a vacuum and \( \nu_{\text{medium}} \) is the speed of light in the medium. Note that since light always slows down when it travels through a medium, \( n \geq 1 \).

**Simulation**

For this part, we will use the **Bending Light** PhET simulation.


Open the simulation up and select the **Intro** mode. Keep the display set to **Ray** (not Wave).

Notice that you have a **protractor** (for measuring angles) and an **intensity meter** (for measuring light intensity as a percentage of the incident light intensity) in the lower left corner. Also note that you can select to turn turn on or off the dotted line marking the normal (or perpendicular) to the interface between your two media.

As usual, the orange circle in the lower right corner will reset the simulation back to its default starting settings.

**Getting oriented**

Answer the following questions for yourself... they do not need to be recorded in your lab report.

Turn on your laser pointer, and get oriented by observing how a ray of light is reflected and/or refracted at different surfaces.

- What happens when the index of refraction of the two media is the **same**? When the incident side is **greater than** the refracted side? When the incident side is **less than** the refracted side?
- Can you find cases where **no refraction** occurs? (If so, what are the conditions?)
- Can you find cases where **no reflection** occurs? (If so, what are the conditions?)

For one angle of incidence and for air into water...

- What is the angle of incidence?
- What is the angle of reflection? What is the light intensity of this ray?
- What is the angle of refraction? What is the light intensity of this ray?

**Exercises**

Three students – Julio, Margo and Alex – brainstormed ideas for how the angle of refraction could depend on the angle of incidence and the index of refraction of the two media. After some discussion, the three proposed the following ideas (where the subscript 1 is the incident medium and 2 is the refracted medium):

- **Julio:** \( n_1 \sin \theta_1 = n_2 \sin \theta_2 \)
- **Margo:** \( n_1 \theta_1 = n_2 \theta_2 \)
- **Alex:** \( n_1 + n_2 = \sin \theta_1 + \sin \theta_2 \)

What kind of experiment can you devise to determine which suggestion (if any) is correct? Perform it and decide who is correct!

As the three played around to test out their hypotheses, they also noticed that the intensity of the reflected light changed with both the angle and the index of refraction. Picking the simple case of \( \theta_1 = \theta_2 = 0 \) (that is, sending the beam directly normal (perpendicular) to the surface, not at an angle), they again came up with three suggestions, as follows (where \( r \) is the reflected ray, and \( i \) is the incident wave):

- **Julio:** \( \frac{I_r}{I_i} = \frac{n_2 - n_1}{n_2 + n_1} \)
- **Margo:** \( \frac{I_r}{I_i} = \left( \frac{n_2 - n_1}{n_2 + n_1} \right)^2 \)
- **Alex:** \( \frac{I_r}{I_i} = \frac{n_2 + n_1}{n_2 - n_1} \)

What kind of experiment can you devise to determine which suggestion (if any) is correct? Perform it and decide who is correct!
Once you decide what the correct forms relating $n_1$ and $n_2$, use them to determine the index of refraction for Mystery Material A and Mystery Material B. (Do not worry about uncertainties here.)

Simulation: Mirrors and lenses

To explore ray tracing and the behavior of mirrors and lenses, we are going to use some optical ray simulators from oPhysics. But first, a little bit of theory.

Theory

When reflecting or refracting materials like mirrors or clear glass are shaped in special ways, they can be used to redirect light to form images. If the reflecting or refracting surfaces are spherical, this geometry (together with the laws of reflection and refraction) give rise to the ray diagrams illustrated in Fig. 2. The lenses shown in Fig. 2 are considered thin lenses for simplicity and it is assumed that all of the refraction takes place at the center of the lenses.

![Diagram of lenses and mirrors]

(Note that the double convex lens and the concave mirror of Figs. 1(a) and 1(b) redirect the light so that the light rays converge at the focal points. Images formed in this way are called real images, since light actually passes through them. Real images can be projected onto a screen. Note also that the double concave lens and the convex mirror of Figs. 1(c) and 1(d) cause the rays to diverge. Images formed this way must be inferred by extending the light rays back to where they appear to have come from as the dashed lines show. Since no light actually passes through these images they are referred to as virtual images and they cannot be projected onto a screen.

A consequence of the laws of reflection and refraction and the spherical shape of the mirror or lens surface is the relationship

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i},$$

(3)

where $f$ is the focal length, $d_o$ is the object distance (the distance from the object to the lens or mirror), and $d_i$ is the image distance (the distance from the lens or mirror to the image). It is remarkable that Eq. (3) applies both to mirrors and lenses with spherical surfaces even though the physics of refraction and reflection is quite different.

The magnification of a lens or mirror is defined as the ratio of the image height, $h_i$, to the object height, $h_o$:

$$M = \frac{h_i}{h_o},$$

(4)

Simulation: Plane mirror

Open up the Plane Mirror simulation from oPhysics:


Click Show Grid & Axes (along the bottom) and Show Control Points (at the top). You should now be able to click the two ends of the object (the arrow) and move them around. Pick any size and orientation for your arrow that you want, like the one shown as an example in Fig. 3.
We want to predict the location of the image as reflected in the mirror. You actually have a lot of natural intuition about this, so let’s see if we can figure this out before using ray tracing.

For the following, think about what happens when you look at a reflection of yourself in a plane mirror (like the kind that hangs above the sink in a bathroom). Answer these questions for yourself... they do not need to be recorded in your report.

- Does your reflection ("mirror you") seem to be located on your side of the mirror or the other side of the mirror?
- Does "mirror you" seem to be bigger, smaller, or the same size?
- Does "mirror you" seem closer, further away or the same distance from the face of the mirror as you?
- Is "mirror you" upside down or right side up?

