THE BIG IDEA

Heat can be transferred by conduction, by convection, and by radiation.

The spontaneous transfer of heat is always from warmer objects to cooler objects. If several objects near one another have different temperatures, then those that are warm become cooler and those that are cool become warmer, until all have a common temperature.

22.1 Conduction

In conduction, collisions between particles transfer thermal energy, without any overall transfer of matter.

22.1 Conduction

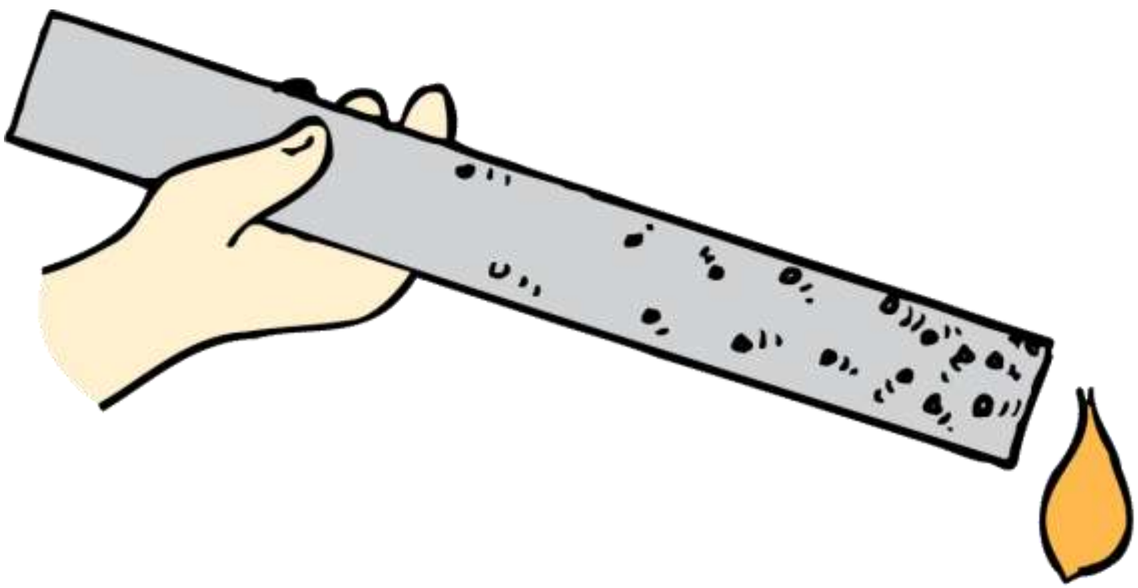
If you hold one end of an iron rod in a flame, the rod will become too hot to hold. Heat transfers through the metal by *conduction.*

Conduction of heat is the transfer of energy within materials and between different materials that are in direct contact.

Materials that conduct heat well are known as heat **conductors.**

22.1 Conduction

Heat from the flame causes atoms and free electrons in the end of the metal to move faster and jostle against others. The energy of vibrating atoms increases along the length of the rod.



22.1 Conduction

Conduction is explained by collisions between atoms or molecules, and the actions of loosely bound electrons.

- When the end of an iron rod is held in a flame, the atoms at the heated end vibrate more rapidly.
- These atoms vibrate against neighboring atoms.
- Free electrons that can drift through the metal jostle and transfer energy by colliding with atoms and other electrons.

22.1 Conduction

Conductors

Materials composed of atoms with “loose” outer electrons are good conductors of heat (and electricity also).

Because metals have the “loosest” outer electrons, they are the best conductors of heat and electricity.

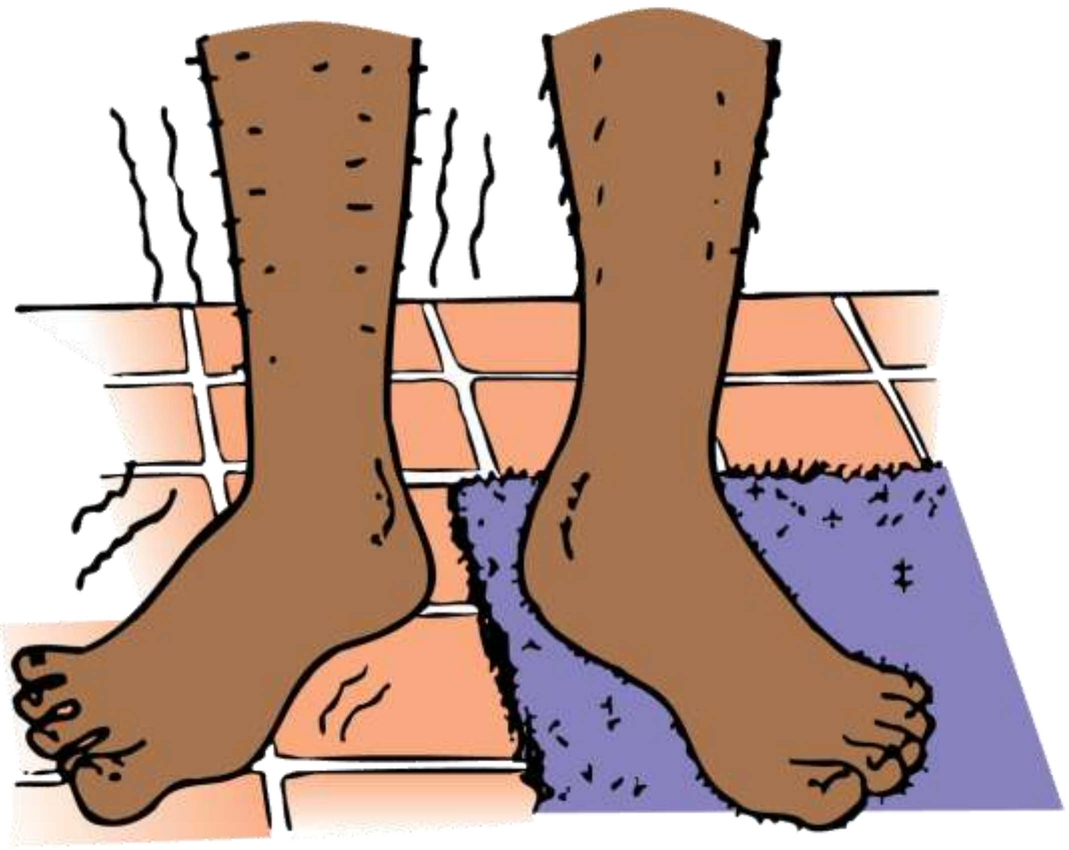
22.1 Conduction

Touch a piece of metal and a piece of wood in your immediate vicinity. Which one *feels* colder? Which is *really* colder?

- If the materials are in the same vicinity, they should have the same temperature, room temperature.
- The metal *feels* colder because it is a better conductor.
- Heat easily moves out of your warmer hand into the cooler metal.
- Wood, on the other hand, is a poor conductor.
- Little heat moves out of your hand into the wood, so your hand does not sense that it is touching something cooler.

22.1 Conduction

The tile floor feels cold to the bare feet, while the carpet at the same temperature feels warm. This is because tile is a better conductor than carpet.



22.1 Conduction

Insulators

Liquids and gases generally make poor conductors.

An **insulator** is any material that is a poor conductor of heat and that delays the transfer of heat.

- Air is a very good insulator.
- Porous materials having many small air spaces are good insulators.

22.1 Conduction

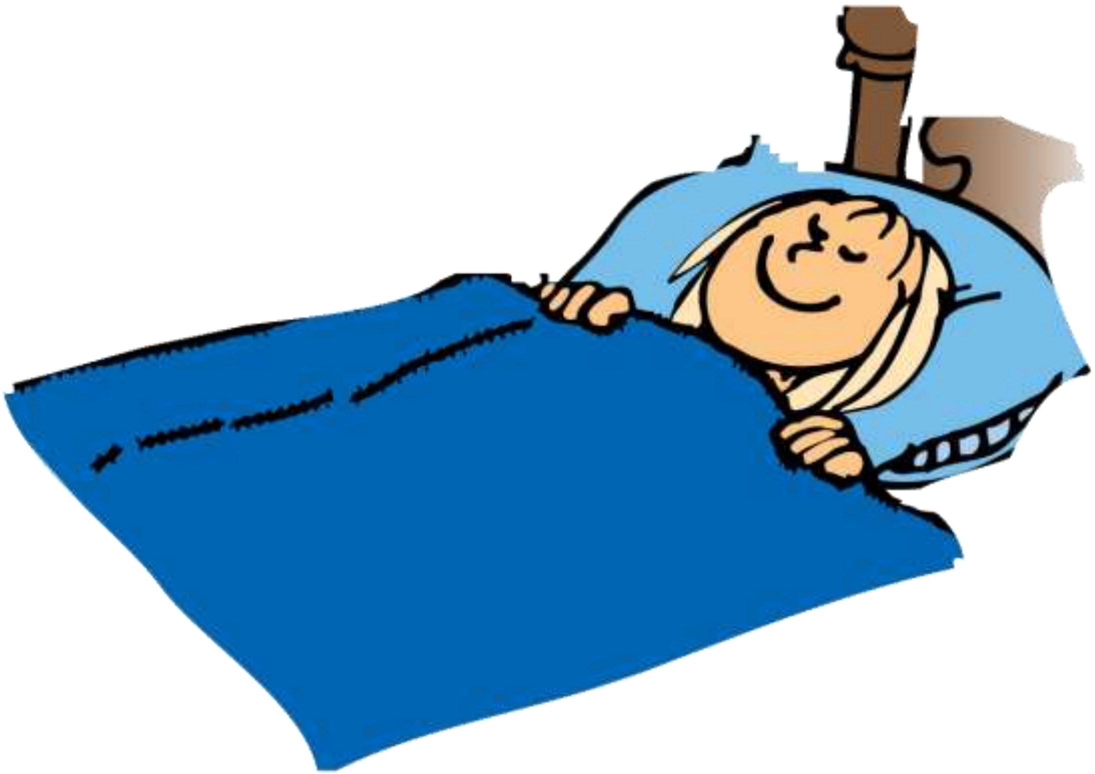
The good insulating properties of materials such as wool, wood, straw, paper, cork, polystyrene, fur, and feathers are largely due to the air spaces they contain.

