Does size matter?

Chris Finlay

Chris Finlay discusses the importance of size to all organisms and why researchers like to make comparisons

Key words

Body mass
Comparative physiology
Adaptation
Metabolic rate
Surface area to volume ratio
Logarithmic scale

The consequences of having a small or large body are huge. As this article explains, size ultimately dictates how an organism will look, feed, move, and interact with its environment and other species.

Size, more commonly referred to as **body mass**, is one of the most important aspects of any organism. You will often see comparisons made between an elephant and a mouse. This is fine when comparing mammals, but looking beyond mammals you hopefully start to consider the extreme differences between a bacterium and an elephant, or a single cell and a redwood tree.

Size comparisons

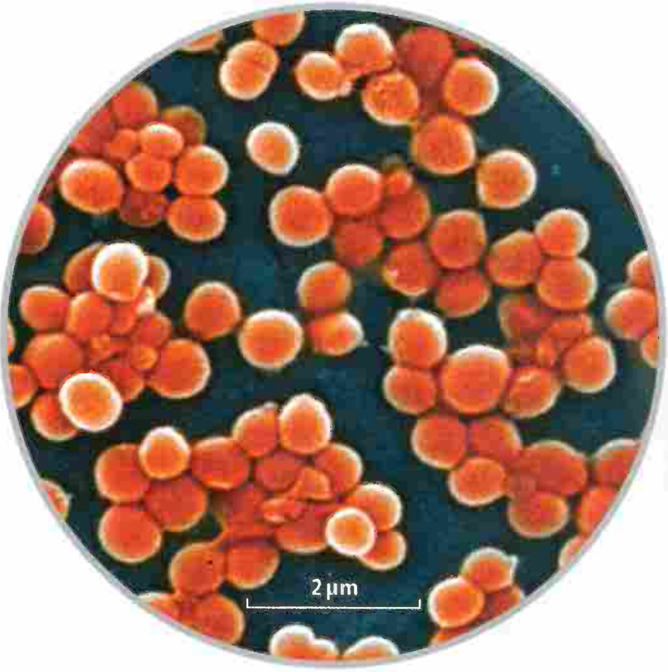
This is where **comparative physiology** plays such an important role in biological research. Comparison across all living organisms allows researchers to question the origins of life, the evolution of different **body plans**, and a vast number of biological adaptations. Ultimately this research is investigating how evolutionary change has impacted on life in the past and how this will continue to impact us all into the future.

The variation of size in biological life is huge (see Box 1 on p. 4). Blue whales, the largest animals ever to have lived, can reach over 30 metres in length, bringing lots of physiological pressures. For example, they have to consume a huge amount of food to remain alive. This can only be achieved by travelling long distances across the globe.

Compare this to the largest plants, which grow to even larger sizes. The largest multi-stemmed tree — the quaking aspen (*Populus tremuloides*) covers more than 100 acres of land with a body mass in excess of 6000 tonnes. This means that it is in constant competition with other plants for sunlight, water and nutrients.

