Mechanisms of Heat Transfer

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Outline

Definition of Heat and Temperature

Conduction, Convection, Radiation

Demonstrations and Examples

What is Heat?

Heat is the spontaneous flow of energy from one object to another, caused by a difference in temperature between the two objects.

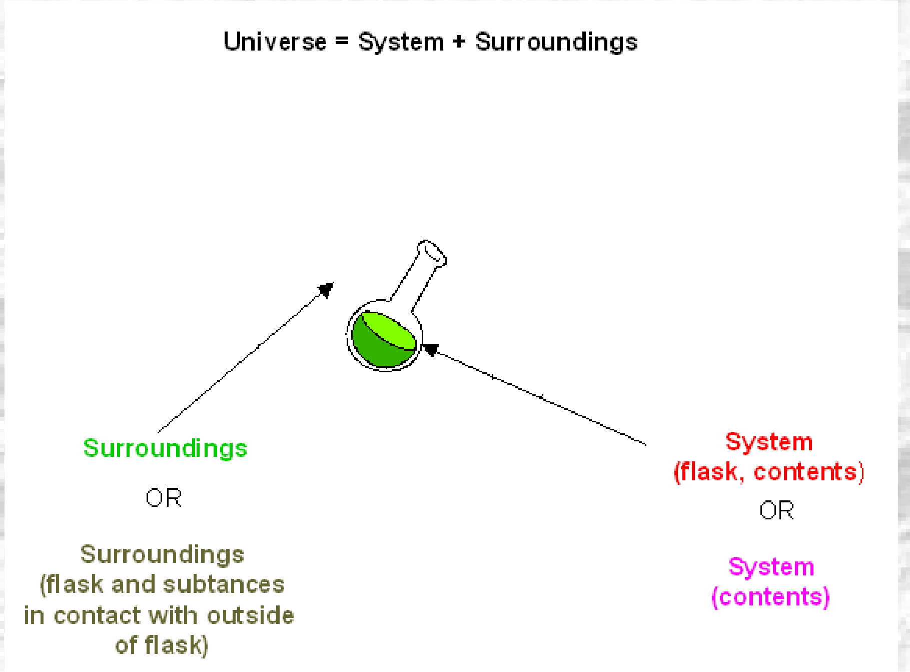
What is Temperature?

Temperature is a measure of the average kinetic energy of the atoms or molecules in a system.

(Towards) Formal Definitions of Heat and Temperature

System: A part of the universe that is under consideration.

Surroundings: The rest of the universe



Universe = System + Surroundings

Surroundings

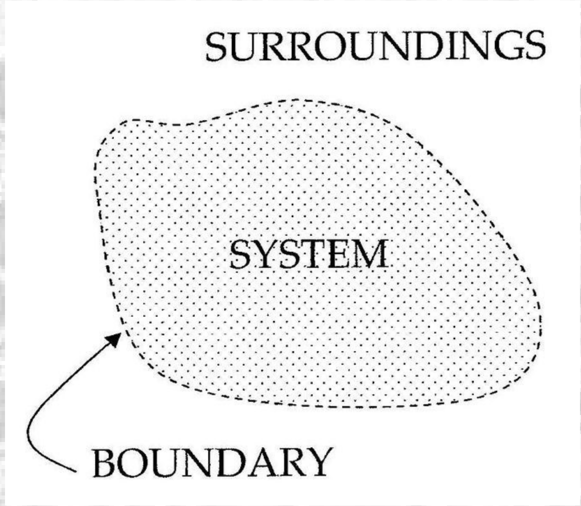
OR

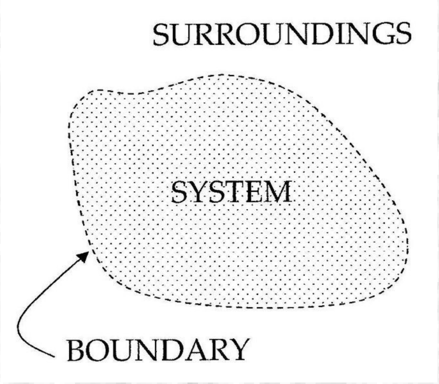
Surroundings
(flask and subtances
in contact with outside
of flask)

System
(flask, contents)

OR

System
(contents)





