Light
Light: Three models

• **Newton’s particle model (rays)**
  – Models light as bits of energy traveling very fast in straight lines.

• **Huygens’s/Maxwell wave model**
  – Models light at waves (transverse EM waves). Color determined by frequency, intensity by square of a total oscillating amplitude.

• **Einstein’s photon model**
  – Models light as “wavicles” == quantum particles whose energy is determined by frequency and that can interfere with themselves.
Quantum Electrodynamics

Physical Optics (Wave model)

Geometric Optics (Ray model)

Einstein’s photon model
Modeling in Biology

Are there examples in biology where you also need different models?

Each model highlights different properties of the protein
- Hydrophobic character
- Folding property
Reason for multiple models

• Each “model” of light highlights a particular characteristic of light (just like each model of a protein highlights a particular aspect of what proteins are and how they work)
Light: Purpose of the three models

• Newton’s particle model (rays)
  – Models how light interacts with mirrors and lenses

• Huygens’s/Maxwell wave model
  – Models cancellation and interference

• Einstein’s photon model
  – Models absorption and emission of light
The Ray Model
Classical Electromagnetism - Maxwell’s Equations

Everything in models (1) and (2) is contained in Maxwell’s Equations

\[ \nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \]  
Charge density

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]

\[ \nabla \cdot \vec{B} = 0 \]

\[ \nabla \times \vec{B} = \mu_0 \left( \vec{J} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \right) \]  
Current density

You are not expected to know these. Just know they exist.
Electromagnetic Waves are one type of solution to Maxwell’s equations.

1. A sinusoidal wave with frequency $f$ and wavelength $\lambda$ travels with wave speed $v_{\text{em}}$.

2. $\vec{E}$ and $\vec{B}$ are perpendicular to each other and to the direction of travel. The fields have amplitudes $E_0$ and $B_0$.

3. $\vec{E}$ and $\vec{B}$ are in phase. That is, they have matching crests, troughs, and zeros.
Special Case Sinusoidal Waves

\[ E_y(x, t) = f(x - v_{em} t) = E_0 \cos[k(x - v_{em} t)] \]

(b) A snapshot graph at one instant of time

Wavenumber and wavelength

\[ k = \frac{2\pi}{\lambda} \]
\[ \lambda = \frac{2\pi}{k} \]

These two contain the same information
Special Case Sinusoidal Waves

\[ E_y(x, t) = f_+ (x - v_{em} t) = E_0 \cos[k(x - v_{em} t)] \]

(b) A snapshot graph at one instant of time

\[ 2\pi = k v_{em} T \]

Introduce

\[ \omega = \frac{2\pi}{T} \]
\[ f = \frac{1}{T} \]

Different ways of saying the same thing:

\[ \frac{\omega}{k} = v_{em} \]
\[ f\lambda = v_{em} \]
Polarizations

We picked this combination of fields: $E_y - B_z$

Could have picked this combination of fields: $E_z - B_y$

(a) Vertical polarization

(b) Horizontal polarization

These are called plane polarized. Fields lie in plane
THE ELECTROMAGNETIC SPECTRUM

Penetrates Earth Atmosphere?

Wavelength (meters)

Radio 10^3  Microwave 10^{-2}  Infrared 10^{-5}  Visible 0.5 x 10^{-6}  Ultraviolet 10^{-8}  X-ray 10^{-10}  Gamma Ray 10^{-12}

About the size of...

Buildings  Humans  Honey Bee  Pinpoint  Protozoans  Molecules  Atoms  Atomic Nuclei

Frequency (Hz)

10^4  10^8  10^{12}  10^{15}  10^{16}  10^{18}  10^{20}

Temperature of bodies emitting the wavelength (K)

1 K  100 K  10,000 K  10 Million K
Waves emanating from a point source

(a)

Wave fronts are the crests of the wave. They are spaced one wavelength apart.

The circular wave fronts move outward from the source at speed $v$. 14
Very far from the source, small segments of spherical wave fronts appear to be planes. The wave is cresting at every point in these planes.
When can one consider waves to be like particles following a trajectory?

Motion of crests

Direction of power flow


- Ray model: approximate propagation of light as that of particles following specific paths or “rays”. Called geometric optics.

- Quantum optics: Light actually comes in chunks called photons
What is the difference?

Diffraction.

λ Comparable to opening size

λ Much smaller than opening size
Long wavelength, $\lambda \approx a$. This wave quickly fills the region behind the opening.

