Chapter 3 Heat, Energy, Work

Energy measures capacity to do work.

It is instructive to put energy use into perspective

2005 – worldwide human consumption
487×10^{18} joules (139×10^{15} watt-hr)

Human being (metabolism) relative to light bulb

$$\frac{8400 \text{ kjoule}}{\text{day}} = 97 \text{ watt}$$

1 food Cal ≡
1 kcal = 4.184 kjoule

So to maintain metabolism: a person requires an energy input about equal to a 100 watt light bulb

However, rich countries: people use about 100x this energy (transportation, heating, lighting, etc)

1 gallon gasoline ≈140,800 kjoule/mol

So a person uses ~ 6 gallons of gas per day
(Actually more, allowing for efficiencies)

Solar energy hitting earth

3.8 x 10^{24} J/yr or 174 10^{15} watts (174 petawatts)

10^4 x greater than human energy use

amount of solar energy per unit time arriving a 1m^2 area

341 watt/m^2 → 70 watt/m^2(using a 20% solar panel)

A 10 x 10 m area needed to provide all energy consumed by a person in a high energy consumption country (neglects reflection)

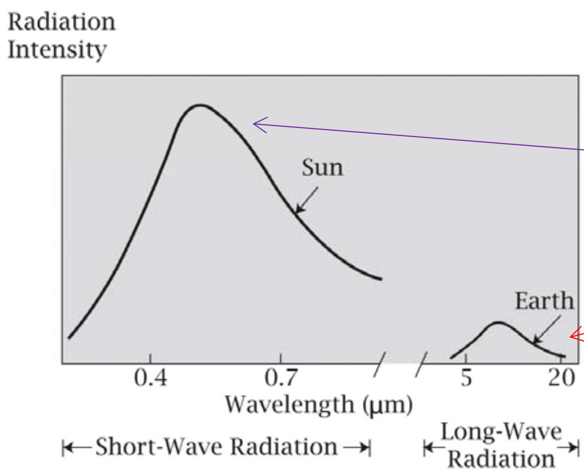


Figure 3.2 Molecular Driving Forces 2/e (© Garland Science 2011)

Radiation reaching earth peaked in visible/UV

Earth radiates energy in the IR (heat)

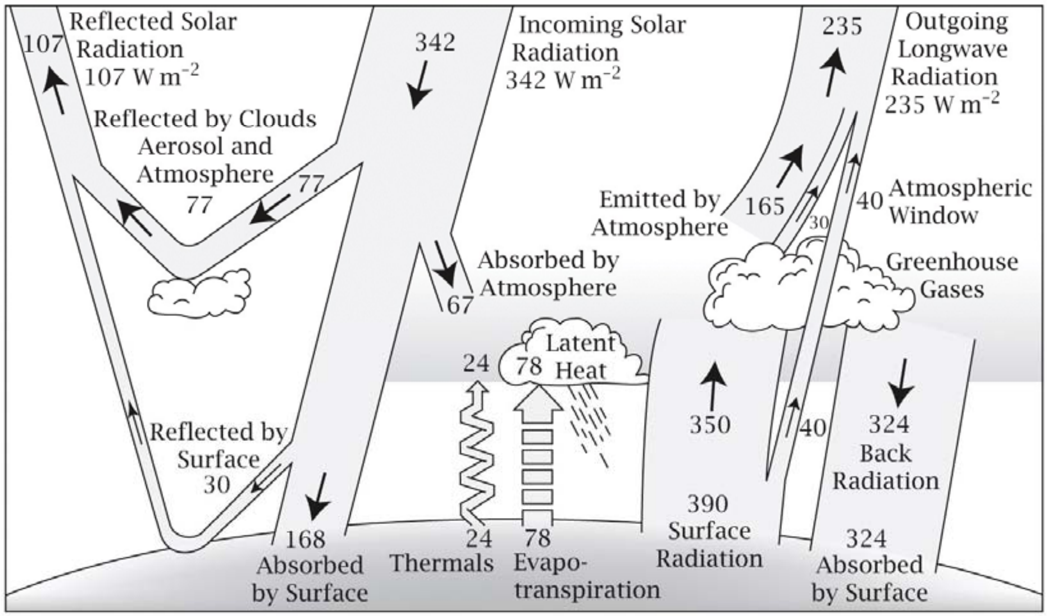


Figure 3.3 Molecular Driving Forces 2/e (© Garland Science 2011)

107 reflected

342 watt /m^2 → 67 ads by atmosphere

From sun

168 to surface

Earth core radiates 390 watt/m^2 (heat)

Also energy losses (102) due to evaporation, generation of wind

But greenhouse gases reflect back to earth about 324 watt/m^2

Clearly a very complex system

Without greenhouse gases, Earth's T would be ~255 K

With greenhouse gases T ≈ 288 K

Evidence that CO_2 from burning fuels is now causing this to rise.

