Lectures 13/14 (Energy). EngGen 140

Recall :

Overview of Part II [Energy/Material

Split into three related sections

✓ 5. Basic Physics of Energy (~4/5 Lectures)

- Sources & consumption of energy
- Forms of energy, units etc
- Basic balance calculations

✓ 6. Basics of Energy Transfer (~6/7 Lectures)

- Thermodynamics
- More sophisticated balance calculations etc.

Here → 7. Basics of Biological Energetics (~4/5 lectures)

- How do animals, cells etc store & use energy
- Thermodynamics & kinetics of energy use in biological systems

Lecture 13

Topics
- sources & transformations of energy in biological systems
- scales of biological systems
- cells, membranes & organelles

what you should be able to do
- understand general sources & transformations of energy in biol. syst.
- understand & describe the basic functions, structure & scales of the cell, cell membrane, nucleus & mitochondria

Examples

Exam 2017

24) The radiant energy from the Sun that reaches the Earth is 1.74×10^{17} W. Approximately 52% of these photons are either reflected back to space, or absorbed by the atmosphere. We know that 0.025% of the energy that reaches the land is absorbed by photosynthetic organisms. Calculate the radiant energy that is converted by photosynthetic organisms over one year. **(3 marks)**

38) There are over 200 different cell types in the human body. Different cells have different proportions of organelles to suit their function. Which organelle would a human cardiac (heart) cell have in significantly greater number than a human skin cell? Why? **(2 marks)**

Organelle: ______________________

Justification: ____

Test SS·2017

1. List two key functions required of the cell membrane and briefly explain the features that enable it to meet these requirements. (2 mark)

Answer

?

Biological systems

Biological systems (incl. humans, animals, cells etc)

- are open systems

  ↳ exchange energy & matter with environment

  eg consume food & convert this chemical energy into work : walking, talking, breathing

- same laws of physics & chemistry apply!

  ↳ Gibbs free energy is key for spontaneous processes

  (open system but constant pressure & temp. are good approx.)

