Physics PreLab 212-9 Version A

Properties of Light and the Eye

Name ________________________________

Section ____________

Date ____________

Polarization

Light is an electromagnetic wave. Electromagnetic waves are *transverse waves* in which, by definition, the oscillations are perpendicular to the direction of travel (unlike a *longitudinal wave* such as sound, in which the oscillations are along the direction of travel). Typically we characterize this property of light by describing the oscillations of the electric field, which we call the "polarization". The electric field can oscillate in a single plane (linear or plane-polarization), in a circle (right or left circular polarization), or in an ellipse (elliptical polarization).

One way to change the polarization state of light is to pass it through a polarizer. No matter what the initial state of polarization, the light that gets through a linear polarizer is simply plane polarized, oriented along the transmission axis of the polarizer. Of course, the intensity may be reduced; if the initial polarization is linear with intensity I_1, the resulting intensity I_2 according to Malus' Law is $I_2=I_1 cos^2\theta$, where $\theta\theta$ is the angle between the initial polarization and the polarization axis of the polarizer.

Q1[8'] If we start out with plane-polarized light with intensity I_0, with its plane of polarization at 30° to the horizontal, what will be the intensity after it is passed through a horizontal polarizer?[4'] What is the state of polarization?[4']

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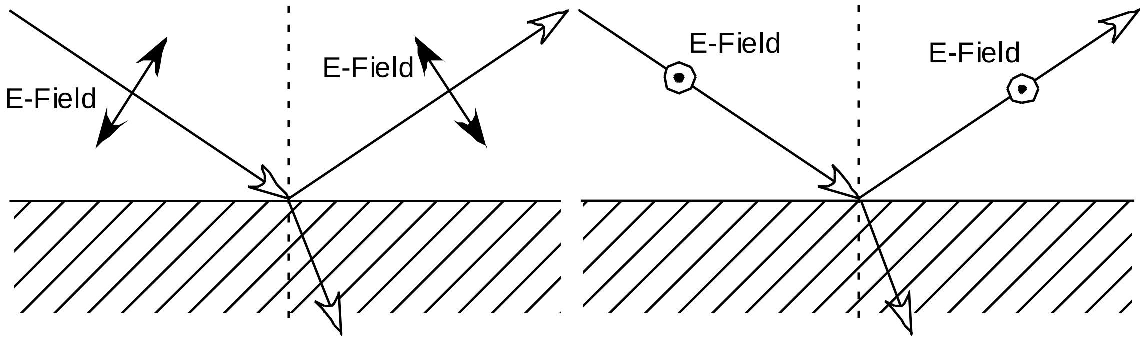
Another way to change the polarization is by reflecting off a tilted flat surface as shown in the diagram below. If the light is not incident perpendicular to the surface, then this defines a "plane of incidence". The plane of incidence is perpendicular to the surface, and contains both the incident and the reflected beams. We can now differentiate two special linear polarization states. There is the state where the linear polarization lies in the plane of incidence (call this "parallel"), and there is the state where the linear polarization lies perpendicular to the plane of incidence (call this "perpendicular"). Note that the electric field for the "perpendicular" case is actually parallel to the surface, while the electric field for the "parallel" case has a component that is perpendicular to the surface.



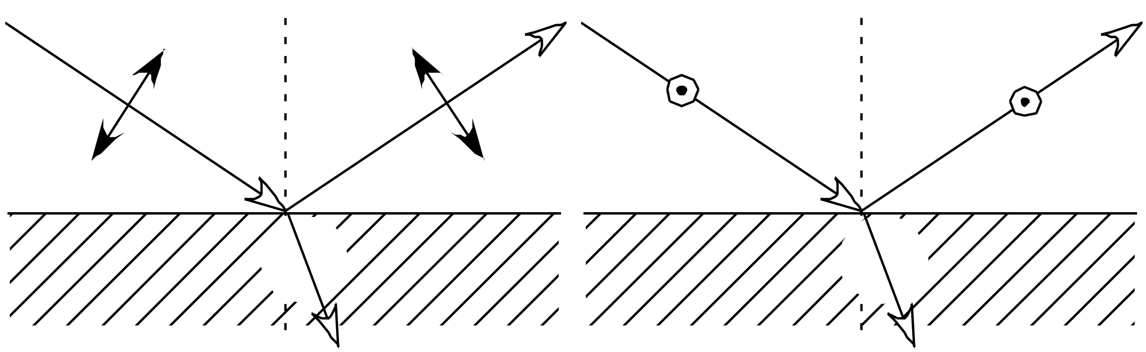
"Parallel" polarization "Perpendicular" polarization

