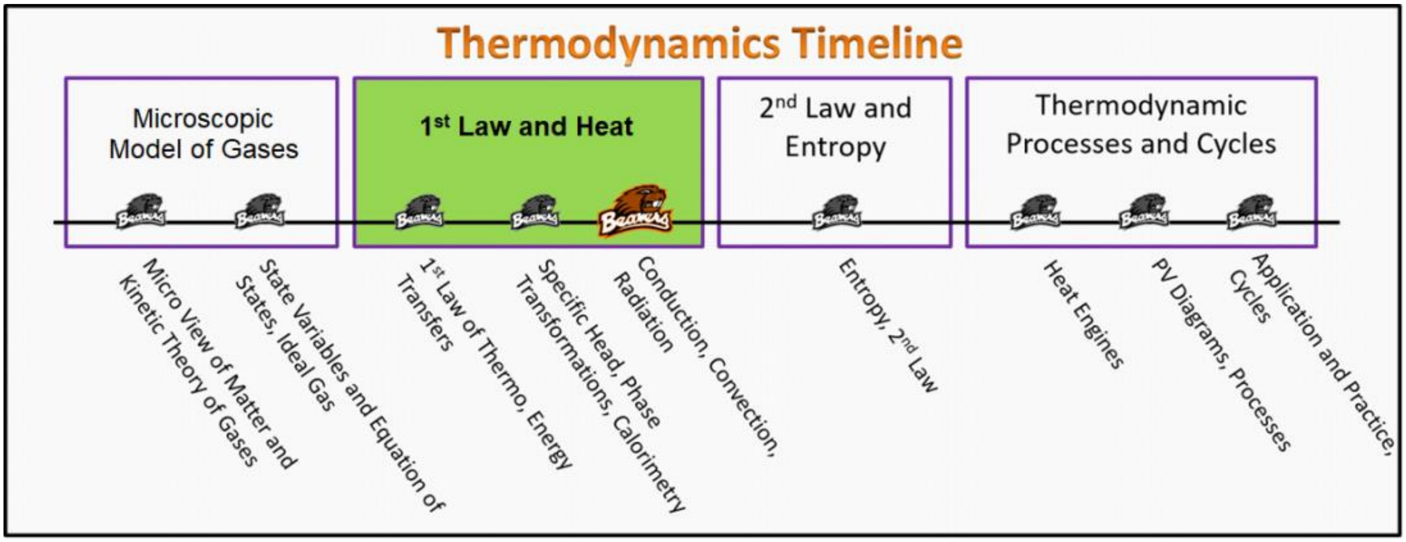
1H.2.L3 - Solutions

Tuesday, January 29, 2019 10:01 AM

Thermodynamics
Foundation Stage (1H.2.L3)

Lecture 3
Conduction, Convection, Radiation



Textbook Chapters (* Calculus version)

- **BoxSand** :: KC videos (Conduction, Convection, and Radiation)
- **Knight** (College Physics : A strategic approach 3rd) ::
- ***Knight** (Physics for Scientists and Engineers 4th) ::
- **Giancoli** (Physics Principles with Applications 7th) ::

Warm up

1H.2.L3-1:

Description: Conduction, convection, and radiation examples

Learning Objectives: [?] - Can you identify the objectives from the previous lecture, and this lecture, that this question is relevant to?

Problem Statement: Think of three situations, one for each of the methods of heat transfer where the method is the clearly dominant method of energy transfer. Think of a fourth situation where all three methods are present and it is not clear which is dominant.

Submit your favorite situation to the word cloud on LC!

Selected Learning Objectives

1. Coming soon to a lecture template near you.

Key Terms

- Temperature
- Thermal energy
- Thermodynamic equilibrium
- Specific heat
- Solid, liquid, and gas phases
- Heat of transformation (vaporization, fusion)
- Melting point
- Boiling temperature

Key Equations

Questions

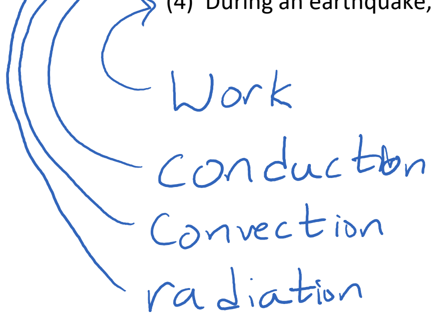
1H.2.L3-2:

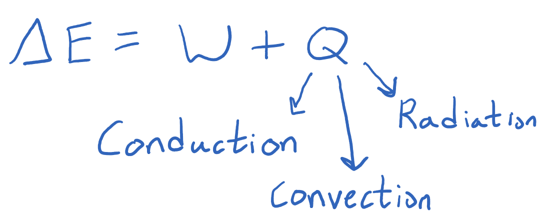
Description: Match situations with energy transfer mechanisms. (2 minutes)

Learning Objectives: [?]

