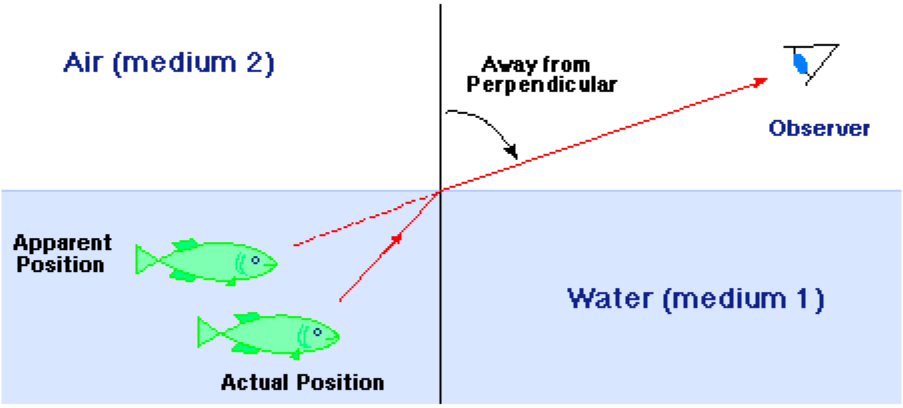
Telescopes & Spectroscopy Lab Guide *Experiment A05*

Why does light bend through certain objects? We see this effect more often than we think – for example, we experience the bending of light when we look at an object in a pool or lake.



Taken from http://www.pas.rochester.edu/~blackman/ast104/ref-diff.html

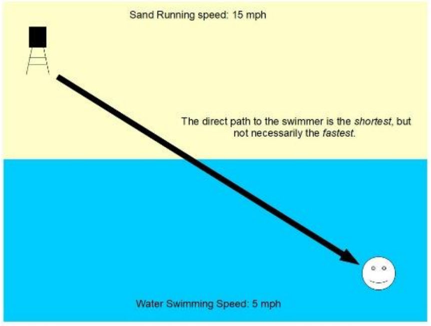
Without getting into too deep into the physics, how can we think about *why* this is happening? Well, the first step is to actually talk about the *speed of light*.

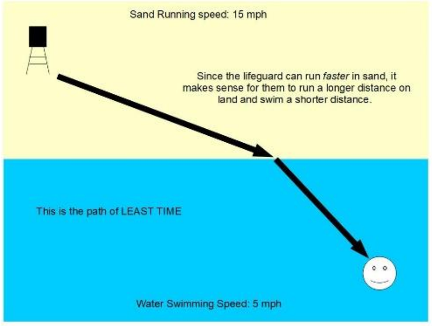
Physicists know the fundamental equation that governs exactly how any kind of wave propagates (moves) through space. Once we determine what kind of wave we want to look at, this equation will automatically tell us how *fast* this wave should propagate. The kind of wave we are most interested in here is an electromagnetic wave, i.e., *light.* Thus, the fundamental equations will give us a speed at which light should propagate (through a vacuum), and this value is the usual $v = c = 2.99\text{x}10^8$ m/s.

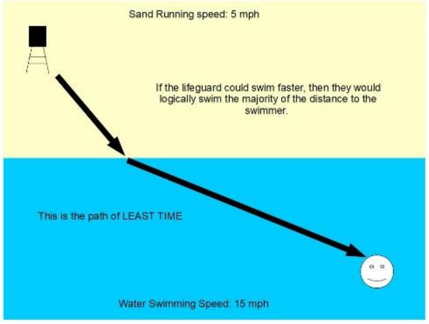
Now, Einstein's theory of special relativity introduces a "cosmic speed limit," a speed at which no object with mass can move at. This is because as you go faster through space, it requires more energy to speed up even more. Thus, it would take an *infinite* amount of energy to move an object at this "cosmic speed limit." However, objects with NO mass *have* to move at this speed. The most well-known object that we know that has no mass is a photon, *light!* Thus, the speed of light (in a vacuum) *is* the "cosmic speed limit" because all massless objects *must* move at this velocity (again, in a vacuum)! So, in the end the universe shows no favoritism towards light specifically – the universe sets its speed limit for particles that have NO mass (or better yet, *information*), and it so happens that light falls into this category.