Birds fluff their feathers to create air spaces for insulation.

Snowflakes imprison a lot of air in their crystals and are good insulators. Snow is not a source of heat; it simply prevents any heat from escaping too rapidly.

22.1 Conduction

A "warm" blanket does not provide you with heat; it simply slows the transfer of your body heat to the surroundings.



22.1 Conduction

Strictly speaking, there is no “cold” that passes through a conductor or an insulator.

Only heat is transferred. We don’t insulate a home to keep the cold out; we insulate to keep the heat in.

No insulator can totally prevent heat from getting through it. Insulation slows down heat transfer.

22.1 Conduction

Snow lasts longest on the roof of a well-insulated house. The houses with more snow on the roof are better insulated.

22.1 Conduction

think!

If you hold one end of a metal bar against a piece of ice, the end in your hand will soon become cold. Does cold flow from the ice to your hand?

22.1 Conduction

think!

If you hold one end of a metal bar against a piece of ice, the end in your hand will soon become cold. Does cold flow from the ice to your hand?

Answer:

Cold does not flow from the ice to your hand. Heat flows from your hand to the ice. The metal is cold to your touch because you are transferring heat to the metal.

22.1 Conduction

think!

You can place your hand into a hot pizza oven for several seconds without harm, whereas you'd never touch the metal inside surfaces for even a second. Why?

22.1 Conduction

think!

You can place your hand into a hot pizza oven for several seconds without harm, whereas you'd never touch the metal inside surfaces for even a second. Why?

Answer:

Air is a poor conductor, so the rate of heat flow from the hot air to your relatively cool hand is low. But touching the metal parts is a different story. Metal conducts heat very well, and a lot of heat in a short time is conducted into your hand when thermal contact is made.

22.1 Conduction

CONCEPT CHECK

How does conduction transfer heat?

22.2 Convection

In convection, heat is transferred by movement of the hotter substance from one place to another.

22.2 Convection

Another means of heat transfer is by movement of the hotter substance.

- Air in contact with a hot stove rises and warms the region above.
- Water heated in a boiler in the basement rises to warm the radiators in the upper floors.

This is **convection,** a means of heat transfer by movement of the heated substance itself, such as by currents in a fluid.

22.2 Convection

Convection occurs in all fluids, liquid or gas.

When the fluid is heated, it expands, becomes less dense, and rises.

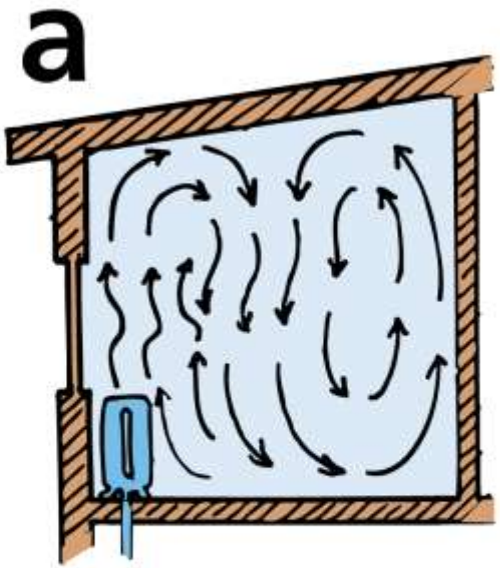
Cooler fluid then moves to the bottom, and the process continues.

In this way, convection currents keep a fluid stirred up as it heats.

22.2 Convection

Convection occurs in all fluids.

a. Convection currents transfer heat in air.

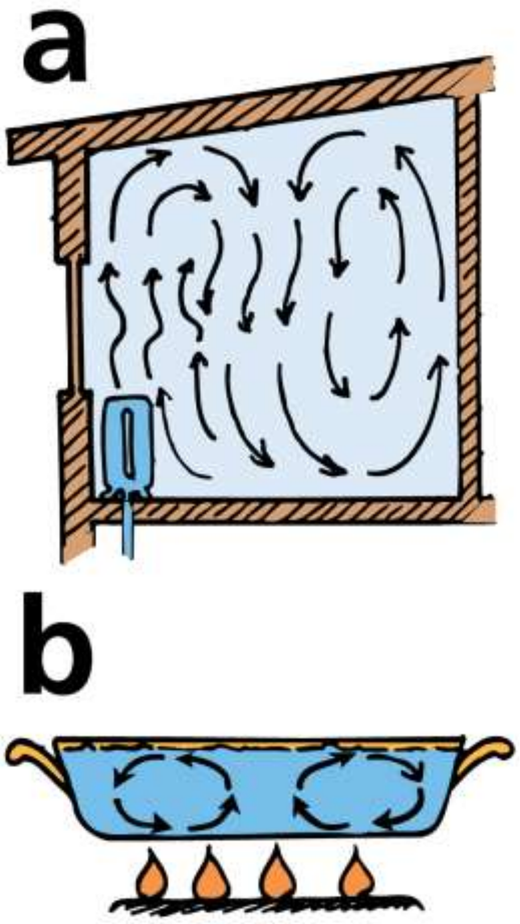


22.2 Convection

Convection occurs in all fluids.

a. Convection currents transfer heat in air.

b. Convection currents transfer heat in liquid.



22.2 Convection

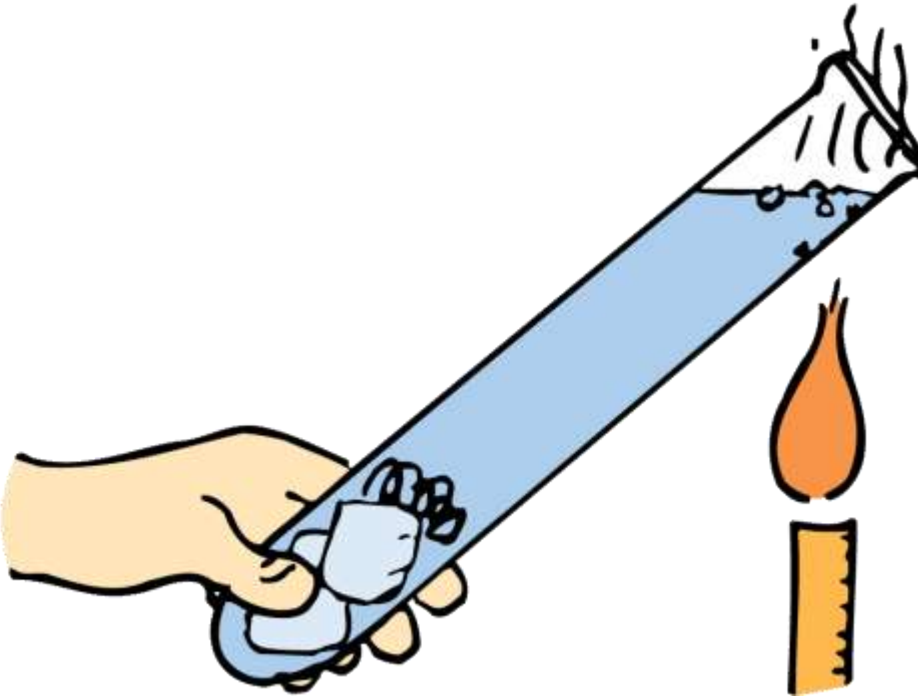
With a bit of steel wool, trap a piece of ice at the bottom of a test tube nearly filled with water.

Place the top of the tube in the flame of a Bunsen burner.

The water at the top will come to a vigorous boil while the ice below remains unmelted.

22.2 Convection

When the test tube is heated at the top, convection is prevented and heat can reach the ice by conduction only. Since water is a poor conductor, the top water will boil without melting the ice.

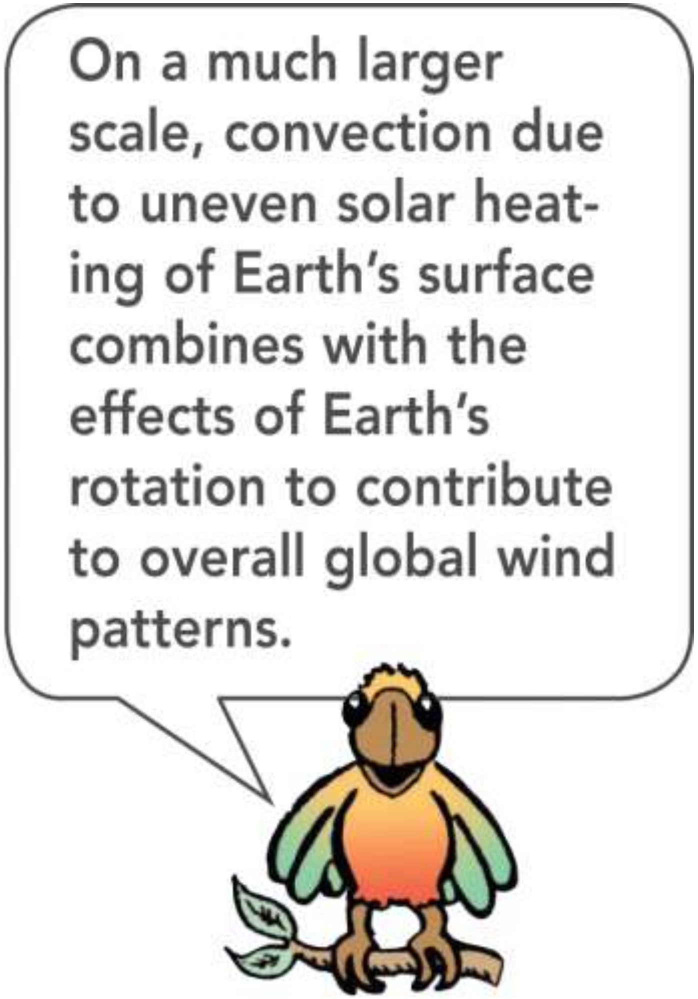


22.2 Convection

Moving Air

Convection currents stirring the atmosphere produce winds.

