

Module 2 - Interaction of Light with Materials



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1 Introduction

Do you ever wonder what happens to light when it hits a material? Why do some objects appear transparent or opaque, clear or colored? What happens to an electromagnetic wave when it interacts with a particle? Why is this important and why should we care? We care because it is the interaction of light and materials that enables us to see light and guide it. Understanding the principles of light and material interactions enables us to observe and manipulate our environment.

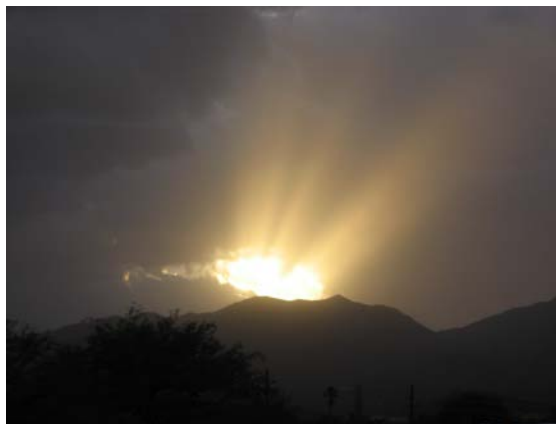


Figure 1 Sunset - Wasson Peak, Tucson, Arizona; Photo by S. Kolchens

1.1 The Field of Optics

Optics is a science that deals with the genesis and propagation of light in the in all ranges of the electromagnetic spectrum and is an engineering discipline that uses materials and optical principles to build optical instruments. Optics is a very old discipline and there is evidence that Mesopotamian scribes may have used lenses to produce breathtakingly miniscule texts on clay tablets more that 4,000 years ago. As a very modern science today’s way of life would not be possible without applications utilizing the interaction of light and matter. These applications include DVD players, TV remote controls, and fiber optic cables used for high-speed communications. Many applications not only guide light but also generate or receive an optical response (i.e. remote control or digital camera). Other applications include medical diagnostic and environmental sensing applications. Future applications will include optical switches to build super fast computers and even faster communication systems.

1.2 A Road Map of Light and Matter

When describing a complex field, like the interaction of light and matter, we gain a better understanding when we create a “road map”; a bird eyes view of the subject.

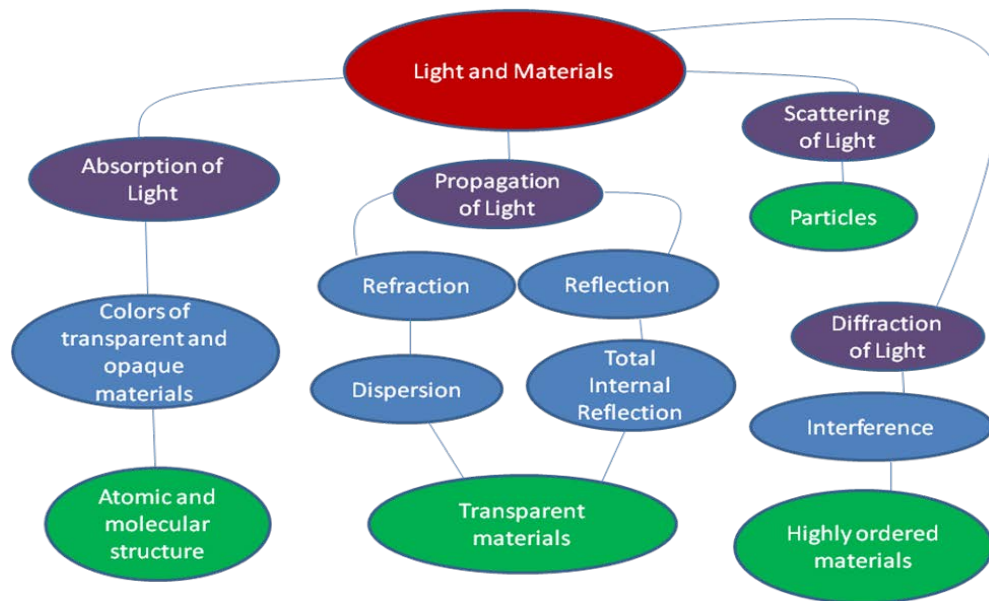


Figure 2 Interactions of Light and Material

1.3 List of Topics

In this module we will discuss: 1) the propagation of light through different medium; 2) the absorption of light, which is responsible for the colors of materials; 3) the scattering of light by particles, in comparison to the size to the wavelength of light; 4) the diffraction of light, through ordered structures to create interference. Diffraction of light occurs in highly ordered structures with a long-range order in the range of the visible light to create interference patterns. This is typically accomplished through diffraction gratings, but on the atomic or molecular scale structures as crystalline structures are too small to cause any diffraction of the visible light and show only diffraction of X-ray electromagnetic radiation.

2 Discussion

2.1 When Light Hits a Material

2.1.1 Seeing Light

The ability to see everyday objects is something that we often taken for granted. Do you realize that no matter how much light is around you if light could not enter your eyes, you would not be able to see anything? A familiar observation is that of the moon at night. Being on the dark side of the Earth you cannot see the Sun. But we know that sunlight is projected into space. The Sun's light remains invisible to us unless it hits an object, such as the Moon or a satellite, and light reflects back to Earth's surface. Stars at night are visible to us because they are direct sources of light. In other words: You cannot see a beam of light unless it is directed at you. This statement may seem paradoxical without a simple experiment.

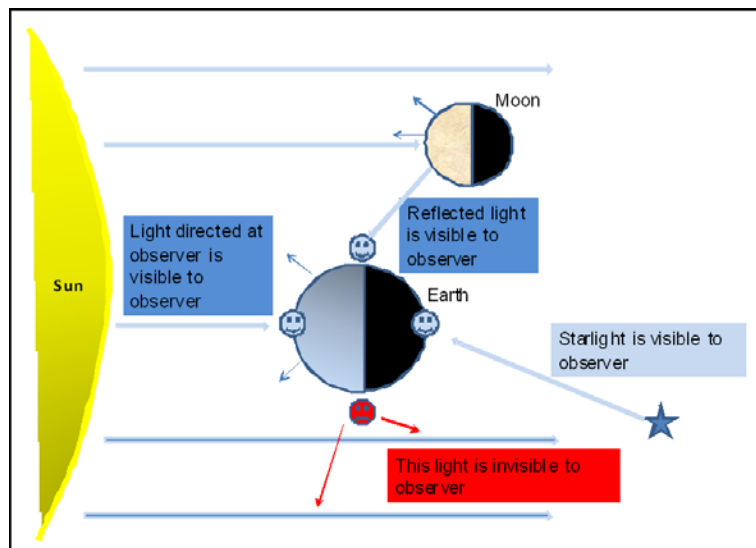


Figure 3 Sunlight directed towards observer at different locations on Earth

Activity 1 Shine a red laser pointer onto a wall.

WARNING: Never point a laser at the eye, doing so may cause damage to the eye.

You will notice the red dot on the wall but you won't actually see the laser beam itself. Now take a little piece of white paper and place it into the beam: observe the paper from the side while moving it back and forth. You will notice that the red beam is reflected off the paper and hence you can see it. Now let's take our experiment a little further. Darken the room and continue to shine the red laser onto a wall. Now take a spray bottle filled with water and spray some water mist into the beam. You will observe that the beam is now partially visible due to the laser beam reflecting off the little water droplets. In general, you will find that a laser in vacuum, or a very clean room without dust particles, is invisible to us; only when dust particles are visible is the laser visible too. This leads to our first observation:

Observation: Light must be directed at the observer for the observer to see the light.

2.1.2 Scatter of Light

Now we will examine what we are seeing. Look around a room and observe an object, you will find that no matter where you stand, your eyes can see that object. When light falls on an object, light is redirected in all direction, this is called scattering. You can see an object only when light is scattered in the direction of the observer.

Observation: An object is only visible when it scatters light.

Try this: look straight at a very clean window which does not scatter light much and you will notice that the window is difficult to see. An example of this is when birds fly into windows because they cannot see them.