This may be a surprise to you, but the speed of light as a wave/particle is NOT constant. The speed of light changes depending on what it is moving through, and since the speed of light cannot be GREATER than the "cosmic speed limit," it means the speed of light DECREASES as it moves through different materials. This is why the usual speed of light, c ($2.99\text{x}10^8$ m/s) is usually accompanied by the description, " in a vacuum." A *vacuum* is practically empty space, i.e., there is virtually nothing to impede the motion of light and thus it is its *fastest* through a vacuum. Once light has to move through something with some density (like water), then it slows down. Remember, we said the universe doesn't play favorites when it comes to light – just because the speed of light is changing due to the electrical properties of the substance it is traveling through does NOT mean that the "cosmic speed limit" has changed! This leads to some real cool physics; for example, because the speed of light decreases in some specific substance while the "cosmic speed limit" remains unchanged, *it is possible for an object/particle to reach speeds* ***faster*** *than the reduced speed of the light in that substance!* This leads to something called the **Cherenkov Effect**, in which a particle releases a brief flash of light once it crosses this speed threshold. This is JUST LIKE how if an object moves faster than the speed of *sound* we hear a loud sonic boom – the Cherenkov Effect is a very similar phenomenon but specifically for *light*.

So, the discussion above was to establish that light changes *speed* as we move from one substance to another. The second thing we must establish is the fact that light will travel the path between two points that requires the *least* *amount of time* – which is not necessarily the shortest path. This idea is called *Fermat's Principle*.







We'll introduce this idea using a simple analogy – the lifeguard and the drowning swimmer. A lifeguard is patrolling the beach from his stand and sees a young swimmer drowning off to his left. The first thing to come to mind would be to run in a straight line towards the swimmer – the path of *least distance*. However, we don't care about the *distance* in this situation, we care about getting to the swimmer in the *least amount of time!* What if the lifeguard could run 3 times faster than he could swim? In this case, a straight line would NOT be the path of least time because he's spending a lot more time swimming than he could be running on land! In the second picture above, we can see what the path of least time looks like – the lifeguard travels over a longer distance, but most of that total distance has him moving at a greater speed (i.e., running on land)! What if the lifeguard could swim faster than he could run? Now, in order to get to the swimmer in the *least* amount of time, he should now swim most of the way there instead (as shown in the third picture above). What if the lifeguard could travel at the same speed in both? In this case, the straight line, which is the path of least distance, would also become the path of least time.

How does this analogy relate to light? Just like the lifeguard, light will choose the path between two points that would require the *least time*. As we discussed above the speed of light changes depending on the type of material it is shining through. We can determine how much slower light travels through a material by looking at its *index of refraction, n*. The *n* of a specific material is simply the speed of light in a vacuum divided by the speed of light in this material:

$$n = \frac{c_{(vacuum)}}{v_{(speed\ in\ material)}}$$

So, the *larger* the value of the index of refraction, the *slower* the speed of light is through a material.

Let's talk about how we would know whether light would bend to the right or left at the boundary between two materials [I will refer to the analogy and images above in brackets]. If light is traveling from a substance with a *lower* index of refraction (IOR) to one with a *higher* IOR (as in the speed of light is slower in the second material), then the light will bend *to the right* relative to what it would be if it kept going straight [see that in image 2, the lifeguard has a faster speed on land than in the water, so at the boundary of the land and water his path must deviate *to the right*]. If light is traveling from a substance with a *higher* IOR to one with a *lower* IOR (as in the speed of light is faster in the second material), then the light will bend *to the left* relative to what it would be if it kept going straight [see that in image 3, the lifeguard has a faster speed in the water than on land, so at the boundary of the land and water his path must deviate *to the left*].

Part A: Reflection and Refraction

Light rays (like these laser beams) will bend at the boundary between two objects due to the different properties of the objects themselves. Thus, the laser beams are straight once they leave the source until they hit the prism (an object with obviously different properties than air). At this point, immediately at the boundary between the prism and the air, the light rays will bend and then remain straight throughout the prism. Once these beams get through the prism and reach the other side, i.e., the other boundary between the prism and air, the beams will bend AGAIN. Once they leave the prism and are bent at the boundary, they then continue straight in the air once again. As you should observe in this experiment, there are no *curves*; the light rays make very abrupt angles at the boundaries between the air and the prism. This abrupt change in direction (or bending) of light at the boundary of two different substances is called *Refraction*. *Snell's Law:*

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

can tell you how abrupt this bending is (rather, how larger the bending angle is) if you know the *indices of refraction*, which depend on the two substances (or *media* as you might read in texts) and one of the angles at which your light beam is hitting the boundary (as measured from the direction that is exactly perpendicular to the surface of the boundary – called its *normal*).

Mirrors are easier to understand since we deal with them on a daily basis. We know that if we shine a laser on a mirror at an angle, it will bounce off in the other direction at that same angle! This is called the *law of reflection*; the angle of incidence is equal to the angle of reflection.

