Cambridge University Press
978-1-108-42334-2 — Introductory Physics for Biological Scientists
Christof M. Aegerter
Excerpt
More Information

# 1 Physics as a Basis for Describing Biological Systems

You may be asking yourself, why a book on physics for biologists? Why do I as a biologist need to know anything about physics? The fact that many universities have a physics class as a requirement for life science students does not actually answer this question, but possibly makes you think that there might be a reason. We will try to elucidate this reason or these reasons, for there are several, in this introductory chapter, where we'll look at the history of biology as well as a few specific biological problems. The short summary of this answer is:

- Principles from physics and physical effects are of great importance in understanding how biological systems behave and which constraints evolution has to fulfill in shaping organisms.
- Experimental methods developed in physics have time and again revolutionized the practice of biological research and biology itself and are still doing so today.
- Physics is a prime example for scientific and quantitative thinking, which is the endeavor that turns scholarly research into science.

This introductory chapter will make all of these point more specific and give some detailed accounts of where physical principles can lead to a better understanding of biological systems or where physics-based methods have yielded novel insights into biology. Finally, we'll see how the methods of physics of quantitatively analyzing a problem and finding abstract toy models for real-life situations can give deep insights into how nature works as well as what science actually can (and cannot) achieve. Apart from these methods of a quantitative description of nature, the other main aspect of this book is to give you some of the basic physics principles behind biological phenomena – from the molecular to the organismal scales.

## 1.1 Physical Effects in Biological Systems

Physical effects can have a major influence on the shapes and forms, the development, and the behavior of biological systems. This is because animals, plants, and all living beings adapt to their environment by the means of evolution. This environment, however, is determined by the laws of physics – and these already existed before there were biochemical entities, let alone living beings. In the following, we shall briefly look at four examples, which we discuss in more detail in later chapters, in which physical circumstances require a certain kind of biological system. Such examples will continue

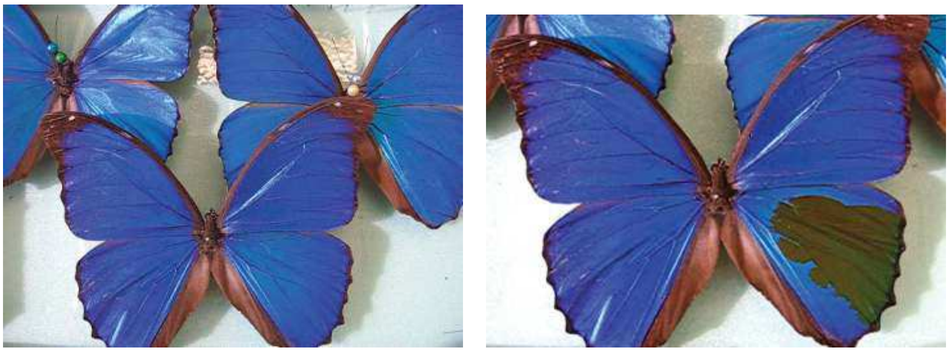

Figure 1.1 The butterfly *Morpho menelaus* captivates with its clear blue color (left). The origin of this coloration from a physical point of view is investigated in this section. When adding alcohol to the wing, it turns green and reverts to blue when the alcohol has evaporated (right). This indicates that the blue is not due to a pigment.

to concern us in the rest of the book, and we will use them to highlight various physical concepts.

### 1.1.1 The Coloration of Butterfly Wings

The South American butterfly *Morpho menelaus* is noted for its bright blue color (see Figure 1.1). However, blue pigments are extremely rare in nature, and also the blue color of *Morpho menelaus* is not caused by a pigment. We can make this plausible by placing a drop of alcohol on the wing. We see that the color changes to a clear green, which should not happen with a pigment. The effect is reversible. As soon as the alcohol evaporates, the butterfly is blue again. We get another hint on the color's origin if we repeat the same experiment with a drop of water. Here nothing happens; the water pearls off the surface of the wing. This is due to the greater surface tension of water and means that there are very small structures on the butterfly wing scales, which can be filled by alcohol, but not by water. You can read more on surface tension later in Section 7.5.

In order to see these structures, however, we need a microscope, one with a resolution that is better than the wavelength of the light, because the relevant structures are of roughly this size. Figure 1.2 shows a schematic of the nanometer-sized structures found on the cross-section of the scales on a wing of *Morpho menelaus* when imaging it with an electron microscope. In this cross-section, it is noticeable that layers of wing material (cuticular structures) form in highly ordered structures. These layers have a period, which corresponds approximately to a quarter of the wavelength of blue light (blue light has a wavelength of about 480 nanometers [nm], red one of 630 nm). What does this have to do with color?