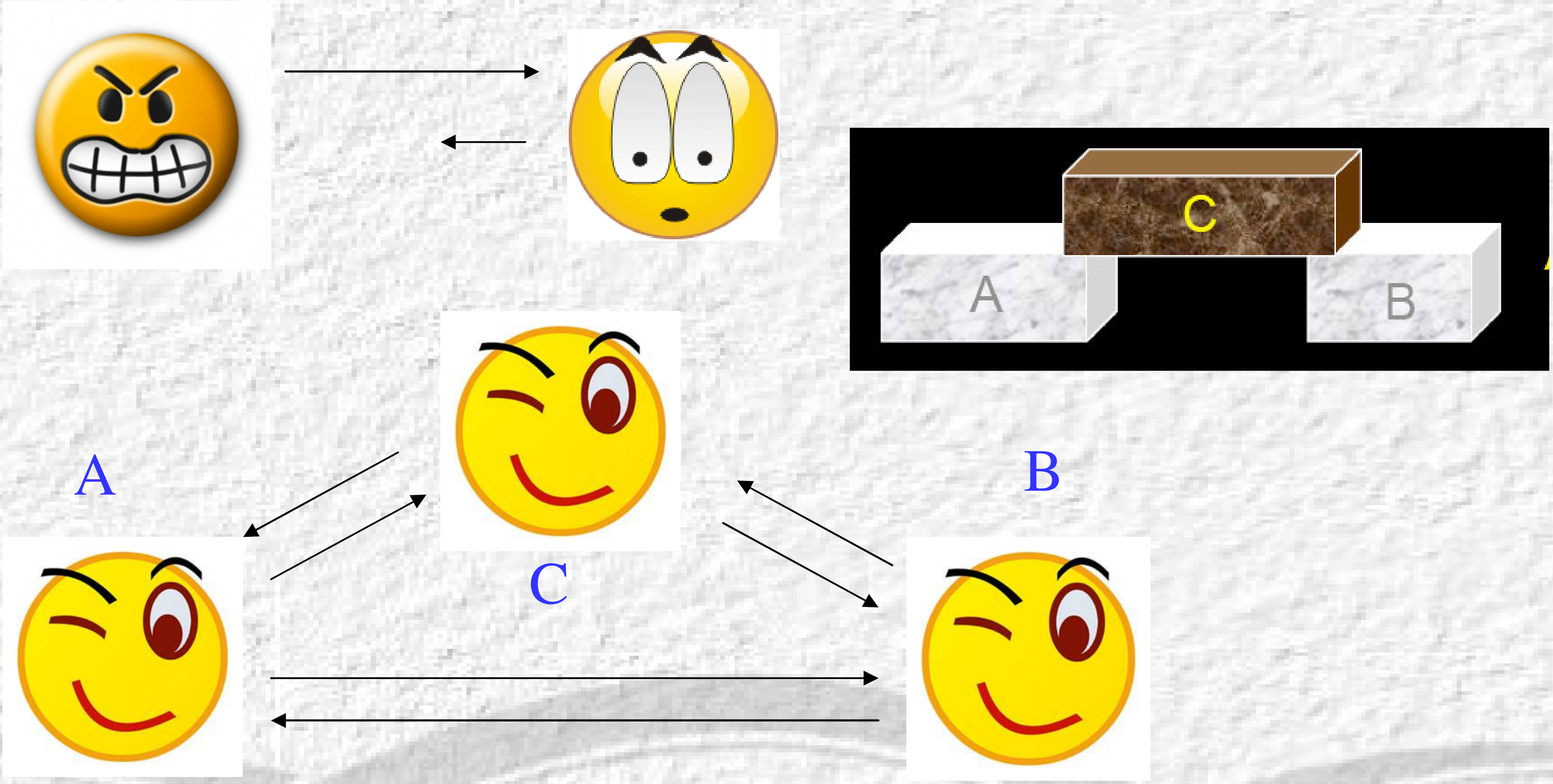
Types of Systems

Open systems can exchange both matter and energy with the suroundings

Closed systems can exchange energy but not matter with the surroundings

Isolated systems are unable to exchange energy or matter with the surroundings.

Zeroth Law of Thermodynamics



When two objects are separately in thermodynamic equilibrium with a third object, they are in equilibrium with each other.

The common thermodynamic property they all share is temperature

Closed System

First Law of Thermodynamics: $\Delta U = Q + W$

The change in internal energy (ΔU) of a closed system is equal to the amount of heat (Q) added to the system plus the Work (W) done by the system on the surroundings.

