Light is the ONLY thing you see! All visible objects either emit or reflect light.
Almost everything we see is made visible by the light it reflects. Some materials, such as air, water, or window glass, allow light to pass through. Other materials, such as thin paper or frosted glass, allow the passage of light in diffused directions so that we can’t see objects through them.
Scientists now agree that light has a dual nature, part particle and part wave.
27.1 Early Concepts of Light

Light has been studied for thousands of years. Some ancient Greek philosophers thought that light consists of tiny particles, which enter the eye to create the sensation of vision.

Others thought that vision resulted from streamers or filaments emitted by the eye making contact with an object.
27.1 Early Concepts of Light

Up until the time of Newton and beyond, most philosophers and scientists thought that light consisted of particles. However, one Greek, Empedocles, thought that light traveled in waves.

One of Newton’s contemporaries, the Dutch scientist Christian Huygens, also argued that light was a wave.
27.1 Early Concepts of Light

The particle theory was supported by the fact that light seemed to move in straight lines instead of spreading out as waves do. Huygens showed that under some circumstances light does spread out and other scientists found evidence to support the wave theory. The wave theory became the accepted theory in the nineteenth century.
In 1905, Einstein published a theory explaining the photoelectric effect.

According to this theory, light consists of particles called photons, massless bundles of concentrated electromagnetic energy.

Scientists now agree that light has a dual nature, part particle and part wave.
27.1 Early Concepts of Light

What is the nature of light?
27.2 The Speed of Light

Michelson’s experimental value for the speed of light was 299,920 km/s, which is usually rounded to 300,000 km/s.
27.2 The Speed of Light

It was not known whether light travels instantaneously or with finite speed until the late 1600s. Galileo tried to measure the time a light beam takes to travel to a distant mirror, but it was so short he couldn’t begin to measure it. Others tried the experiment at longer distances with lanterns they flashed on and off between distant mountaintops. All they succeeded in doing was measuring their own reaction times.
27.2 The Speed of Light

Olaus Roemer

The first demonstration that light travels at a finite speed was supplied by the Danish astronomer Olaus Roemer about 1675. Roemer carefully measured the periods of Jupiter’s moons.

- The innermost moon, Io, revolves around Jupiter in 42.5 hours.
- The Io disappears periodically into Jupiter’s shadow, so this period could be measured with great accuracy.
27.2 The Speed of Light

- Roemer found that while Earth was moving away from Jupiter, the periods of Io were all somewhat longer than average.
- When Earth was moving toward Jupiter, the measured periods were shorter than average.
- Roemer estimated that the cumulative discrepancy amounted to about 22 minutes.
27.2 The Speed of Light

Light coming from Io takes longer to reach Earth at position D than at position A. The extra distance that the light travels divided by the extra time it takes gives the speed of light.
27.2 The Speed of Light

Christian Huygens

Christian Huygens correctly interpreted this discrepancy.

- The Io passed into Jupiter’s shadow at the predicted time.
- The light did not arrive until it had traveled the extra distance across the diameter of Earth’s orbit.
- This distance is now known to be 300,000,000 km.
27.2 The Speed of Light

Using the travel time of 1000 s for light to move across Earth’s orbit makes the calculation of the speed of light quite simple:

\[
\text{speed of light} = \frac{d}{t} = \frac{\text{extra distance traveled}}{\text{extra time measured}}
\]

\[= \frac{300,000,000 \text{ km}}{1000 \text{ s}} = 300,000 \text{ km/s}\]

The speed of light is 300,000 km/s.

Light travels a million times faster than sound.
27.2 The Speed of Light

Albert Michelson

The most famous experiment measuring the speed of light was performed by the American physicist Albert Michelson in 1880.

- Light was directed by a lens to an octagonal mirror.
- A beam of light was reflected to a stationary mirror on a mountain 35 km away and then reflected back.
- The distance was known, so Michelson had to find only the time it took to make a round trip.
27.2 The Speed of Light

- When the mirror was spun, short bursts of light reached the stationary mirror and were reflected back to the spinning octagonal mirror.
- If the rotating mirror made one-eighth rotation while the light made the trip, the mirror reflected light to the observer.
- If the mirror was rotated too slowly or too quickly, it would not be in a position to reflect light.
27.2 The Speed of Light

a. Light is reflected back to the eyepiece when the mirror is at rest.
27.2 The Speed of Light

a. Light is reflected back to the eyepiece when the mirror is at rest.
b. Reflected light fails to enter the eyepiece when the mirror spins too slowly . . .
27.2 The Speed of Light

- Light is reflected back to the eyepiece when the mirror is at rest.
- Reflected light fails to enter the eyepiece when the mirror spins too slowly . . .
- . . . or too fast.
27.2 The Speed of Light

a. Light is reflected back to the eyepiece when the mirror is at rest.
b. Reflected light fails to enter the eyepiece when the mirror spins too slowly . . .
c. . . or too fast.
d. When the mirror rotates at the correct speed, light reaches the eyepiece.
27.2 The Speed of Light

When the light entered the eyepiece, the time for the light to make the trip and the time for the mirror to make one eighth of a rotation were the same. Michelson divided the 70-km round trip distance by this time and found the speed of light was 299,920 km/s, which is usually rounded to 300,000 km/s. Michelson received the 1907 Nobel Prize in physics for this experiment.
27.2 The Speed of Light

The speed of light in a vacuum is a universal constant. Light is so fast that if a beam of light could travel around Earth, it would make 7.5 trips in one second. Light takes 8 minutes to travel from the sun to Earth and 4 years from the next nearest star, Alpha Centauri. The distance light travels in one year is called a light-year.
think!

Light entered the eyepiece when Michelson’s octagonal mirror made exactly one eighth of a rotation during the time light traveled to the distant mountain and back. Would light enter the eyepiece if the mirror turned one quarter of a rotation in this time?
27.2 The Speed of Light

**think!**

Light entered the eyepiece when Michelson’s octagonal mirror made exactly one eighth of a rotation during the time light traveled to the distant mountain and back. Would light enter the eyepiece if the mirror turned one quarter of a rotation in this time?

**Answer:**

Yes, light would enter the eyepiece whenever the octagonal mirror turned in multiples of 1/8 rotation—¼, ½, 1, etc.—in the time the light made its round trip.
What was Michelson’s experimental value for the speed of light?
27.3 Electromagnetic Waves

The electromagnetic spectrum consists of radio waves, microwaves, infrared, light, ultraviolet rays, X-rays, and gamma rays.
27.3 Electromagnetic Waves

Light is energy that is emitted by accelerating electric charges—often electrons in atoms. This energy travels in a wave that is partly electric and partly magnetic. Such a wave is an **electromagnetic wave**.
27.3 Electromagnetic Waves

Light is a portion of the family of electromagnetic waves that includes radio waves, microwaves, and X-rays. The range of electromagnetic waves is called the electromagnetic spectrum.
27.3 Electromagnetic Waves

The lowest frequency of light we can see appears red. The highest visible light, violet, has nearly twice the frequency of red light.

Electromagnetic waves of frequencies lower than the red of visible light are called **infrared**. Heat lamps give off infrared waves.

Electromagnetic waves of frequencies higher than those of violet are called **ultraviolet**. They are responsible for sunburns.
27.3 Electromagnetic Waves

What are the waves of the electromagnetic spectrum?
27.4 Light and Transparent Materials

Light passes through materials whose atoms absorb the energy and immediately reemit it as light.
27.4 Light and Transparent Materials

Light is energy carried in an electromagnetic wave, generated by vibrating electric charges. When light strikes matter, electrons in the matter are forced into vibration.
27.4 Light and Transparent Materials

Just as a sound wave can force a sound receiver into vibration, a light wave can force charged particles in materials into vibration.
27.4 Light and Transparent Materials

Exactly how a material responds to light depends on the frequency of light and the natural frequency of electrons in the material.

Visible light vibrates at a very high rate, more than 100 trillion times per second ($10^{14}$ hertz).

To respond to these ultrafast vibrations, a particle must have very little inertia. Electrons, with their small mass, can vibrate this fast.
27.4 Light and Transparent Materials

Materials that transmit light are **transparent**. Glass and water are transparent.

Materials that are springy (elastic) respond more to vibrations at some frequencies than at others.

The natural vibration frequencies of an electron depend on how strongly it is attached to a nearby nucleus.
27.4 Light and Transparent Materials

The electrons of atoms in glass can be imagined to be bound to the atomic nucleus as if connected by springs.
27.4 Light and Transparent Materials

Electrons in glass have a natural vibration frequency in the ultraviolet range.

- In ultraviolet light, resonance occurs as the wave builds a large vibration between the electron and the nucleus.
- The energy received by the atom can be either passed on to neighboring atoms by collisions or reemitted as light.
- If ultraviolet light interacts with an atom that has the same natural frequency, the vibration amplitude is unusually large.
27.4 Light and Transparent Materials

The atom typically holds on to this energy for about 1 million vibrations or 100 millionths of a second. During this time, the atom makes many collisions with other atoms and gives up its energy in the form of heat. That’s why glass is not transparent to ultraviolet.
27.4 Light and Transparent Materials

When the electromagnetic wave has a lower frequency than ultraviolet, as visible light does, the electrons are forced into vibration with smaller amplitudes.

- The atom holds the energy for less time, with less chance of collision with neighboring atoms.
- Less energy is transferred as heat.
- The energy of the vibrating electrons is reemitted as transmitted light.
27.4 Light and Transparent Materials

Glass is transparent to all the frequencies of visible light. The frequency of the reemitted light is identical to that of the light that produced the vibration to begin with. The main difference is a slight time delay between absorption and reemission. This time delay results in a lower average speed of light through a transparent material.
A light wave incident upon a pane of glass sets up vibrations in the atoms. Because of the time delay between absorptions and reemissions, the average speed of light in glass is less than $c$. 

27.4 Light and Transparent Materials
27.4 Light and Transparent Materials

In a vacuum, the speed of light is a constant 300,000 km/s; we call this speed of light \( c \).

- Light travels slightly less than \( c \) in the atmosphere, but the speed is usually rounded to \( c \).
- In water, light travels at 75% of its speed in a vacuum, \( 0.75c \).
- In glass, light travels at about \( 0.67c \), depending on glass type.
- In a diamond, light travels at only \( 0.40c \).

When light emerges from these materials into the air, it travels at its original speed, \( c \).
27 Light

27.4 Light and Transparent Materials

Infrared waves, with frequencies lower than visible light, vibrate not only the electrons, but also the entire structure of the glass.

This vibration of the structure increases the internal energy of the glass and makes it warmer.

Glass is transparent to visible light, but not to ultraviolet and infrared light.
27.4 Light and Transparent Materials

What kind of materials does light pass through?
27.5 Opaque Materials

In opaque materials, any coordinated vibrations given by light to the atoms and molecules are turned into random kinetic energy—that is, into internal energy.
27.5 Opaque Materials

Materials that absorb light without reemission and thus allow no light through them are **opaque**.

Wood, stone, and people are opaque.

In opaque materials, any vibrations from light are turned into random kinetic energy—that is, into internal energy. The materials become slightly warmer.
27.5 Opaque Materials

Metals are also opaque.
In metals, the outer electrons of atoms are not bound to any particular atom.
When light shines on metal and sets these free electrons into vibration, their energy does not “spring” from atom to atom.
It is reemitted as visible light. This reemitted light is seen as a reflection. That’s why metals are shiny.
27.5 Opaque Materials

Our atmosphere is transparent to visible light and some infrared, but almost opaque to high-frequency ultraviolet waves.

The ultraviolet that gets through is responsible for sunburns.

Clouds are semitransparent to ultraviolet, so you can get a sunburn on a cloudy day.

Ultraviolet also reflects from sand and water, so you can sometimes get a sunburn while in the shade of a beach umbrella.
27.5 Opaque Materials

think!

Why is glass transparent to visible light but opaque to ultraviolet and infrared?
think!

Why is glass transparent to visible light but opaque to ultraviolet and infrared?

*Answer:*

The natural frequency of vibration for electrons in glass matches the frequency of ultraviolet light, so resonance in the glass occurs when ultraviolet waves shine on it. These vibrations generate heat instead of wave reemission, so the glass is opaque to ultraviolet. In the range of visible light, the forced vibrations of electrons in the glass result in reemission of light, so the glass is transparent. Lower-frequency infrared causes entire atomic structures to resonate so heat is generated, and the glass is opaque.
27.5 Opaque Materials

Why does light not pass through opaque materials?
27.6 Shadows

When light shines on an object, some of the rays may be stopped while others pass on in a straight-line path.
27.6 Shadows

A thin beam of light is often called a ray. Any beam of light—no matter how wide—can be thought of as made of a bundle of rays. A shadow is formed where light rays cannot reach.
27.6 Shadows

Sharp shadows are produced by a small light source nearby or by a larger source farther away. However, most shadows are somewhat blurry, with a dark part on the inside and a lighter part around the edges.

A total shadow is called an **umbra**.

A partial shadow is called a **penumbra**. A penumbra appears where some of the light is blocked but where other light fills in.
27.6 Shadows

A large light source produces a softer shadow than a smaller source.
27.6 Shadows

a. An object held close to a wall casts a sharp shadow.
27.6 Shadows

a. An object held close to a wall casts a sharp shadow.

b. As the object is moved farther away, penumbras are formed and cut down on the umbra.
27.6 Shadows

a. An object held close to a wall casts a sharp shadow.

b. As the object is moved farther away, penumbras are formed and cut down on the umbra.

c. When it is very far away, all the penumbras mix together into a big blur.
27.6 Shadows

A penumbra occurs when the moon passes between Earth and the sun—during a solar eclipse.
The moon’s shadow barely reaches Earth.
If you stand in the umbra shadow, you experience brief darkness during the day.
If you stand in the penumbra, you experience a partial eclipse. The sunlight is dimmed, and the sun appears as a crescent.
27.6 Shadows

Earth, like most objects in sunlight, casts a shadow. This shadow extends into space, and sometimes the moon passes into it. When this happens, we have a lunar eclipse. A lunar eclipse can be seen by all observers on the nighttime half of Earth.
Shadows also occur when light is bent in passing through a transparent material such as water. Light travels at slightly different speeds in warm and in cold water.

The change in speed causes light to bend, just as layers of warm and cool air in the night sky bend starlight and cause twinkling.

