Heat transfer mechanisms

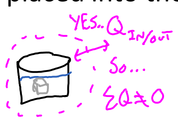
Select LEARNING OBJECTIVES:

- Understand there are three mechanisms by which thermal energy can be transferred *as heat.*
- Understand that all objects, everywhere, are constantly radiating (just maybe not in the visible spectrum so we don't notice it).
- Identify prevalent heat transfer mechanisms in systems.

TEXTBOOK CHAPTERS:

- Giancoli (Physics Principles with Applications 7th) :: 14-6, 14-7, 14-8
- Knight (College Physics : A strategic approach 3rd) :: 12.8
- BoxSand :: [Conduction, Convection, and Radiation]

WARM UP: A metal at 300 °C is placed into a glass beaker filled with water initially at 80 °C. The system is in an oven at 100 °C. Would you use calorimetry to find the final temperature of the water after the metal is placed into the 80 °C water?

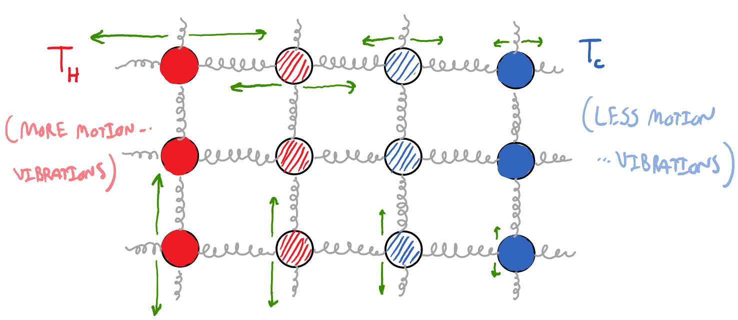


NOPE... THE GLASS BEAKER + WATER ARE IN A "HEAT BATH", THUS ENERGY CAN TRANSFER BETWEEN THE SYSTEM + THE ENVIRONMENT.

Recall that heat is the general term we use for describing the different mechanisms for transferring thermal energy between systems. This lecture will explore the 3 different mechanisms of heat transfer; conduction, convection, and radiation.

Conduction

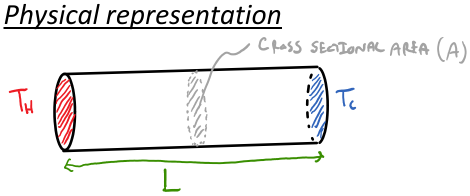
Microscopic model (solid)



Descriptive model

Molecules on the hot side are moving (vibrating) on average more than the molecules on the cold side. This motional energy propagates through the material via collisions with adjacent molecules. Basically, one vibrates the next which vibrates the next and so on.

Physical representation



Math model

$$\frac{Q}{\Delta t} = \frac{kA}{L}\Delta T$$

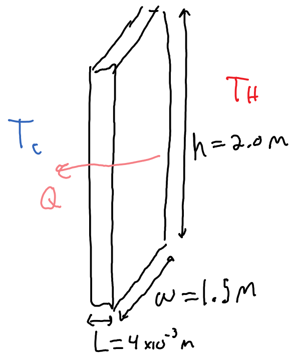
ENERGY / TIME

CHANGE IN TEMPERATURE

THERMAL CONDUCTIVITY $\equiv k$

- MATERIAL PROPERTY
- UNITS $\rightarrow \frac{W}{mK}$ ~ WATTS = $\frac{J}{s}$

PRACTICE: A glass pane in a window has dimensions 2.0 m by 1.5 m and is 4.0 mm thick. The outside temperature is 0 °C, and the inside temperature is 20 °C. How much energy is lost in one hour? Ignore radiation effects. The glass has a thermal conductivity of 0.84 J/(m s K)



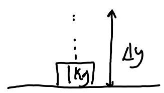
$$\frac{Q}{\Delta t} = \frac{KA}{L}\Delta T$$

$$Q = \frac{KA\Delta T\Delta t}{L}$$

$$Q = \frac{(0.84)(2\times1.5)(20-0)(3600)}{4\times10^{-3}}\ J$$

$$Q = 45360000\ J$$

Assume 25% of the heat could be transferred into lifting a 1 kg object upward. How high could that object be lifted in an hour?



$$\Delta U^g = mg\Delta y$$

$$e = \frac{GET}{PAY} = \frac{\Delta U^g}{Q} = \frac{mg\Delta y}{K\frac{A}{L}\Delta T\Delta t}$$

$$\Delta y = \frac{eKA\Delta T\Delta t}{Lmg} = 1160000\ m$$

LARGE ENOUGH THAT WE SHOULD NOT USE $\Delta U^g = mg\Delta y$, INSTEAD USE THE UNIVERSAL LAW OF GRAVITY... ALSO WINDOWS WASTE A LOT OF ENERGY.