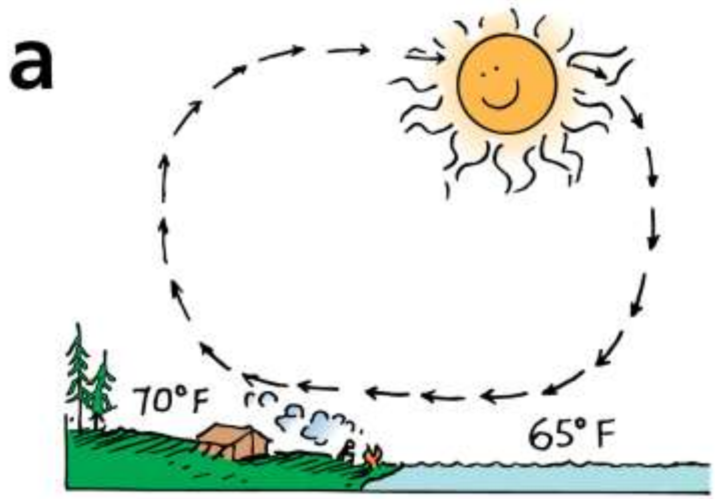
- Some parts of Earth's surface absorb heat from the sun more readily than others.
- The uneven absorption causes uneven heating of the air near the surface and creates convection currents.



22.2 Convection

Convection currents are produced by uneven heating.

a. During the day, the land is warmer than the air, and a sea breeze results.

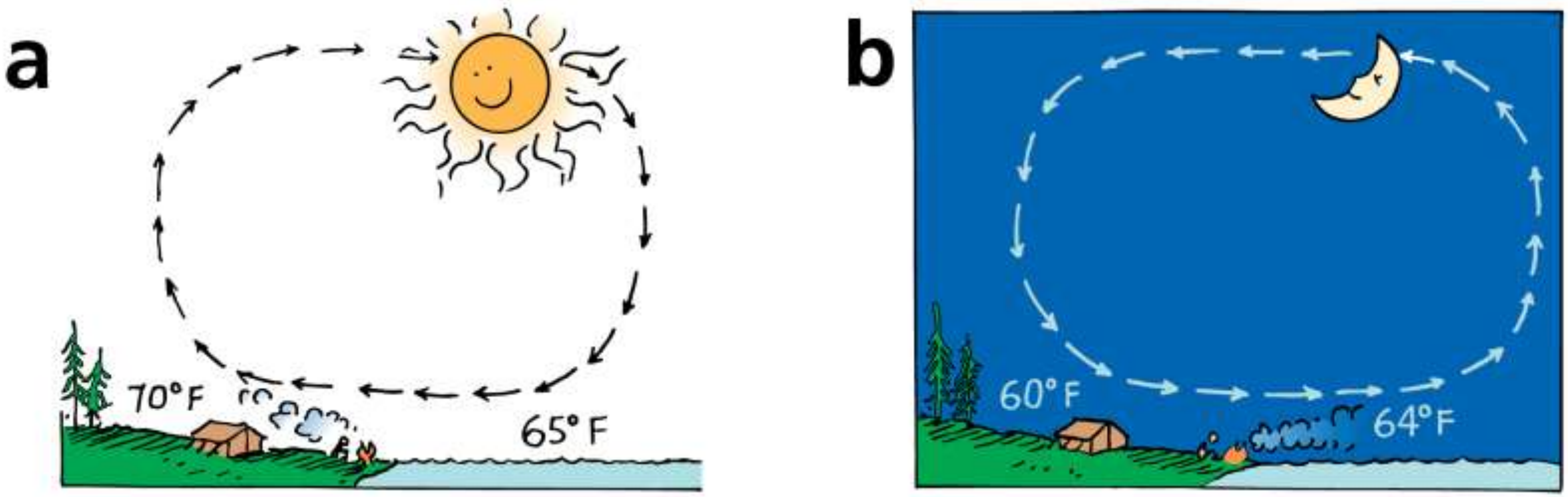


22.2 Convection

Convection currents are produced by uneven heating.

a. During the day, the land is warmer than the air, and a sea breeze results.

b. At night, the land is cooler than the water, so the air flows in the other direction.



22.2 Convection

Cooling Air

Rising warm air, like a rising balloon, expands because less atmospheric pressure squeezes on it at higher altitudes.

As the air expands, it cools—just the opposite of what happens when air is compressed.

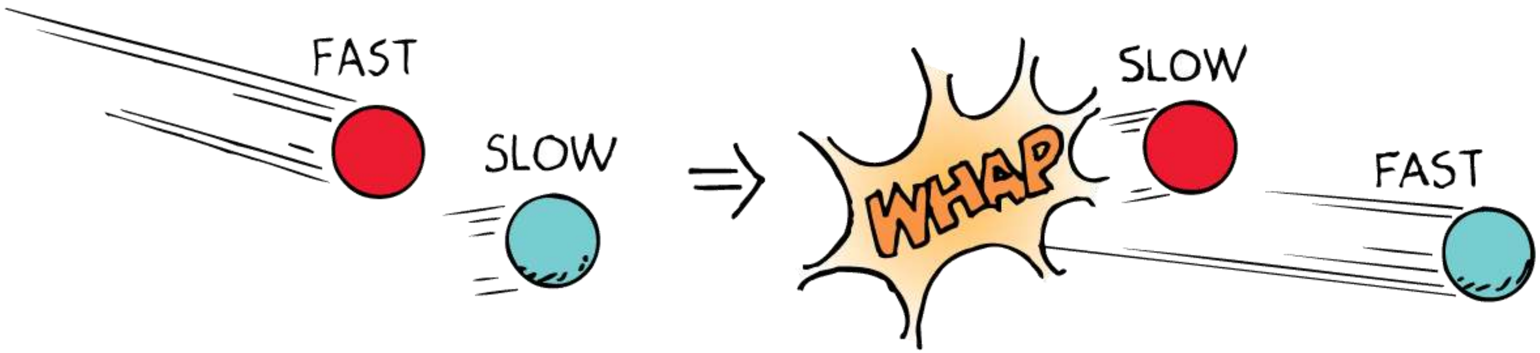
22.2 Convection

Think of molecules of air as tiny balls bouncing against one another.

- Speed is picked up by a ball when it is hit by another that approaches with a greater speed.
- When a ball collides with one that is receding, its rebound speed is reduced.

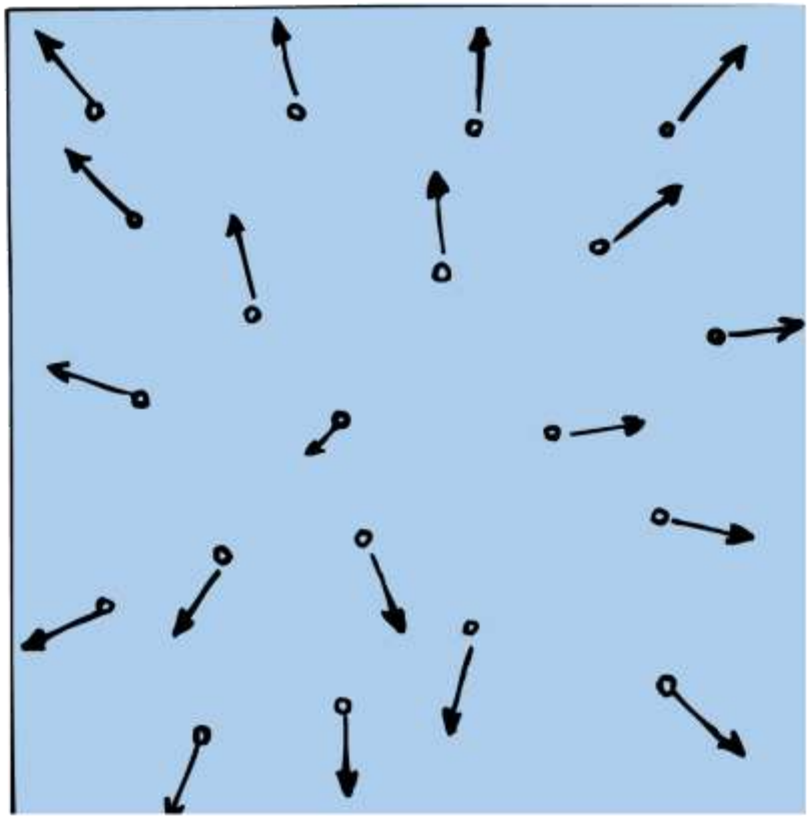
22.2 Convection

When a molecule collides with a molecule that is receding, its rebound speed after the collision is less than before the collision.



