0.1 Introduction

Unlike other scientists, astronomers are far away from the objects they want to examine. Therefore astronomers learn everything about an object by studying the light it emits. Since objects of astronomical interest are far away, they appear very dim and small to us. Thus astronomers must depend upon telescopes to gather more information. Lenses and mirrors are used in telescopes which are the instruments astronomers use to observe celestial objects. Therefore it is important for us to have a basic understanding of optics in order to optimize telescopes and interpret the information we receive from them.

The basic idea of optics is that mirrors or lenses can be used to change the direction which light travels. Mirrors change the direction of light by *reflecting* the light, while lenses redirect light by *refracting*, or bending the light.

The theory of optics is an important part of astronomy, but it is also very useful in other fields. Biologists use microscopes with multiple lenses to see very small objects. People in the telecommunications field use fiber optic cables to carry information at the speed of light. Many people benefit from optics by having their vision corrected with eyeglasses or contact lenses.

This lab will teach you some of the basic principles of optics which will allow you to be able to predict what mirrors and lenses will do to the light which is incident on them. At the observatory you use real telescopes, so the basic skills you learn in this lab will help you understand telescopes better.

- *Goals:* to discuss the properties of mirrors and lenses, and demonstrate them using an optics kit and worksheet
- *Materials:* optics kit, ray trace worksheet, ruler

0.2 Discussion

The behavior of light depends on how it strikes the surface of an object. All angles are measured with respect to the **normal** direction. The normal direction is defined as a line which is perpendicular to the surface of the object. The angle between the normal direction and the surface of the object is 90°. Some important definitions are

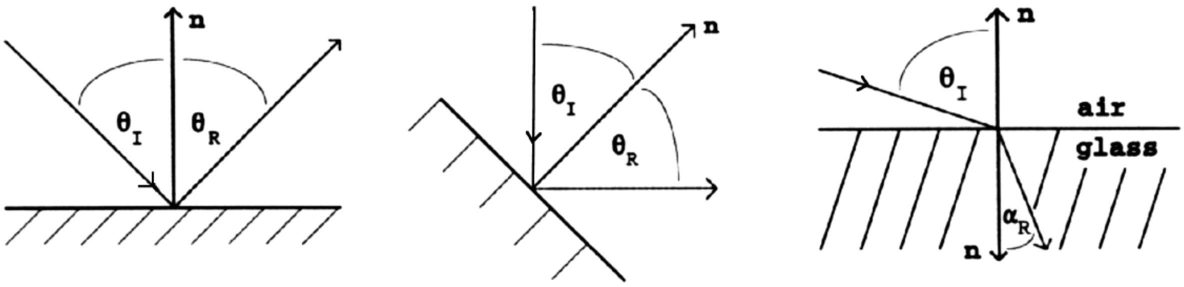

Fig 1a. **Fig 1b.** **Fig 1c.**

Figure 1: The definition of the “normal” direction **n**, and other angles found in optics.

given below. Pay special attention to the pictures in Figure 1 since they relate to the reflective (mirrors) and refractive (lenses) optics which will be discussed in this lab.

- $\mathbf{n}$ = line which is always perpendicular to the surface; also called the *normal*
- θ_I = angle of *incidence*; the angle between the *incoming* light ray and the normal to the surface
- θ_R = angle of *reflection*; the angle between the *outgoing* light ray and the normal to the surface
- α_R = angle of *refraction*; the angle between the *transmitted* light ray and the normal direction

0.3 Reflective Optics: Mirrors

How do mirrors work? Let’s experiment by reflecting light off of a simple flat mirror.

As part of the equipment for this lab you have been given a device that has a large wooden protractor mounted in a stand that also has a flat mirror. Along with this set-up comes a “Laser Straight” laser alignment tool. Inside the Laser Straight is a small laser. There is a small black switch which turns the laser on and off. Keep it off, except when performing the following exercise (always be careful around lasers–they can damage your eyes if you stare into them!).

With this set-up, we can explore how light is reflected off of a flat mirror. Turn on the Laser Straight, place it on the wooden part of the apparatus outside the edge of the protractor so that the laser beam crosses across the protractor scale and intercepts the mirror. Align the laser at some angle on the protractor, making sure the laser beam passes through the *vertex* of the protractor. Note how the "incident" laser beam is reflected. Make a sketch of what you observe in the space below.