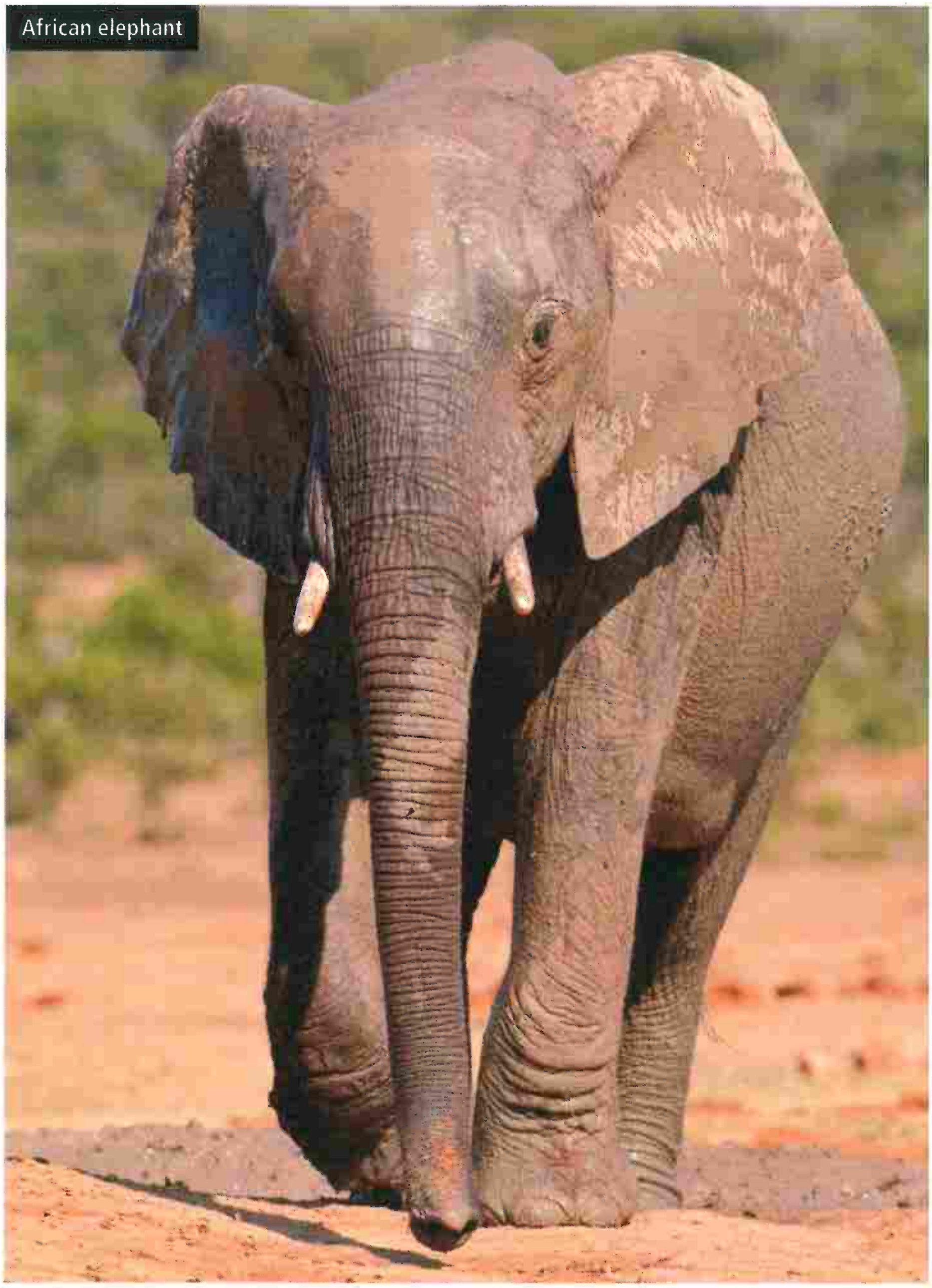
Now consider a bacterium. Most bacteria are around 5 micrometres (μm) in diameter. The smallest examples (*Mycoplasma* species) can be much smaller, at 50–200 nanometres (nm). Their entire ecosystem can be measured in metres, and small differences — such as being in shade or in direct sunlight — can make the difference between life and death.


House mouse



Coloured scanning electron micrograph of MRSA


Redwood tree in California


African elephant

Starting at the bottom

The majority of bacteria are around 1–5 µm in diameter. At this scale they inhabit a very different world from us. For example, small changes in environmental conditions such as temperature, pH or salt concentrations can easily result in death for these microbes. The distance to a food source can also become problematic as bacteria experience their external environment in a very different way from larger organisms. For example, a bacterium living in water will have a much harder time moving through the water than larger organisms such as fish. For more detail see Box 2 on p. 5.

Going up a size: animal and plant cells

Individual cells of most multicellular organisms are of a similar size, irrespective of the overall size of the organism, typically around 10 µm. There are two very specific reasons for a cell being this size — surface area to volume ratio and diffusion time. To illustrate these let's imagine that a cell is a sphere of radius *r* (see Figure 1). As the radius of a sphere increases, the surface area also increases, but by a lesser amount. Therefore a cell with a large diameter will have a smaller surface area relative to its diameter than a smaller cell. A smaller relative surface area means the area available for vital exchange processes such as gas and nutrient exchange is decreased. The relationship between surface area and volume can be shown as:

$$\text{surface area} \propto \text{volume}^{\frac{2}{3}}$$

Multicellular organisms need signals to be transported around their bodies. For example, if you put your hand on something hot, a quick signalling process tells your muscles to move your hand away. These signals rely on diffusion of signalling molecules to trigger an electrical impulse in your nerves. Diffusion takes time because it depends on the distance the molecule has to travel. We find that it takes four times as long to go twice as far, but a

