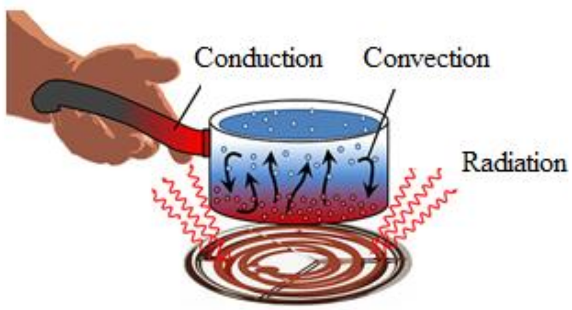
# Part J Notes

Video Lecture 1: Heat Transfer Intro; Infrared Radiation
Video Lecture 2: Infrared Radiation Problem
Video Lecture 3: Block Cut in Half IR Problem
Video Lecture 4: Heat Conduction Intro with Problem
Video Lecture 5: Heat Conduction Block Cut in Half
Video Lecture 6: Humidity

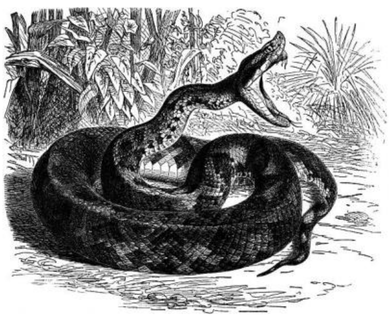
## Heat Transfer

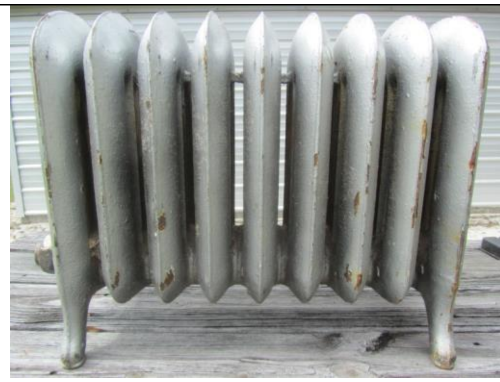
| | |
|---|---|
| There are three methods by which thermal energy is moved from one location to another one:<br><br>-Radiation<br>-Convection<br>-Conduction<br><br>We begin below with a discussion of radiation. |  |

## Infra-Red Radiation

All objects radiate a form of electromagnetic energy called "infra-red" (IR) radiation arising from the vibration of atoms on the surface of the object-- vibrations that are caused by the object's thermal energy. Thermal energy in the object is radiated away, resulting in a cooling of the object.

Humans and most animals cannot see infra-red, but snakes can. The pit viper below uses this ability to hunt its prey at night.





Radiator filled with steam radiates IR to heat the room and its occupants.

## Radiation Rate

The rate at which thermal energy is radiated away is symbolized as R, and its units are watts.

$R = \sigma e A T^4$

$\sigma = 5.67 \times 10^{-8}$ W/m$^2$-$^o$K$^4$ (Stefan's constant)
A = Surface area of the object
T = Kelvin temperature
e = Emissivity

Emissivity is a unit-less property of the surface of the object, and has a value ranging between zero and one:

$0 < e < 1$

Example A:

The IR radiation rate from an object is 2000 watts. What would be the new rate if the object's temperature is doubled?

Solution: Before the doubling,

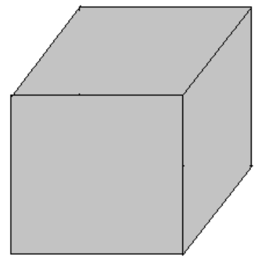
$R = \sigma e A T^4$
$= 2000$ W

If T is doubled, $T^4$ increases to a value that is sixteen ($2^4$) times its previous value, so the new radiation rate is sixteen times 2000 W:

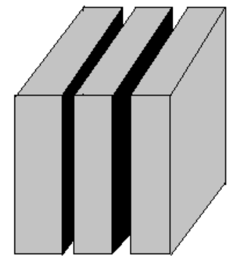
$R = 32{,}000$ W

Example B:

A cubic block of side-length L radiating 2400 watts is sliced into three equal rectangular blocks.



