Lecture 32 - Temperature and heat

What's important:

- definitions of temperature and heat
- heat transfer

Demonstrations:

- convection tube; hot and cold dyes in water; match and parabolic mirrors

Text: Walker, Secs. 16.1, 16.2, 16.4, 16.6
Problems:

Thermodynamics

The study of thermodynamics, as the name implies, is the study of the transfer of heat. What is heat? In times past, heat was thought of as a fluid that flowed from one object to another. The words "heat flow" remain today. We now know that a body possess heat, or has a temperature, by virtue of the motion of its atoms and molecules. In this sense, heat is another manifestation of kinetic energy.

In general, we shall talk about "systems" in thermodynamics, where a system is a collection of molecules, a material, etc. Some categories of systems:

- *open systems*: can exchange mass or energy with their environment; most systems of interest on Earth are open

- *closed systems*: can exchange energy, but not mass, with their surroundings; example would be plants in a closed terrarium

- *isolated systems*: can exchange neither mass nor energy; example would be the contents of an ideal Thermos bottle.

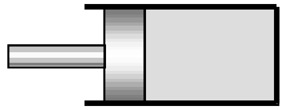
Temperature

Consider two systems **A** and **B**, with a portable system **T** that we can place in contact with each of them separately. We place **T** in contact with system **A**, permitting them to reach equilibrium. Now let's place **T** in contact with system **B**, isolated from **A**. If **T** is unchanged by this second operation, we say that **A** and **B** have the same temperature. This is the zeroth law of thermodynamics (the *what happens if nothing happens* thermal version of Newton's laws):

If object **A** is in thermal equilibrium with object **T**, and object **B** is separately in thermal equilibrium with object **T**, then objects **A** and **B** will be in thermal equilibrium if they are placed in thermal contact.

System **T** is then a measure of temperature - it is a thermometer.

Suppose we have a gas confined to a container by a frictionless piston:



If we compress the gas by exerting a force on the piston, we have done work on the gas. Yet its center of mass is not moving: rather, we have raised its temperature

Similarly, if we heat the gas, then it can do work against the original force that held the piston in its place.

Hence, work and heat can be interconverted, obeying conservation of energy just like we found for linear and angular kinematics. This is the **first law of thermodynamics**

$$Q - W_{\text{by system}} = \Delta E$$

$W_{\text{by system}}$ = mechanical work done **by** the system
Q = energy transferred **to** the system by conduction, convection, radiation...
ΔE = the change in the internal energy of the system

The heat capacity C of a system measures what the change in temperature is for the addition of a given amount of (heat) energy Q:

$Q = C\,\Delta T$.

C depends upon the material of the system and its overall mass: it takes twice as much heat to raise the temperature of 1 kg of water as half a kilogram. For the purposes of calculating the heat capacity of an object, it is useful to divide C by the mass of the object to obtain the specific heat c:

$c = C/m$,

such that

$Q = cm\,\Delta T$.

Some examples:

material	c (J/K-kg)
water	4.186×10^3
glass	0.84×10^3
iron	0.448×10^3

Notes:

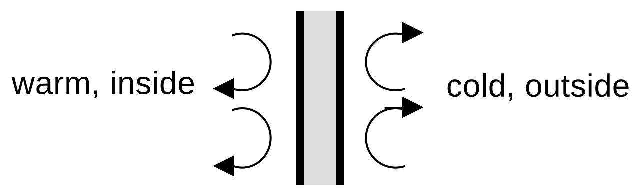
- chemists also work in molar heats, which is the heat capacity per mole
- for gases, *c* depends on whether the heat is added at constant volume or constant pressure
- an energy unit called the calorie (cal) is the amount of heat required to raise 1 gram of water from 14.5 to 15.5 C; 1 cal = 4.186 J.

Heat transfer

We have described how mechanical work can be performed on a system. Heat may be transferred by several ways:

Convection

Transfer involves the movement of the medium to supply heat from an external source. It is difficult to calculate because it involves fluid dynamics



double-pane glass window
motion of air indicated by circles

If the air is not stagnant, the rate of heat transfer obeys **Newton's law of cooling**:

[*rate of heat transfer*] [*surface area*] • [*temperature difference*]

Radiation

This transfer involves the emission or adsorption of electromagnetic radiation, typically at wavelengths of 1 µm to 100 µm. It efficiency depends on the material at the surface; highest efficiency is with so-called black bodies. For a black body, the emissive power $\mathcal{E}$ is given by the **Stefan-Boltzmann equation**

$$\mathcal{E} = \sigma T^4$$

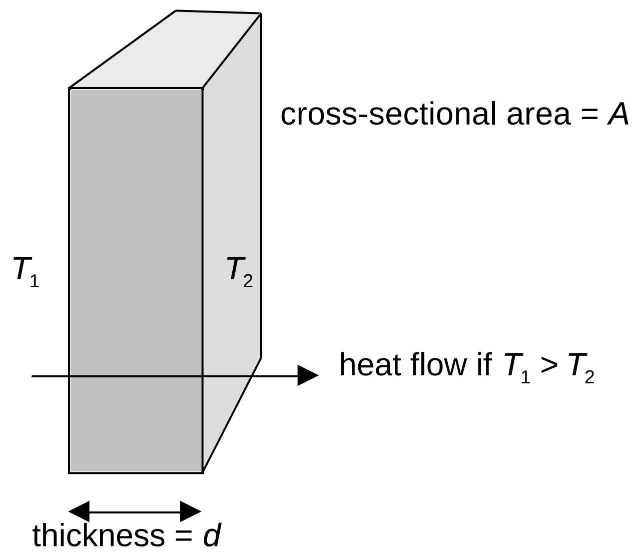
where:

- $\mathcal{E}$ = the energy per unit area per unit time (or power per unit area)
- T is in K
- σ = Stefan's constant = 5.67×10^{-8} watts / m^2 K^4.

Conduction

Conduction involves the transfer of heat without the movement of fluids as found in convection. Consider a slab of material subject to a temperature difference

$\Delta T = T_1 - T_2$



We call the heat flow or heat current H the rate of heat flow

--> hence, H has units of watts.

Conduction is described by **Fourier's Law of Thermal Conduction**

$$H = K A \Delta T / d$$

K is the thermal conductivity of the material, Some examples

material	K (watts / K•m)
silver	417
copper	395
aluminum	217
steel	67
concrete	1.3
water	0.60
wood	0.10