Unit 12: Light and Optics

In this unit we will investigate some of the properties of light. Some of these properties are consistent with particle-like behavior. For example, light travels in well localized beams. Some of these properties are consistent with wave-like behavior; light waves can be made to interfere and diffract when passed through slits. This confusing mix of properties has to do with the very short wavelength of light, but if you continue your study of physics, you will find that this mixture of particle and wave properties is and important and intrinsic property of all matter.

Session 1: An Introduction to Optics: Converging Lenses

In this session you will discover some basic properties and laws about converging lenses and image formation. The first experience you should have is to simply see what a converging lens does. Many of you have done this already, but for some of you this may be a first time experience. Each group has a lens to work with; if you desire at any time, we have more lenses of a variety of types for you to look at.

Guidebook Entry XII.1: Looking Through a Lens and Forming an Image

Place the large blue lens up close to your eye, and look through it at an object across the room. Describe what you see.

Now hold the lens at arms length from your eye and look through it at a distant object. What do you see, and how does it compare with what you saw before?

You should have seen something distinctly different between the two cases. You should check with an instructor, especially if you didn't see much difference. Now see if you can find (roughly) the distance from your eye at which the lens behavior seems to change from the former (close) case to the latter (arm's length) case.

It is important to note here that there is a characteristic length associated with lenses, and we will see this length reappear throughout this session. This length is called the focal length. The blue lens has a focal length of about 25 cm.

Place the lens roughly one focal length away from some writing–this page will do nicely. Look through the lens from a comfortable distance (30 cm or so). Adjust the lens back and forth a bit so that you can see the writing clearly through it. Describe what you see.

Lay a blank sheet of paper on your table. Hold your lens roughly one focal length above the paper. Move the lens up and down a bit, and describe what you see on the paper (*don't* try to look through the lens now).

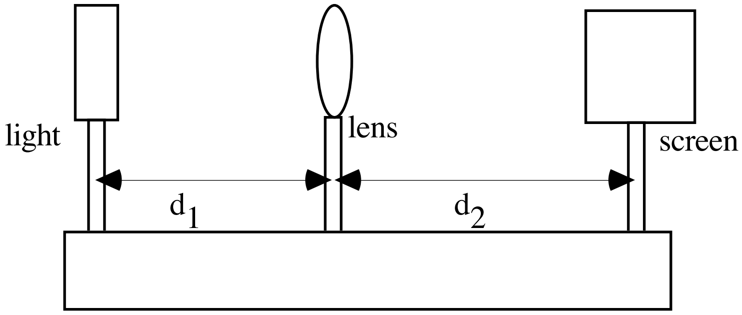
Feel the lens between your fingers. Sketch what you think a cross-sectional cut of the lens would look like.

You should have now observed the two primary functions of converging lenses: 1) magnification of objects seen with our own eyes, and 2) the formation of images on screens.

Guidebook Entry XII.2: Getting Quantitative: Using the Optical Bench

Take the red lens from the lens set. Form an image of the overhead lights to get an estimate of the focal length, and write that value below.

Place your lens in the holder on the optical bench at a distance of roughly twice the focal length from the light source. Move the screen back and forth until you get an image. Describe the image that is produced, especially how it compares to the original light source.



Are things inverted?

Are right and left swapped?

Are east and west swapped?

Are the last two questions different?

Now consider the distances d_1 and d_2 from light to lens and lens to screen, respectively, when you have a sharp image.

What happens to d_2 as you increase d_1?

Are the two distances related symmetrically? That is, if you interchange the values of d_1 and d_2, do you still get a sharp image? If so, is the image the same as before?

Move the lens and screen so as to create a sharp image. What do you predict will happen if you cover up half of the light source (say the bottom half)?

Do this, and compare what you see to your prediction.

What do you predict will happen if you cover up the lower half of the lens?

Do this, and compare what you see with your prediction.

In the next activities, you will attempt to discover the laws that govern where images are formed, and how big they are.

You discovered earlier that the light to lens distance (d_1) and lens to screen distance (d_2) seemed to vary inversely to one another. In other words, as d_1 increased, d_2 decreased. In this activity, you will discover the mathematical relationship between d_1 and d_2.