When light impinges on the different layers, a part of this light is reflected and another part is transmitted. This is like a glass pane where we mainly see the reflected part of the light from inside at night and the transmitted part of the light from outside during the day. How much of the light passes through and how much is reflected depends on the refractive index difference of the two materials, and we will look at this quantitatively in Section 5.2.

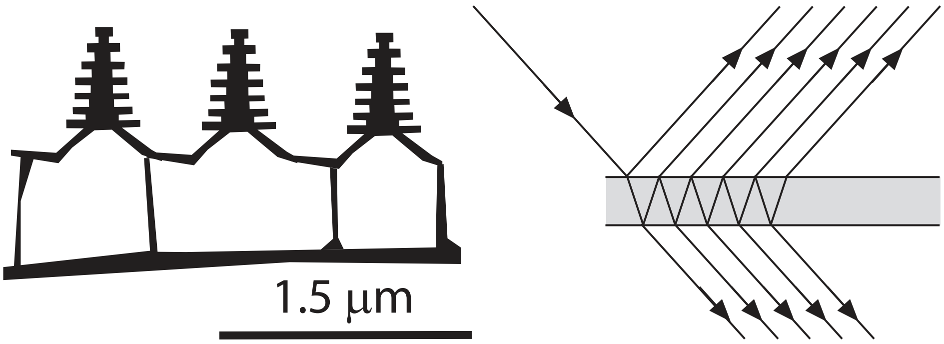


Figure 1.2 Left: Schematic illustration of the nano-structures found on the cross-section of the scales on a wing of *Morpho menelaus*. These terraced structures effectively form several thin layers of chitin approximately 100 nm thick and also roughly 100 nm apart. The reflection of light on these layers forms the secret of the blue color. Right: Light paths reflected on a thin layer have different lengths depending on which boundary they are reflected from. If this difference corresponds to half the wavelength of light, constructive interference occurs.

For a glass–air interface, one obtains that approximately 4% of the light is reflected. As it happens, this is similar on wing scales, since the refractive index of the cuticular structures is approximately equal to that of glass (about 1.5). The situation is shown schematically on the right of Figure 1.2 for one such layer.

The light that passes through the first boundary meets a second boundary at the other end of the layer, where it again can be either be reflected or transmitted. The light reflected there will finally arrive at the same position as the light that was reflected already at the first boundary – that is, at least if it is transmitted again at the upper boundary. Now we have the situation that two beams of light originating from the same place also arrive at the same place, but they have taken different paths for this. In this case, they can do something special due to the wave nature of the light: they can interfere. This means that depending on what the path-length difference between those two beams is, they can either intensify or even cancel out completely. To decide which of these happens, it is important whether the path-length difference is half of a wavelength (where the light beams will cancel out) or an entire wavelength (where the light beams will amplify). Therefore, depending on how thick the layer is (light reflected on the bottom will have passed through the layer twice), light of different colors, or wavelengths, will either cancel out or amplify. This can be seen not only in butterfly scales, but also directly in the coloring of a soap film. Soap films are very thin layers filled with water, and their color actually directly indicates their thickness. As we have said previously, the reflected part of the light is very small for a single layer; we need to stack several layers on top of each other to obtain an intense reflection. This will also lead to a reduction of the reflection for those colors that cancel each other out, and the reflection spectrum (or color dependence) will become increasingly sharp, appearing only at wavelengths, which are about four times the thickness of the layers. We will discuss in detail why this is so in Section 5.3.3. For the thicknesses of the butterfly structures, this is shown in Figure 1.3 for an increasing number of layers (up to 10) and the obtained sharp reflection band corresponds to the bright blue we observe.