Some light gets deflected a bit and leaves darker places on the wall. The shapes of the shadows depend on how the light is bent.
27.6 Shadows

A heater at the tip of this submerged J-tube produces convection currents in the water. They are revealed by shadows cast by light that is deflected differently by the water of different temperatures.
27.6 Shadows

think!
Why are lunar eclipses more commonly seen than solar eclipses?
27.6 Shadows

think!

Why are lunar eclipses more commonly seen than solar eclipses?

Answer:

There are usually two of each every year. However, the shadow of the moon on Earth is very small compared with the shadow of Earth on the moon. Only a relatively few people are in the shadow of the moon (solar eclipse), while everybody who views the nighttime sky can see the shadow of Earth on the moon (lunar eclipse).
27.6 Shadows

What causes the formation of shadows?
27.7 Polarization

Light that reflects at glancing angles from nonmetallic surfaces, such as glass, water, or roads, vibrates mainly in the plane of the reflecting surface.
27.7 Polarization

Light travels in waves. The fact that the waves are transverse—and not longitudinal—is demonstrated by the phenomenon of **polarization**.

- If you shake the end of a horizontal rope, a transverse wave travels along the rope.
- The vibrations are back and forth in one direction.
- The wave is said to be polarized.
27.7 Polarization

If the rope is shaken up and down, a vertically polarized wave is produced. The waves traveling along the rope are confined to a vertical plane.
27.7 Polarization

If the rope is shaken up and down, a vertically polarized wave is produced. The waves traveling along the rope are confined to a vertical plane. If the rope is shaken from side to side, a horizontally polarized wave is produced.
27.7 Polarization

A vibrating electron emits a polarized electromagnetic wave. A vertically vibrating electron emits vertically polarized light.
27.7 Polarization

A vibrating electron emits a polarized electromagnetic wave. A vertically vibrating electron emits vertically polarized light. A horizontally vibrating electron emits horizontally polarized light.
27.7 Polarization

An incandescent or fluorescent lamp, a candle flame, or the sun all emit light that is not polarized. The electrons that produce the light vibrate in random directions.
27.7 Polarization

When light shines on a polarizing filter, the light that is transmitted is polarized.

The filter is said to have a polarization axis that is in the direction of the vibrations of the polarized light wave. Light passes through two polarizing filters when the polarization axes are aligned but not when they are crossed at right angles.
27.7 Polarization

A rope analogy illustrates the effect of crossed sheets of polarizing material.
27.7 Polarization

Try skipping flat stones across the surface of a pond.

- Stones with flat sides parallel to the water bounce ("reflect").
- Stones with flat sides at right angles to the surface penetrate the water ("refract").
- Light behaves similarly. The flat side of a stone is like the plane of vibration of polarized light.

Light reflecting from nonmetallic surfaces, such as glass, water, or roads, vibrates mainly in the plane of the reflecting surface.
27.7 **Polarization**

So glare from a horizontal surface is horizontally polarized. The axes of polarized sunglasses are vertical so that glare from horizontal surfaces is eliminated.

Polarization tells us whether a wave is transverse or longitudinal. Polarization occurs for a transverse wave only.
27.7 Polarization

a. Light is transmitted when the axes of the polarizing filters are aligned.
27.7 Polarization

a. Light is transmitted when the axes of the polarizing filters are aligned.
b. Light is absorbed when they are at right angles to each other.
27.7 Polarization

a. Light is transmitted when the axes of the polarizing filters are aligned.
b. Light is absorbed when they are at right angles to each other.
c. Surprisingly, when a third filter is sandwiched between the two crossed ones, light is transmitted. (The explanation involves vectors!)
27.7 Polarization

Why is glare from a horizontal surface horizontally polarized?
A pair of photographs or movie frames, taken a short distance apart (about average eye spacing), can be seen in 3-D when the left eye sees only the left view and the right eye sees only the right view.
27.8 Polarized Light and 3-D Viewing

Vision in three dimensions depends on both eyes giving impressions simultaneously from slightly different angles.

The combination of views in the eye-brain system gives depth.

A pair of photographs taken a short distance apart is seen in 3-D when the left eye sees only the left view and the right eye sees only the right view.
27.8 Polarized Light and 3-D Viewing

Slide shows or movies can project a pair of views through polarization filters onto a screen with their polarization axes at right angles to each other. The overlapping pictures look blurry to the naked eye. To see in 3-D, the viewer wears polarizing eyeglasses with the lens axes also at right angles. Each eye sees a separate picture. The brain interprets the two pictures as a single picture with a feeling of depth.
27.8 Polarized Light and 3-D Viewing

A 3-D slide show uses polarizing filters. The left eye sees only polarized light from the left projector; the right eye sees only polarized light from the right projector.
27.8 Polarized Light and 3-D Viewing

Depth is also seen in computer-generated stereograms. In computer-generated stereograms, the slightly different patterns are hidden from a casual view. In your book, you can view the message of Figure 27.20 with the procedure for viewing Figure 27.18. Once you’ve mastered the viewing technique, head for the local mall and check the variety of stereograms in posters and books.
27.8 Polarized Light and 3-D Viewing

think!

Which pair of glasses is best suited for automobile drivers? (The polarization axes are shown by the straight lines.)
27.8 Polarized Light and 3-D Viewing

think!

Which pair of glasses is best suited for automobile drivers? (The polarization axes are shown by the straight lines.)

Answer:

Pair A is best suited because the vertical axes block horizontally polarized light that compose much of the glare from horizontal surfaces. (Pair C is suited for viewing 3-D movies.)
27.8 Polarized Light and 3-D Viewing

Try these optical illusions.

Are the vertical lines parallel?
27.8 Polarized Light and 3-D Viewing

Do these lines move?
27.8 Polarized Light and 3-D Viewing

What does this sign read?

PARIS IN THE SPRING
27.8 Polarized Light and 3-D Viewing

How can you see photographs or movies in 3-D?
Assessment Questions

1. Scientists now agree that light is composed of
   a. only electromagnetic waves.
   b. only photons.
   c. electromagnetic waves and particles called photons.
   d. an unknown source.
Assessment Questions

1. Scientists now agree that light is composed of
   a. only electromagnetic waves.
   b. only photons.
   c. electromagnetic waves and particles called photons.
   d. an unknown source.

   Answer: C
27 Light

Assessment Questions

2. The time it takes light to travel across the orbit of Earth is about
   a. less than a second.
   b. 8 minutes.
   c. 22 minutes.
   d. 4 years.
2. The time it takes light to travel across the orbit of Earth is about
   a. less than a second.
   b. 8 minutes.
   c. 22 minutes.
   d. 4 years.

Answer: C
Assessment Questions

3. All of the following are part of the electromagnetic spectrum EXCEPT
   a. light.
   b. sound.
   c. radio waves.
   d. X-rays.
3. All of the following are part of the electromagnetic spectrum EXCEPT
   a. light.
   b. sound.
   c. radio waves.
   d. X-rays.

Answer: B
Assessment Questions

4. Strictly speaking, the photons of light that shine on glass are
   a. the ones that travel through and exit the other side.
   b. not the ones that travel through and exit the other side.
   c. absorbed and transformed to thermal energy.
   d. reflected.
Assessment Questions

4. Strictly speaking, the photons of light that shine on glass are
   a. the ones that travel through and exit the other side.
   b. not the ones that travel through and exit the other side.
   c. absorbed and transformed to thermal energy.
   d. reflected.

Answer: B
Assessment Questions

5. Light that is not transmitted by opaque materials is
   a. converted to internal energy in the material.
   b. mainly reflected.
   c. mainly refracted.
   d. transmitted at a lower frequency.
Assessment Questions

5. Light that is not transmitted by opaque materials is
   a. converted to internal energy in the material.
   b. mainly reflected.
   c. mainly refracted.
   d. transmitted at a lower frequency.

Answer: A
Assessment Questions

6. When the shadow of the moon falls on Earth we have a
   a. lunar eclipse.
   b. solar eclipse.
   c. solar eclipse if it’s daytime and lunar eclipse if it’s nighttime.
   d. very dangerous event.
Assessment Questions

6. When the shadow of the moon falls on Earth we have a
   a. lunar eclipse.
   b. solar eclipse.
   c. solar eclipse if it’s daytime and lunar eclipse if it’s nighttime.
   d. very dangerous event.

Answer: B
Assessment Questions

7. Polarization occurs when waves of light are
   a. undergoing interference.
   b. longitudinal.
   c. aligned.
   d. in harmony.
Assessment Questions

7. Polarization occurs when waves of light are
   a. undergoing interference.
   b. longitudinal.
   c. aligned.
   d. in harmony.

Answer: C
Assessment Questions

8. The best way to view something in 3-D is to
   a. have keen eyesight.
   b. use two eyes.
   c. use only one eye.
   d. be slightly cross-eyed.
Assessment Questions

8. The best way to view something in 3-D is to
   a. have keen eyesight.
   b. use two eyes.
   c. use only one eye.
   d. be slightly cross-eyed.

Answer: B
The colors of the objects depend on the color of the light that illuminates them.
Color is in the eye of the beholder and is provoked by the frequencies of light emitted or reflected by things. We see red in a rose when light of certain frequencies reaches our eyes. Many organisms, including people with defective color vision, see no red in a rose.
By passing a narrow beam of sunlight through a triangular-shaped glass prism, Newton showed that sunlight is composed of a mixture of all the colors of the rainbow.
28.1 The Color Spectrum

Isaac Newton was the first to make a systematic study of color. Passing sunlight through a glass prism, Newton showed that sunlight is composed of a mixture of all the colors of the rainbow.

Newton called this spread of colors a **spectrum**, and noted that the colors were formed in the order red, orange, yellow, green, blue, and violet.
28.1 The Color Spectrum

Sunlight is an example of what is called white light. White light is a combination of all the colors. Under white light, white objects appear white and colored objects appear in their individual colors.
28.1 The Color Spectrum

Newton showed that the colors in the spectrum were a property not of the prism but of white light itself. He recombined the colors with a second prism to produce white light again.

In other words, all the colors, one atop the other, combine to produce white light.

White is not a color but a combination of all colors.
28.1 The Color Spectrum

When sunlight passes through a prism, it separates into a spectrum of all the colors of the rainbow.
28.1 The Color Spectrum

Black is similarly not a color, but is the absence of light. Objects appear black when they absorb light of all visible frequencies.

Even a polished surface may look black under some conditions.

Highly polished razor blades stacked together and viewed end on appear black. Light that gets between the closely spaced edges of the blades gets trapped and is absorbed after being reflected many times.
28.1 The Color Spectrum

Black objects that you can see do not absorb all light that falls on them, for there is always some reflection at the surface. If not, you wouldn’t be able to see them.
How did Isaac Newton show that sunlight is composed of a mixture of all colors of the rainbow?
28.2 Color by Reflection

The color of an opaque object is the color of the light it reflects.
28.2 Color by Reflection

The colors of most objects around you are due to the way the objects reflect light.

The color of an opaque object is the color of the light it reflects.

Light reflects from objects similar to the way sound “reflects” from a tuning fork when another sets it into vibration.
28.2 Color by Reflection

We can think of atoms and molecules as three-dimensional tuning forks.

Electrons behave as tiny oscillators in orbits around the nuclei.

Electrons can be forced temporarily into larger orbits by the vibrations of electromagnetic waves.

Like tuning forks, once excited to more vigorous motion, electrons send out their own energy waves in all directions.
28.2 Color by Reflection

Differences Among Materials

Different materials have different natural frequencies for absorbing and emitting radiation.

At the resonant frequencies where the amplitudes of oscillation are large, light is absorbed.

At frequencies below and above the resonant frequencies, light is reemitted.
28.2 Color by Reflection

If the material is transparent, the reemitted light passes through it.

If the material is opaque, the light passes back into the medium from which it came. This is reflection.

Most materials absorb light of some frequencies and reflect the rest.

If a material absorbs light of most visible frequencies and reflects red, for example, the material appears red.
28.2 Color by Reflection

a. This square *reflects* all the colors illuminating it. In sunlight, it is white. When illuminated with blue light, it is blue.
28.2 Color by Reflection

a. This square *reflects* all the colors illuminating it. In sunlight, it is white. When illuminated with blue light, it is blue.

b. This square *absorbs* all the colors illuminating it. In sunlight it is warmer than the white square.
28.2 Color by Reflection

When white light falls on a flower, light of some frequencies is absorbed by the cells in the flower and some light is reflected.

Cells that contain chlorophyll absorb light of most frequencies and reflect the green part, so they appear green.

The petals of a red rose, on the other hand, reflect primarily red light, with a lesser amount of blue.
28.2 Color by Reflection

Petals of most yellow flowers, such as daffodils, reflect red and green as well as yellow. Yellow daffodils reflect light of a broad band of frequencies. The reflected colors of most objects are not pure single-frequency colors, but a spread of frequencies. So something yellow, for example, may simply be a mixture of colors without blue and violet—or it can be red and green together.
28.2 Color by Reflection

Light Sources

The color of an object depends on the kind of light used.

- A candle flame is deficient in higher frequencies; it emits a yellowish light. Things look yellowish in candlelight.
- An incandescent lamp emits light of all the visible frequencies, but is richer toward the lower frequencies, enhancing the reds.
- A fluorescent lamp is richer in the higher frequencies, so blues are enhanced when illuminated with fluorescent lamps.
28.2 Color by Reflection

think!

When red light shines on a red rose, why do the leaves become warmer than the petals?
28.2 Color by Reflection

**think!**

When red light shines on a red rose, why do the leaves become warmer than the petals?

*Answer:*

The leaves absorb rather than reflect red light, so the leaves become warmer.
28.2 Color by Reflection

think!

When green light shines on a red rose, why do the petals look black?
think!
When green light shines on a red rose, why do the petals look black?

Answer:
The petals absorb rather than reflect the green light. So, the rose appears to have no color at all—black.
28.2 Color by Reflection

What determines the color of an opaque object?
28.3 **Color by Transmission**

The color of a transparent object is the color of the light it transmits.
28.3 Color by Transmission

A red piece of glass appears red because it absorbs all the colors that compose white light, except red, which it transmits. A blue piece of glass appears blue because it transmits primarily blue and absorbs the other colors that illuminate it.
28.3 Color by Transmission

Blue glass transmits only energy of the frequency of blue light; energy of the other frequencies is absorbed and warms the glass.
28.3 Color by Transmission

The material in the glass that selectively absorbs colored light is known as a **pigment**.

Electrons in the pigment atoms selectively absorb light of certain frequencies in the illuminating light.

Other frequencies are reemitted from atom to atom in the glass.

