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**Physics & Education -
Perspectives from Condensed Matter and Biophysics**

PT 3/2022

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Physics education has in the past often been centred either on technological applications or the very large or small scales of the universe. As a middle ground, everyday phenomena, biological or soft matter systems are however also very useful to particularly stimulate students without an innate interest in Physics. In this presentation I will show how simple experiments on everyday phenomena can excite children for the subject of Physics. In addition, I will show how a standard Physics curriculum can be adjusted to cover the same topics with an emphasis on living matter and biological phenomena. This is not only useful for introductory lectures for life science students, but can also be used in high schools in order to increase the level of interest of the students by connecting the subject to their world.

Physics is often perceived as dry and technical at least partly due to how it is taught given examples that can be treated exactly using abstractions that take into account the essence of a phenomenon. While this abstraction from

the actual system is one of the core strengths of Physics, such problems often do not speak to the imagination of students. Thus while treating the 'big questions' of Particle and Astro-Physics is useful to show the extent of the physical understanding from the smallest to the largest structures, which gets those students motivated that usually end up studying Physics, there is a large class of students that may not be excited by the subject in this way. Therefore, in order to get students interested, while still showing the strengths of physical abstractions, it is very useful to use real world examples, often from biological systems to grab the students attention and then explain these phenomena using the abstraction of Physics. Basing the Physics content in a context that is relevant to the students then also leads to an increased retention of the subject [1].

While there is no type of example that will be of interest to everyone, it is important to use many different types of hooks to get the students attention and have such examples present for many different Physics concepts. This ranges

from questions of energy production, which are of particular interest at the moment, to sustainability, where the basis of climate change is thoroughly based on Physics, to debunking conspiracy theories concerning the moon landing using ballistic analysis of the dust of the lunar rover [2]. One aspect, which is of particular interest in reducing gender imbalances in Physics is the use of biological examples [3, 4]. Therefore, I will discuss two such examples in detail below. However, I would like to begin with a set of examples that shows that an understanding of Physics can also be used to see beautiful structures in the world around us that are perceived as inherently beautiful, such as spectral colour in rainbows and related phenomena. However, understand-



ing what gives rise to these phenomena also means that one knows in what circumstances they are likely to appear such that one can keep an eye out for them. In the example of a rainbow, whenever the sun is visible when it rains, a look away from the sun often reveals a rainbow. Knowing that there is always a secondary, faint and reversed rainbow about 10 degrees further out makes that one can almost invariably also perceive the secondary if the primary is seen. In Fig. 1 below, there are four less well-known examples of such structures, mostly based in optics, that appear relatively often, but are mostly overlooked due to the fact that one does not pay attention.

On the side of biological examples, the concept of interference can be introduced not only using the double slit, or the working principle of noise reducing headsets (a real-world example with a close connection to most students), but also with the colouration of many insects. As an example of this, the blue of the butterfly morpho menelaus (see Fig. 2) with its striking blue colour is highly instructive. In order to show that the colouration originates from something else than a pigment, one can add a drop of ethanol to the butterfly wing, which changes its colour to green [4]. This reverts when the ethanol evaporates. The reason behind this is the layered structures on the scales of the butterfly, whose distance and refractive index contrast lead to constructive interference in reflection for blue light [5, 6]. Adding ethanol changes the refractive index contrast, thus changing the condition for constructive interference. Knowing the layer thicknesses and distances, as well as the refractive index, the reflectivity can be well modelled as a Bragg-mirror, where the demonstration can actually be explained quantitatively with just some little abstractions.