  ↳ stored at molecular & cellular level

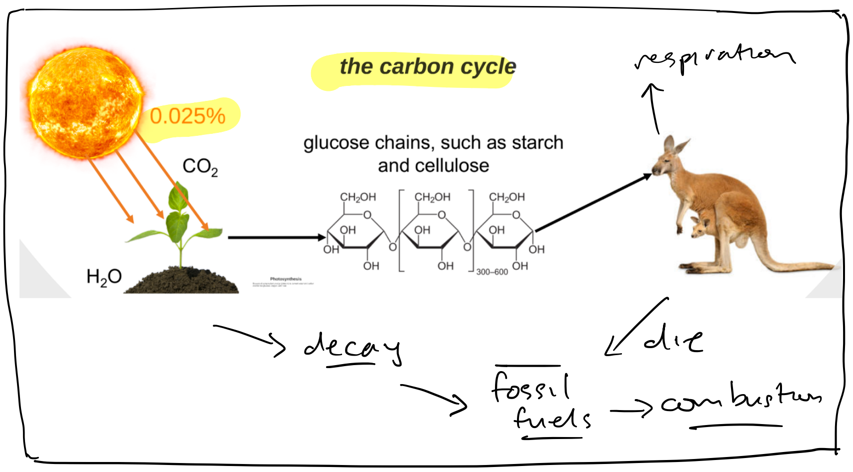
Composition

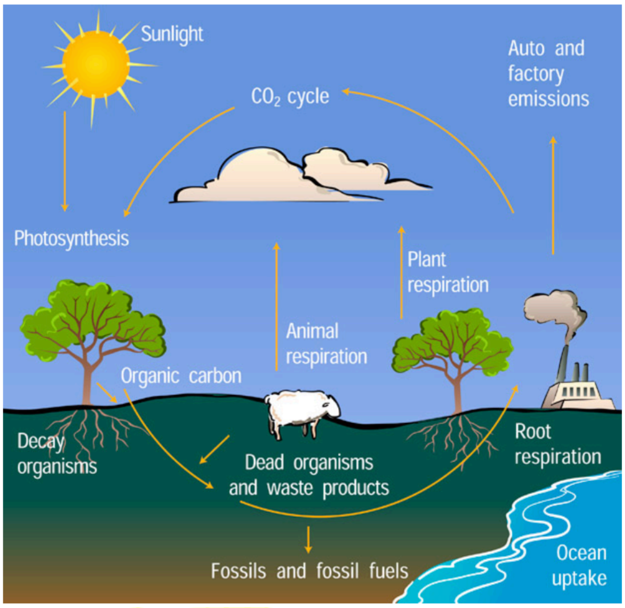
- Fundamentally 'made from star stuff'

→ hydrogen, carbon, nitrogen, oxygen & phosphorus

→ humans are 3/5 carbon

Carbon cycle





This fairly basic carbon cycle diagram shows how carbon atoms 'flow' between various 'reservoirs' in the Earth system. This depiction of the carbon cycle focusses on the terrestrial (land-based) part of the cycle; there are also exchanges with the ocean which are only hinted at here. Note that carbon atoms are incorporated into various molecules as they flow around the cycle; for example, photosynthesis in plants captures carbon atoms in sugar molecules and atmospheric carbon is contained in molecules such as carbon dioxide and methane. Credit: UCAR

Photosynthesis : energy absorbed

Recall :

$T = 10^{12}$; $1 W = 1 J/s$

24) The radiant energy from the Sun that reaches the Earth is 1.74 x 10^{17} W. Approximately 52% of these photons are either reflected back to space, or absorbed by the atmosphere. We know that 0.025% of the energy that reaches the land is absorbed by photosynthetic organisms. Calculate the radiant energy that is converted by photosynthetic organisms over one year. **(3 marks)**

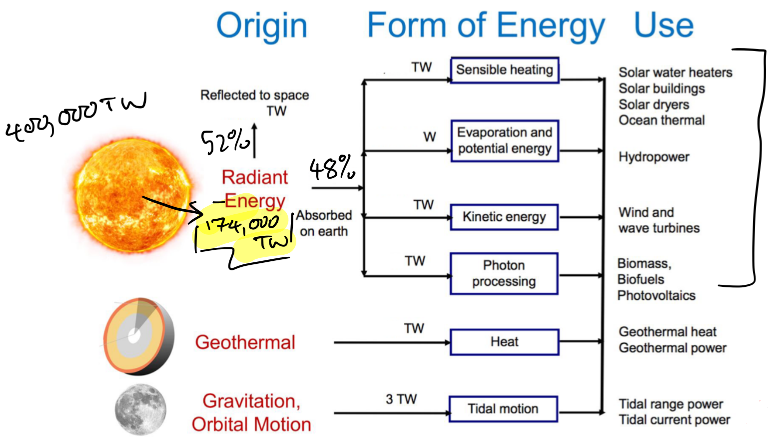
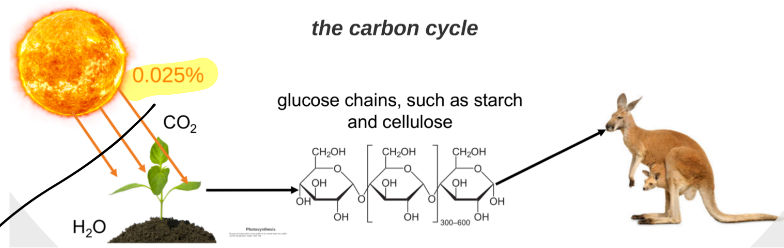


Figure 7: Planetary energy balance. Radiant energy from the sun provides orders of magnitude greater energy compared to geothermal or gravitational energy. 1TW = 10^{12}W.