Guidebook Entry XI.3: Discovering the Lens Law (Criteria for a Focused Image)

We need to start with a set of values for d_1 and d_2 that satisfy the conditions for a sharp focus. Use a meterstick and the optical bench to obtain these values. Set the d_1 distance, and then adjust the screen to find a focus and therefore d_2. Take at least a half dozen measurements over a wide range of values (from 20 cm or less to around 50 cm).

d_1	d_2

Imagine that the focus condition was that d_1 was inversely proportional to d_2, that is

$$d_1 = \frac{k}{d_2}?$$

What would a graph of d_1 against d_2 look like?

Put these data into an Excel spreadsheet, and plot d_1 against d_2. Do you see a graph that qualitatively looks like an inverse relationship? Show your graph, or a sketch of it here.

If there is an inverse relationship, then plotting d_2 against $1/d_1$ should give a graph that is a straight line (make sure you understand why this is so–ask if you are not sure). Try plotting your data this way. Does it now look like a straight line?

You should have gotten a graph that wasn't very linear at all, indicating that the relationship is more complicated. Let's take some clues from experiment. What happens to d_2 if d_1 is very large?

What happens to d_2 if d_1 is very small?

Our guess that a 1/d was present looks likely here, because we seem to have ok behavior when d is large (going toward infinity) but misbehaves (no sharp image) when d is small (going toward zero). With this hint, try plotting $1/d_1$ versus $1/d_2$. Do you get a straight line?

With this graph, can you unravel the lens equation?

Test your equation by setting d_1= 60 cm. Predict what d_2 should be.

Measure d_2 for this case. Does it agree with your prediction?

Given the lens equation, what is the closest distance at which you can still get a focus?

Does the focal length enter into your lens formula anywhere? Use units to help you see if this is a constant in the lens formula.

Most conventionally, the lens equation is written

$$\frac{1}{d_1}+\frac{1}{d_2}=\frac{1}{f}$$

where f is the focal length of the lens. We have not proven this equation, but simply justified it on the basis of observations. Although we won't try to actually derive this theoretically, it is not a terribly complicated proof, and certainly within your understanding.

You have certainly noticed that the sizes of the image vary quite dramatically as you vary d_1 and d_2. In the next exercise, you will see how the image sized depends on d_1 and d_2.

Guidebook Entry XII.4: Magnification of Images

Does the image tend to get larger or smaller as d_2 gets larger? Verify this by experiment.

Does the image tend to get larger or smaller as d_1 gets larger? Verify this by experiment.

Measure the height of the image as you vary d_1 and d_2. Choose a wide range of values for the d's, as you did before.

d_1	d_2	height

The absolute height of the image is probably not very meaningful, since that is dependent on the size of the source. Let's instead look at the magnification M which is the ratio of the image size to the source size. Use Excel to plot M vs. d_2. See if you can find an expression for the magnification in terms of d_2 and the focal length f.

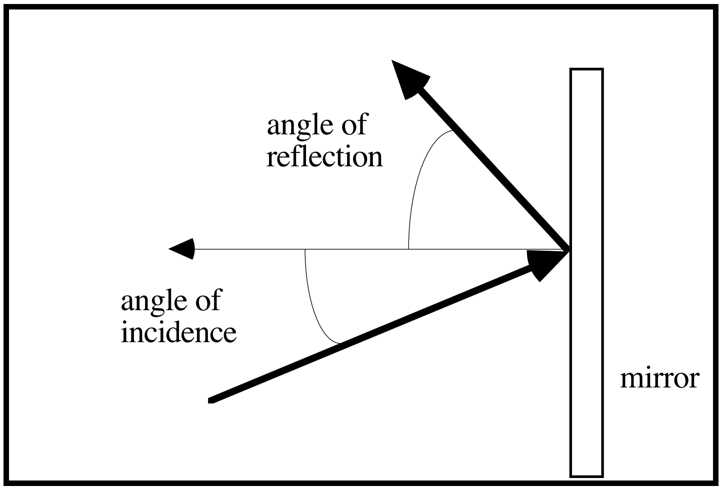
Attempt to eliminate f by using the lens equation. You should be able to find an expression for M as

$$M = \frac{d_2}{d_1}.$$

Session 2: Why Image Formation?

The purpose of this session is to understand the process of image formation, with both lenses and mirrors. We will start with mirrors, because they are easier to understand, and then talk about how lenses work.

Guidebook Entry XII.5: Law of Reflection



In this exercise, you will use a laser to show how the angle of incidence is related to the angle of reflection for a plane mirror. First, describe how you are going to test this.