Fig. 1: Examples of beautiful structures that can be observed much more easily when understanding the physical basis of their appearance. Top left: When only a thin layer of water freezes on a pool or a lake, i.e. when the temperature is not too far below freezing, one can observe the freezing front that shows a self-similar structure of freezing arms akin to an 'ideal snowflake' magnified to a length scale of about 10 cm as in the picture shown. Top right: When street signs, particularly white ones, have been re-painted and the sun is high in the sky, an almost circular 'glassbow' can be observed when the sun is in the back. This is because to increase reflection of the street signs, small glass spheres are added to the paint as retro-reflectors to increase the reflectivity in the direct back-direction, whatever the direction of illumination. Thus with the sun in the back, only a small angular range of about 25° is illuminated with reflected light and the dispersion of glass leads to a dependence of the maximum angle on the colour. This is basically exactly the same as a rainbow, except that glass spheres take the role of reflector rather than spheres of water and due to their higher index of refraction, the angle is smaller, such that a full circle is more easily observed. Bottom left: A similar circular spectrum can be observed when watching a large field of fog with the sun in the back. In contrast to the above example, here the angular opening of the spectrum is due to diffraction of the light at the small (roughly $50\ \mu\text{m}$ sized) droplets of fog. From the angular opening of the spectral ring, the size of the fog droplets can thus be determined. Bottom right: In situations when there is rain, but also a small haze, raindrops reflect light in the limited angular range known from a rainbow. Due to the haze, the incoming light from the sun is however not strictly parallel, but distributed over a range large enough to mix the different colours of the rainbow resulting in a 'white rainbow'.

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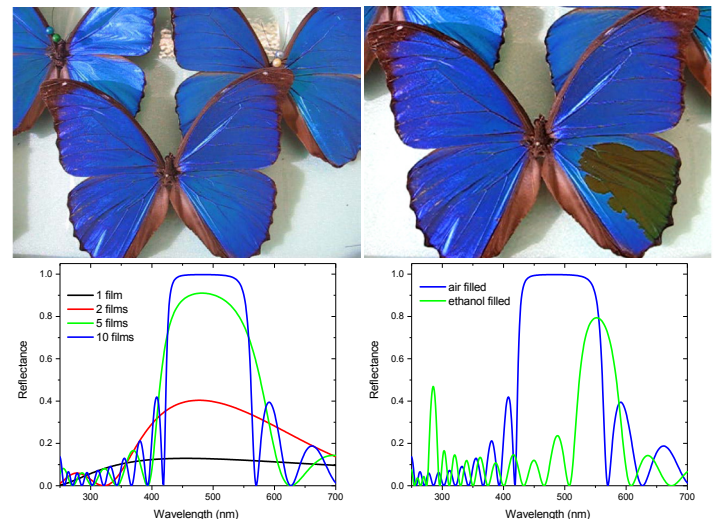


Fig. 2: Structural colours as an example of optical interference appearing in biology. The blue colour of the butterfly morpho menelaus is not due to a pigment as can be shown by the experiment in the top two panels, where some ethanol is added to the butterfly wing [4]. The striking blue colour is changed to a green, which reverses to blue after the ethanol is evaporated. The blue colour can be explained by the constructive interference of light from reflections on small lamellae roughly $80\ \text{nm}$ thick and $100\ \text{nm}$ apart that happen predominantly for blue light due to the path length difference [5]. Modelling this as a Bragg mirror of 2 to 10 layers (bottom left) shows a reflection predominantly in the blue. Filling the spaces between the layers with ethanol and performing the same model calculation shows that the maximum now shifts to the green (bottom right) [4].

This principle of structural colouration is very widespread in nature and not just limited to insects, but also observed in birds [7] and even colour-changing lizards, where the colour change is actually due to the changing of the spacing of refractive structures [8]. These principles can even be used to create colours that do not contain any pigments [9].