Ordinary window glass is colorless because it transmits light of all visible frequencies equally well.
28.3 Color by Transmission

What determines the color of a transparent object?
28.4 Sunlight

Yellow-green light is the brightest part of sunlight.
28.4 Sunlight

White light from the sun is a composite of all the visible frequencies. The brightness of solar frequencies is uneven.

The lowest frequencies of sunlight, in the red region, are not as bright as those in the middle-range yellow and green region.

Humans evolved in the presence of sunlight and we are most sensitive to yellow-green.

The blue portion of sunlight is not as bright, and the violet portion is even less bright.
28.4 Sunlight

The radiation curve of sunlight is a graph of brightness versus frequency. Sunlight is brightest in the yellow-green region.
28.4 Sunlight

Which visible frequencies make up the brightest part of sunlight?
28.5 Mixing Colored Light

You can make almost any color at all by overlapping red, green, and blue light and adjusting the brightness of each color of light.
28.5 Mixing Colored Light

Light of all the visible frequencies mixed together produces white.

- White also results from the combination of only red, green, and blue light.
- Red and green light alone overlap to form yellow.
- Red and blue light alone produce the bluish-red color called magenta.
- Green and blue light alone produce the greenish-blue color called cyan.
28.5 Mixing Colored Light

When red light, green light, and blue light of equal brightness are projected on a white screen, the overlapping areas appear different colors.
28.5 Mixing Colored Light

The frequencies of white light can be divided into three regions:

- the lower-frequency red end
- the middle-frequency green part
- the higher-frequency blue end

Low and middle frequencies combine to form yellow to the human eye. The middle and high frequencies appear greenish blue (cyan). The low and high frequencies appear bluish red (magenta).
28.5 Mixing Colored Light

The low-frequency, middle-frequency, and high-frequency parts of white light appear red, green, and blue.

To the human eye, red + green = yellow; red + blue = magenta; green + blue = cyan.
28.5 Mixing Colored Light

This amazing phenomenon is due to the way the human eye works.

The three colors do not have to be red, green, and blue, although those three produce the highest number of different colors.

For this reason, red, green, and blue are called the additive primary colors.
28.5 Mixing Colored Light

Color television is based on the ability of the human eye to see combinations of three colors as a variety of different colors. The picture is made up of tiny spots, each less than a millimeter across. When the screen is lit, some of the spots are red, some green, and some blue. At a distance the mixtures of these colors provide a complete range of colors, plus white.
28.5 Mixing Colored Light

think!

What color does red light plus blue light make?
28.5 Mixing Colored Light

think!
What color does red light plus blue light make?

Answer:
Magenta
28.5 Mixing Colored Light

Which three visible frequencies combine to form almost any color?
28.6 Complementary Colors

Every color has some complementary color that when added to it will produce white.
28.6 Complementary Colors

When two of the three additive primary colors are combined:

- red + green = yellow
- red + blue = magenta
- blue + green = cyan

When we add in the third color, we get white:

- yellow + blue = white
- magenta + green = white
- cyan + red = white
28.6 Complementary Colors

When two colors are added together to produce white, they are called **complementary colors**.

Yellow and blue are complementary because yellow is the combination of red and green.

Red, green, and blue light together appear white.

By similar reasoning we see that magenta and green are complementary colors, as are cyan and red.
28.6 Complementary Colors

Six blocks and their shadows appear as different colors depending on the color of light that illuminates them.

- a The blocks are lit by white light.
- b The blocks are lit by red light from the right and green light from the left.
- c The blocks are lit by blue light.
- d The blocks are lit by blue light from the left and red light from the right.
28.6 Complementary Colors

Begin with white light and *subtract* some color from it. The resulting color appears to be the complement of the one subtracted.

Some of the light incident upon an object is absorbed. The part that is absorbed is in effect subtracted from the incident light.

For example, if white light falls on a pigment that absorbs red light, the light reflected appears cyan.

Subtract a color from white light and you have the complementary color.
28.6 Complementary Colors

When white light passes through all three transparencies, light of all frequencies is blocked (subtracted) and we have black.
28.6 Complementary Colors

think!

What color does white light minus yellow light appear?
28.6 Complementary Colors

Think!
What color does white light minus yellow light appear?

Answer:
Blue
28.6 Complementary Colors

think!

What color does white light minus green light appear?
28.6 Complementary Colors

think!
What color does white light minus green light appear?

*Answer:* Magenta
What happens when you combine any color with its complementary color?
When paints or dyes are mixed, the mixture absorbs all the frequencies each paint or dye absorbs.
28.7 Mixing Colored Pigments

Red and green paint do not combine to form yellow as red and green light do.

The mixing of paints and dyes is an entirely different process from the mixing of colored light.

Paints and dyes contain particles of pigment that produce colors by absorbing light of certain frequencies and reflecting others.
28.7 Mixing Colored Pigments

When paints or dyes are mixed, the mixture absorbs all the frequencies each paint or dye absorbs. Blue paint, for example, reflects mostly blue light, but also violet and green; it absorbs red, orange, and yellow light. Yellow paint reflects mostly yellow light, but also red, orange, and green; it absorbs blue and violet light.
28.7 Mixing Colored Pigments

When blue and yellow paints are mixed, then between them they absorb all the colors except green. This process is called color mixing by subtraction.
28.7 Mixing Colored Pigments

Mixing colored light is called *color mixing by addition*. When you cast lights on a stage, you use the rules of color addition, but when you mix paint, you use the rules of color subtraction.
28.7 Mixing Colored Pigments

The three colors most useful in color mixing by subtraction are:

- magenta (bluish red)
- yellow
- cyan (greenish blue)

Magenta, yellow, and cyan are the **subtractive primary colors**, used in printing illustrations in full color.
# 28.7 Mixing Colored Pigments

<table>
<thead>
<tr>
<th>Pigment</th>
<th>Absorbs</th>
<th>Reflects</th>
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<tbody>
<tr>
<td>red</td>
<td>blue, green</td>
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<td>green</td>
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<td>blue</td>
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<td>yellow</td>
<td>blue</td>
<td>red, green</td>
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<tr>
<td>cyan</td>
<td>red</td>
<td>green, blue</td>
</tr>
<tr>
<td>magenta</td>
<td>green</td>
<td>red, blue</td>
</tr>
</tbody>
</table>
28.7 Mixing Colored Pigments

Color printing is done on a press that prints each page with four differently colored inks (magenta, yellow, cyan, and black).

- Each color of ink comes from a different plate, which transfers the ink to the paper.
- The ink deposits are regulated on different parts of the plate by tiny dots.
- The overlapping dots of three colors plus black give the appearance of many colors.
28.7 Mixing Colored Pigments

Only four colors of ink are used to print color illustrations and photographs—magenta, yellow, cyan, and black.

a. magenta  
b. yellow  
c. cyan  
d. magenta + yellow + cyan  
e. black  
f. magenta + yellow + cyan + black
28.7 Mixing Colored Pigments

Which visible frequencies are absorbed by a mixture of paints or dyes?
28.8 Why the Sky Is Blue

The sky is blue because its component particles scatter high-frequency light.
28.8 Why the Sky Is Blue

Scattering is a process in which sound or light is absorbed and reemitted in all directions. Light is scattered by molecules and larger specks of matter that are far apart from one another in the atmosphere.

There are no blue pigments in the feathers of a blue jay. Instead there are tiny alveolar cells in the barbs of its feather that scatter light—mainly high-frequency light. So a blue jay is blue for the same reason the sky is blue scattering.
28.8 Why the Sky Is Blue

A beam of light falls on an atom and causes the electrons in the atom to move temporarily in larger orbits. The more vigorously oscillating electrons reemit light in various directions.
28.8 Why the Sky Is Blue

The Sky

Atoms and molecules reemit light waves. Very tiny particles do the same.

The nitrogen and oxygen molecules and the tiny particles that make up the atmosphere are like tiny bells that “ring” with high frequencies when energized by sunlight.

Like the sound from bells, the light is sent in all directions.
28.8 Why the Sky Is Blue

Most ultraviolet light is absorbed by a layer of ozone gas in the upper atmosphere. The rest is scattered by atmospheric particles and molecules.
28.8 Why the Sky Is Blue

Of the visible frequencies, violet light is scattered the most, followed by blue, green, yellow, orange, and red, in that order.

- Violet light is scattered more than blue but our eyes are not very sensitive to violet light.
- Our eyes are more sensitive to blue, so we see a blue sky.
28.8 Why the Sky Is Blue
28.8 Why the Sky Is Blue

The blue of the sky varies under different conditions. Where there are a lot of particles larger than oxygen and nitrogen molecules, the lower frequencies of light are scattered more. This makes the sky less blue, and it takes on a whitish appearance. After a heavy rainstorm, when the particles have been washed away, the sky becomes a deeper blue.
28.8 Why the Sky Is Blue

The higher that one goes into the atmosphere, the fewer molecules there are in the air to scatter light. The sky appears darker.
When there are no molecules, as on the moon, for example, the “sky” is black.
The Clouds

Water droplets in a variety of sizes—some of them microscopic—make up clouds. The different-size droplets result in a variety of frequencies for scattered light: low frequencies from larger droplets and high frequencies from tinier droplets of water molecules. The overall result is a white cloud.
28.8 Why the Sky Is Blue

Why is the sky blue?
28.9 Why Sunsets Are Red

By the time a beam of light gets to the ground at sunset, all of the high-frequency light has already been scattered. Only the lower frequencies remain, resulting in a red sunset.
28 Color

28.9 Why Sunsets Are Red

The lower frequencies of light are scattered the least by nitrogen and oxygen molecules.

Red, orange, and yellow light are transmitted through the atmosphere more readily than violet and blue. Red light, which is scattered the least, passes through more atmosphere without interacting than light of any other color.

At dawn and at sunset, sunlight reaches us through a longer path through the atmosphere than at noon.
28.9 Why Sunsets Are Red

At noon sunlight travels through the least amount of atmosphere, so a relatively small amount of light is scattered.

As the sun is lower in the sky, the path through the atmosphere is longer, and more blue is scattered from the sunlight.

Less and less blue remains in the sunlight that reaches Earth.

The sun appears progressively redder, going from yellow to orange, and finally, red.
28.9 Why Sunsets Are Red

By the time a beam of sunlight gets to the ground at sunset, only the lower frequencies survive, producing a red sunset.
28.9 Why Sunsets Are Red

The colors of the sun and sky are consistent with our rules for color mixing.

- When blue is subtracted, the complementary color that is left is yellow.
- The subtraction of violet leaves orange.
- When green is subtracted, magenta is left.

The relative amounts of scattering depend on atmospheric conditions, changing from day to day for a variety of sunsets.
28.9 Why Sunsets Are Red
28.9 Why Sunsets Are Red

The sunset sky is red because of the absence of high-frequency light.

You see the scattered blue when the background is dark, but not when the background is bright because the scattered blue is faint.

When you look from Earth’s surface at the atmosphere against the darkness of space, the atmosphere is sky blue.

When astronauts look down through the same atmosphere to the bright surface of Earth, they do not see the same blueness.
28.9 Why Sunsets Are Red

think!

If molecules in the sky scattered low-frequency light more than high-frequency light, how would the colors of the sky and sunsets appear?
28.9 Why Sunsets Are Red

**think!**

If molecules in the sky scattered low-frequency light more than high-frequency light, how would the colors of the sky and sunsets appear?

**Answer:**

If low frequencies were scattered more, red light would be scattered out of the sunlight on its long path through the atmosphere at sunset, and the sunlight to reach your eye would be predominantly blue and violet.
28.9 Why Sunsets Are Red

think!

Distant dark mountains are bluish in color. What is the source of this blueness? (*Hint*: What is between you and the mountains you see?)
28.9 Why Sunsets Are Red

**think!**
Distant dark mountains are bluish in color. What is the source of this blueness? (*Hint:* What is between you and the mountains you see?)

**Answer:**
If you look at distant dark mountains, very little light from them reaches you, and the blueness of the atmosphere between you and the mountains predominates. The blueness is of the low-altitude “sky” between you and the mountains.
28.9 Why Sunsets Are Red

Why are sunsets red?
28.10 Why Water Is Greenish Blue

Water is greenish blue because water molecules absorb red.
28.10 Why Water Is Greenish Blue

We often see a beautiful deep blue when we look at the surface of a lake or the ocean. That is not the color of water. It is the reflected color of the sky.

The color of water itself, as you can see by looking at a piece of white material under water, is a pale greenish blue.
28.10 Why Water Is Greenish Blue

Ocean water is cyan because it absorbs red. The froth in the waves is white because its droplets of many sizes scatter many colors.
28.10 Why Water Is Greenish Blue

Water is transparent to nearly all the visible frequencies of light.

Water molecules absorb infrared waves because they resonate to the frequencies of infrared. The energy of the infrared waves is transformed into kinetic energy of the water molecules. Infrared is a strong component of the sunlight that warms water.
28.10 Why Water Is Greenish Blue

Water molecules resonate somewhat to the visible-red frequencies. This causes a gradual absorption of red light by water.

A 15-m layer of water reduces red light to a quarter of its initial brightness. There is very little red light in the sunlight that penetrates below 30 m of water.

The complementary color of red is cyan—a greenish-blue color. In seawater, everything at these depths looks greenish blue.
The sky is blue because blue from sunlight is reemitted in all directions by molecules in the atmosphere. Water is greenish blue because water molecules absorb red.

The colors of things depend on what colors are reflected by molecules, and also by what colors are absorbed by molecules.
28.10 Why Water Is Greenish Blue

**think!**

Distant snow-covered mountains reflect a lot of light and are bright. But they sometimes look yellowish, depending on how far away they are. Why are they yellow? *(Hint: What happens to the reflected white light as it travels from the mountain to you?)*
28.10 Why Water Is Greenish Blue

**think!**

Distant snow-covered mountains reflect a lot of light and are bright. But they sometimes look yellowish, depending on how far away they are. Why are they yellow? (*Hint:* What happens to the reflected white light as it travels from the mountain to you?)

**Answer:**

Distant snow-covered mountains often appear a pale yellow because the blue in the white light from the snowy mountains is scattered on its way to you. The complementary color left is yellow.
28.10 Why Water Is Greenish Blue

Why is water greenish blue?
After an excited atom emits light, it returns to its normal state.
Every element has its own characteristic color when it emits light.

The color is a blend of various frequencies of light. Light of each frequency is emitted when the electrons change energy states.

Electrons have well-defined energy levels—lower energy near the atomic nucleus and higher energy farther from the nucleus.