22.2 Convection

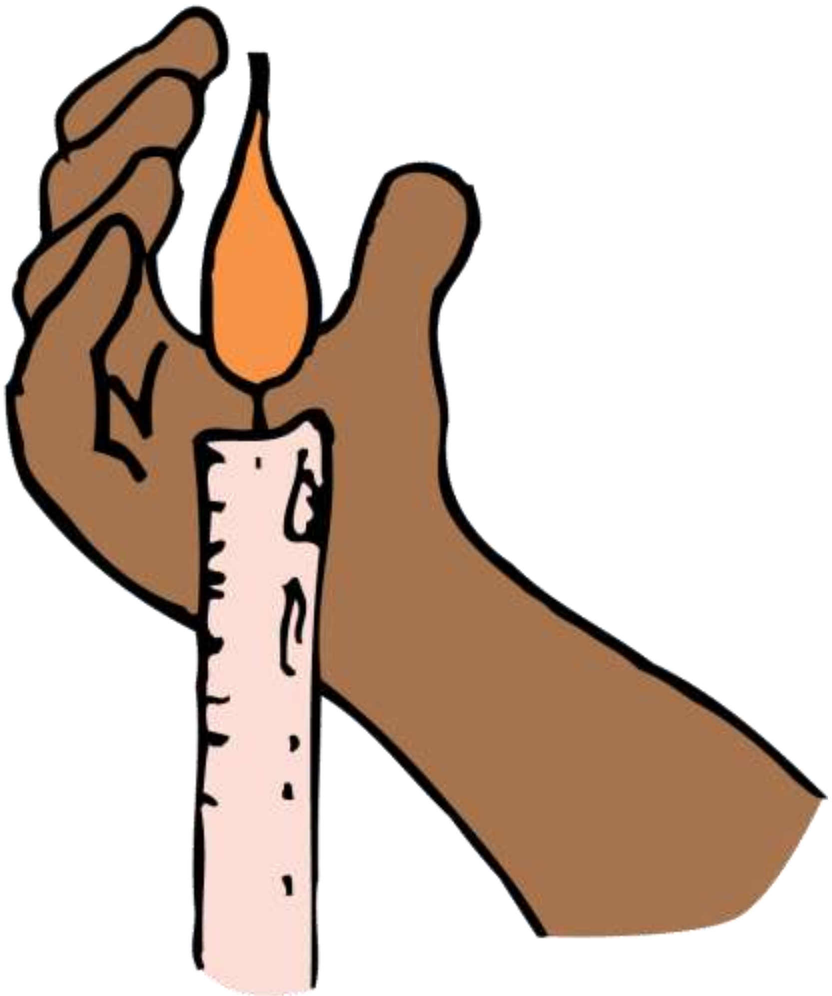
Molecules in a region of expanding air collide more often with receding molecules than with approaching ones.



22.2 Convection

think!

You can hold your fingers beside the candle flame without harm, but not above the flame. Why?



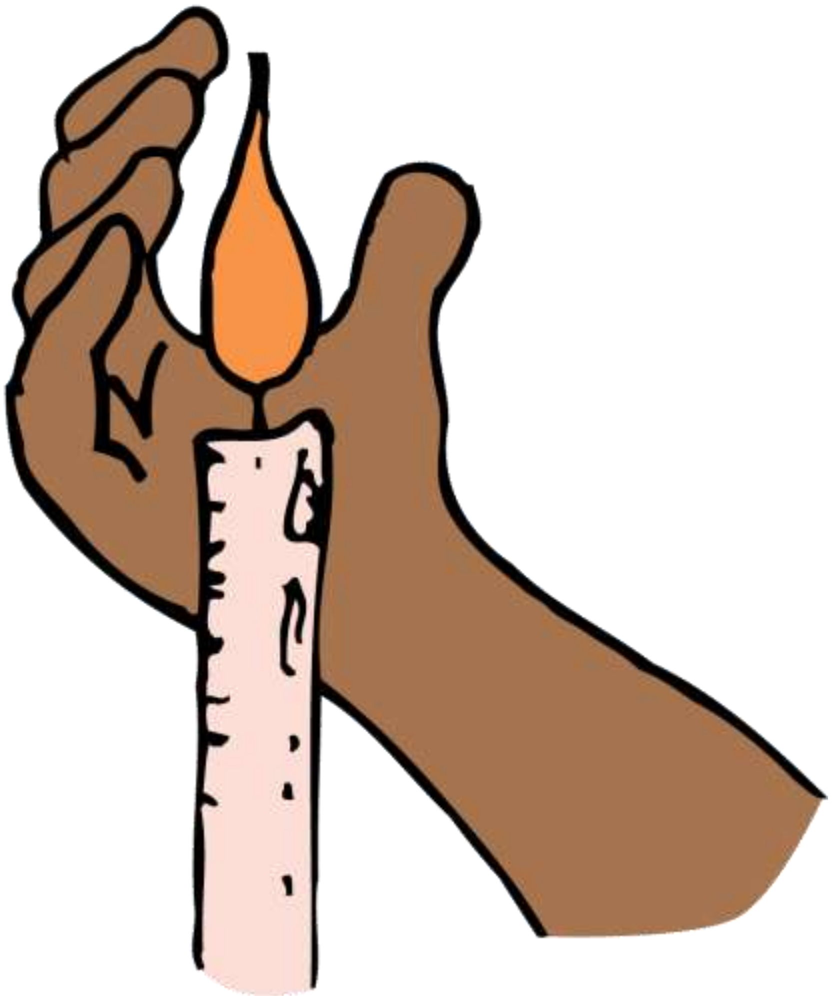
22.2 Convection

think!

You can hold your fingers beside the candle flame without harm, but not above the flame. Why?

Answer:

Heat travels up by convection. Air is a poor conductor, so very little heat travels sideways.



22.2 Convection

CONCEPT CHECK

How does convection transfer heat?

22.3 Radiation

In radiation, heat is transmitted in the form of radiant energy, or electromagnetic waves.

22.3 Radiation

How does the sun warm Earth's surface?

It can't be through conduction or convection, because there is nothing between Earth and the sun.

The sun's heat is transmitted by another process.

Radiation is energy transmitted by *electromagnetic waves*. Radiation from the sun is primarily light.

22.3 Radiation

Radiant energy is any energy that is transmitted by radiation.

From the longest wavelength to the shortest, this includes:

- radio waves,
- microwaves,
- infrared radiation,
- visible light,
- ultraviolet radiation,
- X-rays,
- and gamma rays.

22.3 Radiation

a. Radio waves send signals through the air.

a

22.3 Radiation

a. Radio waves send signals through the air.

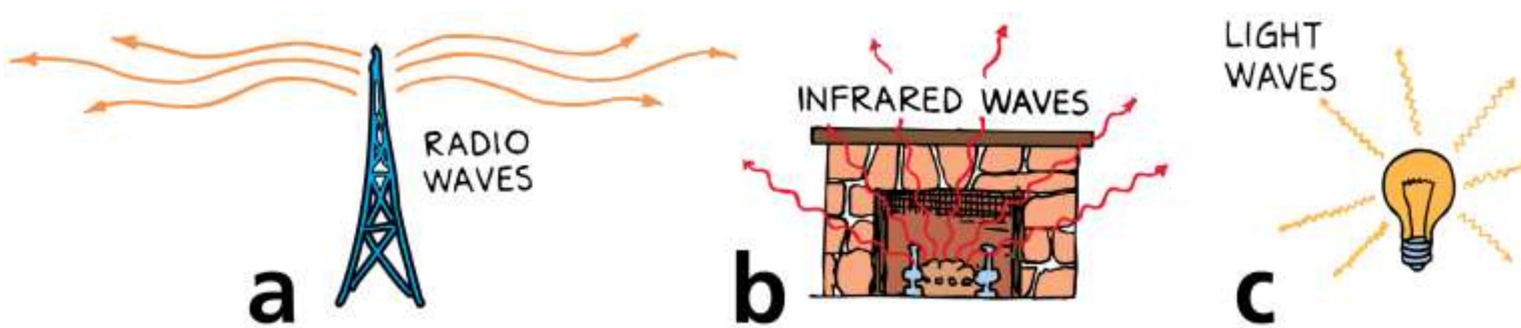
b. You feel infrared waves as heat.

22.3 Radiation

a. Radio waves send signals through the air.

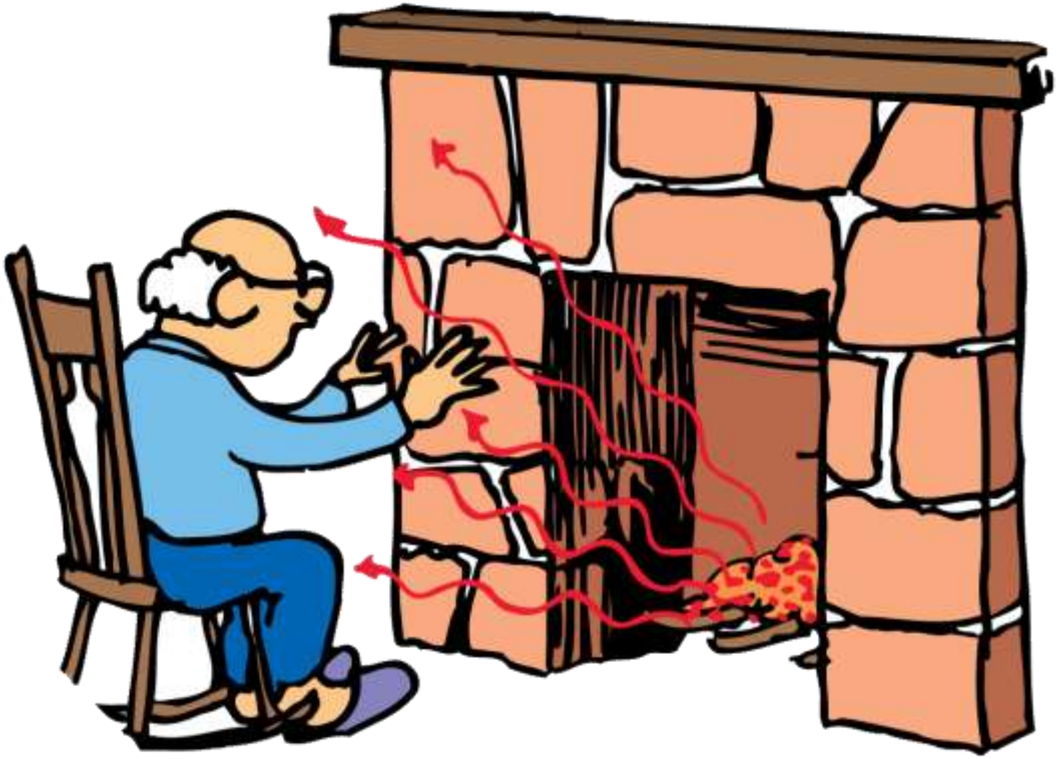
b. You feel infrared waves as heat.

c. A visible form of radiant energy is light waves.



