Physics 123, Fall 2012 Name ______________________________

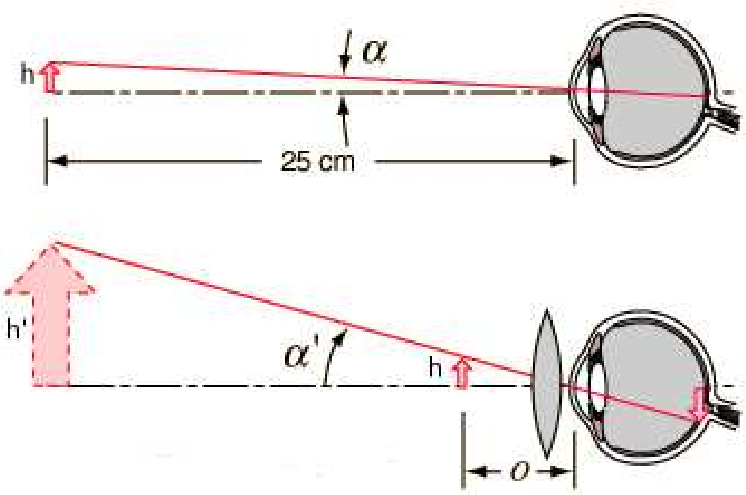
Optical Instruments

I. Magnifier

The lens in the human eye adjusts its shape to change the focal length, so that objects at a variety of distances can be observed. The closest distance at which the eye can observe an object without extreme eye strain is called the *nearpoint.* The average value for humans of all ages is 25 cm. The value varies with age, average around 7 cm for teens, 12 cm for young adults, 28-40 cm for middle age, and 100 cm for senior citizens. The value also depends on your eyesight; i.e., near-sighted people have a closer nearpoint than those with normal vision.

Where is your nearpoint? Measure by estimating where you can focus on this page comfortably and then letting your partner measure the distance. If you wear glasses, you can measure with and without your glasses:

A magnifier works by creating an image of an object at a larger angular size at or near the eye's nearpoint. The geometry of the magnifier is shown in these images from Hyperphysics:



At top, the eye views an object of height h, viewed at the nearpoint distance of 25 cm. This results in an angular size of α. At bottom, the diagram shows the view the eye has of the image of the much closer object viewed through a converging lens. The image is shown at the nearpoint (i= 25 cm). It has a physical size of h' and an angular size of α'. The magnification of the lens is defined as:

$$m = \frac{\alpha'}{\alpha}$$

Complete this section at home or after you have completed the rest of the lab. (Jump to next page.)
In this section, you will calculate the magnification possible for a lens of a given focal length. First refer to the magnifier geometry, and write α' in two ways: (i) as a function of h and s(=O in diagram) and (ii) as a function of h' and s':

For small angles, with α measured in radians, the small-angle approximation is:

$$tan\alpha \sim sin\alpha \sim \alpha$$

Rewrite expressions for the angle using the small-angle approximation:

The lens has a varying magnification depending on where the object, and therefore image, is located. Show that the configuration in the figure, with the image at the nearpoint (assumed to be 25 cm; add correct sign), results in a magnification of:

$$m = \frac{h'}{h} = \frac{25}{s}$$

Now consider the angular magnification from top figure to bottom figure. Write α in terms of h and the 25 cm distance. Then find an expression for p in terms of f and show that

$$m = \frac{\alpha'}{\alpha} = 1 + \frac{25cm}{f}$$

It is less stressful on the eye to observe objects/images located at infinity. Where would you move the object so that the image produced by the magnifier appears to the eye to be located at infinity? Make a sketch illustrating a couple of rays leaving the object and entering the eye:

The magnification of this configuration is:

$$m = \frac{25cm}{f}$$

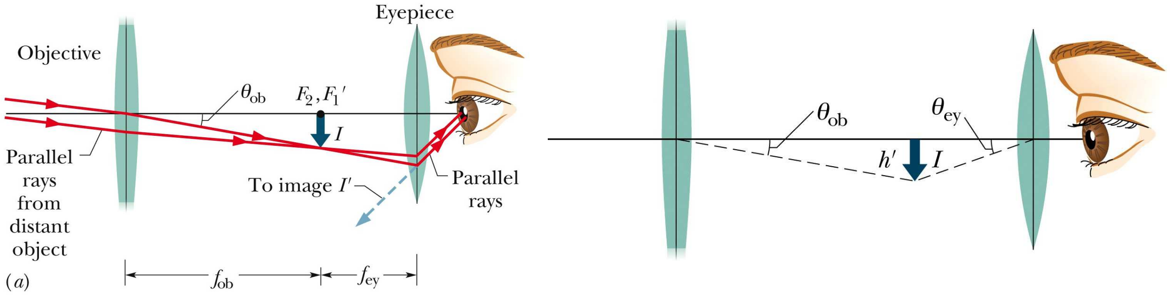
Determine the magnification range of one of your converging lenses, using the given focal length. Confirm that this is indeed the approximate magnification by looking at this sheet with the lens.

II. Telescopes

The telescope is one example of an optical system. The purpose of a telescope is two-fold: (i) to magnify a distant object and (ii) to use a large diameter optical component to collect light, so that faint objects may be observed.

A. Modern Refracting (Keplerian) Telescope

Most modern refracting telescopes contain two converging lenses, as shown in the figure below. This design was first used by Kepler.



