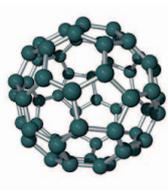




Football (approximately 22 cm)



carbon 60 (0.7 nm)  
*R. Drautz*

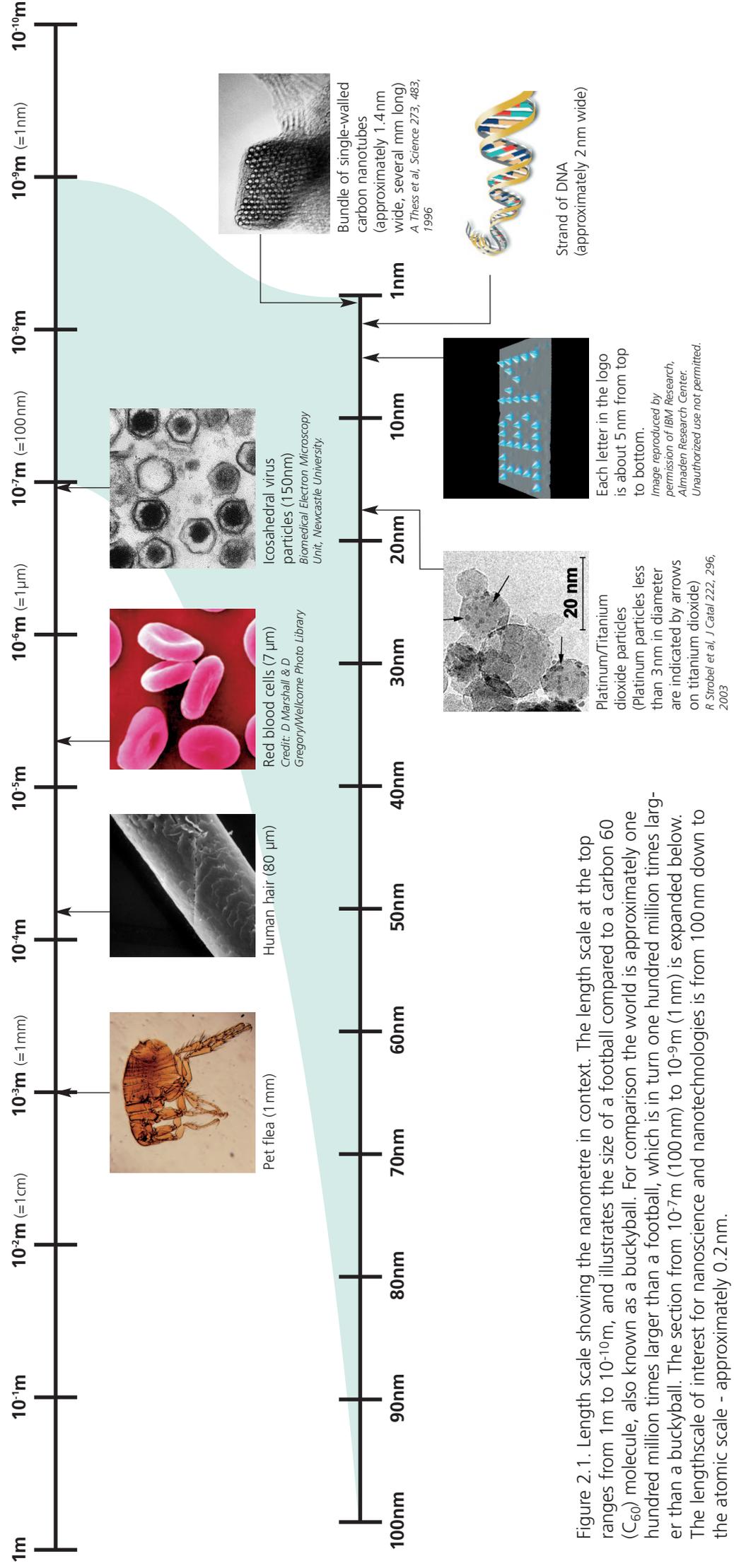


Figure 2.1. Length scale showing the nanometre in context. The length scale at the top ranges from 1 m to 10<sup>-10</sup>m, and illustrates the size of a football compared to a carbon 60 (C<sub>60</sub>) molecule, also known as a buckyball. For comparison the world is approximately one hundred million times larger than a football, which is in turn one hundred million times larger than a buckyball. The section from 10<sup>-7</sup>m (100nm) to 10<sup>-9</sup>m (1 nm) is expanded below. The lengthscale of interest for nanoscience and nanotechnologies is from 100nm down to the atomic scale - approximately 0.2 nm.

## 2 What are nanoscience and nanotechnologies?

1 The first term of reference of this study was to define what is meant by nanoscience and nanotechnology. However, as the term 'nanotechnology' encompasses such a wide range of tools, techniques and potential applications, we have found it more appropriate to refer to 'nanotechnologies'. Our definitions were developed through consultation at our workshop meeting with scientists and engineers and through comments received through the study website.

2 Although there is no sharp distinction between them, in this report we differentiate between nanoscience and nanotechnologies as follows.

### *Box 2.1 Definitions of nanoscience and nanotechnologies*

**Nanoscience** is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

**Nanotechnologies** are the design, characterisation, production and application of structures, devices and systems by controlling shape and size at nanometre scale.

3 The prefix 'nano' is derived from the Greek word for dwarf. One nanometre (nm) is equal to one-billionth of a metre,  $10^{-9}$ m. A human hair is approximately 80,000nm wide, and a red blood cell approximately 7000nm wide. Figure 2.1 shows the nanometre in context. Atoms are below a nanometre in size, whereas many molecules, including some proteins, range from a nanometre upwards.

