Matter and Energy

Heat Transfer

- Heat Conduction
- Convection
- Radiation

Objectives

1. Explain the relationship between temperature and thermal equilibrium.
2. Explain how heat flows in physical systems in terms of conduction, convection, and radiation.
3. Apply the concepts of thermal insulators and conductors to practical systems.
4. Describe free and forced convection and recognize these processes in real-life applications.
5. Identify the relationship between wavelength, color, infrared light, and thermal radiation.
6. Calculate the heat transfer in watts for conduction, convection, and radiation in simple systems.
7. Explain how the three heat-transfer processes are applied to evaluating the energy efficiency of a house or building.

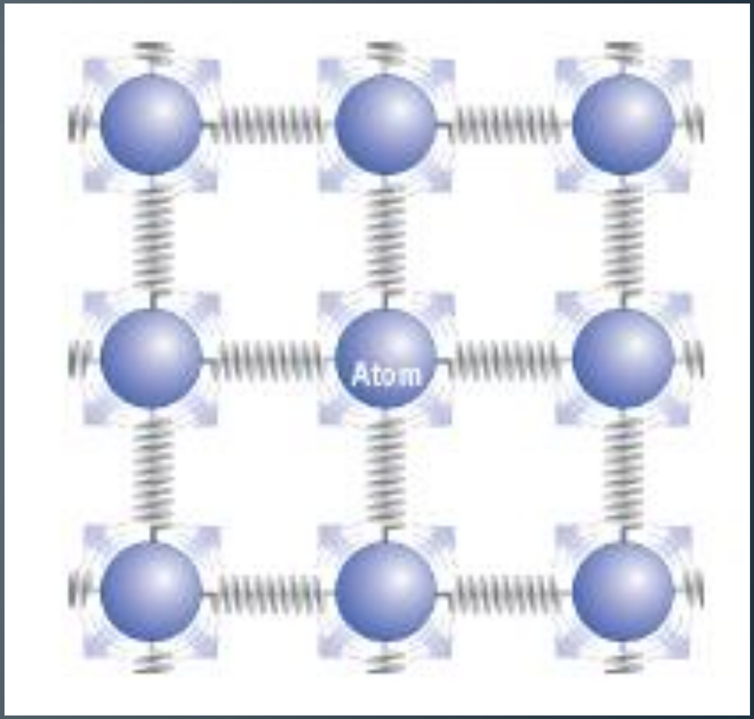
Vocabulary Terms

- infrared
- windchill factor
- thermal insulator
- thermal equilibrium
- forced convection
- R-value
- convection
- blackbody spectrum
- thermal conductivity
- thermal conductor
- blackbody
- heat transfer
- thermal radiation
- free convection
- heat transfer coefficient
- conduction

Heat Conduction

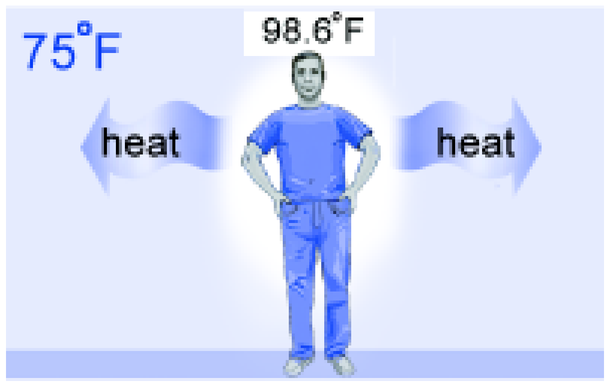
Key Question:

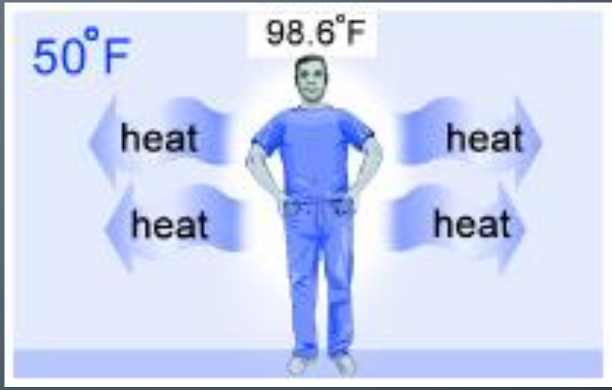
How does heat pass through different materials?

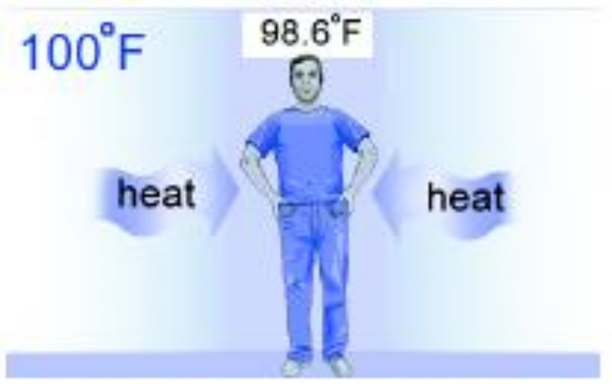


Heat Transfer

- The science of how heat flows is called heat transfer.
- There are three ways heat transfer works: conduction, convection, and radiation.
- Heat flow depends on the temperature difference.

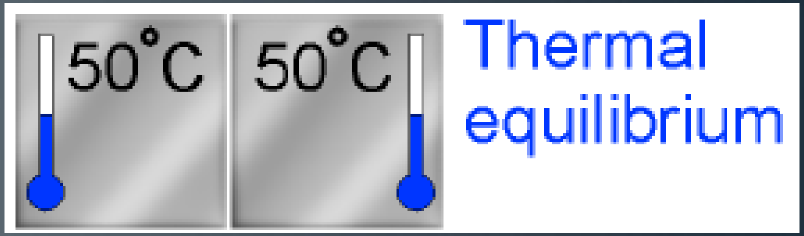


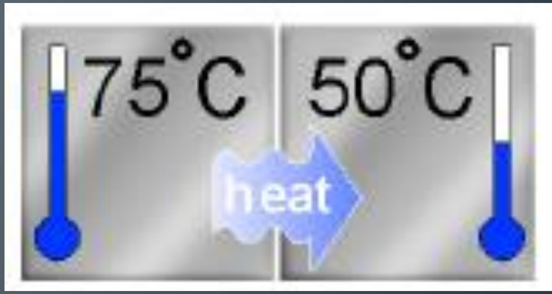




Thermal Equilibrium

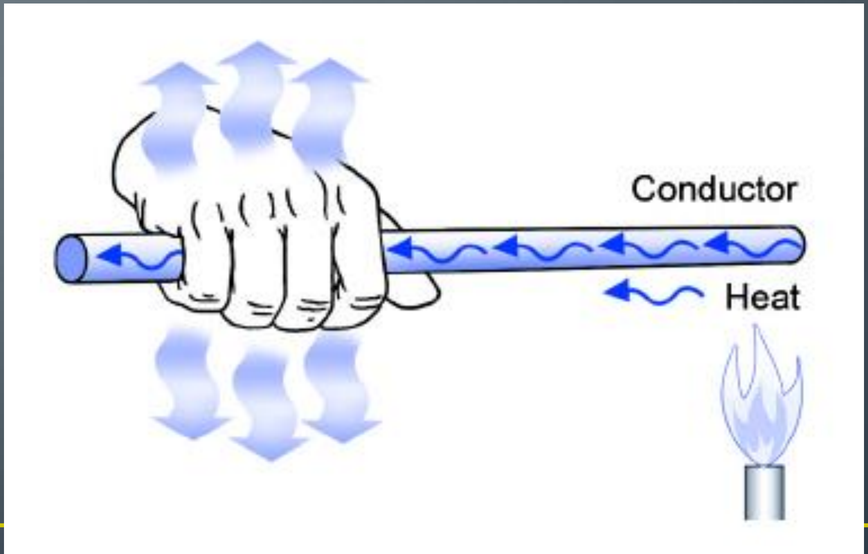
- Two bodies are in thermal equilibrium with each other when they have the same temperature.
- In nature, heat always flows from hot to cold until thermal equilibrium is reached.





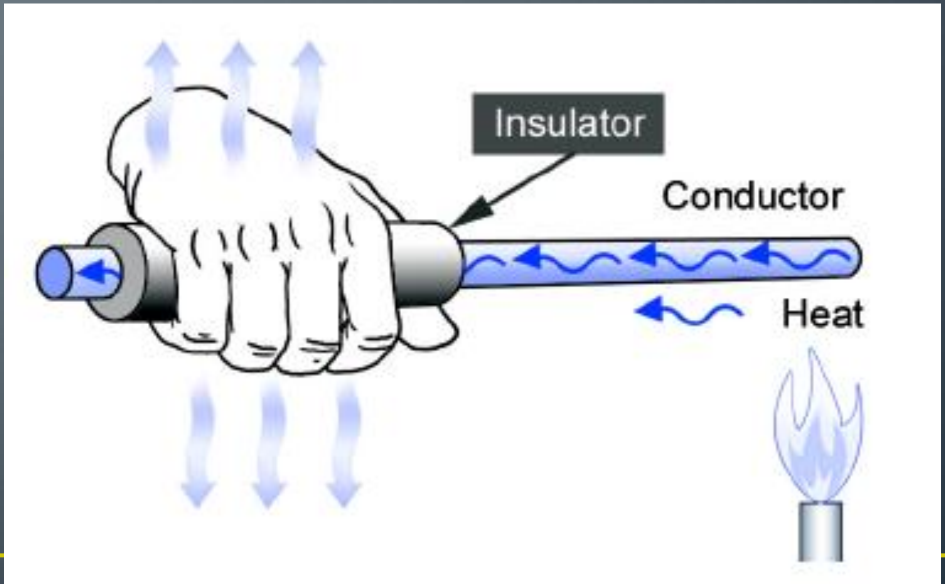
Heat Conduction

- Conduction is the transfer of heat through materials by the direct contact of matter.
- Dense metals like copper and aluminum are very good thermal conductors.