Now experiment using different angles of incidence by rotating the Laser Straight around the edge of the protractor, always insuring the laser hits the mirror exactly at the vertex of the protractor. Note that an angle of incidence of 90° corresponds to the "normal" defined above (see Fig. 9.1.a). Fill in the following table of angle of incidence vs. angle of reflection. *(3 points)*

Table 1: Data Table

Angle of Incidence	Angle of Reflection
20^{o}	
30^{o}	
45^{o}	
60^{o}	
75^{o}	
90^{o}	

What do you conclude about how light is reflected from a mirror? *(2 points)*

The law governing the behavior of light when it strikes a mirror is known as the **Law of Reflection**:

$$\text{angle of incidence} = \text{angle of reflection}$$
$$\theta_I = \theta_R$$

OK, now what happens if you make the mirror curved? First let's consider a *concave* mirror, one which is curved *away* from the light source. Try to think about the curved mirror as being made up of lots of small sections of flat mirrors, and make a prediction for what you will see if you put a curved mirror in the light path. You might try to make a drawing in the space below:

At the front of the classroom is in fact just such a device: A curved wooden base to which are glued a large number of flat mirrors, along with a metal stand that has three lasers mounted in it, and the "disco5000" smoke machine. Have your TA turn on the lasers, align them onto the multi-mirror apparatus, and spew some smoke!

Was your prediction correct?

Also at the front of the room are two large curved mirrors. There are two types of curved mirrors, “convex” and “concave”. In a convex mirror, the mirror is curved outwards, in a concave mirror, the mirror is curved inwards (“caved” in). Light that is reflected from these two types of mirrors behaves in different ways. In this section of the lab, you will investigate how light behaves when encountering a curved mirror.

1) Have your TA place the laser apparatus in front of the convex mirror, and spew some more smoke. **BE CAREFUL NOT TO LET THE LASER LIGHT HIT YOUR EYE.** What happens to the laser beams when they are reflected off of the convex mirror? Make a drawing of how the light is reflected (using the attached work sheet, the diagram labeled “Convex Mirror” in Figure 4. *(5 points)*

2) Now have your TA replace the convex mirror with the concave mirror. Now what happens to the laser beams? Draw a diagram of what happens (using the same worksheet, in the space labeled “Concave Mirror”). *(5 points)*

Note that there are three laser beams. Using a piece of paper, your hand, or some other small opaque item, block out the top laser beam on the stand. Which of the reflected beams disappeared? What happens to the images of the laser beams upon reflection? Draw this result *(5 points)*:

The point where the converging laser beams cross is called the “focus”. From these experiments, we can draw the conclusion that *concave mirrors focus light, convex* *mirrors diverge light.* Both of the mirrors are 61 cm in diameter. Using a meter stick, how far from the mirror is the convergent point of the reflected light ("where is the best focus achieved")? *(3 points)*

This distance is called the "focal length". For concave mirrors the focal length is one half of the "radius of curvature" of the mirror. If you could imagine a spherical mirror, cut the sphere in half. Now you have a hemispherical mirror. The radius of the hemisphere is the same as the radius of the sphere. Now, imagine cutting a small cap off of the hemisphere–now you have a concave mirror, but it is a piece of a sphere that has the same radius as before!

What is the radius of curvature of the big concave mirror? *(1 point)*

Ok, with the lasers off, look into the concave mirror, is your face larger or smaller? Does a concave mirror appear to magnify, or demagnify your image. How about the convex mirror, does it appear to magnify, or demagnify? *(1 point)*:

0.4 Refractive Optics: Lenses

OK, how about lenses? Do they work in a similar way?

At your table is an apparatus called an "optical bench". It is basically a meter stick with some lens holders and a source of light to allow you to mount various bits of optics and experiment with how lenses work. As with mirrors, there are two types of lenses: convex and concave. But in the case of lenses, you have two surfaces, so one side can be convex, and one side can be concave. Or, you can have both sides being convex, or concave. The latter types of lenses are called "double convex" and "double concave". We will be experimenting with both types of lenses.

To start begin this section of the lab, we will be using an "optical bench" that has a light source on one end, and a projection (imaging) screen on the other end. To start with, there will be three lenses attached mounted on the optical bench. Loosen the (horizontal) thumbscrews and remove the three lenses from the optical bench. Two of the lenses have the same diameter, and one lens is larger. Holding one of the lenses by the steel shaft, examine whether this lens can be used as a "magnifying glass", that is when you look through it, do objects appear bigger, or smaller? You will find that two of the lenses are "positive" lenses in that they magnify objects, and one is a "negative" lens that acts to "de-magnify" objects. Note how easy it is to decide which lenses are positive and which one is the negative lens.