Problem Statement: Match each system with the energy transfer mechanism.

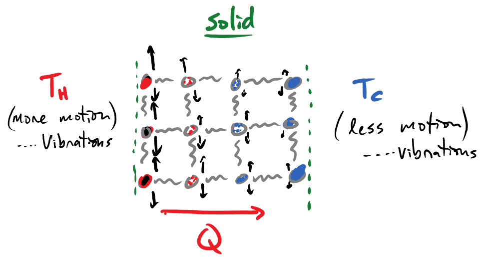
(1) The transfer of energy from the Sun to the Earth.
(2) The Atlantic conveyer belt of ocean currents that mixes cold water from the north with warm water from the equator.
(3) Underground liquid hot magma warming up your favorite hot spring.
(4) During an earthquake, two tectonic plates slide, warming up adjacent rocks.



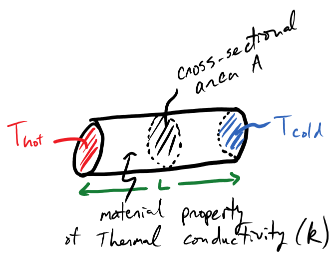


Act I: Conduction

Conduction is the transfer of heat that occurs when two objects or substances come into physical contact. The microscopic model is as pictured below:



If one side of a solid (liquid) has a high temperature, those atoms will vibrate (move) more quickly. These hot atoms will interact via bonds with neighboring atoms giving some of their energy to them, causing them to vibrate (move) more rapidly. This is how energy is conducted through and between solids (and liquids). The rate at which heat is transferred via conduction depends on the length over which the heat travels, the cross-sectional area of the material, the temperature difference between the ends of the material, and on a parameter called the thermal conductivity. Different materials conduct heat more readily. Metals typically have higher thermal conductivities (they transfer heat very quickly), and materials like glass and ceramics have relatively low thermal conductivities (they do not transfer heat quickly).



The above picture shows an object and the temperature difference, length, cross-sectional area, and thermal conductivity, k. The greater the distance the heat must flow, the slower the rate at which energy will transfer. With a greater cross-sectional area, there will be more atoms in contact and energy will flow more rapidly. Likewise, a larger temperature difference will provide a steeper "hill" resulting in a faster rate of conduction. Mathematically, this looks like the following:

$$\frac{J}{s} \qquad \frac{Q}{\Delta t} = \left(\frac{kA}{L}\right)\Delta T = \text{Power}$$

A steady state can be reached if the hot and cold reservoirs are large enough that their temperatures are constant. If the cross sectional area and distance over which the heat flows is also constant, then the right hand side of the above equation will be constant. The amount of heat transferred per time would then be a constant.

1H.2.L3-3:

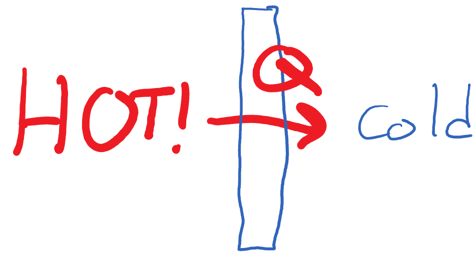
Description: Glass windows and conduction. (1 minute, 5 minutes, 3 minutes)

Learning Objectives: [?]

Problem Statement: In a cold Corvallis winter, the temperature outside your house is 0 °C. The temperature inside is a comfortable room temperature of 20 °C.

(a) Which direction does energy conduct through the panes of your window?

(1) The inside gains energy while the outside loses energy.
(2) The outside gains energy while the inside loses energy.
(3) There is no energy flow as an equilibrium has been reached.