Short wavelength, $\lambda \ll a$. This wave spreads slowly and remains a well-defined beam.
The Ray Model of Light

The ray model applies when light interacts with objects that are very large compared to the wavelength. You’ll learn that...

...light rays travel in straight lines unless they are...

...reflected by a surface or...

...refracted at a boundary.

Light rays can also be scattered or absorbed by the medium they travel through.
In the Ray Picture a beam of light is a bundle of parallel traveling rays.
Foothold Ideas 1:  
Light as Rays - The Physics

• Through empty space (or ~air) light travels in straight lines.
• Each point on an object scatters light, spraying it off in all directions.
• A polished surface reflects rays back again according to the rule: *The angle of incidence equals the angle of reflection.*
Foothold Ideas 2: Light as Rays - the perception

• We only see something when light coming from it enters our eyes.

• Our eyes identify a point as being on an object when rays traced back converge at that point.
Light travels through a transparent material in straight lines called light rays.

The speed of light is \( v = \frac{c}{n} \), where \( n \) is the index of refraction of the material.

Light rays do not interact with each other.

Two rays can cross without either being affected in any way.
Light interacts with matter in four different ways:

At an interface between two materials, light can be either *reflected* or *refracted*.

Within a material, light can be either *scattered* or *absorbed*. 
- An **object** is a source of light rays.
- Rays originate from every point on the object, and each point sends rays in *all* directions.

- The eye “sees” an object when *diverging* bundles of rays from each point on the object enter the pupil and are focused to an image on the retina.
Objects can be either self-luminous, such as the sun, flames, and lightbulbs, or reflective.

Most objects are reflective.
The diverging rays from a **point source** are emitted in all directions.

Each point on an object is a point source of light rays.

A **parallel bundle** of rays could be a laser beam, or light from a *distant object*.
• Rays originate from *every* point on an object and travel outward in *all* directions, but a diagram trying to show all these rays would be messy and confusing.
• To simplify the picture, we use a **ray diagram** showing only a few rays.

These are just a few of the infinitely many rays leaving the object.
A **camera obscura** is a darkened room with a single, small hole, called an **aperture**.

The geometry of the rays causes the image to be upside down.

The object and image heights are related by:

\[
\frac{h_i}{h_o} = \frac{d_i}{d_o}
\]
We can apply the ray model to more complex apertures, such as the L-shaped aperture below.

Some rays are blocked by the opaque screen.
The dark screen has a small hole, \(\approx 2 \text{ mm}\) in diameter. The lightbulb is the only source of light. What do you see on the viewing screen?

A. 

B. 

C. 

21% 

51% 

27%
Two point sources of light illuminate a narrow vertical aperture in a dark screen. What do you see on the viewing screen?
Suppose you have a small brightly lit bulb, a mask (a cardboard screen with a small circular hole cut in it), and a screen. You see a small circle of light on the screen. What would happen to the spot if you moved the bulb straight upward a bit?

A. The spot would stay where it was.
B. The spot would move up a bit.
C. The spot would move down a bit.
D. The spot would move right a bit.
E. The spot would move left a bit.
F. Something else would happen.
Suppose you have two lit bulbs, the top one red and the bottom one blue, a mask (a cardboard screen with a small circular hole cut in it), and a screen, as shown. What would you see on the screen if you held the bulbs one over the other as shown?

A. One purple circle.
B. Two circles, one above the other with the top one red, the lower one blue.
C. Two circles, one above the other with the top one blue, the lower one red.
D. Something else.
Kinds of Images: Real

- In the case of the previous slide, the rays seen by the eye do in fact converge at a point.
- When the rays seen by the eye do meet, the image is called real.
- If a screen is put at the real image, the rays will scatter in all directions and an image can be seen on the screen, just as if it were a real object.
When I arrived in New York for the first time, we flew low over Manhattan and I was impressed with the view of the city lights in the dark. Being tired after a long flight, I tried to take a picture through the window using my flash. Explain why this is a bad idea and what the picture was likely to show.
Reflection

Light rays can bounce, or **reflect**, off a surface. There are two important cases:

**Specular reflection**, like from a mirror.   **Diffuse reflection**, like from the page of this book.

You’ll learn to use the *law of reflection.*
Foothold Ideas 3: Mirrors

• For most objects, light scatters in all directions. For some objects (mirrors) light scatters from them in controlled directions.