Now we are going to attempt to measure the "focal lengths" of these lenses. First, remount the smaller positive lens back on the optical bench. Turn on the light by simply connecting the light source to the battery or transformer using the alligator clips (be careful not to let the alligator clips touch each other or else the transformer will be damaged). Take the smaller *positive* lens move it to the middle of the optical bench (tightening or loosing the vertical clamping screw to allow you to slide it back and forth). At the one end of the optical bench mount the white plastic viewing screen. It is best to mount this at a convenient measurement spot–let's choose to align the plastic screen so that it is right at the 10 cm position on the meter stick. Now slowly move the lens closer to the screen. As you do so, you should see a circle of light that decreases in size until you reach "focus" (for this to work, however, your light source and lens have to be at the same *height* above the meter stick!). Measure the distance between the lens and the plastic screen. Write down this number, we will call it "a".

The distance "a" = cm

Now measure the distance between the lens and the front of the light source. Write down this number, we will call it "b":

The distance "b" = cm

To determine the focal length of a lens ("F"), there is a formula called "the lens maker's formula":

$$\frac{1}{F} = \frac{1}{a} + \frac{1}{b} \tag{1}$$

Calculate the focal length of the small positive lens: F = cm

Now replace the positive lens with the small *negative* lens. Repeat the process. Can you find a focus with this lens? What appears to be happening? *(5 points)*

How does the behavior of these two lenses compare with the behavior of mirrors? Draw how light behaves when encountering the two types of lenses using Figure 5. Note some similarities and differences between what you have drawn in Fig. 4, and what you drew in Fig. 5 and write them in the space below. *(5 points)*

Ok, now let's go back and mount the larger lens on the optical bench. This lens has a very long focal length. Remove the light source from the optical bench. Now mount the big lens exactly 80 cm from the white screen. Holding the light source, move it until you can get a sharp focus (Note that this focus will not be a point, but will be a focused image of the filament in the light bulb and show-up as a small, bright line segment. This is a much higher power lens, so the image is not squished down like occured with the smaller positive lens.) Using the wooden meter stick, have your lab partners measure the distance between the light source and the lens. This is hard to do, but you should get a number that is close to 80 cm. Assuming that $a = b = 80$ cm, use the lens makers formula to calculate F:

The focal length of the large lens is F = cm

Making a Telescope

As you have learned in class, Galileo was the first person to point a telescope at objects in the night sky. You are now going to make a telescope just like that used by Galileo. Remove the white screen (and light source) from the optical bench and mount (and lock) the large positive lens at the 10 cm mark on the yardstick scale. Now mount the small negative lens about 40 cm away from the big lens. Looking at the furthest "eyechart" mounted in the lab room (maybe go to the back of the room if you are up front, or vice versa), focus the telescope by moving the little lens backwards or forwards. Once you achieve focus, let your lab partners look through the telescope too. Given that everyone's eyes are different, they may need to re-focus the little lens. Write down the distance "N" between the two lenses:

The distance between the two lenses is N = cm

Describe what you see: What does the image look like? Is it distorted? Are there strange colors? What is the smallest set of letters you can read? Is the image right side up? Any other interesting observations? (**5 pts**):

This is exactly the kind of telescope that Galileo used. Shortly after Galileo's observations became famous, Johannes Kepler built his own telescopes, and described how they worked. Kepler suggested that you could make a better telescope using two *positive* lenses. Let's do that. Remove the small negative lens and replace it with the small positive lens. Like before, focus your telescope on the eyechart, and let everyone in your group do the same. Write down the distance "P" between the two lenses after achieving best focus:

The distance between the two lenses is P = cm

Describe what you see: What does the image look like? Is it distorted? Are there strange colors? What is the smallest set of letters you can read? Is the image right side up? Any other interesting observations? (**5 pts**):

Compare the two telescopes. Which is better? What makes it better? Note that

Kepler's version of the telescope did not become popular until many years later. Why do you think that is? (**5 pts**):

The Magnifying and Light Collecting Power of a Telescope

Telescopes do two important things: they collect light, and magnify objects. Astronomical objects are very far away, and thus you must magnify the objects to actually see any detail. Telescopes also collect light, allowing you to see fainter objects than can be seen by your eye. It is easy to envision this latter function as two different size buckets in the rain. The bigger diameter bucket will collect more water than the smaller bucket. In fact, the amount of water collected goes as the area of the top of the bucket. If we have circular buckets, than given that the area of a circle is $\pi \mathrm{R}^2$, a bucket that is twice the radius, has four times the area, and thus collects four times the rain. The same relationship is at work for your eye and a telescope. The radius of a typical human pupil is 4 mm, while the big lens you have been using has a radius of 20 mm. Thus, the lens collects 25 times as much light as your pupil.

