



## The Big Idea

Light is a *wave* of changing electric and magnetic fields. Light waves are caused by disturbances in the electromagnetic field, for example, the acceleration of charged particles (such as electrons). Light has a dual nature: at times, it acts like waves; at other times it acts like particles, called *photons*. Light travels through space at the maximum speed allowed by the laws of physics, called the speed of light. Light has no mass, but it carries energy and momentum. Of all possible paths *light will always take the path that takes the least amount of time* (not distance). This is known as Fermat's Principle.

Fermat's Principle governs the paths light will take and explains the familiar phenomena of reflection, refraction, diffraction, scattering and color absorption and dispersion. Light rarely travels in a straight line path. When photons interact with electrons in matter the time it takes for this interaction determines the path. For example, higher frequency blue light is refracted more than red because blue interacts more frequently with electrons than red and the path of least time is for blue to bend more than red in order to get out of this 'slow' area faster. The rainbows we see are a result of this. Fermat's Principle explains the many fascinating phenomena of light from rainbows to sunsets to the haloes around the moon.

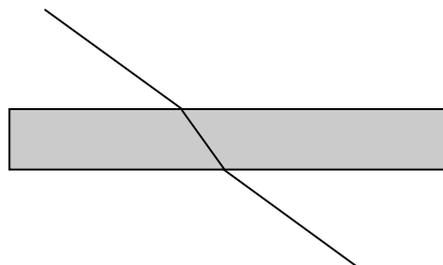
## Key Concepts

- Light is produced when charged particles *accelerate*. As a result changing electric and magnetic fields radiate outward. The traveling electric and magnetic fields of an accelerating (often oscillating) charged particle are known as electromagnetic radiation or light.
- The color of light that we observe is nothing more than the frequency of the light: the *smaller* the frequency, the *redder* the light.
- Light can have any frequency at all. Our *vision* is restricted to a very narrow range of colors between red and violet.

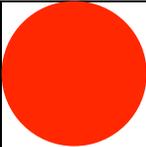
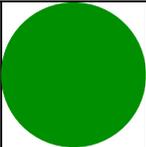
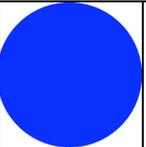
- The spectrum of electromagnetic radiation can be roughly broken into the following ranges:

<i>Color</i>	<i>Wavelength range</i>	<i>Comparison size</i>
gamma-ray ( $\gamma$ -ray)	$10^{-11}$ m and shorter	atomic nucleus
x-ray	$10^{-11}$ m – $10^{-8}$ m	hydrogen atom
ultraviolet (UV)	$10^{-8}$ m – $10^{-7}$ m	small molecule
violet (visible)	$\sim 4 \times 10^{-7}$ m (400 nm)*	typical molecule
blue (visible)	$\sim 450$ nm	typical molecule
green (visible)	$\sim 500$ nm	typical molecule
red (visible)	$\sim 650$ nm	typical molecule
infrared (IR)	$10^{-6}$ m – 1 mm	human hair
microwave	1 mm – 10 cm	human finger
radio	Larger than 10 cm	car antenna

- Fermat's Principle makes the angle of incident light equal to the angle of reflected light. This is the *law of reflection*.
- When light travels from one type of material (like air) into another (like glass), the effective speed slows down due to interactions between photons and electrons. If the ray enters the material at an angle Fermat's Principle dictates that the light also changes the direction of its motion. One way to think about this is that light takes the path of least time to get from points A to point B, thus it takes a more straight path through 'slower' mediums, so it can get out of the slow part faster. Light does not always travel in a straight line, it travels on the path of least time. This is called *refraction*. See figure at right, which demonstrates the refraction a light ray experiences as it passes from air into a rectangular piece of glass and out again.
- White light consists of a mixture of all the visible colors: red, orange, yellow, green, blue, indigo, and violet (ROYGBIV). Our perception of the color black is tied to the *absence* of light.
- Different frequencies of light (and hence different colors in the visible spectrum), will travel at slightly different speeds in materials, like glass, and thus have slightly different refracting angles. This phenomena gives rise to rainbows.
- Our eyes include color-sensitive and brightness-sensitive cells. The three different color-sensitive cells (cones) can have sensitivity in three colors: red, blue, and green. Our perception of other colors is made from the *relative amounts* of each color that the cones register from light reflected from the object we are looking at. Our brightness-sensitive cells work well in low light. This is why things look 'black and white' at night.
- The chemical bonds in pigments and dyes – like those in a colorful shirt – absorb light at frequencies that correspond to certain colors. When you shine white light on these pigments and dyes, some colors are absorbed and some colors are reflected. We only see the colors objects *reflect*.