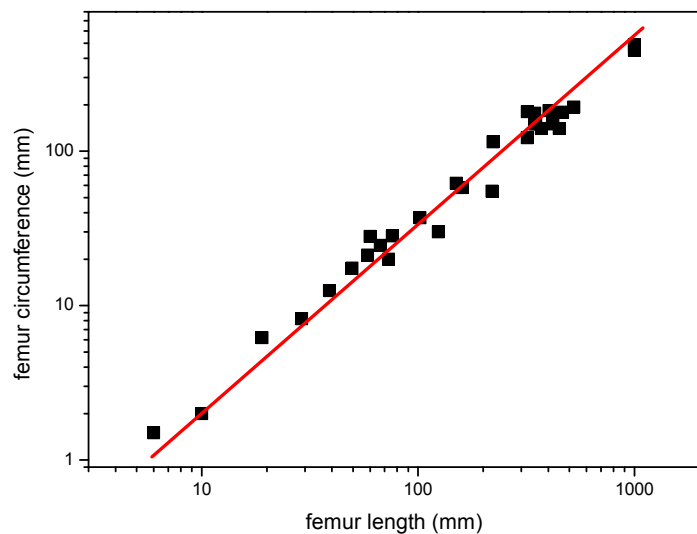
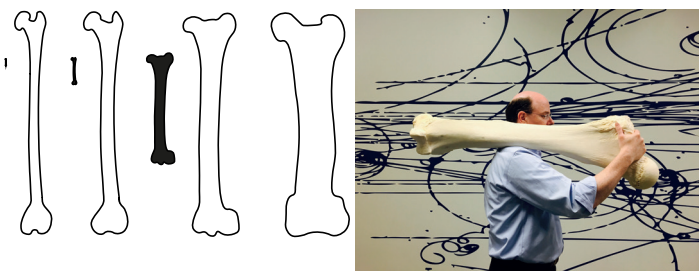


Fig. 3: The scaling of the structure of bones gives insights on the mechanical loads and stability of biological structures. Larger animals therefore have much sturdier bones than smaller animals as can be seen from comparing different bones drawn to the same length (top left). This is particularly striking in elephant bones, which make for an impressive demonstration (top right). Quantitatively, the scaling can be explained by the breaking due to buckling or twisting, which both have the same scaling law of the diameter growing with the length to the $5/4^{\text{th}}$ power [4]. This is in contrast to the argument made by Galilei, which argues with compressional or tensile strength that would lead to a power law with an exponent of $3/2$ [10].

As a second example, consider the thigh bones of different animals shown in Fig. 3, top left, when they are drawn to the same length. As the animal that the bones come from get bigger, the width to length ratio increases. This is particularly striking when comparing for instance the bones of an elephant (Fig. 3 top right) to that of a cat. This example was actually already known to Galilei and is discussed in his (second) dialogues [10]. There, he argues that compressional and tensile strength scales with the cross-sectional area of the bone, whereas the weight scales with the volume of the animal and thus with the cube of the bone's length. Taking together data from many different animals, this can actually be checked quantitatively, indeed showing a power-law dependence of the bone diameter on the bone length given by $d \propto L^{5/4}$ (Fig. 3 bottom). However, this is different from the expectation due to Galilei's argument, which would have been $d \propto L^{3/2}$. A more careful analysis [4] shows

that the load due to buckling, which leads to the breaking of bones is in fact limiting the bones' size and does lead to the observed scaling behaviour. Incidentally, the breaking due to twisting gives the same scaling.

This example shows several things apart from mechanical principles at the heart of this argument. For one, the usefulness of scaling arguments in obtaining physical laws and how this can be made quantitative. Moreover, it shows that even the great scientists of the past, such as Galilei can occasionally be not quite correct, but that this can be observed by empirical data and does not diminish their stature. Finally, one can then discuss that these bone structures are not in fact genetically determined but the growth of bones is in fact dependent on mechanical forces [11], which in a self-regulatory way leads to the bones having the ideal structure to carry the load they are exposed to. This is known as Wolff's law and for instance explains why bones are hollow inside as there are no mechanical stresses along the neutral fibre, such that bone is degraded in these places. Similarly, this shows why there is no such scaling of bone size in fish as they live in a buoyant environment [12]. Finally, in anthropological studies, it forms the basis of determining which of our humanoid ancestors started walking on two legs, as the correspondingly different mechanical load leads to different bone structures [11]. In spite of its wide range use and long history, its biochemical basis is still actively studied [13–16].

In conclusion, the teaching of Physics can benefit greatly by anchoring the concepts covered in real world examples that have a direct connection to the students' experience. Of particular interest here can be biological examples, which are of interest to many students that are not too keen on technical examples. This does however not mean that solely such examples should be used, but in order to keep the interests of a large cohort of students, it should pay out to broaden our usage of examples, while not forgetting the ones that have been established as very useful in the past.

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