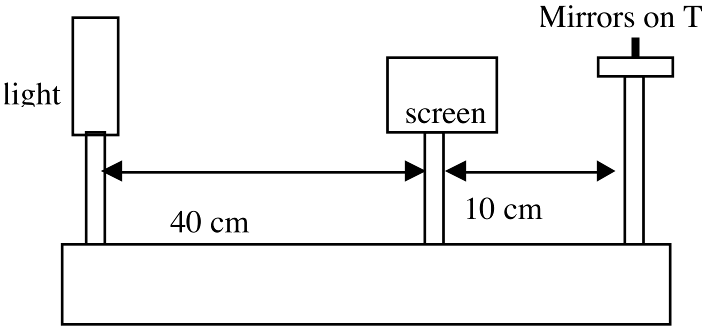
Now make your measurements and record your data. We have two lasers and plane mirrors out for you, so please do your measurement at one of those tables and share with other groups.

Can you summarize your observations in a simple sentence?

Now that we know how flat mirrors work, let us use a bunch of small flat mirrors to approximate the operation of a curved mirror. Curved mirrors behave just like lenses, except that they, naturally, reflect rather than transmit light, so what we learn will be applicable to lenses as well.

Guidebook Entry XII.6: A More Concentrated Reflection

Using clay, you will eventually mount all the tiny mirror bits so as to reflect the optical rail lamp onto the center of the screen about 10 cm away from the mirrors. Position the screen so its shadow is close to the base of the T, but does not obscure it.



Now imbed a single mirror bit on some clay on top of the "T" mount and orient it appropriately so the light falls on center of the screen.

Place a second mirror bit about a centimeter to the side of the first, and orient it to also reflect onto the target. (You may find it helps to cover the first mirror bit with a slip of paper, although it is not necessary.) Sketch your arrangement below.

Continue this process with at least five mirror bits, placed over the full width of the T. Try to arrange the mirrors into a nice smooth curve. Sketch your arrangement.

Show with angle-of-incidence = angle-of-reflection that the focusing property of this arrangement makes sense.

Could you make such a surface from a single piece of shiny metal? What shape would it be?

Move the lamp about 10 cm to one side. Where does the bright spot (the image) move?

What would happen if there were two lamps at those two locations at the same time? What would you observe on a screen at the location of the "target?"

Recall in our lens exercises last time, that if one covered half the lens, the image only became dimmer. Can you explain this effect now with your mirror case?

Move the screen a bit further away from the mirrors, maybe an additional 5 cm. Describe what happens to the reflections on the screen.

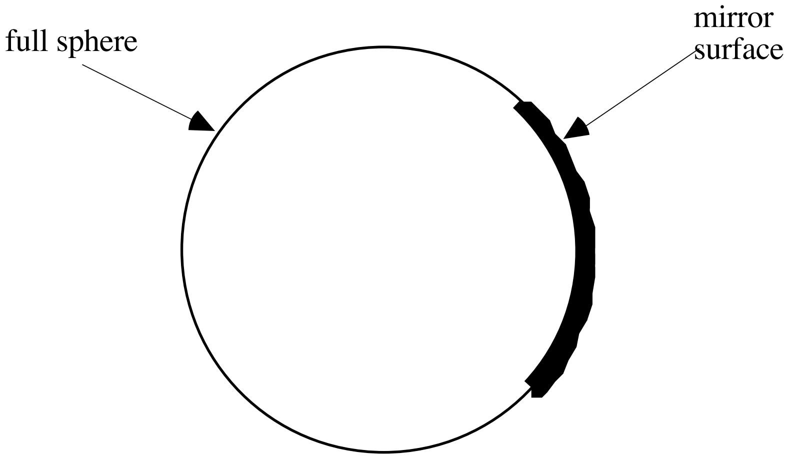
Can you use the results of this last observation to explain why things come into focus only at a particular distance from a lens (or curved mirror)?

You should now have the basic concept of image formation. You should explain this to an instructor to check your understanding.

In the next example, we will actually calculate the focal length of a curved mirror.

Guidebook Entry XII.7: A Spherical Mirror

We can form a focusing mirror by taking a bite out of a spherical surface; this sort of a mirror is often called a spherical mirror. It is easy to calculate the focal length of a spherical mirror. Imagine that we have a source of light at the center of a spherical mirror. Use angle of incidence = angle of reflection to show where the light rays converge.



Assume that the lens formula works. What is d_1?

What is d_2?

Use the lens formula to find the focal length of a spherical mirror of radius R.