Determining the magnification of a telescope is also very simple:

$$M = \frac{F}{f} \tag{2}$$

Where "M" is the magnification, "F" is the focal length of the "objective" lens (the bigger of the two lenses), and "f" is the focal length of the "eyepiece" (the smaller of the two lenses). You have calculated both "F" and "f" in the preceeding for the two positive lenses, and thus can calculate the *magnification of the "Kepler" telescope*:

The magnification of the Kepler telescope is M =   times.

Ok, how about the magnification of the Galileo telescope? The magnification for the Galileo telescope is calculated the same way:

$$M = \frac{F}{f} \tag{3}$$

But remember, we could not measure a focal length for the negative lens. How can this be done? With specialized optical equipment it is rather easy to measure the focal length of a negative lens. But since we do not have that equipment, we have to use another technique. In the following two figures we show a "ray diagram" for both the Kepler and Galileo telescopes.

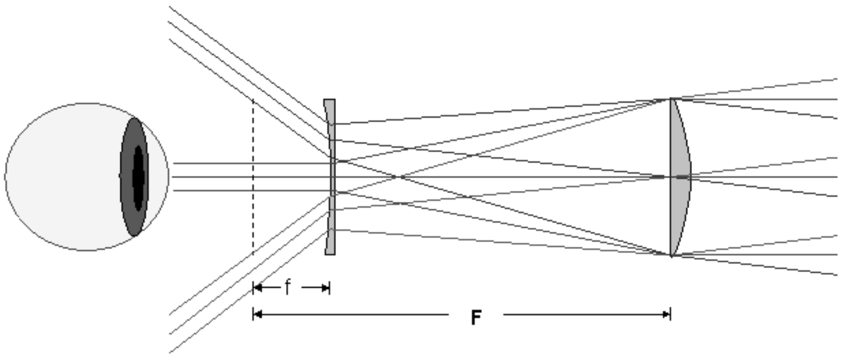

Figure 2: The ray diagram for Galileo's telescope.

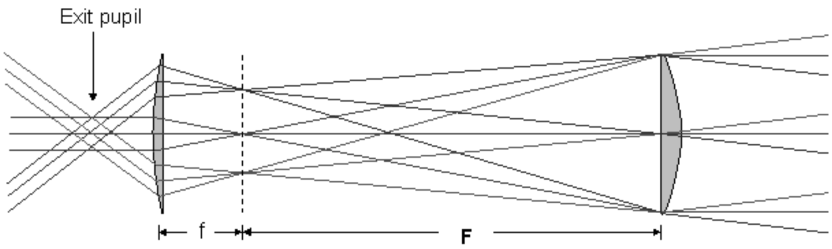

Figure 3: The ray diagram for Kepler's telescope.

Earlier, we had you make various measurements of the lenses, and measure separations of the lenses in both telescopes once they were focused. If you look at Figure 2 and

Figure 3, you will see that there is a large "F". This is the focal length of the large, positive lens (the "objective"). In Kepler's telescope, when it is focused, you see that the separation between the two lenses is the sum of the focal lengths of the two lenses. We called this distance "P", above. You should confirm that the "P" you measured above is in fact equal (or fairly close) to the sum of the focal lengths of the two positive lenses: P = f + F (where little "f" is the focal length of the smaller positive lens).

Ok, now look at Figure 2. Note that now when the telescope is focused, the separation between the two lenses in the Galileo telescope is N = F − f (where F and f have the same definition as before).

Find "f" for the Galileo telescope that you built, and determine the magnification of this telescope (**5 pts**):

Compare the magnification of your Galileo telescope to that you just calculated for the Kepler telescope (**2 pts**):

0.5 Summary

(*35 points*) Please summarize the important concepts of this lab.

- Describe the properties of the different types of lenses *and* mirrors discussed in this lab
- What are some of the differences between mirrors and lenses?
- Why is the study of optics important in astronomy?

Use complete sentences, and proofread your lab before handing it in.