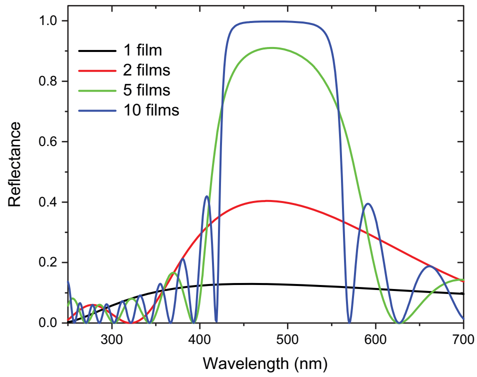


**Figure 1.3** When several layers are stacked one after the other, the effect of the individual layer is strengthened (left) (Filmetrics, 2017). This is shown here by the color dependence (or spectrum) of the reflection for different layers chitin with a thickness of 80 nm at a distance of 125 nm. Already with five layers, only a very narrowly limited area of wavelengths is well reflected. These layers and their spacing correspond well to those observed on a butterfly wing scale, and the observed peak in reflection corresponds to a blue color. On the right, a simulation of a stack of 10 layers is shown, once when air is filling the voids between the layers and once when this is filled by ethanol. As can be seen, the peak in reflection shifts in wavelength to around 530 nm, corresponding to green.

But why does the wing turn green when alcohol is added? As previously mentioned, the alcohol wets the nano-structures of the butterfly wing. This means that we no longer have a structure consisting of layers of air and cuticular structures, but one in which alcohol and cuticular structures alternate. Since alcohol has a refractive index of about 1.3, the path difference of the differently reflected light beams changes (it is lengthened relative to the wavelength). This implies that the distance between the layers no longer corresponds to the wavelength of blue light, but to that of green light (see Figure 1.3, on the right).

This principle of coloring is, however, by no means limited to butterflies. Almost all shades of blue in nature and many shades of green are made by such structural effects, e.g., all colors of peacock feathers, the green of the feathers of ducks, the colors of the armor of many beetles or the colors of the scales of many fish, and so on. Due to the fact that the path-length actually changes when the angle of reflection of the light changes, you can easily check which colors are likely to be so iridescent. If the shade of the color changes with viewing angle, the origin of this color is probably due to interference.

It is even possible that animals control their coloring by controlling the corresponding nano-structures themselves. This leads, for example, to the adaptability of lizards, chameleons, and squid, which can be very impressive.

### 1.1.2 Navigation of Ants

Let us take the desert ant *Cataglyphis* as another example. In an impressive series of experiments over several decades, Rüdiger Wehner from the former Zoological Institute at the University of Zurich has extensively studied the navigation behavior of these insects and described the various navigation mechanisms in detail. Desert ants are well suited as an

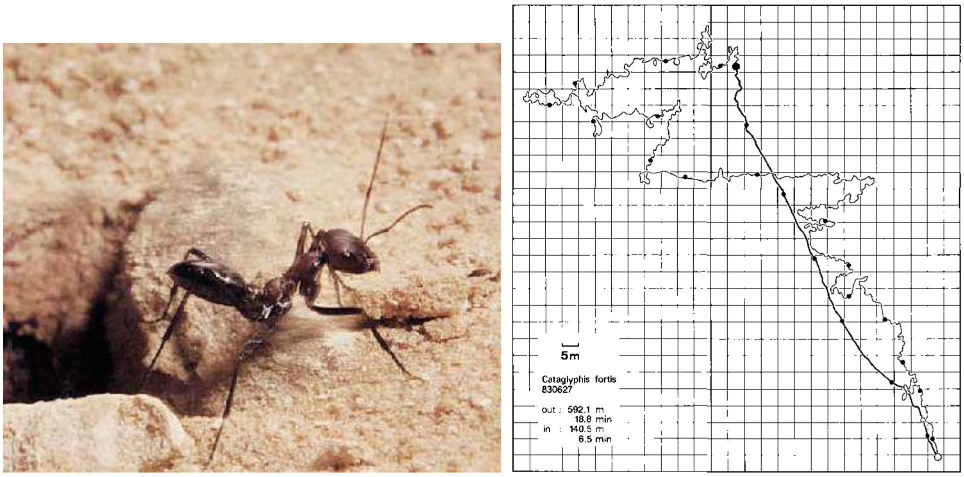


**Figure 1.4** Left: The desert ant *Cataglyphis*. Right: The path of a *Cataglyphis* to the food source and back again. Beginning at nest (open circles), the ant looks for food and goes on a tortuous path until it finds the food source (filled circles). From this point onward, it directly moves toward the nest and goes straight back. Figures from Wehner (1982, 2000); Wehner and Wehner (1990), used with permission from EMH Swiss Medical Publishers Ltd and Taylor & Francis Ltd, respectively.

experimental system because, unlike bees, they move on a surface and are easy to observe in their natural habitat (the experiments were carried out in Algeria and Namibia), i.e., their paths can be recorded very well (see Figure 1.4 on the right).