(b) The glass pane in a window has dimensions of 2.0 m by 1.5 m and is 4.0 mm thick. How much energy is lost in one hour? Ignore radiation effects and assume the glass has a thermal conductivity of 0.78 J/(m·s·K)

$$\frac{Q}{\Delta t} = \left(\frac{kA}{L}\right)\Delta T \Rightarrow Q_{tot} = \underbrace{\left(\frac{kA}{L}\right)\Delta T}_{\frac{\text{energy}}{\text{time}}}\underbrace{\Delta t}_{\text{time}} = 42{,}120{,}000\ \text{J}$$

3600 seconds

(c) Assuming 25% of the heat could be transferred into lifting a 1-kg-object upward, how high could that object be lifted in an hour?

$$E = 42{,}120{,}000 \times 25\% = \frac{42{,}120{,}000}{4} = mgh$$

$$\Rightarrow h = \frac{42{,}120{,}000}{(1)(10)(4)} \sim 1000\ \text{km}\ !!$$

1H.2.L3-4:

Description: Energy transfer effects of thermal conductivity and specific heat. (2 minutes, 2 minutes, 1 minute)

Learning Objectives: [?]

Problem Statement: An iron skillet, glass casserole dish, and silver ingot are all of equal mass and have been in an oven at 120 °C for a long time.

Material	c	k
Iron Skillet	448 J/kg K	80 J/s m K
Glass Casserole Dish	837 J/kg K	0.8 J/s m K
Silver Ingot	235 J/kg K	420 J/s m K

$$\frac{Q}{\Delta t} = k\frac{A}{L}\Delta T$$

$$\Delta E = mc\Delta T$$

(a) Rank each object based on the time (smallest to largest) it will take to burn you significantly if you touch them.

(k)

$$t_{silver} < t_{iron} < t_{glass}$$

(b) They are all put into separate equal baths of 10 °C water. Rank each object based on the final equilibrium temperature.

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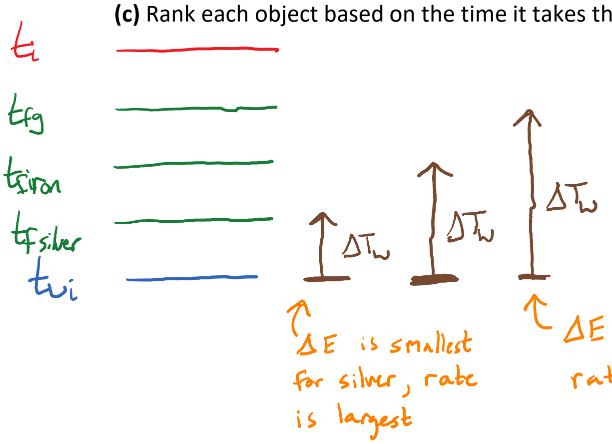
(C) $T_{silver} < T_{iron} < T_{glass}$

(c) Rank each object based on the time it takes them to reach their equilibrium temperature with the bath.

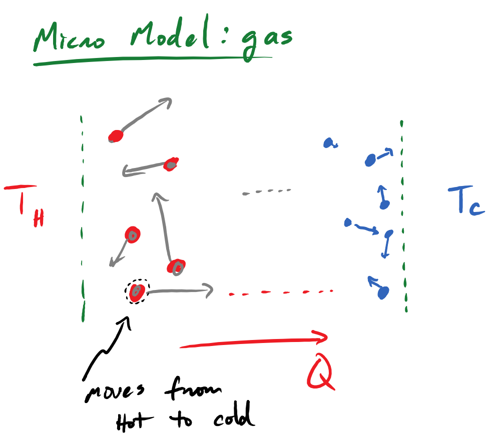
$\Delta E = mc\Delta T$

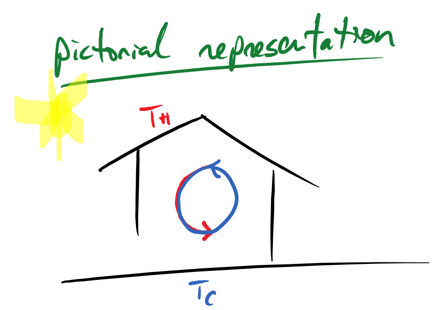


ΔE is greatest for the glass rate of energy transfer is slowest → $t_{silver} < t_{iron} < t_{glass}$

Act II: Convection

Convection is heat transfer that happens when particles with large kinetic energies physically travel to a location where the average particle has lower kinetic energies. Often, this results in the displacement of the colder particles to the location where the hotter particles gained their energy. This results in cyclic "convection currents" between a hot and a cold reservoir. Particles gain energy from the heat source, travel to the cold sink, lose their energy, and then get displaced back to the heat source where the process repeats.





The mathematical model is quite complicated, but is studied often in meteorology and oceanography as convection is very important in the description of weather patterns and ocean currents. Convection is the reason that Britain took over the world instead of getting really good at the Winter Olympics like the Scandinavians did!