• A polished surface reflects rays back again according to the rule: *The angle of incidence equals the angle of reflection.*
Where does an object seen in a mirror appear to be?

Light rays do not carry information on whether they were reflected!
An observer O, facing a mirror, observes a light source S. Where does O perceive the mirror image of S to be located?

A. 1  
B. 2  
C. 3  
D. 4  
E. Some other location  
F. O cannot see S in the mirror when they are as shown.
Kinds of Images: Virtual

• In the case of the previous slide, the rays seen by the eye do not actually meet at a point – but the brain, only knowing the direction of the ray, assumes it came directly from an object.

• When the rays seen by the eye do not meet, but the brain assumes they do, the image is called virtual.

• If a screen is put at the position of the virtual image, there are no rays there so nothing will be seen on the screen.
I have a small mirror – about 8 inches high – hanging on my wall. When I’m standing right in front of it, I can only see my head. Can I see all of myself at once by moving far back enough?

1. Yes
2. No
3. I can if I …
Reflection from a flat, smooth surface, such as a mirror or a piece of polished metal, is called **specular reflection**.
The **law of reflection** states that:

1. The incident ray and the reflected ray are in the same plane normal to the surface, and
2. The angle of reflection equals the angle of incidence:

\[ \theta_r = \theta_i \]
Light reflecting from a mirror

A dressing mirror on a closet door is 1.50 m tall. The bottom is 0.50 m above the floor. A bare lightbulb hangs 1.00 m from the closet door, 2.50 m above the floor. How long is the streak of reflected light across the floor?

**MODEL**  Treat the lightbulb as a point source and use the ray model of light.
Light reflecting from a mirror

**VISUALIZE** The figure below is a pictorial representation of the light rays. We need to consider only the two rays that strike the edges of the mirror. All other reflected rays will fall between these two.
Light reflecting from a mirror

SOLVE The figure below has used the law of reflection to set the angles of reflection equal to the angles of incidence. Other angles have been identified with simple geometry. The two angles of incidence are

\[ \theta_1 = \tan^{-1}\left(\frac{0.50 \text{ m}}{1.00 \text{ m}}\right) = 26.6^\circ \]

\[ \theta_2 = \tan^{-1}\left(\frac{2.00 \text{ m}}{1.00 \text{ m}}\right) = 63.4^\circ \]
Light reflecting from a mirror

The distances to the points where the rays strike the floor are then

\[ l_1 = \frac{2.00 \text{ m}}{\tan \theta_1} = 4.00 \text{ m} \]

\[ l_2 = \frac{0.50 \text{ m}}{\tan \theta_2} = 0.25 \text{ m} \]

Thus the length of the light streak is \( l_1 - l_2 = 3.75 \text{ m} \).
Most objects are seen by virtue of their reflected light.

For a “rough” surface, the law of reflection is obeyed at each point but the irregularities of the surface cause the reflected rays to leave in many random directions.

This situation is called **diffuse reflection**.

It is how you see this slide, the wall, your hand, your friend, and so on.

Each ray obeys the law of reflection at that point, but the irregular surface causes the reflected rays to leave in many random directions.
Consider $P$, a source of rays which reflect from a mirror.

- The reflected rays appear to emanate from $P'$, the same distance behind the mirror as $P$ is in front of the mirror.
- That is, $s' = s$.

The reflected rays *all* diverge from $P'$, which appears to be the source of the reflected rays. Your eye collects the bundle of diverging rays and “sees” the light coming from $P'$.
The rays from P and Q that reach your eye reflect from different areas of the mirror.

Your eye intercepts only a very small fraction of all the reflected rays.
You are looking at the image of a pencil in a mirror. What do you see in the mirror if the top half of the mirror is covered with a piece of dark paper?

A. The full image of the pencil.
B. The top half only of the pencil.
C. The bottom half only of the pencil.
D. No pencil, only the paper.
1. (3 pts) If we start our beaded string off in a sinusoidal shape $y(x) = A \sin(\pi x/L)$ it will oscillate with a period $T_0$. If we start it out with a shape $y(x) = A \sin(2\pi x/L)$ with what period will it oscillate?