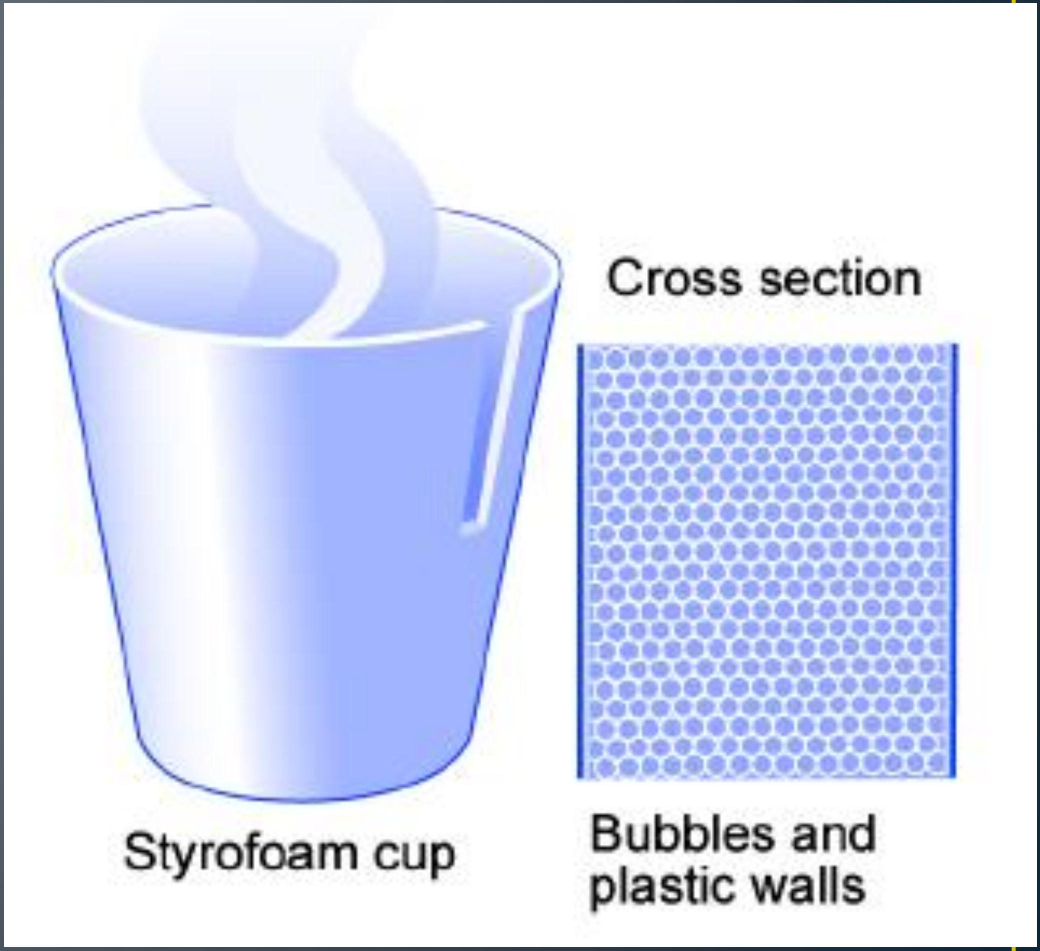
Heat Conduction

- A thermal insulator is a material that conducts heat poorly.
- Heat flows very slowly through the plastic so that the temperature of your hand does not rise very much.



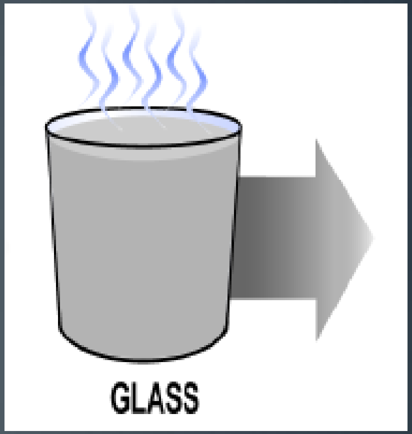
Heat Conduction

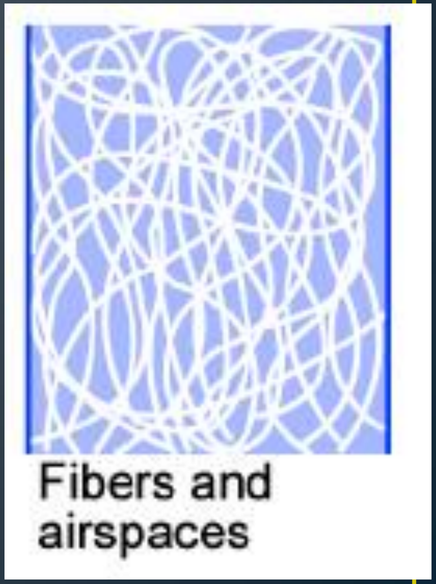
- Styrofoam gets its insulating ability by trapping spaces of air in bubbles.
- Solids usually are better heat conductors than liquids, and liquids are better conductors than gases.



Heat Conduction

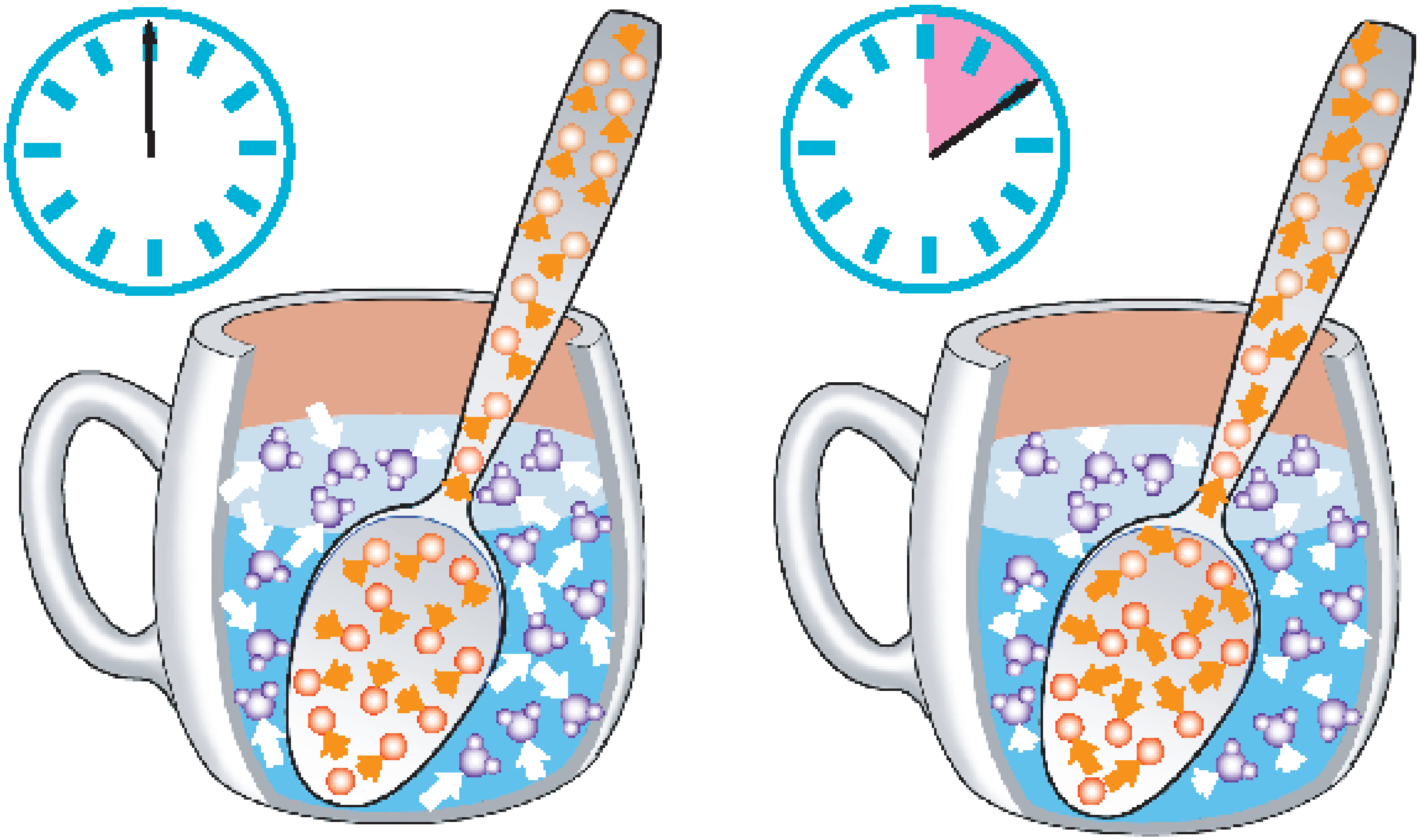
- The ability to conduct heat often depends more on the structure of a material than on the material itself.
  - Solid glass is a thermal conductor when it is formed into a beaker or cup.
  - When glass is spun into fine fibers, the trapped air makes a thermal insulator.





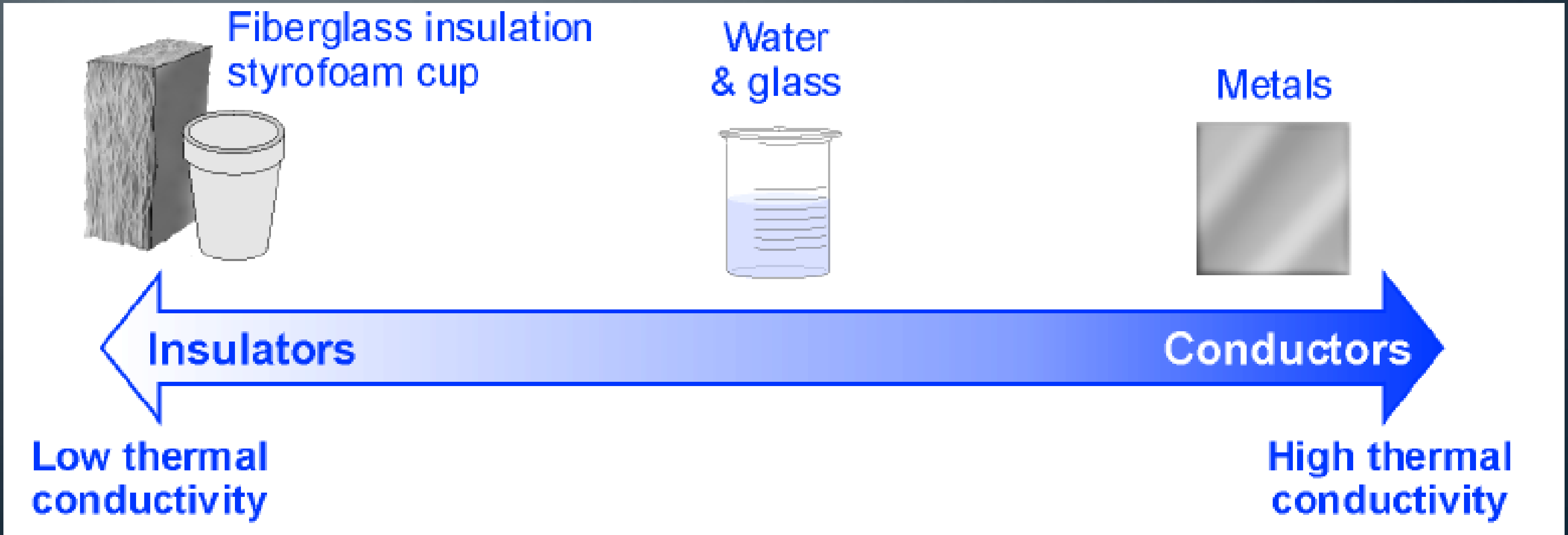
Conduction

Conduction is the transfer of heat by the direct contact of particles of matter. The molecules in the hot cup of liquid transfer their heat energy to the molecules in the cold spoon.



Thermal Conductivity

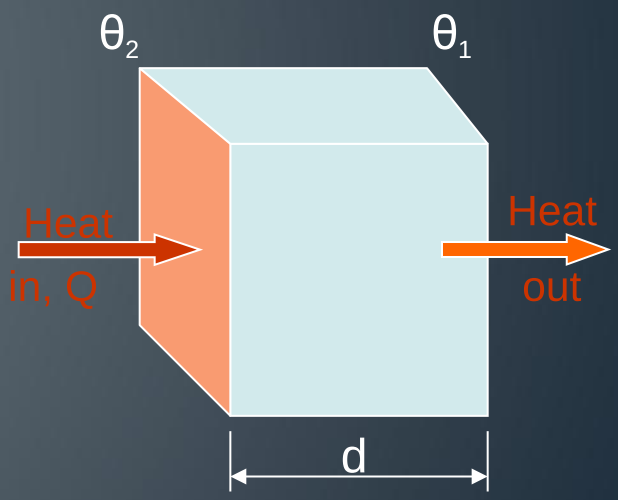
- The thermal conductivity of a material describes how well the material conducts heat.



Thermal conductivity: Thermal conductivity or λ-value (also known as k-value) of a material is a measure of the rate at which heat is conducted through it under specified conditions.