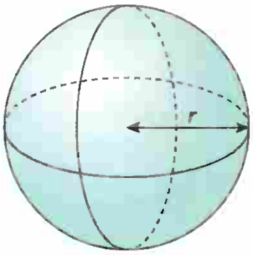


Figure 1 A sphere with radius *r*

Box 1 Working with scale

All biologists have to become familiar with the internationally recognised measurement scales — **the SI units**. SI units are used to quantify any physical parameter, for example metres are the SI unit of length.

Biologists work with the full range of SI units, so an understanding of the names and symbols is very important.

The unit used in the scale in Figure 1.1 is the metre, so let's start there.

Unit	Symbol	Factor
1 metre	1 m	1×10^{0} m
1 millimetre	1 mm	1×10^{-3} m
1 micrometre	1 µm	1×10^{-6} m
1 nanometre	1 nm	1×10^{-9} m
1 picometre	1 pm	1×10^{-12} m

It is important to note that the scale used in Figure 1.1 is not linear. It is a logarithmic scale. Each horizontal band represents increasing powers of 10. Therefore there are 1000 mm in 1 m.

Researchers often use a logarithmic scale because it allows for data that range over several orders of magnitude to be plotted and compared. For example, the difference in mass between a blue whale and a bacterium will be somewhere in the order of 10^{21}, i.e. a blue whale has approximately 10 thousand trillion times more mass than a bacterium.

Plotting a logarithmic graph also allows researchers to determine if the data they plot are changing in an exponential fashion. If they are the plotted data will give a straight line.

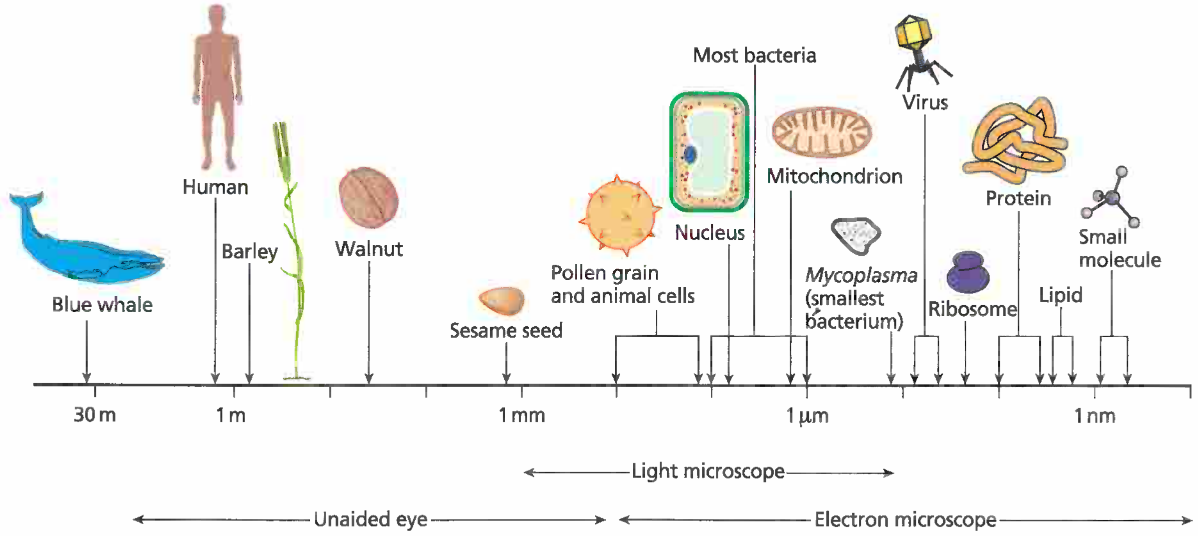


Figure 1.1 An illustration of the size range of life

quarter as long to go half as far. This relationship can be shown as:

$$\text{diffusion time} \propto \text{distance}^2$$

The biological consequences of this relationship are described in Box 3.

