Thermodynamics
Heat Transfer

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May 1, 2020

Last time

- one more 1st law example
- heat transfer
- conduction

Overview

- continue heat transfer mechanisms
- conduction over a distance
- convection
- radiation and Stephan's law

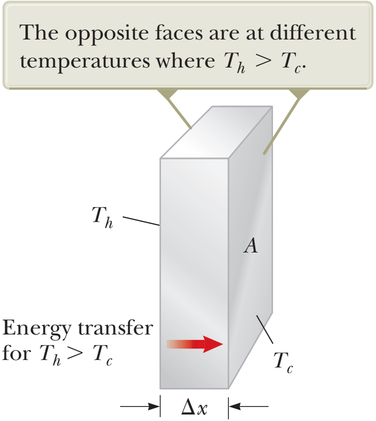
Reminder: Heat Transfer

When objects are in thermal contact, heat is transferred from the hotter object to the cooler object

There are various mechanisms by which this happens:

- conduction
- convection
- radiation

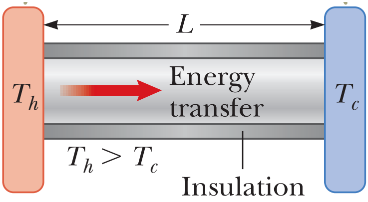
Reminder: Thermal Conduction over distance



Rate of heat transfer between surfaces:

$$\text{power, } P = \frac{Q}{\Delta t} = kA\,\frac{\Delta T}{\Delta x}$$

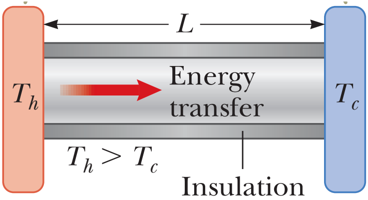
Reminder: Thermal Conduction over distance



Then,

$$P = kA\left(\frac{T_h - T_c}{L}\right)$$

Reminder: Thermal Conduction over distance

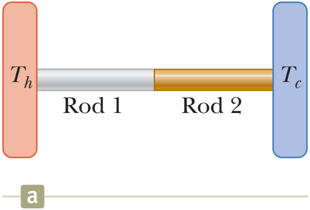


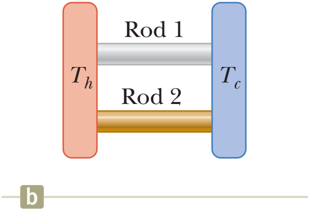
Then,

$$P = kA\left(\frac{T_h - T_c}{L}\right)$$

What if there are many different bars for heat to be transferred through?

Thermal Conduction through multiple materials





For situation (a):

$$P = \frac{A(T_h - T_c)}{(L_1/k_1) + (L_2/k_2)}$$

(See ex. 20.8)

For situation (b):

$$\begin{aligned} P &= P_1 + P_2 \\ &= \left(\frac{k_1 A_1}{L_1} + \frac{k_2 A_2}{L_2}\right)(T_h - T_c) \end{aligned}$$

Thermal Conduction through multiple materials

Compare:

$$P = \left(\frac{kA}{L}\right)\Delta T$$
$$I = \left(\frac{1}{R}\right)\Delta V$$

On the LHS we have transfer rates, on the RHS differences that propel a transfer.

You can think of $\frac{L}{kA}$ as a kind of resistance. k is a conductivity, like σ (electrical conductivity). Recall, $R = \frac{\rho L}{A} = \frac{L}{\sigma A}$.

Thermal Conduction through multiple materials

For multiple thermal transfer slabs in series:

$$P = \frac{1}{\sum_i (L_i/(k_i A))} \Delta T$$

For multiple thermal transfer slabs in parallel:

$$P = \left(\sum_i \frac{k_i A_i}{L_i} \right) \Delta T$$

Now for convenient comparison, let $r_i = \frac{L_i}{k_i A_i}$. Then r_i is a thermal resistance, for the ith slab.

Thermal Conduction through multiple materials

For multiple resistors in series:

$$I = \left(\frac{1}{\sum_i R_i} \right) \Delta V$$

For multiple thermal transfer slabs in series:

$$P = \left(\frac{1}{\sum_i r_i} \right) \Delta T$$

For multiple resistors in parallel:

$$I = \left(\sum_i \frac{1}{R_i} \right) \Delta V$$

For multiple thermal transfer slabs in parallel:

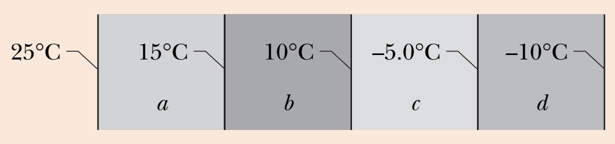
$$P = \left(\sum_i \frac{1}{r_i} \right) \Delta T$$

Thermal Conduction and Ohm's Law

Fourier's work on thermal conductivity inspired Ohm's model of electrical conductivity and resistance!