## Color Addition

			<i>Perceived color</i>
<i>Red</i>	<i>Green</i>	<i>Blue</i>	
√	√	√	white
			black
√		√	magenta
√	√		yellow
	√	√	cyan

## Key Applications

- *Total internal reflection* occurs when light goes from a slow (high index of refraction) medium to a fast (low index of refraction) medium. With total internal reflection, light refracts *so* much it actually refracts back into the first medium. This is how fiber optic cables work: no light leaves the wire.
- *Rayleigh scattering* occurs when light interacts with our atmosphere. The shorter the wavelength of light, the more strongly it is disturbed by collisions with atmospheric molecules. So blue light from the Sun is preferentially *scattered* by these collisions into our line of sight. This is why the sky appears blue.
- *Beautiful sunsets* occur when light travels long distances through the atmosphere. The blue light and some green is scattered away, leaving only red and a little green, making the sun appear red.
- *Lenses*, made from curved pieces of glass, focus or de-focus light as it passes through. Lenses that focus light are called *converging* lenses, and these are the ones used to make telescopes and cameras. Lenses that de-focus light are called *diverging* lenses.
- Lenses can be used to make visual representations, called *images*.
- *Mirrors* are made from highly reflective metal that is applied to a curved or flat piece of glass. Converging mirrors can be used to focus light – headlights, telescopes, satellite TV receivers, and solar cookers all rely on this principle. Like lenses, mirrors can create images.
- The *focal length,  $f$* , of a lens or mirror is the distance from the surface of the lens or mirror to the place where the light is focused. This is called the *focal point* or *focus*. For diverging lenses or mirrors, the focal length is negative.
- When light rays converge in front of a mirror or behind a lens, a *real* image is formed. Real images are useful in that you can place photographic film at the physical location of the real image, expose the film to the light, and make a two-dimensional representation of the world, a photograph.



Converging lens



Diverging lens

- When light rays diverge in front of a mirror or behind a lens, a *virtual* image is formed. A virtual image is a trick, like the person you see “behind” a mirror’s surface when you brush your teeth. Since virtual images aren’t actually “anywhere,” you can’t place photographic film anywhere to capture them.
- Real images are upside-down, or *inverted*. You can make a real image of an object by putting it farther from a mirror or lens than the focal length. Virtual images are typically right-side-up. You can make virtual images by moving the mirror or lens closer to the object than the focal length.
- Waves are characterized by their ability to constructively and destructively *interfere*. Light waves which interfere with themselves after interaction with a small aperture or target are said to *diffract*.
- Light creates interference patterns when passing through holes (“slits”) in an obstruction such as paper or the surface of a CD, or when passing through a thin film such as soap.

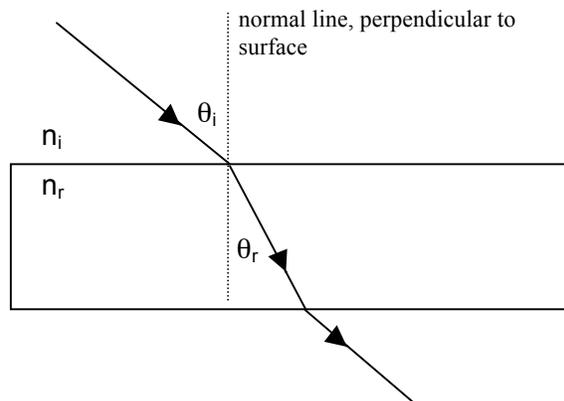
### Key Equations

- $c = \lambda f$
- $n = c / u$

The product of the wavelength  $\lambda$  of the light (in meters) and the frequency  $f$  of the light (in Hz, or 1/sec) is always equal to a constant, namely the speed of light  $c = 300,000,000$  m/s.