Refraction is the process by which a light ray is bent as it moves from one medium (say air) into a second medium (such as glass). In the next section, you will learn qualitatively how the refraction process works. Here we will have to share a single refraction demonstration apparatus, although we also have several prisms to use with the other two lasers you used earlier today with the mirrors.

Guidebook Entry XII.8: Refraction

Use the refraction demonstrator with a laser beam going from air into the plastic medium. How does the angle of refraction depend on the angle of incidence? Make a rough sketch of angle of refraction versus angle of incidence.

Does a light beam traveling backwards through the device bend just as much in the opposite sense? Make one such pair of measurements carefully.

Now use a laser beam through the small angle prism.
What direction is the beam bent? Show in a sketch.

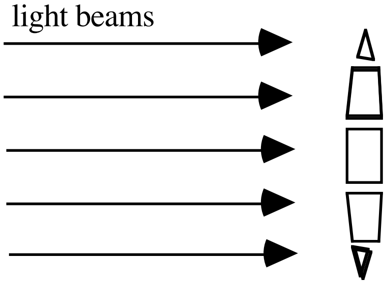
How much is the beam bent in degrees?

Now pass the laser beam through one of the less sharp prisms (i.e. one with a larger angle) How much is the beam bent now? Is it more or less than the small angle prism?

Now that you know a bit about how prisms work, you can (conceptually) take a number of them and arrange them to make a focusing device, just like we did with the mirrors.

Guidebook Entry XII.9: Making a Lens

Imagine the following array of prisms. How would a set of parallel light beams be bent?



Sketch how this would look if you could connect the prisms and smooth the figure out to a smooth surface.

How does this compare with a lens shape?

Session 3: Light as a Wave

In this session we will observe wave properties of light, and see how they are consistent with some of the ray properties that we observed earlier (reflection and refraction).

In the first activity, we will review some of the ways we can recognize a wave. This is especially important in the case of light, because the wavelength is too short to see with our own eyes, and because the oscillating part of the wave, electric and magnetic fields, are not directly observable but only observable by their effects. Since light IS how we see, we are helped considerably by the fact that while we can't see the light while it is traveling, we can see it when it hits our eyes. So, we later shine laser light onto the wall and observe some wave phenomena, and from that deduce the wavelength.

Guidebook Entry XII.10: Recognizing a Wave

We want to observe the wavelike properties of light, but we can't directly observe the waving as we can with a water wave. So we need to look for one of the primary properties of wave behavior: interference.

To refresh your memory, interference results from the superposition principle: if two waves are present at the same place at the same time, the resulting amplitude of the oscillation is just the algebraic sum of the individual oscillations. This means that if a crest lines up with an equal amplitude trough at some point, the result is zero wave (destructive interference). If instead, the crest lines up with a crest, they reinforce one another and the wave is reinforced (constructive interference: bigger, louder, brighter, or what have you).

This is very easily observed by having two waves that are out of synchronization with one another (slightly different wavelengths and frequencies). This means that they will be in phase for a while and reinforce one another, then a bit later get out of phase because of their frequency difference and cancel each other out.

How do you expect the sound from two slightly detuned tuning forks to sound, given this superposition principle?

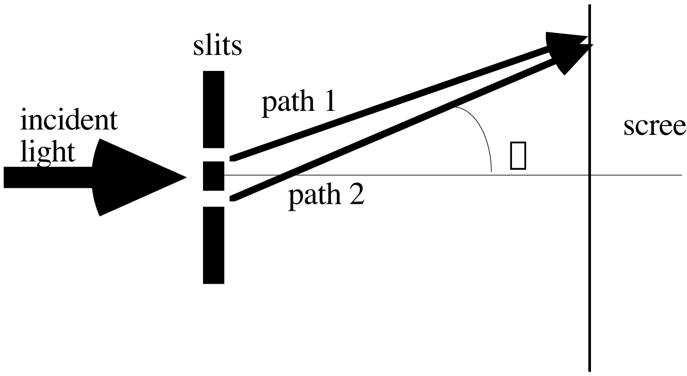
Listen to the two forks we have. What do you hear?

Is it what you expected?

Just passing a wave through a single slit gives evidence of wave behavior, if the slit is comparable to the wavelength. If it is, the wave no longer travels in a straight line, but spreads out. Can you observe this with the laser? Use one of the glass plates that has a variety of slits in it to spread out the laser beam.