Rectangular Prism

4.) **(Drawing 4 points, Answer 2 points)** First note that in the large boxes below this problem is where you will need to include your drawings – these can either be drawn by hand, pictured, and pasted into your lab report OR you can utilize Microsoft Words draw feature if you can.

Your drawing should include 1) the lasers entering the prism, 2) the lasers *through* the prism, and 3) the lasers exiting the prism.

5.) You should see that the light rays are bending quite a bit once they hit the rotated prism. You should see first the laser beams bending IN the prism and then again coming OUT of the prism.

6.) **(Drawing 4 points, Answer 2 points)** Again, you need to make sure you draw all three areas like before: the rays entering the prism, the rays through the prism, and the rays exiting the prism.

Convex Lens

7.) You'll do the same procedure with this as you did with the rectangular prism.

8.) **(Drawing 4 points, Answer 2 points)** Here, position your convex lens exactly how it is shown in the picture in your manual. Once you turn on the lasers, this is the image you need to draw in the box below.

What the question in the box means when it asks, "*are the laser rays bent as they pass into the lens*," is that at the point where the laser enters the lens (i.e., the surface of the prism towards the laser device), do the rays look to be bent?

What do we mean by light beams being *focused*? In the case of these individual laser beams, it is asking you whether all of them end up *converging* (or, coming together to a point). The opposite would be if they were all moving away from each other so that they would never cross paths again – this means they are *diverging*.

9.) Add a picture of the tilted lens next to the one you drew in the previous step.

Concave Lens

10.) You'll do the same procedure with this as you did with the rectangular prism.

11.) **(Drawing 4 points, Answer 2 points)** Just like for the convex lens, start with the exact set up that is shown in the picture in your lab manual. In the big box below, draw how the laser beams are behaving in all three regions: 1) entering the prism, 2) through the prism, and 3) exiting the prism. Also, see the above discussion on what it means when the laser beams are *focused*.

12.) Again, add a picture of the tilted lens next to the one you drew for the previous step.

Flat Mirror

1.) See that this "three-sided mirror" has a flat side, a concave side, and a convex side. You are obviously going to be using the flat side for this one.

2.) Create your set up just like it is shown in the picture in your lab manual.

3.) **(Drawing 4 points, Answer 2 points)** In this case, since you have no transmission of light through the solid mirror, you need to include the light beams coming from the device and hitting the mirror, as well as the beams that are being reflected off the surface of the mirror. You'll see that if the mirror is exactly perpendicular to the laser beams, they'll reflect exactly back along the coming beams. Once you rotate the three-sided mirror just a little bit, you'll see more of the reflected beams going off at an angle; make sure you draw a picture of this too and add it next to the picture of the previous one.

Convex Mirror

4.) **(Drawing 4 points, Answer 2 points)** Just like before, using the convex side of the three-sided mirror, copy the set up that's shown in your lab manual and sketch a picture of the incoming and reflected laser beams. The idea of the laser beams being *focused* is the same as with the lenses described above.

Concave Mirror

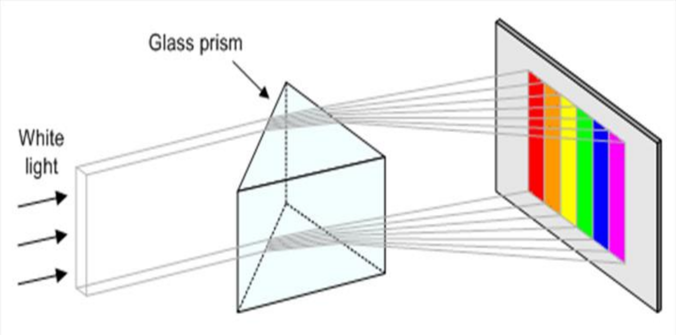
5.) Now spin the three-sided mirror so the concave side is facing the lasers.

6.) **(Drawing 4 points, Answer 2 points)** Again, sketch the incoming and reflected laser beams. The idea of these beams being *focused* is the same as for lenses described above.

Part B: Diffraction of Light

In part A and our introduction discussion, we talked about the fact that the speed of light will change as it shines through different objects which leads to *refraction* – the bending of light at the boundary between two materials with different indices of refraction. We now need to go just a little bit deeper in this discussion. We had assumed before that we were working with a single light ray that had a specific wavelength [in our analogy, a single lifeguard]. However, we know that light can have all kinds of different wavelengths [the beach can have many different lifeguards] – hence the fact that we can see different *colors*! Now, the *index of refraction* of light through a material itself can change depending on the wavelength of the light passing through the material (because v in the equation for n above is dependent on the wavelength). This means that how much a light ray bends at the boundary between two different materials also depends on the wavelength (i.e., its COLOR) [all our lifeguards can run/swim at different speeds, thus the path of shortest *time* is different for each one]!