So



$$(0.025 \times 10^{-2}) \times 0.48 \times 174,000 \times 10^{12} \ J/s$$

$$=$$

$$(0.025 \times 10^{-2}) \times 0.48 \times 174,000 \times 10^{12} \ J/\cancel{s} \times \frac{60 \times 60 \times 24 \times 365 \ \cancel{s}}{1 \ year}$$

$$\simeq 6.6 \times 10^{20} \ J/year$$

Photosynthesis ?

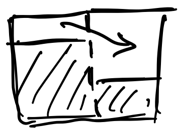
- using radiant energy to convert water & carbon dioxide into glucose, oxygen & heat

- Glucose monomers joined together to form polymers of various types including cellulose
  - └ most abundant organic compound on earth.

- Performed in plants by chlorophylls
  - └ molecular antennas that absorb photons over a limited energy spectrum
  - └ Efficiency : 1%

- Energy is stored in
  - covalent & non-covalent bonds of macromolecules
  - unequal concentrations of ions across semi-permeable membranes

cell membranes !



└ just like potential energy gradients
(in fact, is a potential energy)

Cells

→ cells are the fundamental functional units of all living things

→ Humans are made up of trillions of cells, each performing different functions

→ Some organisms such as bacteria function as one cell

→ Key energy transfers & functions ultimately at molecular & cellular level:

Eg

- They take in radiant or chemical energy and use this energy to do mechanical work or create molecules (most energy gets discarded as heat)
- They make their own internal structure, mostly in terms of proteins.
- They reproduce or duplicate
- They maintain their internal composition and their volume despite the changing exterior conditions.
- Many move about by crawling or swimming
- They sense and respond to environmental conditions
- They sense their internal conditions and use this in feedback loops

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History

- First cell was described by Robert Hooke in 1665
- Cell theory (1800s): all things made from cells
- Electron microscopes in 1950s
  ↳ inner structure & workings of cell →
  → membranes →
  → organelles → ...

Cells, membranes, organelles

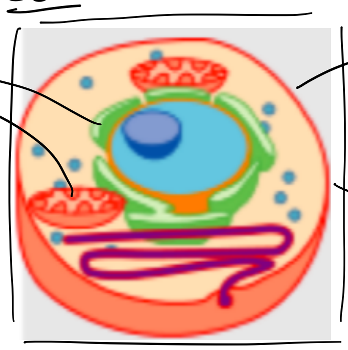
Cell structure

cell

organelles

(think 'organs of cells')

