Lecture 13 : New topic.

Intro to energy ✓ done

Thermodynamics ✓ done.

Bioenergetics! ← ~5 lectures + 1 tutorial.

Eg

- How do animals, cells etc store & use energy?

- How can we apply thermodynamics & chemical kinetics to understand & design biological systems?

  ↳ Physics & engineering approach to biology.

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

Example questions

Exam 2017 S1

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)**

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: ____

Exam 2018 SS :

33) List two key physiological functions of the cell membrane and the features of it that enable it to carry out these functions. **(2 marks)**

3 Biological Energetics

Learning Objectives

- Understand the general sources and transformations of energy in biological systems.
- Understand and describe the basic functions, structure and scales of the cell, cell membrane, nucleus and mitochondria.
- Calculate the energy content of food and conversion into activities. Understand the concept of 'indirect calorimetry' and carry out basic calculations.
- Understand the key role of Gibbs free energy in biological problems and known how to apply it/ calculate with it. Understand the role and use of ATP as an energy source driving cellular processes.
- Calculate reaction rates and interpret chemical kinetics figures. Understand the role of and factors affecting catalysts/enzymes.
- Understand the three stages of cellular respiration - glycolysis, Krebs cy-cle and electron transport - and their inputs/outputs. Calculate cellular efficiency.
- Understand the process of fermentation, when it occurs and its inputs/outputs.

L13

3.1 Sources and transformations of energy in biological systems

L13

3.1.1 Thermodynamics in biology

From a thermodynamics point of view, biological systems are **open systems**: they constantly exchange energy and matter with their environments. They are also 'non-equilibrium' systems, e.g. operating near 'non-equilibrium steady states' (or just non-equilibrium states in general!). Since equilibrium means 'no energy/mass exchanges or other processes occurring', for a biological system **equilibrium = death!**

While the 'far from equilibrium' conditions can make applications of thermodynamics to biology more difficult, we nevertheless find that **thermodynamic concepts are typically still very useful** in understanding biological processes. After all, **the same laws of physics and chemistry apply to biology as to the rest of the universe!**

We will see in particular that the **Gibbs free energy** is a key driver of spontaneous processes in biological systems: we can often approximate biological systems as **open systems at constant pressure and temperature.**

In contrast to some of the more 'human-scale' applications common in traditional engineering, the energy in biological systems tends to be stored mainly at the **molecular and cellular levels**.

60–70% water (H_2O)
rest mostly carbon.

3.1.2 Composition

What are biological systems made of? They are usually distinguished from 'non-organic matter' by being based heavily on **carbon compounds**. For example, humans are about ~~60% carbon.~~

Fundamentally, **life is made of 'star stuff'**: hydrogen, carbon, nitrogen, oxygen and phosphorus.

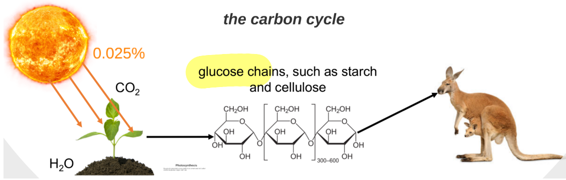
3.1.3 The carbon cycle and photosynthesis

This leads to the important idea of the **carbon cycle**, pictured below.

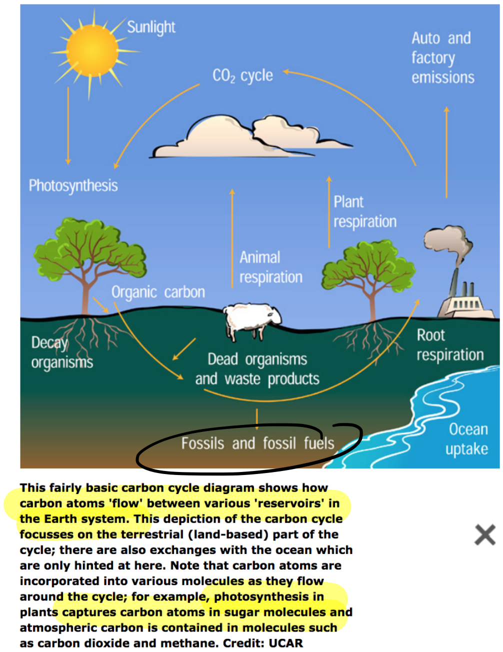
A key process involved in this is **photosynthesis**, carried out by plant life. This is the process of *using the radiant energy of the Sun to convert water and carbon dioxide into glucose, oxygen and heat.*

Glucose monomers are joined together to form polymers of various types, including **cellulose**, which is the most abundant organic compound on earth.