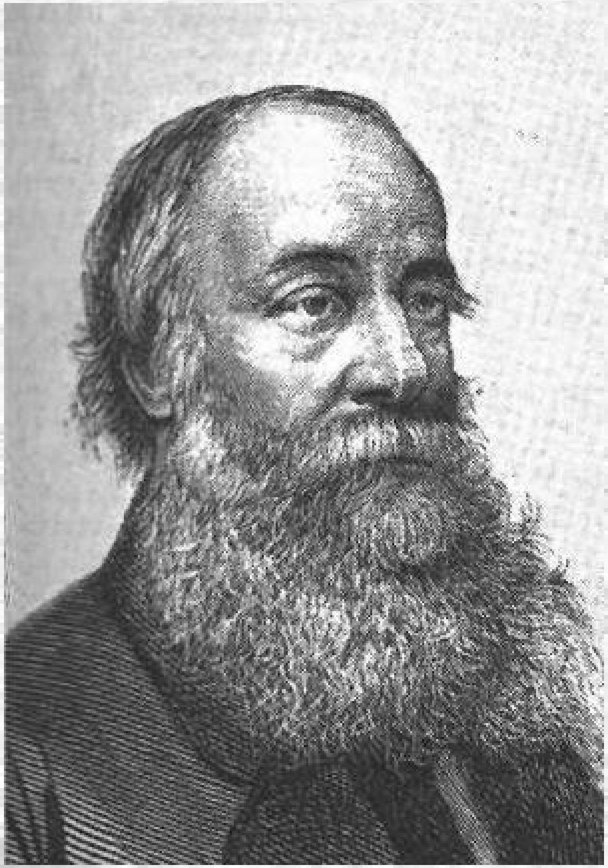
There are variations in sign conventions for work

Heat entering the system is positive, heat leaving the system is negative

$\Delta U = Q + W$ 1st Law

Mechanical equivalence of heat:
Work and Heat are related, and can be converted into one another

Heat is energy transfer in the realm of microscopic thermal motion of particles



James Joule

Work is energy transfer by other means, such as dealing with macroscopic quantities. An example of work is raising a weight against gravity.

Heat VS Work

If water is the system → **Heat from the battery enters the system**

If the system is the water and the battery combined. → **System undergoes electrical work**

Heating materials

- $Q=mc\Delta T$.

- The heat required to raise the temperature of an object by ΔT is dependant on the mass(m), and the specific heat capacity (c) of the material.

For example, to raise one gram of water by one degree Celcius:
$Q = (1g)(4.186\ J/gram\ °C)(1\ °C) = 4.168J = 1$ calorie

Work to Heat Demonstration

1kg of lead shot in a 1 metre tube.
Turning the tube upside down once does an amount of work equal to
$W = \Delta E_p = mgh = 1\text{kg}(9.8\text{m/s}^2)(1\text{m}) = 9.8\text{ J}$

Turn it over 50 times to have a significantly detectable amount of work

$$Q = 50(9.8\text{J}) = 490\text{ J} = mc\Delta T = (1\text{kg})(130\text{J/kg °C})\,\Delta T$$

$$\Delta T = 490\text{ J} / (1\text{kg})(130\text{J/kg °C}) = 3.8\text{ °C}$$

Summary up to this point

$\Delta U = Q + W$ 1st Law of Thermodynamics

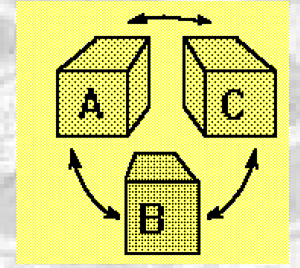
Open system: mass and energy exchange

Closed: energy exchange only

Isolated : No mass and
no energy exchange

Heat: energy transfer as a result of by temperature difference between system and surroundings

A measure of the average kinetic energy of the atoms or molecules in a system

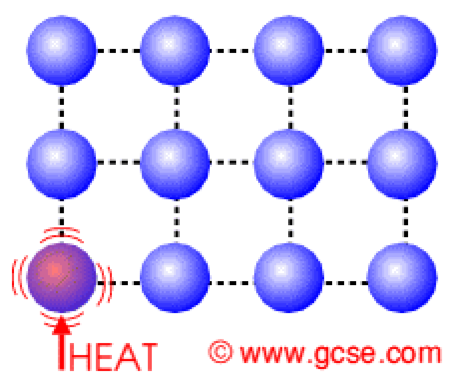


Zeroth Law Conclusion:

Objects A, B, and C are
In thermal equilibrium;
they have a common temperature

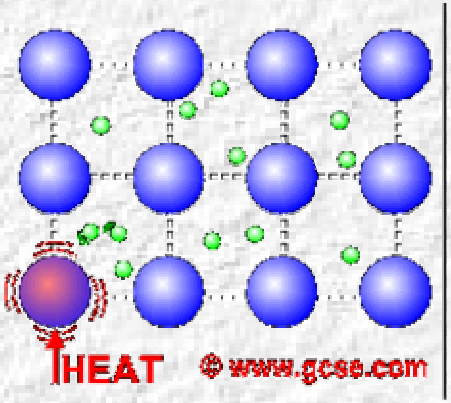
Mechanisms of heat transfer

Basic Conduction



Conduction is a method of heat transfer that requires physical contact between the heat source and target. Atoms in the region of higher temperature have a higher average kinetic energy then their cooler neighbours. These atoms collide with their neighbors, transferring some of their kinetic energy. The neighbors in turn, collide into atoms further away from the region of higher temperature, and energy is transferred along the material. Most metals are good thermal conductors.

Conduction in Metals



In metals, there are free electrons
that wander around and carry energy
from hotter to cooler regions of the metal.

The rate of heat flow is called a heat current, and is in units of Energy (Joules) per time, equivalent to power (Watts).

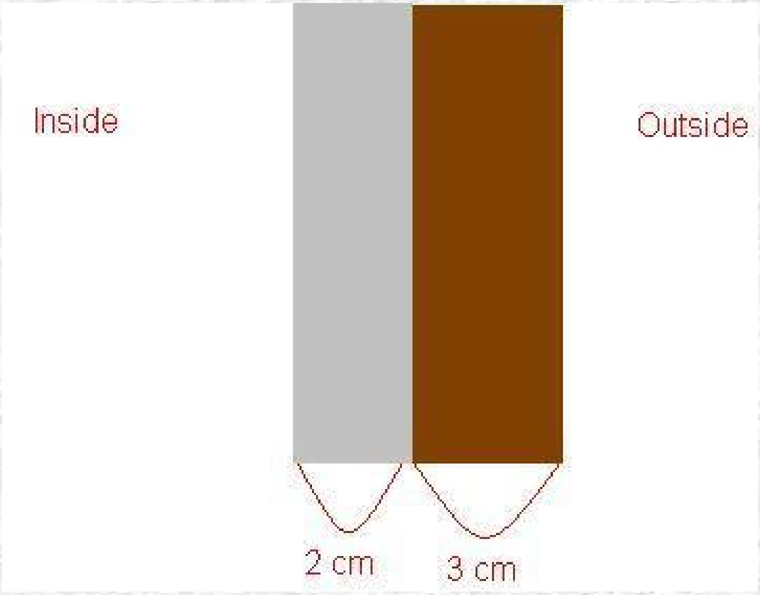
The formula for conductive heat flow is

$H = dQ/dt = kA(T_h - T_c)/L$

The rate of heat flow is proportional to the area of the material (A), the temperature difference (T_h-T_c) and the length of the material.

There is also a constant of proportionality called the thermal conductivity of the material (k)

House cooling example



Temperature is 20°C inside and -5°C outside

Kw = 0.080W/m°C

Ks = 0.010 W/m°C

What is the temperature between the wood and Styrofoam?

$H = (K_s)(A)(20°C-T)/0.02m = (K_w)(A)(T- - 5°C)/0.03m$

$(K_s)(20°C)/0.02m - (K_s)T/0.02 = (K_w)(T)/0.03m + (K_w)(5°C)/0.03m$

$$(K_s)(20^\circ C)/0.02m - (K_s)T/0.02m = (K_w)(T)/0.03m + (K_w)(5^\circ C)/0.03m$$

$$(K_s)T/0.02m + (K_w)T/0.03m = (K_s)(20^\circ C)/0.02m - (K_w)(5^\circ C)/0.03m$$

$$T\,\{(K_s)/0.02m + (K_w)/0.03m)\} = (K_s)(20^\circ C)/0.02m - (K_w)(5^\circ C)/0.03m$$

$$T = (K_s)(20^\circ C)/0.02m - (K_w)(5^\circ C)/0.03m \,/\, (K_s)/0.02m + (K_w)/0.03m)$$

$K_w = 0.080 W/m^\circ C$ $K_s = 0.010 W/m^\circ C$

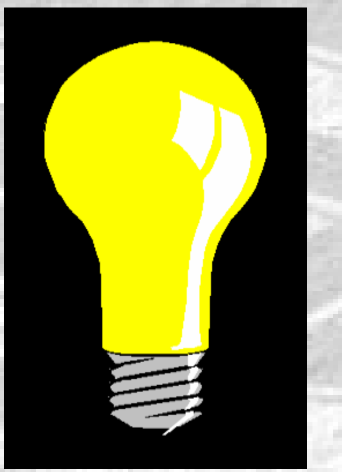
$$T = -1.05^\circ C$$

Initial Heat Flow through the Wall (per m^2)?