When an atom absorbs external energy, one or more of its electrons is boosted to a higher energy level.
The energized atom is in an excited state. An **excited state** is a state with greater energy than the atom’s lowest energy state.

The excited state is only momentary, for the electron is quickly drawn back to its original or a lower level.

When this electron transition occurs, the atom emits a pulse of light—a photon.
28.11 The Atomic Color Code—Atomic Spectra

Light is emitted by excited atoms.
28.11 The Atomic Color Code—Atomic Spectra

a. The different electron orbits in an atom are like steps in energy levels.
28.11 The Atomic Color Code—Atomic Spectra

a. The different electron orbits in an atom are like steps in energy levels.
b. When an electron is raised to a higher level, the atom is excited.
28.11 The Atomic Color Code—Atomic Spectra

a. The different electron orbits in an atom are like steps in energy levels.
b. When an electron is raised to a higher level, the atom is excited.
c. When the electron returns to its original level, it releases energy in the form of light.
28.11 The Atomic Color Code—Atomic Spectra

Relating Frequency and Energy

The frequency of the emitted photon, or its color, is directly proportional to the energy transition of the electron.

\[ f \sim E \]

A photon carries an amount of energy that corresponds to its frequency. Red light from neon gas, for example, carries a certain amount of energy. A photon of twice the frequency has twice as much energy and is found in the ultraviolet part of the spectrum.
When many atoms in a material are excited, many photons with many different frequencies are emitted. They correspond to electron transitions between different levels.

Measuring the frequencies of light in a spectrum is also measuring the relative energy levels in the atom emitting that light.

The frequencies, or colors, of light emitted by elements are the “fingerprints” of the elements.
28.11 The Atomic Color Code—Atomic Spectra

Analyzing Light

The light from glowing elements can be analyzed with an instrument called a **spectroscope**.

A spectroscope displays the spectra of the light from hot gases and other light sources. (*Spectra* is the plural of *spectrum*.)

The spectra of light sources are viewed through a magnifying eyepiece.
28.11 The Atomic Color Code—Atomic Spectra

A fairly pure spectrum is produced by passing white light through a thin slit, two lenses, and a prism.
28.11 The Atomic Color Code—Atomic Spectra

A spectroscope separates light into its constituent frequencies. Light illuminates the thin slit at the left, and then it is focused by lenses onto either a diffraction grating (shown) or a prism on the rotating table in the middle.
When light from a glowing element is analyzed through a spectroscope, the colors are the composite of a variety of different frequencies of light. The spectrum of an element appears not as a continuous band of color but as a series of lines. Each line corresponds to a distinct frequency of light in a line spectrum.
An incandescent bulb has a continuous spectrum. Three elements: hydrogen, sodium, and mercury have different line spectra.
28.11 The Atomic Color Code—Atomic Spectra

Much of the information that physicists have about atomic structure is from the study of atomic spectra. The atomic composition of common materials, the sun, and distant galaxies is revealed in the spectra of these sources. The element helium, the second most common element in the universe, was discovered through its “fingerprint” in sunlight.
What happens to an excited atom after it emits light?
Assessment Questions

1. Black is
   a. a combination of all the colors of the spectrum.
   b. a combination of two or more appropriate colors.
   c. light when a prism is held upside down.
   d. the absence of light.
Assessment Questions

1. Black is
   a. a combination of all the colors of the spectrum.
   b. a combination of two or more appropriate colors.
   c. light when a prism is held upside down.
   d. the absence of light.

Answer: D
Assessment Questions

2. To say that rose petals are red is to say that they
   a. absorb red.
   b. reflect red.
   c. emit red.
   d. transmit red.
Assessment Questions

2. To say that rose petals are red is to say that they
   a. absorb red.
   b. reflect red.
   c. emit red.
   d. transmit red.

Answer: B
Assessment Questions

3. The color light that gets through a piece of transparent blue glass is
   a. blue.
   b. yellow, the opposite color of blue.
   c. actually green.
   d. red minus magenta.
Assessment Questions

3. The color light that gets through a piece of transparent blue glass is
   a. blue.
   b. yellow, the opposite color of blue.
   c. actually green.
   d. red minus magenta.

Answer: A
Assessment Questions

4. The solar radiation curve is
   a. the path the sun takes at nighttime.
   b. a plot of amplitude versus frequency for sunlight.
   c. a plot of brightness versus frequency of sunlight.
   d. a plot of wavelength versus frequency of sunlight.
Assessment Questions

4. The solar radiation curve is
   a. the path the sun takes at nighttime.
   b. a plot of amplitude versus frequency for sunlight.
   c. a plot of brightness versus frequency of sunlight.
   d. a plot of wavelength versus frequency of sunlight.

Answer: C
Assessment Questions

5. When red and blue light are overlapped, the color produced is
   
   a. magenta.
   b. yellow.
   c. cyan.
   d. white.
Assessment Questions

5. When red and blue light are overlapped, the color produced is
   a. magenta.
   b. yellow.
   c. cyan.
   d. white.

Answer: A
Assessment Questions

6. The complementary color of blue is
   a. magenta.
   b. yellow.
   c. cyan.
   d. white.
Assessment Questions

6. The complementary color of blue is
   a. magenta.
   b. yellow.
   c. cyan.
   d. white.

Answer: B
For mixing pigments or dyes, the primary colors are magenta, cyan, and
a. red.

b. green.
c. yellow.
d. blue.
Assessment Questions

7. For mixing pigments or dyes, the primary colors are magenta, cyan, and
   a. red.
   b. green.
   c. yellow.
   d. blue.

Answer: C
The blueness of the daytime sky is due mostly to light
a. absorption.
b. transmission.
c. reflection.
d. scattering.
28 Color

Assessment Questions

8. The blueness of the daytime sky is due mostly to light
   a. absorption.
   b. transmission.
   c. reflection.
   d. scattering.

Answer: D
Assessment Questions

9. The redness of a sunrise or sunset is due mostly to light that has not been
   a. absorbed.
   b. transmitted.
   c. scattered.
   d. polarized.
Assessment Questions

9. The redness of a sunrise or sunset is due mostly to light that has not been
   a. absorbed.
   b. transmitted.
   c. scattered.
   d. polarized.

   Answer: C
Assessment Questions

10. The greenish blue of ocean water is due mostly to the absorption of
   a. infrared light.
   b. ultraviolet light.
   c. polarized light.
   d. scattered light.
Assessment Questions

10. The greenish blue of ocean water is due mostly to the absorption of
    a. infrared light.
    b. ultraviolet light.
    c. polarized light.
    d. scattered light.

Answer: A
Assessment Questions

11. The frequency of an emitted photon is related to its
   a. amplitude.
   b. polarization.
   c. momentum.
   d. energy.
Assessment Questions

11. The frequency of an emitted photon is related to its
   a. amplitude.
   b. polarization.
   c. momentum.
   d. energy.

Answer: D
When waves interact with matter, they can be reflected, transmitted, or a combination of both. Waves that are transmitted can be refracted.
Light doesn’t travel through a mirror, but is returned by the mirror’s surface. These waves are reflected. When waves strike the surface of a medium at an angle, their direction changes. These waves are refracted. Usually waves are partly reflected and partly refracted when they fall on a transparent medium.
29.1 Reflection

When a wave reaches a boundary between two media, usually some or all of the wave bounces back into the first medium.
29.1 Reflection

The return of a wave back to its original medium is called reflection. Fasten a spring to a wall and send a pulse along the spring’s length. The wall is a very rigid medium compared with the spring, so all the wave energy is reflected back along the spring. Waves that travel along the spring are almost *totally reflected* at the wall.
29.1 Reflection

If the wall is replaced with a less rigid medium, such as a heavy spring, some energy is transmitted into the new medium. Some of the wave energy is still reflected. The incoming wave is partially reflected.
29.1 Reflection

A metal surface is rigid to light waves that shine upon it. Light energy does not propagate into the metal, but instead is returned in a reflected wave.

This is why metals such as silver and aluminum are so shiny. They reflect almost all the frequencies of visible light.
Materials such as glass and water are not as rigid to light waves.

- When light shines perpendicularly on the surface of still water, about 2% of its energy is reflected and the rest is transmitted.
- When light strikes glass perpendicularly, about 4% of its energy is reflected.
- Except for slight losses, the rest is transmitted.
29.1 Reflection

What happens when a wave reaches a boundary between two media?
29.2 The Law of Reflection

The law of reflection states that the angle of incidence and the angle of reflection are equal to each other.
29.2 The Law of Reflection

In one dimension, reflected waves simply travel back in the direction from which they came.

In two dimensions, the situation is a little different. The direction of incident and reflected waves is described by straight-line rays.
29.2 The Law of Reflection

Incident rays and reflected rays make equal angles with a line perpendicular to the surface, called the normal.

- The angle between the incident ray and the normal is the angle of incidence.
- The angle between the reflected ray and the normal is the angle of reflection.
- Angle of incidence = Angle of reflection
29.2 The Law of Reflection

The law of reflection states that the angle of incidence and the angle of reflection are equal to each other. The incident ray, the normal, and the reflected ray all lie in the same plane. The law of reflection applies to both partially reflected and totally reflected waves.
think!

If you look at your blue shirt in a mirror, what is the color of its image? What does this tell you about the frequency of light incident upon a mirror compared with the frequency of the light after it is reflected?
29.2 The Law of Reflection

**think!**

If you look at your blue shirt in a mirror, what is the color of its image? What does this tell you about the frequency of light incident upon a mirror compared with the frequency of the light after it is reflected?

**Answer:**

The color of the image will be the same as the color of the object because the frequency of light is not changed by reflection.
29.2 The Law of Reflection

What is the law of reflection?
29.3 Mirrors

Mirrors produce only virtual images.
29.3 Mirrors

If a candle flame is placed in front of a plane (flat) mirror, rays of light from the candle are reflected from the mirror in all directions.

- Each of the infinite number of rays obeys the law of reflection.
- The rays diverge (spread apart) from the tip of the flame, and continue diverging from the mirror upon reflection.
- These divergent rays appear to originate from a point located behind the mirror.
29.3 Mirrors

You perceive the candle flame to be located behind the mirror.

A virtual image appears to be in a location where light does not really reach.

Mirrors produce only virtual images.
29.3 Mirrors

Your eye cannot ordinarily tell the difference between an object and its virtual image.

- The light enters your eye in exactly the same manner as it would if there really were an object where you see the image.
- The image is the same distance behind the mirror as the object is in front of it.
- The image and object are the same size.
29.3 Mirrors

The law of reflection holds for curved mirrors. However, the sizes and distances of object and image are no longer equal. The virtual image formed by a *convex* mirror (a mirror that curves outward) is smaller and closer to the mirror than the object is.
29.3 Mirrors

The law of reflection holds for curved mirrors. However, the sizes and distances of object and image are no longer equal.

The virtual image formed by a convex mirror (a mirror that curves outward) is smaller and closer to the mirror than the object is.

When an object is close to a concave mirror (a mirror that curves inward), the virtual image is larger and farther away than the object is.
What kind of images do mirrors produce?
When light is incident on a rough surface, it is reflected in many directions.
29.4 Diffuse Reflection

Diffuse reflection is the reflection of light from a rough surface.
Each ray obeys the law of reflection.
The many different angles that incident light rays encounter at the surface cause reflection in many directions.
29.4 Diffuse Reflection

If the differences in elevations in a surface are small (less than about one eighth the wavelength of the light that falls on it), the surface is considered polished.

A surface may be polished for long wavelengths, but not polished for short wavelengths.

Whether a surface is a diffuse reflector or a polished reflector depends on the wavelength of the waves it reflects.
29.4 Diffuse Reflection

Visible light that reflects from a sheet of paper is diffusely reflected. Rays of light incident on paper encounter millions of tiny flat surfaces facing in all directions, so they are reflected in all directions. Diffuse reflection allows us to read the page from any direction or position. We see most of the things around us by diffuse reflection.

Ordinary paper has a rough surface when viewed with a microscope.
29.4 Diffuse Reflection

Diffuse reflection allows us to see most things around us.
a. Light is diffusely reflected from paper in many directions.
29.4 Diffuse Reflection

Diffuse reflection allows us to see most things around us.

a. Light is diffusely reflected from paper in many directions.

b. Light incident on a smooth mirror is only reflected in one direction.
What happens when light is incident on a rough surface?
Reflection and Refraction

29.5 Reflection of Sound

Sound energy not reflected is absorbed or transmitted.
29.5 Reflection of Sound

An echo is reflected sound.

More sound energy is reflected from a rigid and smooth surface than from a soft and irregular surface.

Sound energy not reflected is absorbed or transmitted.

The study of the reflective properties of surfaces is *acoustics*.
29.5 Reflection of Sound

When walls are too reflective, the sound becomes garbled because of multiple reflections of sound waves called **reverberations**.

When the reflective surfaces are more absorbent, the sound level is lower, and the hall sounds dull and lifeless. In the design of an auditorium or concert hall, a balance between reverberation and absorption is desired.
The walls of concert halls are often designed with grooves so that the sound waves are diffused. A person in the audience receives a small amount of reflected sound from many parts of the wall.
29.5 Reflection of Sound

a. With grooved walls, sound reflects from many small sections of the wall to a listener.
29.5 Reflection of Sound

a. With grooved walls, sound reflects from many small sections of the wall to a listener.

b. With flat walls, an intense reflected sound comes from only one part of the wall.
Reflective surfaces are often placed behind and above the stage to direct sound out to an audience. Both sound and light obey the same law of reflection. If a reflector is oriented so that you can see a particular musical instrument, you will hear it also. Sound from the instrument will follow the line of sight to the reflector and then to you.
29.5 Reflection of Sound

The shiny plates above the orchestra in Davies Symphony Hall in San Francisco reflect both light and sound.
29.5 Reflection of Sound

What happens to sound energy that is not reflected?
29.6 Refraction

When a wave that is traveling at an angle changes its speed upon crossing a boundary between two media, it bends.
29.6 Refraction

Let an axle with two wheels roll along a pavement that slopes downward onto a downward-sloping mowed lawn.

