Visible light, and all EM waves travel thru a vacuum with speed $c$.

But light can also travel thru many different materials.

The atoms in these materials absorb, reemit, and scatter the light.

Thus, the speed of light slows down as it travels thru a material.

The actual speed of light in some material depends on the material.

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$  \hspace{1cm} \text{Speed of light in vacuum.}

$$v = \frac{1}{\sqrt{\mu \varepsilon}}$$  \hspace{1cm} \text{Speed of light in some material.}

Material dependent

To describe the speed of light in a material, we use a parameter called the **index of refraction** ($n$):

$$n = \frac{C}{v}$$

*Note: $n \geq 1$*
26.2 Snell’s Law

When light in a vacuum enters a more dense material, like water for example, the light not only slows down, but it also changes direction.

This bending of light as it travels between two different materials is called **refraction**.

As the incident wave strikes the water’s surface, the lower part of the wave front hits first – slowing that side of the wave. The wave bunches up here, but not on the top side where it’s still moving fast. This causes the wave to turn or bend.

*Note: The refracted wave has a new wavelength. Shorter in this case.*
As the light passes thru different media, it’s frequency stays the same, but its wavelength changes!

\[ f = \frac{v}{\lambda} \]

Since \( \lambda \) changes, the speed changes too to keep \( f \) constant.

So how does the light get bent (refracted)?

If the light is passing from a less dense medium into a more dense medium, it gets bent toward the normal.

If the light is passing from a more dense medium into a less dense medium, it gets bent away from the normal.
Notice that the incident and refracted angles are measured with respect to the normal.

The relationship between the two angles is given by **Snell’s Law of Refraction.**

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

\( n_1 \) is the index of refraction in medium 1 and \( n_2 \) is the index of refraction in medium 2.
Apparent Depth

Let’s say you’re standing on the shore of a lake and you want to kill a little fishy with a spear.

Pick one little point on the fish, say his dorsal fin, and look at a light ray from there. The ray gets bent away from the normal as it leaves the water before it enters your eye. Thus, you see the fish at a different position.

By extrapolating the ray back, we see the fish appears closer to the surface than he actually is.

Thus, in order to kill the fish with the spear, you learn to aim slightly below the fish’s apparent position!
Calculating the **apparent depth** is easy if you are looking directly down from above at the object.

Light rays from a treasure chest sitting on the bottom of the ocean floor refract at the water’s surface, making the chest look closer to the surface than it actually is.

**Apparent depth for observer directly above object:**

\[
d' = d \left( \frac{n_2}{n_1} \right)
\]

What if the observer is sitting in the water looking at something in the air above it????????
Now I’m standing on the dock again, but this time I want to kill the fishy with a laser beam. Where should I aim?

1. Below the fish
2. Above the fish
3. **Directly at the fish**

`mmmm...lunch!`
26.3 Total Internal Reflection

Consider a light ray in air striking the surface of water:

Part of the ray is refracted, and part is reflected.

The refracted ($\theta_R$) and reflected ($\theta_i$) angles will both change if we change the incident angle (Law of Reflection and Snell’s Law of Refraction).

Now consider what happens when a light ray emerges from a more dense medium into a less dense medium: water to air, for example.
Part of the ray is reflected, and part is refracted.

Notice that the refracted angle is greater than the incident angle since $n_{\text{air}} < n_{\text{water}}$.

Now let's keep increasing the incident angle so that the refracted angle keeps increasing.

Notice: There is a point when the refracted angle = $90^\circ$ (red ray).

This occurs when $\theta_i = \theta_c$, where $\theta_c$ is known as the critical angle.

Thus, when $\theta_i = \theta_c$, $\theta_{\text{refracted}} = 90^\circ$.

Now, if $\theta_i > \theta_c$, then there is no refracted ray (purple ray)!

All the incident light is completely reflected back into the medium.

This is called **total internal reflection**.
From Snell’s Law: 
\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

But we know when \( \theta_1 = \theta_c, \theta_2 = 90^\circ \).