Flow of heat through a material is directly proportional to:

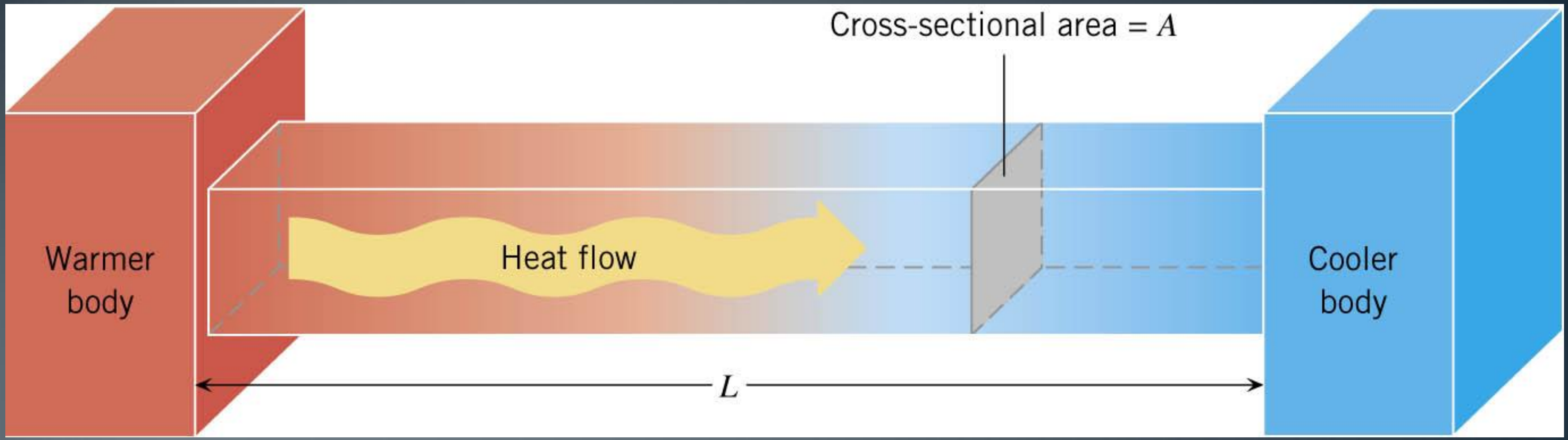
- surface area (A)
- temperature difference between the opposite faces ($\theta_2 - \theta_1$)
- time for which heat flows (t)



Flow of heat is indirectly proportional to the thickness of material (d)

Combining the above factors, the amount of heat flowing through a material, Q, is proportional to:

Taking a Solid Metal Bar as an Example



The amount of heat Q conducted through the bar from the warmer end to the cooler end depends on a number of factors:

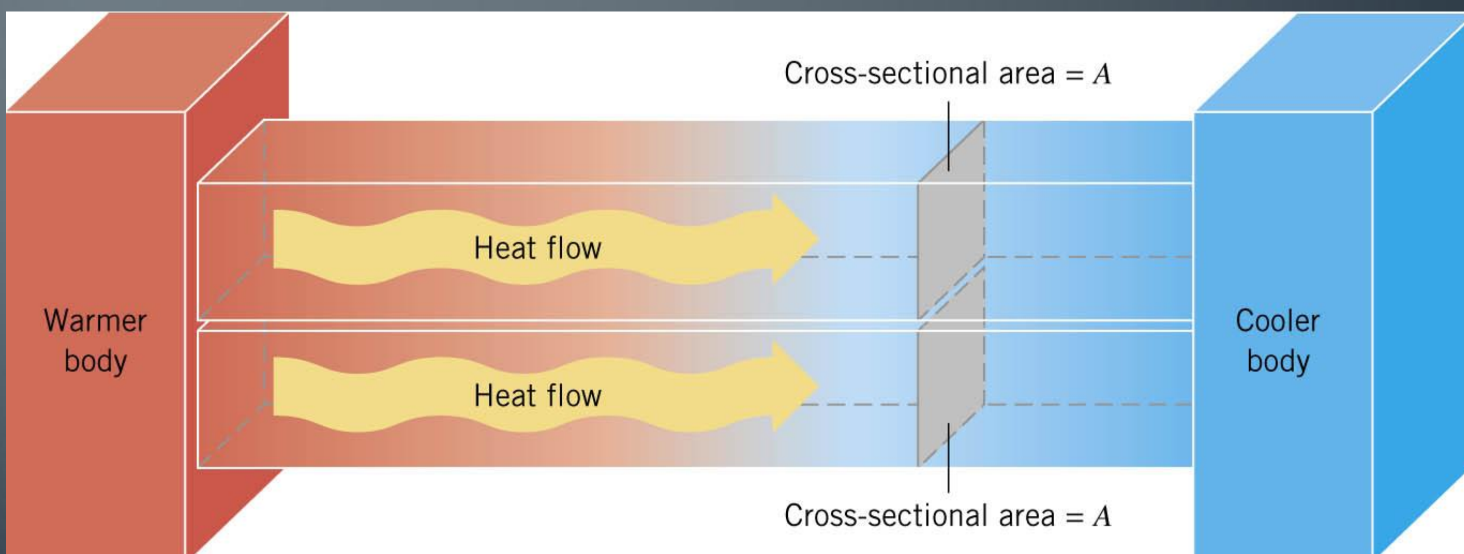
1. **Q is proportional to the time t during which conduction takes place ($Q \propto t$).**
2. **Q is proportional to the temperature difference ΔT between the ends of the bar ($Q \propto \Delta T$).**

3. Q is proportional to the cross-sectional area A of the bar ($Q \propto A$).

4. Q is inversely proportional to the length L of the bar

($Q \propto 1/L$).

$$Q \propto (A\,\Delta T)t/L.$$



$$Q \propto \frac{t.A.(\theta_2 - \theta_1)}{d}$$

$$\frac{Q}{t} \propto \frac{A.(\theta_2 - \theta_1)}{d}$$

$$\frac{Q}{t} = \frac{\lambda.A.(\theta_2 - \theta_1)}{d}$$

$$\therefore \lambda\,(\text{or } k) = \frac{Q.d}{t.A.(\theta_2 - \theta_1)}$$

where λ (or k) is the thermal conductivity of the material

To work out the unit of thermal conductivity, the symbols in the equation are replaced with appropriate units:

- Quantity of heat, Q: Joules (J)
- Thickness of material, d: m
- Time during which heat flows, t: seconds (s)
- Surface area of the material, A: m^2
- Temperature difference, $\theta_2 - \theta_1$ = ºC or K

$$\therefore \lambda\,(\text{or}\,k) = \frac{J.m}{s.m^2.^\circ C}$$

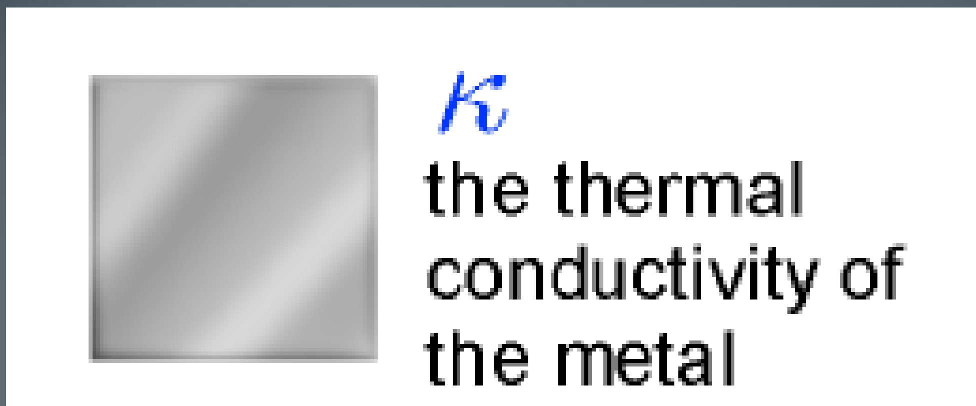
$$= \frac{W}{m\ ^\circ C} \quad \text{or} \quad \frac{W}{m\ K}$$

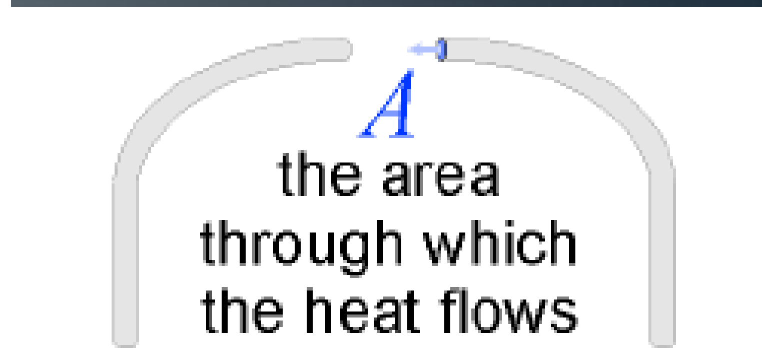
Thermal Conductivity

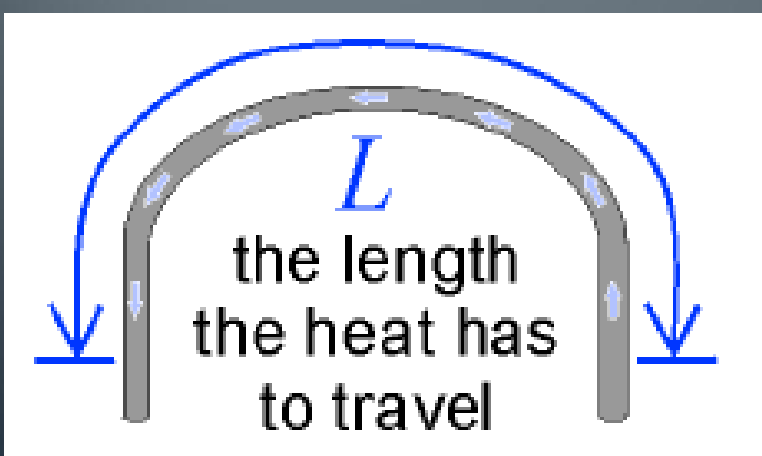
Material	Thermal cond. (W/m°C)
IIa diamond	2,650
Copper	401
Aluminum	226
Steel	43
Rock	3
Glass	2.2
Ice	2.2
Liquid water	0.58
Wood	0.11
Wool fabric	0.038
Fiberglass insulation	0.038
Styrofoam	0.025
Air	0.026

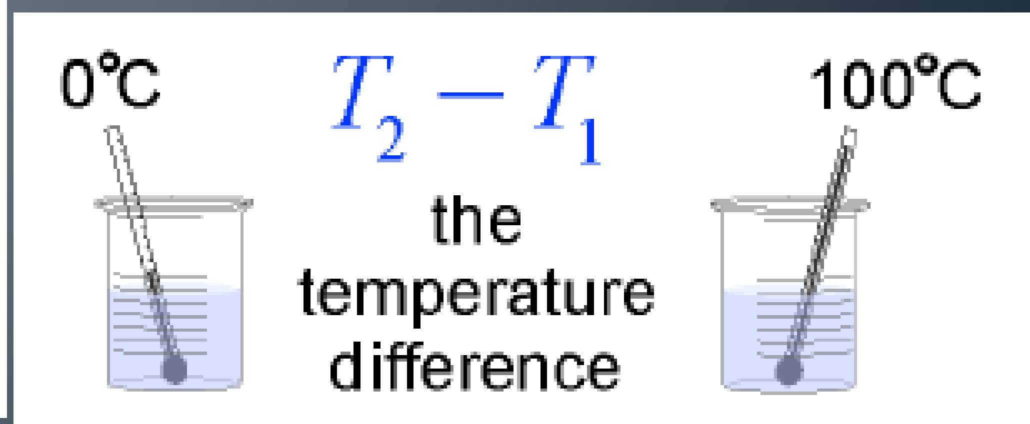
- Heat conduction in solids and liquids works by transferring energy through bonds between atoms or molecules.