What we call "white light" is actually light that is composed of ALL of the different visible wavelengths of light together, i.e., it is just the combination of all the visible colors (ROYGBIV). We can actually use a prism to break up this "white light" into an organized collection of these colors; a *spectrum* (rainbow). We have just discussed how light bends differently at the boundary between two objects depending on its *color*, and this is exactly what happens to the different wavelengths of "white light" as it hits a prism - all the components of the "white light" that are a specific wavelength get bent at a specific angle, and so on. This leads to a nice spectrum as seen to the right, taken from your lab manual.



Newton's experiment for splitting white light into a spectrum

In Question 3 below, you will be using a small colored cardboard diffraction grating. This little piece allows you to see the spectrum of light sources when you put it up to your eye using *diffraction*. A diffraction grating is just a bunch of closely spaced, parallel grooves that bends "white light" into its component colors – a similar result to what we got with the prism above.

1.) Set up your experiment just like the picture here.

2.) **(8 points)** You'll take a picture similar to that one already in the lab manual, except I want you to focus more on the prism and the spectra you find. The best way to do this would be to take a picture with your smart phone, send the .jpg file to the email of whoever is working on the word document, and then have them copy and paste the image directly into your lab report. Make sure you and I can both see whatever you're trying to take a picture of! Note that the triangular prism in this picture in the long (tall) one you have; not the larger flat one.

3.) This little piece of cardboard will look like a toy – its just a cardboard square with what looks like a clear plastic sheet in the middle of it (like some of those old, cheap 3D glasses). Look through this at this (or any) light source. See the small paragraph above (or Google it) to know the difference between this and a prism.

4.) **(4 points)** Here you need to describe what you see. Compare what you see through the cardboard grating to what you find from the picture you should've taken in step 2.

5.) **(4 points)** Looking through the cardboard grating, you should see a 'rainbow" of sorts; the *spectrum* of the light (since this IS simply a diffraction grating that is splitting up the light into its component colors). What is the color that is the CLOSEST to the light source? Is the wavelength of this color larger or smaller than that of the color that is FARTHEST from the source? You can always Google the colors you see and find their wavelengths, or you can realize the fact that as you move along through the rainbow (Red Orange Yellow Green Blue Indigo Violet) the wavelengths get *shorter*.

6.) **(4 points)** Tell me if you see many more of the same spectra around the same source. Is there anything else you see or find interesting as you look at the source some more?

Part C: Spectroscopy

How do Neon signs work? First you have a tube of Neon, but why Neon? Well, Neon is one of the Noble gases, which means it has a FULL outer shell of valence electrons. If you set up a voltage across this tube (i.e., hook it up to a power source in a complete circuit), then one of these outer electrons from many of these Neon atoms can be ripped away – creating a *plasma* of negatively charged electrons (flowing one way) and the now ionized (positively charged) Neon atoms (flowing the other way). This is what "completes the circuit" through this tube of gas.

So, we know how the circuitry works now, but where does the light come from? Well, as some of the atoms are being stripped of electrons, some of the electrons in the Neon atoms are being *excited*; or *gaining energy*. The special thing about this is that its not just any amount of energy, it's a very specific amount of energy dictated by the electron *energy levels* of the Neon atom - the exact values of these levels can be determined by quantum mechanics and/or experimentation. So, an electron can only "live" at these specific energy levels, however, they will always want to return to their least-energetic energy level. Similar to how these electrons had to *absorb* energy to become excited, they have to *release* energy to become deexcited, and they do this by releasing the energy in the form of a *photon* (light!). Since the electrons can only "live" on these specific levels, for an electron in a Neon atom to deexcite to a lower level would mean that it would have to release *exactly* a certain amount of energy. Thus, the released photon will have a very specific (and predictable) energy.

What does this mean? Well, the energy of a photon will immediately determine its *wavelength;* $\mathrm{E} \propto 1/\lambda$, where λ is the common Greek letter for wavelength. If the photon has a wavelength within the visible spectrum, then we see it as visible light – the nice bright color we see from a Neon sign! Thus, when electrons in atoms are excited and then deexcite, they release photons with a very specific energy, and thus a very specific wavelength (color)!

We can now look at many elements/molecules in the laboratory and find what wavelengths their deexcited electrons have. Since these different elements/atoms are all usually unique when it comes to their energy levels, they will have unique spectrums as well. We can then compare these unique spectrums to those spectrums gathered, for example, in surveys of distant stars. This, in theory, would allow us one way to determine the composition of these objects! All from looking at the light they emit!