Thus, 
\[ n_1 \sin \theta_c = n_2 \sin 90^\circ \Rightarrow \sin \theta_c = \frac{n_2}{n_1} \]
True for \( n_1 > n_2 \).

Example:
What is \( \theta_c \) for water to air?

\[
\sin \theta_c = \frac{n_2}{n_1} = \frac{1.00}{1.33} \Rightarrow \theta_c = \sin^{-1}\left(\frac{1.00}{1.33}\right) = 48.8^\circ
\]

Thus, for light rays traveling in water toward air, if the incident angle is greater than 48.8°, the water acts like a perfect mirror.
Under bright lights diamonds sparkle. If you immerse the diamond in water, will it shine with more brilliance, or less?

1. More
2. Less

✓ 2. Less
Because of total internal reflection, glass prisms can be used to turn light rays around.

Consider a light ray striking a right-triangular glass prism:

\[ \theta_c = \sin^{-1}\left(\frac{n_{\text{air}}}{n_{\text{glass}}}\right) = \sin^{-1}\left(\frac{1.00}{1.52}\right) = 42^\circ \]

The ray strikes surface 1 perpendicularly and travels straight thru to surface 2.

At surface 2, the incident angle is greater than \( \theta_c \), so we get total internal reflection.

At surface 3, the incident angle is again greater than \( \theta_c \), so we get total internal reflection.

The ray turns completely around!
Total internal reflection is utilized in fiber optics:

Light enters essentially a glass “tube” and gets totally internally reflected since the glass cladding has a smaller index of refraction than the glass core.

The glass fibers are flexible, and as long as they are not bent too sharply, will reflect all of the light down them internally.

Used primarily as a low-loss, high-speed transmission cable for information, such as voice communications.

Also used by doctors and surgeons for endoscopic examinations and procedures.
26.4 Polarization, Reflection, and Refraction of Light

Light that gets reflected at some angle off of a non-metallic surface becomes partially polarized.

Consider, for example, sunlight reflecting off of water:

Sunlight, unpolarized

Reflected ray, partially polarized

Sunlight is unpolarized, but upon reflection, becomes partially polarized.

Polarized sunglasses are polarizers with a vertical transmission axis.

Thus, they block the reflected glare that comes from the surface of the water.

Most of the reflected light is polarized parallel to the surface of the water (i.e. horizontally), so it gets blocked by the sunglasses.

However, there is a special incident angle such that the reflected ray is completely polarized parallel to the surface.

This is called the Brewster Angle ($\theta_B$).
So, at the Brewster angle, the reflected light is polarized parallel to the surface.

And…..the angle between the reflected and refracted rays is 90° – they are perpendicular to each other!

To find the Brewster angle between two media:

\[ \tan \theta_B = \frac{n_2}{n_1} \]

Thus, at the Brewster angle:

\[ \theta_B + \theta_R = 90° \]

26.5 Dispersion of Light

Light passing thru a prism gets bent or refracted.

However, how much it gets bent depends on the “color” of the light, i.e. its wavelength.
Violet light has a higher refractive index than red light, so it gets bent more, in accord with Snell’s Law.

Thus, a prism can separate white light into all the visible colors.

The spreading out of light into its component colors (or wavelengths) is called **dispersion**. It is a refraction effect!

Dispersion is responsible for the formation of rainbows:
26.6 Lenses

A **lens** is an **optical system** that refracts (bends) light to form an image of the object.

A lens consists of two or more surfaces, at least one of which is curved.

An optical system with just **one lens** is called a **simple lens system**.

An optical system **more than one lens** is called a **compound lens system**.

We know that prisms bend light, so can we use a prism to form an image?

Prisms bend the light, but they don’t form clear images.

But, if we make the lens with a spherical surface, then incoming parallel rays converge at a common point ($F$), **the focal point**.

Like for mirrors, we can identify a **focal length** for the lens ($f$).

*Remember, parallel light rays come from objects that are very far away.*
For this lens (bowed outward) the rays converge at a common point: **Converging Lens** or **Convex Lens**.