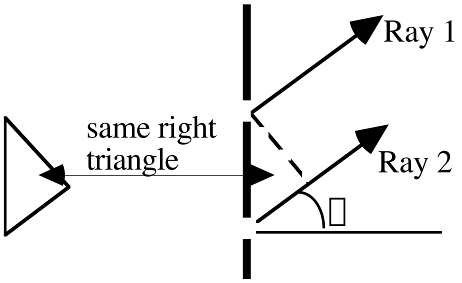
For the case of light, we will artificially create *two* sources by passing the light through a pair of slits. If we pass the laser through two slits, the two frequencies will be the same, but at any given point, light arriving from one slit will be slightly out of phase with the light from the other slit because they have traveled different distances.

Consider the sketch below. The two paths are different in length. What do you expect to see on the screen if the paths are exactly one half wavelength different?



What do you expect to see if they are exactly one wavelength different?

Can you estimate the difference in path traveled by the two light beams? The estimate can be made much simpler if you assume that the screen is very far away; much farther than the slit spacing (see the expanded diagram below). The easiest way to do this is to consider the screen so far away that the two paths are essentially parallel to one another. I have labeled the beginnings of those paths Ray 1 and Ray 2. For clarity, I made a copy of a right triangle from within the figure to the left of the original figure. Label the slit spacing d, the angle θ and the path difference on this copy of the triangle



Mathematically relate that difference in path length to the angle θ and the spacing d between the two slits.

What then would be the criterion for the angle at which one expects to see a bright spot in the resulting diffraction pattern.

The law for slit diffraction is usually expressed $d \sin\theta = n\lambda$, where d is the slit spacing, λ is the wavelength, and n is any integer. We'll use this formula heavily in the next two activities.

Guidebook Entry XII.11: Measuring the Wavelength with Two-Slit Diffraction

First, let's see if light really does behave like a wave. What do you expect to see if you shine light through a pair of closely spaced slits?

Try the experiment with one of the glass diffraction plates. What do you see?

Now use the diffraction law and measurement of the angle between two adjacent bright spots to determine the wavelength of the laser light. You won't be able to measure that angle with a protractor--it is too small--so you will have to infer it from the spacing between adjacent bright spots. The slit spacings are given on a little key card (these values are only approximate, with about 5% error).

Try this with a different color laser. We have several green lasers that you may try. Make your measurements at the one shared setup, and see if the wavelength is the same or different.

If one were to add a slit in between the two slits, it will produce a central third beam with a phase shift that is half as big as the phase shift between the two original beams. This means that for the spot where the original beams were out of phase by one wavelength and constructive, it will be out of phase by half a wavelength and give destructive interference. But, for the next spot where the original beams interfered constructively and were two wavelengths out of phase, the middle slit will give one full wavelength out of phase, and constructive interference is retained. So only half of the spots stay, and they are spaced twice as far.

Guidebook Entry XII.12: The Diffraction Grating

For the case described above, with slits twice as close but spots twice as far separated, show that $d\sin\theta = n\lambda$ is still obeyed.

Adding many slits in between produces a pattern that has very sharply defined spots, with mostly blank space in between. Can you explain this?

A diffraction grating provides many closely spaced slits. Use the cardboard mounted diffraction grating with the laser. Can you explain what you see?

Assume that the laser wavelength is 650 nm. What is the slit spacing of the grating?

Because diffraction is wavelength dependent, a grating will work much like a prism. Hold the grating to your eye and look at some light sources. Can you see the light broken into its constituents? Describe what you see.

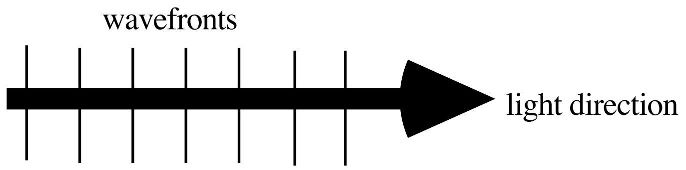
Now look at one of the discharge tubes. Do you see something different? Describe this.

Both refraction (light bending as it changes medium, as we saw with lenses and prisms) and reflection can be explained by the wave properties of light. The important principle to remember is that of causality: the wave leaving a surface is a direct result of the wave incident on a surface.