For example, Rüdiger Wehner and his coworkers put “sunglasses” on the ants, which consisted of a resin that predominantly filtered out the blue to ultraviolet light from the spectrum of the white light coming from the sun. These ants with “sunglasses” no longer found their way home. A microscope image of an ant’s eye with and without this filter is shown in Figure 1.5. There, it can also be seen that the filters can be removed again, showing that one can examine whether the effect is reversible, i.e., whether the ants find their way home again when the sunglasses are removed (which they do).

The experiments with the ants wearing “sunglasses” are summarized on the right side of Figure 1.5. For very many different ants, the directions of departure after they have found the food source are shown (see also Figure 1.4). The upward direction in the graph represents the direct line to the nest. On the right side, the paths chosen by ants without filters are shown, while on the left side those with filters are shown. As is clearly visible, almost all ants without filters reliably find their way home, whereas most of the ants with filters get lost.

What is so special about blue or ultraviolet (UV) light? Well, the sky is blue (and actually also ultraviolet, which we cannot see), so maybe it has something to do with some pattern in the sky that we normally cannot observe, but the ants can. As can be seen in Figure 1.6, the light from the sky is polarized. This means that the electromagnetic waves that make up the light have a certain direction of vibration, depending on where they come from in the sky. Polarization will be discussed in greater detail in Chapter 5 concerned with optics. At the

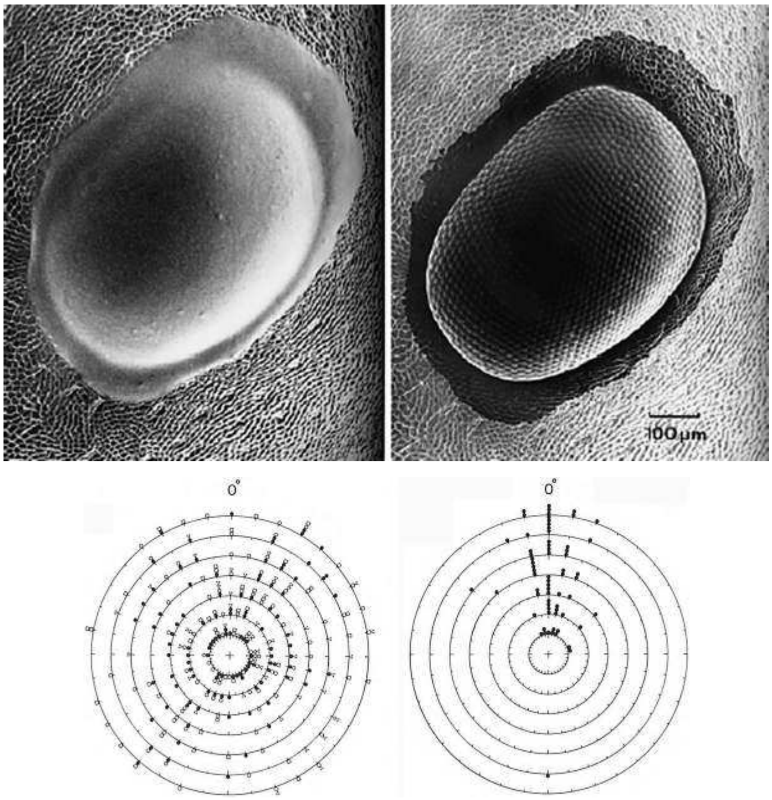


Figure 1.5 Top: Ant's eye with and without "sunglasses." Bottom: Direction of the ants after finding food relative to the direction toward the nest (0 degrees). The ants with "sunglasses" (green) do not find their way home anymore. Figures from Wehner (1982, 2000), used with permission from EMH Swiss Medical Publishers Ltd.

moment, we only need to know that the polarization corresponds to a certain direction and that it does have a certain pattern in the sky. If one makes the experiment in Figure 1.6 at different times, one can see that the polarization pattern changes together with the position of the sun, but is actually constant relative to the sun. Specifically, the sky is always polarized in the direction that makes a right angle to the direction pointing toward the sun.