Organisms

Basal metabolic rate (BMR) – energy consumed at rest

Data well fit to $E_{BMR} \sim M^{3/4}$, M = mass

if dominated by surface area $E_{BMR} \sim M^{2/3}$

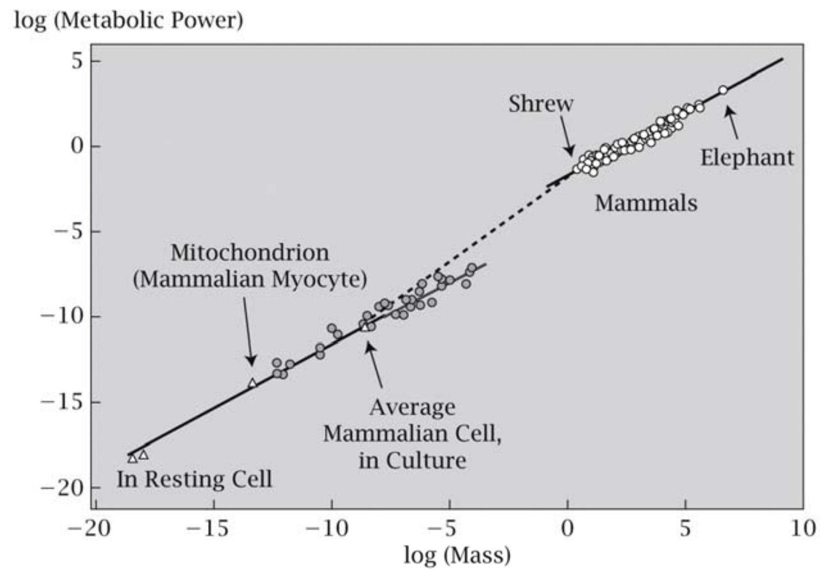


Figure 3.5 Molecular Driving Forces 2/e (© Garland Science 2011)

Conservation Laws

- conservation of momentum (mv) - (Wallis, 1668)
- conservation of mass
- conservation of angular momentum
- conservation of energy

Energy describes capacity to do work

that capacity can be moved from one phase to another

Mechanical system

$$E = K + V$$

K = kinetic E
V = potential E

$$K = \frac{1}{2}mv^2 =$$ Work object can do due to motion

$$V =$$ Work object can do due to position (or positions of its components)

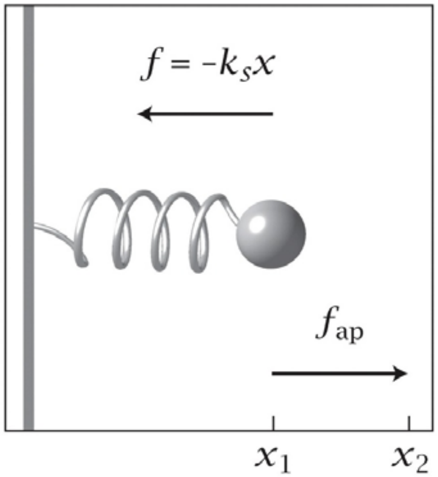


Figure 3.6 Molecular Driving Forces 2/e (© Garland Science 2011)