2.1.3 White Light

The Sun's light is what is called white light, because it contains all colors of visible light or the colors of the rainbow. Looking around the room you will notice that objects have different colors. Since we are mostly surrounded by white light, we can identify individual colors such as red, green, etc. Let's try a thought experiment: if we were to take a white light (like the sun) and shine it on a leaf. The leaf appears green because it reflects the green wavelength of visible light. If we then took the light that is reflected off a green surface such as a leaf, and then pass it through a prism, which separates the wavelengths of light into its components. We could measure the intensity of each wavelength and obtain an intensity distribution curve that favors green colors. Likewise, if white light is transmitted through a green leaf, the overall color perception is green.

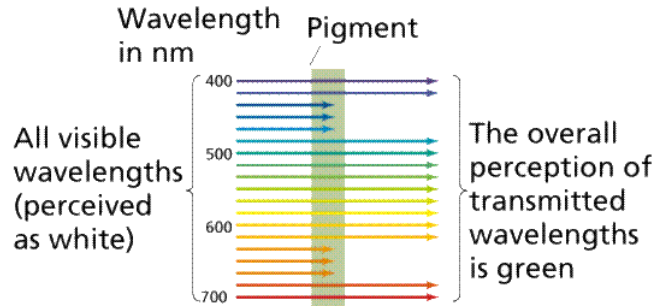


Figure 4 Intensity distribution curve of light reflected off a green leaf

2.1.4 Absorption of Light

You will notice that only the green portion appears in high intensity and portions of the electromagnetic spectrum are missing. So, what happened to the rest of the white light? It appears to be absorbed by the material. But what happens if you hold one object under different colors of light? For example: a yellow light (“bug light”) or fluorescent light (“black light”)? What we perceive, as the color of the object, changes as we change the wavelength of the incoming light. So, where does the color go? Doing a similar experiment, using perfectly white or black objects, we will find that the white objects reflect all wavelengths of the incoming light source, while the black objects absorb it.

Observation: An object can absorb the light’s energy.

2.1.5 Different Types of Light Interactions and Observations

So far, we have dealt with objects that either absorb or scatter light; but what if you shine your beam of light onto a clear window or a glass filled with water? One observation is that light can also be transmitted through a material. Other observations may include that light can be dispersed, or that interference patterns form -through the diffraction of light. We may notice that light may: 1) be reflected off a shiny surface, such as metal; 2) be transmitted and refracted by a glass filled with water; and 3) be scattered, dispersed, polarized or absorbed by small particles, such as the air or fog on a cold winter morning. How we perceive these interactions depends not only on the interaction between the material and light itself, but also on our vision and how light interacts with our eyes to make vision possible.

Observation: Objects can reflect, refract, transmit, absorb, disperse, and scatter incoming light.

2.1.6 Quantum Electrodynamics (QED)

When light hits matter it is absorbed, reflected or refracted. The correct way to approach this problem is called quantum electrodynamics (QED).

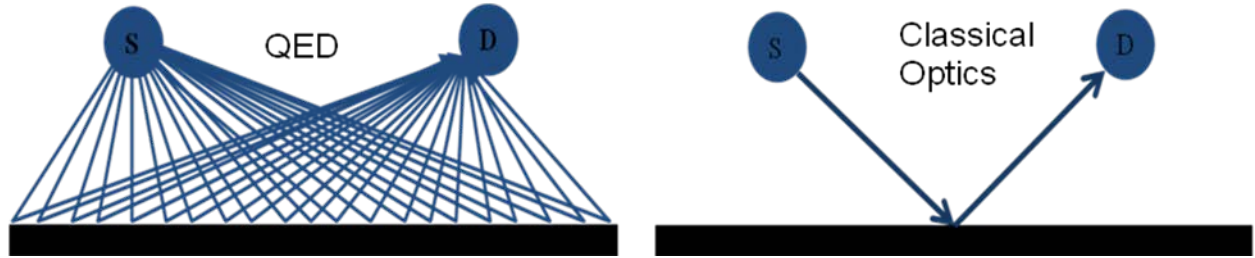


Figure 5 The Interaction of light with matter according to Quantum Electrodynamics (QED) and classical physics

Quantum electrodynamics considers the probability of a photon leaving the light source (S), hitting each point on the glass, and reaching the detector (D). When the math is done we find that many probabilities cancel out leaving only the one where the angles of incident and reflected light are equal. Less probable quantum electrodynamic scenarios cancel out reducing to the “physics” classically used to describe observations in optics.

2.1.7 Electromagnetic Radiation

Light is **electromagnetic radiation** and can be thought of as a wave of energy. Electromagnetic waves have an **electric** and a **magnetic field** component oriented at right angles to each other. Matter is comprised of atoms and atoms are composed of positively charged nuclei surrounded by negatively charged electrons.

Electromagnetic Propagation

$c = f \cdot \lambda$
Speed (m/s) = Frequency (1/s) · Wavelength (m)

$c = \text{speed of light}$

Animation 1: Electromagnetic Waves have an Electric and Magnetic Field Component

Light’s energy can interact with the electric and magnetic field of the atoms, hence changing their total energy. Depending on the material and the energy levels of its electrons, light can be absorbed or transmitted. Absorption occurs when the gaps between **electron energy levels** are comparable to the energy of the incoming light; transmission occurs when the energy gap between electron energy levels are larger than the energy of the incoming light. Once absorbed,

light can also be emitted resulting in reflection or scattering. In other words, reflection and scattering occur when absorption and emission are taking place at the same time.

Observation: Reflection and scattering occur when absorption and emission take place at the same time.

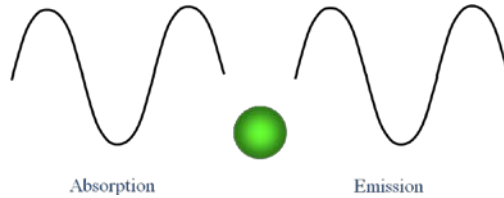


Figure 6 Absorption and Emission of light by matter

Activity 2 Inspection and characterization of interaction of light with various materials.

The following student activity lets you explore some of the interactions of light with different materials and objects. Record your observations and discuss your findings in class.

<p>You will need the following:</p> <p>Materials</p> <p>Glass filled with water</p> <p>Milk</p> <p>Food coloring</p> <p>Ruler</p> <p>Shiny surface (metal or a mirror)</p> <p>Charcoal or other black material</p> <p>Pigments</p> <p>Diffraction grating</p> <p>Lens, Prism</p>	<p>Instructions</p> <p>Using a flashlight and a laser pointer, examine the optical properties of the materials listed and present your findings in a table format for in-class discussion.</p> <p>Optical properties could include: reflection, refraction, diffraction, dispersion, absorption, transmittance, and scattering.</p> <ol style="list-style-type: none"> 1. Based on your observations, can you make any predictions about the properties of the material? 2. Can you suggest any material design components that could enhance the observed properties? 3. If you were asked to construct a fiber optics cable, what design considerations should be taken into account?
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2.2 Object Size and Wavelength of Light

2.2.1 Objects Much Larger than the Wavelength of Light

Objects much larger than the wavelength of light are able to reflect (mirrors), refract (lenses), and/or disperse (prisms) light. The passage of light through these materials can be described using principles of geometrical optics in which light is typically described as rays; the way rays are bent or reflected is described using principles of geometry.