To find out why this could be so, we carry out an experiment. Since we have no sky and no sun in our laboratory, we illuminate a water tank from one side. We now add scatterers to the water, for instance add a few drops of milk to a bucket, and observe two things. First, the transmitted light becomes reddish and increasingly so with increasing scatterer concentration, and second, the scattered light, i.e., the light at an angle to the transmitted light, becomes blueish. Again this increases with increasing scatterer density. You can try this at home by shining white light into a glass of water with a few drops of milk dissolved in it. If you look at the glass, such that you do not have the light source in sight (preferably it is at a right angle to where you look from), the water appears blue. If you look directly at the light source though the glass, the light appears red or orange. With this, we have

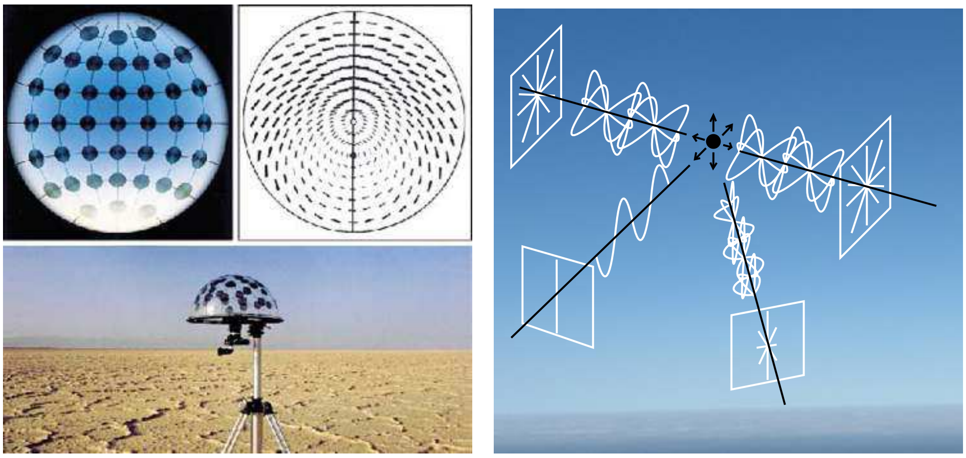

Figure 1.6 Picture of the sky with a fish-eye lens such that the whole sky is imaged (below). At different points, polarizers are attached which can indicate the direction of the polarization (upper left). Top right: The polarization pattern of the sky when the sun is at an angle of about 60 degrees. The length of the bars indicates the degree of polarization, and the direction of the lines is that of the polarization. On the far right: Schematic representation of the polarization of the light by scattering. The light is completely polarized only in the direction perpendicular to the incident light. This leads to the polarization pattern of the light in the sky. Figure on the left from Wehner (1994, 2000), used with permission from EMH Swiss Medical Publishers Ltd.

made an experimental model for the sky in the color of the light that is scattered and at the same time we have a model for the sunset in the transmitted light that looks reddish. The white, incident light contains all the wavelengths of the visible spectrum, but the blue portion, which corresponds to shorter wavelengths, is scattered more strongly, such that the scattered light appears blue to us, just as the sky appears blue. The transmitted light lacks the blue component and therefore appears red. But we actually wanted to explain the polarization pattern with our experiment. For this purpose, take a polaroid filter (or polarizing filter), as you may have in your sunglasses at home, and hold it in front of the direct transmitted light. While the light will become a little dimmer due to the absorption of the filter, there will be no change if you turn the filter at varying angles. The transmitted light is not polarized. If, on the other hand, you hold the filter in front of the scattered light (the one that appears blue), rotating the filter will show large variations in intensity, with the glass becoming dark after turning the filter by 90 degrees. The physical interpretation is that the light that is scattered at right angles must be fully polarized. The same thing happens in the sky. Here, the air molecules (but also dust particles and other impurities) scatter the sunlight. This means that there is light that hits our eyes from other directions than the sun because it has been scattered. If this scattering is at a right angle, then the light reaching us is completely polarized (see Figure 1.6, far right). Therefore, the direction of the polarization is at a right angle to the direction of the sun, as we have seen. It follows that a *Cataglyphis* can read the direction to the sun on any part of the sky if it can determine the polarization of the sky. However, this light needs to be scattered, and this only happens for blue or UV light, i.e., this signal is only available in blue (or UV) light. So if you remove