H / area = (0.010 W/m°C)(20°C – 1.05 °C)/0.02m

H / area = (0.080W/m°C)(-1.05°C - - 5°C)/0.03m

H = 10.5 W / m^2

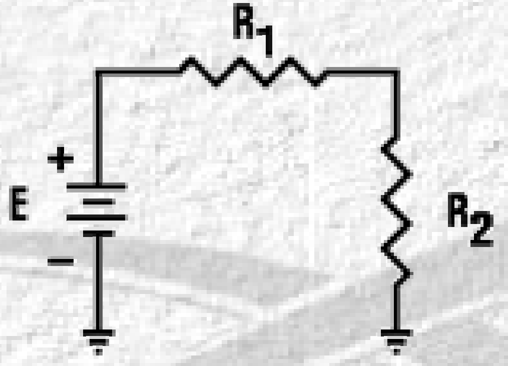


100 W lightbulb

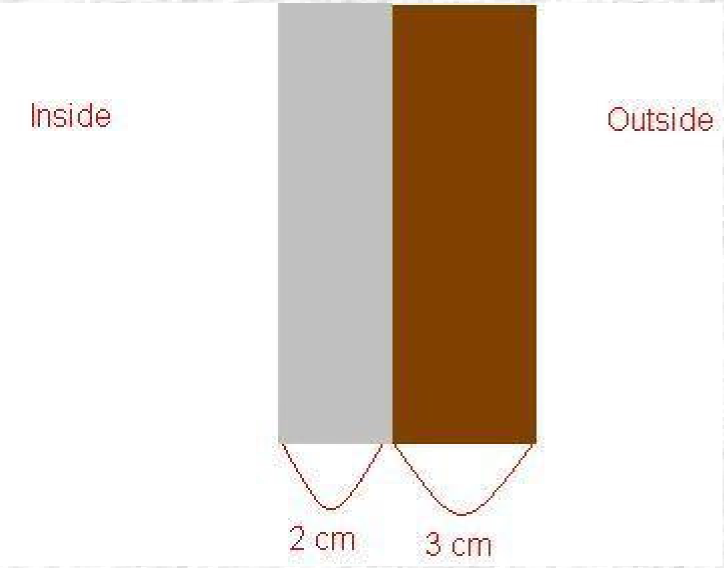
More clever method

For electric circuits : $\Delta V = I\,R$ or $R = \Delta V / I$ (Ohm's Law)

For heat conduction: $\Delta T = (H/A)\,R$ or $R = \Delta T / (H/A)$



Rtotal = R1 + R2



R is the Thermal Resistance

$R = \Delta T / (H/A) = L / k$

Rtotal = R1+ R2

Rtotal = (0.02m/ **0.010 W/m**°C) + (0.03m/ **0.080W/m**°C)

Rtotal = 2.375 m^2°C/W   Rtotal = $\Delta T / (H/A)$

H/A = Δ *T/ Rotal* = (20°C – –5°C)/ 2.375 m^2°C/W = 10.5 W/m^2

“Hand Boiler”

How does it work?

It’s a closed system. Heat flows via conduction from your hand through the glass bulb and into the liquid.

The temperature of the vapour increases, as does the pressure in the bottom bulb

The high pressure of the vapour pushes liquid up the little glass rod and into the top bulb.

The liquid is not vaporizing and condensing at the top. The increased pressure of the vapour pushes liquid upwards.

That is why if you hold it upside down, the hand boiler does work. The vapour escapes upward, and isn't harnessed properly as it is in the lower bulb.

Drinking Bird

After wetting the head, the water evaporates, taking heat

$Q = mL_v = m$ (2260 kJ /kg)

resulting in the cooling of the head

The (red liquid) vapor in the head lowers in temperature, and the greater vapor pressure at the bottom pushes the liquid up the body tube, similar to the hand boiler.