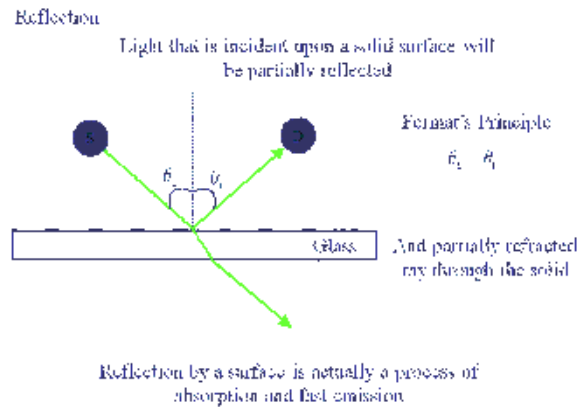
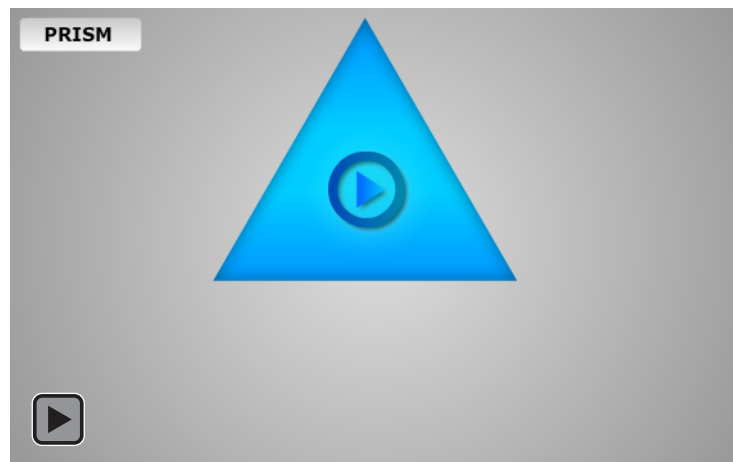


Figure 7 Reflection of light off of a material's surface

2.2.1.1 Dispersion

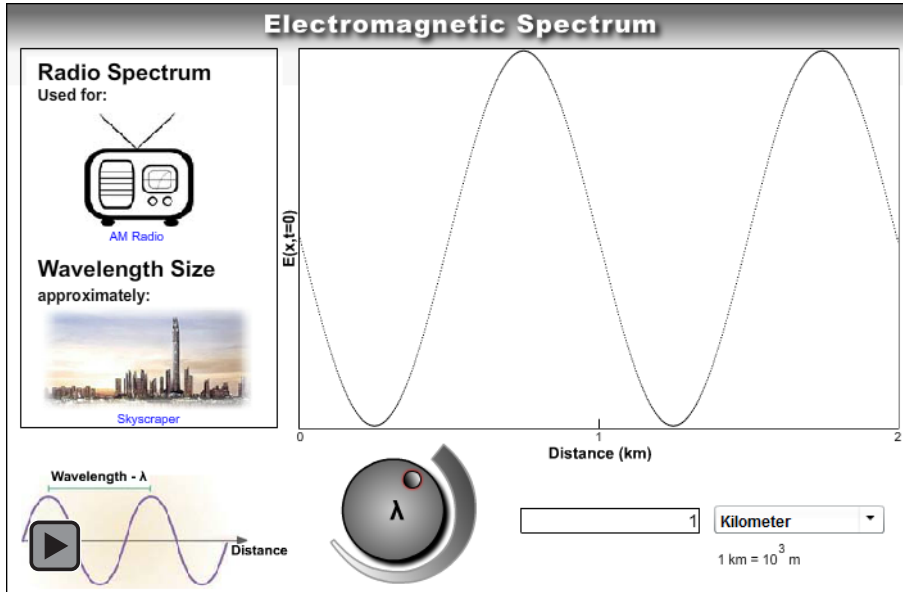
When we shine white light through a prism, instead of a glass plate, you may observe that the exiting light has been separated into its components or individual colors, which is called dispersion. Dispersion is caused by the wavelength dependent interaction of light with the refractive index of an optically transmissive material. Dispersion is not always a good thing as it causes chromatic aberration in optical instruments, which leads to unclear or poorly colored images:



Animation 2 Chromatic Dispersion of Light

2.2.2 Objects Comparable in Size to the Wavelength of Light

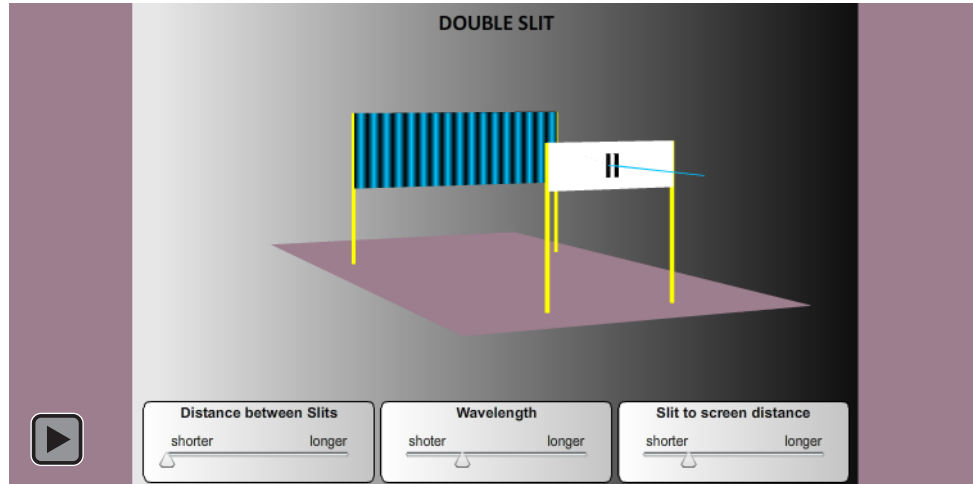
Objects comparable in size to the physical wavelength of light are able to either bend light around the objects, called diffraction or scatter light in random directions.



Animation 3 Wavelength of Visible Light

2.2.2.1 Diffraction of Light

Diffraction occurs when light passes by small stationary openings, such as pinholes or narrow slotted openings and is bent or redirected around the edges. Such openings are called diffraction gratings. Light exiting a diffraction grating act as waves and overlap to form diffraction patterns through constructive or destructive **interference**. The overlapping light waves form regular patterns of light and dark dots or lines respectively on a screen.



Animation 4 Diffraction light at an aperture and resulting interference pattern

2.2.2.2 Scattering of Light

Light scattering occurs when light interacts with randomly dispersed particles, comparable in size to the wavelength of light; it is radiated in all directions. The scattering pattern depends on the size of the particles and the wavelength of light. Larger particles scatter light more than smaller particles. Often stormy days will have beautiful sunsets because a lot of dust has been kicked up into the atmosphere.

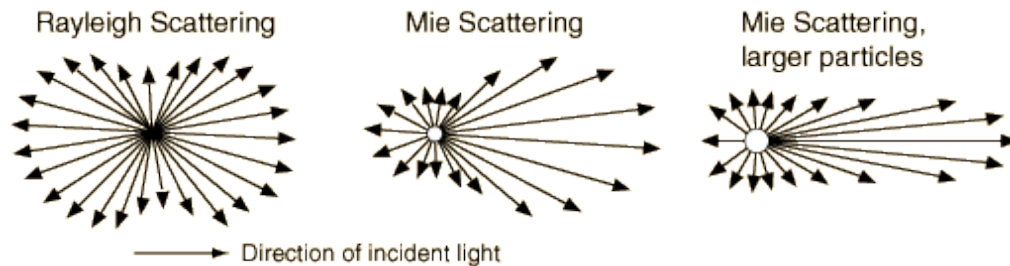


Figure 8 Particle size and resultant types of Scattering

The blue wavelengths of sunlight are more easily bent and consequently scattered more uniformly through the Earth's atmosphere. Light of shorter wavelength is scattered more than light of larger wavelength and that's why throughout the middle of the day the sky is blue and at sunset the sky appears orange or red.

2.2.3 Objects Smaller than the Wavelength of Light

2.2.3.1 Photons and the Absorption of Light

Objects smaller than the wavelength of light, such as atoms or molecules, can absorb light. Atomic interaction with light is best described when we think of light as discrete energy packets, called **photons**. **Absorption** occurs when the energy of these photons equals the energy difference between energy levels in a particle.

2.2.3.2 Seeing Light based upon its Relative Size

Our observations lead us to the conclusion that the way in which we “see” light directed to our eyes is dependent on the relative size of the object and the energy level of the light (either as an electromagnetic wave or photon energy). In other words:

Observation: The smaller the wavelength of light, the smaller the structures with which the light interacts.

2.2.4 The Relation of Object Size to what we See

The relation of object size to wavelength has broad applications in imaging techniques such as microscopy or medical imaging; the selection of the imaging wavelength will determine what we see:

- If the wavelength is much smaller than the size of the object being imaged, the light rays are not bent or distorted and a sharp image results.
- If the wavelength is similar in size to the object, a diffraction of light rays occurs resulting in a blurry image.
- If the wavelength is much larger than size of object, there is no interaction and hence the image cannot be resolved.

2.2.4.1 Short Wavelength and Resonance Frequency

An interesting phenomenon also occurs when the wavelength is too short. If electromagnetic radiation oscillates with a very high frequency (and very small wavelength) the resonance frequency of the material cannot keep up with the EM waves and there is very little interaction. As a result, the radiation passes right through the object. An example is medical imaging or X-rays; which uses X-ray EM energy because they penetrate soft tissues but not bone.