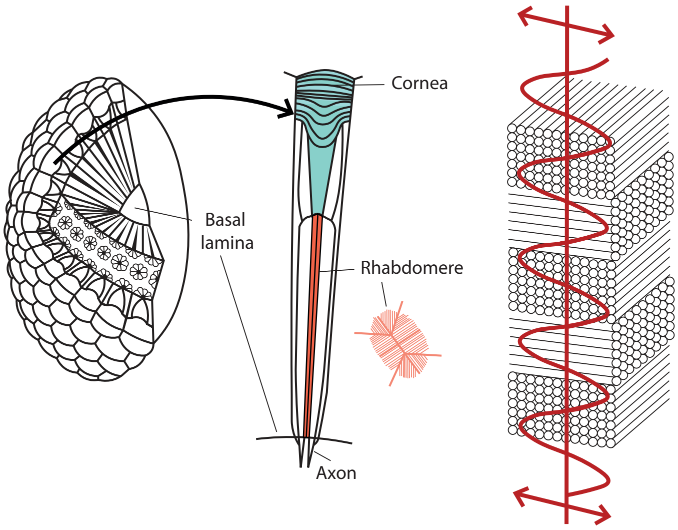


Figure 1.7 The structure of an ant's eye. Inside the facet eye are the visual cells. The light-sensitive part (the rhabdom) has a special nano-structure, which arranges the light-absorbing rhodopsin in two perpendicular directions. This is done in the microvilli (right) forming the rhabdomeres. The mutually perpendicular parts are antagonistically transmitted into the brain so that a polarization measurement is carried out. The size of the structures is adapted to the wavelength of blue to ultraviolet light in order to obtain the largest possible signal by constructive interference.

the blue light (filter it out with "sunglasses"), the *Cataglyphis* is missing the compass and it does not find its way home anymore.

There remains the question how the ants can see this polarization pattern of the sky. We humans cannot do this without technical aids (the Vikings used sunstones to navigate via the polarized sky). For this purpose, we look at the structure of the ant eye more closely, as shown in Figure 1.7. In the facet eye of the ant, the light receptor molecules are present in ordered structures (the microvilli). As a result, the molecules can only be excited by one direction of oscillation of the light, and thus the degree of polarization and its direction can be seen by the eyes. Since, in particular, the blue and UV light shows a polarization, the distance of the arrangement of microvilli actually corresponds precisely to the wavelength of UV light. This implies that only the blue and UV light reaches the receptor molecules. This is precisely the same interference effect as we have just seen in the butterfly wings.

### 1.1.3 Propagation of Nerve Signals

Whenever we interact with the world, we use our nervous system, be it to hear, see, or use muscles. Signals from our sensory organs are translated to nerve signals and action signals from our brain are transported to the muscles via nerve cells. All of these signals are transported in a fraction of a second. How these electrical signals are transported in the nervous system is something that we will study in Chapter 9. In doing so, we will deal with the conduction of electrical currents in general, but in the course of this, we will see

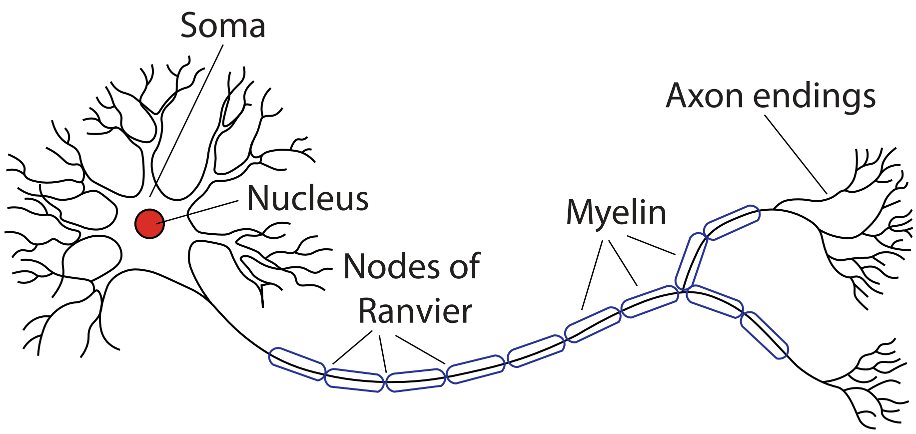


**Figure 1.8** Schematic representation of a nerve cell with a myelinated axon for better nerve conduction.

that that if the axons were used as a normal cable, they would not be able to transport the nerve signals with the necessary speed. In fact, it would take several seconds for your brain to send a signal to your hands and reaction times would be very different. In this context, we will look at two different solutions that nature has found for this. One of them is indicated in the schematic structure of a nerve cell shown in Figure 1.8: our treatment of electrical currents will show that a thicker insulation layer around the axon of the nerve cells will result in a much faster transport. This solution is found in many neural systems where the axons are surrounded by a myelin sheath produced by the Schwann cells. The other solution of nature is to use voltage-dependent ion channels for transporting charges in and out of neurons.