0.6 Extra Credit

Astronomers constantly are striving for larger and larger optics so that they can collect more light, and see fainter objects. Galileo's first telescope had a simple lens that was 1" in diameter. The largest telescopes on Earth are the Keck 10 m telescopes (10 m = 400 inches!). Just about all telescopes use mirrors. The reason is that lenses have to be supported from their edges, while mirrors can be supported from behind. But, eventually, a single mirror gets too big to construct. For this extra credit exercise look up what kind of mirrors the 8 m Gemini telescopes have (at http://www.gemini.edu) versus the mirror system used by the Keck telescopes (http://www2.keck.hawaii.edu/geninfo/about.php). Try to find out how they were made using links from those sites. Write-up a description of the mirrors used in these two telescopes. How do you think the next generation of 30 or 100 m telescopes will be built, like Gemini, or Keck? Why? *(4 points)*

0.7 Possible Quiz Questions

1) What is a "normal"?
2) What is a concave mirror?
3) What is a convex lens?
4) Why do astronomers need to use telescopes?

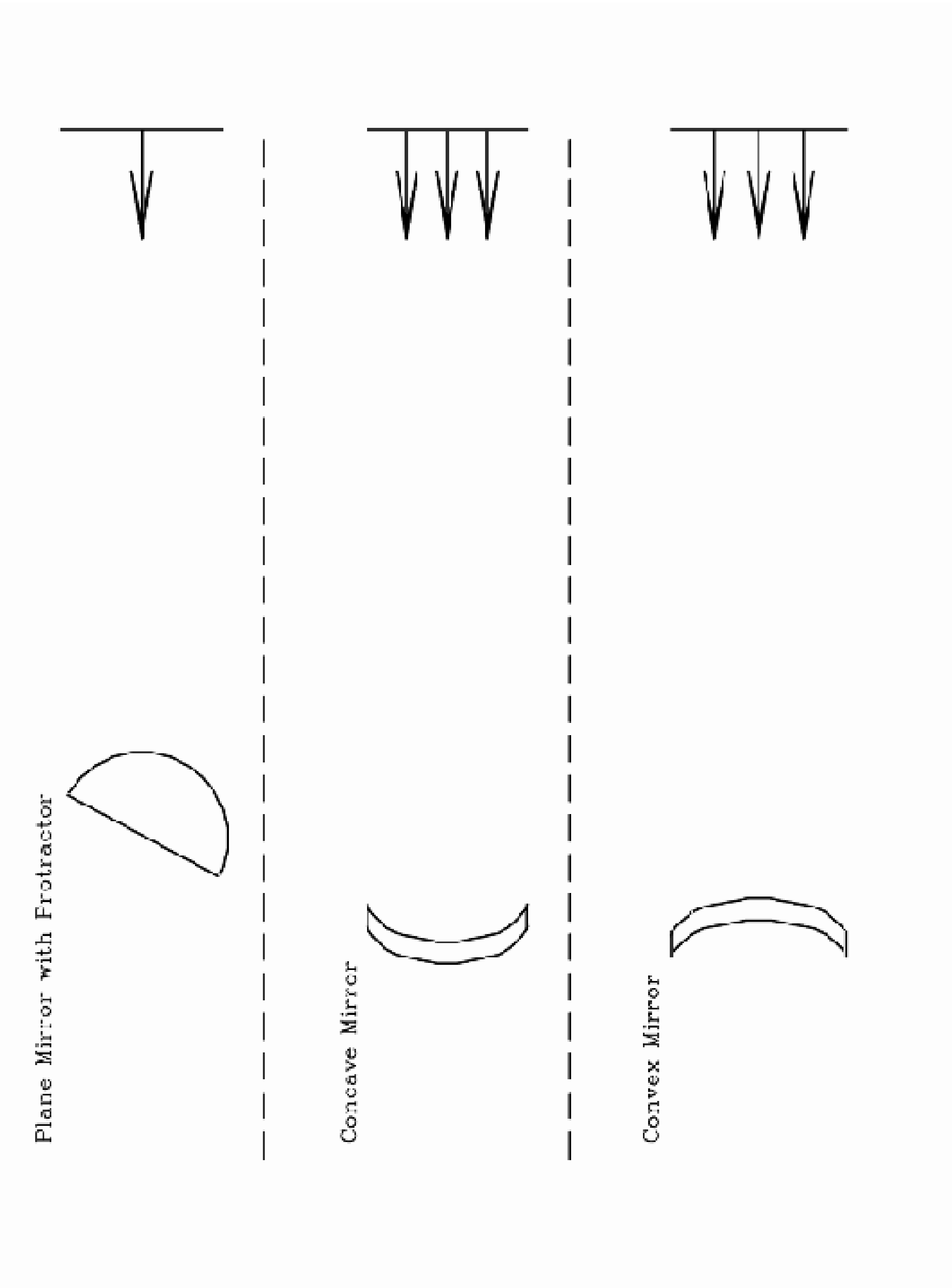

Figure 4: The worksheet needed in section 9.2

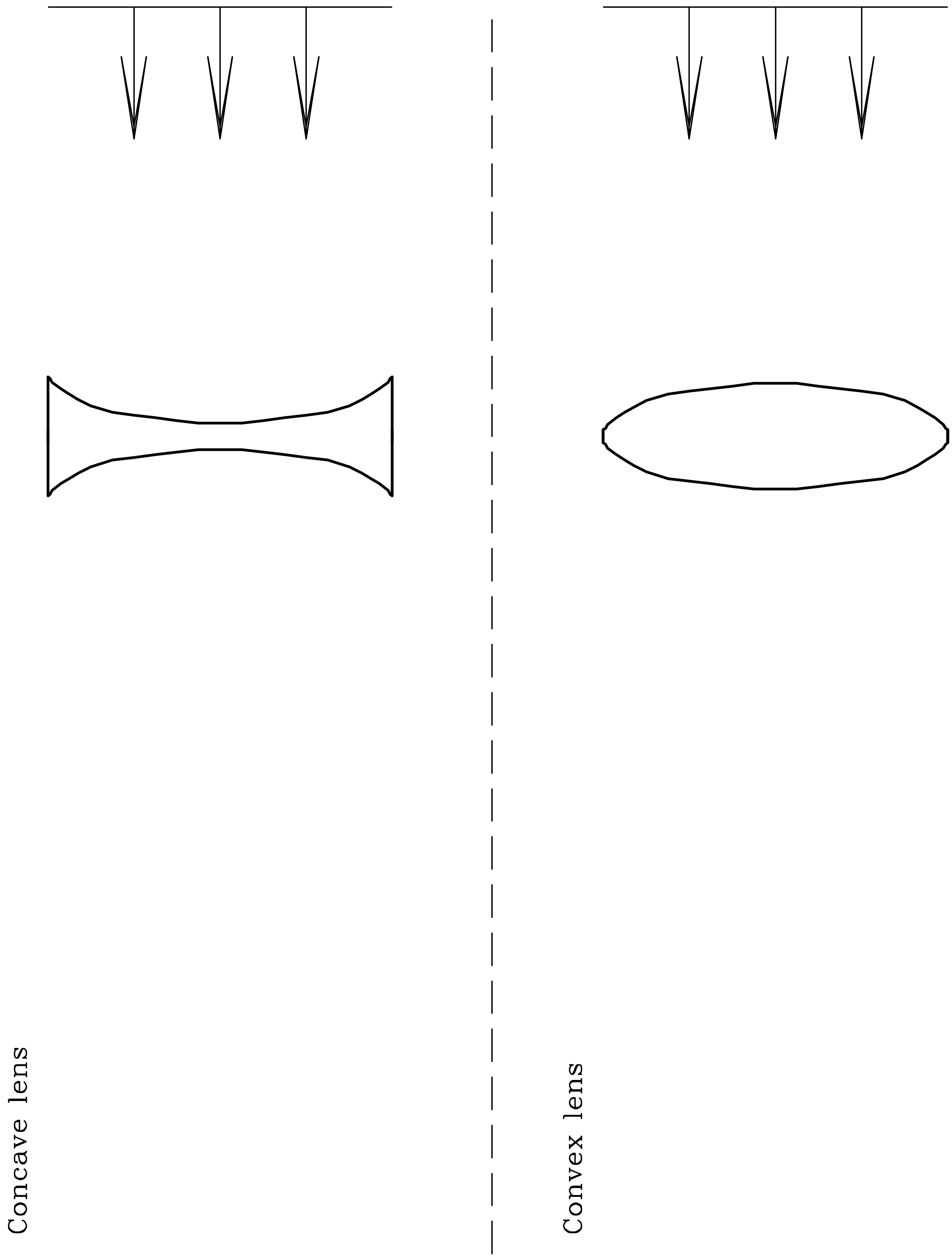

Figure 5: The worksheet needed in section 9.3