membrane

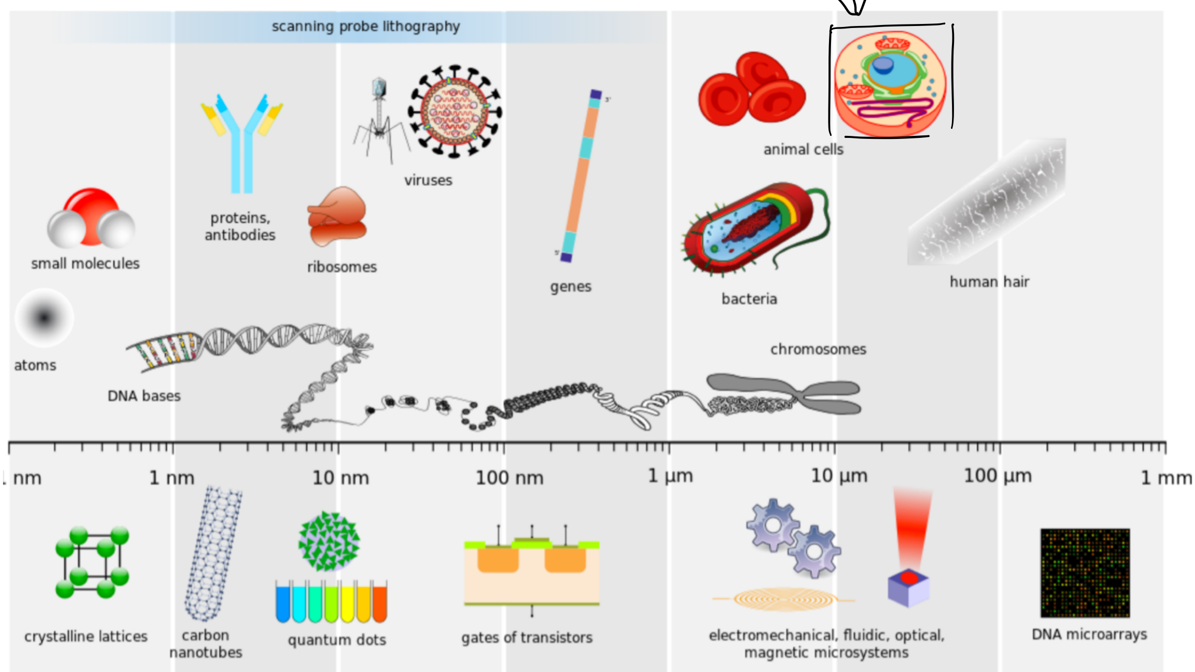


~10 – 20 μm

($\mu = 10^{-6}$)

But first

Scales

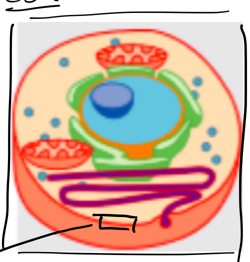


[https://commons.wikimedia.org/w/index.php?curid=4326462]

Figure 25: Logarithmic scale illustrating the size of biological structures and comparing them to several man-made technologies

Plasma membrane

cell



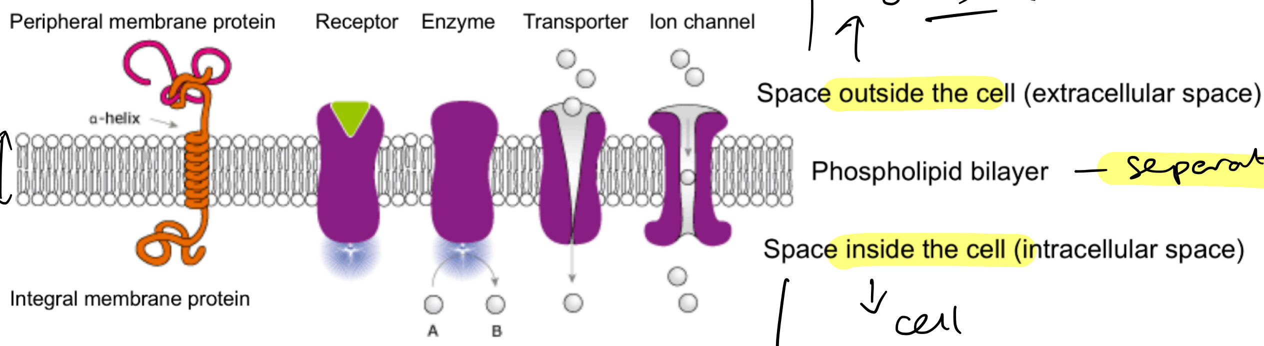
~10 – 20μm

~7–9μm

Membrane structure

membrane

outside



— separates

cell

Figure 26: Functions of the membrane proteins within the phospholipid bilayer of a cell. Membrane proteins control the regulation of substances in and out of the cell and also communicate to other cells and sense the external environment. Oxygen can pass freely into the cell and carbon dioxide can pass freely out of the cell through the membrane. Glucose can only be transported into the cell using a transport protein.

cell membrane

Function	Feature
separates the internal environment of the cell from external environment	phospholipid bilayer
allows/facilitates selective passage of substances & molecules; enables cell cell communication	specialised proteins in membranes

Some key organelles < nucleus / mitochondria

(think cell 'organs')