Variables for conduction









Heat Conduction Equation

Thermal conductivity (watts/m°C)

Area of cross section (m^2)

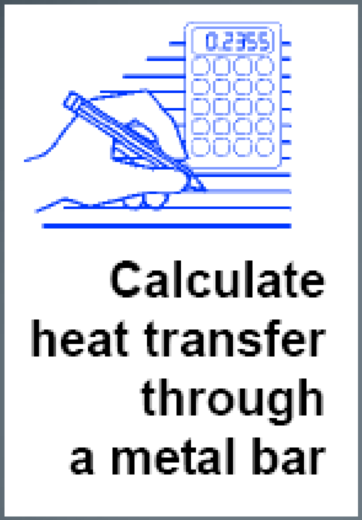
Heat flow (watts)

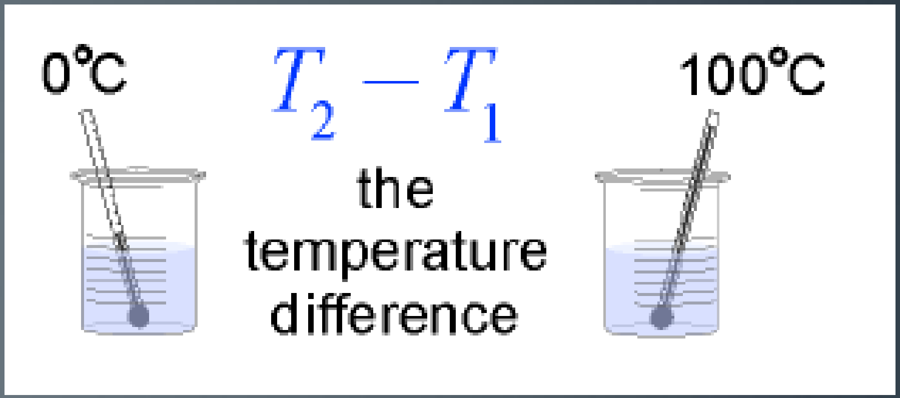
$$Q = \kappa \frac{A}{L} (T_2 - T_1)$$

Temperature difference (°C)

Length (m)

Calculate Heat Transfer

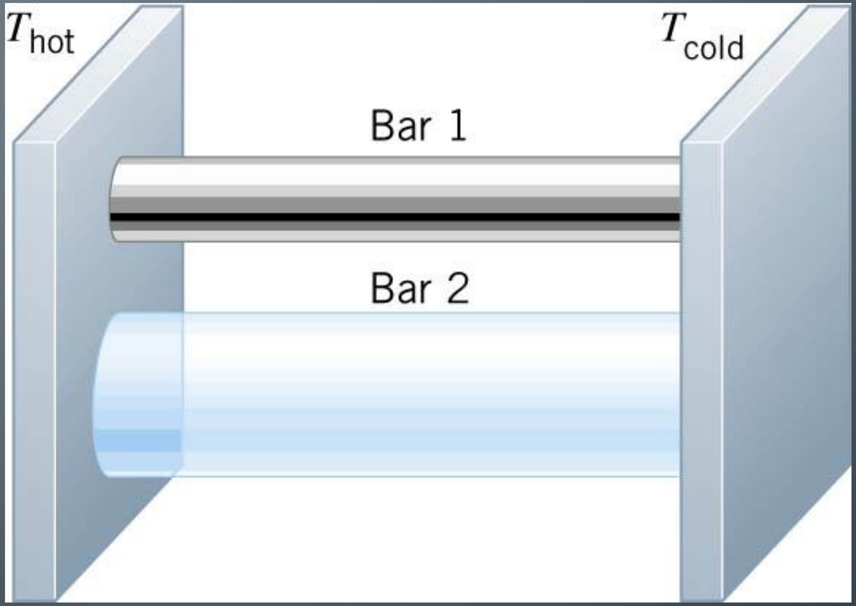




- A copper bar connects two beakers of water at different temperatures.
- One beaker is at 100°C and the other is at 0°C.
- The bar has a cross section area of 0.0004 m^2 and is one-half meter (0.5 m) long.
- How many watts of heat are conducted through the bar from the hot beaker to the cold beaker?
- The thermal conductivity of copper is 401 W/m°C.

Check Your Understanding

Two bars are placed between plates whose temperatures are T_{hot} and T_{cold} (see the drawing). The thermal conductivity of bar 1 is six times that of bar 2 ($k_1 = 6k_2$), but bar 1 has only one-third the cross-sectional area ($A_1 = \frac{1}{3}A_2$). Ignore any heat loss through the sides of the bars. Which statement below correctly describes the heat conducted by the bars in a given amount of time?



a. **Bar 1 conducts 1/4 the heat as does bar 2;** $Q_1 = \frac{1}{4} Q_2$

b. **Bar 1 conducts 1/8 the heat as does bar 2;** $Q_1 = \frac{1}{8} Q_2$

c. **Bar 1 conducts twice the heat as does bar 2;** $Q_1 = 2 Q_2$

d. **Bar 1 conducts four times the heat as does bar 2;** $Q_1 = 4 Q_2$

e. **Both bars conduct the same amount of heat;** $Q_1 = Q_2$

c

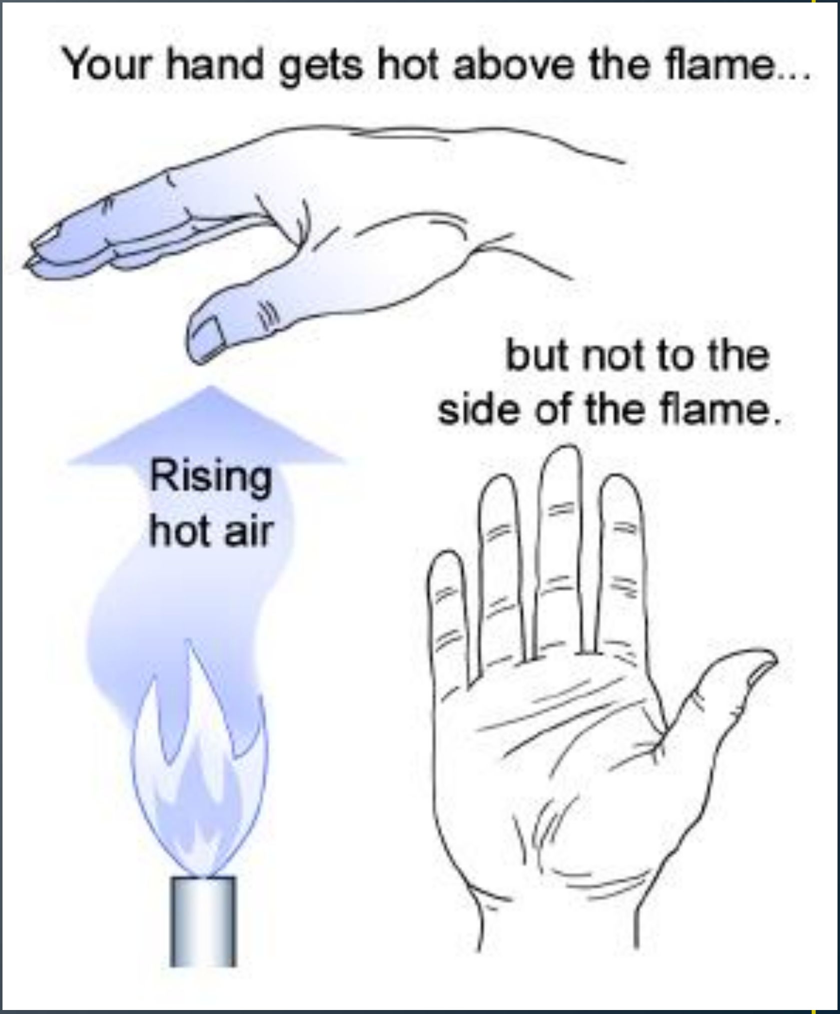
Convection

Key Question:

Can moving matter carry thermal energy?

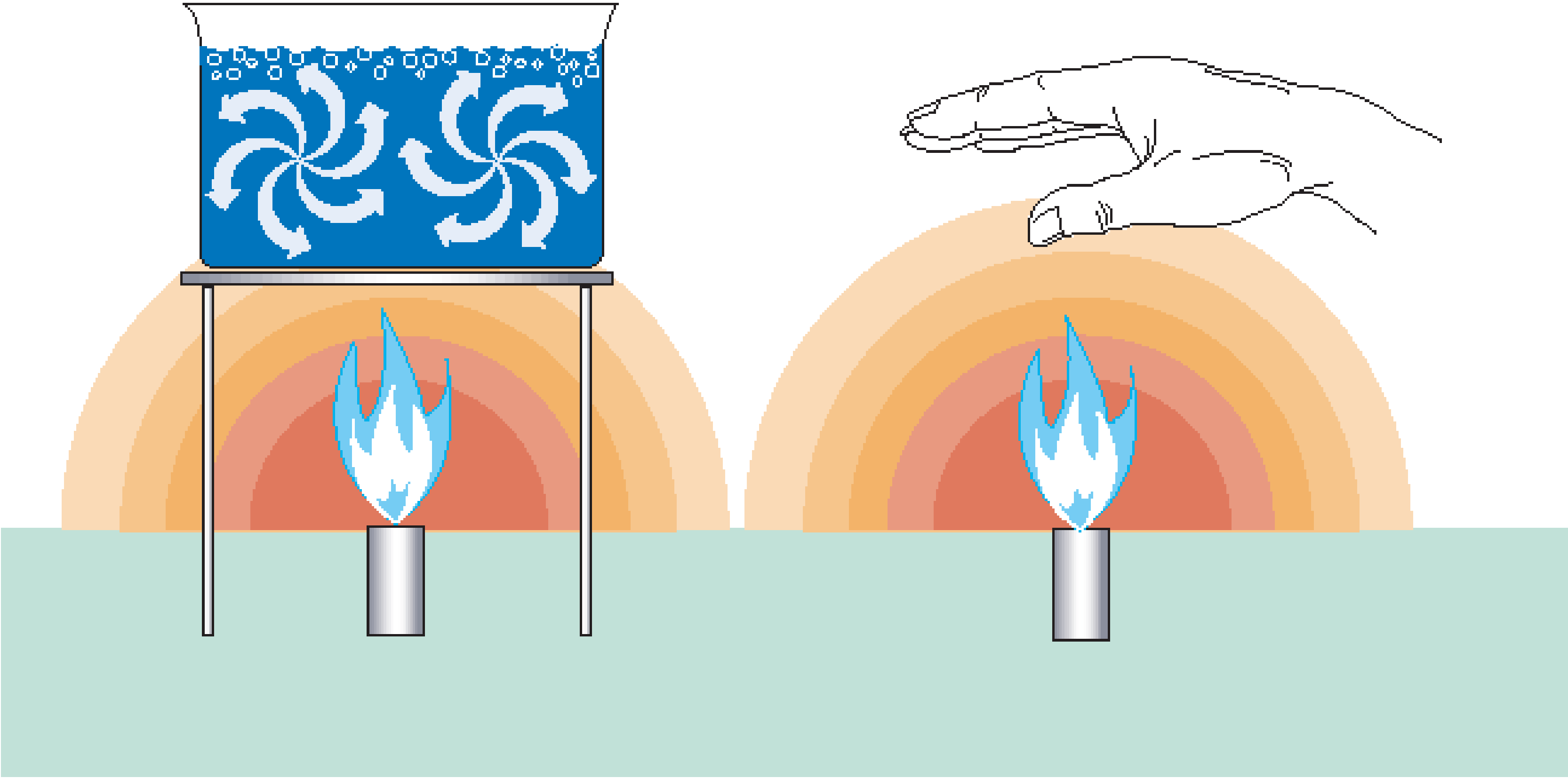
Convection

- Convection is the transfer of heat by the motion of liquids and gases.
  - Convection in a gas occurs because gas expands when heated.
  - Convection occurs because currents flow when hot gas rises and cool gas sink.
  - Convection in liquids also occurs because of differences in density.