1H.2.L3-5:

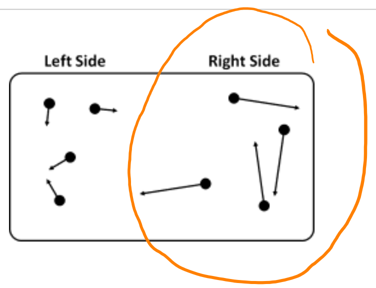
Description: (1 minute, 3 minutes)

Learning Objectives: [?]

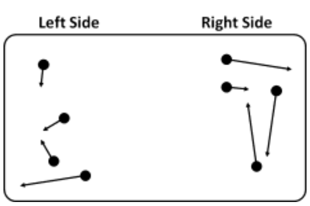
Problem Statement: You have a box containing eight gas particles. The four particles on the left each have speeds of 20 km/s, while the particles on the right each have speeds of 100 km/s.

(a) Which side has a larger temperature?

T ⇒ avg KE



(b) One particle on each side happens to have a momentum towards the other side. If this causes them to switch sides, what is the new average speed on the warm side?



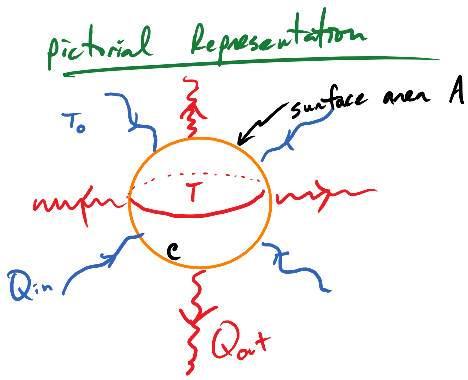
$$\frac{100 + 100 + 100 + 20}{4} = \frac{320 \text{ km/s}}{4} = \boxed{80 \text{ km/s}}$$

↑ colder!

Act III: Radiation

Radiation is the form of energy transfer that occurs when electromagnetic waves are emitted by one object and absorbed by another. Electromagnetic radiation is more commonly called light! We see only a tiny portion of the electromagnetic spectrum. The human eye can see wavelengths of light between about 400 and 800 nm. Other common examples of light are: x-rays (0.01 to 1.0 nm wavelength), microwaves (your microwave oven uses 12.2 cm wavelength light which is easily absorbed by the water and fat in your food), infrared (wavelengths between 1 mm and 800 nm. Snakes, mosquitos, fish, frogs, military goggles, and your phone camera can all see these), and radio (> 1 meter, which is why they can travel through and around large objects easily).

All objects that are above 0 K (which is everything! You even!) emit light. You, and most things on earth are roughly the same temperature and emit light in the infrared wavelengths.



An object's temperature, surface area, and emissivity are important when determining the rate at which it radiates energy away. The higher an objects temperature and the more surface area it has, the larger the rate of energy transfer. Emissivity is a measure of how readily an object radiates light and is a number between 0 and 1. It is actually a ratio of its emissivity relative to that of an ideal black object (black body if you are an astronomer) at the same temperature. The following equation relates these quantities.

$$\frac{Q_{out}}{\Delta t} = e\sigma A T^4$$

The Stefan-Boltzmann constant is represented by a σ, and has a value of 5.67 x 10^{-8} W/(m^2 K^4). The emissivity is given the symbol e, and A is the surface area. The temperature, T, must be given in Kelvin.

Since an object interacts with its environment, which also has a temperature, the net radiative energy transfer must include a term for the radiation the object is absorbing from the environment. If T is the temperature of the object and T_0 is the temperature of the surrounding environment, then the net transfer of energy is given by:

$$\frac{\sum Q}{\Delta t} = -e\sigma A T^4 + e\sigma A T_0^4 = e\sigma A\left(T_0^4 - T^4\right)$$

Note that the signs in the above equation indicate that energy absorbed by the object from the environment is positive, and energy leaving the object is negative heat. This is an indication that we have chosen our object as the system.

1H.2.L3-6:

Description: (1 minute)

Learning Objectives: [?]

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Problem Statement: ΔT is the same in both Celsius and Kelvin temperature scales. $T_f^4 - T_i^4$ is also the same in both scales.

(1) True
(2) False

	T_f	T_i	$T_f - T_i$	$T_f^4 - T_i^4$
Celsius	1°C	0°C	1°C	~~1°C⁴~~ ← don't use celsius! (for radiation)
Kelvin	274 K	273K	1 K	81,833,935 K^4 Correct

1H.2.L3-7:

Description: (4 minutes, 4 minutes)

Learning Objectives: [?]