As the liquid goes up the tube, the head falls downwards into the water

While the head is down, liquid drains from the head back into the bottom.

As the fluid accumulates at the bottom, the bird stands up again, and repeats the cycle with the renewed wet head.

α

Convection

Convection is a complicated form of heat that occurs in liquids and gases.

As a liquid or gas is heated, the molecules spread out, causing the heated region to be less dense than the surrounding regions

The heated liquid or gas components rise, while
the relatively cooler components sink. A convection current forms.

Lava Lamp

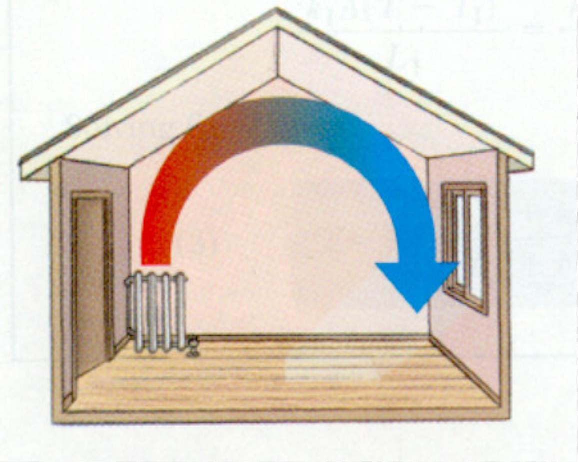
Filled with oil and pieces of wax

Wax more dense than oil at room temperature

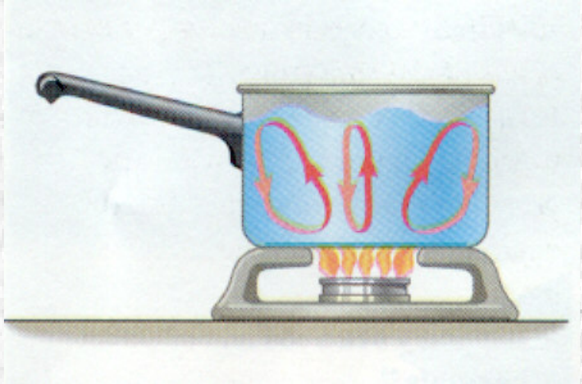
Both oil and wax expand when heated at bottom, but wax expands more, and becomes less dense than oil

Wax rises, reaches the top, cools down, becomes more dense than oil, and falls down

Cycle continues – “Macroscopic” Convection



Heated air rises, cools, then falls. A cycle occurs.