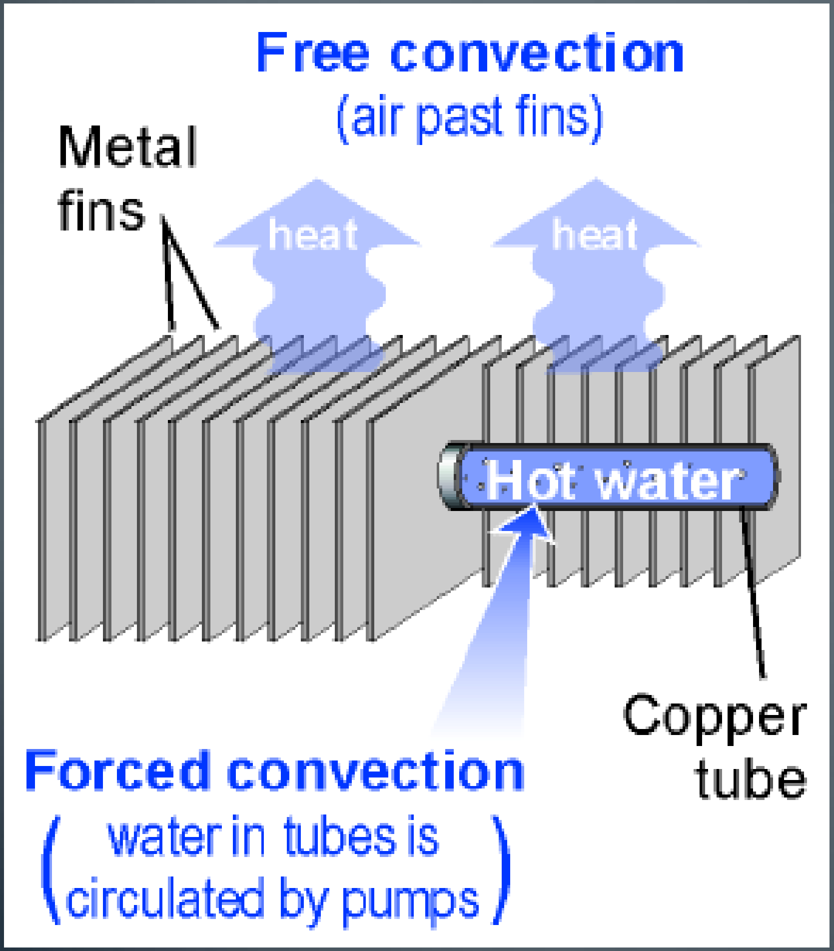


Convection

Convection is the transfer of heat by the actual motion of a fluid (liquid or gas) in the form of currents.

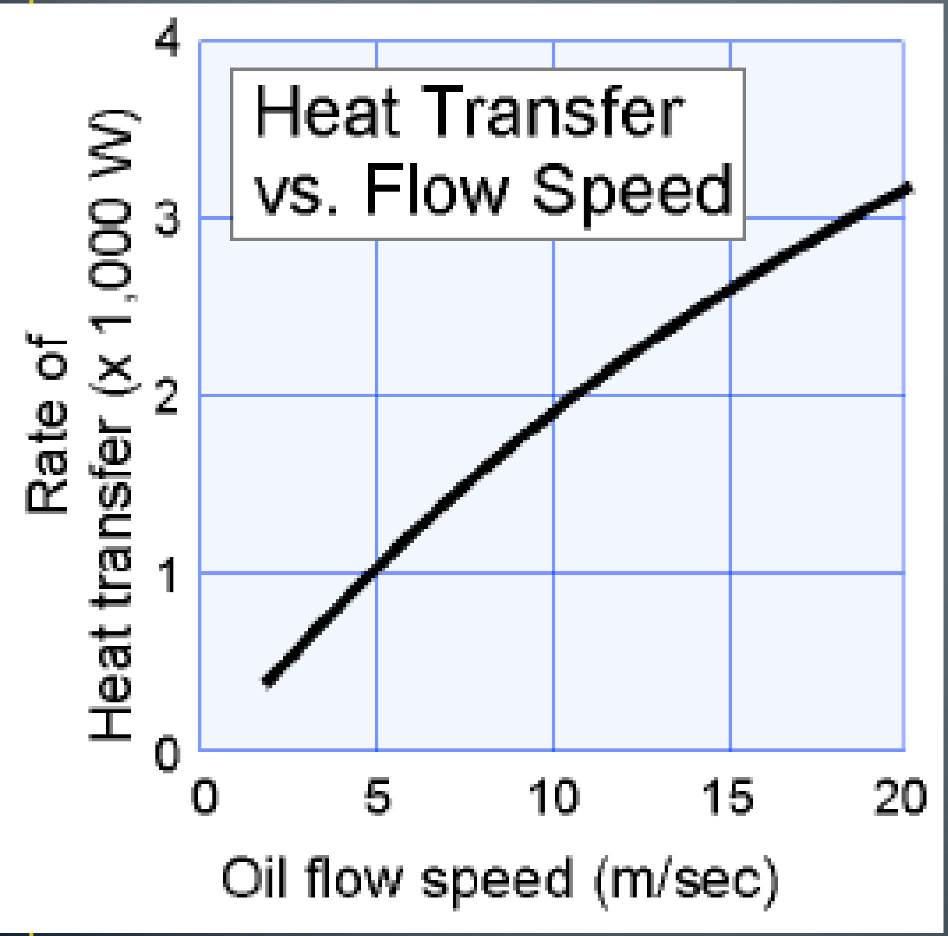


Convection



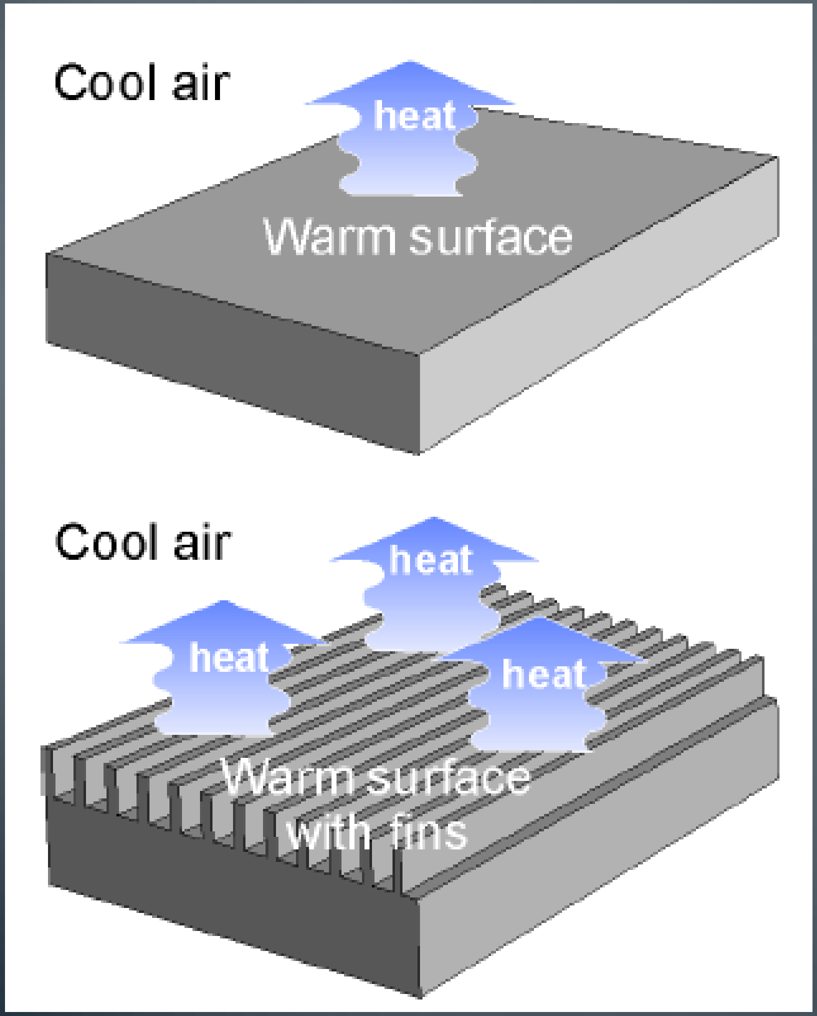
- When the flow of gas or liquid comes from differences in density and temperature, it is called free convection.
- When the flow of gas or liquid is circulated by pumps or fans it is called forced convection.

Convection



- Convection depends on speed.
- Motion increases heat transfer by convection in all fluids.

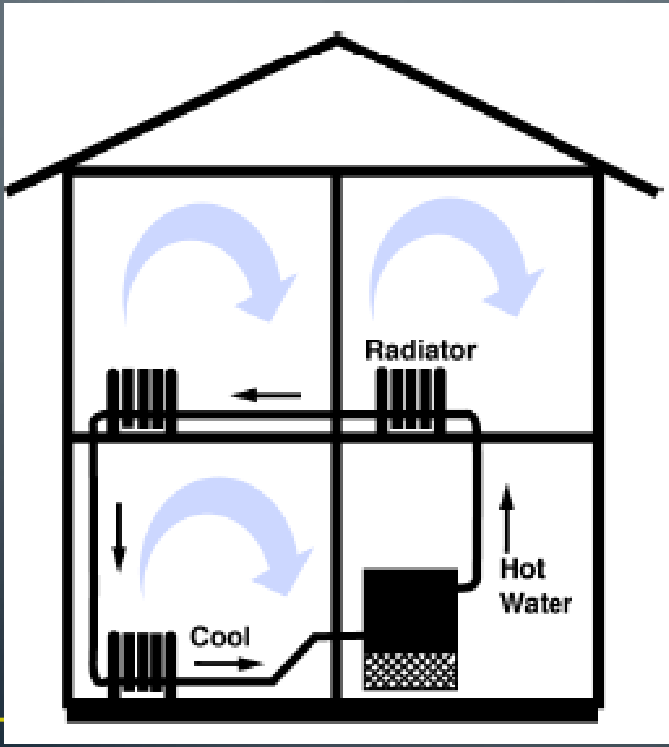
Convection

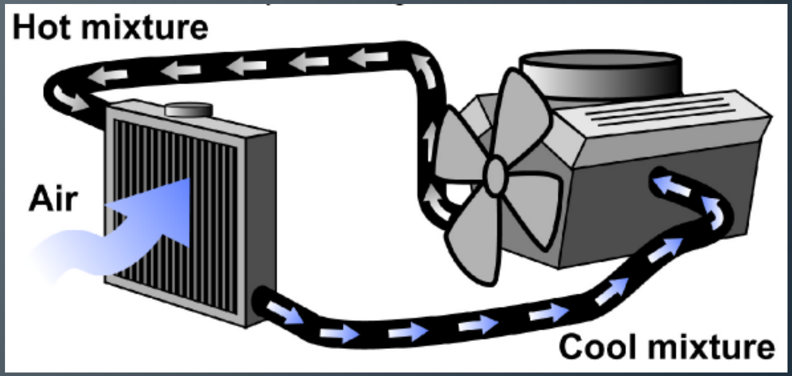


- Convection depends on surface area.
- If the surface contacting the fluid is increased, the rate of heat transfer also increases.
- Almost all devices made for convection have fins for this purpose.