Photosynthesis is performed in plants by **chlorophylls**, which are 'molecular antennas' that absorb photons over a limited energy spectrum. The efficiency of this process is quite low - only about 1%!



(a)



(b)

Figure 17: Illustrations of the carbon cycle.

can 'use' a potential diff. to do work.

The resulting energy is **stored** in, for example,

1. The **covalent and non-covalent bonds** of macromolecules
2. **Unequal concentrations** of ions across semi-permeable membranes (cell membranes).

Note: an unequal concentration gradient is just like an energy potential - in fact it *is* a form of potential energy, available to do work (e.g. osmotic work etc). The energy in chemical bonds is also a type of potential energy that can be 'released' and used

'Free energy' : available to do work

2nd Law : free energy decreases (useful, available work → thermal, non-useful work) to do useful work.

(power → W)

Example Problems 1: Sources and transformations of energy

1. The radiant energy of from the Sun that reaches the Earth is 1.74 $\times 10^{17}$ 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.

$\frac{\text{Energy}}{\text{year}}$

Answers

$$(1.74 \times 10^{17}\ J/s) \times \underbrace{0.48}_{\text{reaches land}} \times \underbrace{0.025 \times 10^{-2}}_{\text{photosyn.}} \times \frac{60 \times 60 \times 24 \times 365\ s}{1\ \text{year}}$$

$$\approx 6.6 \times 10^{20}\ J/\text{year}\ (\text{power}) \rightarrow \boxed{6.6 \times 10^{20}\ J \text{ in one year.}}$$

Exercise: Calculate in TW.h /year [=] Energy /year

(Hint: see tutorial one)

3.2 Cells, membranes and organelles

Cells are the fundamental functional units of all living things. Humans are made up of *trillions* of cells, each performing different functions, while some organisms, such as bacteria, function as *one cell*.

Again, we emphasise that the key energy transfers and functions of biological systems ultimately occur at the molecular and cellular level. Cells:

1. Take in radiant or chemical energy and use this energy to do mechanical work or create molecules (most energy is 'discarded' as waste heat).

2. Make their own internal structure, mostly in terms of proteins.

3. Reproduce or duplicate.

4. Maintain their internal composition and their volume despite the changing exterior conditions ('homeostasis')

5. Can often move about by 'crawling', 'swimming' or even 'rolling'.

6. Sense and respond to environmental conditions.

7. Sense their own internal conditions and use this in feedback loops.

The first cell was described by Robert Hooke in 1665. **Cell theory** - the idea that all living things are made from cells - was proposed much later, in the 1800s. The invention of **electron microscopes** in the 1950s allowed us to see the *inner structure and workings of the cell*. This leads to...