A. $T_0$
B. $2T_0$
C. $T_0/2$
D. Something else
2.1 (2 pts) A tightly stretched string is oscillating as a function of time. Graph A is a graph of the string's shape at a particular instant of time and graph B is a graph of the string's velocity as a function of position at that same instant. (The vertical axis is greatly magnified.) Is the wave on the string a:

- A. right going traveling wave
- B. left going traveling wave
- C. part of a standing wave growing in amplitude at time $t_1$
- D. part of a standing wave shrinking in amplitude at time $t_1$
- E. None of the above.
- F. You can't tell from the info given.
2.2 (2 pts) Same situation as 2.1 but now graph A is a graph of the string's velocity as a function of position at a particular instant of time and graph B is a graph of the string's shape at that same instant. Is the wave on the string a:

A. right going traveling wave
B. left going traveling wave
C. part of a standing wave growing in amplitude at time $t_1$
D. part of a standing wave shrinking in amplitude at time $t_1$
E. None of the above.
F. You can’t tell from the info given.
3. (3 pts) A wire is rigidly attached to a wall. A pulse is sent along the string toward the wall. What will happen when the pulse reaches the wall? If there is more than one answer, place them all in the box. If none of these will occur, put N in the box.

A. The entire pulse will travel in the wall.
B. Some of the pulse will travel in the wall.
C. Some of the pulse were reflect right-side-up.
D. Some of the pulse will reflect upside-down.
E. The entire pulse will reflect right-side-up
F. The entire pulse will reflect upside-down
You want to put a “full length mirror” on the wall of your room; that is, a mirror that is large enough so that you can see your whole self in it all at the same time. How big should the mirror be?

A. You can see yourself in any size mirror if you go back far enough.
B. It depends on the size of your room and whether you can step back far enough from the mirror.
C. The mirror needs to be about half your size.
D. The mirror needs to be as big as you are.
E. Some other answer
How high is the mirror?

If your height is $h$, what is the shortest mirror on the wall in which you can see your full image? Where must the top of the mirror be hung?

**Model** Use the ray model of light.
**How high is the mirror?**

**VISUALIZE** The figure below is a pictorial representation of the light rays. We need to consider only the two rays that leave your head and feet and reflect into your eye.
How high is the mirror?

**SOLVE** Let the distance from your eyes to the top of your head be $l_1$ and the distance to your feet be $l_2$. Your height is $h = l_1 + l_2$. A light ray from the top of your head that reflects from the mirror at $\theta_r = \theta_i$ and enters your eye must, by congruent triangles, strike the mirror a distance $\frac{1}{2}l_1$ above your eyes. Similarly, a ray from your foot to your eye strikes the mirror a distance $\frac{1}{2}l_2$ below your eyes.
How high is the mirror?

The distance between these two points on the mirror is \( \frac{1}{2}l_1 + \frac{1}{2}l_2 = \frac{1}{2}h \). A ray from anywhere else on your body will reach your eye if it strikes the mirror between these two points. Pieces of the mirror outside these two points are irrelevant, not because rays don’t strike them but because the reflected rays don’t reach your eye. Thus the shortest mirror in which you can see your full reflection is \( \frac{1}{2}h \). But this will work only if the top of the mirror is hung midway between your eyes and the top of your head.
How high is the mirror?

**ASSESS** It is interesting that the answer does not depend on how far you are from the mirror.
What does a mirror do to an image?

A. Flips it left to right
B. Flips it upside down
C. Does both
D. Does something else
Refraction
When light rays travel from one medium to another, they change directions, or refract, at the boundary.

Refraction causes the laser beam to change direction as it goes through the prism.

You’ll learn to use Snell’s law to find the angles on both sides.
Images Formed by Lenses and Mirrors

You’ll discover how lenses and mirrors form **images**. We’ll start with a graphical method called **ray tracing**.

Ray tracing shows how this lens forms a **real image** on the opposite side of the lens from the object.

We’ll then develop the **thin-lens equation** for more quantitative results.

A magnifying glass creates a **virtual image** that you see by looking through the lens.

We’ll use the same graphical and mathematical techniques to understand how curved mirrors create images.

The passenger-side rearview mirror is curved, allowing you to see a wider field of view.
Two things happen when a light ray is incident on a smooth boundary between two transparent materials:

1. Part of the light *reflects* from the boundary, obeying the law of reflection.
2. Part of the light continues into the second medium. The transmission of light from one medium to another, but with a change in direction, is called *refraction*. 
The ray has a kink at the boundary.