- It rolls more slowly on the lawn due to interaction of the wheels with the blades of grass.
- Rolled at an angle, it will be deflected from its straight-line course.
- The wheel that first meets the lawn slows down first.
- The axle pivots, and the path bends toward the normal.
- When both wheels reach the grass, it continues in a straight line at reduced speed.
29.6 Refraction

When a wave that is traveling at an angle changes its speed upon crossing a boundary between two media, it bends. **Refraction** is the bending of a wave as it crosses the boundary between two media at an angle.
Water waves travel faster in deep water than in shallow water.

a. The wave refracts at the boundary where the depth changes.
29.6 Refraction

Water waves travel faster in deep water than in shallow water.

a. The wave refracts at the boundary where the depth changes.

b. The sample ray is perpendicular to the wave front it intersects.
29.6 Refraction

In drawing a diagram of a wave, it is convenient to draw lines, called wave fronts, that represent the positions of different crests.

- At each point along a wave front, the wave is moving perpendicular to the wave front.
- The direction of motion of the wave is represented by rays that are perpendicular to the wave fronts.
- Sometimes we analyze waves in terms of wave fronts, and at other times in terms of rays.
29.6 Refraction

What causes a wave to bend?
29.7 Refraction of Sound

Sound waves are refracted when parts of a wave front travel at different speeds.
29.7 Refraction of Sound

Sound refraction occurs in uneven winds or when sound is traveling through air of uneven temperature.

- On a warm day the air near the ground may be appreciably warmer than the air above.
- Sound travels faster in warmer air, so the speed of sound near the ground is increased.
- The refraction is not abrupt but gradual.
- Sound waves tend to bend away from warm ground, making it appear that the sound does not carry well.
29.7 Refraction of Sound

When the layer of air near the ground is colder than the air above, the speed of sound near the ground is reduced. The higher speed of the wave fronts above causes a bending of the sound toward Earth. Sound can then be heard over considerably longer distances.
29.7 Refraction of Sound

At night, when the air is cooler over the surface of the lake, sound is refracted toward the ground and carries unusually well.
Suppose you are downwind from a factory whistle. In which case will the whistle sound louder—if the wind speed near the ground is more than the wind speed several meters above the ground, or if it is less?
29.7 Refraction of Sound

think!

Suppose you are downwind from a factory whistle. In which case will the whistle sound louder—if the wind speed near the ground is more than the wind speed several meters above the ground, or if it is less?

Answer:

You’ll hear the whistle better if the wind speed near the ground is less than the wind speed higher up. For this condition, the sound will be refracted toward the ground.
What causes sound waves to refract?
29.8 Refraction of Light

Changes in the speed of light as it passes from one medium to another, or variations in the temperatures and densities of the same medium, cause refraction.
29.8 Refraction of Light

Due to the refraction of light:

- swimming pools appear shallower,
- a pencil in a glass of water appears bent,
- the air above a hot stove seems to shimmer, and
- stars twinkle.

The directions of the light rays change because of refraction.
29.8 Refraction of Light

Rays and wave fronts of light refract as they pass from air into water.

Wave fronts that enter the water first are the first to slow down.

The refracted ray of light is closer to the normal than is the incident ray.
29.8 Refraction of Light

As a light wave passes from air into water, its speed decreases.

A light ray is always at right angles to its wave front.
29.8 Refraction of Light

When light rays enter a medium in which their speed decreases, as when passing from air into water, the rays bend toward the normal.

When light rays enter a medium in which their speed increases, such as from water into air, the rays bend away from the normal.

The light paths are reversible for both reflection and refraction. If you can see somebody in a reflective or refractive device, such as a mirror or a prism, then that person can see you by looking through the device also.
29.8 Refraction of Light

The laser beam bends toward the normal when it enters the water, and away from the normal when it leaves.
29.8 Refraction of Light

a. The apparent depth of the glass block is less than the real depth.
a. The apparent depth of the glass block is less than the real depth.
b. The fish appears to be nearer than it actually is.
29.8 **Refraction of Light**

a. The apparent depth of the glass block is less than the real depth.
b. The fish appears to be nearer than it actually is.
c. The full glass mug appears to hold more root beer than it actually does.

These effects are due to the refraction of light whenever it crosses a boundary between air and another transparent medium.
29.8 Refraction of Light

What causes the refraction of light?
A mirage is caused by the refraction of light in Earth’s atmosphere.
29.9 Atmospheric Refraction

The speed of light in air is only 0.03% less than $c$, but in some situations, atmospheric refraction is quite noticeable. A distorted image, called a *mirage*, is caused by refraction of light in Earth’s atmosphere.

- A layer of very hot air is in contact with the ground on very hot days.
- Light travels faster through it than through the cooler air above.
- The speeding up of the part of the wave nearest the ground produces a gradual bending of the light rays.
- Light is refracted.
29.9 Atmospheric Refraction
29.9 Atmospheric Refraction

Wave fronts of light travel faster in the hot air near the ground, thereby bending the rays of light upward.
A motorist experiences a similar situation when driving along a hot road that appears to be wet ahead. The sky appears to be reflected from a wet surface, but, in fact, light from the sky is being refracted through a layer of hot air. A mirage is not a “trick of the mind.” A mirage is formed by real light and can be photographed.
29.9 Atmospheric Refraction

When you watch the sun set, you see the sun for several minutes after it has really sunk below the horizon.

Since the density of the atmosphere changes gradually, refracted rays bend gradually to produce a curved path.

The same thing occurs at sunrise, so our daytimes are about 5 minutes longer because of atmospheric refraction.
29.9 Atmospheric Refraction

When the sun is near the horizon, the rays from the lower edge are bent more than the rays from the upper edge. This produces a shortening of the vertical diameter and makes the sun look elliptical instead of round. Atmospheric refraction produces a “pumpkin” sun.
29.9 Atmospheric Refraction

think!

If the speed of light were the same for the various temperatures and densities of air, would there still be mirages?
29.9 Atmospheric Refraction

think!

If the speed of light were the same for the various temperatures and densities of air, would there still be mirages?

*Answer:*

No! There would be no refraction if light traveled at the same speed in air of different temperatures and densities.
29.9 Atmospheric Refraction

What causes the appearance of a mirage?
Since different frequencies of light travel at different speeds in transparent materials, they will refract differently and bend at different angles.
29.10 Dispersion in a Prism

The average speed of light is less than $c$ in a transparent medium. How much less depends on the medium and the frequency of light.

- Light of frequencies closer to the natural frequency of the electron oscillators in a medium travels more slowly in the medium.
- The natural frequency of most transparent materials is in the ultraviolet part of the spectrum.
- Visible light of higher frequencies travels more slowly than light of lower frequencies.
29.10 Dispersion in a Prism

Different frequencies of light travel at different speeds in transparent materials so they bend at different angles. The separation of light into colors arranged according to their frequency is called dispersion.
29.10 Dispersion in a Prism

Dispersion through a prism occurs because different frequencies of light travel at different speeds.
What causes dispersion of light?
29.11 The Rainbow

In order for you to see a rainbow, the sun must be shining in one part of the sky, and the water droplets in a cloud or in falling rain must be in the opposite part of the sky.
A rainbow is an illustration of dispersion.
Water droplets in a cloud or in falling rain must be in the opposite part of the sky as the sun.
All rainbows would be completely round if the ground were not in the way.
29.11 The Rainbow

The rainbow is seen in a part of the sky opposite the sun and is centered on the line extending from the sun to the observer.
29.11 The Rainbow

Dispersion by a Raindrop

As the ray of sunlight enters a spherical raindrop near its top surface, some of the light is refracted.

- The light is dispersed into its spectral colors. Violet is bent the most and red the least.
- At the opposite part of the drop, rays are partly reflected back into the water.
- Some rays are refracted into the air. This second refraction is similar to that of a prism.
- Refraction at the second surface increases the dispersion produced at the first surface.
29.11 The Rainbow

Dispersion of sunlight by a water drop produces a rainbow.
29.11 The Rainbow

Observing a Rainbow

Each drop disperses a full spectrum of colors. An observer sees only a single color from any one drop. By observing several drops, the arcs for each color form the familiar rainbow shape.
29.11 The Rainbow

At a particular angle, you sweep out the portion of a cone, with your eye at the apex. The raindrops that disperse light to you lie at the far edges of such a cone.

The thicker the region of water drops, the thicker the conical edge you look through, and the more vivid the rainbow.
29.11 The Rainbow

Only raindrops along the dashed arc disperse red light to the observer at a $42^\circ$ angle.
29.11 The Rainbow

Your cone of vision that intersects the raindrops creating your rainbow is different from that of a person next to you. Everybody sees his or her own personal rainbow, so when you move, your rainbow moves with you. This means you can never approach the side of a rainbow, or see it end-on. You can’t get to its end.
Often a larger, secondary bow with colors reversed can be seen arching at a greater angle around the primary bow. The secondary bow is formed by similar circumstances and is a result of double reflection within the raindrops. Most of the light is refracted out the back of the water drop during the extra reflection, so the secondary bow is much dimmer.
29.11 The Rainbow

Light from droplets inside the rainbow form a bright disk with the colored rainbow at its edge. The sky appears darker outside the rainbow because there is no light exiting raindrops in the way that produces the main rainbow.
29.11 The Rainbow

think!
If light traveled at the same speed in raindrops as it does in air, would we still have rainbows?
29.11 The Rainbow

think!
If light traveled at the same speed in raindrops as it does in air, would we still have rainbows?

Answer:
No. If there is no change in speed, there is no refraction. If there is no refraction, there is no dispersion of light and hence, no rainbow!
29.11 The Rainbow

think!

Point to a wall with your arm extended to approximate a 42° angle to the normal of the wall. Rotate your arm in a full circle while keeping the same 42° angle. What shape does your arm describe? What shape on the wall does your finger sweep out?
29.11 The Rainbow

think!
Point to a wall with your arm extended to approximate a 42° angle to the normal of the wall. Rotate your arm in a full circle while keeping the same 42° angle. What shape does your arm describe? What shape on the wall does your finger sweep out?

Answer:
Your arm describes a cone, and your finger sweeps out a circle. Likewise with rainbows.
What are the conditions necessary for seeing a rainbow?
29.12 Total Internal Reflection

Total internal reflection occurs when the angle of incidence is larger than the critical angle.
29.12 Total Internal Reflection

The Critical Angle

Fill a bathtub with water and shine a submerged waterproof flashlight straight up and then slowly tip it.

- The intensity of the emerging beam diminishes and more light is reflected from the water surface to the bottom of the tub.
- At a certain angle, the beam no longer emerges into the air.
- The critical angle is the angle of incidence at which the light is refracted at an angle of $90^\circ$ with respect to the normal.
- The intensity of the emerging beam reduces to zero.
Beyond the critical angle (48° from the normal in water), the beam cannot enter the air; it is only reflected.

The beam is experiencing **total internal reflection**, which is the complete reflection of light back into its original medium.

Total internal reflection occurs when the angle of incidence is larger than the critical angle.
29.12 Total Internal Reflection

a-d. Light emitted in the water at angles below the critical angle is partly refracted and partly reflected at the surface.
29.12 Total Internal Reflection

a-d. Light emitted in the water at angles below the critical angle is partly refracted and partly reflected at the surface.

e. At the critical angle, the emerging beam skims the surface.
29.12 Total Internal Reflection

a-d. Light emitted in the water at angles below the critical angle is partly refracted and partly reflected at the surface.

e. At the critical angle, the emerging beam skims the surface.

f. Past the critical angle, there is total internal reflection.
29.12 Total Internal Reflection

The critical angle for glass is about 43°, depending on the type of glass.

This means that within the glass, rays of light that are more than 43° from the normal to a surface will be totally internally reflected.

Total internal reflection is as the name implies: total—100%. Mirrors reflect only 90 to 95% of incident light, so prisms are used instead of mirrors in many optical instruments.
29.12 **Total Internal Reflection**

Prisms are more efficient at reflecting light than mirrors because of total internal reflection.
Total Internal Reflection in Diamonds

The critical angle for a diamond is 24.6°, smaller than in other common substances.

This small critical angle means that light inside a diamond is more likely to be totally internally reflected than to escape.

All light rays more than 24.6° from the normal to a surface in a diamond are kept inside by total internal reflection.
29.12 Total Internal Reflection

In a cut diamond, light that enters at one facet is usually totally internally reflected several times, without any loss in intensity. It then exits from another facet in another direction. A small critical angle, plus high refraction, produces wide dispersion and a wide array of brilliant colors.
29.12 Total Internal Reflection

The brilliance of diamonds is a result of total internal reflection.
Optical Fibers

Optical fibers, sometimes called light pipes, are transparent fibers that pipe light from one place to another. They do this by a series of total internal reflections. Optical fibers are useful for getting light to inaccessible places. Mechanics and machinists use them to look at the interiors of engines, and physicians use them to look inside a patient’s body.
29.12 Total Internal Reflection

Light that shines down some of the fibers illuminates the scene and is reflected back along others. Optical fibers are important in communications, replacing bulky and expensive copper cables to carry telephone messages. More information can be carried in the high frequencies of visible light than in the lower frequencies of electric current.
What causes total internal reflection to occur?
Assessment Questions

1. When a wave reaches a boundary it
   a. can partially or totally reflect.
   b. cannot reflect into the first medium.
   c. scatters.
   d. is absorbed into the second medium.
Assessment Questions

1. When a wave reaches a boundary it
   a. can partially or totally reflect.
   b. cannot reflect into the first medium.
   c. scatters.
   d. is absorbed into the second medium.

Answer: A
Assessment Questions

2. The law of reflection applies to
   a. only partially reflected waves.
   b. only totally reflected waves.
   c. only normal waves.
   d. both partially and totally reflected waves.
Assessment Questions

2. The law of reflection applies to
   a. only partially reflected waves.
   b. only totally reflected waves.
   c. only normal waves.
   d. both partially and totally reflected waves.

Answer: D
Assessment Questions

3. Your image behind a plane mirror is at a distance equal to
   a. half your height.
   b. half your distance from the mirror.
   c. your distance in front of the mirror.
   d. slightly more than your distance in front of the mirror.
Assessment Questions

3. Your image behind a plane mirror is at a distance equal to
   a. half your height.
   b. half your distance from the mirror.
   c. your distance in front of the mirror.
   d. slightly more than your distance in front of the mirror.

Answer: C
Assessment Questions

4. A surface may be a polished reflector or a diffuse reflector depending on the
   a. color of light.
   b. brightness of light.
   c. wavelength of light.
   d. angle of incoming light.
Assessment Questions

4. A surface may be a polished reflector or a diffuse reflector depending on the
   a. color of light.
   b. brightness of light.
   c. wavelength of light.
   d. angle of incoming light.