Figure 1. E-fields for parallel and perpendicular polarizations

Now, when the electric field in the light acts on the electrons in the material, it causes them to oscillate side to side (i.e., in the direction of the electric field). This in turn causes them to radiate a new electromagnetic field at exactly the same frequency as the original. In this way, light is propagated through a dielectric, and also reflected at an air-dielectric interface (it is less trivial to derive the fact that the angle of reflection equals the angle of incidence, so for now take that as a given).

As you saw in lecture, the oscillating electrons can only reradiate the light in certain directions – it is mostly radiated perpendicular to the direction of oscillation, and *not at all in the direction the electron is actually moving*. Consequently, if the reflected beam would be in a direction parallel to the oscillation direction of the electrons, then the intensity of the reflected beam is zero – **there is no reflected beam**!

Consider the electric fields of the two possible polarization states (parallel and perpendicular) in Figure 1. Draw in the oscillation directions of the electrons in the interface due to the transmitted light (the oscillation for the incident and reflected beams has already been drawn for you).



Q2[8'] For which case above are the electrons more likely to radiate light into the reflected beam?

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Q3[8'] If you wanted to reduce glare off a lake, or the hood of a car, how should the polarizers in your sunglasses be oriented?

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Note that this same explanation predicts that the sky should appear polarized. In this case the light is "reflected" off the molecules in the atmosphere.

Q4[8'] Assume you are looking up at the sky, with the sun behind you as shown in the sketch below. Which way will the sky be polarized? [Note: Honeybees use this fact to navigate!]

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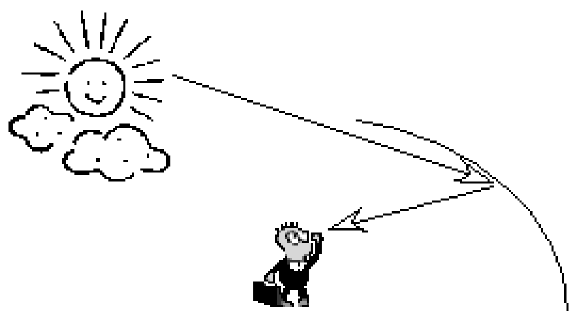

Figure 2. Sketch of light scattering off sky.

The three ways to change polarization that we've studied so far (polarizers, angled-reflection off an interface, and scattering off small particles) all change the polarization by absorbing or scattering away one component of polarization. We can also use birefringence to change polarization without loss.

In a birefringent material, the speed of the wave depends on its polarization. The speed of light in any material is governed by the *index of refraction* (so named because one commonly uses refraction to measure it), defined as $v = c/n$, where c is the speed of light in vacuum, and v is the speed of the wave in the material. For birefringent materials, the index of refraction depends on the polarization and direction of the light. In general for light traveling in a particular direction, there will be a "slow"-propagating polarization and a "fast"-propagating polarization. While propagating through the birefringent material, the "fast" polarization component will pull ahead of the "slow" component, changing their relative phase.

Q5[8'] Is the index of refraction greater for the "slow" polarization component or the "fast" polarization component?