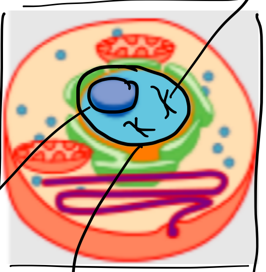
Nucleus

or 'alphabet'/language

- contains DNA, the 'code' that makes the proteins that carry out the key processes of life
- DNA is the molecular basis of inheritance

cell

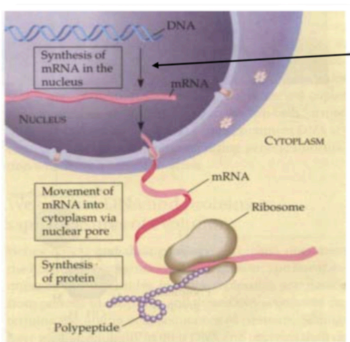
chromosomes



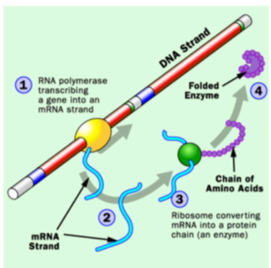
nucleolus

nucleus

From DNA to ... you?



RNA Polymerase



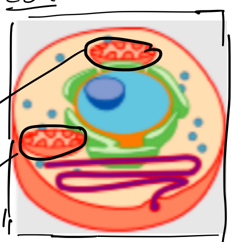
$$\text{DNA} \xrightarrow[\textit{(transcription)}]{\text{RNA polymerase}} \text{mRNA} \xrightarrow[\textit{(translation)}]{\text{Ribosomes}} \text{Protein} \rightarrow \text{functions}$$

'code'

("genotype") → "The central dogma of molecular biology" → ("phenotype")

Mitochondria

- The 'power plants' of the cell
- convert food to energy
  - cellular 'respiration' (later)



More energy required of a cell → more mitochondria

- Eg a heart cell has more mitochondria than a skin cell
- There are more mitochondria in our bodies than there are stars in our galaxy ($\sim 10^{15}$)
- Even have their own genome!
  - bacterial ancestry

Figure 27: Electron micrograph of a mitochondrion. Mitochondria vary greatly in both size (0.5 micrometers - 10 micrometers) and number (1 - over 1000) per cell. However, regardless of their size, number per cell, plant or animal origin, they have similar structures.

The collective inner membrane surface area of mitochondria within our body is ~14,000m^2

Mitochondria pump 10^{21} protons (H^+) per second during respiration, which generates a voltage gradient across the 6 nm mitochondrial membrane of 180 mV

Calculate the voltage gradient across the mitochondria in terms of volts/m.

$$\frac{\Delta V}{nm} = \frac{180\,mV}{6\,nm} = \frac{30 \times 10^{-3}\,V}{1 \times 10^{-9}\,m} = 30 \times 10^{6}\,\frac{V}{m}$$

ie 30 million volts per metre!

Examples

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(3 marks)

(see previous pages)

38) There are over 200 different cell types in the human body. Different cells have different proportions of organelles to suit their function. Which organelle would a human cardiac (heart) cell have in significantly greater number than a human skin cell? Why?

1

(2 marks)

Organelle: mitochondria;

Justification: greater energy needs

Test SS·2017

1. List two key functions required of the cell membrane and briefly explain the features that enable it to meet these requirements. (2 mark)

Answer

- separate interior from external environment
  ↳ phospholipid bilayer
- allow/facilitate selective transfer of molecules between cell & environment
  ↳ membrane proteins

Lecture 14

Topics
- Animal energy consumption & measurement
- Gibbs free energy applied to biological systems

What you should be able to do
- Calculate energy content of food & conversion into activities
- Understand 'indirect calorimetry' & carry out basic calculations
- Understand the role of & how to apply Gibbs free energy in biological problems

Examples

Exam 2017

Energetics of biological systems – 18 marks

37) A 65g 'power bar' developed for endurance athletes contains 4.5g of fat, 47g of carbohydrate and 8.5g of protein. The energy densities of the food constituents are as follows: fat contains 39 kJ/g, carbohydrate contains 16 kJ/g, protein contains 18 kJ/g.

a. What is the total energy content of the power bar? **(1 mark)**

Total energy of power bar: ____________

b. Jogging requires a total energy expenditure of 570 kcal/h, as measured using indirect calorimetry. Given the chemical energy provided by the energy bar above, determine how long you could jog for after eating the energy bar. One calorie = 4.184 J. **(2 marks)**

39) The phosphorylation of glucose is the initial step in the catabolism of glucose in the cell.