2.2.5 Summary of Light Interaction with based upon Wavelength Size

When light hits a material we may observe reflection, refraction, diffraction, scattering, absorption, and transmittance. The interaction of light and material depends on the size of the

objects relative to wavelength. The light's electromagnetic field interacts with electrons in atoms and molecules, for matched energy levels this may lead to absorption and emission.

Assessment:

Lets discuss what we see when we look at a painting. First off paint; which usually consists of colored pigments and a medium in which the pigment is dispersed Pigments are fine particles that reflect specific wavelengths of visible light and give the painting the appearance of color. The paint is applied to a substrate, which can be one of many forms such as paper, canvas, or wood.

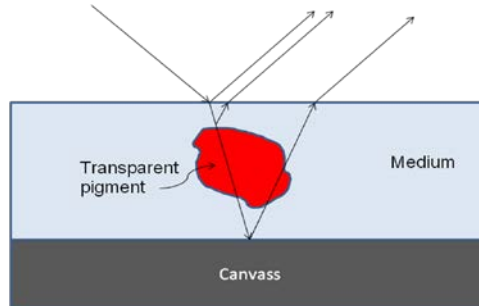


Figure 9 Cross-section of materials present in a typical painting: medium, pigment, and substrate.

Which of the following processes are involved when a painting is observed?

- a) Reflection
- b) Refraction
- c) Dispersion
- d) Absorption
- e) Scattering
- f) All of the above

2.3 Physics Definition of Light

2.3.1 Classical Physics

Classical physics models light as a wave and **wave optics** helps us understand many aspects of light-matter interaction, such as **reflection, refraction, diffraction, scattering**, etc., but it is inadequate when dealing with **light-particle interactions**. Here we are interested in **absorption**. We already observed that light can be absorbed and sometimes renders an object as colored or by transferring the light's energy onto the motion of the objects electron charges resulting in internal friction and heat as a byproduct. Sometimes, however, we like to convert the light's energy into something else like an electric current from a solar panel or a nerve impulse from the eye to the brain. At other times we measure the energy of the absorbed light in a material and draw conclusions about the strength of molecular bonds, and thus the chemical composition of matter.

2.3.2 Modern Physics

Modern physics has discovered that an electron can be knocked loose from an atom by shining light on it. The discovery of the **photoelectric effect** led to an understanding of light energy as a discrete amount called a photon. A photon is a package of energy that interacts with the energy levels of an electron in an atom. Albert Einstein formulated **quantum theory**, which generally states, “Every monochromatic electromagnetic wave can transfer energy only in discrete units (quanta). The size of the energy quantum is proportional to the wave’s frequency.” A **quantum of energy** is called a **photon** and its energy is related to the frequency of light, which can be summarized in the following equation:

$$E = h \cdot \nu \quad \text{Equation 1}$$

Where E is the energy of the photon, h is a constant (**Planck’s constant**) and ν (Greek letter nu) is the **frequency of light**. The frequency and wavelength of light are related through the equation:

$$\lambda \cdot \nu = c \quad \text{Equation 2}$$

Where λ (Greek letter lambda) is the **wavelength of the light**, ν is the **frequency of light** and c is the **speed of light** in vacuum.

2.4 Absorption

When discussing absorption, we most often refer to both wave-like and particle-like properties and adopt the term photon. This interpretation is very useful as it allows us to describe and measure the properties of light in terms of wavelength and frequency (wave-like) or electromagnetic energy (photon or particle-like).

2.4.1 Color Pigments

Artists have been using colorful pigments for centuries to convey their visions. Early pigments were extracted from minerals rich in **transition metals** and their salts. Examples include purple from manganese, orange or green from chromium, and yellow from cadmium. Other pigments such as blue were extracted from seashells. But many times colors were not very intense or faded over time when oxidized. Since some pigments were based on transition metals, they were often very toxic. Along with the development of **organic chemistry**, new classes of compounds were synthesized. Some of these compounds offered color intensity and stability not previously known, such as Prussian blue or Alizarin red, leading to new applications and artist’s expressions (Impressionism, Pointillism).



Figure 10 Impression Sunrise, oil on canvas by Claude Monet

2.4.2 Energy Level of Molecules

What seemingly unrelated compounds had in common was that the electron energy levels of their molecules are in close proximity to the energy of visible light, allowing for some wavelengths of the light to be absorbed while others are reflected.

2.4.2.1 Absorption and Energy Level of Electrons

An atom's energy is related to the spatial distance between its electrons and its nucleus. The greater the distance, the higher the energy of the electrons (it requires energy to move a negative charge (electron) away from a positive charge (nucleus)). Once a photon interacts with matter it disturbs the energy level of the electrons. Absorption is only possible when the energy of the photon is equal to the energy gap between two electronic states, in which case the atom will absorb the photon and will be transported to a higher energy level. This process is called absorption. The reverse process, dropping down to a lower energy level, is called emission. The energy of an electron is not continuous but comes in discrete energy levels; electrons can only move from one energy level to another, but not hover in between. This is analogous to people walking up and down the stairs, coming to rest on each step, but not in between.

2.4.2.2 Absorption and Color Perception

Why are some materials transparent or opaque and why do some appear colored? A particle's energy level is related to the wavelength of the absorbed light and absorption can only occur at discrete frequencies. In other words, if we shine white light onto a transparent material or an opaque material, some part of the electromagnetic spectrum will be absorbed, and only wavelengths that are not absorbed will be transmitted or reflected or scattered, resulting in the observed color of the material.

2.4.2.3 Absorption and Material Analysis Techniques

The use of electromagnetic radiation has great applications in chemical analysis. Although the human eye can detect wavelengths only in the visible part of the **electromagnetic spectrum**, molecules have a somewhat broader range and can also absorb **UV light**, which is higher energy radiation than visible light. **Infrared light** and **radio waves** have lower energy than visible light. This is commonly known as **UV/VIS** or **IR spectroscopy**, respectively. UV photons interact

with the electrons of the chemical bonds in a molecule and are capable of transferring enough energy into an electron as to remove it from the chemical bond. This may result in bond breakage, which can be harmful to organisms (sun burn). The **stratosphere** uses UV photons to form and destroy ozone on a continuous basis. For example, one **UV photon** is used to form ozone, and another UV photon is used to destroy **ozone**, resulting in a dynamic equilibrium that shields the lower atmosphere, our oceans, and terrestrial areas from harmful **UV radiation**. On the other hand, **IR radiation** has lower energy than visible light and therefore transfers only a small amount of energy into electrons resulting in bending and wiggling motions of the molecule, allowing chemists to identify the type of bonds and atoms that are present in a molecule. Radio waves are used to induce resonance with the nucleus of an atom and are used in a technique called **Nuclear Magnetic Resonance (NMR)**, which finds applications in the medical field as **MRI scans (Magnetic Resonance Imaging)**.

Assessment: Below is the absorption spectrum of chlorophyll a and b, which is the green pigment in plant leaves.

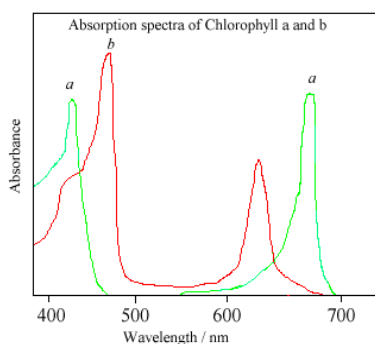


Figure 11 Absorption spectrum of chlorophyll a and b. [1]

- What is the energy of the maximum wavelengths of chlorophyll a that are being absorbed?
- What is the approximate wavelength and color of the light that is being reflected?
- What is the approximate energy of the light that is being reflected?
- Can you get sunburned when sitting behind a car window?
- Does a transparent car window absorb any photons?

2.5 Scattering of Light

Light scattering occurs when absorption and emission take place at the same time. When a photon interacts with a particle, the electron charges of the particle are moved around and moving charges emit their own electromagnetic wave. Light scattering can occur in gases, liquids or solids. In gases, scattering is often due to the presence of fine particles such as smog, dust, or water droplets in the atmosphere. Just imagine driving through a foggy environment at night and not being able to see far ahead because the light emitted by the car's headlights is scattered and reflected, with a higher than normal amount of the light being directed at your eyes resulting in very poor visibility. The same goes for a windy day when a lot of dust has been

kicked up into the atmosphere. Dust scatters the sun’s light resulting in a very beautiful and deeply red sunset.