### 1.1.4 Bone Structure and Allometric Scaling Laws

In Section 2.3, we will deal with scaling laws, i.e., the description of how certain properties of an object depend on its size. Such effects are also very frequent in nature and are of great importance in evolution. For example, you may be interested to know how large a land animal can actually become. This depends, among other things, on how strong the bones have to be in order to carry the animal's weight. Since the load-bearing capacity of the bones depends on their cross-sectional area and hence the cross-sectional area of the animal's legs rather than its weight; the thigh bones of larger animals have to become ever more massive in order to carry the load (see Figure 1.9 on the left). The limiting size is then given by the fact that a leg cannot consist solely of bone or cannot be wider than it is long.

On the other hand, size can also be an advantage. The energy consumption of an animal (its metabolic rate) increases less rapidly with the size than the weight. This is due to the fact that a large part of the energy consumption is used to maintain the body temperature since body heat is constantly lost. This heat loss happens through the surface, as we will see in Section 8.3.6 on heat conduction. Thus metabolic rate is proportional to the body surface.

Cambridge University Press
978-1-108-42334-2 — Introductory Physics for Biological Scientists
Christof M. Aegerter
Excerpt
More Information



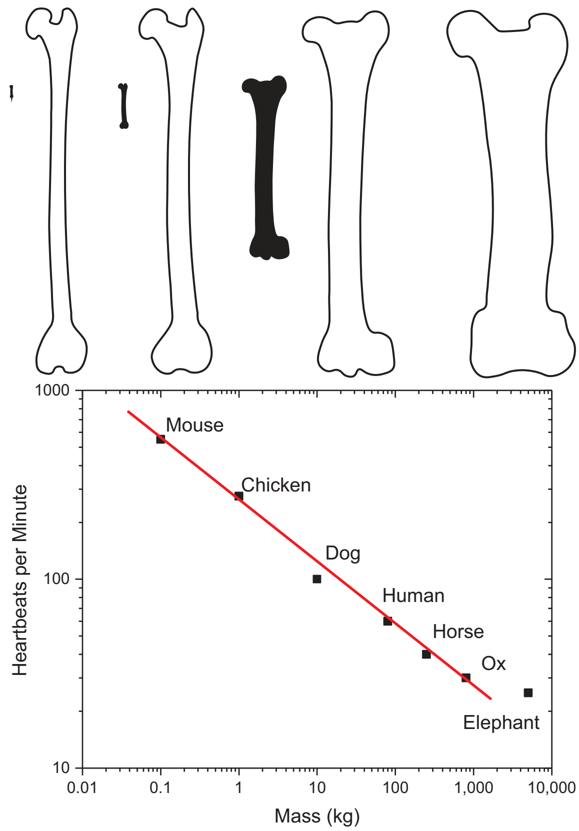


**Figure 1.9** Top: Thigh bones of animals of different sizes ranging from mouse (left) to fox, horse, and elephant (right) spanning several orders of magnitude in weight. More massive animals have more massive bones due to the nonlinear increase in weight relative to bone strength. Bottom: The heart rate of different animals depending on their mass. Small animals have a much higher metabolic turnover. Data are from www.msdvetmanual.com/appendixes/reference-guides/resting-heart-rates.

Because the relative energy consumption decreases with size, predominantly large animals are found in the vicinity of the poles. The exceptions, which normally confirm the rule, are then sufficiently well-insulated animals, i.e., those with a relatively thick coat. For fun, one can calculate, for example, that a mouse, which has the same energy consumption per kilogram of body weight as a cow, should have a coat of 20 centimeters (cm) thickness in order to maintain its body temperature in our latitudes. Turning this around, a cow with the same metabolic rate per kilogram as a mouse would have a body temperature in excess of 100°C, i.e., its blood would be boiling.

The fact that the relative energy consumption depends on the size also has the direct effect that the heart rate decreases with increasing mass. After all, the heat lost in metabolic rate comes from the combustion of oxygen that is transported in the blood. This dependence of heart rate on mass can also be empirically verified, as shown in bottom graph in Figure 1.9, where the number of heartbeats per minute is plotted for different animals.