PRACTICE: An iron skillet (c = 448 J/(kg K) ; k = 80 J/(m s K)), glass casserole dish (c = 837 J/(kg K) ; k = 0.8 J/(m s K)), and a silver ingot (c = 235 J/(kg K) ; k = 420 J/(m s K)) are all equal masses and have been in an oven at 120 °C for some time. Rank each object based on the time it will take to burn you significantly if you touch them.

TIME?... SPECIFIC HEAT NO TIME
THERMAL CONDUCTIVITY ... HAS TIME } USE K

$$\frac{Q}{\Delta t} = \frac{KA}{L}\Delta T$$

LARGER K → MORE ENERGY TRANSFER PER TIME

MORE $\frac{ENERGY}{TIME}$ BURN QUICKER... $\Delta t_{SILVER} < \Delta t_{IRON} < \Delta t_{GLASS}$

→ CONDUCTIVITY DECREASES

HOT? WE PERCEIVE $\frac{ENERGY}{TIME}$ WHEN WE TOUCH OBJECTS

If they are all put into separate equal baths of 10 °C water, rank each object based on the final temperature.

CALORIMETRY... $c = \frac{1}{m}\frac{\Delta E^{th}}{\Delta T}$

w/ m = constant

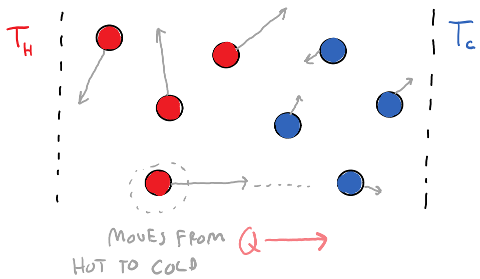
$c \sim \frac{\Delta E^{th}}{\Delta T}$ → LARGER c .... MORE STORED THERMAL ENERGY AVAILABLE TO INCREASE TEMP OF WATER...

$\Delta T_{SILVER} < \Delta T_{IRON} < \Delta T_{GLASS}$

→ SPECIFIC HEAT INCREASES

Convection

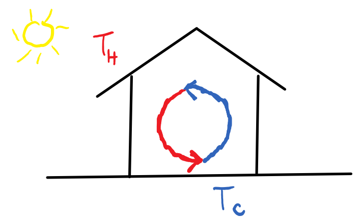
Microscopic model (gas)



Descriptive model

Faster moving "hot" molecules move to the slower moving "cold" side, increasing the average translational kinetic energy of the cold side thus raising the temperature. This action may cause "cold" molecules to be pushed to the hot side, creating convection currents.

Pictorial representation



Math model

Coupled partial differential equations…
…complicated…

Radiation

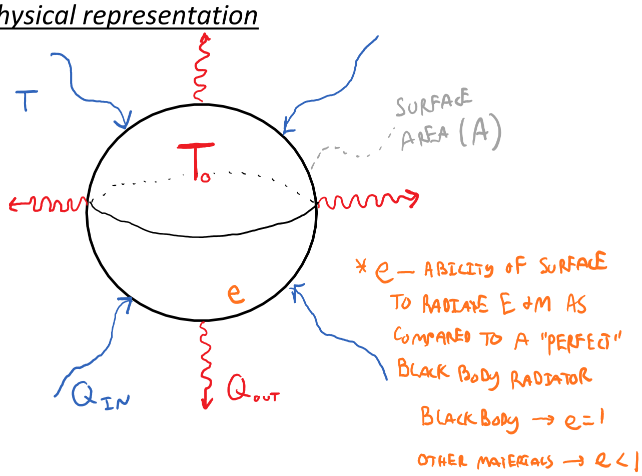
Microscopic model

Radiation does not require the presence of matter to act as the medium to transfer energy from hotter locations to colder locations.

Descriptive model

Radiation is energy transfer via electromagnetic radiation.

