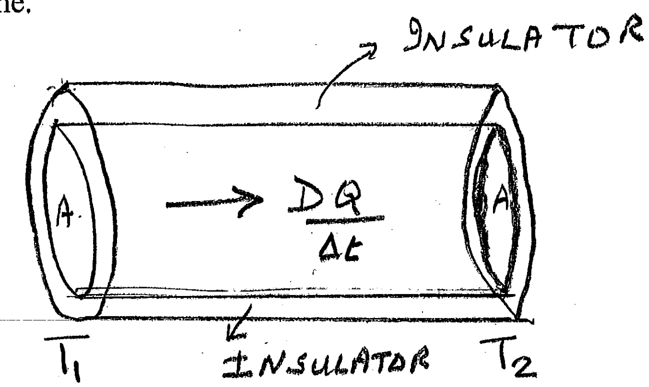
MODES OF HEAT TRANSFER

I: Heat is the energy transfer or exchange caused by a temperature difference. Hence if there is a temperature difference there shall be a heat transfer whether the two locations of the temperature are separated by a solid, liquid, gas or vacuum.

The three modes are:
Conduction: Operates in solids and stationary liquids and gases (no stirring allowed).
Convection: Operates in liquids and gases due to thermal stirring.
Radiation: Operates in vacuum. Indeed interposition of matter impedes radiation.

CONDUCTION

Transfer of heat occurs layer by layer. Higher temperature (higher kinetic energy) layer hands over energy to a lower temperature layer thereby causing a heat "current" to "flow" from high T to low T.
We will concentrate on the steady state situation. That is, the temperatures don't vary with time.



(Assume that there is no heat loss from the curved surfaces)
Consider a block of cross section A and length ℓ where the temperatures are T_1 (left face) and T_2 (right face).
For example: $T_1 = 373$ K (Steam)
$T_2 = 273$ K (Ice)
The heat current is equal to amount of heat flow per second

$$\frac{DQ}{\Delta t}$$

We can measure $\frac{DQ}{\Delta t}$ by keeping track of the amount of ice melting per second (It costs 80cal/gm at 273K). Expts. will show that:

$\frac{DQ}{\Delta t}$ is proportional to area A

$\frac{DQ}{\Delta t}$ is proportional to $\frac{1}{\ell}$ *or* $\left(\frac{1}{\Delta x}\right)$

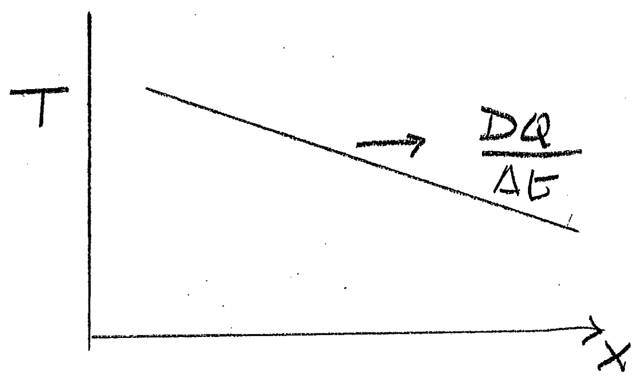
$\frac{DQ}{\Delta t}$ is proportional to $(T_1 - T_2)$ *or* ΔT

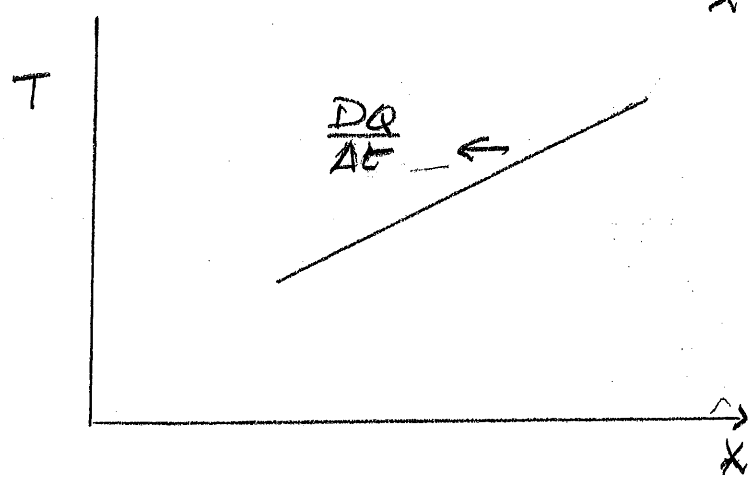
and of course $\frac{DQ}{\Delta t}$ is governed by the material of the block so the steady state equation for conduction becomes

$$\boxed{\frac{DQ}{\Delta t} = -kA\frac{\Delta T}{\Delta x}}$$

where k = Thermal Conductivity of the material $\lfloor ML^{-1}T^{-3}\theta^{-1} \rfloor$

Note the minus sign on the right of this equation. It <u>ensures</u> that heat always flows form high T to low T. Indeed,





Typical k values

$$k_{cu} \approx 400 J/m/\sec/°C$$
$$k_{wood} \approx 0.1 J/m/\sec/°C$$

So our conducting boundary will be made of thin copper of large area while insulating boundary would need thick wood with a small area.