Answer: C
Assessment Questions

5. Sound energy can be
   a. reflected.
   b. absorbed.
   c. transmitted.
   d. all of these
Assessment Questions

5. Sound energy can be
   a. reflected.
   b. absorbed.
   c. transmitted.
   d. all of these

Answer: D
Assessment Questions

6. Refraction occurs when a wave crosses a boundary and changes
   a. speed and direction.
   b. intensity.
   c. frequency.
   d. amplitude.
6. Refraction occurs when a wave crosses a boundary and changes
   a. speed and direction.
   b. intensity.
   c. frequency.
   d. amplitude.

Answer: A
Assessment Questions

7. Changes in wind speed and temperature cause sound waves to
   a. reflect.
   b. reverberate.
   c. refract.
   d. scatter.
Assessment Questions

7. Changes in wind speed and temperature cause sound waves to
   a. reflect.
   b. reverberate.
   c. refract.
   d. scatter.

Answer: C
Assessment Questions

8. Refracted light that bends away from the normal is light that has
   a. slowed down.
   b. speeded up.
   c. nearly been absorbed.
   d. diffracted.
Assessment Questions

8. Refracted light that bends away from the normal is light that has
   a. slowed down.
   b. speeded up.
   c. nearly been absorbed.
   d. diffracted.

Answer: B
Assessment Questions

9. Atmospheric refraction occurs with changes in
   a. wind speed.
   b. air temperature.
   c. the presence of water.
   d. both wind speed and air temperature.
Assessment Questions

9. Atmospheric refraction occurs with changes in
   a. wind speed.
   b. air temperature.
   c. the presence of water.
   d. both wind speed and air temperature.

Answer: B
Assessment Questions

10. When light incident on a prism separates into a spectrum, we call the process
   a. reflection.
   b. interference.
   c. diffraction.
   d. dispersion.
Assessment Questions

10. When light incident on a prism separates into a spectrum, we call the process
   a. reflection.
   b. interference.
   c. diffraction.
   d. dispersion.

Answer: D
Assessment Questions

11. A rainbow is the result of light in raindrops that undergoes
   a. internal reflection.
   b. dispersion.
   c. refraction.
   d. all of these
Assessment Questions

11. A rainbow is the result of light in raindrops that undergoes
   a. internal reflection.
   b. dispersion.
   c. refraction.
   d. all of these

Answer: D
12. The critical angle in total internal reflection occurs when incident light on a surface is
   a. refracted at 90° to the normal.
   b. reflected at 90° to the normal.
   c. at maximum diffraction.
   d. totally absorbed.
Assessment Questions

12. The critical angle in total internal reflection occurs when incident light on a surface is
   a. refracted at 90° to the normal.
   b. reflected at 90° to the normal.
   c. at maximum diffraction.
   d. totally absorbed.

Answer: A
Lenses change the paths of light.
A light ray bends as it enters glass and bends again as it leaves. Light passing through glass of a certain shape can form an image that appears larger, smaller, closer, or farther than the object being viewed.
A lens forms an image by bending parallel rays of light that pass through it.
30.1 Converging and Diverging Lenses

A lens is a piece of glass or plastic that refracts light. A lens forms an image by bending parallel rays of light that pass through it.

Learning about lenses is a hands-on activity. Not manipulating lenses while learning about them is like taking swimming lessons out of water.
30.1 Converging and Diverging Lenses

Shapes of Lenses

The shape of a lens can be understood by considering a lens to be a large number of portions of prisms.

a. The incoming parallel rays converge to a single point.
30.1 Converging and Diverging Lenses

Shapes of Lenses

The shape of a lens can be understood by considering a lens to be a large number of portions of prisms.

a. The incoming parallel rays converge to a single point.

b. The incoming rays diverge from a single point.
30.1 Converging and Diverging Lenses

The most net bending of rays occurs at the outermost prisms, for they have the greatest angle between the two refracting surfaces.

No net bending occurs in the middle “prism,” for its glass faces are parallel and rays emerge in their original direction.
30 Lenses

30.1 Converging and Diverging Lenses

Real lenses are made not of prisms, but of solid pieces of glass or plastic with surfaces that are usually ground to a spherical shape.

- A **converging lens**, also known as a **convex lens**, is thicker in the middle, causing rays of light that are initially parallel to meet at a single point.

- A **diverging lens**, also known as a **concave lens**, is thinner in the middle, causing the rays of light to appear to originate from a single point.
30.1 Converging and Diverging Lenses

Wave fronts travel more slowly in glass than in air.

a. In the converging lens, the wave fronts are retarded more through the center of the lens, and the light converges.
30 Lenses

30.1 Converging and Diverging Lenses

Wave fronts travel more slowly in glass than in air.

a. In the converging lens, the wave fronts are retarded more through the center of the lens, and the light converges.

b. In the diverging lens, the waves are retarded more at the edges, and the light diverges.
30.1 Converging and Diverging Lenses

Key Features of Lenses

The principal axis of a lens is the line joining the centers of curvature of its surfaces.

For a converging lens, the focal point is the point at which a beam of light parallel to the principal axis converges.

The focal plane is a plane perpendicular to the principal axis that passes through either focal point of a lens.
30.1 Converging and Diverging Lenses

For a converging lens, any incident parallel beam converges to a point on the focal plane.

A lens has two focal points and two focal planes.

When the lens of a camera is set for distant objects, the film is in the focal plane behind the lens in the camera.
30.1 Converging and Diverging Lenses

The key features of a converging lens include the principal axis, focal point, and focal plane.
30.1 Converging and Diverging Lenses

For a diverging lens, an incident beam of light parallel to the principal axis is diverged so that the light appears to originate from a single point.

The **focal length** of a lens, whether converging or diverging, is the distance between the center of the lens and its focal point.

When the lens is thin, the focal lengths on either side are equal, even when the curvatures on the two sides are not.
30.1 Converging and Diverging Lenses

How does a lens form an image?
30.2 Image Formation by a Lens

The type of image formed by a lens depends on the shape of the lens and the position of the object.
30 Lenses

30.2 Image Formation by a Lens

With unaided vision, a far away object is seen through a relatively small angle of view.
When you are closer, the object is seen through a larger angle of view.
Magnification occurs when the use of a lens allows an image to be observed through a wider angle than would be observed without the lens.
A magnifying glass is simply a converging lens that increases the angle of view and allows more detail to be seen.
30.2 Image Formation by a Lens

a. A distant object is viewed through a narrow angle.
30.2 Image Formation by a Lens

a. A distant object is viewed through a narrow angle.
b. When the same object is viewed through a wide angle, more detail is seen.
30.2 Image Formation by a Lens

Images Formed by Converging Lenses

When you use a magnifying glass, you hold it close to the object you wish to see magnified. A converging lens will magnify only when the object is between the focal point and the lens. The magnified image will be farther from the lens than the object and right-side up.
30.2 Image Formation by a Lens

If a screen were placed at the image distance, no image would appear on the screen because no light is actually directed to the image position.

The rays that reach your eye, however, behave as if they came from the image position, so the image is a virtual image.
30.2 Image Formation by a Lens

A converging lens can be used as a magnifying glass to produce a virtual image of a nearby object.
30.2 Image Formation by a Lens

When the object is beyond the focal point of a converging lens, light converges and can be focused on a screen.

An image formed by converging light is called a **real image**.

A real image formed by a single converging lens is upside down. Converging lenses are used for projecting pictures on a screen.
30.2 Image Formation by a Lens

Images Formed by Diverging Lenses

When a diverging lens is used alone, the image is always virtual, right-side up, and smaller than the object. It makes no difference how far or how near the object is. A diverging lens is often used for the viewfinder on a camera.
30.2 Image Formation by a Lens

think!

Why is the greater part of the photograph out of focus?
Why is the greater part of the photograph out of focus?

**Answer:**
Both Jamie and his cat and the virtual image of Jamie and his cat are “objects” for the lens of the camera that took this photograph. Since the objects are at different distances from the camera lens, their respective images are at different distances with respect to the film in the camera. So only one can be brought into focus.
What determines the type of image formed by a lens?
The size and location of the object, its distance from the center of the lens, and the focal length of the lens are used to construct a ray diagram.
30.3 Constructing Images Through Ray Diagrams

Ray diagrams show the principal rays that can be used to determine the size and location of an image. The size and location of the object, distance from the center of the lens, and the focal length are used to construct the ray diagram.
30.3 Constructing Images Through Ray Diagrams

An arrow is used to represent the object. For simplicity, one end of the object is placed right on the principal axis.
30.3 Constructing Images Through Ray Diagrams

The Three Principal Rays

To locate the position of the image, you only have to know the paths of two rays from a point on the object. Any point except for the point on the principal axis will work, but it is customary to choose a point at the tip of the arrow.
30.3 Constructing Images Through Ray Diagrams

- A ray parallel to the principal axis will be refracted by the lens to the focal point.
30.3 Constructing Images Through Ray Diagrams

- A ray parallel to the principal axis will be refracted by the lens to the focal point.
- A ray will pass through the center with no appreciable change in direction.

We use these particular rays only because their paths through the lens are easy to predict. You should know that all light passing through a lens contributes to image formation.
30.3 Constructing Images Through Ray Diagrams

- A ray parallel to the principal axis will be refracted by the lens to the focal point.
- A ray will pass through the center with no appreciable change in direction.
- A ray that passes through the focal point in front of the lens emerges from the lens parallel to the principal axis.

We use these particular rays only because their paths through the lens are easy to predict. You should know that all light passing through a lens contributes to image formation.
30.3 Constructing Images Through Ray Diagrams

The image is located where the three rays intersect. Any two of these three rays is sufficient to locate the relative size and location of the image.
If the distance from the lens to the object is less than the focal length, the rays diverge as they leave the lens. The rays of light appear to come from a point in front of the lens. The location of the image is found by extending the rays backward to the point where they converge.
30.3 Constructing Images Through Ray Diagrams

The virtual image that is formed is magnified and right-side up.
30 Lenses

30.3 Constructing Images Through Ray Diagrams

The three rays useful for the construction of a ray diagram are:

1. A ray parallel to the principal axis that passes through the focal point on the opposite side.
2. A ray passing through the center of the lens that is undeflected.
3. A ray through the focal point in front of the lens that emerges parallel to the principal axis after refraction by the lens.

Interestingly, when half a lens is covered, half as much light forms the image. This does not mean half the image is formed! Even a piece of broken lens can form a complete image on a screen. Try it and see.
Ray Diagrams for Converging and Diverging Lenses

For a converging lens, as an object, initially at the focal point, is moved away from the lens along the principal axis, the image size and distance from the lens changes.

For a converging lens, if the object is not located between the focal point and the lens, the images that are formed are real and inverted.
30.3 Constructing Images Through Ray Diagrams

The method of drawing ray diagrams applies to diverging lenses.

- A ray parallel to the principal axis from the tip of the arrow will be bent by the lens as if it had come from the focal point.
- A ray through the center goes straight through.
- A ray heading for the focal point on the far side of the lens is bent so that it emerges parallel to the axis of the lens.
30.3 Constructing Images Through Ray Diagrams

On emerging from the lens, the three rays appear to come from a point on the same side of the lens as the object. This is the position of the virtual image. The image is nearer to the lens than the object. The image formed by a diverging lens is always virtual, reduced, and right-side up.
What information is used to construct a ray diagram?
A converging lens forms either a real or a virtual image. A diverging lens always forms a virtual image.
30 Lenses

30.4 Image Formation Summarized

For a converging lens, when the object is within one focal length of the lens, the image is then virtual, magnified, and right-side up.

When the object is beyond one focal length, a converging lens produces a real, inverted image.

- If the object is close to (but slightly beyond) the focal point, the image is far away.
- If the object is far from the focal point, the image is nearer.
- In all cases where a real image is formed, the object and the image are on opposite sides of the lens.
30.4 Image Formation Summarized

When the object is viewed with a diverging lens, the image is virtual, reduced, and right-side up.

This is true for all locations of the object.

In all cases where a virtual image is formed, the object and the image are on the same side of the lens.
30.4 Image Formation Summarized

think!

Where must an object be located so that the image formed by a converging lens will be (a) at infinity? (b) as near the object as possible? (c) right-side up? (d) the same size? (e) inverted and enlarged?
think!

Where must an object be located so that the image formed by a converging lens will be (a) at infinity? (b) as near the object as possible? (c) right-side up? (d) the same size? (e) inverted and enlarged?

Answer:

The object should be (a) at one focal length from the lens (at the focal point); (b) and (c) within one focal length of the lens; (d) at two focal lengths from the lens; (e) between one and two focal lengths from the lens.
30.4 Image Formation Summarized

What types of images are produced by lenses?
30.5 Some Common Optical Instruments

Optical instruments that use lenses include the camera, the telescope (and binoculars), and the compound microscope.
30.5 Some Common Optical Instruments

The first eyeglasses were probably invented in Italy in the late 1200s.

The telescope wasn’t invented until some 300 years later.

Today, lenses are used in many optical instruments.
30 Lenses

30.5 Some Common Optical Instruments

Camera

A camera consists of a lens and sensitive film (or light-detecting chip) mounted in a light-tight box. The lens forms a real, inverted image on the film or chip. In practice, most cameras use compound lenses to minimize distortions called aberrations.
30.5 Some Common Optical Instruments

The amount of light that gets to the film is regulated by a shutter and a diaphragm.

The shutter controls the length of time that the film is exposed to light.

The diaphragm controls the opening that light passes through to reach the film.

Varying the size of the opening (aperture) varies the amount of light that reaches the film at any instant.
30.5 Some Common Optical Instruments

Telescope

A simple telescope uses a lens that forms a real image of a distant object. The real image is projected in space to be examined by another lens, called the **eyepiece**, used as a magnifying glass.

The eyepiece is positioned so that the image produced by the first lens is within one focal length of the eyepiece.

The eyepiece forms an enlarged virtual image of the real image.
30.5 **Some Common Optical Instruments**

(The image is shown close here; it is actually located at infinity.)
In an *astronomical telescope*, the image is inverted, which explains why maps of the moon are printed with the moon upside down.
A third lens or a pair of reflecting prisms is used in the *terrestrial telescope*, which produces an image that is right-side up.
A pair of these telescopes side by side, each with a pair of prisms, makes up a pair of *binoculars*. Each side of a pair of binoculars uses a pair of prisms that flips the image right-side up.
30.5 Some Common Optical Instruments

No lens transmits 100% of the light so astronomers prefer the brighter, inverted images of a two-lens telescope.