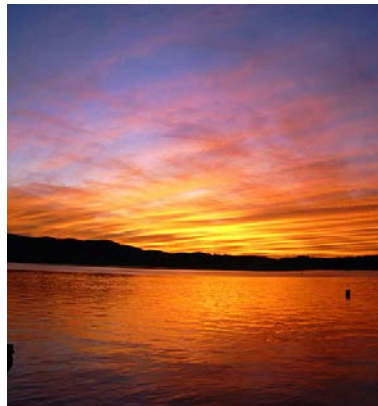


Figure 12 Display of colored light at sunset.[2].

2.5.1 Scatter in Optical Systems

In the realm of optics, we are dealing mostly with solid materials such as lenses or optical fibers whose purpose is to transmit. But optical materials can also scatter light, which is mostly caused by impurities in the material. For optical instrumentation and applications, we would like to use materials where scattering is minimized.

Activity 3 Explore the effect of wavelength and particle size on scattering patterns and intensity. You can explore the scattering of light using everyday objects as outlined below. Record your observations and discuss in class.

Material	Instructions
Milk A clear container (glass or fish tank) Cooked and raw egg whites White and colored lights (red, blue) Water spray bottle	Observe scattered light from the following systems. Using light of different wavelengths, describe any changes in the scattering pattern or intensity. Qualitatively describe your observations. (a) Add a few drops of milk to water and observe the scattered light. (b) Observe smoke emanating from a burning cigarette versus smoke exhaled by a smoker. (c) Cooked versus non-cooked egg white. (d) Spraying water into a light path.

You may observe:

- (a) Milk added to water will increase the amount of light that is being scattered. Comparing different colored light, it appears that light of shorter wavelength (blue) is more scattered than light of longer wavelength (red).
- (b) Spraying water into a light path will scatter the light and is similar to the result of activity (a): it appears that light of shorter wavelength (blue) is more scattered than light of longer wavelength (red).
- (c) Smoke emanating from a burning cigarette appears bluish, while smoke exhaled by a person appears white.
- (d) Non-cooked egg white scatters very little light, while cooked egg white scatters a lot of light up to the point where it becomes opaque.

You may notice that both experiment (c) and (d) include systems where the particle size changes. Cigarette smoke reacts with moisture from the respiratory system and thus the particles get larger. Egg white tends to denature under high temperature thus forming larger aggregates. In other words, the pattern and intensity of the scattered light depend upon the size of the particles.

Experiment (a) and (b) explore systems that do not change in particle size as it is just the number of particles that is increased; we find that for a higher number of particles, more scattering occurs.

Observation: The angular distribution and intensity of scattered light depends on the size and the amount of particles.

You can repeat the above experiments using different colored light, such as a red versus green laser beam, and you may notice that light of shorter wavelength (green) is scattered more than light of longer wavelength (red).

Observation: Light of a shorter wavelength is scattered more than light of a longer wavelength.

2.5.2 Scattering versus Particle Size and Wavelength

Rayleigh scattering occurs with particles that are smaller than the wavelength of light, about 100 nm or less in diameter. The Rayleigh scattering patterns are symmetric and there is very little angular dependency. Larger particles, about the wavelength of visible light (400 – 700 nm), exhibit scattering patterns that strongly favor forward directions, and the intensity of the scattered light varies for different scattering angles. This type of scattering is called **Mie Scattering**.

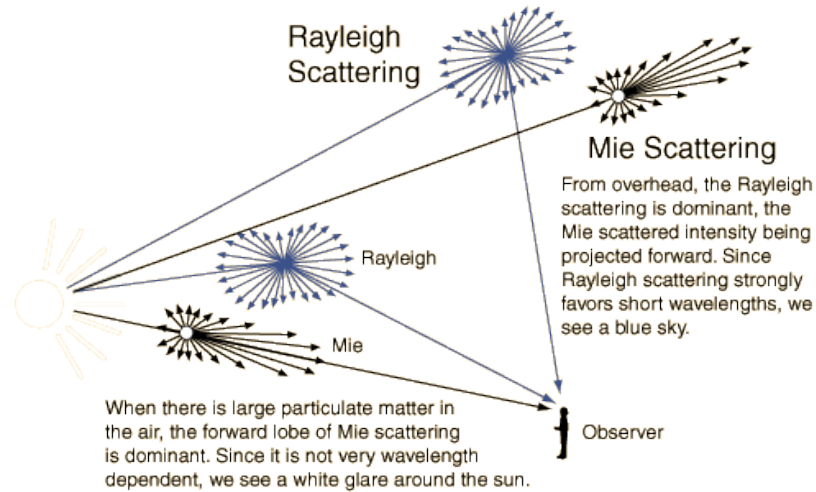


Figure 13 Rayleigh and Mie scattering in atmosphere relative to observer

2.5.3 Scattering versus Quantity of Particles

When observing a sunrise, we notice an orange color in the atmosphere. The more dust or water droplets that are suspended in the air between the sun and the observer the higher the intensity of orange and red wavelengths. This is caused by Mie scattering of longer wavelengths, which favors scattering of light in the forward direction within the Earth's atmosphere.

2.5.4 Light Intensity versus Wavelength of Light

Lord Rayleigh investigated the relationship between the intensity of scattered light and the wavelength of the incident light and discovered that the intensity of scattered light is inversely proportional to the fourth power of the wavelength of the incoming light. Shorter wavelengths are scattered more strongly than longer wavelengths due to this strong wavelength dependence.

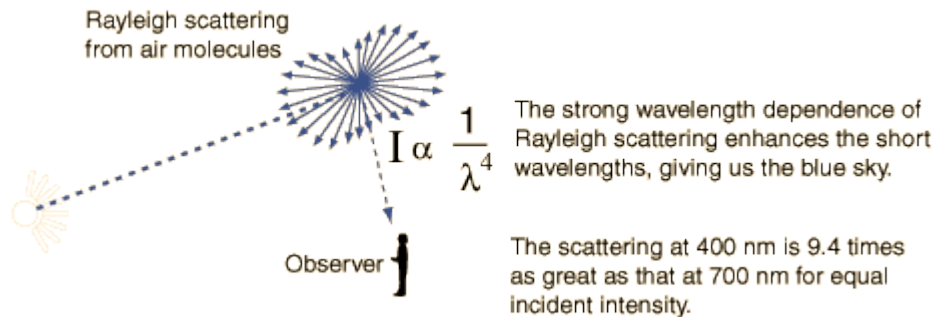


Figure 14 Rayleigh scattering of light favors short wavelengths

Rayleigh scattering occurs from small particles, such as air molecules. Our sky appears blue because the blue wavelength of the visible light spectrum scatters the most in our atmosphere.

2.5.5 Scattering of Light in Solids

So far, we have dealt with light scattering in gases and liquids, but scattering occurs also in solid materials. Imperfections in solids cause light to bend and the size and amount of imperfections in solids, determine whether a material is transparent (such as lenses or prisms), translucent (such as frosted window glass), or opaque (such as a pigment).

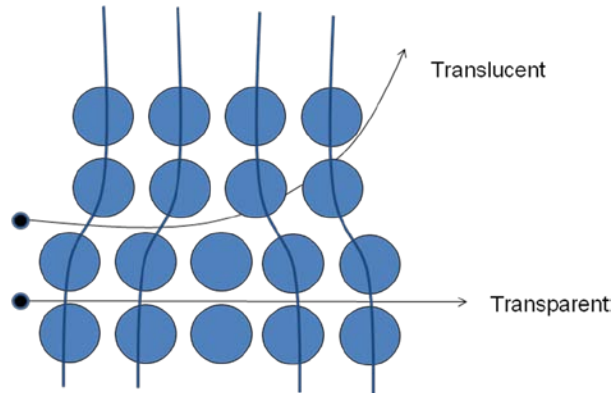


Figure 15 Defects in a solid can scatter light

2.5.5.1 Types of Scattering in Solids

There are other scattering phenomena that can occur. So far the phenomena discussed are **elastic scattering**, meaning that the incoming and exiting light wave maintain the same frequency or wavelength; energy is not lost in the absorption/emission process. **Brillouin scattering** of light occurs in a medium, such as water or a crystal, when it interacts with time-dependent optical density fluctuations. Brillouin scattering deals with correlated, periodic fluctuations, whereas Rayleigh scattering deals with random fluctuations. **Bragg scattering** is observed when electromagnetic radiation is diffracted by a crystal structure, but since the lattice parameters of a crystal are in the range of 10^{-10} m, they are too small to interact with visible light. Bragg scattering is typically observed using electromagnetic radiation of much shorter wavelength, such as X-ray. **Raman scattering** is an **inelastic scattering** process: after a photon has been absorbed by a molecule or atom, some of the energy is retained by the system or given off as heat, whereas the emitted light is of lower energy. These types of scattering interactions are very useful for analyzing the chemical composition of liquids, gases and solids, but they are very undesirable when constructing optical instrumentation. **Compton scattering** also falls into the realm of inelastic scattering, but with much smaller wavelengths such as X-ray or gamma-ray.