Thermal Conductivity Question

The figure shows the face and interface temperatures of a composite slab consisting of four materials, of identical thicknesses, through which the heat transfer is steady. Rank the materials according to their thermal conductivities, greatest first.



(A) a, b, c, d

(B) (b and d), a, c

(C) c, a, (b and d)

(D) (b, c, and d), a

[1] Halliday, Resnick, Walker, page 495.

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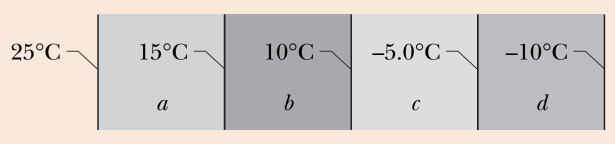

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Thermal Conduction and Insulation

Engineers generally prefer to quote "R-values" for insulation, rather than using thermal conductivity, k.

For a particular material:

$$R = \frac{L}{k}$$

This is its "length-resistivity" to heat transfer.

A high value of R indicates a good insulator.

The units used are $\text{ft}^2\,{}^\circ\text{F h / Btu}$. (h is hours, Btu is British thermal units, 1 Btu = 1.06 kJ)

Convection

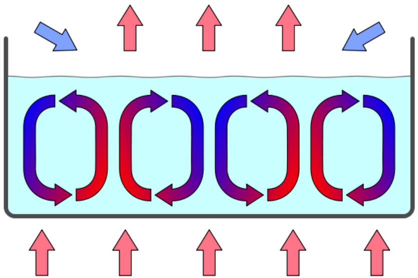
In **liquids and gases** convection is usually a larger contributor to heat transfer.

In convection, the fluid itself **circulates** distributing hot (fast moving) molecules throughout the fluid.

When there is gravity present, convection current circulations can occur.

Convection

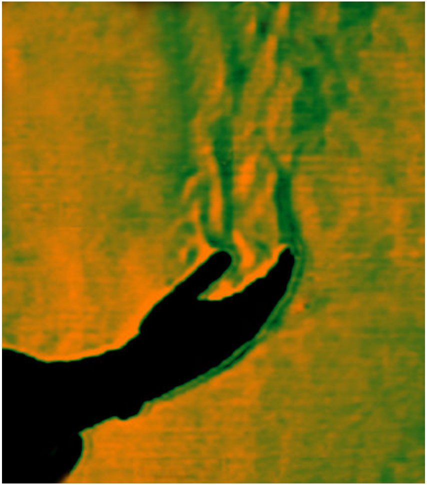
Hot fluid expands, and since it is less dense, it will have a greater buoyant force and rise.



Cooler, denser fluid will tend to sink.

Convection

Heat loss by convection from a person's hand:



This type of convection is called "free convection".

Forced Convection

External energy can also drive convection by means of a pump or fan.

This is used in convection ovens to evenly heat food.

It is also used in cooling systems to keep cool air flowing over hot components.

Radiation

Heat can also be transferred, even across a vacuum, by **radiation**.

This radiation takes the form of electromagnetic (em) radiation (light). However, most of this radiation is not in the range of wavelengths that are visible to us.

Light carries energy, so this an energy transfer.

Dark colored surfaces absorb and emit radiation more readily that white or shiny surfaces.

Stefan's Law

How fast does a hot object radiate away energy?

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

where

- P is power
- $\sigma = 5.6696 \times 10^{-8}$ W m^{-2} K^{-4}
- A is the surface area of the object
- e is the emissivity ($0 \leqslant e \leqslant 1$ always)
- T is temperature

The net rate of energy change depends on the difference in temperature ΔT, between an object and its environment.

$$P_{\text{net}} = \sigma A e (T_o^4 - T_e^4)$$

Emissivity and Absorptivity

Properties of a surface tell us how it will interact with light.

- emissivity, e (or ϵ), ratio of emitted energy to the amount that would be radiated if the object were a perfect black body
- absorptivity, α, the ratio of energy absorbed to energy incident

These are not independent of each other, and both depends on the wavelength of light.

Emissivity and Absorptivity

Kirchhoff's law of thermal radiation can be stated (this isn't how Kirchhoff stated it):

"For an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity."

This is true for every wavelength: $e(\lambda) = \alpha(\lambda)$.