4 The conceptual underpinnings of nanotechnologies were first laid out in 1959 by the physicist Richard Feynman, in his lecture 'There's plenty of room at the bottom' (Feynman 1959). Feynman explored the possibility of manipulating material at the scale of individual atoms and molecules, imagining the whole of the Encyclopaedia Britannica written on the head of a pin and foreseeing the increasing ability to examine and control matter at the nanoscale.

5 The term 'nanotechnology' was not used until 1974, when Norio Taniguchi, a researcher at the University of Tokyo, Japan used it to refer to the ability to engineer materials precisely at the nanometre level (Taniguchi 1974). The primary driving force for miniaturisation at that time came from the electronics industry, which aimed to develop tools to create smaller (and therefore faster and more complex) electronic devices on silicon chips. Indeed, at IBM in the USA a

technique called electron beam lithography was used to create nanostructures and devices as small as 40–70nm in the early 1970s.

6 The size range that holds so much interest is typically from 100nm down to the atomic level (approximately 0.2 nm), because it is in this range (particularly at the lower end) that materials can have different or enhanced properties compared with the same materials at a larger size. The two main reasons for this change in behaviour are an increased relative surface area, and the dominance of quantum effects. An increase in surface area (per unit mass) will result in a corresponding increase in chemical reactivity, making some nanomaterials useful as catalysts to improve the efficiency of fuel cells and batteries. As the size of matter is reduced to tens of nanometres or less, quantum effects can begin to play a role, and these can significantly change a material's optical, magnetic or electrical properties. In some cases, size-dependent properties have been exploited for centuries. For example, gold and silver nanoparticles (particles of diameter less than 100 nm; see section 3.2) have been used as coloured pigments in stained glass and ceramics since the 10th century AD (Erhardt 2003). Depending on their size, gold particles can appear red, blue or gold in colour. The challenge for the ancient (al)chemists was to make all nanoparticles the same size (and hence the same colour), and the production of single-size nanoparticles is still a challenge today.

7 At the larger end of our size range, other effects such as surface tension or 'stickiness' are important, which also affect physical and chemical properties. For liquid or gaseous environments Brownian motion, which describes the random movement of larger particles or molecules owing to their bombardment by smaller molecules and atoms, is also important. This effect makes control of individual atoms or molecules in these environments extremely difficult.

8 Nanoscience is concerned with understanding these effects and their influence on the properties of material. Nanotechnologies aim to exploit these effects to create structures, devices and systems with novel properties and functions due to their size.

9 In some senses, nanoscience and nanotechnologies are not new. Many chemicals and chemical processes have nanoscale features – for example, chemists have been making polymers, large molecules made up of tiny nanoscale subunits, for many decades. Nanotechnologies have been used to create the tiny features on computer chips for the past 20 years. The natural world also contains many examples of nanoscale structures, from milk (a nanoscale colloid) to sophisticated nanosized and nanostructured proteins

that control a range of biological activities, such as flexing muscles, releasing energy and repairing cells. Nanoparticles occur naturally, and have been created for thousands of years as the products of combustion and food cooking.

10 However, it is only in recent years that sophisticated tools have been developed to investigate and manipulate matter at the nanoscale, which have greatly affected our understanding of the nanoscale world. A major step in this direction was the invention of the scanning tunnelling microscope (STM) in 1982, and the atomic force microscope (AFM) in 1986. These tools use nanoscale probes to image a surface with atomic resolution, and are also capable of picking up, sliding or dragging atoms or molecules around on surfaces to build rudimentary nanostructures. These tools are further described in Box 3.1. In a now famous experiment in 1990, Don Eigler and Erhard Schweizer at IBM moved xenon atoms around on a nickel surface to write the company logo (Eigler and Schweizer 1990) (see Figure 2.1), a laborious process which took a whole day under well-controlled conditions. The use of these tools is not restricted to engineering, but has been adopted across a range of disciplines. AFM, for example, is routinely used to study biological molecules such as proteins.

11 The technique used by Eigler and Schweizer is only one in the range of ways used to manipulate and produce nanomaterials, commonly categorised as either 'top-down' or 'bottom-up'. 'Top-down' techniques involve starting with a block of material, and etching or milling it down to the desired shape, whereas 'bottom-

up' involves the assembly of smaller sub-units (atoms or molecules) to make a larger structure. The main challenge for top-down manufacture is the creation of increasingly small structures with sufficient accuracy, whereas for bottom-up manufacture, it is to make structures large enough, and of sufficient quality, to be of use as materials. These two methods have evolved separately and have now reached the point where the best achievable feature size for each technique is approximately the same, leading to novel hybrid ways of manufacture.

12 Nanotechnologies can be regarded as genuinely interdisciplinary, and have prompted the collaboration between researchers in previously disparate areas to share knowledge, tools and techniques. An understanding of the physics and chemistry of matter and processes at the nanoscale is relevant to all scientific disciplines, from chemistry and physics to biology, engineering and medicine. Indeed, it could be argued that evolutionary developments in each of these fields towards investigating matter at increasingly small size scales has now come to be known as 'nanotechnology'.

13 It will be seen in Chapters 3 and 4 that nanoscience and nanotechnologies encompass a broad and varied range of materials, tools and approaches. Apart from a characteristic size scale, it is difficult to find commonalities between them. We should not therefore expect them to have the same the same health, environmental, safety, social or ethical implications or require the same approach to regulation; these issues are dealt with in Chapters 5 – 8.