Why do elephants need thicker bones?

Every species has adaptations that allow it to grow and flourish in its natural environment. A lot of these adaptations can be explained by the size of the organism. We can use mammals to help illustrate this point. Let's go back to the mouse and elephant comparison. Both these mammals have a similar body plan. However, due to their different sizes they have specific adaptations, such as their bone structure.

Figure 2 shows an illustration of a mouse femur (leg bone) and an elephant femur. If the bone structure in mammals follows an **isometric growth** pattern then, in an elephant, we would expect to see a larger version of the bone, meaning it would have increased at the same rate for all parts of the bone so that the shape remains identical. However, in reality a very different bone structure is seen in the elephant. There is a marked difference in the bone shape and thickness compared with the mouse bone. This is described as **allometric growth** — the phenomenon whereby parts of a structure (or organism) grow at different rates.

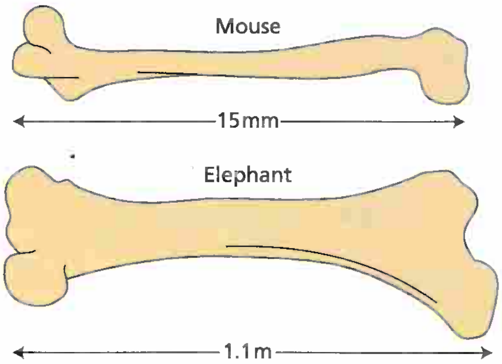


Figure 2 Illustration of a mouse femur and an elephant femur

Box 2 Reynolds numbers

To bacteria, water is extremely viscous, that is, thick and sticky. This makes it very hard to move through. This effect is quantified by the **Reynolds number**. The Reynolds number divides organisms into two groups depending on their size.

Organisms larger than 1 mm in diameter

Humans have a diameter greater than 1 mm and so have a **high Reynolds number**. The dominant forces to act on an organism with a high Reynolds number are gravitational forces. This means that **inertia** comes into play. Inertia in this context means that once something is moving it tends to stay moving. For example, if you are swimming and stop moving your arms and legs, you will glide for quite a distance before stopping.

Organisms less than 1 mm in diameter

Bacteria have a diameter less than 1 mm and so have a **low Reynolds number**. The dominant forces to act on an organism with a low Reynolds number are molecular forces. This means that **viscosity** comes into play. For bacteria, water feels like thick treacle would to us. If bacteria stop propelling themselves forward, they stop immediately (within a nanometre).

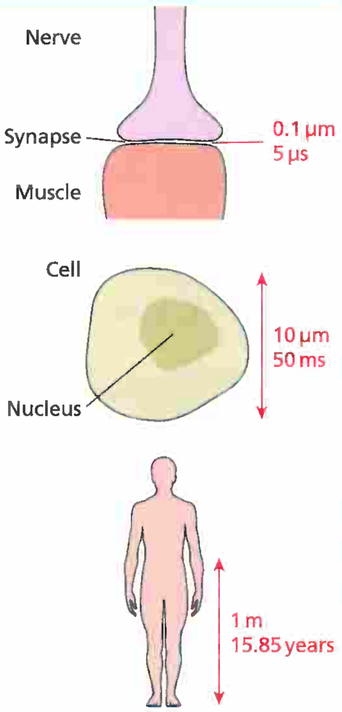
Box 3 Impact of diffusion time $\propto$ distance^2

Consider what this relationship means for different structures in the human body.

Diffusion across a synapse:
$0.1\,\mu\text{m} = 1 \times 10^{-7}\,\text{m}$
A diffusion time of $5\,\mu\text{s}$ (5×10^{-6} seconds) is observed. This, combined with electrical signalling in the nerves, allows for extremely fast signalling throughout an organism.

Diffusion across a cell:
$10\,\mu\text{m} = 1 \times 10^{-5}\,\text{m}$
A diffusion time of 50 ms (5×10^{-2} seconds) is observed. This is quick enough for most biological processes in a cell.

Diffusion across 1 metre:
$1\,\text{m} = 1 \times 10^{0}\,\text{m}$
A diffusion time of 15.85 years is observed. This is much too slow for biological processes and helps to illustrate why we could not rely on diffusion alone to transmit signals throughout the body.