The index of refraction,  $n$ , is the ratio of the speed  $c$  it travels in a vacuum to the slower speed it travels in a material.  $n$  can depend slightly on wavelength .

- $n_i \sin(\theta_i) = n_r \sin(\theta_r)$



- $m\lambda = d\sin(\theta)$  double slit interference ;  $m$  is an integer counting up to the number of interference maxima in question,  $d$  is the distance between slits (double-slit interference.) and  $\theta$  is the angular separation of the maximum
- $m\lambda = d\sin\theta$  single slit diffraction ;  $m, \theta$  are defined as above,  $d$  is the slit width
- $m\lambda = d\sin\theta$  diffraction grating ;  $m$  and  $\theta$  are defined as above  $d$  is the distance between the lines on the grating.

- $m\lambda = 2nd$

; thin film interference;  $n$  is the index of refraction of the film,  $d$  is the thickness of the film, and  $m$  is an integer. There is a  $\lambda/2$  phase change if the light is reflected from an object with an index of refraction greater than that of the incident material.

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

For lenses, the distance from the center of the lens to the focus is  $f$ . Focal lengths for foci behind the lens are positive in sign. The distance from the center of the lens to the object in question is  $d_o$ , where distances to the left of the lens are positive in sign. The distance from the center of the lens to the image is  $d_i$ . This number is positive for real images (formed to the right of the lens), and negative for virtual images (formed to the left of the lens).

For mirrors, the same equation holds! However, the object and image distances are both positive for real images formed to the left of the mirror. For virtual images formed to the right of the mirror, the image distance is negative.

- $M = \frac{-d_i}{d_o}$

The size of an object's image is larger (or smaller) than the object itself by its magnification,  $M$ . The level of magnification is proportional to the ratio of  $d_i$  and  $d_o$ . An image that is double the size of the object would have magnification  $M = 2$ .

- $R = 2f$

The radius of curvature of a mirror is twice its focal length.

## Light Problem Set

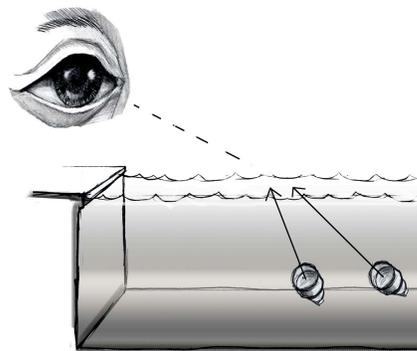
1. Which corresponds to light of longer wavelength, UV rays or IR rays?
2. Which corresponds to light of lower frequency,  $x$ -rays or millimeter-wavelength light?
3. Approximately how many blue wavelengths would fit end-to-end within a space of one millimeter?
4. Approximately how many short (“hard”)  $x$ -rays would fit end-to-end within the space of a single red wavelength?
5. Calculate the frequency in Hz of a typical green photon emitted by the Sun. What is the physical interpretation of this (very high) frequency? (That is, what is oscillating?)
6. FM radio stations list the frequency of the light they are emitting in MHz, or millions of cycles per second. For instance, 90.3 FM would operate at a frequency of  $90.3 \times 10^6$  Hz. What is the wavelength of the radio-frequency light emitted by this radio station? Compare this length to the size of your car’s antenna, and make an argument as to why the length of a car’s antenna should be about the wavelength of the light you are receiving.
7. Consult the color table for human perception under the ‘Key Concepts’ section and answer the questions which follow.
  - a. Your coat looks magenta in white light. What color does it appear in blue light? In green light?
  - b. Which secondary color would look black under a blue light bulb?
  - c. You look at a cyan-colored ribbon under white light. Which of the three primary colors is your eye *not* detecting?
8. Consider the following table, which states the indices of refraction for a number of materials.