For perfect blackbodies $e = 1$.

Very reflective surfaces have low e and α.

Emissivity and Absorptivity

Why are survival and rescue blankets now made out of shiny material?

Light (Electromagnetic Radiation)

Light travels at this fixed speed, $c = 3.00 \times 10^8$ m s^{-1}.

For any wave, if v is the wave propogation speed:

$$v = f\lambda$$

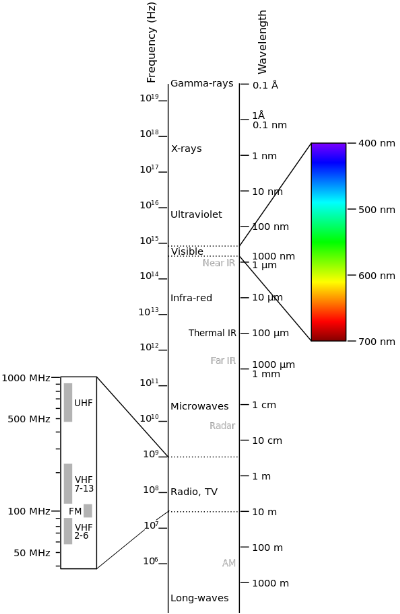
For light:

$$c = f\lambda$$

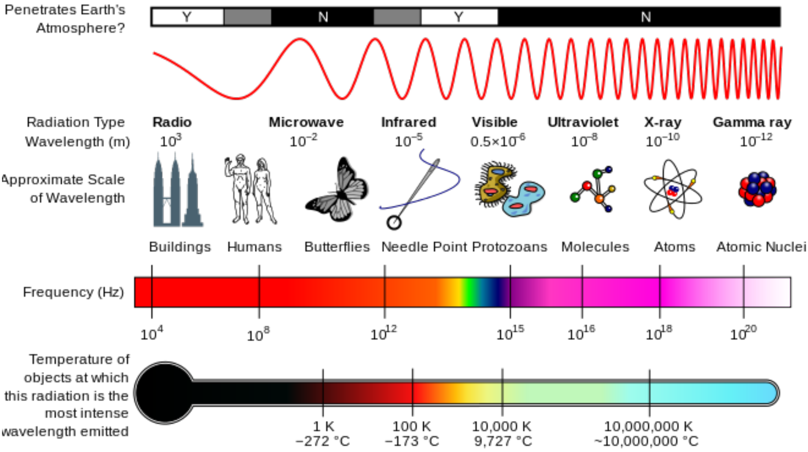
So, if the frequency of the light is given, you also know the wavelength, and vice versa.

$$\lambda = \frac{c}{f} \quad ; \quad f = \frac{c}{\lambda}$$

Electromagnetic spectrum

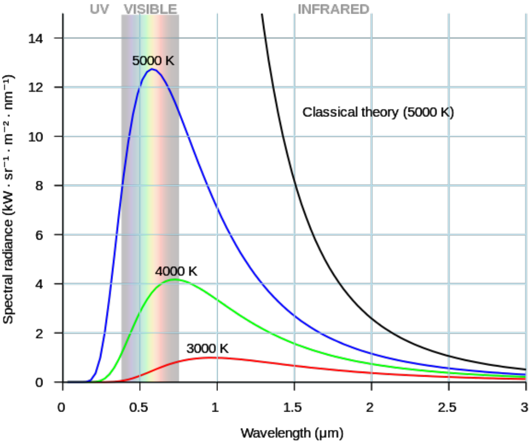


Electromagnetic spectrum



Blackbody Radiation

All objects radiate light with characteristic wavelengths depending on the object's temperature.



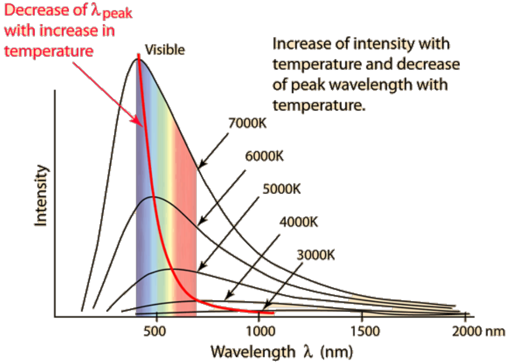
Hotter objects emit light with shorter wavelengths (on average).

[1]Graph from Wikipedia, created by user Darth Kule.

Blackbody Radiation: Wien's Law

Wien's (Displacement) Law relates the peak wavelength emitted by a blackbody to its temperature:

$$\lambda_{max} = \frac{b}{T}$$



$b = 2.898 \times 10^{-3}$ m K is a constant.