Forced Convection

- Both free and forced convection help to heat houses and cool car engines.



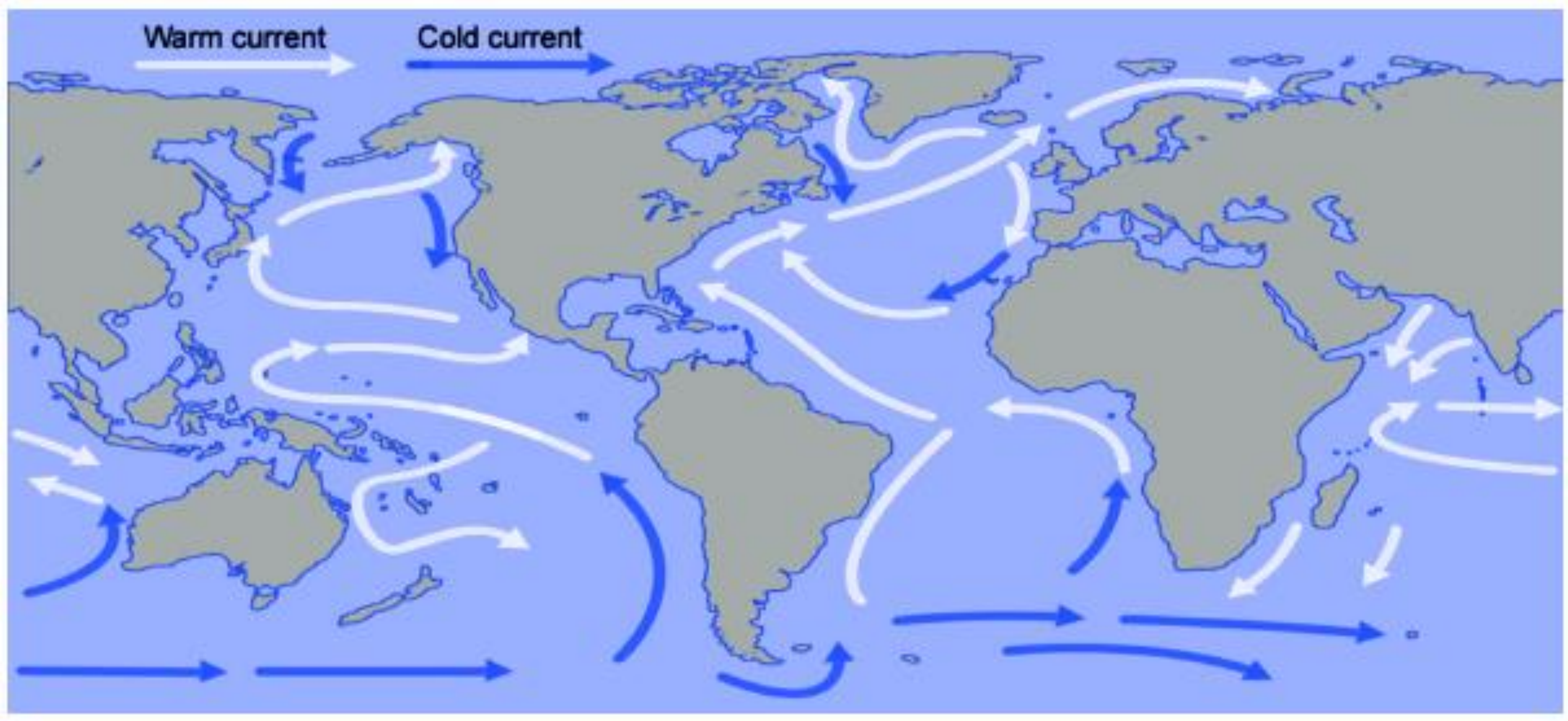


Convection and Sea Breezes

- On a smaller scale near coastlines, convection is responsible for sea breezes.
- During the daytime, land is much hotter than the ocean.
- A sea breeze is created when hot air over the land rises due to convection and is replaced by cooler air from the ocean.
- At night the temperature reverses so a land breeze occurs.

Convection Currents

- Much of the Earth's climate is regulated by giant convection currents in the ocean.



Heat Convection Equation

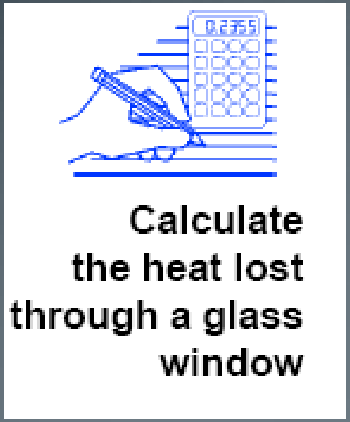
Heat transfer coefficient (watts/m^2°C)

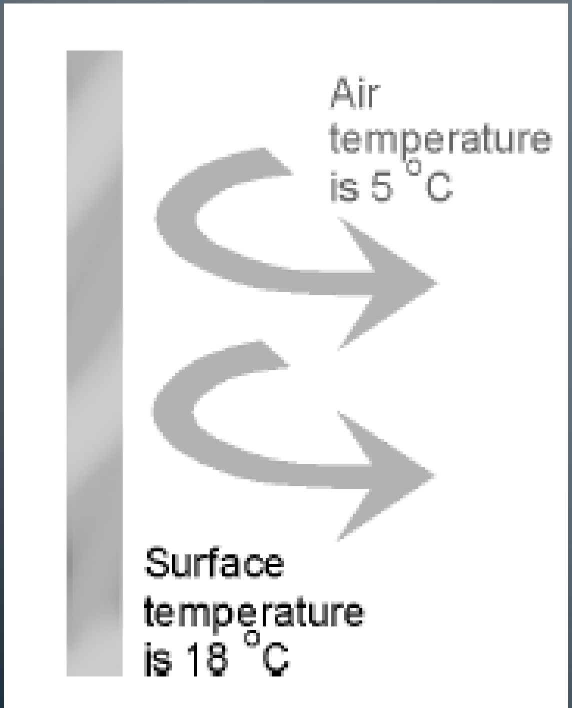
Area contacting fluids (m^2)

Heat flow (watts)

$$Q = h A (T_2 - T_1)$$

Temperature difference (°C)





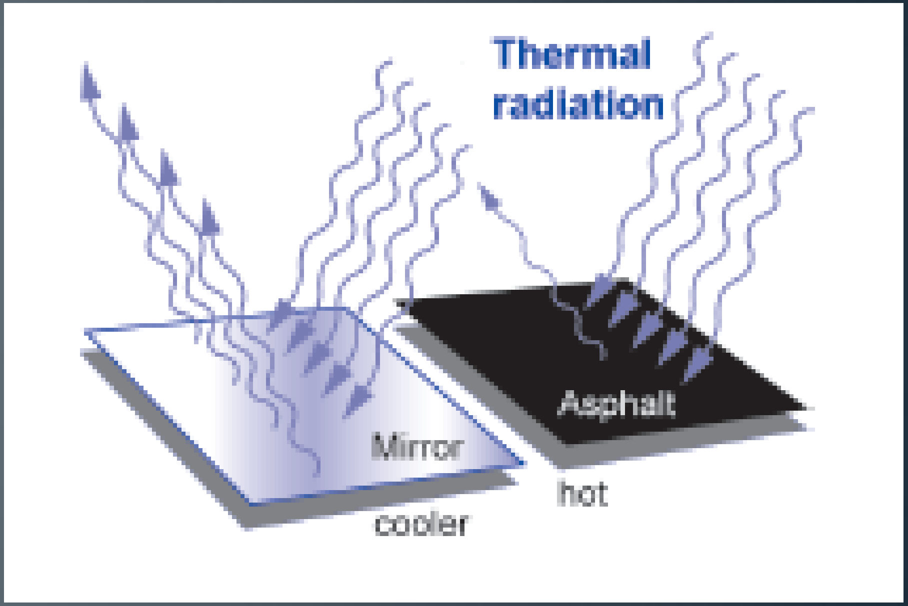
Calculating convection

- The surface of a window is a temperature of 18°C (64°F).
- A wind at 5°C (41°F) is blowing on the window fast enough to make the heat transfer coefficient 100 $W/m^2 °C$.
- How much heat is transferred between the window and the air if the area of the window is 0.5 square meters?

Radiation

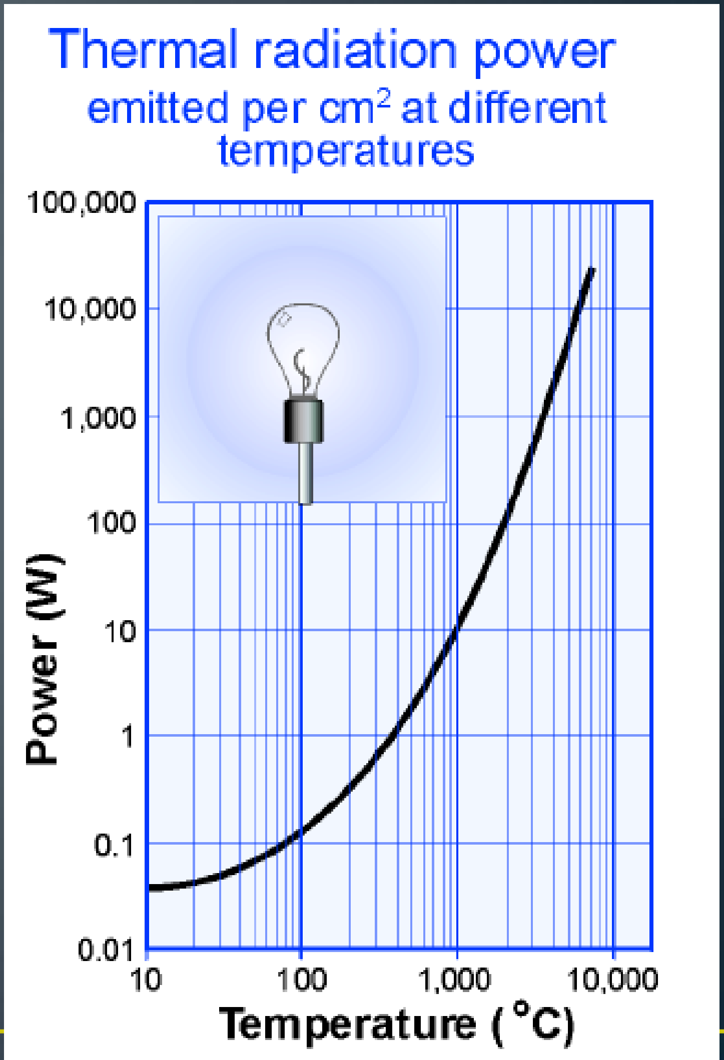
Key Question:

How does heat from the sun get to Earth?