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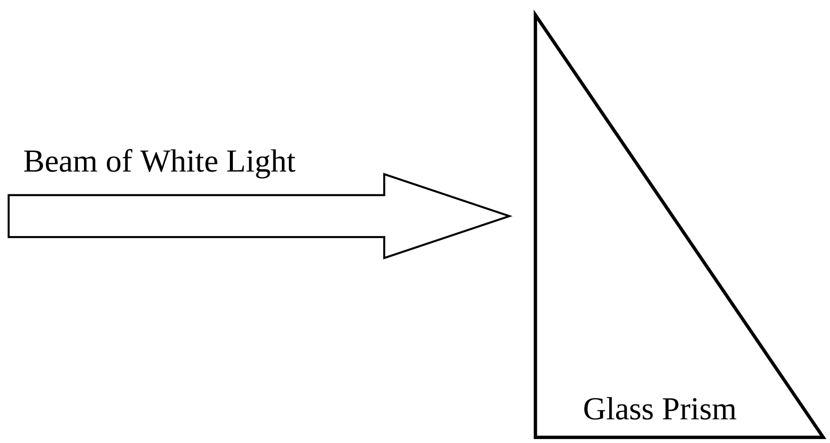
In most materials the index of refraction does *not* depend on polarization. However, in *every material the index does depend on the frequency of the light, a phenomenon known as "dispersion"*. This has a number of very important practical consequences. It limits how well various imaging and projection systems can be made – the different indices of refraction mean that the optical performance of a system of lenses will depend on the color of the light, and it will be difficult to have a system that is simultaneously in focus for blue and red light. Dispersion also leads to such beautiful objects as rainbows.

On the diagram of a triangular prism below, sketch the approximate trajectory for violet light. Now sketch the trajectory for red light (clearly indicating which is which). You need to know that in glass, the index of refraction for violet light is slightly larger (n = 1.52) than the index of refraction for red light (1.51).



Dispersion also limits how much information can be encoded on a light pulse propagating through a fiber optic cable. You might think that if you wanted more information you could simply send more pulses. But on the receiving end you don't want them to overlap, so more pulses means shorter pulses. However, shorter pulses necessarily are made up of more colors, which will travel at different speeds due to dispersion in the glass of the fiber. Therefore, a short pulse will start to spread out, and overlap the nearby pulses. Finding ways to overcome this is a multi-billion dollar industry (telecommunications) these days.

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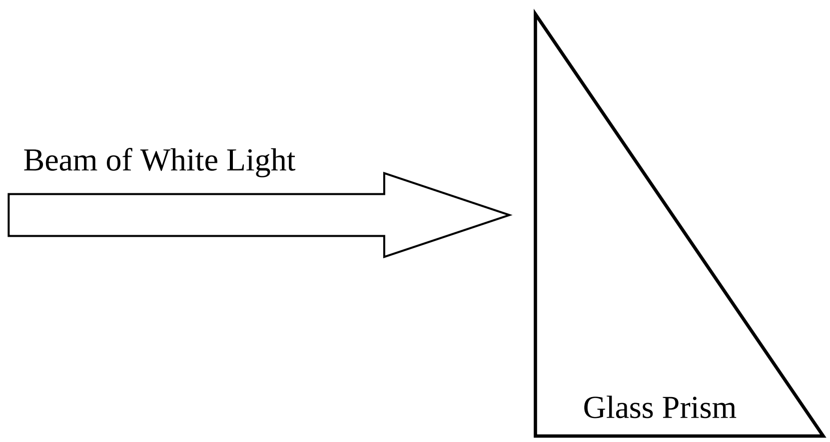

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The Eye

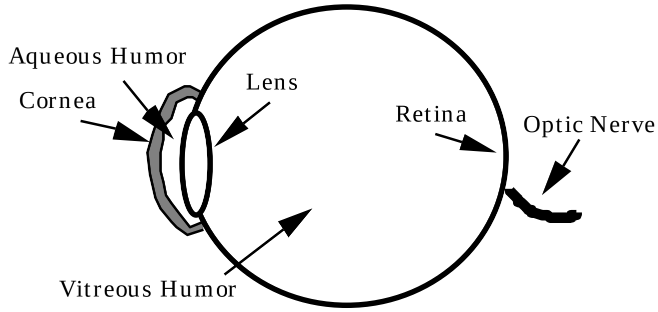

Figure 1. The eye

In class you have been learning about the refraction of light through different media and lenses. However, even before coming to class you were already quite familiar with this process. Why? Because every time you open your eyes, you are refracting light and focusing it in order to see the world around you.