What do these things tell you about the image which is formed in the mirror?

**Exercises**

Returning now to our arrow object in the simulation, can you predict where the image will be formed?

- What are the locations (x and y coordinates) of the top and bottom points of your object?
- What is your prediction for the locations of the top and bottom points of your image? Why? (You will not lose points for an incorrect prediction. Be honest!)

Now, the simulation can do the ray tracing for us in the following steps:

- Turn on Show Incident Rays. This sends to rays to arbitrary test points on the mirror. You can adjust the position of the test points if you want.
- Next, turn on Show Normals and Show Reflected Rays. These create reflected rays whose angle of reflection is equal to the angle of incidence.
- Finally, turn on Show Virtual Rays. These rays trace the reflected rays backwards through the mirror.
- To find the image...
  - ...the position of the top point of the image is the point where the two virtual rays from the top point of the object intersect.
  - ...the position of the bottom point of the image is the point where the two virtual rays from the bottom point of the object intersect.

Turn on Show Image to verify.

- What are the positions of the top and bottom points of your image? Was your prediction correct?
- Include a screenshot of your final configuration with all rays and the image shown.

**Simulation: Concave and convex mirrors**

Open up the Concave and Convex Mirrors simulation from oPhysics:


As you move the object and/or focus around, the simulation will automatically trace rays and compute quantities like image distance, image height, and magnification. Play around to see how it works! You can click the reset (the two arrows forming a circle) in the upper right corner at any time to return to the original state.
Note that when the focus and object are on the both on the left, it will behave as a concave mirror. When the focus is on the left and the object is on the right, it will behave like a convex mirror.

**Exercises**

Answer the following questions based on the simulation:

- What is the connection between the focus of the mirror and the center of curvature (marked CC in the simulation)?
  - As a mirror becomes flatter and flatter, how does CC change? (Does it get larger or smaller?) What does this mean for the focal length? (Does it get larger or smaller?)
  - In the limit of a completely flat (plane) mirror, what is the focal length? If parallel rays come in, will they ever be focused down to a point?

- For a concave mirror...
  - ...when (if ever) do you find a real image? When (if ever) do you find a virtual image? When (if ever) do you find no image produced (such that all the rays exit parallel)?
  - ...when (if ever) do you find the image gets bigger (M > 1)? When (if ever) do you find it gets smaller (M < 1)? Do you ever find an image that is exactly the same size (M = 1)?

- For a convex mirror...
  - ...when (if ever) do you find a real image? When (if ever) do you find a virtual image? When (if ever) do you find no image produced (such that all the rays exit parallel)?
  - ...when (if ever) do you find the image gets bigger (M > 1)? When (if ever) do you find it gets smaller (M < 1)? Do you ever find an image that is exactly the same size (M = 1)?

Now go grab a metal spoon from your kitchen drawer. One side should act as a concave mirror and one side should act like a convex mirror. (Your spoon probably isn’t quite a spherical mirror, but everything we want to look at will be fine anyway.)

- Find your own reflection by looking at the convex side. Are you right side up or upside down? Bigger or smaller?
- Find your own reflection by looking at the concave side. Are you right side up or upside down? Bigger or smaller?
- On the concave side, can you find the point where the image flips between upside-down and right-side up?
  - Tip: You probably can’t get your face close enough. Try using your finger or the tip of a pencil. Look for the image when you are far away and then slowly move closer and closer until you see the flip.
  - What’s the meaning of this point? (Go back to the simulation if you need a reminder.)

**Simulation: Concave and convex lenses**

Open up the Concave and Convex Lenses simulation from oPhysics:


Just like with the mirror simulation, as you move the object and/or focus around, the simulation will automatically trace rays and compute quantities like image distance, image height, and magnification. Play around to see how it works!

Note that when the object and focus’ are both on the left, it will behave as a convex lens. When the object is on the left and focus’ is on the right, it will behave like a concave lens.

**Exercises**

Answer the following questions based on the simulation:

- For a convex lens...
  - ...when (if ever) do you find a real image? When (if ever) do you find a virtual image? When (if ever) do you find no image produced (such that all the rays exit parallel)?
  - ...when (if ever) do you find the image gets bigger (M > 1)? When (if ever) do you find it gets smaller (M < 1)? Do you ever find an image that is exactly the same size (M = 1)?

- For a concave lens...
  - ...when (if ever) do you find a real image? When (if ever) do you find a virtual image? When (if ever) do you find no image produced (such that all the rays exit parallel)?
  - ...when (if ever) do you find the image gets bigger (M > 1)? When (if ever) do you find it gets smaller (M < 1)? Do you ever find an image that is exactly the same size (M = 1)?

The lens of your eye is flexible and can be stretched (to make it thinner) or allowed to relax (to make it thicker), thereby changing the focal length. Ideally, the lens can change over a wide range of values so that light coming in through the front is always focused onto the retina (as shown in Fig. 4.)
• Is the lens of your eye concave or convex?
• Is the image formed on the retina right side-up or upside-down?
• If a person is nearsighted (that is, they can focus fine on near objects, but cannot focus on far objects), does it mean their eye can't relax enough (to get thick) or can't stretch enough (to get thin)?
  • When the image is out-of-focus, is the image formed in front of the retina (too close) or behind the retina?
  • To correct for nearsightedness, would you want eyeglasses made with concave or convex lenses? (Put another way, do you want the corrective lenses to pre-focus the light or pre-diverge the light before it enters the eye’s natural lens?)

Report submission

Take a look over your report and make sure it’s complete. Download your report as a PDF and upload it to the appropriate Assignment spot on Canvas.