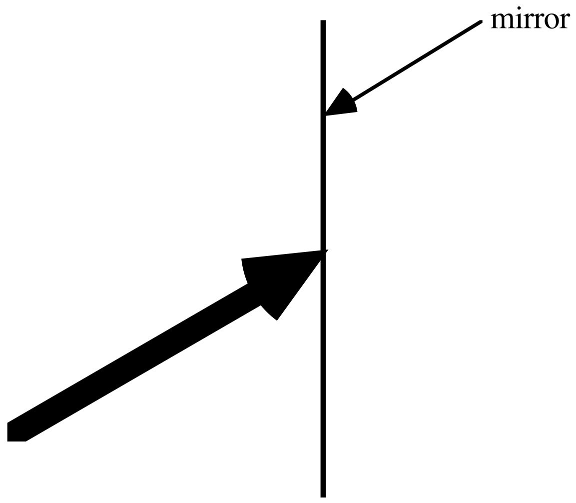
> **This means that a crest leaving the surface was caused by a crest incident on the surface; the wave fronts must line up on the surface.**

Guidebook Entry XII.13: Explaining Refraction and Reflection

We often draw pictures of waves in which we imagine the crests of the waves as wavefronts that we draw as lines:

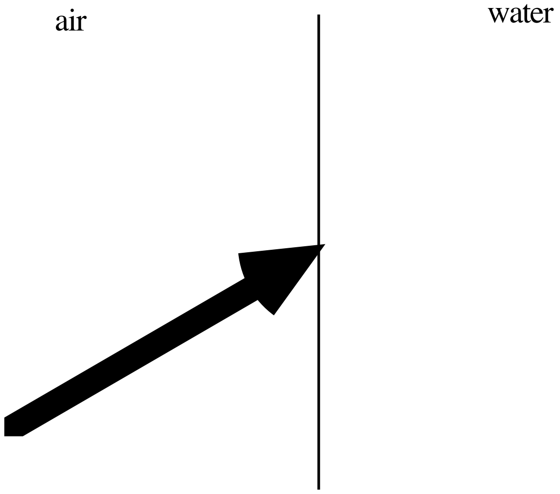


Use a pair of beams like this incident on a mirror to show that the angle of incidence is equal to the angle of reflection.



One remarkable feature of light is that its wavelength changes when it is traveling through some material.

If the wavelength of a light ray is reduced, use a wavefront diagram to show that the direction of propagation must bend at the interface:



As an extra challenge, try the following. If the wavelength of the light is reduced by a factor of n to λ/n in the medium, show that the angle of refraction is given by Snell's law:

This last equation is generalized for travel between any two media (not necessarily one like air where n, the index of refraction, is about one) as the full Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 .$$

Session 4: Combinations of Lenses

In this session we will investigate some combinations of lenses both theoretically and experimentally. These combinations form most practical lens systems, such as microscopes and telescopes. Even apparently simple lenses (such as camera lenses) are actually made up of several lenses together (feel free to ask me why that might be!). Even perhaps the simplest and most common use of a lens, that of a magnifier, really is a compound lens system, where one of those lenses is in your eye.

Guidebook Entry XII.14: Use of Magnifiers

Look at several lenses in your set and use them each as magnifiers (i.e. look through them at some small object). Show that the greatest magnification occurs when you position the lens about one focal length away from the object you are looking at.
Describe what you see.

For the four different focal lengths available to us (you may have to borrow a blue one), use them each as magnifiers. Compare the relative magnification. Which lens provides the greatest magnification? Which the least?

How does the magnification relate (qualitatively) to the focal length of the lens?

You should have discovered that short focal lengths provide the greatest magnification, although these lenses are often smaller in diameter. As a result, there is a smaller field of view (the area of the lens you are looking at is just smaller). To make up for this, it is often helpful to get your eye up very close to the lens. Try this, and describe what you see.

In the next exercise, we will try using a combination of two lenses--one to produce an image, and then a second lens to look at the image.

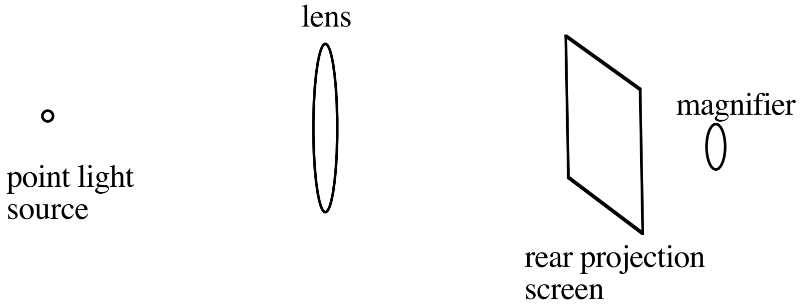
Guidebook Entry XII.15: A Rear Projection System

Take an intermediate focal length lens, and project an image of the light source onto your screen on the on your optics rail. Now, take a second lens and use that at a magnifier to look at the image. Describe any difficulties you might have.