Glucose + P $\rightarrow$ glucose-6-phosphate + H_2O
ΔG = 13.8 kJ/mol

a. Explain why this reaction does not take place spontaneously. **(1 mark)**

Answer:

Animal energy consumption

or.... food, energy & life!

- Food content.

  primarily composed of the macromolecules:

  - carbohydrate
  - protein
  - fat

  (macromolecules = very large molecules!) ~1000s of atoms

About 40% of the energy of food is converted to cellular work & the rest to body heat, via....

Cellular respiration (see later!):

Heat Energy

Cellular Work

$$\underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6\,O_2} \rightarrow \underset{\text{Carbon dioxide}}{6\,CO_2} + \underset{\text{Water}}{6\,H_2O} + \underset{\text{Energy}}{ATP}$$

Measuring energy : food

→ Can use the same bomb calorimetr techniques for food (burn it!)

↳ heat given off during oxidation to CO_2 & H_2O

Measuring energy : activity of people (etc)

→ can't burn/explode!

→ instead can calculate indirectly

↳ $\boxed{\text{indirect calorimetry}}$

- consumption of oxygen
- production of waste (carbon dioxide & nitrogen)

Weir equation

$$\boxed{\text{Energy Expenditure} = [(3.94\ VO2) + (1.106\ VCO2)] \times 1.44}$$

↑ oxygen consumption (volume of O_2)

↑ carbon dioxide (volume of CO_2)

Upshot?

Can measure energy of { food (input), activity (output) }

Table 8: Heat released upon oxidation to CO_2 and H_2O and total energy expenditure during some example activities (measured using indirect calorimetry [i.e. not a bomb calorimeter!]).

Substance	Energy yield $kJ.mol^{-1}$	Energy yield $kJ.g^{-1}$	Form of Activity	Total energy expenditure ($kcal.h^{-1}$)
Glucose	2,817	15.6	Lying still, awake	77
Lactate	1,364	15.2	Sitting at rest	100
Palmitic acid	10,040	39.2	Walking, level ground	200
Carbohydrate	-	16	Sexual intercourse	280
Fat	-	37	Biking, level ground	305
Protein	-	23	Walking, uphill	360
Ethyl alcohol	-	29	Jogging	570
Coal	-	28	Rowing	830
Oil	-	48	Maximal activity (untrained)	1440

sugar → Carbohydrate

burning/exploding

indirect calorimetry

Examples

A calorie is a unit of energy that is often found in older texts and is still common in food science. One calorie = 4.184 J, which is the energy required to increase the temperature of 1 g of H_2O from 14.5 °C to 15.5 °C. Using the table ~~below,~~ which illustrates some example activities and their energy expenditures, calculate the total energy expenditure (in J) following 20 mins of jogging, and compare this to 2 h of walking on level ground.

Jogging 20 min $= \left[570\times10^3 \frac{\text{Cal}}{\text{h}} \times \frac{4.184\text{ J}}{1\text{Cal}} \times \left(\frac{1\text{ h}}{60\text{ min}}\right)\right] \times 20\text{ min} \approx 795\text{ kJ}$

Walking 2h $= \left[200\times10^3 \frac{\text{cal}}{\text{h}} \times \frac{4.184\text{ J}}{1\text{cal}}\right] \times 2\text{h} \approx 1700\text{ kJ} = 1.7\text{ MJ}$

Estimate how high a ladder could a 70kg person climb, fuelled by a Cadbury Moro bar, which has the following nutritional content: 10g fat, 45g sugar, and 3g protein. Assume muscle is 24% efficient and obtain energy yield from Table 8 ~~below.~~