$A = 6\,L^2$



$A = 10\,L^2$

What is the new total rate of radiation?

Before cutting, the total area was six times the area of a face. Each of the two cuts opened up two additional faces, for a total of ten faces. Thus, the total area increases to (10/6) times its previous value, so the new rate increases to (10/6) times 2400 W:

(10/6) 2400 = 4000 W

# Absorbing Infra-Red

Objects not only radiate IR, but also *absorb* IR radiated from their surroundings. The net rate of loss of thermal energy is the radiated rate, minus the absorption rate.

Objects immersed in a fluid--such as air, or water--not only radiate IR, but receive it, too, from the fluid.

$T_1$ = Air temperature
$T_2$ = Body temperature

$R_1 = \sigma e A T_1^4$
= Rate of Object's Absorption

$R_2 = \sigma e A T_2^4$
= Rate of Radiation by Object

Net Rate of Loss:

$$R = R_2 - R_1 = \sigma e A T_2^4 - \sigma e A T_1^4 = \sigma e A (T_2^4 - T_1^4)$$

Example:

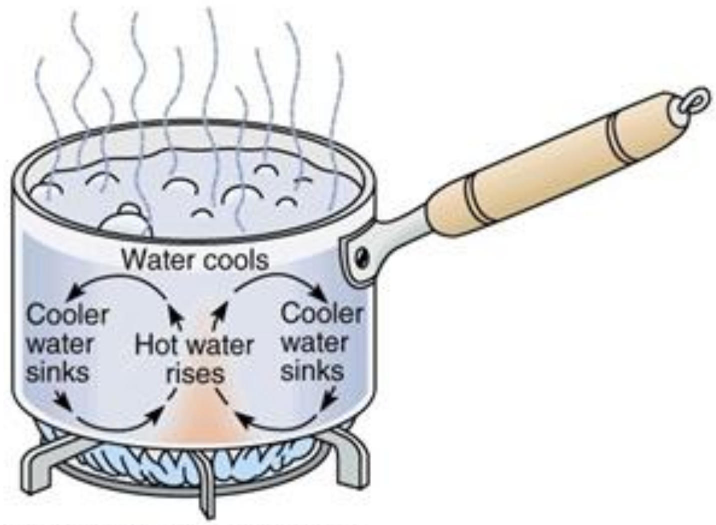
The skin temperature of a sun-bather is 307 $^oK$, her emissivity is e = 0.70, and her skin area is 1.2 $m^2$. The air temperature is 280 $^oK$. At what net rate is this person losing heat?

$R_{net} = \sigma eA\ (T_2^4 - T_1^4)$
$= (5.67 \times 10^{-8})\ (0.70)(1.2)\ (307^4 - 280^4)$
$= 130.32$ watts

Each second, the sun-bather loses about 130 joules of thermal energy via IR loss. Some of this heat is recovered as consumed nutrients are metabolized in exothermic (heat releasing) reactions.