My guess is that you noted that if you try to look closely at the image, especially with your best magnifier (shortest focal length lens), you get in the way and block out the image. At the very least, you are not able to look at the image squarely, but rather off at an angle. To fix this, replace your screen with a piece of copy paper. You should be able to see the image from the *back* side of the paper. This technique is called *rear projection*. Try this and describe your results.

Now take your magnifier, and look at the back side of the image. Does this work better in some ways than looking at the front side? What are the advantages? What are the disadvantages?

Position your magnifier at the correct location on your optics rail so you don't have to hold it, if you hadn't done so yet. Let's consider what the paper does. The original screen scattered the light back in all directions allowing you to see it. This rear projection screen now scatters the light in the forward direction as well, so you can see the image from either side. Imagine light coming from a point light source, as shown below. Sketch a variety (at least five) of light paths from the source to their final scattering off the screen. Make sure to mark the image on the screen.



Now imagine we were to simply remove the screen. How would this change the light rays that ultimately get to the magnifier? This is subtle, so discuss it in your group, then talk with an instructor.

Now, do that experiment. Remove the paper screen, and look through the magnifier. Describe what you see. You may want to go back and forth between screen and no screen.

This technique of using one lens to produce an image, and a second lens as a magnifier to look at that image is the fundamental basis for telescopes and microscopes. You may have noticed that they produce inverted images--usually considered ok for microscopes, but not so desirable for telescopes. We'll look first at the microscope case, and build one on our optics rail. You might well ask why not just use magnifiers? The answer to that is that to achieve greatest magnification, one needs very short focal length lenses. These lenses, by necessity, are small in diameter, so they provide a rapidly diminishing field of view (you can readily observe this with our own lens selection--the shorter focal length lenses are also smaller in diameter). Before long, they simply become too small to be useful as magnifiers. The microscope provides a way around this

Guidebook Entry XII.16: A Simple Microscope

Microscopes are used to look at small objects that we can hold wherever we like (in contrast to, say, the moon or a wild bird perched in a tree). Since we want the greatest magnification possible of the image that we will look at, recall first the image magnification formula for a single lens:

$$M = \frac{d_2}{d_1}$$

We want all of our microscope to fit on our optics rail. Given this, what type of lens to we want to use as our first lens (the objective--the one that produces our image in contrast to our magnifier). That is, do we want a long or short focal length? Explain.

Choose a lens as your objective, and produce an image of your light source on your paper screen. Position a second lens as your magnifier, and then remove the screen. Describe what you observe.

The first compound lens application was actually the telescope, and this was done by Galileo. He was interested in looking at the night sky more carefully, an application that simply would not yield to simple magnifiers! He invented the inverting (or Galilean) telescope you will build next, and turned it almost immediately on Jupiter, and discovered four moons around Jupiter, which in one fell swoop spelled the end of the earth-centered view of the solar system, and thereby the universe! All of that history is to help you excuse the unfortunate inverting property of this telescope!

Guidebook Entry XII.17: Galileo's Telescope

Imagine now that we want to create an image of a very distant object, one that we cannot move. As a result d_1 is already a large number that we cannot change, a number larger than any focal length we have. With that in mind, what focal length lens do we want to choose to maximize the magnification of our image, as given by our magnification formula

$$M = \frac{d_2}{d_1} \ ?$$

Explain your answer

Use the same technique you used with the microscope using one of the lights at either end of the room as an object. That is, form the image on the paper, adjust a suitable magnifier, then remove the paper. Sketch your setup, and describe the results

To make a non-inverting telescope requires either additional lenses, or a different type of lens instead of the magnifier (a diverging lens--try it if you wish--but placement of the second lens is a bit tricky). It should be clear that a large focal length lens is most desirable. It also should not be a surprise that a bigger lens (diameter) collects more light, giving a brighter image. It is difficult to satisfy both of these in glass, especially if one needs to avoid problems of different focal lengths for different colors of light. As a result, most big telescopes use mirrors instead of lenses for the objective.