Radiation

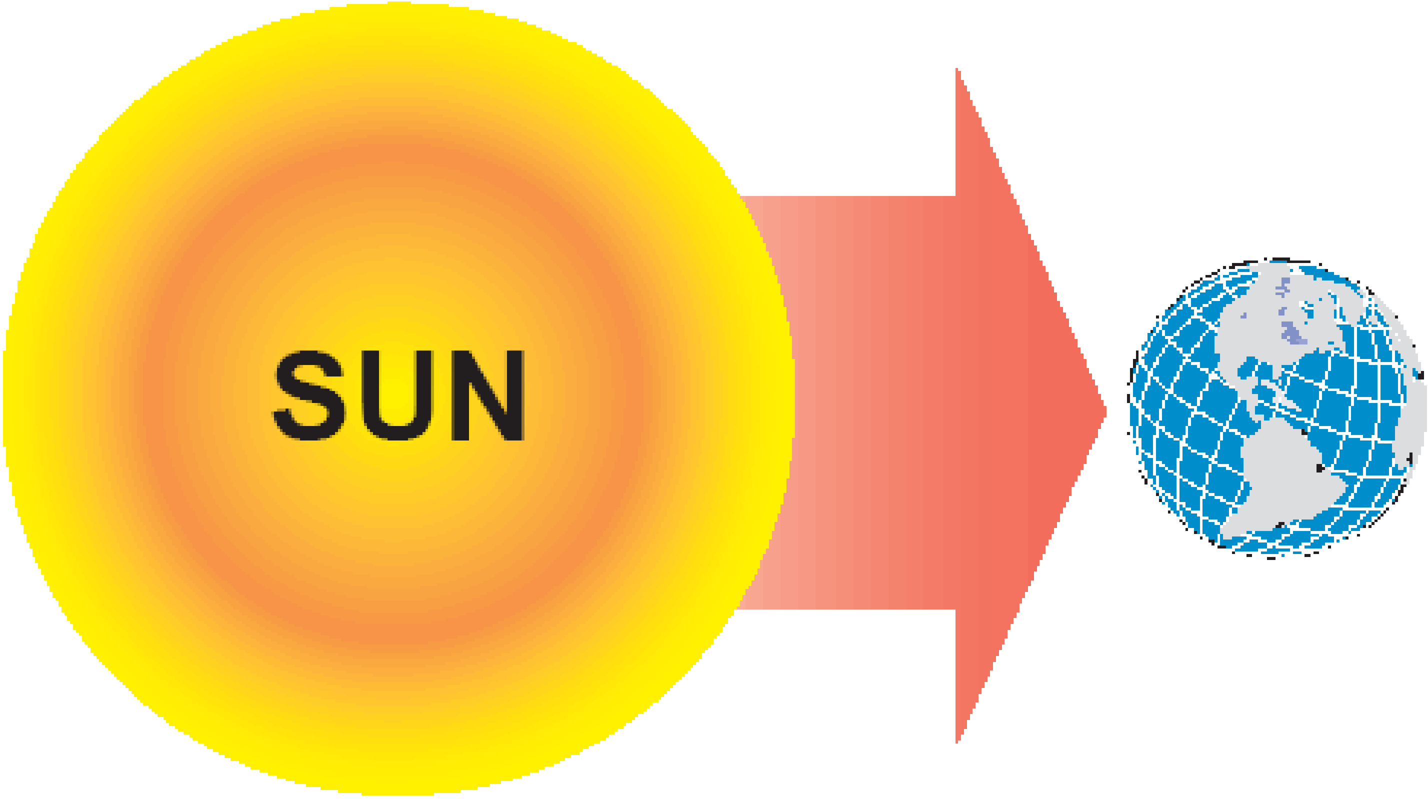
- Radiation is heat transfer by electromagnetic waves.
- Thermal radiation is electromagnetic waves (including light) produced by objects because of their temperature.
- The higher the temperature of an object, the more thermal radiation it gives off.



Radiation

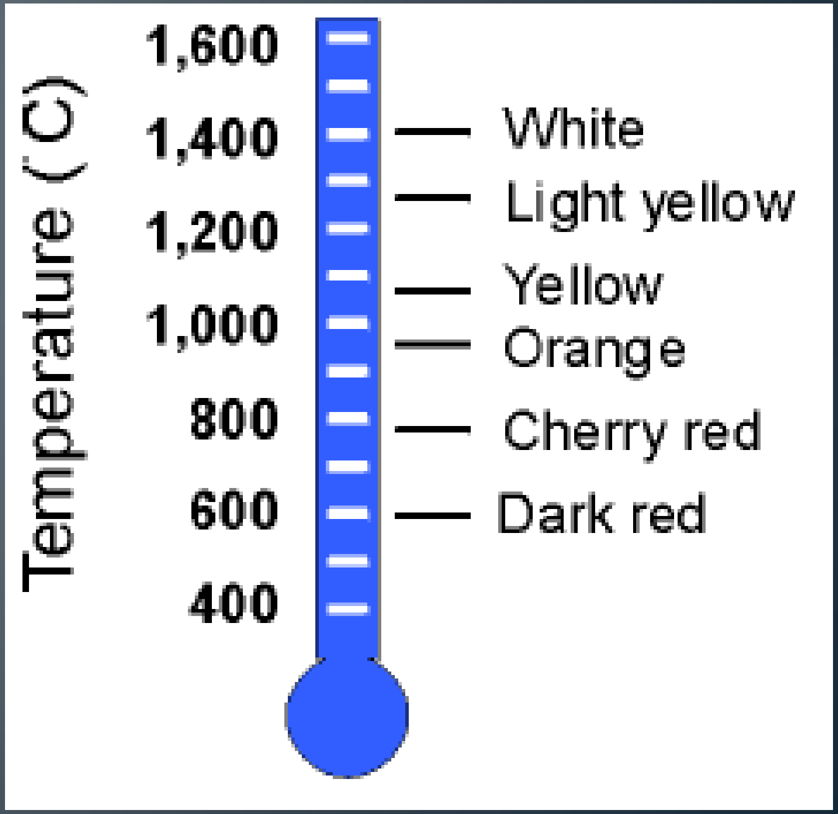
Radiation is heat transfer by electromagnetic waves.

Electromagnetic radiation from the sun heats Earth.



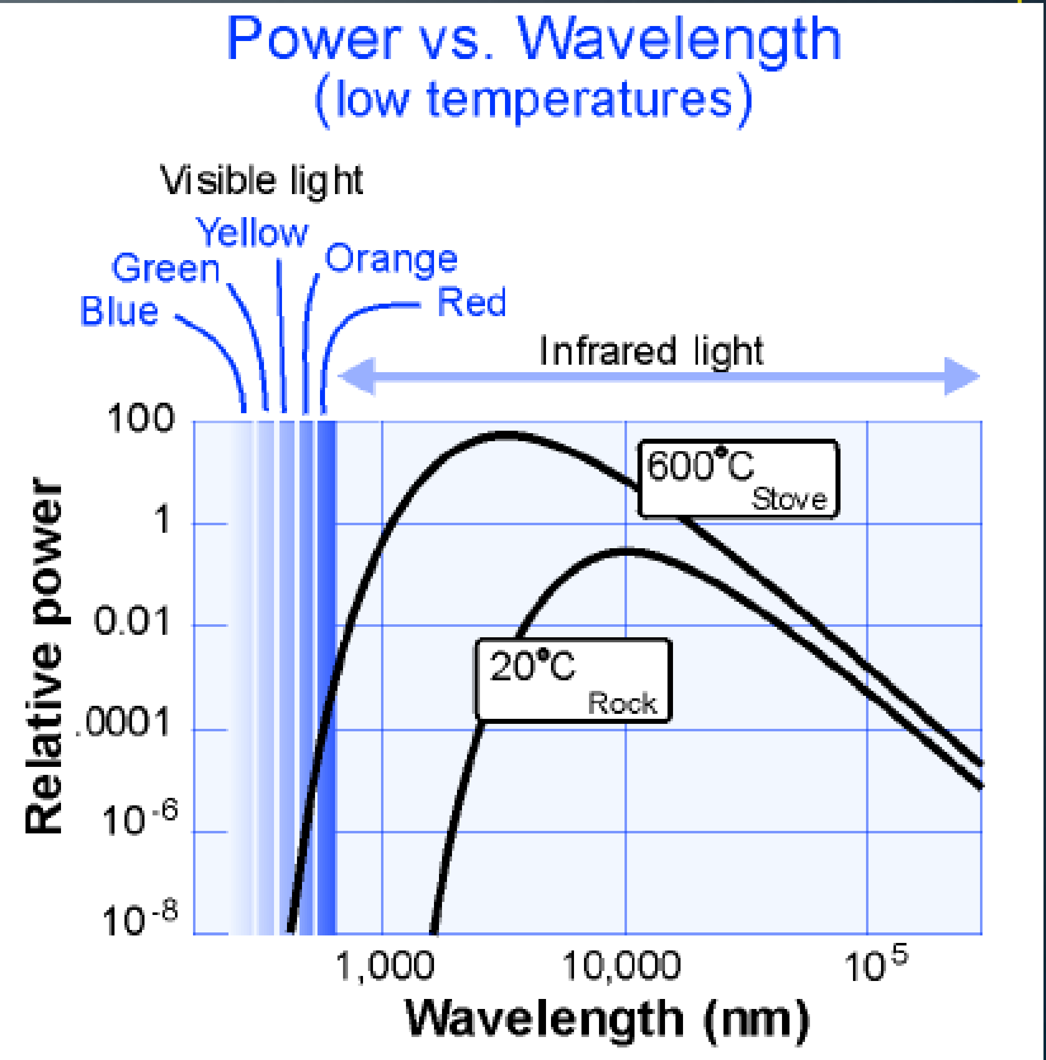
Radiant Heat

- We do not see the thermal radiation because it occurs at infrared wavelengths invisible to the human eye.
- Objects glow different colors at different temperatures.



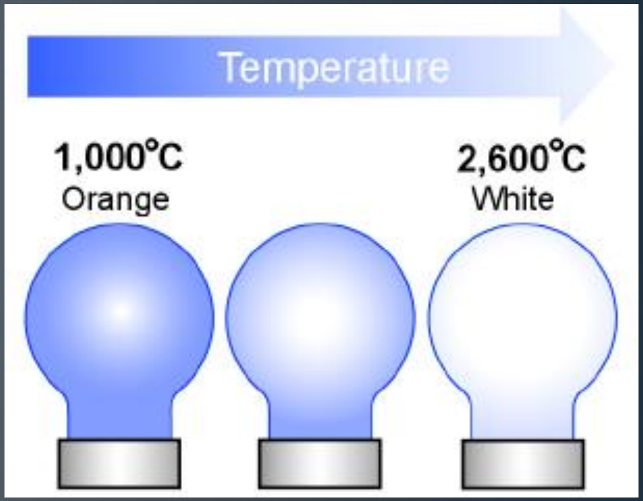
Radiant Heat

- A rock at room temperature does not “glow”.
- The curve for 20°C does not extend into visible wavelengths.
- As objects heat up they start to give off visible light, or glow.
- At 600°C objects glow dull red, like the burner on an electric stove.