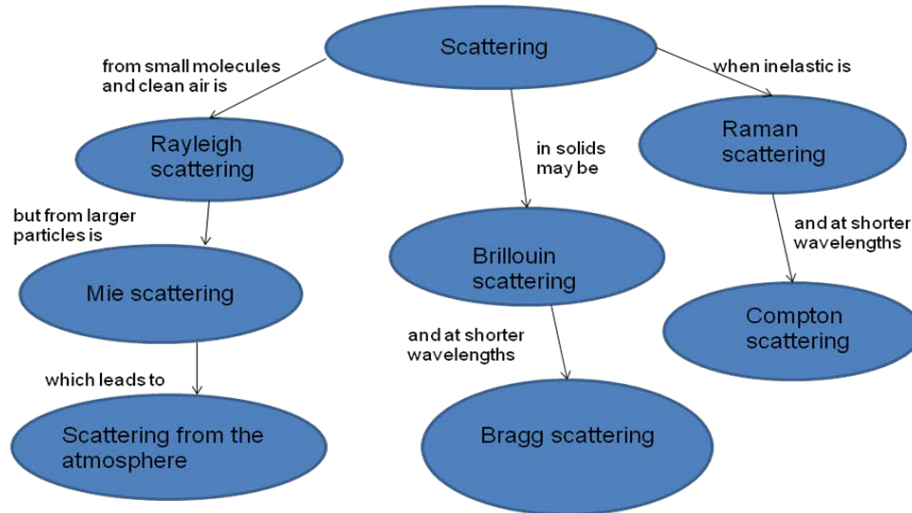


Figure 16 Scattering electromagnetic radiation

2.6 Dispersion of Light

2.6.1 Separation of Light based on Wavelength

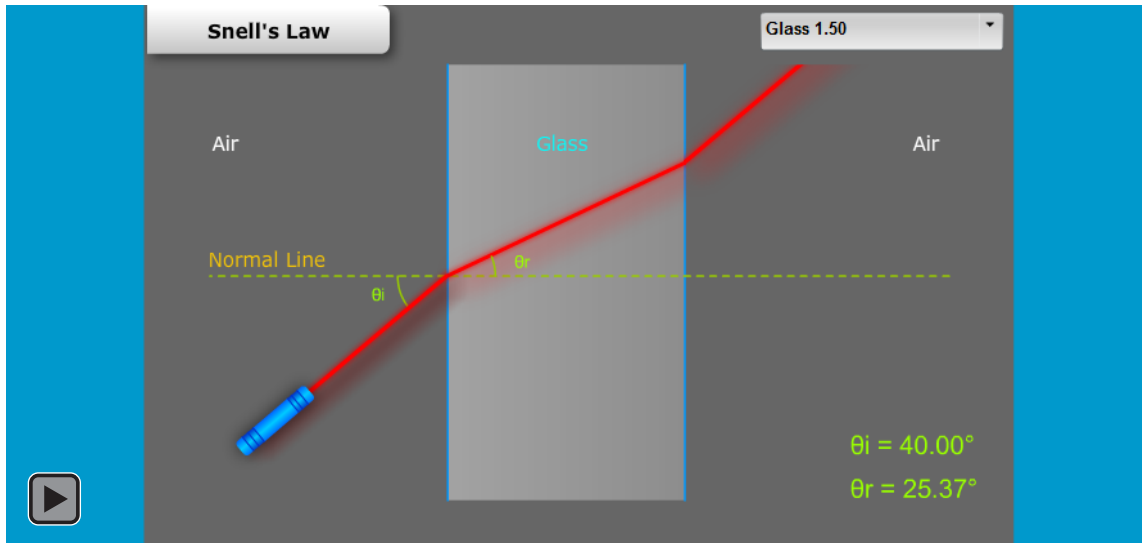
Visible light is made up of different colors and each color bends by a different amount when **refracted** by glass. Hence, visible light is split, or **dispersed**, into different colors when it passes through a lens or prism. Shorter wavelengths, like purple and blue light, bend more than longer wavelengths, like red and orange light. When light passes through optical instrumentation, such as **telescopes** or **microscopes**, dispersion through lenses can significantly alter an image as it shows rainbow colors at the image edge. This effect is known as a **chromatic aberration** and optical instrument builders and glass manufacturers go to great length to minimize this effect.

2.6.2 Dispersion of Light in a Transparent Medium

When light falls onto a transparent medium, some light will be **reflected** and some light will be **transmitted**. **Refraction** is observed in the transmitted light at the interface of two optical media of different optical indexes, when the light travels from one medium to another. This is also known as the Law of Refraction or Snell's Law. It is generally observed that light going from a fast medium to a slow medium bends toward the normal of the surface interface, and light going from a slow medium to a fast medium bends away from the normal. The bending or refraction of light occurs because light travels at different speeds in different media. In a vacuum, the **speed of light** is $\sim 3.0 \times 10^8$ m/s, but any other medium will be denser than a vacuum, and hence the speed of light will be reduced. The ratio of the speed of light in vacuum over the speed of light in a medium is called the **index of refraction** and is represented as the letter n . The higher the index of refraction, the more the light will be bent. An example of refraction can be observed when looking into a fish tank when refraction makes underwater objects appear where they aren't.

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

Equation 3



Animation 5 Snell's Law

Material	Refractive index, n [unitless]
Vacuum	1.0
Air	1.0003
Water	1.33
Glass	1.5

Figure 17 Refractive Index of common materials

2.6.3 Index of Refraction versus Wavelength

So far, we have assumed that each substance has one index of refraction for all kinds of light, but the speed of light depends on the interaction between the electron charges in the glass and the light wave. The greater the light-material interaction, the slower the speed of light, the higher the refractive index and the more the light will be bent. Therefore, blue light, being of higher frequency and energy, interacts more strongly with a material than red light and will be refracted more. In other words, the index of refraction depends on the frequency of light and we observe that $1 < n_{\text{red}} < n_{\text{blue}} < n_{\text{UV}}$.

2.7 Attenuation of Light

When designing any type of transparent material such as microscope lenses, vision correction optics or fiber optic cables the loss of light intensity is of concern. Of course the loss is greater

for longer path lengths through the material and hence is a most important design parameter for fiber optic cables. Light can be lost due to **attenuation** caused by absorption, dispersion, or scattering. Here we describe an experiment that allows us to measure the attenuation of light as it travels through a medium.