1.) This webcam is just a much more advanced version of that little cardboard diffraction grating you used before. Make sure you plug it into the USB slot on your computer.

2.) This program should already be installed on your lab desktops.

3.) If you do not see anything from the camera view, you need to go to the bottom left of the program, in the “live camera” tab and click “open.” This will give you an option to choose between the webcam you just plugged in or the built in one it is trying to use instead.

4.) Make sure your webcam is positioned similarly to the way it is in the image in your lab manual – the source should be to the left of the screed in between the two orange lines so that you can see the colored spectrum also between the orange lines to the right.

5.) **(2 points)** This question has you looking at the spectrum that is present between the orange lines (mentioned above).

6.) **(2 points)** Reading the lab manual, you should know that the plot that is present on the right side of the program is showing the wavelengths that the webcam is seeing after it separates all the individual components (on the x-axis), and how bright (or prominent) each one of these wavelength components are (the y-axis). The visible part of the spectrum is clearly shown with the appropriate colors that those wavelengths represent. This question is asking for the brightest colors – so which colors (in the visible spectrum) are the brightest (i.e., the tallest peaks in the visible part of the plot)?

7.) Make sure you use the power cord with the green “Next” logo on it, not the power cord we used for the laser.

8.) Don’t be afraid to put some muscle in it to turn the black part of the carousel.

9.) Just like in the picture from your lab manual, your source (the lamp on the carousel) should be to the left of your screen between the orange lines. To the right you should see a spectrum, just like the one you saw looking through the cardboard diffraction grating.

10.) See the image on page 14 of your manual – see how the yellow vertical line goes through the peak here. This is what you need to mimic as the first step of your calibration process.

11.) This button is right on top of where your brightness vs. wavelength graph is.

12.) Make sure you drag the “Elements” pop-up over without exiting out of the window.

13.) The entire table should be clear before you start adding any data.

14.) Note that once you set the cursor in the table to the top left-most box the program will automatically fill in data as you click. Also note that when your cursor hovers over the RED line, the wavelength pops up highlighted in red, and when you hover over a vertical blue guideline it is highlighted blue.

15.) The entire setup is now calibrated – thus when a new source is placed in where the helium was we should now get accurate wavelengths when we look at the peaks.

16.) **(6 points, 1 per blank)** Hover your mouse over the six blue lines; the wavelength for these lines will pop up.

17.) Once you set the hydrogen bulb in place and it lights up, there may be some play in that it won't be exactly set in one place. You can rotate the black part of the carousel by a small amount and try to match the higher peaks in the new hydrogen spectrum with the new blue lines that show up once you do the next step.

18.) **(7 points, 1 per blank)** Again, once you deselect "helium" and select "hydrogen Balmer" in the "Elements" window, you will get a new set of 7 blue lines that should match up with the peaks in the red plot (if you've lined them up correctly from part 17). Hover your cursor over these lines and you'll see the wavelengths you need to report in your manual.

19.) This is on the same line the "Elements" button was on.

20.) **(4 points)** Remember that the spectrum is coming from the photons that are being released by the element, more specifically from the exciting electrons giving off a very specific amount of energy in order to deexcite to a lower energy level. These photons have a very specific amount of energy and thus specific wavelengths (colors). Since the elements in question are fundamentally different, the energy levels are different. Thus, the energy (wavelengths) of the released photons is different resulting in the spectra being different.

21.) Reference -> Close Reference Series.

22.) **(9 points)** Here you are going to want to make sure your setup is still calibrated – as in if you have messed with the position of the webcam or the carousel then you may have to do the calibration procedure again. If you use the "Elements" option, your goal is to pick the element that has its vertical lines matching with the peaks in the unknown spectrum as best as it can. If you find that the blue lines of an element you have chosen matches perfectly (or some what closely) to the higher peaks in the spectrum you're viewing, then you have most likely identified that unknown element. Try as best you can – b and c may be much easier than a; I'd use the link to find a.

23.) Creating a trace of air lets us compare its spectrum to other known spectra with the goal of figuring out the elemental (or molecular) composition of air.

24.) **(4 points)** This question is hoping that you have found what the first unknown element was in question 22. Just know that this mystery element is a major component of the air we breathe. So, you need to answer why the two spectra would be similar? It makes sense that air should have traits of the spectra of all its components, right?

25.) **(4 points)** Again, air is primarily this mystery element, but not its ONLY component. What else is in air that could be present in its spectrum?