If the parallel rays are bent away from the principal axis, they appear to diverge from a common point: **Diverging Lens** or **Concave Lens**.

Lenses come in a variety of shapes:

Snell’s Law at the interface controls the refraction!
26.7 Formation of Images by Lenses

Like mirrors, lenses can form images of objects.

But lenses are different, since the light rays actually pass thru the lens.

We will again use ray tracing diagrams to determine the location, size, and orientation of images formed by lenses.

In doing so, we will assume the lens is thin relative to it’s focal length.

This ensures that both \( d_i \) and \( d_o \) can be measured from the center of the lens.

Also, we will assume, unless otherwise stated, that the object is located on the principal axis to the left of the lens.

Again, we will use three principle rays to locate the image:

1. A ray traveling parallel to the principal axis gets refracted thru the focal point.
2. A ray traveling thru the center of the lens is unaffected.
3. A ray traveling thru the focal point gets refracted parallel to the principal axis.

There are 3 cases for a converging lens. Let’s take them one at a time.
Case 1: The object is located beyond 2F:

Ray 1 is a paraxial ray from the object that gets refracted thru $F$.
Ray 2 travels thru the center of the lens unaffected.
Ray 3 travels thru $F$ and comes out parallel.

Now we can see where the rays intersect, and thus the image position.

What are the image properties? Real, inverted, and reduced.
Case 2: The object is between $F$ and $2F$:

Ray 1 is a paraxial ray from the object that gets refracted thru $F$.
Ray 2 travels thru the center of the lens unaffected.
Ray 3 travels thru $F$ and comes out parallel.
Now we can see where the rays intersect, and thus the image position.

What are the image properties? **Real, inverted, and enlarged.**
Case 3: The object is within $F$:

Ray 1 is a paraxial ray from the object that gets refracted thru $F$.
Ray 2 travels thru the center of the lens unaffected.
Ray 3 travels thru $F$ and comes out parallel.

Notice: Rays 1, 2, and 3 don’t converge! They diverge!

Extrapolate the refracted rays back to find the image.
Now we can see where the rays intersect, and thus the image position.

What are the image properties? Virtual, upright, and enlarged.
Ray 1 is a paraxial ray from the object that gets refracted as if it came from $F$. Ray 2 travels thru the center of the lens unaffected. Ray 3 travels toward the opposite $F$ and comes out parallel. Now we can see where the rays intersect, and thus the image position.

What are the image properties? **Virtual, upright, and reduced.**
26.8 The Thin Lens and Magnification Equation

We used the law of reflection to find a relationship between the focal length ($f$), the object distance ($d_o$), and the image distance ($d_i$) for mirrors.

We can do the same thing for lenses using Snell’s law.

The result we find is the same:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

Thin Lens Equation

As before, the magnification is:

$$m = \frac{h_i}{h_o} = \frac{-d_i}{d_o}$$
Sign conventions for lenses:

This assumes the object is located to the left of the lens, and your eye is located to the right of the lens.

**Focal length:**

\[ f \] is positive for converging lenses.

\[ f \] is negative for diverging lenses.

**Object Distance:**

\[ d_o \] is positive for objects left of the lens (real).

\[ d_o \] is negative for objects right of the lens (virtual).

**Image Distance:**

\[ d_i \] is positive for images right of the lens (real).

\[ d_i \] is negative for images left of the lens (virtual).

**Magnification:**

\[ m \] is positive for images upright wrt the object.

\[ m \] is negative for images inverted wrt the object.
**Example:**
A movie camera has a converging lens with a focal length of 85.0 mm. It takes a picture of a 145-cm tall person standing 16.0 m away. What is the height of the image on the film? Is the image upright or inverted wrt the object. Give your reasoning.