The lens which light from an object first encounters is called the objective lens. The lens closest to the eye is called the eyepiece. An object located at infinity would focus at the focal point of the objective. Since distant objects have nearly parallel rays, their images will focus near the focal point. The eyepiece is positioned a distance equal to its focal length away from the focal point of the objective, i.e., the objective and eyepiece are separated by $f_{ob} + f_{ey}$.

The effect of the eyepiece is to magnify the intermediate image produced by the objective for ease of viewing with the eye. It can be shown that the angular magnification of this system is:

$$|m| = \frac{\theta_{ey}}{\theta_{ob}} = \frac{f_{ob}}{f_{ey}}$$

where the θ_{ob} (see figure) is the angular size of the object, θ_{ey} is the angular size of the image, and f_{ob} and f_{ey} are the focal lengths of the objective and eyepiece, respectively. Thus the angular magnification increases as the focal length of the objective is increased. The sign convention for magnification holds: if the image is inverted, m is negative.

1. First we will investigate the role of the objective. Place the f = 127mm lens on the optical bench and look through the lens at a distant object. Move your head until the object comes in focus. Does the image appear larger or smaller? Right-side-up or inverted? Is your eye approximately at the focal point? Why or why not? As part of your answer to the last question, draw a sketch of the system and show the light paths of several rays entering the eye.

Note that telescopes often have only an objective, with instruments such as cameras or spectrographs placed in the focal plane.

2. Now add the eyepiece to construct the telescope pictured in the figure. Use the 127mm lens for the objective and the 48mm lens for the eyepiece.

Use your telescope to focus on an object across the room. Choose a reference object that you can easily find again and observe it near the center of the field-of-view. You will compare the apparent size of this object and the field-of-view of this setup with another setup in the next step. Does the image appear right-side-up or inverted?

3. Do a calculation to **predict** how the magnification of the distant object would be changed by replacing the 48mm lens with an 18mm lens. Show your work. What do you expect to happen to the field-of-view?

Now test your prediction by substituting the 18mm lens for the eyepiece. Aim it at your reference object. What has happened to the apparent size of your reference object? The field of view?

B. Historic Refracting (Galilean) Telescope

Galileo first popularized the telescope, pointing the telescope at the sky about 400 years ago. He used a different arrangement of lenses than today's astronomical refracting telescopes. A diverging lens was used as the eyepiece rather than a converging lens, as shown in the figure. The converging objective was a plano-convex lens (rather than the bi-convex lens shown in the figure).

1. Based on the diagram, predict whether the image will be inverted or right-side-up.

2. Set up a Galilean telescope, using a diverging lens as the eyepiece and the 48 or 127mm converging lens as an objective. Confirm your prediction.

3. Think of an advantage of the Galilean design.

4. Think of an advantage of the Keplerian (Part A) design.

C. Reflecting Telescope

One of the objects of building a telescope is to gather as much light as possible, in order to see fainter objects (in fact, large telescopes are often called 'light buckets' !). A larger objective lens will gather more light, but will not change the magnification unless the focal length is changed. However, there are practical difficulties with large lenses. It is hard and expensive to construct well-made large lenses. In addition, the lens is supported in the telescope only by its edges, so that large, heavy lenses will tend to sag and distort the image. For this reason, large astronomical telescopes use a mirror in place of an objective lens. A large mirror is less expensive to produce and it can be supported from the back. A telescope which uses a mirror in place of an objective lens is called a reflecting telescope.

1. Most reflecting telescopes have a large 'primary' mirror and an smaller 'secondary' mirror. Two common types are displayed in the lab room and are sketched below. First identify each type of telescope. Write an advantage of each telescope design.

150mm Newtonian, f=1000mm
Primary mirror is concave parabolic, secondary mirror is planar.

8-inch Cassegrain, f = 80 inch = 2032 mm
Primary mirror is concave parabolic, secondary mirror is convex hyperbolic.

These telescopes have smaller 'finder' telescopes attached to their sides. Finder scopes are usually refracting telescopes. Why is a low magnification finder scope necessary?

2. The magnification of the image viewed through the eyepiece of one of these telescopes is determined by the focal length of the eyepiece. You will experiment with two different focal length eyepieces.

Predict: Which eyepiece will provide the greatest magnification?

Obtain the eyepieces and test your prediction. If your prediction was incorrect, explain where you were mistaken.

Why do you need to refocus when you change eyepieces?

Predict whether you will have to move the eyepiece in or out when you change the eyepiece to one with greater magnification? (Assume that the eyepieces have the same length housing, which may not be true for the eyepieces you are using.) Explain your reasoning.

3. Union's 20-inch reflecting telescope is a variation on the Cassagrain design, but with a concave hyperbolic primary mirror, which is designed to reduce aberrations. This type of telescope is called a Ritchey-Chretien after the original designers and is probably the most common type of professional reflecting telescope. The '20-inch' refers to the diameter of the primary mirror. Imaging is done from a detector placed at the focal plane of the primary + secondary configuration. The primary-secondary distance can be changed to accommodate different detectors (eyepiece for eye-viewing, CCD for digital imaging, spectroscope).

The Hubble Space Telescope is also an example of a Ritchey-Chretien telescope. Attached at the end of this lab is a diagram of the HST telescope. The HST has a rather small mirror for a modern telescope - only 2.4m in diameter. Why is the HST still superior to ground-based telescopes of larger size? Explain using your knowledge of how light travels through a medium.