Energy in bar $= 10\text{g} \times 37\frac{\text{kJ}}{\text{g}} + 45\text{g} \times 16\frac{\text{kJ}}{\text{g}} + 3\text{g} \times 23\frac{\text{kJ}}{\text{g}}$

$\approx 1159\text{ kJ}$

Energy available $= 0.24 \times 1159\text{ kJ} \approx 278\text{ kJ}$

energy used $= mgh = 70 \times 9.81 \times h$ J

$\Rightarrow h = \frac{278\times10^3\text{ J}}{70\times9.81} \approx 404\text{ m}$

Examples

Exam 2017

Energetics of biological systems – 18 marks

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(2 marks)

→ same idea as previous!

Thermodynamics : Gibbs free energy

Recall :

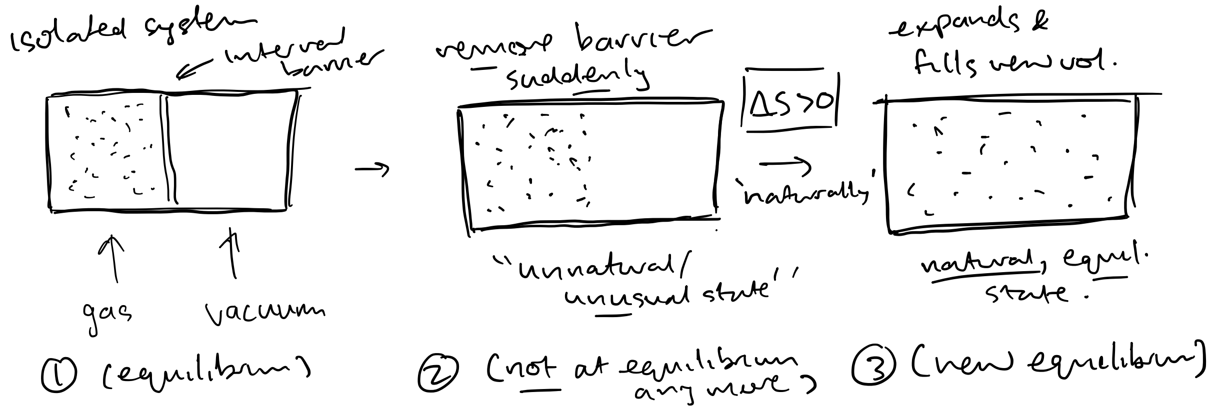
Spontaneous process :

- unnatural → natural

For isolated system :

- 'order' → 'disorder'
- entropy increases

Example : Free expansion of a gas



For open systems

entropy maximisation $\xrightarrow{\text{translates to}}$ energy minimisation

isolated   open

Thermodynamics : Gibbs free energy

- Gibbs free energy $\boxed{G = U + PV - TS = H - TS}$

enthalpy $H = U + PV$

at constant temperature & pressure :

- ΔG = − maximum chemical work by system ($\Delta G = -\mu \Delta N$)

  ie $-\Delta G$ = maximum chemical work by system

- $\Delta G < 0$ spontaneous

  ↳ free energy decreases, & chemical work is done

- Tells you what's possible, not how or how fast

  → [see kinetics for how & how fast]

- Overall vs individual

  - We need the overall process to be favourable, but individual steps/components can be unfavourable as long as they can be appropriately coupled