Problem Statement: An aluminum cup is filled with hot coffee and a lid is placed on the cup. The coffee-cup system quickly reaches a common temperature of 368 K. The cup is sitting in a local coffee shop with an air temperature of 293 K. The cup's emissivity is 0.09 and it has a cross sectional area of 0.045 m^2.

(a) How much heat is transferred into the environment via radiation in one minute (assume the temperature of the room and coffee do not change significantly)

$$\frac{Q}{\Delta t} = e\sigma A T_0^4 - e\sigma A T^4$$

(absorbed from environment; radiated away from cup)

$$= e\sigma A (T_0^4 - T^4)$$

$$= (0.09)(5.67\times10^{-8})(0.045)(293^4 - 368^4)$$

$$= 2.52 \text{ J/s}$$

$$Q = (2.52)(60) = \boxed{151 \text{ J}}$$

(b) Assuming a contraption of 50% efficiency, how fast could you spin a hot dog with this amount of energy? (answer in rad/sec) The moment of inertia of a hotdog about its center of mass is 8.5x10^{-5} kg m^2.

$KE_{rot} = \frac{1}{2} I \omega^2$

Energy available = 75.5J

$75.5 = \frac{1}{2}(8.5\times10^{-5})\omega^2$

$\boxed{\omega = 1{,}330 \frac{rad}{sec}}$ (thats 212 rot/sec!)

Energy available = 75.5J

$$\omega = 1{,}330 \ \frac{\text{rad}}{\text{sec}}$$ (thats 212 rot/sec!)

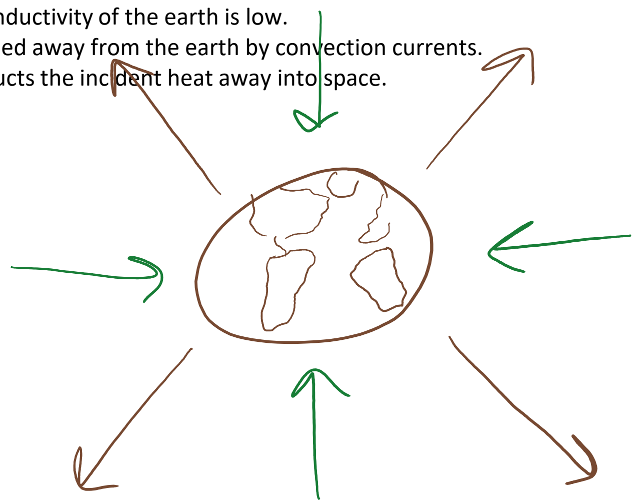
1H.2.L3-8:

Description: (3 minutes)

Learning Objectives: [?]

Problem Statement: 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 current global climate change effects).

(1) The earth reflects all the sun's light.
(2) The earth radiates an amount of energy into space equal to the amount it receives.
(3) The energy only raises the temperature of the upper atmosphere and never reaches the surface.
(4) The thermal conductivity of the earth is low.
(5) The heat is carried away from the earth by convection currents.
(6) The earth conducts the incident heat away into space.



$$\Delta E_{tot} = 0 = \Delta E_{in} - \Delta E_{out}$$

1H.2.L3-9:

Description: (1 minute, 1 minute, 1 minute)

Learning Objectives: [?]

Problem Statement: Which heat mechanism is most prevalent in the following phases?

(a) Solids?

(1) Conduction
(2) Convection
(3) Radiation

(a) gas?

(1) Conduction
(2) Convection
(3) Radiation

(a) Select all the heat transfer mechanisms that occur in an ideal gas (regardless of how large in effect they are).

(1) Conduction
(2) Convection
(3) Radiation

1H.2.L3-10:

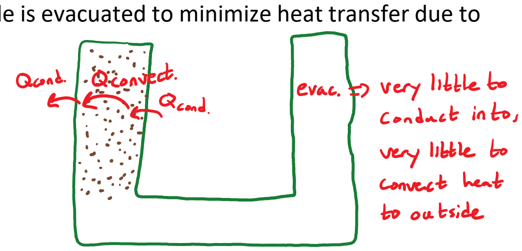
Description: (3 minute, 2 minute)

Learning Objectives: [?]

Problem Statement: Finish the following statements with one, two, or all three of the following terms: conduction, convection, radiation.

(a) The space between the inner walls of a thermos bottle is evacuated to minimize heat transfer due to

Conduction, convection



(b) The interior of a thermos bottle is silvered (made reflective) to minimize heat transfer due to

radiation

Conceptual questions for discussion

1. .

Hints

1H.2.L2-1: No hints.