$\sigma = 6 \times 10^{-8}$ W/m^2/ K^4. Notice, if T goes from 300K to 900, $\left(\frac{DQ}{\Delta t}\right)$ increases by a factor of 81! Of course, if the surroundings have temperature T_s they also radiate and their energy must go through the same surface so

$$\left(\frac{DQ}{\Delta t}\right)_{in} = A\,e\,\sigma T_s^{\,4}$$

Hence

$$\left(\frac{DQ}{\Delta t}\right)_{net} = A\,e\,\sigma\left(T_s^{\,4} - T^4\right)$$

The object will increase its T if $T_s > T$ and will cool if $T_s < T$. Again, all exchange stops if $T_s = T$.

Further,

$$\left(\frac{DQ}{\Delta t}\right)_{net} = A\,e\,\sigma\left(T_s - T\right)\left(T_s + T\right)\left(T_s^{\,2} + T^2\right)$$

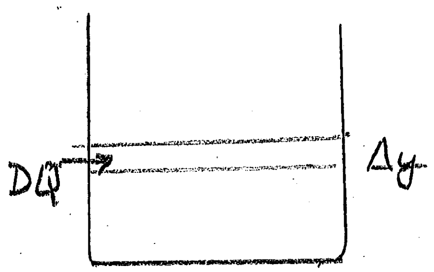
So if $(T_s - T) << T_s$ and T, $(T_s + T)$ and $(T_s^2 + T^2)$ are essentially constant, yielding.

$$\left(\frac{DQ}{\Delta t}\right)_{net} \alpha.\left(T_s - T\right)$$

which is Newton's Law of Cooling. That is, for small temperature differences, rate of cooling, by radiation, is proportional to the temperature difference.

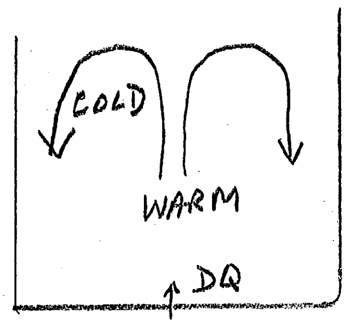
The emissivity e depends on surface roughness, color etc. Rough, Dark surfaces have $e \approx 1$. Highly polished, shiny surfaces have very low emissivity. They are shiny because they reflect thereby cutting down on the leakage.

CONVECTION



Occurs only in liquids and gases as it involves thermal stirring. There are no equations (aren't we glad!) but we can roughly understand it as follows: let us concentrate on a layer of thickness Δy. It is in equilibrium because the sum of the forces is equal to zero giving $\Delta p = -\rho g \Delta y$.

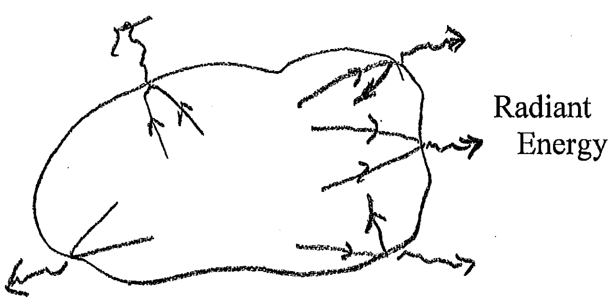
Supposing we add some heat DQ to it. The fluid expands and ρ drops, the equilibrium is disturbed, upward force becomes larger and the fluid starts moving up. This will cause the colder fluid on the top to start moving down thereby setting up thermal stirring some thing like



Causing a net heat current upwards. Convection is a very efficient process as the warm fluid carries energy rapidly to the colder regions while the cooler fluid quickly makes its way to the warmer spots.
Simple example of convection is the so-called "WIND CHILL FACTOR" in winter.

RADIATION

Radiation is most effective in vacuum. It is most difficult to understand as it involves knowledge of waves. For now we imagine that when any object is at a finite temperature T, radiant heat continuously comes out of its surface because of "leakage" (i.e. transmission) each time a "wave" hits the surface from the inside.



The Heat Current depends on surface Area A, nature of surface, emissivity e, the fourth power of the temperature, in Kelvin T and the universal constant σ (Stefan-Boltzmann)

$$\left(\frac{DQ}{\Delta t}\right)_{out} = A e \sigma T^4$$