Clearly the difference in size between a mouse and an elephant is not down to a change in one dimension. An elephant is not simply taller than a mouse. The difference is due to an increase in all three dimensions. In other words, the animal's volume, or body mass, has increased greatly (the cube of the dimensions).

This increase in body mass of an elephant means that a bigger version of the mouse leg bone would be too thin to support the weight of the elephant. It would snap under the pressure. The bone structure has to change to accommodate the increased mass. A much thicker bone develops because the strength of the bone depends on the cross sectional area. This can be illustrated by considering how much of an organism's mass can be accounted for by its skeleton:

- 8% of the body mass of a mouse
- 18% of the body mass of a human
- 26% of the body mass of an elephant

Surface area to volume ratio

It is simplistic but we can also consider the mouse or the elephant to be spheres with a specific radius. Remember:

$$\text{surface area} \propto \text{volume}^{\frac{2}{3}}$$

Therefore an elephant has a much smaller relative surface area than a mouse. Surface area is important for a lot of vital processes in any organism — for example, heat exchange, gas exchange, nutrition exchange and transport systems.

This itself is an important finding. Larger organisms require a range of physiological support systems to deal with this decrease in relative surface area. For example:

- big ears/skin wrinkles to allow for faster heat exchange
- lungs/gills for more efficient gas exchange
- longer gastrointestinal tract, with specific structures such as villi (see Figure 3) and microvilli to greatly increase the surface area available for nutrient absorption

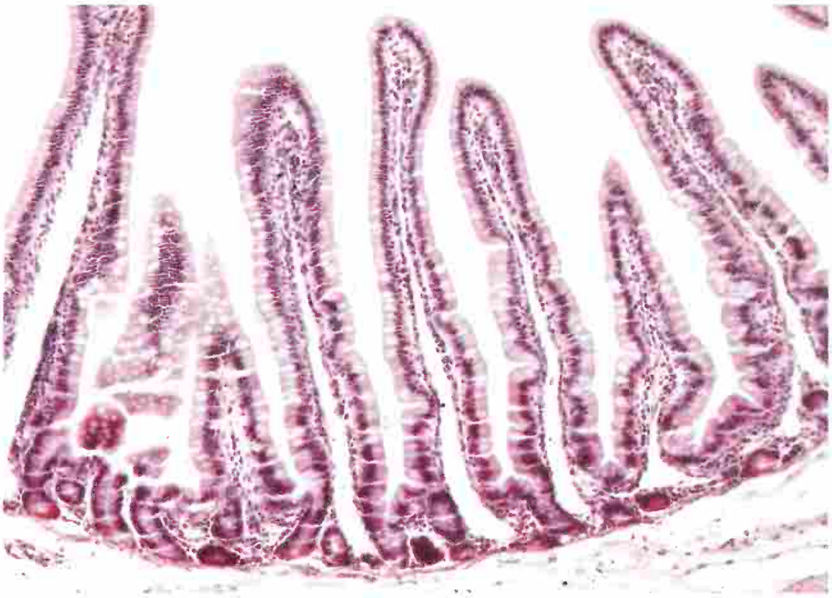


Figure 3 Light microscope image of a section through the finger-like projections in the small intestine (villi) (×125)