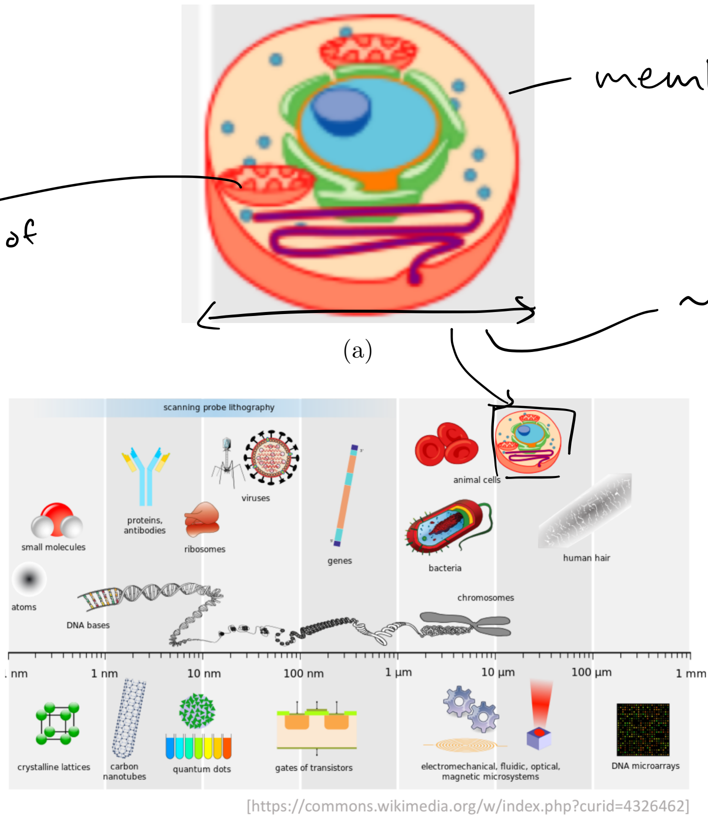
3.2.1 The structure of cells

An overview of cell structure and relevant reference scales is shown below.

cell

membrane

organelles
"the 'organs' of cells".



~10–20μm
($\mu = 10^{-6}$)

(a)

(b)

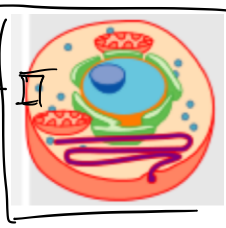
Figure 18: (a) A typical animal cell and (b) Logarithmic scale illustrating the size of biological structures and comparing them to several man-made technologies.

Key features include the ① **cell membrane**, ② **the nucleus** and the **mitochondria**, ③ which we look at in more detail next.

3 key features for us.

2 & 3 : organelles

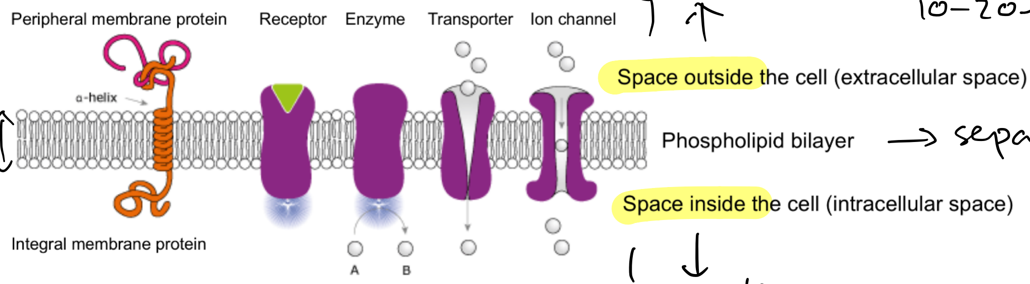
3.2.2 The cell membrane



10–20um

Membrane structure

outside



~10nm

$n = 10^{-9}$

→ separates

inside

Figure 19: The cell membrane and 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. From `https://www.proteinatlas.org/humanproteome/secretome`.

Cell membrane

Function	Feature
◦ separate the internal environ. of the cell from the external environment	phospholipid bilayer
◦ allow/facilitate selective passage of substances/molecules ◦ enable cell-cell communication	specialised proteins in membrane.

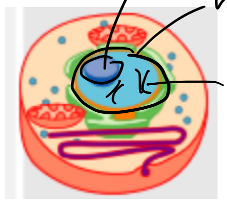
3.2.3 The nucleus

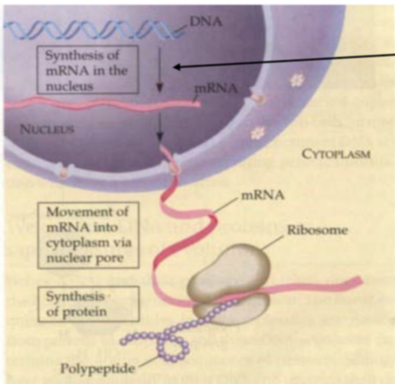
or alphabet/ language

– Contains DNA, the 'code' that says how to make the proteins that carry out the key processes of life