Spring: stretch from x_1 to x_2, stores potential energy

Battery: separates +, - charges

Gravitational: potential energy due to gravitational force

Chemical: energy stored in bonds

K or V can change but E is constant

Force: to do work, a system must exert a force

Newton's 2nd Law

$$f = ma = m\frac{d^2x}{dt^2}$$

acceleration

Spring example: f = -kx

Hooke's Law

talking equilibrium position as x = 0. otherwise generalize to $f = -k(x - x_o)$

apply opposite force to stretch spring

$$f_{ap} = -f = kx$$

work performed on system $\delta w = f_{ap} dx = -f dx$

Total work $w = \int_{x_1}^{x_2} f_{ap} dx = \int_{x_1}^{x_2} -f dx = \int_{x_1}^{x_2} xk dx$

$$= \left. \frac{kx^2}{2} \right|_{x_1}^{x_2} = \frac{1}{2} k \left(x_2^2 - x_1^2 \right)$$

work to lift weight

$$w = -\int_0^h mg(-dx) = mgh,$$ g = gravitational constant

Conservative forces

No friction or other dissipation of energy

Isn't energy supposed to be conserved?

No net work done on moving an object through a closed cycle

$$w = -\int_A^B f dx - \int_B^A f dx = 0$$

Now consider heat

Through the mid 1800's It was believed that heat is conserved –
(calorie fluid idea)
Now known not to be true

- Different materials have different heat capacities
- Latent heat $\Rightarrow$ heat and temperature are different things
  (melting of ice, evaporation of water)
- Radiant heat is transmitted through a vacuum
- Work can be converted to heat

First Law of Thermodynamics

q = heat transferred

w = work done on system

$\Delta U = q + w =$ internal energy change

heat is a form of energy transfer

$\Delta U^{system} + \Delta U^{surr} = 0$ | Internal energy (system + surroundings) is conserved

- Internal energy is a property of a system
- Heat and work are flows

Kinetic Theory of Gases

- Molecules (atoms) move
- Heat is exchange of energy due to motion + collisions of molecules
- Electromagnetic energy can influence motions of molecules

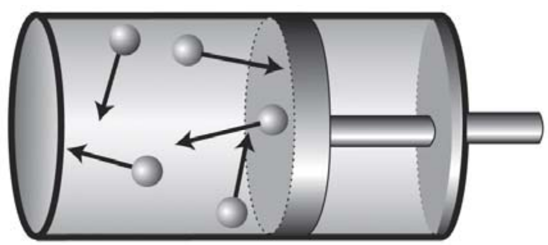


Figure 3.10 Molecular Driving Forces 2/e (© Garland Science 2011)

particle collides with piston, loses KE, moves piston, does work

Kinetic energy of molecules in gas

particle collides with walls ⟶ heat

$$\frac{3}{2}kT = \frac{m\langle v^2 \rangle}{2},$$ k = Boltzmann's constant

Refinement to account for QM
energies are quantized

Energy levels ε_0, ε_1, ε_2

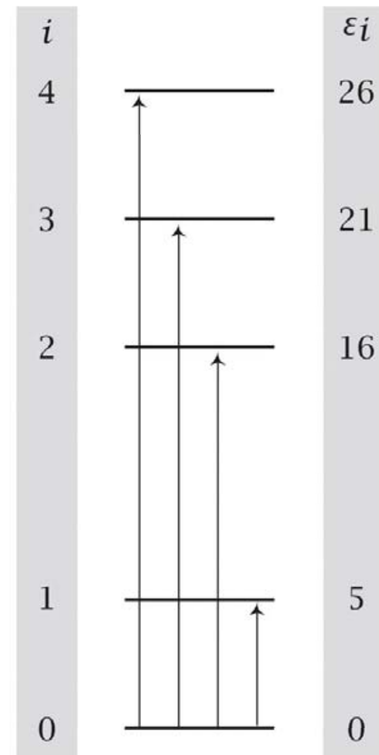


Figure 3.11 Molecular Driving Forces 2/e (© Garland Science 2011)

Ideal gas: $U = \sum N_i \varepsilon_i$

> in U due to heating
Populations change rather than energy levels

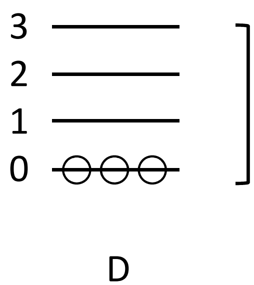
Heat flows due to tendency toward maximum multiplicity
≡ Second Law of Thermodynamics

Chapter 2 we found that gases expand because W > with > V
w = pΔV, p (pressure) is a force (actually force/unit area)