Physical representation



Math model

• RADIATION OUT: $\frac{Q_{OUT}}{\Delta t} = e\sigma A T_o^4$ (OBJECT TEMP)

• RADIATION IN: $\frac{Q_{IN}}{\Delta t} = e\sigma A T^4$ (ENVIRONMENT TEMP)

• NET RADIATION: $\frac{\Sigma Q}{\Delta t} = e\sigma A (T^4 - T_o^4)$

• EMISSIVITY ≡ e
  • UNITLESS

• STEFAN-BOLTZMANN CONSTANT ≡ σ

$$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$$

PRACTICE: ΔT is the same in both Celsius and Kelvin temperature scales. (T_o^4 - T^4) is also the same in both scales.

ex) T_o T $T_o^4 - T^4$

PRACTICE: ΔT is the same in both Celsius and Kelvin temperature scales. $(T_0^4 - T^4)$ is also the same in both scales.

(a) True
(b) False

ex) | T_0 | T
°C: 1°C, 0°C
K: 274K, 273K

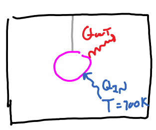
$\Delta T(°C) = 1 - 0 = 1$ unit temp
$\Delta T(K) = 274 - 273 = 1$ unit temp ✓

$T_0^4 - T^4$
Celsius: $1^4 - 0^4 = 1$ unit temp
Kelvin: $274^4 - 273^4 = 81833935$ unit temp ✗

PRACTICE: The sun continuously radiates energy into space, some of which is intercepted by the earth. The average temperature of the earth remains about 300 K. Why doesn't the earth's temperature rise as it intercepts the sun's energy? (Ignore any global climate change effects).

(a) The earth reflects all the sun's light. ~ then no Q_{in} and only Q_{out} due to radiation thus $T \downarrow$
(b) The earth radiates an amount of energy into space equal to the amount it receives.
(c) The energy only raises the temperature of the upper atmosphere and never reaches the surface. — we can observe this
(d) The thermal conductivity of earth is low.
(e) The heat is carried away from the earth by convection currents.
(f) The earth conducts the incident heat away into space.
} no particles in space

PRACTICE: An oven is maintained at 700 K. A hot metal ball is cooling down as it hangs inside the oven. When the temperature of the ball is 900 K, it is losing heat at a rate of 0.10 J/min. At what rate will the ball lose heat when the ball reaches 800 K? Assume that the emissivity of the ball does not change appreciably within this temperature range.



$$\frac{\Delta Q}{\Delta t} = e\sigma A(T^4 - T_0^4)$$ (oven, object)

$e\sigma A$ = constant

@ 900 K; $e\sigma A = \frac{\Delta Q_{900}}{\Delta t}\frac{1}{(T_{700}^4 - T_{900}^4)}$

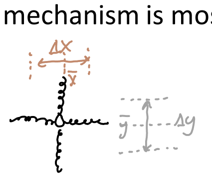
@ 800 K; $e\sigma A = \frac{\Delta Q_{800}}{\Delta t}\frac{1}{(T_{700}^4 - T_{800}^4)}$

Set equal and solve for $\frac{\Delta Q_{800}}{\Delta t}$

$$\frac{\Delta Q_{800}}{\Delta t} = \frac{\Delta Q_{900}}{\Delta t}\left(\frac{T_{700}^4 - T_{800}^4}{T_{700}^4 - T_{900}^4}\right)$$
$$= (0.1\ \tfrac{J}{m})(0.40745)$$
$$\approx 4.1 \times 10^{-2}\ J/min$$

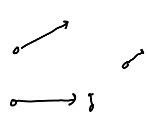
PRACTICE: Which heat transfer mechanism is most prevalent in a solid?

(a) Conduction
(b) Convection
(c) Radiation



PRACTICE: Which heat transfer mechanism is most prevalent in a gas?

(a) Conduction
(b) Convection
(c) Radiation



To make a gas use more of the conduction mechanism to transfer heat, what might you do to the gas?

... increase interactions between particles
... compress gas (closer together, more collisions)

Questions for discussion:

(1) The space between the inner walls of a thermos bottle is evacuated to minimize which heat transfer mechanisms?
(2) The interior of a thermos bottle is silvered (reflective) to minimize which heat transfer mechanism?
(3) Is touch an accurate measure of temperature? Explain your answer. Also, provide an example of an experiment you could do that supports your answer.