**Solution:**

We know: \( f = 0.085 \text{ m} \quad h_o = 1.45 \text{ m} \quad d_o = 16.0 \text{ m} \)

We need: \( h_i \)

\[
\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \quad \Rightarrow \quad \frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} \quad \Rightarrow \quad \frac{1}{d_i} = \frac{1}{0.085} - \frac{1}{16} \quad \Rightarrow \quad \frac{1}{d_i} = 11.7
\]

\[
\Rightarrow \quad d_i = 0.085 \text{ m} = 8.5 \text{ cm}
\]

\[
m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \quad \Rightarrow \quad h_i = -\frac{d_i \cdot h_o}{d_o} \quad \Rightarrow \quad h_i = \frac{(-0.085 \cdot 1.45)}{16} = -7.74 \text{ mm}
\]

Image is inverted, since \( m \) is negative!
An object is located at a distance $d_o$ in front of a lens. The lens produces an upright image that is twice as tall as the object. What kind of lens is it?

1. Converging
2. Diverging
A spherical mirror and a lens are immersed in water. Compared to how they work in air, which one will be more affected?

1. The mirror
2. The lens
26.9 Lenses in Combination

We have been studying single-element optical systems known as simple lenses.

Now let’s look at optical systems with more than one lens – a compound lens system.

A compound microscope, for example, consists of two lenses – an objective and an eyepiece.
The object is placed just outside the focal length of the objective.

Now we see the location of the first image – the one formed by the objective. The eyepiece (2nd lens) is positioned such that the first image lies just inside the focal length of the eyepiece. This image now serves as the object for the 2nd lens focal length of the eyepiece. This image now serves as the object for the 2nd lens.

Now we see the location of the final image.

The final image is virtual, inverted wrt the original object, and it is greatly enlarged.
Example

The objective an eyepiece of a compound microscope have focal lengths $f_o = 15$ mm and $f_e = 25.5$ mm. A distance of 61.0 mm separates the lenses. The microscope is being used to examine an object placed at $d_{o1} = 24.1$ mm in front of the objective. What is the final image distance?

First, we need to find the first image location.

$$\frac{1}{d_{i1}} = \frac{1}{f_o} - \frac{1}{d_{o1}} = \frac{1}{15} - \frac{1}{24.1} \Rightarrow d_{i1} = 39.7 \text{ mm}$$

This first image now becomes the object for the eyepiece.
So what do we use for \( d_{o2} \)?

Well, it’s going to be equal to 61.0 mm – \( d_{i1} \).

Thus,

\[
d_{o2} = 61.0 \text{ mm} - 39.7 \text{ mm} = 21.3 \text{ mm}
\]

\[
\frac{1}{d_{i2}} = \frac{1}{f_e} - \frac{1}{d_{o2}} = \frac{1}{25.5} - \frac{1}{21.3} \quad \Rightarrow \quad d_{i2} = -129 \text{ mm}
\]

This is 129 mm to the left of the eyepiece.

The fact that \( d_{i2} \) is negative tells us the final image lies to the left of the eyepiece and is therefore a virtual image.
26.10 The Human Eye

The eye is an optical system very similar to a camera. Each has a lens, an aperture, and each forms a real, inverted and reduced image.

A camera forms an image on film, and the eye forms an image on the retina.

The iris is the colored part of the eye. It can be blue, brown, gray, green or hazel.

The cornea is a transparent covering over the lens. The majority of the refraction takes place in the cornea (25%) and the lens (~75%).

The lens is the shape of a small bean. It’s about 9 mm tall and 4 mm thick. It is a complex, layered, fibrous mass, similar to a transparent onion. It contains about 22,000 fine layers.

The index of refraction varies throughout the lens. The average is $n = 1.40$. 
Warm-up question

What color are your eyes?

1. Blue
2. Brown
3. Green
4. Gray
5. Hazel
Vitreous humor – mostly water.

Muscae volitantes

So how does the eye form an image?

It has a fixed image distance \( (d_i) \), so if the object distance \( (d_o) \) changes, then \( f \) has to change.

By contracting and relaxing the **ciliary muscles**, the lens gets stretched or compressed, thus changing its focal length.