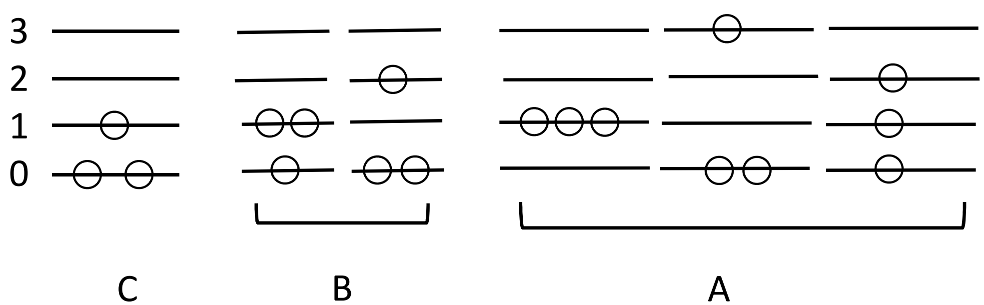
- found particles mix due to > in W
  defines chemical potential
- heat flow from hot to cold object also due to > in W

Why do materials absorb heat?

Consider a simple model with 3 particles distributed over 4 energy levels



D U = 0 W = 1
C U = 1 W = 3
B U = 2 W = 6
A U = 3 W = 10



W > as U >

Why does energy exchange?

Consider two systems A and B each with 10 particles , but with U = 2 for A and U = 4 for B

How many arrangements are there?

A, W = 45

B, W = 210

$$W_{tot} = 45 \bullet 210 = 9450$$

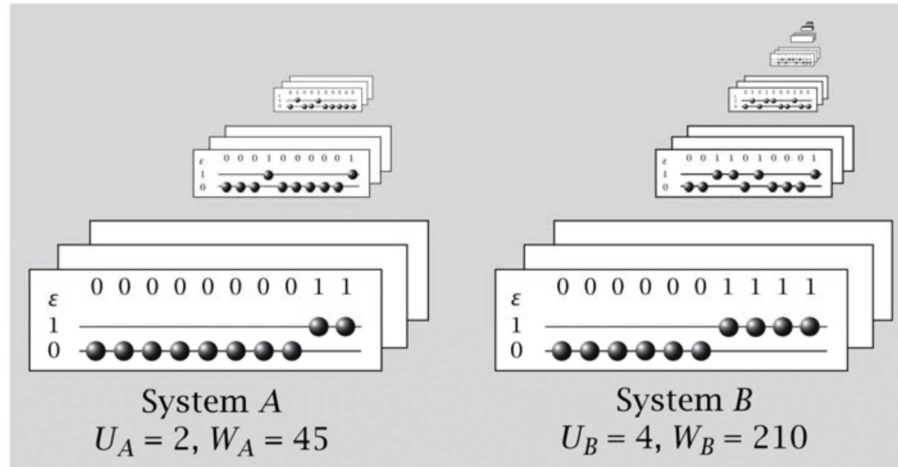


Figure 3.14 Molecular Driving Forces 2/e (© Garland Science 2011)

Now bring the two systems into contact: suppose each achieves U = 3

$$W_{tot} = \frac{10!}{3!7} \bullet \frac{10!}{3!7!} = 14,400$$

Number of arrangements increases

Suppose we assume system evolves to $U_A = 1, \quad U_B = 5$

$W_{tot} < \quad \Rightarrow$ Unlikely

Energy doesn't always flow downhill

Now suppose { A has 10 particles, $U_A = 2$; B has 4 particles, $U_B = 2$ } $W = W_A W_B = 270$

supposes evolves to $U_A = 3$, $U_B = 1$ $W = W_A W_b = 480$

so energy moves from B to A

so tendency for heat to flow is not driven by tendency to equalize energy

$$A \quad n_0 = 8, \quad n_1 = 2 \quad <\varepsilon> = 2/10 = 0.2$$
$$\mathrm{B} \quad n_0 = 2, \quad n_1 = 2 \quad <\varepsilon> = 2/4 = 0.5$$

$$A \quad n_0 = 7, \quad n_1 = 3 \quad <\varepsilon> = 0.3$$
$$\mathrm{B} \quad n_0 = 3, \quad n_1 = 1 \quad <\varepsilon> = 0.25$$

Is it trying to equalize average E per particle?