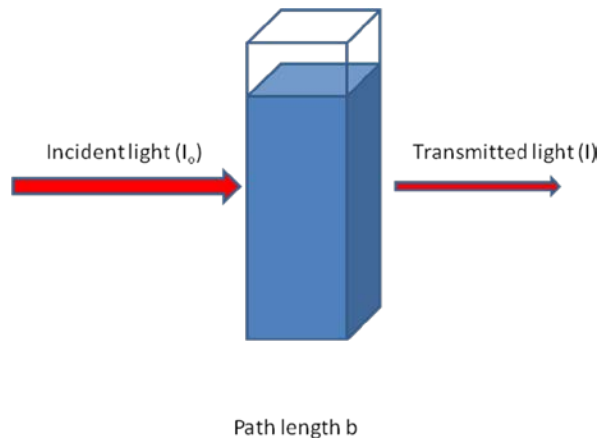


Figure 18 Incident and transmitted light

2.7.1 Measuring Attenuation

We can determine the loss of light intensity as it passes through a medium by measuring the intensity of the incoming light (I_0) and the intensity of the outgoing light (I). The ratio is defined as transmittance, T .

$$T = I/I_0 * 100\% \quad \text{Equation 4}$$

T is proportional to the attenuation of light along the path. The intensity of light exiting a medium (I), as compared to the intensity of light entering the medium (I_0) decreases and can be expressed in the following equation:

$$I = I_0 10^{-\epsilon b C} \quad \text{Equation 5}$$

Where C is the concentration (or Beer), and b is the path length (or Lambert variable). The symbol ϵ (Greek letter epsilon) is the molar extinction coefficient, which is a property of the medium. Beer's and Lambert's relationships are often combined and expressed in a common logarithmic form:

$$-\log T = -\log (I/I_0) = \epsilon b C = A \quad \text{Equation 6}$$

Where the ratio of I/I_0 is the transmittance (T) and A is the absorbance of the medium, ϵ (Greek epsilon) is the molar extinction coefficient (property of the medium), b is the path length, and C is the concentration. Plotting Absorbance (A) versus path length (b) or concentration (C) respectively, gives a straight line with a slope proportional to the molar extinction coefficient (ϵ).

2.7.2 Transmittance

The percent transmittance tells us that some of the incident light has been lost (attenuated), but does not provide us with any information about the parameters that could be responsible for the attenuation of the light.

So, let's explore some experimental parameters such as the nature of the material, its concentration or thickness, and the path length that the light will be traveling through the medium.

Activity 4 Measurements of attenuation and Beer's Law (absorption spectrum as a function of wavelength, concentration, and path length).

Learning objectives:

Gain an understanding of the components and operation of a spectrometer. Explore the relationship of absorbance and transmittance to path length and concentration. Discover the logarithmic relationship between absorbance and path length or concentration by observing the exponential decay of transmittance with path length or concentration.

A simple apparatus can be constructed using a 10 ml graduated pipette as a variable path length cell, a light emitting diode (LED) as a monochromatic light source, and a detector composed of a photoresistor (CdS) in series with a fixed resistor [2 Gordon & Hermann].

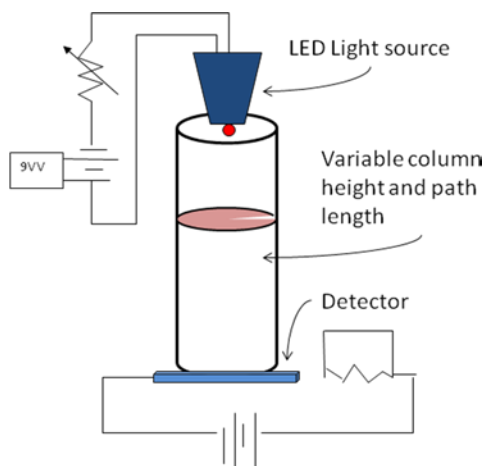


Figure 19 Setup for observing the Intensity of light

Instructions: Add a few drops of food coloring to about 100 ml of water. Fill the graduated cylinder with colored solution at various heights and measure the transmittance. Repeat the experiment by keeping the height of the liquid constant and vary the concentration of the food coloring. Repeat the experiment with a solid transparent material such as window glass, Plexiglas, microscope slides etc.

1. Prepare a graph of transmittance versus path length. What trends do you observe?
2. Prepare a graph of transmittance versus concentration. What trends do you observe?

3. Can you modify the axes of your graphs so that a straight line results?

In case this instrumentation is not available to you, you can work with the following simulated data: (assume the intensity of the incoming light (I_0) to be 1.0).

Table 1 Sample data for Intensity of light measurement.

Variation in path length b			
ϵ	b [cm]	C [g/ml]	Intensity
0.1	1	0.1	0.977237
0.1	5	0.1	0.891251
0.1	10	0.1	0.794328
0.1	50	0.1	0.316228
0.1	100	0.1	0.1

Variation in concentration C			
ϵ	b [cm]	C [g/ml]	Intensity
0.1	5	0.1	0.891251
0.1	5	0.5	0.562341
0.1	5	1	0.316228
0.1	5	5	0.003162

Variation in molar absorptivity ϵ			
ϵ	b [cm]	C [g/ml]	Intensity
0.1	5	1	0.316228
0.3	5	1	0.031623
0.8	5	1	0.0001
3	5	1	1E-15
8	5	1	1E-40

2.4. Fiber Optics: Transmission Medium for Communication: Design Considerations for Selecting a Material for Fiber Optic Cable.

2.8 Optical Materials for the Transmission of Light: Fiber Optics

So far we have discussed various aspects of the interaction of light and materials, which included reflection, refraction, dispersion, absorption, and scattering. One modern application of the principles of optics is optical fiber used for long distance communications. Optical fibers have distinct advantages over copper wires and are characterized by the ability to transmit signals very fast, at the speed of light, and can transmit signals for more than 100 km without the need for amplification. This results in large savings in electronics components and increased system reliability. Optimized optical fibers function with minimum loss of light intensity or encoded information.

2.8.1 Optical Materials: Glass

Let's explore some of the design parameters and optical properties of materials used to fabricate optical fiber. Since ancient times, people have used transparent media, such as glass, to guide light and enhance our naturally limited vision or to light up a room. Glasses are used for the manufacture of windows, telescope lenses, microscopes, and vision correction glasses, and more recently for fiber optic cable for communication. So, why are we using glass rather than any other material so guide light?

2.8.2 How Glass is Made: Silicate Glass

By knowing what glass is made of we can learn how its properties can be modified. Glass is an amorphous, or non-crystalline, solid material and is formed by melting raw material (silicate, silicon dioxide (SiO_2) commonly known as sand) and then rapidly cooling it from the liquid state so that the glass atoms do not have time to crystallize into a regular lattice structure. Silicate glasses are the most common type of glasses. In silicate glasses each silicon atom is linked to four oxygen atoms forming a tetrahedron. These units are then linked and form a large network of atoms with no discernable long-range order or pattern.

2.8.3 Glass Types based upon Impurities

Glass can be modified by adding impurities, which change the network structure and alter its properties. Most common additives are metal oxides such as soda-lime, (Na_2O , soda, and CaO , lime), which lowers the glass transition temperature, which is the softening of the glass that occurs prior to melting. An application of a lower temperature glass melting point is the manufacture of inexpensive glass windows due to energy conserved during the melting and processing of the glass. Another additive used is boric acid, (B_2O_3 , Pyrex glass), which raises the softening temperature and minimizes the thermal expansion of glass. This glass type is well suited for ovenware and laboratory glassware because that is does not crack when cold water is added to hot glass container.

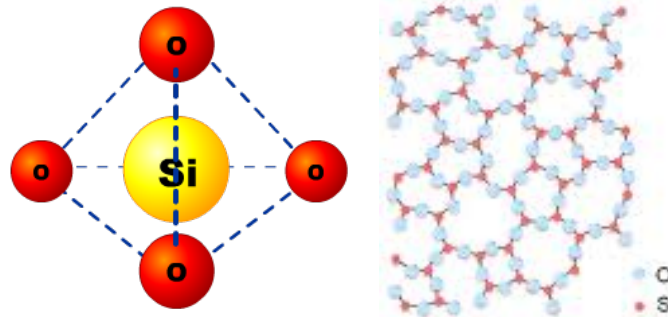


Figure 20 Molecular Structure of glass[3] [4]

2.8.4 Refractive Index of Glass

The optical properties of glasses are a combination of transparency and reflectivity; these properties are controlled by the material's index of refraction. Silicate glasses have optical indices ranging from 1.5-1.9. We have discussed the index of refraction as the ratio of the velocity of light in a vacuum to the velocity of light in material. The index of refraction is always greater than 1 because the propagation speed of light slows upon entering a medium. The refractive index for a vacuum is 1 and dry air is 1.0003. In order to get the most “light bending power”, a larger index of refraction is desirable. This is true, however, due to higher optical densities, the interaction between light and the material is stronger leading to possible side effects such as dispersion or chromatic dispersion.