$n_1 \sin \theta_1 = n_2 \sin \theta_2$  
(Snell’s law of refraction)
Refraction

If the ray direction is reversed, the incident and refracted angles are interchanged but the values of $\theta_1$ and $\theta_2$ remain the same.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$  \hspace{1cm} (Snell’s law of refraction)
### TABLE 23.1 Indices of refraction

<table>
<thead>
<tr>
<th>Medium</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1.00 exactly</td>
</tr>
<tr>
<td>Air (actual)</td>
<td>1.0003</td>
</tr>
<tr>
<td>Air (accepted)</td>
<td>1.00</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.36</td>
</tr>
<tr>
<td>Oil</td>
<td>1.46</td>
</tr>
<tr>
<td>Glass (typical)</td>
<td>1.50</td>
</tr>
<tr>
<td>Polystyrene plastic</td>
<td>1.59</td>
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<tr>
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<td>2.41</td>
</tr>
<tr>
<td>Silicon (infrared)</td>
<td>3.50</td>
</tr>
</tbody>
</table>

\[
n = \frac{c}{v_{\text{medium}}}
\]
When a ray is transmitted into a material with a higher index of refraction, it bends *toward* the normal.

When a ray is transmitted into a material with a lower index of refraction, it bends *away from* the normal.
A laser beam passing from medium 1 to medium 2 is refracted as shown. Which is true?

A. \( n_1 < n_2 \).

B. \( n_1 > n_2 \).

C. There’s not enough information to compare \( n_1 \) and \( n_2 \).
TACTICS

BOX 23.1 Analyzing refraction

1. **Draw a ray diagram.** Represent the light beam with one ray.
2. **Draw a line normal to the boundary.** Do this at each point where the ray intersects a boundary.
3. **Show the ray bending in the correct direction.** The angle is larger on the side with the smaller index of refraction. This is the qualitative application of Snell’s law.
4. **Label angles of incidence and refraction.** Measure all angles from the normal.
5. **Use Snell’s law.** Calculate the unknown angle or unknown index of refraction.

Exercises 11–15
Measuring the index of refraction

The figure below shows a laser beam deflected by a 30°-60°-90° prism. What is the prism’s index of refraction?

**MODEL** Represent the laser beam with a single ray and use the ray model of light.
Measuring the index of refraction

**VISUALIZE** The figure below uses the steps of Tactics Box 23.1 to draw a ray diagram. The ray is incident perpendicular to the front face of the prism ($\theta_{\text{incident}} = 0^\circ$), thus it is transmitted through the first boundary without deflection. At the second boundary it is especially important to draw the normal to the surface at the point of incidence and to measure angles from the normal.

$\theta_1$, and $\theta_2$ are measured from the normal.
Measuring the index of refraction

**SOLVE** From the geometry of the triangle you can find that the laser’s angle of incidence on the hypotenuse of the prism is $\theta_1 = 30^\circ$, the same as the apex angle of the prism. The ray exits the prism at angle $\theta_2$ such that the deflection is $\phi = \theta_2 - \theta_1 = 22.6^\circ$. Thus $\theta_2 = 52.6^\circ$. Knowing both angles and $n_2 = 1.00$ for air, we can use Snell’s law to find $n_1$:

$$n_1 = \frac{n_2 \sin \theta_2}{\sin \theta_1} = \frac{1.00 \sin 52.6^\circ}{\sin 30^\circ} = 1.59$$

$\theta_1$ and $\theta_2$ are measured from the normal.
\[ n_1 = 1.59 \]

**ASSESS** Referring to the indices of refraction in Table 23.1, we see that the prism is made of plastic.

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<tr>
<td>Silicon (infrared)</td>
<td>3.50</td>
</tr>
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</table>
- When a ray crosses a boundary into a material with a lower index of refraction, it bends away from the normal.

- As the angle $\theta_1$ increases, the refraction angle $\theta_2$ approaches $90^\circ$, and the fraction of the light energy transmitted decreases while the fraction reflected increases.

- The critical angle of incidence occurs when $\theta_2 = 90^\circ$:

  $$\theta_c = \sin^{-1} \frac{n_2}{n_1}$$

- The refracted light vanishes at the critical angle and the reflection becomes 100% for any angle $\theta_1 > \theta_c$. 
The angle of incidence is increasing. Transmission is getting weaker.

$n_2 < n_1$

$\theta_2 = 90^\circ$

$\theta_1 > \theta_c$

$\theta_c$

Critical angle when $\theta_2 = 90^\circ$

Reflection is getting stronger.