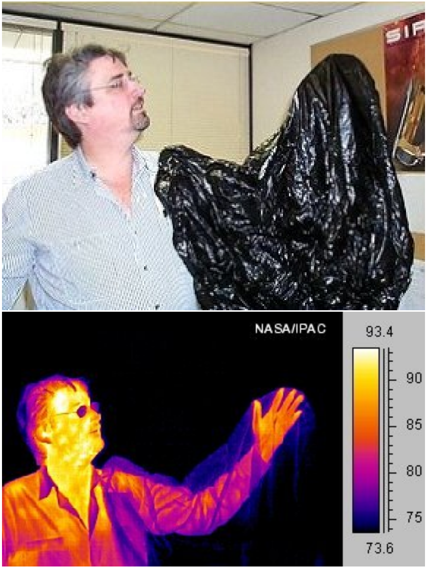
[1] Figure from HyperPhysics.

Radiation

People emit light as well, but the wavelengths corresponding to our body temperature are longer than what we can see with the naked eye.

Humans and warm-blooded animals radiate **infrared radiation**. ("below red")

Visible vs. Infrared radiation



Radiation

Objects much hotter than the human body will radiate at shorter wavelengths that are visible to us.

The Greenhouse Effect

Gardeners use greenhouses, huts made of glass or transparent plastic, to keep plants warm.

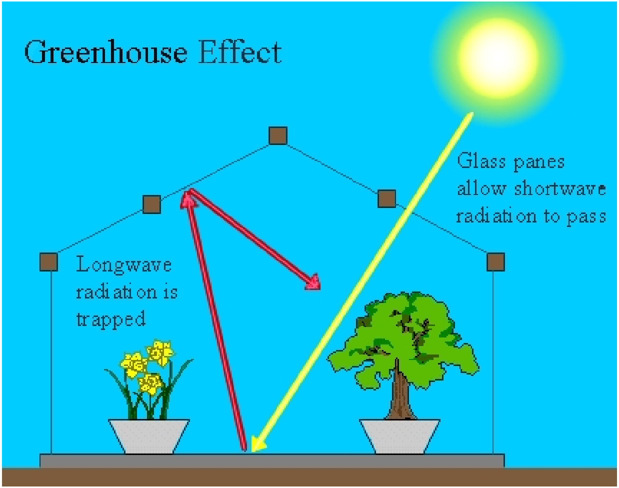
The effect that causes this to work is called the greenhouse effect.

The Sun is very hot and emits a lot of radiation in the visible (shorter) wavelengths.

Objects on Earth absorb this radiation and emit their own. However, since objects on the Earth are substantially cooler than the Sun, the wavelengths re-emitted are longer.

The glass allows the shorter wavelengths through, but traps the longer wavelengths.

The Greenhouse Effect



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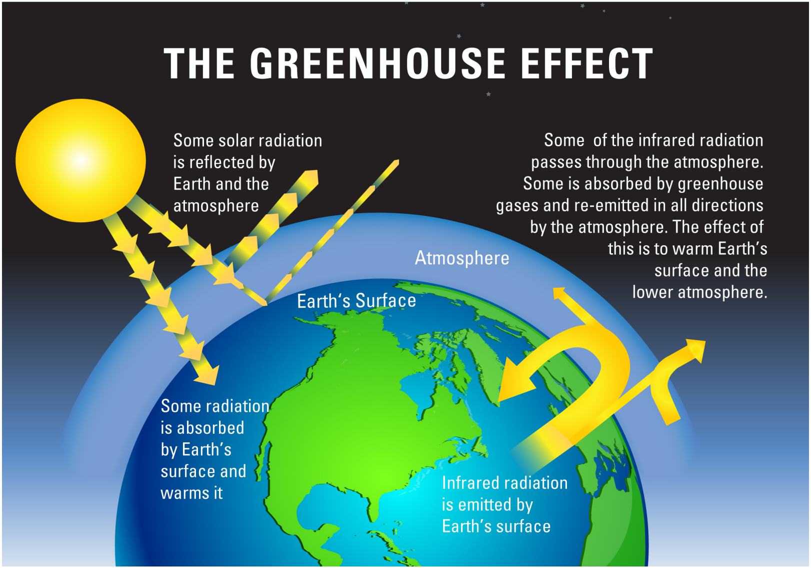

[1]Figure from the National Academy of Sciences, *America's Climate Choices*

Summary

- heat transfer mechanisms: conduction, convection, radiation

Next Test Tuesday, May 5, on Ch19, 20.

Homework

- new full-solution HW posted
- new WebAssign HW posted (due Monday night)