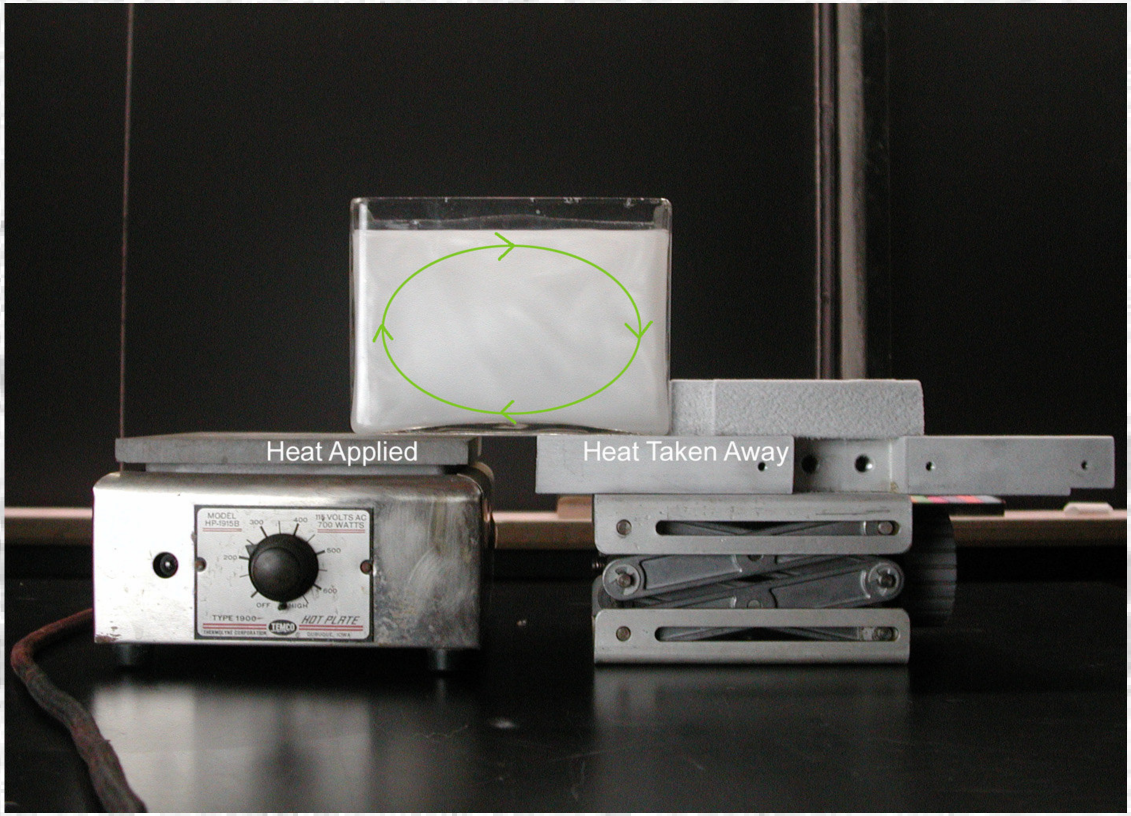
The heated water rises, cools and falls

A fan circulates warm air continuously (forced convection).

Works at a lower temperature and consumes less electricity than a conventional oven

Rheoscopic Fluid

Heating the rheoscopic fluid will allow us to observe convection currents in action.



Radiation

- Radiation is the transfer of heat by electromagnetic waves. This form of heat transfer occurs even in vacuum, and does not require intermediate particles.

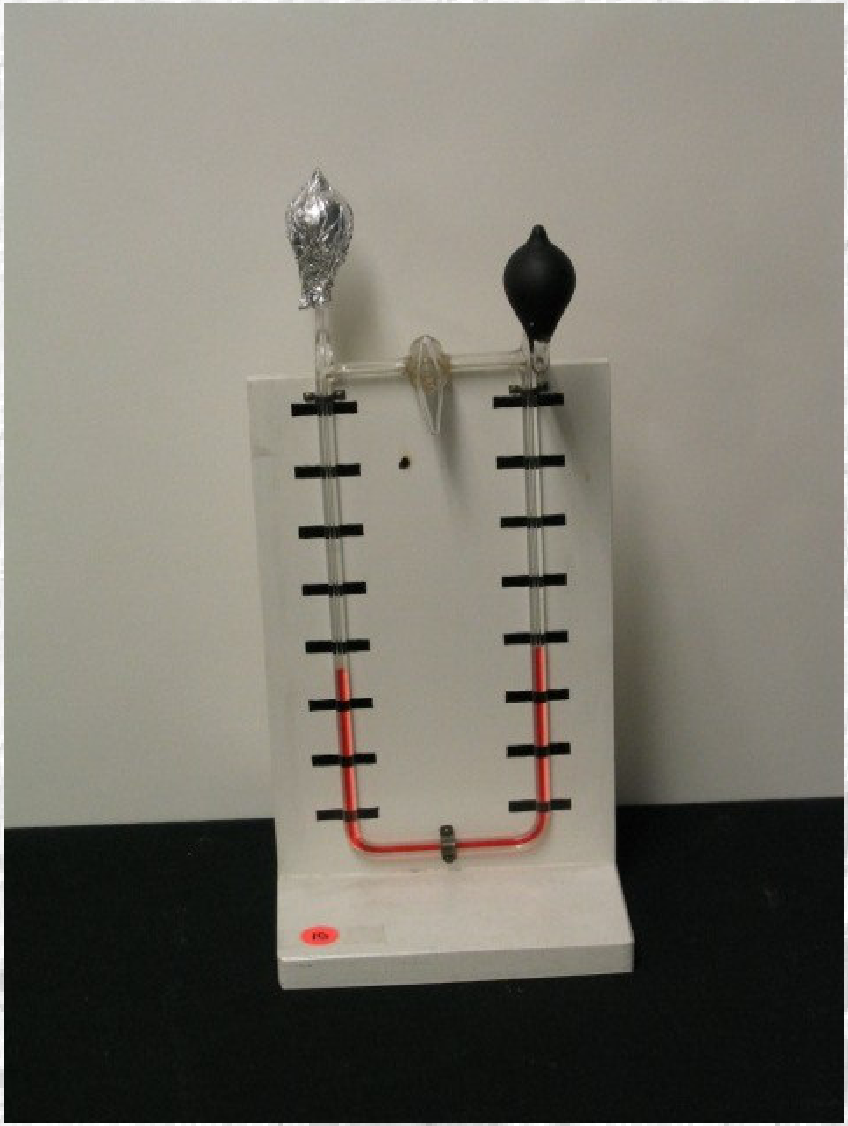
It is calculated via: $\mathbf{H = A\boldsymbol{e\sigma}T^4}$