Total internal reflection occurs when $\theta_1 \geq \theta_c$. 

4/23/2014

PHYS132
A laser beam undergoes two refractions plus total internal reflection at the interface between medium 2 and medium 3. Which is true?

\[ \text{A. } n_1 < n_3. \]
\[ \text{B. } n_1 > n_3. \]
\[ \text{C. There’s not enough information to compare } n_1 \text{ and } n_3. \]
The most important modern application of total internal reflection (TIR) is optical fibers.

Light rays enter the glass fiber, then impinge on the inside wall of the glass at an angle above the critical angle, so they undergo TIR and remain inside the glass.

The light continues to “bounce” its way down the tube as if it were inside a pipe.
In a practical optical fiber, a small-diameter glass core is surrounded by a layer of glass cladding.

The glasses used for the core and the cladding have:

\[ n_{\text{core}} > n_{\text{cladding}} \]
If you see a fish that appears to be swimming close to the front window of the aquarium, but then look through the side of the aquarium, you’ll find that the fish is actually farther from the window than you thought.
- Rays emerge from a material with \( n_1 > n_2 \).
- Consider only paraxial rays, for which \( \theta_1 \) and \( \theta_2 \) are quite small.
- In this case:

\[
s' = \frac{n_2}{n_1} s
\]

where \( s \) is the object distance and \( s' \) is the image distance.
A fish in an aquarium with flat sides looks out at a hungry cat. To the fish, the distance to the cat appears to be

A. less than the actual distance.
B. equal to the actual distance.
C. greater than the actual distance.

Rays refract toward the normal.

Rays seem to come from here. This is a virtual image at a larger distance.

33% 33% 33%
- A prism *disperses* white light into various colors.
- When a particular color of light enters a prism, its color does not change.
Different colors are associated with light of different wavelengths.
The longest wavelengths are perceived as red light and the shortest as violet light.
What we perceive as white light is a mixture of all colors.

<table>
<thead>
<tr>
<th>Color</th>
<th>Approximate wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deepest red</td>
<td>700 nm</td>
</tr>
<tr>
<td>Red</td>
<td>650 nm</td>
</tr>
<tr>
<td>Green</td>
<td>550 nm</td>
</tr>
<tr>
<td>Blue</td>
<td>450 nm</td>
</tr>
<tr>
<td>Deepest violet</td>
<td>400 nm</td>
</tr>
</tbody>
</table>
- The slight variation of index of refraction with wavelength is known as **dispersion**.
- Shown is the dispersion curves of two common glasses.
- Notice that $n$ is **larger** when the wavelength is **shorter**, thus violet light refracts more than red light.
- One of the most interesting sources of color in nature is the rainbow.
- The basic cause of the rainbow is a combination of refraction, reflection, and dispersion.
A ray of red light reaching your eye comes from a drop *higher* in the sky than a ray of violet light.

You have to look higher in the sky to see the red light than to see the violet light.

You see a rainbow with red on the top, violet on the bottom.
A narrow beam of white light is incident at an angle on a piece of flint glass. As the light refracts into the glass,

A. It forms a slightly diverging cone with red rays on top, violet rays on the bottom.

B. It forms a slightly diverging cone with violet rays on top, red rays on the bottom.

C. It remains a narrow beam of white light because all the colors of white were already traveling in the same direction.
- Green glass is green because it absorbs any light that is “not green.”
- If a green filter and a red filter are overlapped, no light gets through.
- The green filter transmits only green light, which is then absorbed by the red filter because it is “not red.”
The figure below shows the absorption curve of *chlorophyll*, which is essential for photosynthesis in green plants.

The chemical reactions of photosynthesis absorb red light and blue/violet light from sunlight and puts it to use.

When you look at the green leaves on a tree, you’re seeing the light that was reflected because it wasn’t needed for photosynthesis.
Light can scatter from small particles that are suspended in a medium.

Rayleigh scattering from atoms and molecules depends inversely on the fourth power of the wavelength:

\[ I_{\text{scattered}} \propto \lambda^4 \]

At midday the scattered light is mostly blue because molecules preferentially scatter shorter wavelengths.

At sunset, when the light has traveled much farther through the atmosphere, the light is mostly red because the shorter wavelengths have been lost to scattering.
Sunsets are red because all the blue light has scattered as the sunlight passes through the atmosphere.