When an object changes its distance, the ciliary muscles respond to change \( f \) and keep the object in focus.

This process is called **accommodation**.

Your eyes do this automatically, and it happens very quickly.

The point nearest the eye to which an object can be placed and still be in focus is called the **near point**.

For objects at the near point, the ciliary muscles are completely contracted with the lens being squashed.
The point farthest from the eye to which an object can be placed and still be in focus is called the **far point**.

For objects located at the far point, the ciliary muscles are completely relaxed and the lens is elongated.

For young adults in their early twenties, the near point is about 25 cm. You can expect this to roughly double by the time your 40.

The far point is the location of objects very far away, like stars and planets, and is therefore at infinity.

There are several common problems with human vision:
Warm-up question

What do you wear?

1. Glasses
2. Contacts
3. I don’t wear corrective eyewear.
Warm-up question

What are you?

1. Farsighted
2. Nearsighted
3. Neither
Nearsightedness (myopia)

A person who is **nearsighted** can focus on objects close up, but not on objects far away.

For nearsightedness, a **diverging lens** forms a virtual image at the far point.
Farsightedness (hyperopia)

A person who is **farsighted** can focus on objects far away, but not on objects close up.

For farsightedness, a **converging lens** forms a virtual image at the near point.
Clicker Question 26 - 6

Bill and Ted are lost in the desert and need to start a fire. Both wear glasses. Ted is farsighted and Bill is nearsighted. Whose glasses should they use to start the fire?

1. Bill
2. Ted

Ted’s glasses would be the more excellent choice.
The Refractive Power of a Lens

The refractive or bending power of a lens depends on $f$, the focal length.

However, optometrists and opticians do not use $f$ in specifying prescription eyewear. They use Refractive Power:

$$\text{Refractive Power} = \frac{1}{f [\text{m}]}$$

Units?

Refractive power is measured in Diopters [D].

$1 \text{ D} = 1 \text{ m}^{-1}$

Thus, what would be the refractive power of a lens with a focal length $f = 25 \text{ cm}$?

$$\text{Refractive Power} = \frac{1}{0.25 \text{ m}} = 4 \text{ D}$$
Ch. 27. Interference and the Wave Nature of Light

Up to now, we have been studying geometrical optics, where the wavelength of the light is much smaller than the size of our mirrors and lenses and the distances between them.

→ The propagation of light is well described by linear rays except when reflected or refracted at the surface of materials.

Now we will study wave optics, where the wavelength of the light is comparable to the size of an obstacle or aperture in its path.

→ This leads to the wave phenomena of light called interference and diffraction.
27.1 The Principle of Linear Superposition

Take two waves of equal amplitude and wavelength and have them meet at a common point:

If the two waves are in-phase, then they meet crest-to-crest and trough-to-trough.

Their two amplitudes add to each other. In this case, the resulting wave would have an amplitude that doubled.

This is called **Constructive Interference (CI)**.

Define Optical Path Difference (OPD):

\[ \text{OPD} = \text{The difference in distance that two waves travel.} \]

For CI to occur, we need the waves to meet crest-to-crest, thus the waves must differ by an integer multiple of the wavelength \( \lambda \):

\[ \text{OPD} = m\lambda, \ m = 0, 1, 2, \ldots \]

**Constructive Interference**
Now take two waves of equal amplitude and wavelength and have them meet at a common point, but this time have them be out-of-phase.

Thus, they now meet crest-to-trough.

The resulting wave has zero amplitude. The two waves cancel out.

This is called **Destructive Interference (DI)**.

For DI to occur, we need the waves to meet crest-to-trough, thus the waves must differ by any odd integer number of $\frac{1}{2}\lambda$:

$$\text{OPD} = (m + \frac{1}{2})\lambda, \quad m = 0, 1, 2, \ldots$$

Destructive Interference

All waves do this, including EM waves, and since light is an EM wave, light waves do this too.
For interference to continue at some point, the two sources of light producing the waves must be coherent, which means that their phase relationship relative to each other remains constant in time.