Diffusion and the problem of Size

All organisms need to exchange substances such as food, waste, gases and heat with their surroundings. These substances must **diffuse** between the organism and the surroundings. The rate at which a substance can diffuse is given by **Fick's law:**

$$\text{Rate of Diffusion} \propto \frac{\text{Surface Area} \times \text{Concentration Difference}}{\text{Distance}}$$

The rate of exchange of substances therefore depends on the organism's surface area that is in contact with the surroundings. The requirement for materials depends on the volume of the organism, so the ability to meet the requirements depends on the **surface area : volume ratio** (SA/V ratio) As organisms get bigger their volume and surface area both get bigger, but volume increases by the length **cubed** whilst surface area increases by the length **squared**. This can be seen with some simple calculations for different-sized organisms, in which each organism is assumed to be cube-shaped (!) to make the calculations easier. The surface area of a cube with length of side L is (LxL) x 6 ($6L^2$), while the volume is L^3.

Organism	Length	SA (m^2)	vol (m^3)	SA/vol (m^{-1})
Bacterium	1 mm (10^{-6} m)	6×10^{-12}	10^{-18}	6,000,000
Amoeba	100 mm (10^{-4} m)	6×10^{-8}	10^{-12}	60,000
Fly	10 mm (10^{-2} m)	6×10^{-4}	10^{-6}	600
Dog	1 m (10^{0} m)	6×10^{0}	10^{0}	6
Whale	100 m (10^{2} m)	6×10^{4}	10^{6}	0.06

So **as organisms get bigger their surface area/volume (SA/V) ratio gets smaller**. A bacterium is all surface with not much inside, while a whale is all insides with not much surface. This means that **as organisms become bigger it becomes more difficult for them to exchange materials with their surroundings**. In fact this problem sets a limit on the maximum size for a single cell of about 100 µm. In anything larger than this materials simply cannot diffuse fast enough to support the reactions needed for life. One partial solution to this problem is to become long and thin (e.g. nerve cells). Very large cells like birds' eggs are mostly inert food storage with a thin layer of living cytoplasm round the outside.

Organisms also need to exchange heat with their surroundings, and here large animals have an advantage in having a small surface area/volume ratio: they lose less heat than small animals. **Large mammals can easily keep warm** and don't need much insulation or heat generation. **Small mammals and birds lose heat very readily**, so need a high metabolic rate in order to keep generating heat, as well as thick insulation. Hence polar bears are the largest species of bear and African elephants, being larger, need larger ears to help them cool down. Large mammals can feed once every day or so, but small mammals must feed continuously. Human babies also lose heat more quickly than adults, which is why they need woolly hats!

So how do organisms larger than 100 µm exist? All organisms larger than this are **multicellular**, which means that their bodies are composed of many small cells, rather than one big cell. Each cell in a multicellular organism is no bigger than about 30µm, and so can exchange materials quickly and independently. Humans have about 10^{14} cells (100 trillion).

Cell Differentiation

Multicellular organisms have another difference from unicellular ones: their cells are specialised, or **differentiated** to perform different functions. So the cells in a leaf are different from those in a root or stem, and the cells in a brain are different from those in skin or muscle. In a **simple organism (i.e. Prokaryotes** and **Protoctista) all the cells are alike**, and each performs all the functions of the organism.

Cell differentiation leads to higher levels of organisation:

- **A tissue is a group of similar cells performing a particular function.**
- **Simple tissues** are composed of one type of cell, whilst
- **Compound tissues** are composed of more than one type of cell. Some examples of animal tissues are:
    - **epithelial**, connective, skeletal, **nervous**, muscle, **blood,** glandular.
- Plants have a number of different tissues too:
    - Parenchyma, sclerenchyma, **aerenchyma,** and **vascular**

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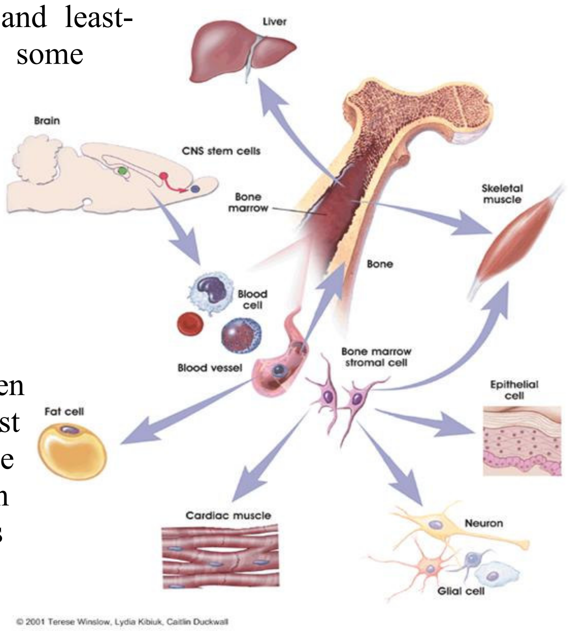
- **An organ is a group of physically linked different tissues working together as a functional unit**. For example the stomach is an organ composed of epithelium, muscular, glandular and blood tissues.
- **A system is a group of organs working together to carry out a specific complex function**. Humans have seven main systems: the circulatory, digestive, nervous, respiratory, reproductive, urinary and muscular-skeletal systems.

Levels of Organisation

atoms
↓
molecules
↓
organelles
↓
cells
↓
tissues
↓
organs
↓
systems
↓
organisms
↓
populations
↓
communities

A multicellular organism like a human starts off life as a single cell (the **zygote**), but after a number of cell divisions the **stem cells** change and develop in different ways, eventually becoming different tissues. This process of **differentiation** is one of the most fascinating and least-understood areas of modern biology. For some organisms differentiation is reversible, so for example we can take a leaf cell and grow it into a complete plant with roots, stem, leaf and vascular tissue. However for humans and other mammals differentiation appears to be irreversible, so we cannot grow new humans from a few cells, or even grow a new arm.



This is one of the main differences between animals and plants. In animals, certain genes must be ‘switched off’ from a very early stage in the organisms’ life. From that point on, only certain cells types are possible for that cell and its descendents. Thus there are many, many different types of animal cell possible (over 2000 in humans).

All plant cells go through a fixed sequence of development; once they arrive at their chosen end-point’ they stop, but essentially they are all the same.