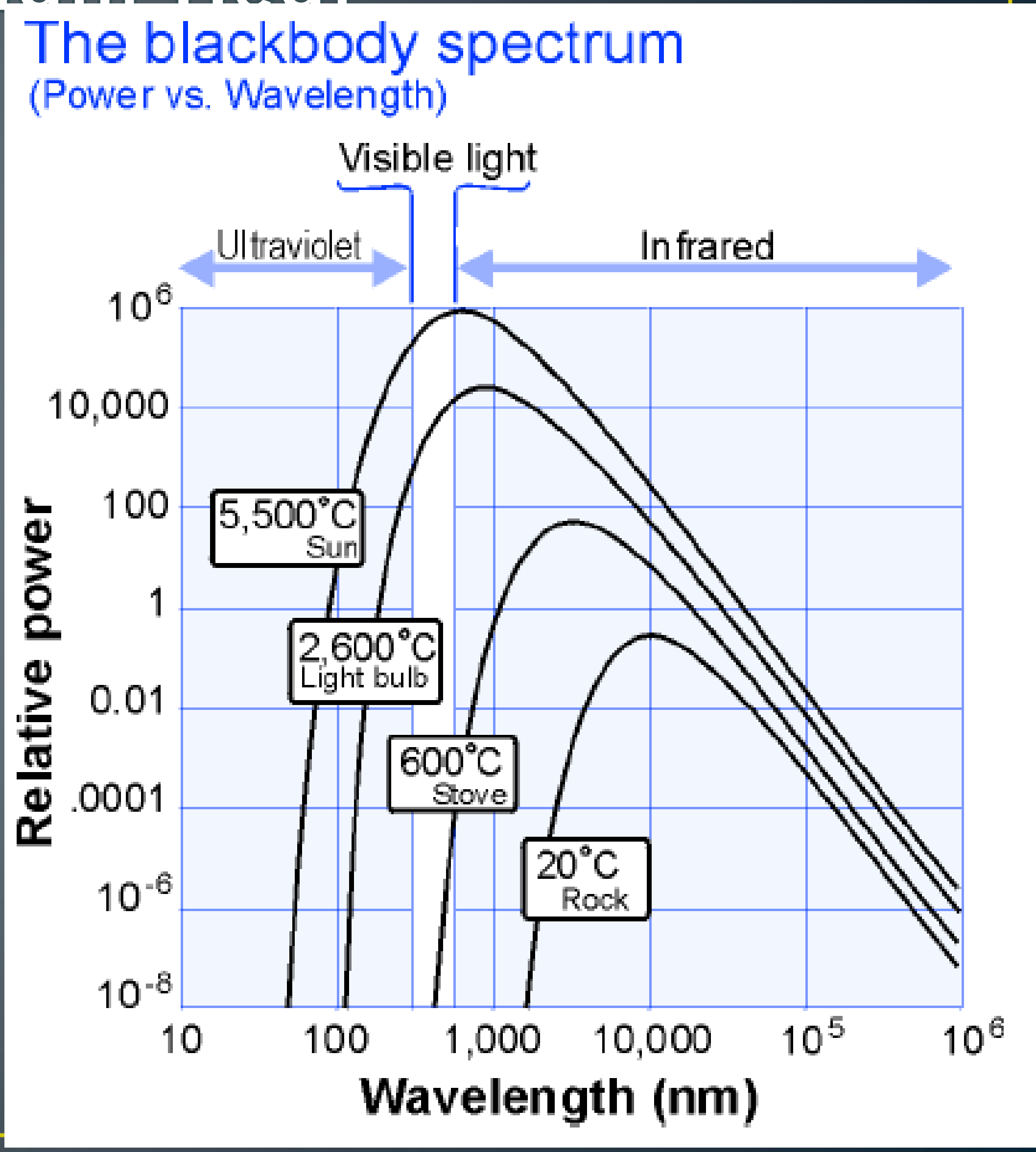
Radiant Heat

- As the temperature rises, thermal radiation produces shorter-wavelength, higher energy light.
- At 1,000°C the color is yellow-orange, turning to white at 1,500°C.
- If you carefully watch a bulb on a dimmer switch, you see its color change as the filament gets hotter.
- The bright white light from a bulb is thermal radiation from an extremely hot filament, near 2,600°C.



Radiant Heat

- The graph of power versus wavelength for a perfect blackbody is called the blackbody spectrum.

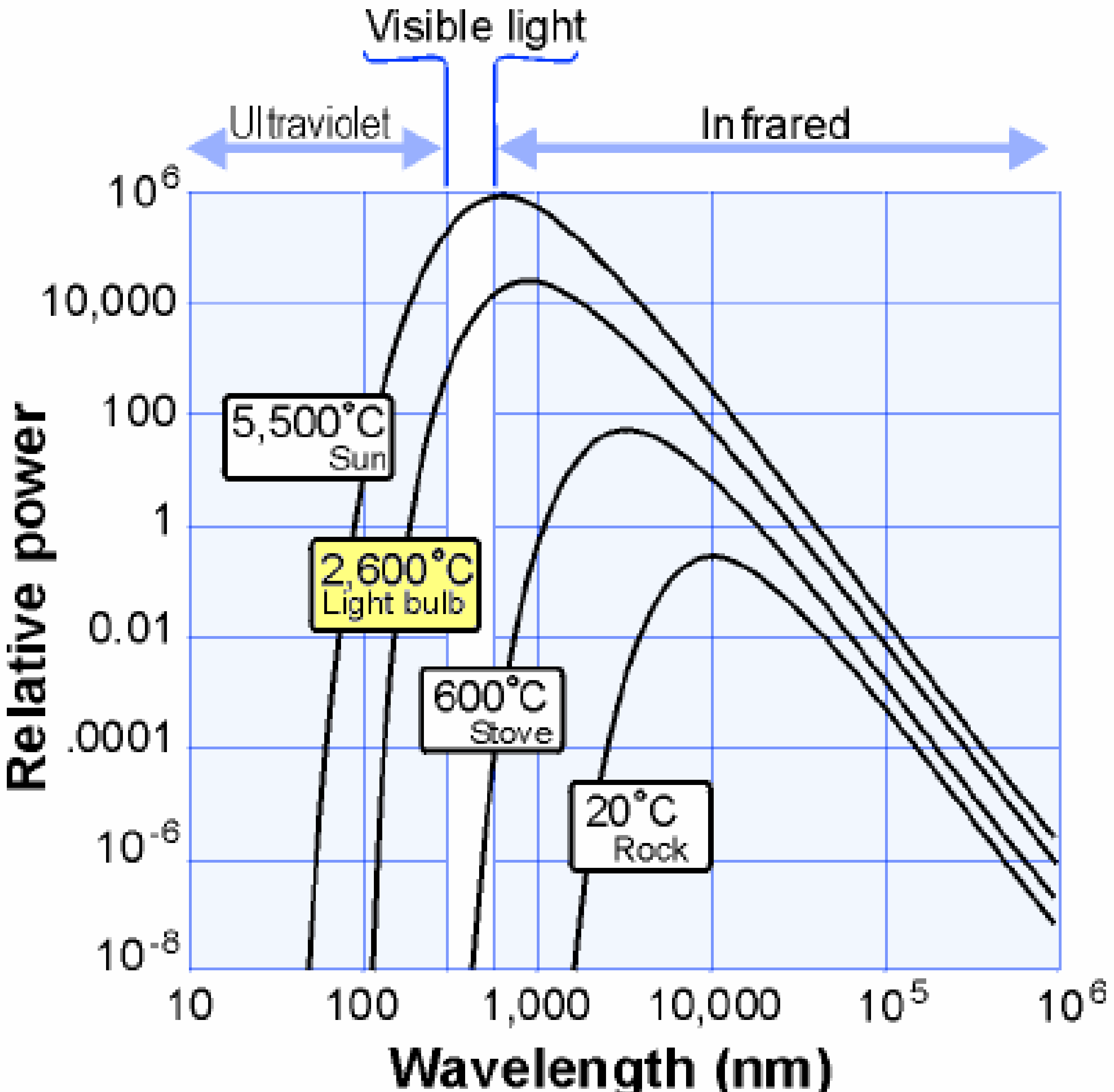


Radiant Heat

- A perfect blackbody is a surface that reflects nothing and emits pure thermal radiation.

- The white-hot filament of a bulb is a good blackbody because all light from the filament is thermal radiation and almost none of it is reflected from other sources.

- The curve for 2,600°C shows that radiation is emitted over the whole range of visible light.


Visible light
Ultraviolet
Infrared
10^6
10,000
100
1
0.01
.0001
10^-6
10^-8
Relative power
5,500°C
Sun
2,600°C
Light bulb
600°C
Stove
20°C
Rock
10
100
1,000
10,000
10^5
10^6
Wavelength (nm)

Radiant Heat

- A star is a near-perfect blackbody.
- The distribution of energy between different wavelengths (colors) depends strongly on the temperature.
- Sirius is a hot, young star about twice as big as the sun and 22 times as bright.
- Because its temperature is hotter, Sirius appears bluer than the sun.

Radiant Heat

- The total power emitted as thermal radiation by a blackbody depends on temperature (*T*) and surface area (*A*).
- Real surfaces usually emit less than the blackbody power, typically between 10 and 90 percent.
- The Kelvin temperature scale is used in the Stefan-Boltzmann formula because thermal radiation depends on the temperature above absolute zero.

Stefan-Boltzmann formula

$$P = \sigma A T^4$$

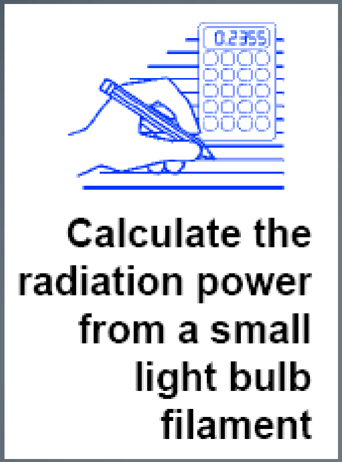
Power (watts) → P

Surface area (m^2) → A

Stefan-Boltzmann constant
5.67 x 10^{-8} watts/m^2K^4) → σ

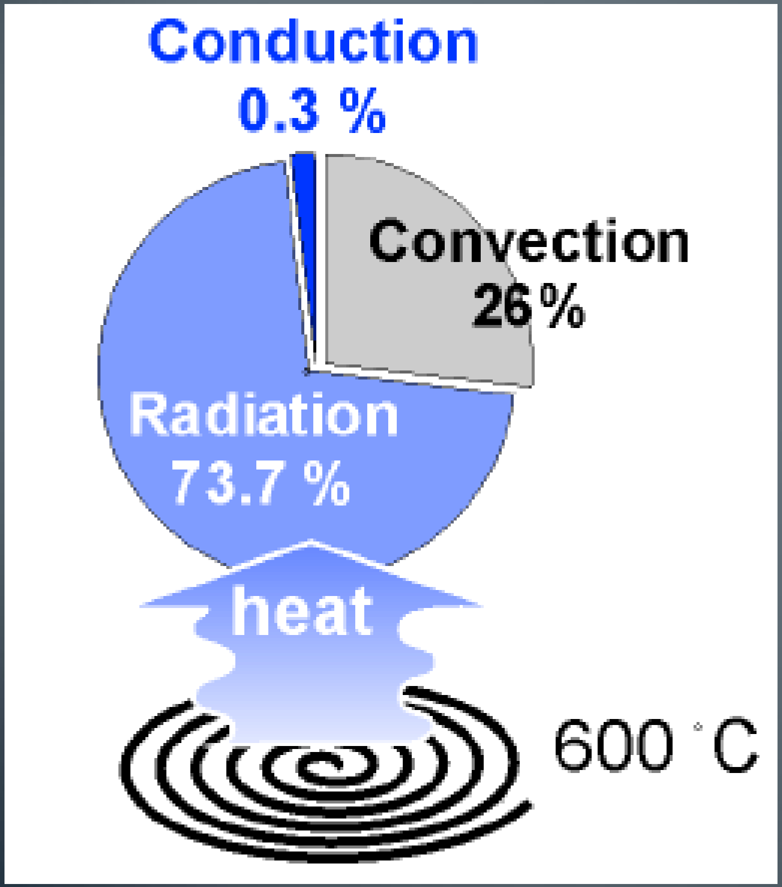
Absolute temperature (K) → T

Calculate Radiant Power



- The filament in a light bulb has a diameter of 0.5 millimeters and a length of 50 millimeters.
- The surface area of the filament is 4×10^{-8} m^2.
- If the temperature is 3,000 K, how much power does the filament radiate?

Radiant Heat



- When comparing heat transfer for a pot 10 cm above a heating element on a stove, radiant heat accounts for 74%
- How is heat transferred when the pot sits on the element?

Application: Energy-efficient Buildings