For uses such as viewing distant landscapes or sporting events, right-side-up images are more important than brightness.
30.5 Some Common Optical Instruments

Compound Microscope

A compound microscope uses two converging lenses of short focal length. The **objective lens** produces a real image of a close object. The image is farther from the lens than the object so it is enlarged. The eyepiece forms a virtual image of the first image, further enlarged.
30.5 Some Common Optical Instruments

What are some optical instruments that use lenses?
The main parts of the eye are the cornea, the iris, the pupil, and the retina.
30.6 The Eye

In many respects, the human eye is similar to the camera.

- Light enters through the transparent covering, the **cornea**.
- The amount of light that enters is regulated by the **iris**, the colored part of the eye that surrounds the pupil.
- The **pupil** is the opening through which light passes.
- Light passes through the pupil and lens and is focused on a layer of tissue at the back of the eye—the **retina**. Different parts of the retina receive light from different directions.

![Eye Diagram]
30.6 The Eye

The Blind Spot

The retina is not uniform. There is a small region in the center of our field of view where we have the most distinct vision. This spot is called the *fovea*. Much greater detail can be seen here than at the side parts of the eye.

There is also a spot in the retina where the nerves carrying all the information leave the eye in a narrow bundle. This is the *blind spot*.
30.6 The Eye

The Camera and the Eye

In both the camera and the eye, the image is upside down, and this is compensated for in both cases. You simply turn the camera film around to look at it. Your brain has learned to turn around images it receives from your retina.
30.6 The Eye

A principal difference between a camera and the human eye has to do with focusing.

- In a camera, focusing is accomplished by altering the distance between the lens and the film or chip.
- In the human eye, most of the focusing is done by the cornea, the transparent membrane at the outside of the eye.
- The image is focused on the retina by changing the thickness and shape of the lens to regulate its focal length. This is called *accommodation* and is brought about by the action of the *ciliary muscle*, which surrounds the lens.
30.6 The Eye

NORMAL DISTANT VISION

NORMAL CLOSE VISION
What are the main parts of the human eye?
30.7 Some Defects in Vision

Three common vision problems are farsightedness, nearsightedness, and astigmatism.
30.7 Some Defects in Vision

With normal vision, your eye can accommodate to clearly see objects from infinity (the *far point*) down to 25 cm (the *near point*).

Unfortunately, not everyone has normal vision.
30.7 Some Defects in Vision

Farsightedness

A farsighted person has trouble focusing on nearby objects.

- The eyeball is too short and images form behind the retina.
- Farsighted people have to hold things more than 25 cm away to be able to focus them.
- The remedy is to increase the converging effect of the eye by wearing eyeglasses or contact lenses with converging lenses.
- Converging lenses converge the rays sufficiently to focus them on the retina instead of behind the retina.
Nearsightedness

A nearsighted person can see nearby objects clearly, but does not see distant objects clearly.

- Distant objects focus too near the lens, in front of the retina.
- The eyeball is too long.
- A remedy is to wear lenses that diverge the rays from distant objects so that they focus on the retina instead of in front of it.
30.7 Some Defects in Vision

**Astigmatism**

Astigmatism of the eye is a defect that results when the cornea is curved more in one direction than the other. Because of this defect, the eye does not form sharp images. The remedy is cylindrical corrective lenses that have more curvature in one direction than in another.
30.7 Some Defects in Vision

What are three common vision problems?
Two types of aberration are spherical aberration and chromatic aberration.
30.8 Some Defects of Lenses

No lens gives a perfect image. The distortions in an image are called **aberrations**. Combining lenses in certain ways can minimize aberrations so most optical instruments use compound lenses.
30.8 **Some Defects of Lenses**

**Aberrations**

*Spherical aberration* results when light passing through the edges of a lens focuses at a slightly different place from light passing through the center of the lens.

Spherical aberration is corrected in good optical instruments by a combination of lenses.
30.8 Some Defects of Lenses

Chromatic aberration is the result of the different speeds of light of various colors, and hence the different refractions they undergo. In a simple lens red light and blue light bend by different amounts (as in a prism), so they do not come to focus in the same place. Achromatic lenses, which combine simple lenses of different kinds of glass, correct this defect.
30.8 Some Defects of Lenses

Vision is sharpest when the pupil is smallest. Light then passes through only the center of the eye’s lens, where spherical and chromatic aberrations are minimal. Also, light bends the least through the center of a lens, so minimal focusing is required for a sharp image. You see better in bright light because your pupils are smaller.
30.8 Some Defects of Lenses

Methods for Correcting Vision

An alternative to wearing eyeglasses for correcting vision is contact lenses.

One option is LASIK (*laser-assisted in-situ keratomileusis*), the procedure of reshaping the cornea using pulses from a laser. Another procedure is PRK (*photorefractive keratectomy*). Still another is IntraLase, where intraocular lenses are implanted in the eye like a contact lens.
30.8 Some Defects of Lenses

think!

Why is there chromatic aberration in light that passes through a lens, but no chromatic aberration in light that reflects from a mirror?
30.8 Some Defects of Lenses

think!

Why is there chromatic aberration in light that passes through a lens, but no chromatic aberration in light that reflects from a mirror?

Answer:

Different frequencies travel at different speeds in a transparent medium, and therefore refract at different angles. This produces chromatic aberration. The angles at which light reflects, on the other hand, have nothing to do with the frequency of light. One color reflects the same as any other.
30.8 Some Defects of Lenses

What types of aberrations can occur in images?
Assessment Questions

1. The action of lenses depends mainly on
   a. convexing light in various directions.
   b. changing the direction of light rays or waves.
   c. converging light rays or waves.
   d. diverging light rays or waves.
Assessment Questions

1. The action of lenses depends mainly on
   a. convexing light in various directions.
   b. changing the direction of light rays or waves.
   c. converging light rays or waves.
   d. diverging light rays or waves.

Answer: B
Assessment Questions

2. A real image can be cast on a screen by
   a. converging lens.
   b. diverging lens.
   c. concave lens.
   d. any lens.
Assessment Questions

2. A real image can be cast on a screen by
   a. converging lens.
   b. diverging lens.
   c. concave lens.
   d. any lens.

Answer: A
30 Lenses

Assessment Questions

3. The minimum number of light rays necessary to construct the position of an image is
   a. one.
   b. two.
   c. three.
   d. four.
3. The minimum number of light rays necessary to construct the position of an image is
   a. one.
   b. two.
   c. three.
   d. four.

Answer: B
Assessment Questions

4. A diverging lens forms
   a. only a real image.
   b. only a virtual image.
   c. both a real image and a virtual image.
   d. a perfect image.
Assessment Questions

4. A diverging lens forms
   a. only a real image.
   b. only a virtual image.
   c. both a real image and a virtual image.
   d. a perfect image.

Answer: B
The amount of light getting into a camera or your eye is regulated by a(n)

a. distorter.

b. diaphragm.

c. eyepiece.

d. set of compound lenses.
Assessment Questions

5. The amount of light getting into a camera or your eye is regulated by a(n)
   a. distorter.
   b. diaphragm.
   c. eyepiece.
   d. set of compound lenses.

Answer: B
Assessment Questions

6. To best test for the blind spots in your eyes,
   a. keep your eyes wide open in bright light.
   b. close one eye.
   c. do not use eyeglasses unless you need them.
   d. focus intently on whatever you’re viewing.
Assessment Questions

6. To best test for the blind spots in your eyes,
   a. keep your eyes wide open in bright light.
   b. close one eye.
   c. do not use eyeglasses unless you need them.
   d. focus intently on whatever you’re viewing.

Answer: B
Assessment Questions

7. A person who is nearsighted wears
   a. no glasses.
   b. glasses that have a uniform thickness.
   c. glasses that are thicker in the middle.
   d. glasses that are thicker at the edges.
Assessment Questions

7. A person who is nearsighted wears
   a. no glasses.
   b. glasses that have a uniform thickness.
   c. glasses that are thicker in the middle.
   d. glasses that are thicker at the edges.

Answer: D
Assessment Questions

8. Chromatic aberrations are caused by
   a. light passing through a lens.
   b. the use of achromatic lenses.
   c. different colors of light traveling at different speeds.
   d. LASIK.
Assessment Questions

8. Chromatic aberrations are caused by
   a. light passing through a lens.
   b. the use of achromatic lenses.
   c. different colors of light traveling at different speeds.
   d. LASIK.

Answer: C
The wave model of light explains diffraction and interference.
Isaac Newton pictured light as a beam of ultra-tiny material particles. With this model he could explain reflection and refraction. In the eighteenth and nineteenth centuries, this particle model gave way to a wave model of light because waves could explain reflection, refraction, and everything else that was known about light at that time.
31.1 Huygens’ Principle

Huygens stated that light waves spreading out from a point source may be regarded as the overlapping of tiny secondary wavelets, and that every point on any wave front may be regarded as a new point source of secondary waves.
31 Diffraction and Interference

31.1 Huygens’ Principle

In the late 1600s, a Dutch mathematician-scientist, Christian Huygens, proposed a very interesting idea about light.

• Light waves spreading out from a point source may be regarded as the overlapping of tiny secondary wavelets.

• Every point on any wave front may be regarded as a new point source of secondary waves.

The idea that wave fronts are made up of tinier wave fronts is called Huygens’ principle.
31.1 Huygens’ Principle

These drawings are from Huygens’ book *Treatise on Light*.

a. Light from A expands in wave fronts.
31.1 Huygens’ Principle

These drawings are from Huygens’ book *Treatise on Light*.

a. Light from A expands in wave fronts.

b. Every point behaves as if it were a new source of waves.
31.1 Huygens’ Principle

Wave Fronts

Every point along the spherical wave front AA’’ is the source of a new wavelet. Only a few of the infinite number of wavelets are shown. The new wave front BB’’ can be regarded as a smooth surface enclosing the infinite number of overlapping wavelets started from AA’.
31.1 Huygens’ Principle

Far away from the source, the wave fronts appear to form a plane.
31.1 Huygens’ Principle

Each point along a wave front is the source of a new wave.

a. The law of reflection can be proven using Huygens’ principle.
31.1 Huygens’ Principle

Each point along a wave front is the source of a new wave.

a. The law of reflection can be proven using Huygens’ principle.

b. Huygens’ principle can also illustrate refraction.
31 Diffraction and Interference

31.1 Huygens’ Principle

Huygens’ Principle in Water Waves

You can observe Huygens’ principle in water waves that are made to pass through a narrow opening. When the straight wave fronts pass through the opening in a barrier, interesting wave patterns result.
31.1 Huygens’ Principle

When the opening is wide, straight wave fronts pass through without change—except at the corners. At the corners, the wave fronts are bent into the “shadow region” in accord with Huygens’ principle.
31.1 Huygens’ Principle

Narrow the width of the opening and less of the wave gets through.

- Spreading into the shadow region is more pronounced.
- Huygens’ idea that every part of a wave front can be regarded as a source of new wavelets becomes quite apparent.
- Circular waves fan out on the other side of the barrier.
31.1 Huygens’ Principle

The extent to which the water waves bend depends on the size of the opening.
31.1 Huygens’ Principle

What did Huygens state about light waves?
The extent of diffraction depends on the relative size of the wavelength compared with the size of the obstruction that casts the shadow.
31.2 Diffraction

Any bending of a wave by means other than reflection or refraction is called **diffraction**.

When the opening is wide compared with the wavelength, the spreading effect is small.

As the opening becomes narrower, the diffraction of waves becomes more pronounced.
31.2 Diffraction

Diffraction of Visible Light

When light passes through an opening that is large compared with the wavelength, it casts a rather sharp shadow. When light passes through a small opening, such as a thin slit in a piece of opaque material, it casts a fuzzy shadow. The light fans out like the water through the narrow opening. The light is diffracted by the thin slit.
31.2 Diffraction

a. Light casts a sharp shadow with some fuzziness at its edges when the opening is large compared with the wavelength.
31 Diffraction and Interference

31.2 Diffraction

a. Light casts a sharp shadow with some fuzziness at its edges when the opening is large compared with the wavelength.

b. Because of diffraction, it casts a fuzzier shadow when the opening is extremely narrow.
31.2 Diffraction

Diffraction is not confined to the spreading of light through narrow slits or other openings.

- Diffraction occurs to some degree for all shadows. Even the sharpest shadow is blurred at the edge.
- When light is of a single color, diffraction can produce sharp *diffraction fringes* at the edge of the shadow.
- In white light, the fringes merge together to create a fuzzy blur at the edge of a shadow.
31.2 Diffraction

Diffraction fringes around the scissors are evident in the shadows of laser light, which is of a single frequency.
31.2 Diffraction

Factors That Affect Diffraction

When the wavelength is long compared with the obstruction, the wave diffracts more.

- Long waves are better at filling in shadows.
- Foghorns emit low-frequency (long-wavelength) sound waves—to fill in “blind spots.”
- AM radio waves are very long compared with the size of most objects in their path. They diffract around buildings and reach more places than shorter wavelengths.
a. Waves tend to spread into the shadow region.
31.2 Diffraction

a. Waves tend to spread into the shadow region.

b. When the wavelength is about the size of the object, the shadow is soon filled in.
31.2 Diffraction

a. Waves tend to spread into the shadow region.

b. When the wavelength is about the size of the object, the shadow is soon filled in.

c. When the wavelength is short compared with the width of the object, a sharper shadow is cast.
31.2 Diffraction

Diffraction of Radio and TV Waves

FM radio waves have shorter wavelengths than AM waves do, so they don’t diffract as much around buildings.

- Many places have poor FM reception but clear AM stations.
- TV waves behave much like FM waves.
- Both FM and TV transmission are “line of sight”—obstacles can cause reception problems.
31.2 Diffraction

Diffraction in Microscopy

If an object under a microscope is the same size as the wavelength of light, the image of the object will be blurred by diffraction.

If the object is smaller than the wavelength of light, no structure can be seen.

No amount of magnification can defeat this fundamental diffraction limit.
31.2 Diffraction

To see smaller details, you have to use shorter wavelengths:

- A beam of electrons has a wavelength that can be a thousand times shorter than the wavelengths of visible light.
- Microscopes that use beams of electrons to illuminate tiny things are called *electron microscopes*.
- The diffraction limit of an electron microscope is much less than that of an optical microscope.
31.2 Diffraction

Diffraction and Dolphins

The echoes of long-wavelength sound give the dolphin an overall image of objects in its surroundings. To examine more detail, the dolphin emits sounds of shorter wavelengths.
31.2 Diffraction

With these sound waves, skin, muscle, and fat are almost transparent to dolphins, but bones, teeth, and gas-filled cavities are clearly apparent. Physical evidence of cancers, tumors, heart attacks, and even emotional states can all be “seen” by the dolphins. The dolphin has always done naturally what humans in the medical field have only recently been able to do with ultrasound devices.
31.2 Diffraction

think!