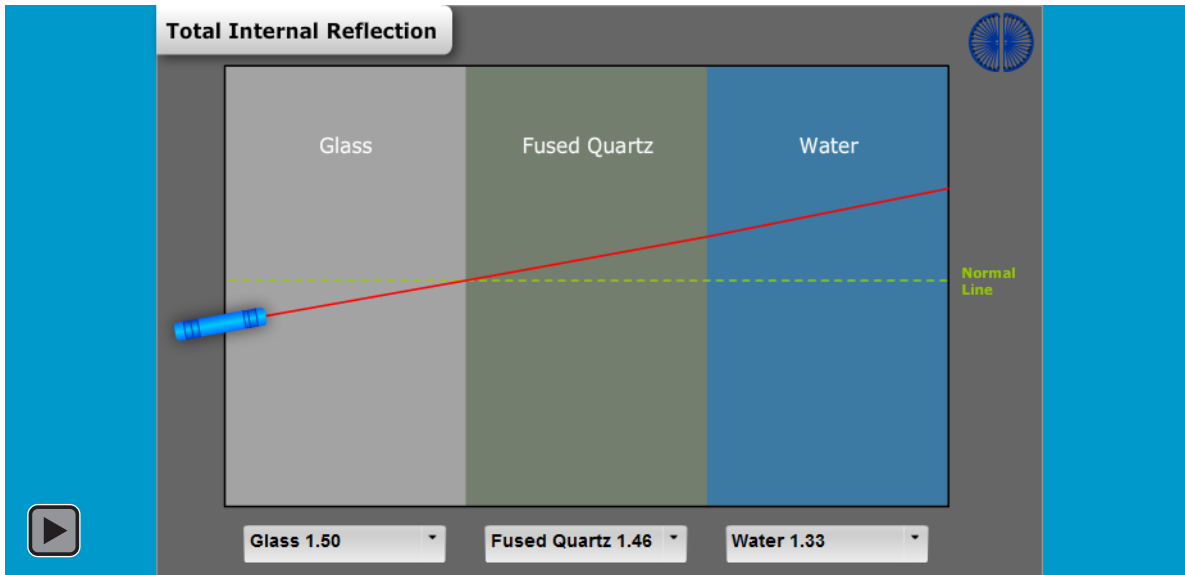
2.8.4.1 Optical Properties and Refractive Index

The index of refraction is controlled, chemically, by adding cationic network modifiers to the glass, positively charged particles that disturb the glass network, and therefore modify its optical properties. This is accomplished through a process called ion-exchange, by which some of the ions (i.e. K^+) are replaced by small amounts of other cations. Optical flint glasses are characterized by high density and a high refractive index, and typically have a composition of 54% silicate (SiO_2) and 45% lead oxide (PbO). Design considerations for optical fibers require a glass composition that not only exhibits certain optical properties but can also be easily drawn into fibers. Optical fiber glasses are typically composed of 55% silicate mixed with aluminum oxide (Al_2O_3), calcium oxide (CaO) and boron oxide (B_2O_3).

2.9 Total Internal Reflection

2.9.1 Refractive Index Boundaries and Total Internal Reflection

When traveling through a medium, some light is reflected and some light is refracted at its boundary or surface. The amount of light reflected or refracted, and the angle at which the light bends is determined by the index of refraction of the two media and the incident angle at which the light hits that boundary.



Animation 6 Light is Bent at the Boundary of a Refractive Index

A particularly interesting phenomenon is total internal reflection (TIR) that occurs when wavelengths of light do not exit into the lower refractive index medium but are internally reflected. Total internal reflection occurs as a light beam travels from a medium of high refractive index to a medium of lower refractive index at or below a low angle called the critical angle. The transition between refractive index boundary and total internal reflection can be explored with the following interactive image.

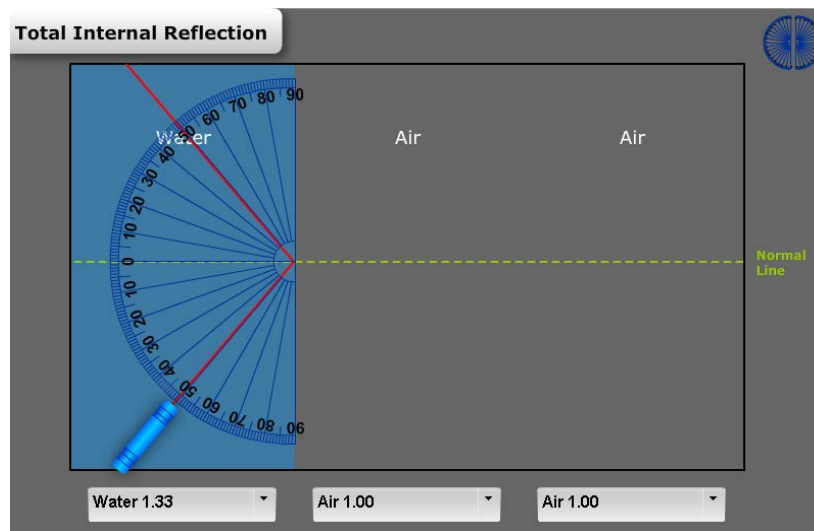


Figure 21 Total internal Reflection at the Boundary of Water and Air

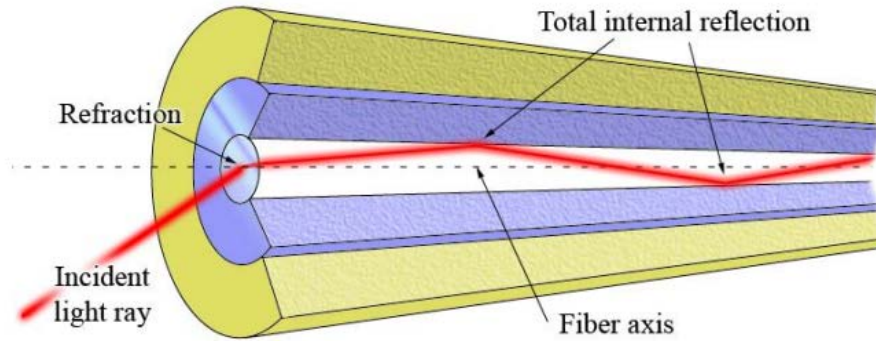


Figure 22 Total Internal Reflection (TIR) and light path in an optical fiber. [6]

2.9.2 Wave Guides and Total Internal Reflection

Scientists and engineers use total internal reflection to guide light through fiber optic glass cables. Light enters at one end of the fiber and stays within the fiber through reflections within the interior surface. The total internal reflection of these fibers can be controlled by the ratio of the indices of refraction between the fiber's core and its outside surface.

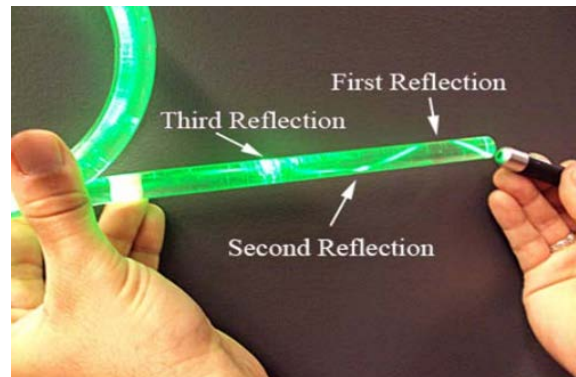


Figure 23 Total Internal Reflection of laser light inside a prism [6]

2.9.3 Transmittance versus Total Internal Reflection

Some loss of light will always occur due to absorption, scattering or dispersion. Since the light's path length in optical cables spans hundreds or thousands of kilometers, even miniscule impurities will lead to some loss of light and consequently a weaker signal. In order to minimize scattering within the optical cable, we can use light of longer wavelength, use a narrow wavelength band and minimize material defects through optimization of the manufacturing process. To combat the loss of signal, signal amplification is needed every 100 km or so. Recently, new ways have been discovered to amplify optical signals without reverting back to an electronic signal first. Erbium-doped optical amplifiers allow an incoming light signal to be amplified through stimulated emission, much like a laser but without the cavity.

2.9.4 Fiber Optic Communications

Current fiber optics technology permits the transmission of information that would otherwise require copper wires weighing about 300,000 times more than optical fiber material. Typical

transmission rates currently range in the Giga Hertz range, or 10^9 (=1 billion) signals per second with an envisioned transmission rate in the Tera Hertz range (10^{12}).

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