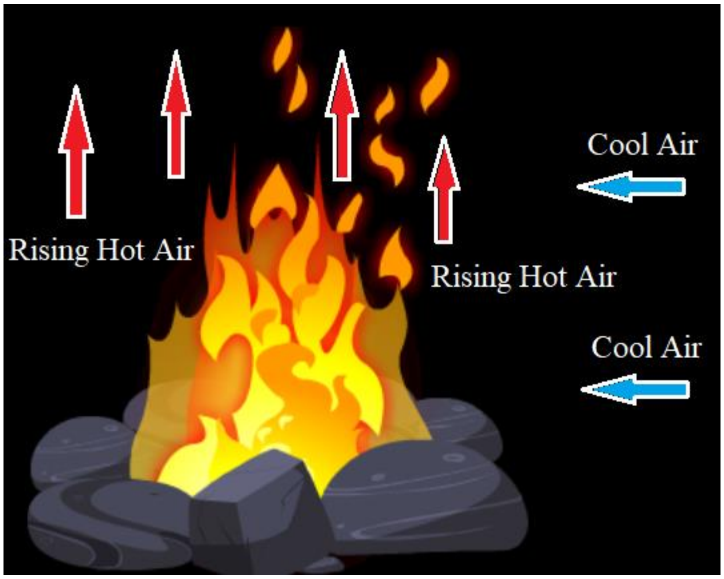
# Convection

When a fluid is heated, it expands, becomes less dense and therefore more buoyant; it rises within more dense fluids. A similar effect was seen in Part I in the discussion of the less dense city air rising within surrounding, more dense, ocean air. On the other hand, when a fluid is cooled, it contracts, becomes more dense and sinks in surrounding less dense fluid.

| | |
|---|---|
| Buoyancy is the essential driving force behind many convection currents.<br><br>Water at the top of the pot of water being heated is exposed to the cooler air; it cools, contracts and becomes more dense than the hotter water below, and sinks.<br><br>At the same time, the water at the bottom of the pot is heated by the flames; it expands, becomes less dense, and rises. Water stops rising and falling when water density is the same everywhere, which happens when the temperature is the same everywhere; this occurs at 212 ºF (100 ºC), when the water is boiling. |  |

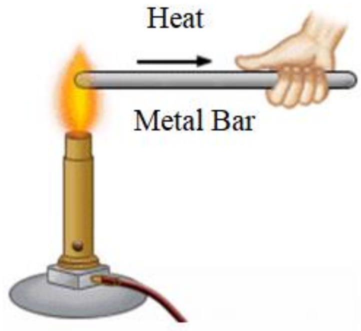
# Campfire Convection Current

Hot air above a barbeque pit or campfire expands and becomes less dense than the surrounding cooler, more dense air.  The less dense air immersed in the more dense cooler air is like a block of wood held under water, then released:  Its buoyancy pushes it upward.




The surrounding cool air rushes in to replace the rising air.

Heat Conduction

<table>
<tr>
<td><br>The hot high-speed gas molecules collide with the iron atoms at the left end of the bar, thereby increasing the kinetic energy of those atoms. Those heated atoms then collide with the atoms to the right of them, transferring kinetic energy to them, and then those atoms do the same to their slower-moving neighbors. Kinetic energy is thereby propagated to the right along the bar like a row of dominos tipping over.</td>
<td><br>The greater the “thermal conductivity,” the more rapidly will the dominos tip over, i.e., the more quickly will thermal energy reach the other end of the iron bar.<br><br>k = “thermal conductivity”<br><br>Units: W/m-C$^{o}$</td>
</tr>
</table>

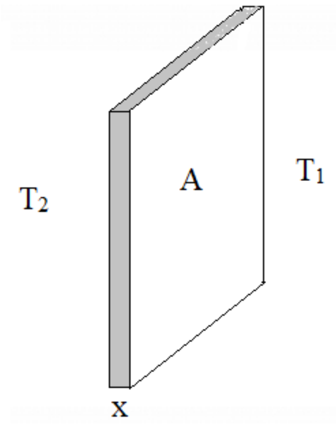
The figure at the right shows a window of thickness x and cross-sectional area A.

The temperatures of the air on either side differ by the absolute amount shown below:

$|\Delta T| = |T_2 - T_1|$

The rate at which thermal energy (heat) is conducted from the hotter side to the cooler side is given by the equation below:

$$R = \frac{kA\,|\Delta T|}{x}$$




Example:

A 6.0-$m^2$ sliding glass door, 0.014 m thick, has a thermal conductivity 0.96 W/m-C°. The air inside the room is at a temperature of 25 °C. The window faces outdoor air at 12 °C.

How much thermal energy will pass into the outdoor air in two hours?

$R = (0.96\ W/m\text{-}C^o)\ (6.0\ m^2)\ (13\ C^o)\ /\ 0.014\ m$
$= 5349\ W$

$Q = (5349\ J/s)(7200\ s)$
$= 3.85 \times 10^7\ J$

# Thermal Conductivity of Air

Double-paned windows drastically reduce the amount of heat loss.