<i>Material</i>	$n$
vacuum	1.00000
air	1.00029
water	1.33
typical glass	1.52
cooking oil	1.53
heavy flint glass	1.65
sapphire	1.77
diamond	2.42

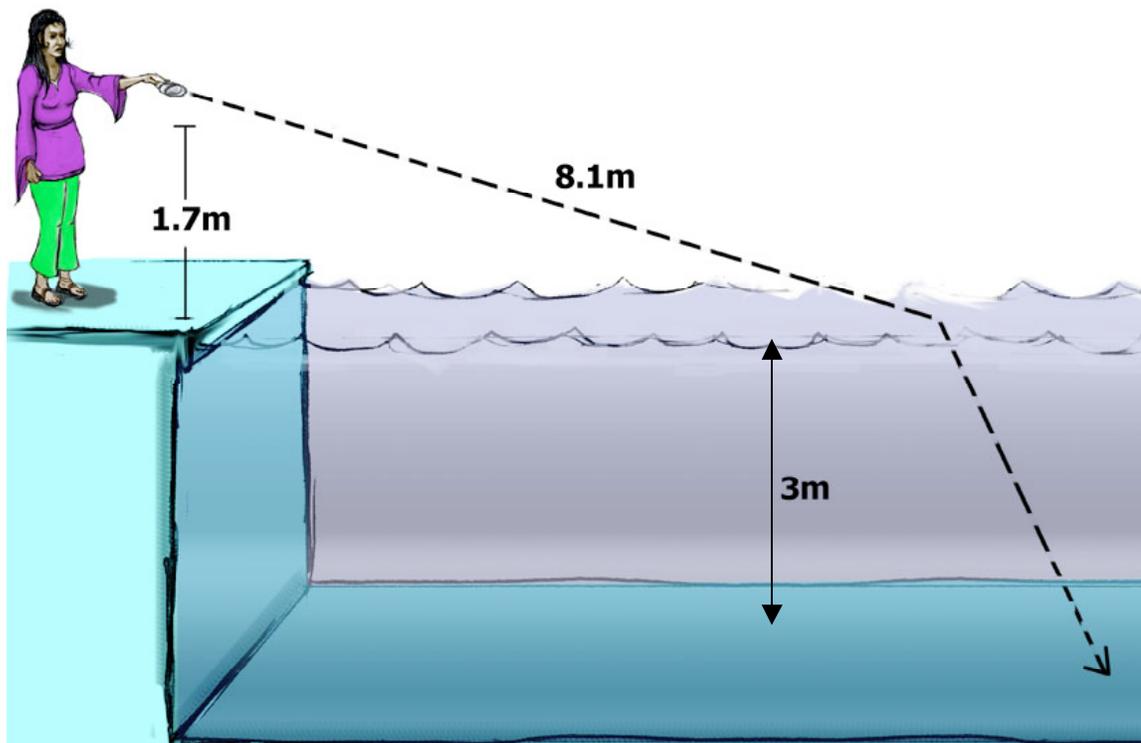
- a. For which of these materials is the speed of light *slowest*?
- b. Which two materials have the most similar indices of refraction?

- c. What is the speed of light in cooking oil?
9. A certain light wave has a frequency of  $4.29 \times 10^{14}$  Hz. What is the wavelength of this wave in empty space? In water?
10. A light ray bounces off a fish in your aquarium. It travels through the water, into the glass side of the aquarium, and then into air. Draw a sketch of the situation, being careful to indicate how the light will change directions when it refracts at each interface. Include a brief discussion of why this occurs.
11. Why is the sky blue? Find a family member who doesn't know why the sky is blue and explain it to them. Ask them to write a short paragraph explaining the situation and include a sketch.
12. Describe the function of the dye in blue jeans. What does the dye do to each of the various colors of visible light?
13. A light ray goes from the air into the water. If the angle of incidence is  $34^\circ$ , what is the angle of refraction?
14. In the "disappearing test tube" demo, a test tube filled with vegetable oil vanishes when placed in a beaker full of the same oil. How is this possible? Would a diamond tube filled with water and placed in water have the same effect?
15. Imagine a thread of diamond wire immersed in water. Can such an object demonstrate total internal reflection? If so, what is the critical angle? Draw a picture along with your calculations.

16. A light source sits in a tank of water, as shown.



- a. If one of the light rays coming from inside the tank of water hits the surface at  $35.0^\circ$ , as measured from the normal to the surface, at what angle will it enter the air?
- b. Now suppose the incident angle in the water is  $80^\circ$  as measured from the normal. What is the refracted angle? What problem arises?
- c. Find the *critical angle* for the water-air interface. This is the incident angle that corresponds to the largest possible refracted angle,  $90^\circ$ .