22.3 Radiation

Most of the heat from a fireplace goes up the chimney by convection. The heat that warms us comes to us by radiation.



22.3 Radiation

CONCEPT CHECK

How does radiation transmit heat?

22.4 Emission of Radiant Energy

All substances continuously emit radiant energy in a mixture of wavelengths.

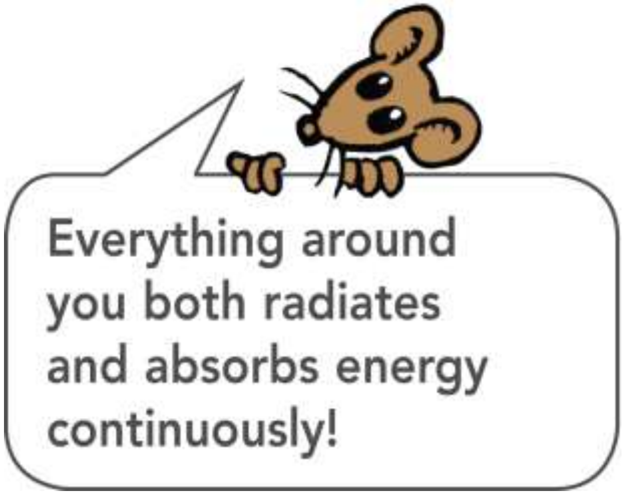
22.4 Emission of Radiant Energy

Objects at low temperatures emit long waves. Higher-temperature objects emit waves of shorter wavelengths.

Objects around you emit radiation mostly in the long-wavelength end of the infrared region, between radio and light waves.

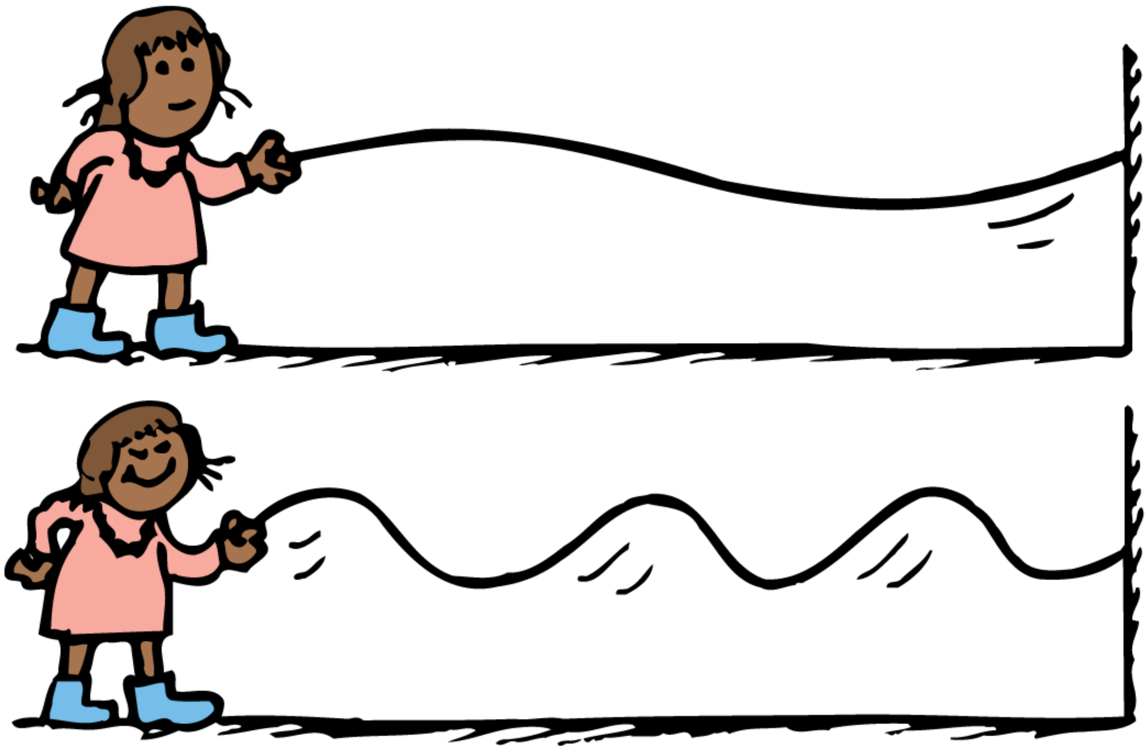
Shorter-wavelength infrared waves are absorbed by our skin, producing the sensation of heat.

Heat radiation is infrared radiation.



22.4 Emission of Radiant Energy

Shorter wavelengths are produced when the rope is shaken more rapidly.



22.4 Emission of Radiant Energy

The fact that all objects in our environment continuously emit infrared radiation underlies infrared thermometers.

Simply point the thermometer at something whose temperature you want, press a button, and a digital temperature reading appears.

22.4 Emission of Radiant Energy

An infrared thermometer measures the infrared radiant energy emitted by a body and converts it to temperature.

22.4 Emission of Radiant Energy

The radiation emitted by the object provides the reading.

The average frequency $\bar{f}$ of radiant energy is directly proportional to the Kelvin temperature *T* of the emitter:

$$\bar{f} \sim T$$

Typical classroom infrared thermometers operate in the range of about -30°C to 200°C.

22.4 Emission of Radiant Energy

People, with a surface temperature of 310 K, emit light in the low-frequency infrared part of the spectrum.

Very hot objects emit radiant energy in the range of visible light.

- At 500°C an object emits red light, longest waves we can see.
- Higher temperatures produce a yellowish light.
- At about 1500°C all the waves to which the eye is sensitive are emitted and we see an object as "white hot."

22.4 Emission of Radiant Energy

A blue-hot star is hotter than a white-hot star, and a red-hot star is less hot.

Since the color blue has nearly twice the frequency of red, a blue-hot star has nearly twice the surface temperature of a red-hot star.

The radiant energy emitted by the stars is called **stellar radiation.**

22.4 Emission of Radiant Energy

The surface of the sun has a high temperature (5500°C).

It emits radiant energy at a high frequency—much of it in the visible portion of the electromagnetic spectrum.

The surface of Earth, by comparison, is cool and the radiant energy it emits consists of frequencies lower than those of visible light.

22.4 Emission of Radiant Energy

Radiant energy emitted by Earth is called **terrestrial radiation.**

Much of Earth's energy is fueled by radioactive decay in its interior. The source of the sun's radiant energy involves thermonuclear fusion in its deep interior.

Both the sun and Earth glow—the sun at high visible frequencies and Earth at low infrared frequencies.

22.4 Emission of Radiant Energy

think!

Why is it that light radiated by the sun is yellowish, but light radiated by Earth is infrared?

22.4 Emission of Radiant Energy

think!

Why is it that light radiated by the sun is yellowish, but light radiated by Earth is infrared?

Answer:

The sun has a higher temperature than Earth. Earth radiates in the infrared because its temperature is relatively low compared to the sun.

22.4 Emission of Radiant Energy

CONCEPT CHECK

What substances emit radiant energy?

22.5 Absorption of Radiant Energy

Good emitters of radiant energy are also good absorbers; poor emitters are poor absorbers.

22.5 Absorption of Radiant Energy

If everything is emitting energy, why doesn't everything finally run out of it?

Everything also absorbs energy from its environment.

22.5 Absorption of Radiant Energy

Absorption and Emission

A book sitting on your desk is both absorbing and radiating energy at the same rate.

It is in *thermal equilibrium* with its environment.

Now move the book out into the bright sunshine.

22.5 Absorption of Radiant Energy

Because the sun shines on it, the book absorbs more energy than it radiates.

- Its temperature increases.
- As the book gets hotter, it radiates more energy.
- Eventually it reaches a *new* thermal equilibrium and it radiates as much energy as it receives.
- In the sunshine the book remains at this new higher temperature.

22.5 Absorption of Radiant Energy

If you move the book back indoors, the opposite process occurs.

- The hot book initially radiates more energy than it receives from its surroundings.
- It cools and radiates less energy.
- At a sufficiently lowered temperature it radiates no more energy than it receives from the room.
- It has reached thermal equilibrium again.

22.5 Absorption of Radiant Energy

A blacktop pavement and dark automobile body may remain hotter than their surroundings on a hot day.

At nightfall these dark objects cool faster! Sooner or later, all objects in thermal contact come to thermal equilibrium.

So a dark object that absorbs radiant energy well emits radiation equally well.

22.5 Absorption of Radiant Energy

Absorption and Reflection

Absorption and reflection are opposite processes.

- A good absorber of radiant energy reflects very little radiant energy, including the range of radiant energy we call light.
- A good absorber therefore appears dark.
- A perfect absorber reflects no radiant energy and appears perfectly black.

22.5 Absorption of Radiant Energy

Look at the open ends of pipes in a stack. The holes appear black.