The thermal conductivity for glass is k = 0.96 W/m-C$^o$. The thermal conductivity of air is k = 0.02 W/m-C$^o$, 48 times smaller. Heat through glass travels 48 times more rapidly than it does through air.

Two panes of glass sandwiching air save a lot of money on energy bills. The air layer effectively blocks the flow of heat across it. A typical family will see their energy bill reduced by 40% if all the windows in the house are replaced by double-paned windows.

| Substance | k (W/m-C$^o$) |
|---|---|
| air | 0.02 |
| oak wood | 0.17 |
| cement | 0.29 |
| water | 0.58 |
| asbestos | 0.74 |
| window glass | 0.96 |
| concrete | 1.40 |
| clay | 1.80 |
| steel | 16 |
| aluminum | 205 |
| diamond | 1000 |

Example:

Heat travels through a window at the rate of 100 W.

What would be the new rate if the window glass were replaced with a different type of glass with triple the thermal conductivity, and a thickness twice as great?

Solution:

Old Rate

$R_1 = k_1 A\ |\Delta T|/x_1$
$\quad = 100\ \text{W}$

$k_2 = 3\ k_1$
$x_2 = 2\ x_1$

New Rate

$R_2 = k_2 A\ |\Delta T|/\ x_2$
$\quad = (3k_1)A\ |\Delta T|/\ (2x_1)$
$\quad = (3/2)\ (k_1 A\ |\Delta T|\ /x_1\ )$
$\quad = (3/2)\ R_1$
$\quad = (3/2)\ 100\ \text{W}$
$\quad = 150\ \text{W}$

# Humidity

Humidity is a measure of the amount of water vapor in the air. When no more water vapor can exist in the air without it condensing, the air is said to be "saturated" with water vapor.

The percentage of the maximum water vapor that is allowed is the humidity.

Let M = Maximum Mass of Water Vapor
Allowed per Cubic Meter
(the saturation mass)

Let m = Actual Mass

$$H = (m/M)\ 100\%$$

Condensation on Leaves

The saturation mass M depends on the air temperature. As the table below shows, the higher the temperature, the greater is the saturation mass.

| T ($^{o}$C) | M (g/m$^3$) |
|---|---|
| 10 | 9 |
| 16 | 13 |
| 21 | 18 |
| 24 | 22 |
| 29 | 30 |
| 32 | 35 |

Example:

In Sacramento at 7:00 pm one evening the temperature was 21 $^{o}$C, and the humidity was 75%.

How many grams (m) of water vapor were there per cubic meter?

Solution:
From the table, we see that at 21 $^{o}$C, M = 18 g

$H = (m/M)\ 100\ \%$
$75 = (m/18)\ 100$
$m = 13.5\ g/m^3$

Example:

In the valley one morning the temperature was 29 $^oC$, and the humidity was 53%.

First, let's determine the value of M at 29 $^oC$ from the table:

M = 30 g

(a) How many grams (m) of water vapor were there per cubic meter?

53% = (m/30) 100%
m = 15.9 g/$m^3$

(b) Two hours later the temperature fell to 24 $^oC$. What was the new humidity?

The value of m is still m = 15.9 g, but the saturation mass changes to 22 g at 24 $^oC$.

H = (15.9/22.0) 100%
= 72.3%

| T ($^oC$) | M (g/$m^3$) |
|---|---|
| 10 | 9 |
| 16 | 13 |
| 21 | 18 |
| 24 | 22 |
| 29 | 30 |
| 32 | 35 |

Example:

(a) At 1:00 pm in the valley the air temperature was 16 $^{o}$C and the humidity was 70%. How many grams of water vapor were there in each cubic meter of air at that time?

$70 = (m/13)\ 100$
$m = 9.1$ g

(b) At 7:00 pm the temperature had risen to 21 $^{o}$C, and during the previous six hours moist wind had swept 2.3 grams of water vapor per cubic meter into the valley. What was the humidity then?

The new saturation mass is $M = 18$ g.

Added to the initial 9.1 g is 2.3 more grams:

$m = 9.1 + 2.3$
$\quad = 11.4$ g

$H = (11.4\ /18) \times 100\%$
$\quad = 63\%$