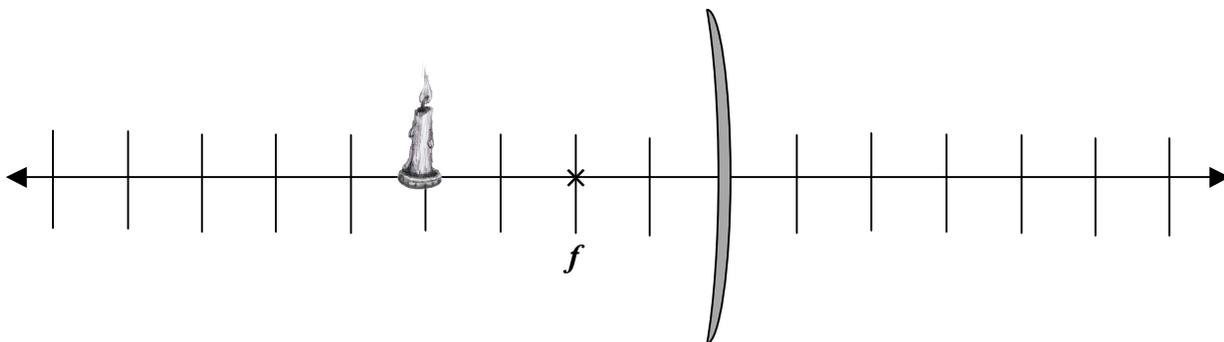
17. Nisha stands at the edge of an aquarium 3.0 m deep. She shines a laser at a height of 1.7 m that hits the water of the pool 8.1 m from the edge.
- Draw a diagram of this situation. Label all known lengths.
  - How far from the edge of the pool will the light hit bottom?
  - If her friend, James, were at the bottom and shined a light back, hitting the same spot as Nisha's, how far from the edge would he have to be so that the light never leaves the water?
18. Here's an example of the "flat mirror problem." Marjan is looking at herself in the mirror. Assume that her eyes are 10 cm below the top of her head, and that she stands 180 cm tall. Calculate the minimum length flat mirror that Marjan would need to see her body from eye level all the way down to her feet. Sketch at least 3 ray traces from her eyes showing the topmost, bottommost, and middle rays.

In the following five problems, you will do a careful ray tracing with a ruler (including the extrapolation of rays for virtual images). It is best if you can use different colors for the three different ray tracings. When sketching diverging rays, you should use dotted lines for the extrapolated lines behind a mirror or in front of a lens in order to produce the virtual image. When comparing measured distances and heights to calculated distances and heights, values within 10% are considered “good.” Use the following cheat sheet as your guide.

CONVERGING (CONCAVE) MIRRORS	Ray #1: Leaves tip of candle, travels parallel to optic axis, reflects back through focus. Ray #2: Leaves tip, travels through focus, reflects back parallel to optic axis. Ray #3: Leaves tip, reflects off center of mirror with an angle of reflection equal to the angle of incidence.
DIVERGING (CONVEX) MIRRORS	Ray #1: Leaves tip, travels parallel to optic axis, reflects OUTWARD by lining up with focus on the OPPOSITE side as the candle. Ray #2: Leaves tip, heads toward the focus on the OPPOSITE side, and emerges parallel to the optic axis. Ray #3: Leaves tip, heads straight for the mirror center, and reflects at an equal angle.
CONVERGING (CONVEX) LENSES	Ray #1: Leaves tip, travels parallel to optic axis, refracts and travels to through to focus. Ray #2: Leaves tip, travels through focus on same side, travels through lens, and exits lens parallel to optic axis on opposite side. Ray #3: Leaves tip, passes straight through center of lens and exits without bending.
DIVERGING (CONCAVE) LENSES	Ray #1: Leaves tip, travels parallel to optic axis, refracts OUTWARD by lining up with focus on the SAME side as the candle. Ray #2: Leaves tip, heads toward the focus on the OPPOSITE side, and emerges parallel from the lens. Ray #3: Leaves tip, passes straight through the center of lens and exits without bending.