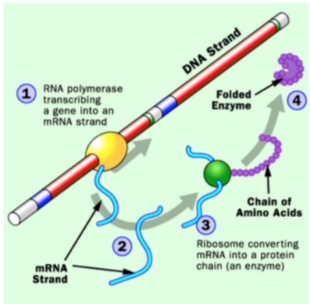
– DNA is the molecular basis of inheritance (info passing on).

cell





RNA Polymerase



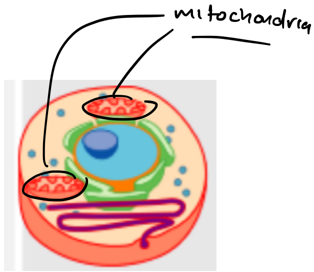
$$\underbrace{\text{DNA} \xrightarrow[\text{(transcription)}]{\text{RNA polymerase}} \text{mRNA} \xrightarrow[\text{(translation)}]{\text{Ribosomes}} \text{Protein}} \longrightarrow \text{functions}$$

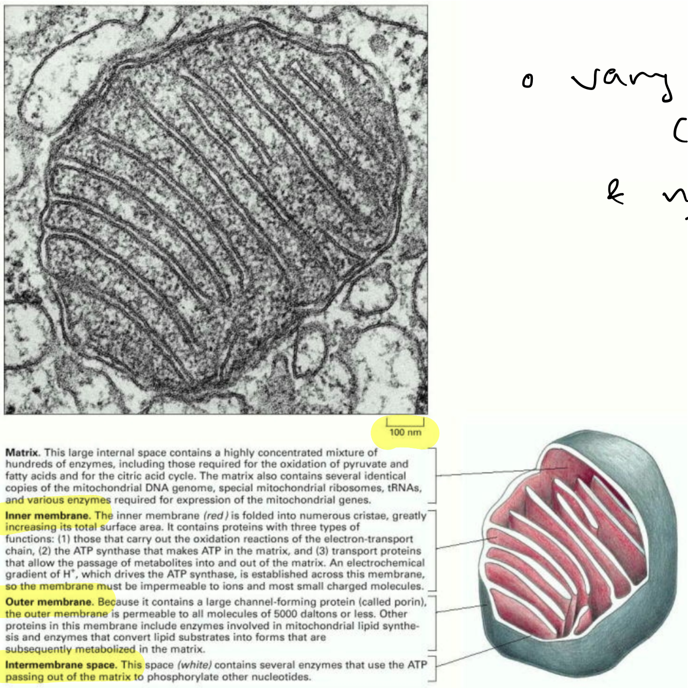
Figure 20: The nucleus and "the central dogma of molecular biology", i.e. DNA (code/genotype) → mRNA → Protein (function/phenotype). From *Molecular Biology of the Cell* (4ed) via `www.ncbi.nlm.nih.gov/books/NBK26887`.

code 'genotype' → info flow → function phenotype

3.2.4 Mitochondria

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





- vary in size
  (0.5 μm – 10 μm)
  & number (1–1000)
  per cell.

will discuss later.

Figure 21: The structure of a mitochondrion (this is the singular term for mitochondria). From *Molecular Biology of the Cell* (4ed) via `www.ncbi.nlm.nih.gov/books/NBK26887`.

- More energy required of a cell → more mitochondria
  Eg a heart cell has more mitochondria than a skin cell
- More mitochondria in our bodies than their are stars in our galaxy (~10^{15})
- Even have their own genome
  ↳ bacterial ancestry.

Example Problems 2: Structure and function of cells

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

3. Mitochondria pump 10^{21} protons (H^+) per second during cellular respiration. This generates a voltage gradient of 180 mV across the 6 nm mitochondrial membrane. Calculate the voltage gradient across the mitochondrial membrane in terms of volts/m.

Answers

1. Mitochondria → due to greater energy requirements.

2. Function: separate interior from external environment
↳ feature: phospholipid bilayer

Function: allow/facilitate selective transfer of molecules between cell & environment
↳ feature: membrane proteins.

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

→ 30 million volts per metre!

End L13