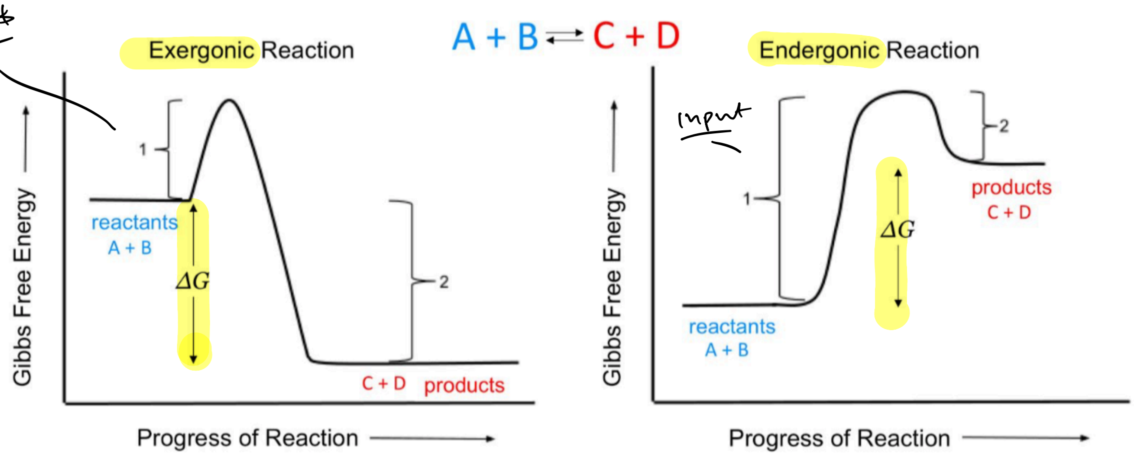
  → this is common!

Overall : Exergonic vs endergonic

gives off energy (internal (free energy decreases)

- $\Delta G \leq o$ represents a reaction that is *exergonic* and will occur spontaneously
- $\Delta G > o$ represents a reaction that is *endergonic* and must be driven by input of free energy

input*



* activation energy for reaction → need to perturb to get started & 'unlock' stored energy

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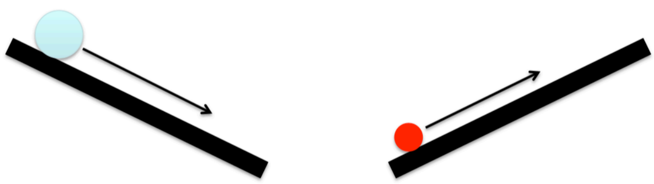
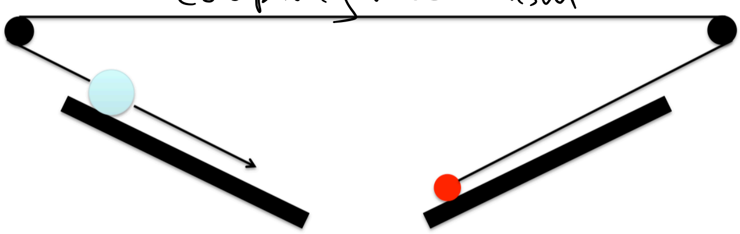
Coupling



couple together

coupling mechanism



overall favourable

Examples

39) The phosphorylation of glucose is the initial step in the catabolism of glucose in the cell.

Glucose + P $\rightarrow$ glucose-6-phosphate + H_2O
$\Delta G = 13.8$ kJ/mol

a. Explain why this reaction does not take place spontaneously. **(1 mark)**

Answer: $\Delta G > 0$ (spontaneous $\Delta G < 0$ at constant T, P)

b. In the cell, the reaction is coupled to the hydrolysis of ATP. Explain how coupling the reaction to ATP hydrolysis enables the phosphorylation of glucose to take place in the cell. **(1 mark)**

Answer: Hydrolysis of ATP is energetically favourable/spon. (see tomorrow/below), $\Delta G < 0$ & ΔG overall $\Delta G = \Delta G^{phos} + \Delta G^{hyd.} < 0$ (see below).

c. Write down the coupled reaction and calculate the free energy change for the coupled reaction under standard conditions. The free energy of hydrolysis of ATP is -29 kJ/mol under standard conditions. **(2 marks)**

Answer:

- Reaction (see tomorrow)
- Overall $\Delta G = +13.8 \frac{kJ}{mol} - 29 \frac{kJ}{mol}$

$= -15.2 \frac{kJ}{mol}$

< 0

(hence spontaneous/energetically favourable)