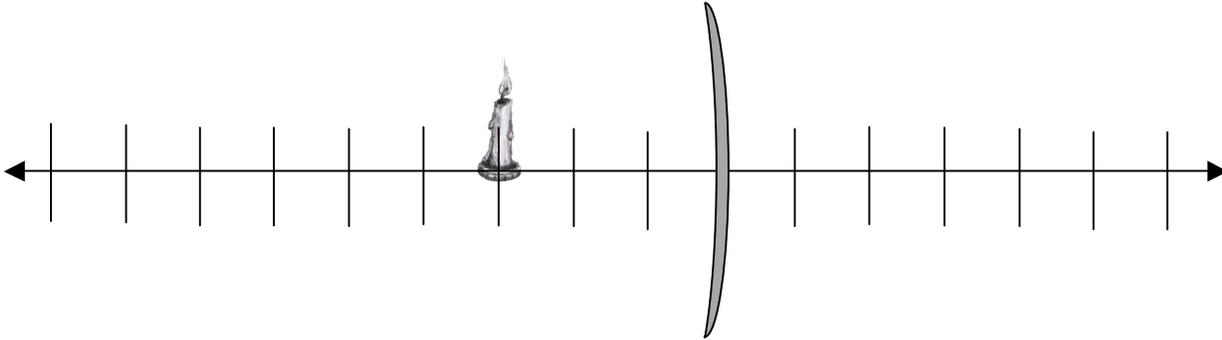
19. Consider a concave mirror with a focal length equal to two units, as shown below.

a. Carefully trace three rays coming off the top of the object in order to form the image.



- Measure  $d_o$  and  $d_i$ .
- Use the mirror/lens equation to calculate  $d_i$ .
- Find the percent difference between your measured  $d_i$  and your calculated  $d_i$ .
- Measure the magnification  $M$  and compare it to the calculated magnification.

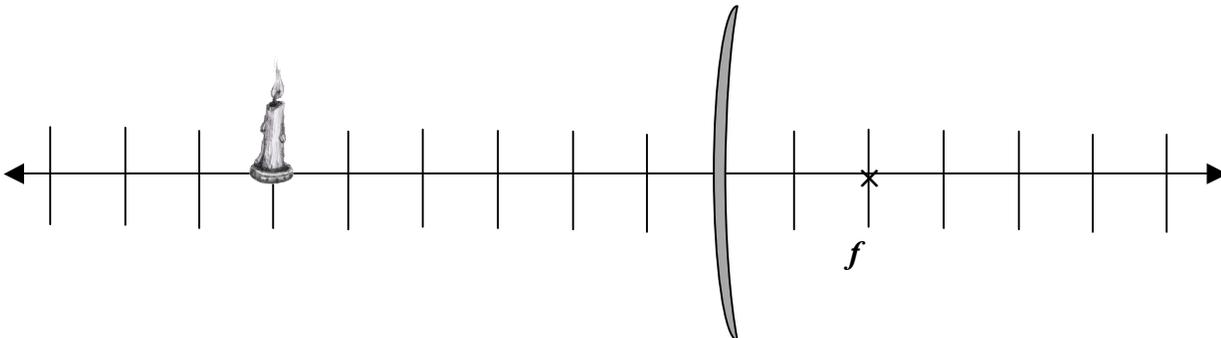
20. Consider a concave mirror with unknown focal length that produces a virtual image six units behind the mirror.
- Calculate the focal length of the mirror and draw an  $\times$  at the position of the focus.
  - Carefully* trace three rays coming off the top of the object and show how they converge to form the image.



- Does your image appear bigger or smaller than the object? Calculate the expected magnification and compare it to your sketch.