Why is blue light used to view tiny objects in an optical microscope?
Why is blue light used to view tiny objects in an optical microscope?

**Answer:**
Blue light has a shorter wavelength than most of the other wavelengths of visible light, so there’s less diffraction. More details of the object will be visible under blue light.
31.2 Diffraction

What affects the extent of diffraction?
Within an interference pattern, wave amplitudes may be increased, decreased, or neutralized.
31.3 Interference

When two sets of waves cross each other they produce what is called an *interference pattern*.

When the crest of one wave overlaps the crest of another, they add together; this is *constructive interference*.

When the crest of one wave overlaps the trough of another, their individual effects are reduced; this is *destructive interference*.
31.3 Interference

Water waves can be produced in shallow tanks of water known as *ripple tanks*. The wave patterns are photographed from above.

- Regions of destructive interference make gray “spokes.”
- Regions of constructive interference make dark and light stripes.

The greater the frequency of the vibrations, the closer together the stripes (and the shorter the wavelength).

The number of regions of destructive interference depends on the wavelength and on the distance between the wave sources.
31.3 Interference

a–b. The separation between the sources is the same but the wavelength in (b) is shorter than the wavelength in (a).
31.3 Interference

a–b. The separation between the sources is the same but the wavelength in (b) is shorter than the wavelength in (a).

b–c. The wavelengths are the same but the sources are closer together in (c) than in (b).
31.3 Interference

How does interference affect wave amplitudes?
Young’s interference experiment convincingly demonstrated the wave nature of light originally proposed by Huygens.
British physicist and physician Thomas Young discovered that when *monochromatic* light—light of a single color—passed through two closely spaced pinholes, fringes of brightness and darkness were produced on a screen behind.

He realized that the bright fringes resulted from light waves from both holes arriving crest to crest (constructive interference—more light).

The dark areas resulted from light waves arriving trough to crest (destructive interference—no light).
31.4 Young’s Interference Experiment

In Young’s original drawing of a two-source interference pattern, the dark circles represent wave crests; the white spaces between the crests represent troughs. Letters $C$, $D$, $E$, and $F$ mark regions of destructive interference.
31.4 Young’s Interference Experiment

Double Slit Experiment

Young’s experiment is now done with two closely spaced slits instead of pinholes, so the fringes are straight lines. A bright fringe occurs when waves from both slits arrive in phase.

Dark regions occur when waves arrive out of phase.
31.4 Young’s Interference Experiment

Young’s experiment demonstrated the wave nature of light.

a. The arrangement includes two closely spaced slits and a monochromatic light source.
31.4 Young’s Interference Experiment

Young’s experiment demonstrated the wave nature of light.

a. The arrangement includes two closely spaced slits and a monochromatic light source.

b. The interference fringes produced are straight lines.
31.4 Young’s Interference Experiment

Light from $O$ passes through slits $A$ and $B$ and produces an interference pattern on the screen at the right.
31.4 Young’s Interference Experiment

Diffraction Gratings

A multitude of closely spaced parallel slits makes up what is called a **diffraction grating**.

Many spectrometers use diffraction gratings rather than prisms to disperse light into colors.

A prism separates the colors of light by refraction, but a diffraction grating separates colors by interference.
31.4 Young’s Interference Experiment

Diffraction gratings are seen in reflective materials used in items such as costume jewelry and automobile bumper stickers. These materials have hundreds or thousands of close-together, tiny grooves that diffract light into a brilliant spectrum of colors.
31.4 Young’s Interference Experiment

The pits on the reflective surface of a compact disc diffract light into its component colors. The feathers of birds are nature’s diffraction gratings. The striking colors of opals come from layers of tiny silica spheres that act as diffraction gratings.
31.4 Young’s Interference Experiment

think!

Why is it important that monochromatic (single-frequency) light be used in Young’s interference experiment?
think!

Why is it important that monochromatic (single-frequency) light be used in Young’s interference experiment?

**Answer:**

If light of a variety of wavelengths were diffracted by the slits, dark fringes for one wavelength would be filled in with bright fringes for another, resulting in no distinct fringe pattern. If the path difference equals one-half wavelength for one frequency, it cannot also equal one-half wavelength for any other frequency.
What did Young’s experiment demonstrate?
The colors seen in thin films are produced by the interference in the films of light waves of mixed frequencies.
31.5 Interference From Thin Films

A spectrum of colors reflects from soap bubbles or gasoline spilled on a wet street.

Some bird feathers seem to change hue as the bird moves.

The colors seen in thin films are produced by the interference in the films of light waves of mixed frequencies.

Iridescence is the interference of light waves of mixed frequencies, which produces a spectrum of colors.
The intriguing colors of gasoline on a wet street correspond to different thicknesses of the thin film.
31.5 Interference From Thin Films

A thin film, such as a soap bubble, has two closely spaced surfaces.

- Light that reflects from one surface may cancel light that reflects from the other surface.
- The film may be just the right thickness in one place to cause the destructive interference of blue light.
- If the film is illuminated with white light, then the light that reflects to your eye will have no blue in it.
- The complementary color will appear so we get yellow.
31.5 Interference From Thin Films

In a thicker part of the film, where green is canceled, the bubble will appear magenta.

The different colors correspond to the cancellations of their complementary colors by different thicknesses of the film.

Soap-bubble colors come from interference of reflected light from inside and outside surfaces of the bubble.
31.5 Interference From Thin Films

For a thin layer of gasoline on a layer of water, light reflects from both the gasoline-air surface and the gasoline-water surface. If the incident beam is monochromatic blue and the gasoline layer is just the right thickness to cause cancellation of light of that wavelength, then the gasoline surface appears dark. If the incident beam is white sunlight, the surface appears yellow.
31.5 Interference From Thin Films

Colors reflected from some types of seashells are produced by interference of light in their thin transparent coatings. So are the sparkling colors from fractures within opals. Interference colors can even be seen in the thin film of detergent left when dishes are not properly rinsed.
31.5 Interference From Thin Films

Physicist Bob Greenler shows interference colors with *big* bubbles.
31.5 Interference From Thin Films

Interference provides the principal method for measuring the wavelengths of light.

Extremely small distances (millionths of a centimeter) are measured with instruments called *interferometers*, which make use of the principle of interference.

They are among the most accurate measuring instruments known.
31.5 Interference From Thin Films

think!

What color will reflect from a soap bubble in sunlight when its thickness is such that red light is canceled?
think!

What color will reflect from a soap bubble in sunlight when its thickness is such that red light is canceled?

Answer:

You will see the color cyan, which is the complementary color of red.
How are the colors seen in thin films produced?
Laser light is emitted when excited atoms of a solid, liquid, or gas emit photons.
Light emitted by a common lamp is incoherent light—the crests and troughs of the light waves don’t line up with one another.

Incoherent light is chaotic.

Interference within a beam of incoherent light is rampant. An incoherent beam of light spreads out after a short distance, becoming wider and wider and less intense with increased distance.
Even if a beam is filtered to be monochromatic, it is still incoherent.

The waves are out of phase and interfere with one another. The slightest differences in their directions result in a spreading with increased distance.
Coherent Light

A beam of light that has the same frequency, phase, and direction is said to be coherent.

There is no interference of waves within the beam. Only a beam of coherent light will not spread and diffuse.
31.6 Laser Light

Coherent light is produced by a laser (whose name comes from *light amplification by stimulated emission of radiation*). In a laser, a light wave emitted from one atom stimulates the emission of light from another atom so that the crests of each wave coincide.

These waves stimulate the emission of others in a cascade fashion, and a beam of coherent light is produced.
31.6 Laser Light

Operation of Lasers

A laser is not a source of energy. It converts energy, using stimulated emission to concentrate some of the energy input (commonly much less than 1%) into a thin beam of coherent light.

Like all devices, a laser can put out no more energy than it takes in.
31.6 Laser Light

In a helium-neon laser, a high voltage applied to a mixture of helium and neon gas energizes helium atoms to a state of high energy. Before the helium can emit light, it gives up its energy by collision with neon, which is boosted to a matched energy state. Light emitted by neon stimulates other energized neon atoms to emit matched-frequency light. The process cascades, and a coherent beam of light is produced.
31.6 Laser Light

Applications of Lasers

There are many applications for lasers.

- Surveyors and construction workers use lasers as “chalk lines.”
Applications of Lasers

There are many applications for lasers.

- Surveyors and construction workers use lasers as “chalk lines.”
- Surgeons use them as scalpels.
31.6 Laser Light

Applications of Lasers

There are many applications for lasers.

- Surveyors and construction workers use lasers as “chalk lines.”
- Surgeons use them as scalpels.
- Garment manufacturers use them as cloth-cutting saws.
31.6 Laser Light

Applications of Lasers

There are many applications for lasers.

- Surveyors and construction workers use lasers as “chalk lines.”
- Surgeons use them as scalpels.
- Garment manufacturers use them as cloth-cutting saws.
- They read product codes into cash registers and read the music and video signals in CDs and DVDs.
31.6 Laser Light

- Lasers are used to cut metals, transmit information through optical fibers, and measure speeds of vehicles for law enforcement purposes.
- Scientists have even been able to use lasers as “optical tweezers” that can hold and move objects.
31.6 Laser Light

What causes a laser to emit light?
31.7 The Hologram

A hologram is produced by the interference between two laser light beams on photographic film.
31.7 The Hologram

A hologram is a three-dimensional version of a photograph that contains the whole message or entire picture in every portion of its surface.

It appears to be an imageless piece of transparent film, but on its surface is a pattern of microscopic interference fringes. Light diffracted from these fringes produces an image that is extremely realistic.
31.7 The Hologram

Producing a Hologram

A hologram is produced by the interference between two laser light beams on photographic film. The two beams are part of one beam.

- One part illuminates the object and is reflected from the object to the film.
- The second part, called the *reference beam*, is reflected from a mirror to the film.

Interference between the reference beam and light reflected from the different points on the object produces a pattern of microscopic fringes on the film.
31.7 The Hologram

Light from nearer parts of the object travels shorter paths than light from farther parts of the object. The different distances traveled will produce slightly different interference patterns with the reference beam. Information about the depth of an object is recorded.
31.7 The Hologram

The laser light that exposes the photographic film is made up of two parts: one part is reflected from the object, and one part is reflected from the mirror.
31.7 The Hologram

Looking at a Hologram

When light falls on a hologram, it is diffracted by the fringed pattern.

It produces wave fronts identical in form to the original wave fronts reflected by the object.

The diffracted wave fronts produce the same effect as the original reflected wave fronts.
31.7 The Hologram

When you look through a hologram, you see a three-dimensional virtual image. You refocus your eyes to see near and far parts of the image, just as you do when viewing a real object. Converging diffracted light produces a real image in front of the hologram, which can be projected on a screen. Holographic pictures are extremely realistic.
31.7 The Hologram

When a hologram is illuminated with coherent light, the diverging diffracted light produces a three-dimensional \textit{virtual} image. Converging diffracted light produces a \textit{real} image.
31.7 The Hologram

If the hologram is made on film, you can cut it in half and still see the entire image on each half.
Every part of the hologram has received and recorded light from the entire object.
**31.7 The Hologram**

If holograms are made using short-wavelength light and viewed with light of a longer wavelength, the image is magnified in the same proportion as the wavelengths. Holograms made with X-rays would be magnified thousands of times when viewed with visible light.
31.7 The Hologram

How is a hologram produced?
Assessment Questions

1. Huygens’ principle for light is primarily described by
   a. waves.
   b. rays.
   c. particles.
   d. photons.
Assessment Questions

1. Huygens’ principle for light is primarily described by
   a. waves.
   b. rays.
   c. particles.
   d. photons.

Answer: A
Assessment Questions

2. At a lake surrounded by hills, you want to listen to a game. The only radio stations that come in are the AM stations, because the radio waves of AM broadcast bands are
   a. high-frequency, which diffract more.
   b. high-frequency, which diffract less.
   c. low-frequency, which diffract more.
   d. low-frequency, which diffract less.
2. At a lake surrounded by hills, you want to listen to a game. The only radio stations that come in are the AM stations, because the radio waves of AM broadcast bands are
   a. high-frequency, which diffract more.
   b. high-frequency, which diffract less.
   c. low-frequency, which diffract more.
   d. low-frequency, which diffract less.

Answer: C
Assessment Questions

3. When light undergoes interference, it
   a. can sometimes build up to more than the sum of amplitudes.
   b. can sometimes cancel completely.
   c. never cancels completely.
   d. can never be destructive interference.
When light undergoes interference, it
a. can sometimes build up to more than the sum of amplitudes.
b. can sometimes cancel completely.
c. never cancels completely.
d. can never be destructive interference.

Answer: B
Assessment Questions

4. A diffraction grating relies on light
   a. interference.
   b. amplitudes.
   c. variations in brightness.
   d. being composed of photons.
Assessment Questions

4. A diffraction grating relies on light
   a. interference.
   b. amplitudes.
   c. variations in brightness.
   d. being composed of photons.

Answer: A
Assessment Questions

5. When a beam of light reflects from a pair of closely spaced surfaces, color is produced because some of the reflected light is
   a. converted to a different frequency.
   b. deflected.
   c. subtracted from the beam.
   d. amplified.
Assessment Questions

5. When a beam of light reflects from a pair of closely spaced surfaces, color is produced because some of the reflected light is
   a. converted to a different frequency.
   b. deflected.
   c. subtracted from the beam.
   d. amplified.

Answer: C
Assessment Questions

6. Unlike incoherent light, light from a laser
   a. sometimes has the same frequency and phase.
   b. has the same speed and frequency and is out of phase.
   c. has the same phase, frequency, and speed.
   d. is chaotic.
Assessment Questions

6. Unlike incoherent light, light from a laser
   a. sometimes has the same frequency and phase.
   b. has the same speed and frequency and is out of phase.
   c. has the same phase, frequency, and speed.
   d. is chaotic.

Answer: C
Assessment Questions

7. A hologram makes best use of the phenomenon of
   a. reflection.
   b. refraction.
   c. diffraction.
   d. polarization.
Assessment Questions

7. A hologram makes best use of the phenomenon of
   a. reflection.
   b. refraction.
   c. diffraction.
   d. polarization.

Answer: C