The entire process of seeing, starting from the rays of light from an object and ending with the brain's processing of the image you "see" is complex and involved, and in fact is not completely understood. However, we can examine a small piece of the puzzle here. The cornea, aqueous humor, and the lens work together to refract incoming light and focus it onto the retina, where sensitive receptors called rods and cones convert the light into electrical impulses. These impulses are then carried along the optic nerve to the brain, where they are finally interpreted and you "see."

We are concerned with the eye's main refracting units: the cornea, the aqueous humor, and the crystalline lens. Nearly 75% of the refracting of light occurs at the cornea; the lens handles the remaining "fine tuning." In Figure 2, you can see how an image of a distant point object is formed on the retina.

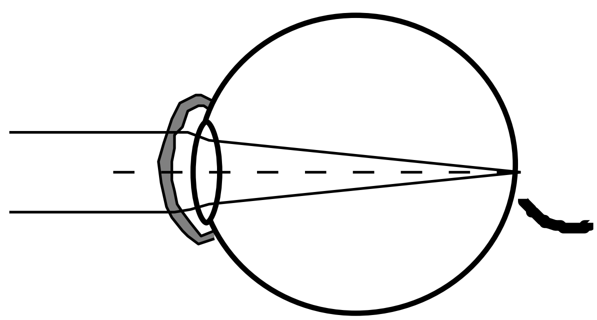

Figure 2. Forming an image of a distant point object onto the retina

Of course, not everybody has perfect eyes. Problems do occur, and we will examine a common one here. Sometimes the eye cannot focus on close objects, while far away objects present no difficulty. This condition is known as *hyperopia*, or farsightedness. The image of a close object falls behind the retina, instead of on it. The result is that a person with hyperopia sees a blurry image for objects that are too close to the eye as in Figure 3.

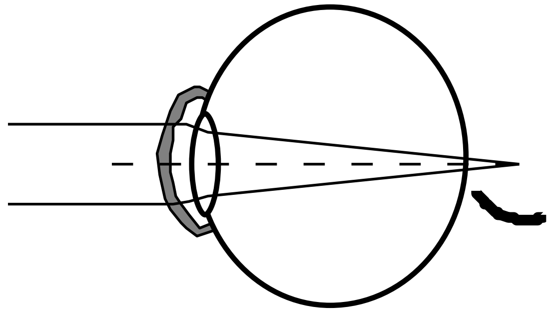

Figure 3. A hyperopic (farsighted) eye unable to focus an image of a close object onto the retina

Q6[2'] A physics student with hyperopia is having a terrible time reading her assignment, because it is too close and all she can see is a blur. But, she remembers that lenses can form images of objects, and that if she could just "move" the *image* of her assignment to another point, she could read it much more easily. Should she move the image closer to or farther away from her eye?

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A normal eye can focus on objects placed up to about 0.25 m in front of the eye without strain. Unfortunately, this student's hyperopic eyes cannot properly focus objects this close. For example, suppose she cannot see objects closer than 1 m from her eyes. To correct her vision, she would need to see objects as close as 0.25 m from her eye, just as a normal eye would. **The trick in this case is to have an object placed 0.25 m from her eye produce an image at the closest point she can see, namely 1 m away from her eye.** This correction can be made using a lens (or lenses to correct each eye.)

Recall the thin lens formula, which states

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f} \qquad \text{(Eq. 1)}$$

where p is the distance between the object and the lens (object distance), q is the distance between the image and the lens (image distance), and f is the focal length of the lens.