21. Consider a convex mirror with a focal length equal to two units.

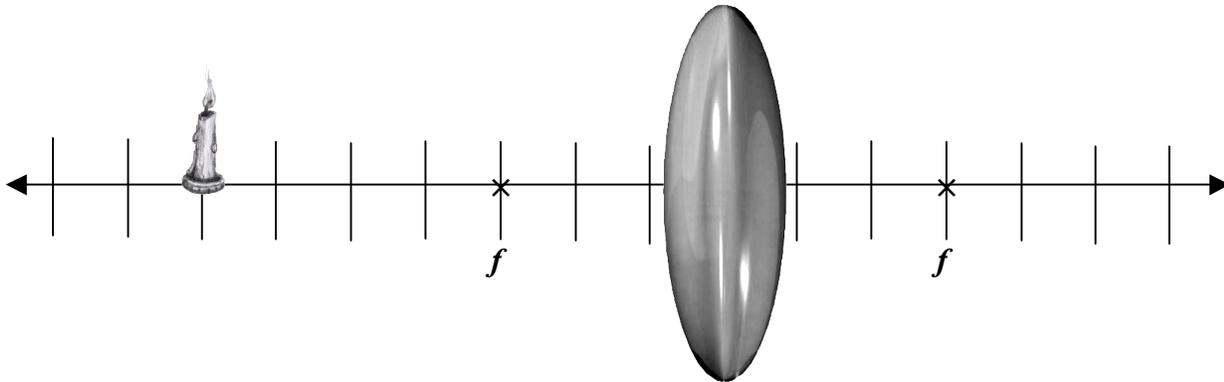
- Carefully* trace three rays coming off the top of the object and form the image.



- Measure  $d_o$  and  $d_i$ .
- Use the mirror/lens equation to calculate  $d_i$ .
- Find the percent difference between your measured  $d_i$  and your calculated  $d_i$ .
- Measure the magnification  $M$  and compare it to the calculated magnification.

22. Consider a converging lens with a focal length equal to three units.

a. *Carefully* trace three rays coming off the top of the object and form the image.



b. Measure  $d_o$  and  $d_i$ .

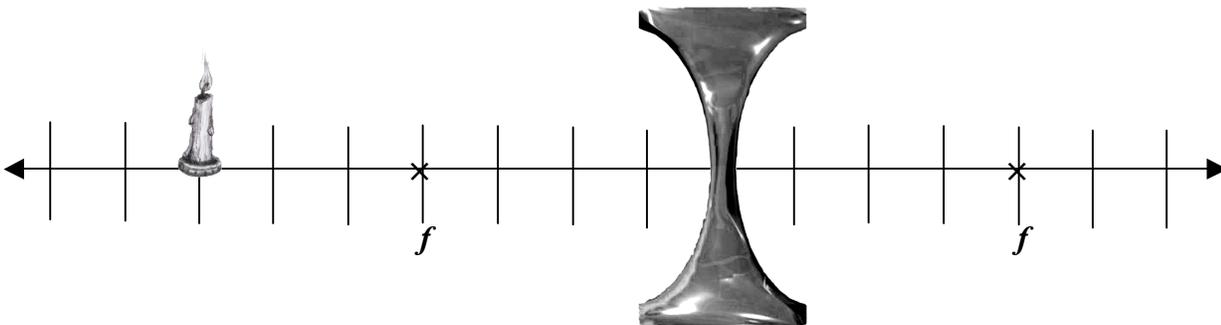
c. Use the mirror/lens equation to calculate  $d_i$ .

d. Find the percent difference between your measured  $d_i$  and your calculated  $d_i$ .

e. Measure the magnification  $M$  and compare it to the calculated magnification.

23. Consider a diverging lens with a focal length equal to four units.

a. *Carefully* trace three rays coming off the top of the object and show where they converge to form the image.



b. Measure  $d_o$  and  $d_i$ .

c. Use the mirror/lens equation to calculate  $d_i$ .

d. Find the percent difference between your measured  $d_i$  and your calculated  $d_i$ .

e. Measure the magnification  $M$  and compare it to the calculated magnification.

24. A piece of transparent goo falls on your paper. You notice that the letters on your page appear smaller than they really are. Is the goo acting as a converging lens or a diverging lens? Explain. Is the image you see real or virtual? Explain.

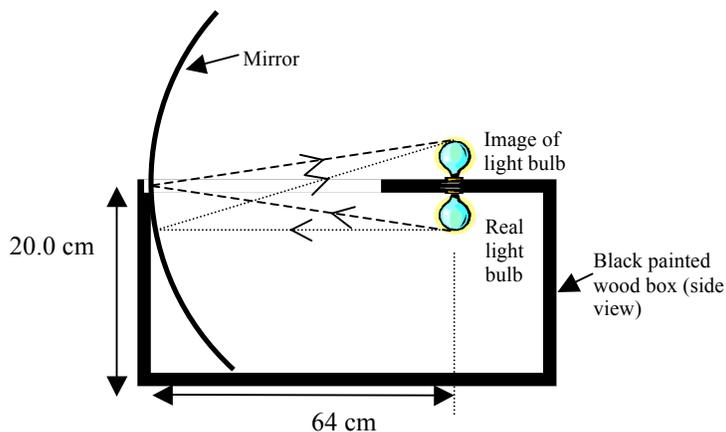
25. An object is placed 30 mm in front of a lens. An image of the object is located 90 mm behind the lens.