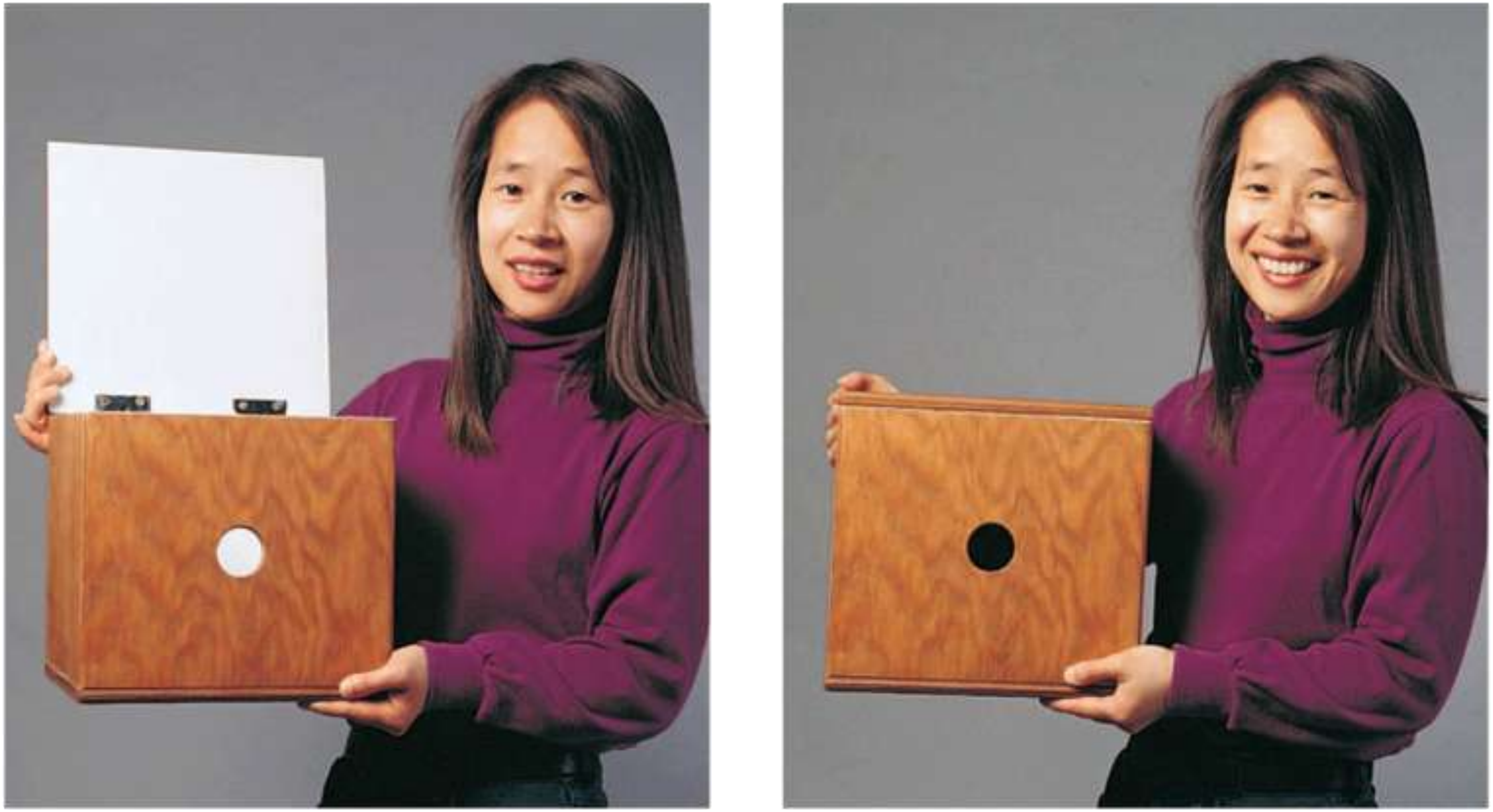
Look at open doorways or windows of distant houses in the daytime, and they, too, look black.

Openings appear black because the radiant energy that enters is reflected from the inside walls many times.

It is partly absorbed at each reflection until very little or none remains to come back out.

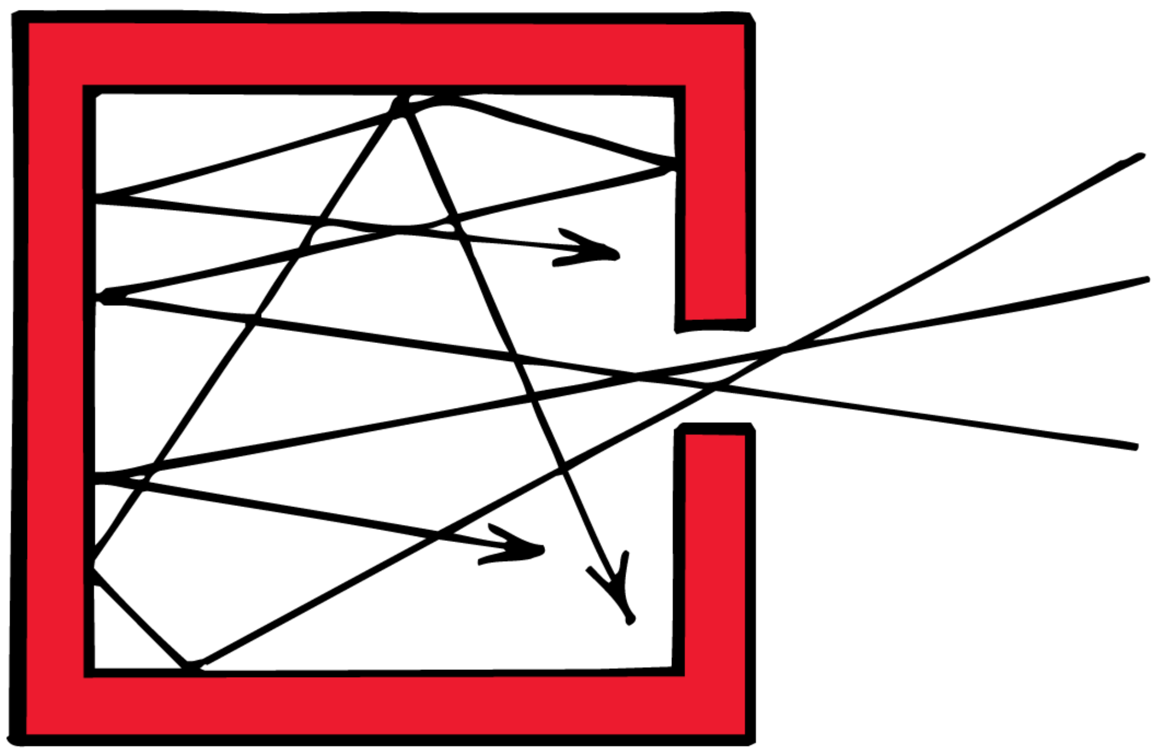
22.5 Absorption of Radiant Energy

Even though the interior of the box has been painted white, the hole looks black.



22.5 Absorption of Radiant Energy

Radiant energy that enters an opening has little chance of leaving before it is completely absorbed.



22.5 Absorption of Radiant Energy

Good reflectors, on the other hand, are poor absorbers.

Light-colored objects reflect more light and heat than dark-colored ones.

In summer, light-colored clothing keeps people cooler.

22.5 Absorption of Radiant Energy

Anything with a mirrorlike surface reflects most of the radiant energy it encounters, so it is a poor absorber of radiant energy.

22.5 Absorption of Radiant Energy

On a sunny day Earth’s surface is a net absorber.

At night it is a net emitter.

On a cloudless night its “surroundings” are the frigid depths of space and cooling is faster than on a cloudy night.

Record-breaking cold nights occur when the skies are clear.

22.5 Absorption of Radiant Energy

When you're in the direct light of the sun, step in and out of the shade.

You'll note the difference in the radiant energy you receive.

Then think about the enormous amount of energy the sun emits to reach you some 150,000,000 kilometers distant.

22.5 Absorption of Radiant Energy

think!

If a good absorber of radiant energy were a poor emitter, how would its temperature compare with its surroundings?

22.5 Absorption of Radiant Energy

think!

If a good absorber of radiant energy were a poor emitter, how would its temperature compare with its surroundings?

Answer:

If a good absorber were not also a good emitter, there would be a net absorption of radiant energy and the temperature of a good absorber would remain higher than the temperature of the surroundings. Things around us approach a common temperature only because good absorbers are, by their very nature, also good emitters.

22.5 Absorption of Radiant Energy

CONCEPT CHECK

How does an object's emission rate compare with its absorption rate?

22.6 Newton's Law of Cooling

The colder an object's surroundings, the faster the object will cool.

22.6 Newton's Law of Cooling

An object hotter than its surroundings eventually cools to match the surrounding temperature.

Its *rate* of cooling is how many degrees its temperature changes per unit of time.

The rate of cooling of an object depends on how much hotter the object is than the surroundings.

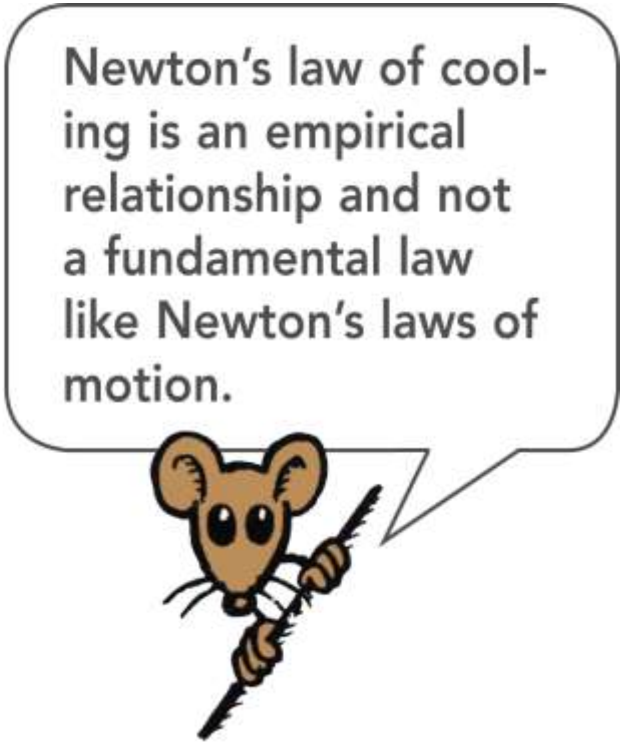
22.6 Newton's Law of Cooling

This principle is known as *Newton's law of cooling.*

Newton's law of cooling states that the rate of cooling of an object is approximately proportional to the temperature difference (ΔT) between the object and its surroundings:

rate of cooling ~ ΔT

It applies to conduction, convection, or radiation.