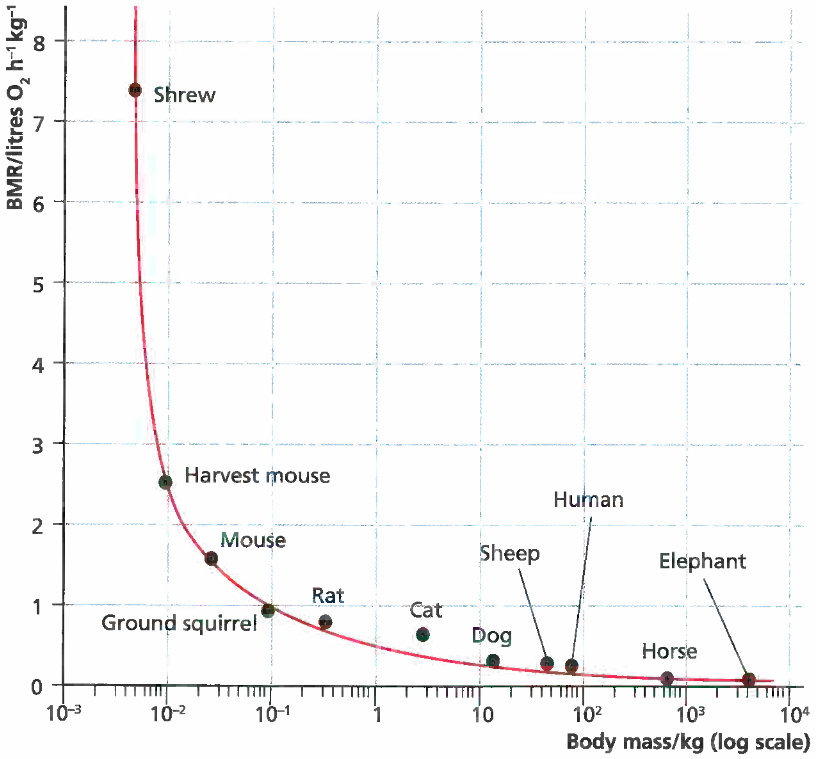


Figure 4 Relationship of basal metabolic rate (BMR) per kilogram of body mass to body size

Energy requirements by size

A larger body size would lead us to think that larger animals require more energy to survive. This is true — larger animals *do* need more energy compared with smaller animals. But when we look at energy requirements — **basal metabolic rate (BMR)** — compared to body mass, we see a very different trend emerging.

Figure 4 shows that BMR decreases as body mass gets bigger according to the following relationship:

$$\text{metabolic rate} \propto \text{mass}^{\frac{3}{4}}$$

In other words, larger animals have adapted to use less energy per unit mass. Without this adaptation they would be unable to eat the huge amount of food needed for their survival.

Conclusion

Size dictates many features of living organisms — how they live, survive, develop and interact with their internal and external environments. This is true from the smallest to the largest organisms on the planet.

As an organism gets bigger, the pressures of size introduce biological limitations that need to be either accommodated or overcome. Comparative physiologists are constantly working to identify and understand the adaptations that have evolved to overcome such limitations.

Researchers are continually classifying new species with specific adaptations and physiologies that allow them to survive in their unique ecosystems and habitats. This opens up a new world of information that will help map evolutionary change across the many species that populate planet Earth. Some of these adaptations have also led to useful innovations that have proved beneficial to us as humans. The best example of this is antibiotics. Some fungi produce antibiotics naturally to kill surrounding bacteria and allow room for the fungus to grow and access more nutrients. We have been able to use this adaptation to our own advantage in treating bacterial infections.

The more knowledge we have of the full scale of life on this planet, the more potential benefits there will be for every living organism.

Further reading

Reynolds number and bacterial movement: http://tinyurl.com/peg2zvg

Allometry: http://tinyurl.com/mwsb56z

The size of organisms: surface area to volume ratio: http://tinyurl.com/q7vcq37

Metabolic rate to mass ratio: http://tinyurl.com/mtgc9q8

Dr Chris Finlay is a senior university teacher in the School of Life Sciences at the University of Glasgow, with a research interest in cancer. He also coordinates the first year biology undergraduate course.

Terms explained

Allometric growth	Growth that occurs at different rates for parts of an organism in relation to the whole organism.
Basal metabolic rate	The rate at which an organism uses energy while at rest.
Body mass	The relationship of an organism's weight (mass) to its size (volume).
Body plan	A collection of morphological features shared by members of a phylum.
Comparative physiology	The study of the similarities and differences in structure and vital processes in different species.
Isometric growth	Growth that occurs at the same rate for all parts of an organism.

Key points

- Reynolds numbers divide organisms into two groups depending on size. This number identifies the predominant force to act on these two groups.
- The surface area and volume of a sphere do not increase at the same rate: surface area $\propto$ volume$^{\frac{2}{3}}$.
- Diffusion time limits the size a cell can reach and still function: diffusion time $\propto$ distance^2.
- Allometric growth allows for changes in various parts of an organism to account for increases in size.
- Larger animals have a lower basal metabolic rate: metabolic rate $\propto$ mass$^{\frac{3}{4}}$.