$\boldsymbol{\sigma}$ is the Stefan Boltzmann constant and is equal to 5.6704×10^{-8} W/m^2K^4

- The heat flow is proportional to the area of the emitting material, the emissivity (*e*), which is between 0 and 1, and the temperature of the emitting object,

Since the surroundings near an object also emit radiation that is absorbed by the source, it is often useful to look at the net radiation coming away from an object, which is given by $H_{net} = A\boldsymbol{e\sigma}\,(T_{object}{}^4 - T_{surroundings}{}^4)$.

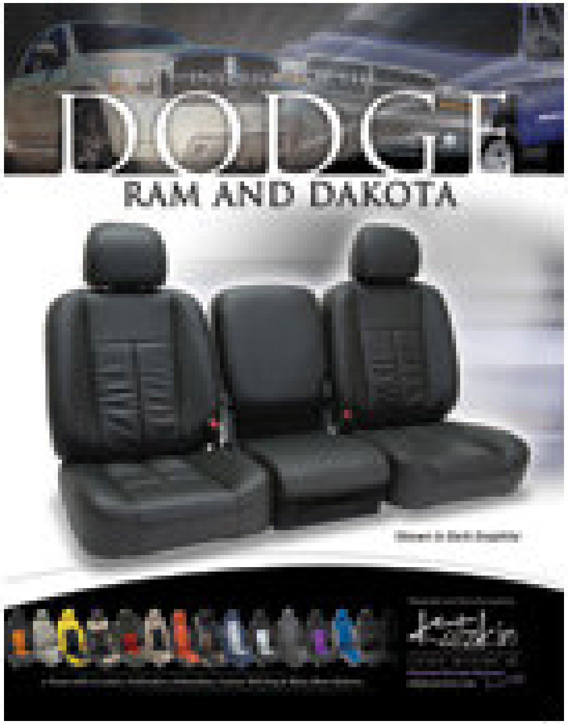
Differential Thermometer Demonstration



A true (ideal) black body has emmisivity of 1

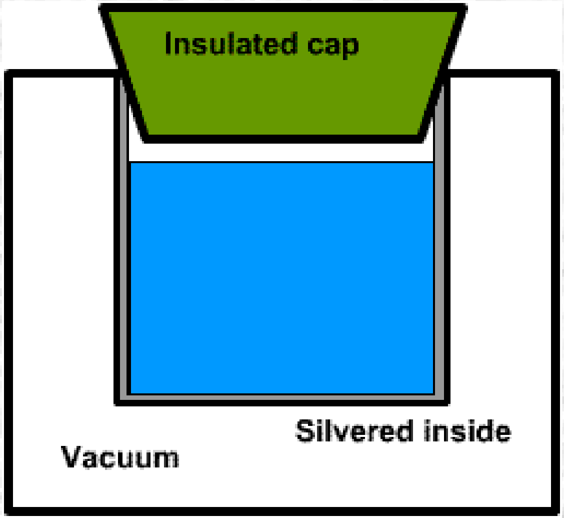
Aluminum foil is ~0.04

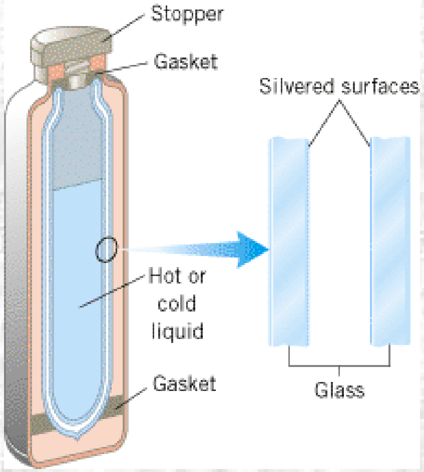
Black paint is ~ 0.8-0.9



Black seats in summer?
Ouch!

Thermos





No conduction or convection in a true vacuum; nearly a vacuum between the glass layers

Reflective silvered surfaces with low emissivity minimize heat transfer by radiation

Finis