22.6 Newton's Law of Cooling

Newton's law of cooling also holds for heating.

If an object is cooler than its surroundings, its rate of warming up is also proportional to ΔT.

22.6 Newton's Law of Cooling

think!

Since a hot cup of tea loses heat more rapidly than a lukewarm cup of tea, would it be correct to say that a hot cup of tea will cool to room temperature before a lukewarm cup of tea will? Explain.

22.6 Newton's Law of Cooling

think!

Since a hot cup of tea loses heat more rapidly than a lukewarm cup of tea, would it be correct to say that a hot cup of tea will cool to room temperature before a lukewarm cup of tea will? Explain.

Answer:

No! Although the rate of cooling is greater for the hotter cup, it has farther to cool to reach thermal equilibrium. The extra time is equal to the time the hotter cup takes to cool to the initial temperature of the lukewarm cup of tea.

22.6 Newton's Law of Cooling

CONCEPT CHECK

What causes an object to cool faster?

22.7 Global Warming and the Greenhouse Effect

The near unanimous view of climate scientists is that human activity is a main driver of global warming and climate change.

22.7 Global Warming and the Greenhouse Effect

An automobile sitting in the bright sun on a hot day with its windows rolled up can get very hot inside.

This is an example of the *greenhouse effect*.

The **greenhouse effect** is the warming of a planet's surface due to the trapping of radiation by the planet's atmosphere.

22.7 Global Warming and the Greenhouse Effect

Causes of the Greenhouse Effect

All things radiate, and the frequency and wavelength of radiation depends on the temperature of the object emitting the radiation.

The transparency of things such as air and glass depends on the wavelength of radiation.

Air is transparent to both infrared (long) waves and visible (short) waves.

22.7 Global Warming and the Greenhouse Effect

If the air contains excess carbon dioxide and water vapor, it absorbs infrared waves.

Glass is transparent to visible light waves, but absorbs infrared waves.

22.7 Global Warming and the Greenhouse Effect

Why does a car get so hot in bright sunlight?

The wavelengths of waves the sun radiates are very short.

These short waves easily pass through both Earth's atmosphere and the glass windows of the car.

Energy from the sun gets into the car interior, where, except for some reflection, it is absorbed. The interior of the car warms up.

22.7 Global Warming and the Greenhouse Effect

The car interior radiates its own waves, but since it is not as hot as the sun, the radiated waves are longer.

The reradiated long waves encounter glass windows that aren’t transparent to them.

Most of the reradiated energy remains in the car, which makes the car’s interior even warmer.

22.7 Global Warming and the Greenhouse Effect

The same effect occurs in Earth's atmosphere, which is transparent to solar radiation.

- Earth's surface absorbs this energy, and reradiates part of this at longer wavelengths.
- Atmospheric gases (mainly water vapor, carbon dioxide, and methane) absorb and re-emit long-wavelength terrestrial radiation back to Earth.
- So the long-wavelength radiation that cannot escape Earth's atmosphere warms Earth.

22.7 Global Warming and the Greenhouse Effect

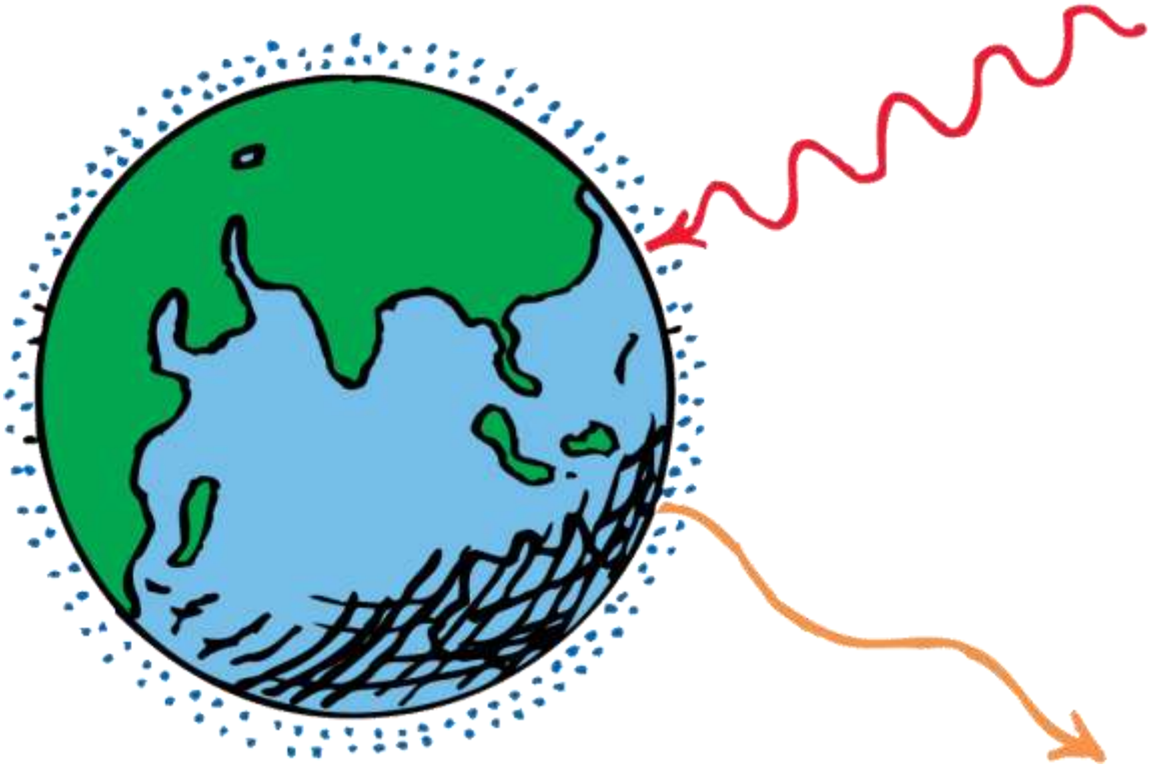
Without this warming process, Earth would be a frigid -18°C.

However, increased levels of carbon dioxide and other atmospheric gases in the atmosphere may further increase the temperature.

This would produce a new thermal balance unfavorable to the biosphere.

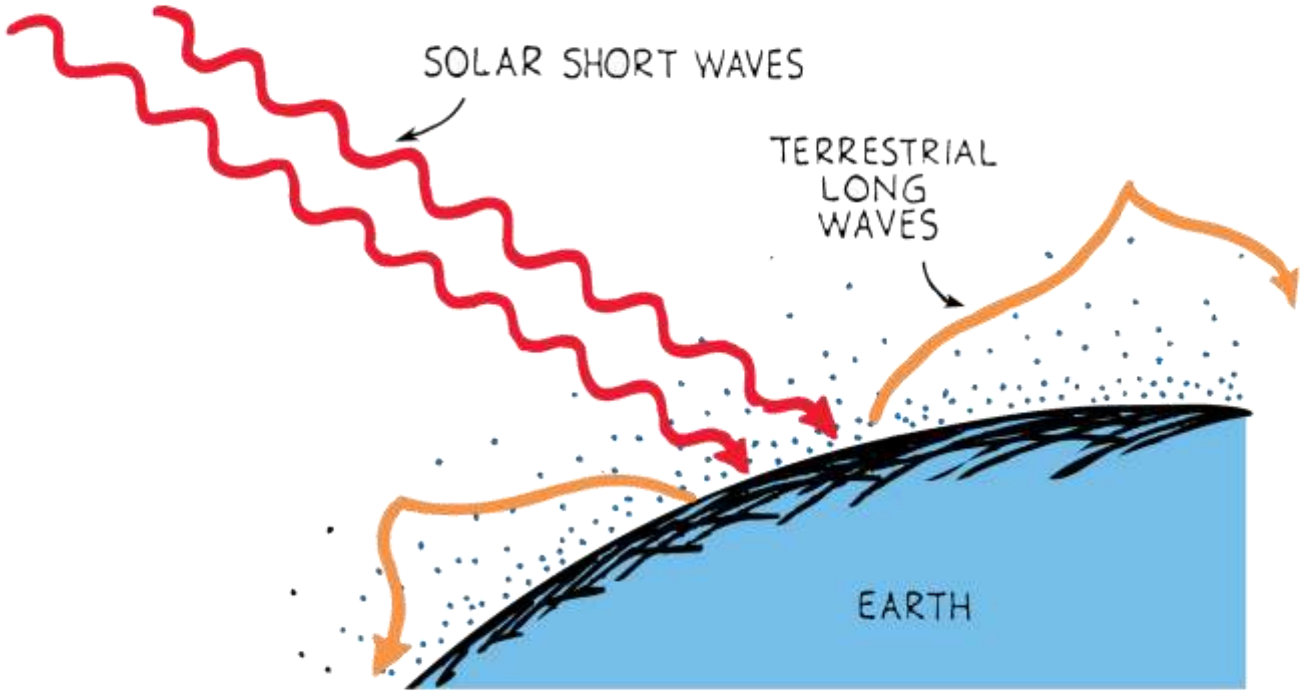
22.7 Global Warming and the Greenhouse Effect

Earth’s temperature depends on the energy balance between incoming solar radiation and outgoing terrestrial radiation.



22.7 Global Warming and the Greenhouse Effect

Earth's atmosphere acts as a one-way valve. It allows visible light from the sun in, but because of its water vapor and carbon dioxide content, it prevents terrestrial radiation from leaving.