To use the thin lens formula properly, you should adhere to a specific sign convention. The conventions we will use are:

the *front* of the lens is the side from which light is coming
the *back* of the lens is side of the lens that is not the front
p is *positive* if the object is in front of the lens
p is *negative* if the object is in back of the lens
q is *positive* if the image is in back of the lens
q is *negative* if the image is in front of the lens
f is *positive* for a converging lens
f is *negative* for a diverging lens

Our goal is to find out the focal length of the additional lens required to correct this student's vision. Remember from the previous paragraph that we require an object 0.25 m from the eye to produce an image far enough away so that the hyperopic eye can see it. Looking at the thin lens formula and Figure 4, we identify the object distance $\boldsymbol{p}$ **= 0.25 m**.

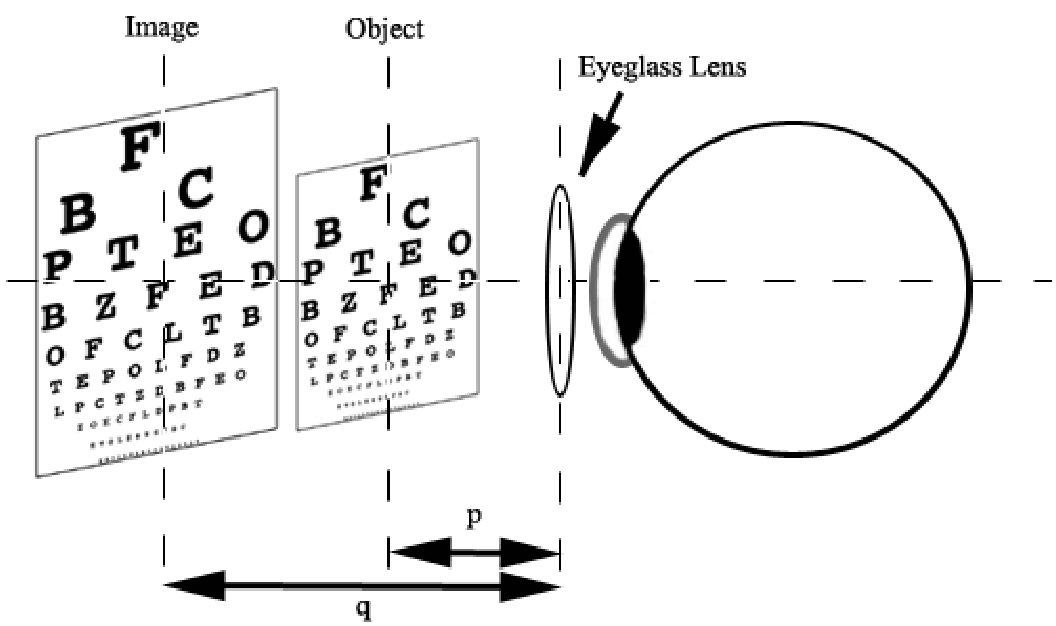

Figure 4. Object and image distances

Q7[3'] What is the image distance q? Remember that q in this case corresponds to the closest distance the image can be to the hyperopic eye and still remain focused. Also note that the value of q must be negative, because an image appearing on the side of the lens where light also enters the lens is considered to be a negative distance from that lens.

$q =$ ________________ [m]

Q8[3'] Given the values for p and q above, what is the focal length of the needed lens?

$f =$ ________________ [m]

Since optometrists do not deal in focal lengths, we cannot make a prescription yet. However, we can convert the focal length, measured in meters, to a "power," measured in *diopters*, which is what optometrists use.

The *power* of a lens is defined as

$$P = \frac{1}{f} \qquad \text{(Eq. 2)}$$

where P is the power, measured in diopters, and f is the focal length, measured in meters. Diopters are symbolized by D.

Q9[2'] What is the power, expressed in units of diopters, of the needed lens?

$P =$ ________________ [D]