- Is the lens converging or diverging? Explain your reasoning.
- What is the focal length of the lens?

26. Little Red Riding Hood (*aka* R-Hood) gets to her grandmother's house only to find the Big Bad Wolf (*aka* BBW) in her place. R-Hood notices that BBW is wearing her grandmother's glasses and it makes the wolf's eyes look magnified (bigger).

- Are these glasses for near-sighted or far-sighted people? For full credit, explain your answer thoroughly. You may need to consult some resources online.
- Create a diagram of how these glasses correct a person's vision.

27. To the right is a diagram showing how to make a "ghost light bulb." The real light bulb is below the box and it forms an image of the exact same size right above it. The image looks very real until you try to touch it. What is the focal length of the concave mirror?



28. In your laboratory, light from a 650 nm laser shines on two thin slits. The slits are separated by 0.011 mm. A flat screen is located 1.5 m behind the slits.

- Find the angle made by rays traveling to the third maximum off the optic axis.
- How far from the center of the screen is the third maximum located?
- How would your answers change if the experiment was conducted underwater?

29. Again, in your laboratory, 540 nm light falls on a pinhole 0.0038 mm in diameter. Diffraction maxima are observed on a screen 5.0 m away.

- Calculate the distance from the central maximum to the first interference maximum.
- Qualitatively explain how your answer to (a) would change if you ...
  - ...move the screen closer to the pinhole.
  - ...increase the wavelength of light.
  - ...reduce the diameter of the pinhole.

30. You are to design an experiment to determine the index of refraction of an unknown liquid. You have a small square container of the liquid, the sides of which are made of transparent thin plastic. In addition you have a screen, laser, ruler and protractors. Design the experiment. Give a detailed procedure; include a diagram of the experiment. Tell which equations you would use and give some sample calculations. Finally, tell in detail what level of accuracy you can expect and explain the causes of lab error in order of importance.
31. Students are doing an experiment with a Helium-neon laser, which emits 632.5 nm light. They use a diffraction grating with 8000 lines/cm. They place the laser 1 m from a screen and the diffraction grating, initially, 95 cm from the screen. They observe the first and then the second order diffraction peaks. Afterwards, they move the diffraction grating closer to the screen.
- a. Fill in the table below with the *expected* data based on your understanding of physics. Hint: find the general solution through algebra *before* plugging in any numbers.

Distance of diffraction grating to screen (cm)	Distance from central maximum to first order peak (cm)
95	
75	
55	
35	
15	

- b. Plot a graph of the first order distance as a function of the distance between the grating and the screen.
- c. How would you need to manipulate this data in order to create a *linear* plot?
- d. In a real experiment what could cause the data to deviate from the expected values? Explain.
- e. What safety considerations are important for this experiment?
- f. Explain how you could use a diffraction grating to calculate the unknown wavelength of another laser.
32. An abalone shell, when exposed to white light, produces an array of cyan, magenta and yellow. There is a thin film on the shell that both refracts and reflects the light. Explain clearly why these and only these colors are observed.
33. A crystal of silicon has atoms spaced 54.2 nm apart. It is analyzed as if it were a diffraction grating using an *x*-ray of wavelength 12 nm. Calculate the angular separation between the first and second order peaks from the central maximum.
34. Laser light shines on an oil film ( $n = 1.43$ ) sitting on water. At a point where the film is 96 nm thick, a 1<sup>st</sup> order dark fringe is observed. What is the wavelength of the laser?

35. You want to design an experiment in which you use the properties of thin film interference to investigate the variations in thickness of a film of water on glass.
- a. List all the necessary lab equipment you will need.
  - b. Carefully explain the procedure of the experiment and draw a diagram.
  - c. List the equations you will use and do a sample calculation using realistic numbers.
  - d. Explain what would be the most significant errors in the experiment and what effect they would have on the data.