22.7 Global Warming and the Greenhouse Effect

Consequences of the Greenhouse Effect

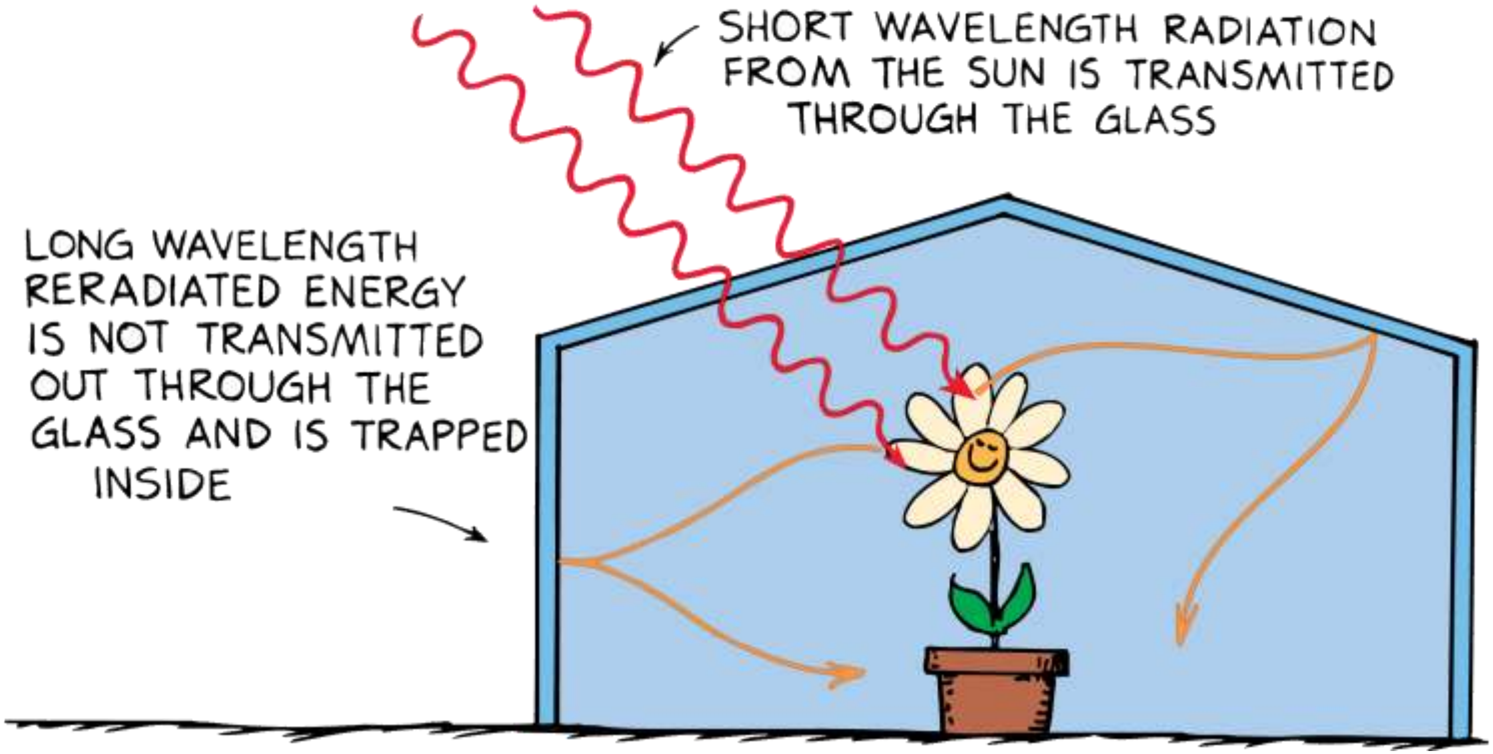
Averaged over a few years, the solar radiation that strikes Earth exactly balances the terrestrial radiation Earth emits into space.

This balance results in the average temperature of Earth—a temperature that presently supports life as we know it.

Over a period of decades, Earth's average temperature can be changed—by natural causes and also by human activity.

22.7 Global Warming and the Greenhouse Effect

Shorter-wavelength radiant energy from the sun enters. The soil emits long-wavelength radiant energy. Income exceeds outgo, so the interior is warmed.

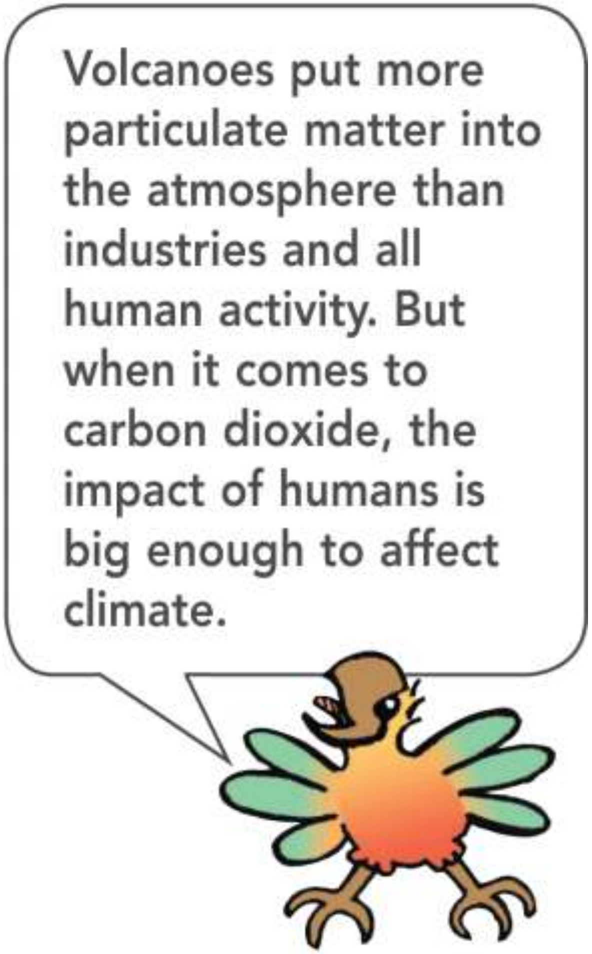


22.7 Global Warming and the Greenhouse Effect

Materials such as those from the burning of fossil fuels change the absorption and reflection of solar radiation.

Except where the source of energy is solar, wind, or water, increased energy consumption on Earth adds heat.

These activities can change the radiative balance and change Earth's average temperature.



22.7 Global Warming and the Greenhouse Effect

Although water vapor is the main greenhouse gas, CO_2 is the gas most rapidly increasing in the atmosphere.

Concern doesn't stop there, for further warming by CO_2 can produce more water vapor as well.

The greater concern is the combination of growing amounts of both these greenhouse gases.

22.7 Global Warming and the Greenhouse Effect

CONCEPT CHECK

How does human activity affect climate change?

Assessment Questions

1. Thermal conduction has much to do with
   a. electrons.
   b. protons.
   c. neutrons.
   d. ions.

Assessment Questions

1. Thermal conduction has much to do with
   a. electrons.
   b. protons.
   c. neutrons.
   d. ions.

Answer: A

Assessment Questions

2. Thermal convection has much to do with
   a. radiant energy.
   b. fluids.
   c. insulators.
   d. conductors.

Assessment Questions

2. Thermal convection has much to do with
   a. radiant energy.
   b. fluids.
   c. insulators.
   d. conductors.

Answer: B

Assessment Questions

3. Heat comes from the sun to Earth by the process of
   a. conduction.
   b. convection.
   c. radiation.
   d. insulation.

Assessment Questions

3. Heat comes from the sun to Earth by the process of
   a. conduction.
   b. convection.
   c. radiation.
   d. insulation.

Answer: C

Assessment Questions

4. A high-temperature source radiates relatively
   a. high-frequency waves with short wavelengths.
   b. high-frequency waves with long wavelengths.
   c. low-frequency waves with long wavelengths.
   d. low-frequency waves with short wavelengths.

Assessment Questions

4. A high-temperature source radiates relatively
   a. high-frequency waves with short wavelengths.
   b. high-frequency waves with long wavelengths.
   c. low-frequency waves with long wavelengths.
   d. low-frequency waves with short wavelengths.

Answer: A

Assessment Questions

5. An object that absorbs energy well also
   a. conducts well.
   b. convects well.
   c. radiates well.
   d. insulates well.

Assessment Questions

5. An object that absorbs energy well also
   a. conducts well.
   b. convects well.
   c. radiates well.
   d. insulates well.

Answer: C

Assessment Questions

6. Newton's law of cooling applies to objects that
   a. cool.
   b. warm up.
   c. both of these
   d. neither of these

Assessment Questions

6. Newton's law of cooling applies to objects that
   a. cool.
   b. warm up.
   c. both of these
   d. neither of these

Answer: C

Assessment Questions

7. Compared with radiation from the sun, terrestrial radiation has a lower frequency. How does this affect climate change?
   a. Lower-frequency radiation, in the form of CO_2, is trapped in Earth's atmosphere. This combined with the incoming radiation from the sun causes the temperature on Earth to rise.
   b. Lower-frequency radiation, in the form of CO_2, leaves Earth's atmosphere more rapidly than the incoming radiation from the sun, causing the temperature on Earth to rise.
   c. Lower-frequency radiation, in the form of water vapor, is trapped in Earth's atmosphere. This combined with the incoming radiation from the sun causes the temperature on Earth to lower.
   d. Lower-frequency radiation, in the form of water vapor, is trapped in Earth's atmosphere. This combined with the incoming radiation from the sun causes the temperature on Earth to rise.

Assessment Questions

7. Compared with radiation from the sun, terrestrial radiation has a lower frequency. How does this affect climate change?
   a. Lower-frequency radiation, in the form of CO_2, is trapped in Earth's atmosphere. This combined with the incoming radiation from the sun causes the temperature on Earth to rise.
   b. Lower-frequency radiation, in the form of CO_2, leaves Earth's atmosphere more rapidly than the incoming radiation from the sun, causing the temperature on Earth to rise.
   c. Lower-frequency radiation, in the form of water vapor, is trapped in Earth's atmosphere. This combined with the incoming radiation from the sun causes the temperature on Earth to lower.
   d. Lower-frequency radiation, in the form of water vapor, is trapped in Earth's atmosphere. This combined with the incoming radiation from the sun causes the temperature on Earth to rise.

Answer: A