Index of refraction

Select LEARNING OBJECTIVES:

- Be able to determine the effect speed of light in a medium using the Index of Refraction.
- Be able to identify what is and is not constant as light passes from one medium to the next.
- Be able to calculate changes in wavelength when light travels from one medium to the next.
- Be able to understand that light always travels at a speed c, but in a medium it's effective speed can be different.
- Understand why the index of refraction must always be greater than or equal to 1.

TEXTBOOK CHAPTERS:

- Boxsand :: Index of refraction

WARM UP: What feature of an interference pattern should you identify to help determine the structure of the object the light was scattered/diffracted form?

When discussing traveling waves, we introduced what happens when a traveling wave encounters a boundary. Our focus at the time was to use the reflected waves to interfere with incoming waves to create standing wave patterns. Recall that not all of the wave is reflected, some of the wave gets transmitted into the medium on the other side of the boundary. The percentage of reflection and transmission depends on the wave itself and the two media that create the boundary. In this lecture we will study the transmission of light rays through transparent media. A material that lets light pass through without scattering the light while inside of the material is called a transparent material. Our goal is to determine what happens to transmitted and reflected light at boundaries between two different transparent media. But before we do that we need to take a closer look at the speed of light which is the purpose of this lecture.

The speed of light

The speed of light in a vacuum is 299,792,458 m/s. This is an exact number because it is defined based off the definition of the meter and the second (NIST definitions). It turns out that the speed of light is a constant value regardless of how fast you are moving relative to a light source; this statement deserves a few lectures dedicated to its consequences (but not at this moment). We use the letter "c" to refer to the speed of light since it is a fundamental constant. Notice that I did not specify any wavelength when I asserted that the speed of light is c in a vacuum. This means that all frequencies of EM waves travel at c in a vacuum.

$$\text{SPEED OF LIGHT} \equiv c = 299{,}792{,}458 \ \text{m/s} \approx 3.0\times10^{8} \ \text{m/s}$$

Index of refraction

What happens, if anything, to the speed of light if a light wave finds itself inside a transparent material instead of a vacuum? As it turns out, it looks like the light wave slows down to some constant value less than c. The details of this are not important at the moment, but interesting nonetheless. Recall that light waves are EM waves, which have oscillating electric and magnetic fields. Transparent media is made up of charged and magnetic particles that interact with electric and magnetic fields. Thus the light wave's electric and magnetic fields cause the particles in the materials to also oscillate. These oscillating particles then radiate energy via EM waves. The net effect of the newly emitted EM waves from oscillating particles and the original light wave is to produce a wave that effectively travels slower than c. Of course this is a very general explanation with many details left out, but hopefully it is a glimpse of where we might be headed in ph213. Back on track now. Every material has a value associated with it that helps us quantify the new speed of light inside that material; this value is called the index of refraction. It is defined mathematically below.

$$n_1 = \frac{c}{v_1}$$

SPEED OF LIGHT (c)

THE EFFECTIVE SPEED OF LIGHT IN MEDIUM 1 (v_1)

INDEX OF REFRACTION FOR MEDIUM 1 (n_1)

Note that the index of refraction is a dimensionless quantity. It can be described as the ratio between the speed of light in a vacuum and the speed of light in a medium. Since the speed of light can never be faster than c, the index of refraction must be equal to or greater than 1. *Ok come talk to me if you want some exceptions to this rule. **And while we are at it, for now we will assume that the index of refraction is the same value for all frequencies of light; we will revisit this statement in the not too distant future. The index of refraction of the vacuum of space is 1. Our atmosphere (i.e. air) is very close to 1 as well.

PRACTICE: What is the effective speed of light in water? Water has an index of refraction of 1.33.

Transmitted light

Now that we know that the speed of light changes in a medium other than a vacuum, let's explore what features of the wave change. Remember that the frequency of traveling waves do not change when they are reflected or transmitted. With this feature of waves and the index of refraction we can determine what happens to the wavelength of light when it travels from medium 1 into medium 2.

CONSTRAINT

$$f_1 = f_2$$

GENERAL WAVE SPEED

$$v_1 = \lambda_1 f_1$$
$$v_2 = \lambda_2 f_2$$
$$\vdots$$
$$\frac{v_1}{\lambda_1} = f_1, \quad \frac{v_2}{\lambda_2} = f_2$$

EQUAL ....

$$\frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$$

INDEX OF REFRACTION

$$n_1 = \frac{c}{v_1} \rightarrow v_1 = \frac{c}{n_1}$$
$$n_2 = \frac{c}{v_2} \rightarrow v_2 = \frac{c}{n_2}$$

$$\frac{c}{n_1 \lambda_1} = \frac{c}{n_2 \lambda_2}$$

$$n_1 \lambda_1 = n_2 \lambda_2$$

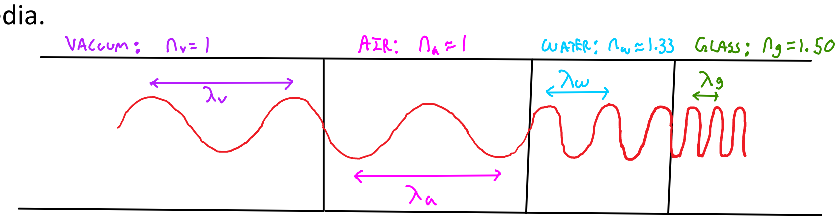
WAVE LENGTH CHANGES IN DIFFERENT MEDIA

Carefully study the above. We used the general definition for wave speed, the definition for index of refraction, and the constraint that the frequency of transmitted light must remain a constant to show that the wavelength of the transmitted light changes when it goes from one medium to the next.

The wavelength of light changes in different medium, but not the frequency. Remember that the energy of a traveling wave is related to frequency. Light that travels through our eyes excites receptors based off of the energy the light carries, not the wavelength. Thus, light of wavelength 650 nm in a vacuum still looks red to us even underwater where the wavelength changes. This can get confusing because we associate wavelength with color which is slightly incorrect; the correct way to state this is that we associate the wavelength of light in a vacuum to the color of light. Thus, when given a wavelength, it is typically implicit that the wavelength is measured in the vacuum of space unless otherwise specifically noted. Below is an example of how wavelength changes through different media.

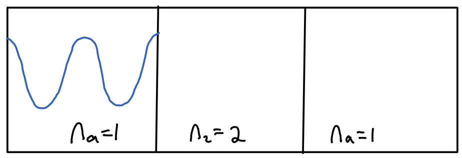
IN GENERAL....

$$n_1 \lambda_1 = n_2 \lambda_2 = n_3 \lambda_3 = \ldots$$



$\lambda_v \approx \lambda_a > \lambda_w > \lambda_g$

PRACTICE: A light wave is incident from the left on a medium with a higher index of refraction. The light then emerges back into air on the other side. Sketch the wave through the medium and back into the air.



PRACTICE: Orange light (λvacuum = 611 nm) shines on a soap film with an index of refraction of 1.33. On either side of the soap film is air. When the light travels from air into the soap film, which features of the wave remain unchanged?

(a) Wavelength
(b) Speed
(c) Wave number
(d) Amplitude
(e) Frequency
(f) Intensity

What is the effective speed of the light in the soap?

(a) 0.45 c
(b) 0.62 c
(c) 0.75 c
(d) 0.98 c
(e) 1.33 c
(f) 1.00 c

What is the wavelength of the light in the soap?

(a) 459 nm
(b) 611 nm
(c) 492 nm
(d) 763 nm
(e) 333 nm

QUESTIONS FOR DISCUSSION:

(1) Why do we most often use the wavelength of light in a vacuum to associate with the colors we see?