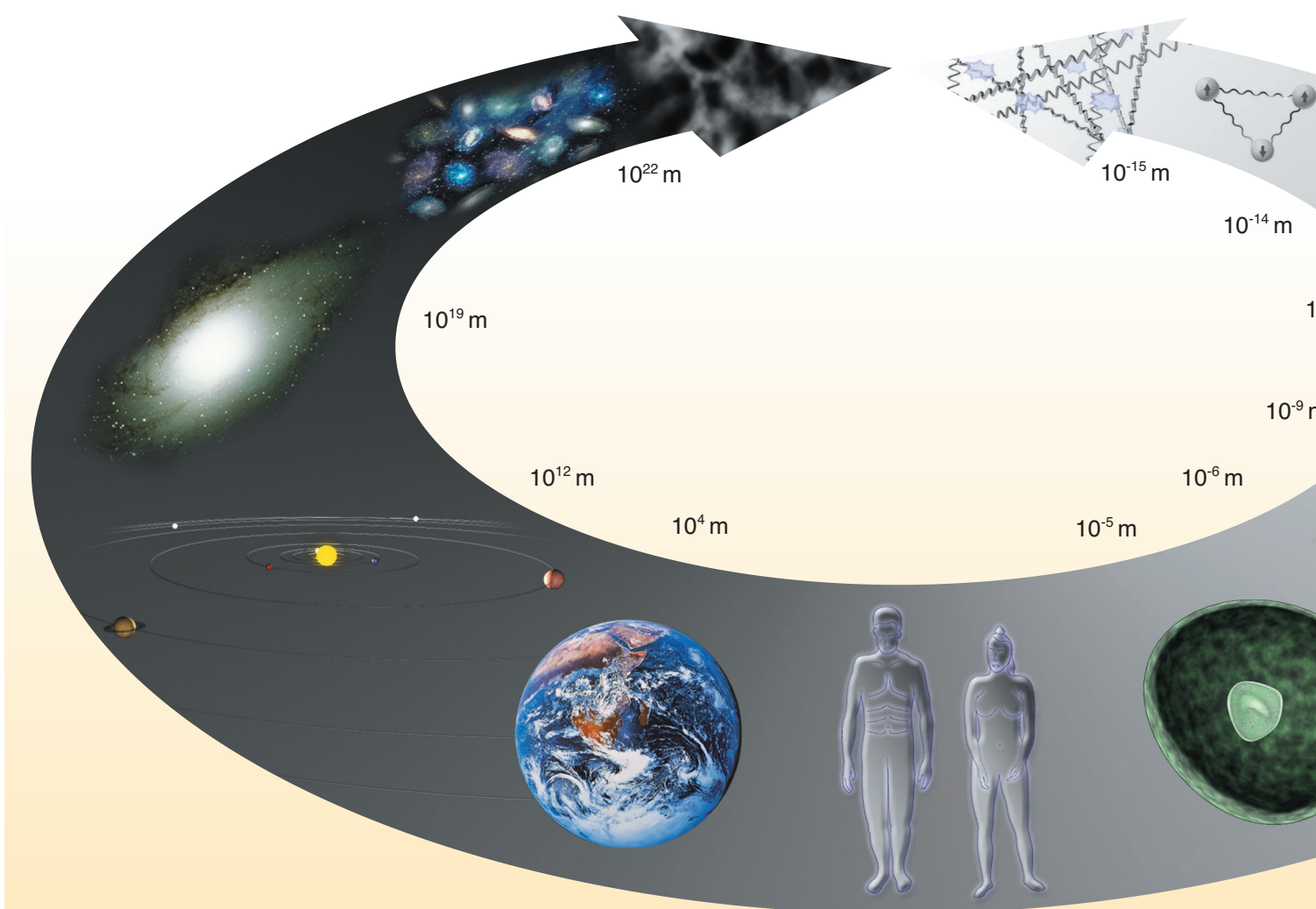


1. The size of things

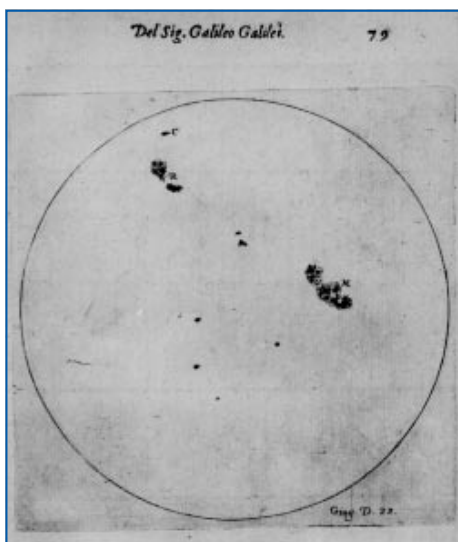
From the immensity of space to the invisible world of the nucleus

Not so many generations ago, our ancestors would very likely have expressed the smallness of something by comparing it with a speck of dust floating in a shaft of sunlight. If they wanted to convey vastness, they might have made a comparison with a mountain, or even, if they were a little more sophisticated, with the Earth itself. If they were very learned, they might even have conjured up something a little larger: the sphere on which the 'fixed stars' were attached.

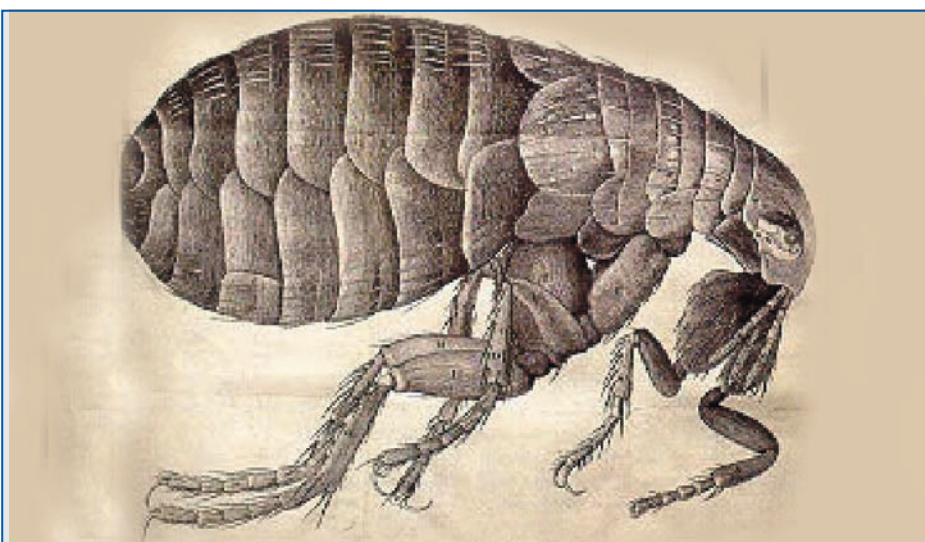
Today, our sense of the large and the small has expanded far beyond the comprehension of our forebears. This is due, at least in part, to the imaginative use of pieces of curved glass: the invention of the microscope and telescope. Our modern



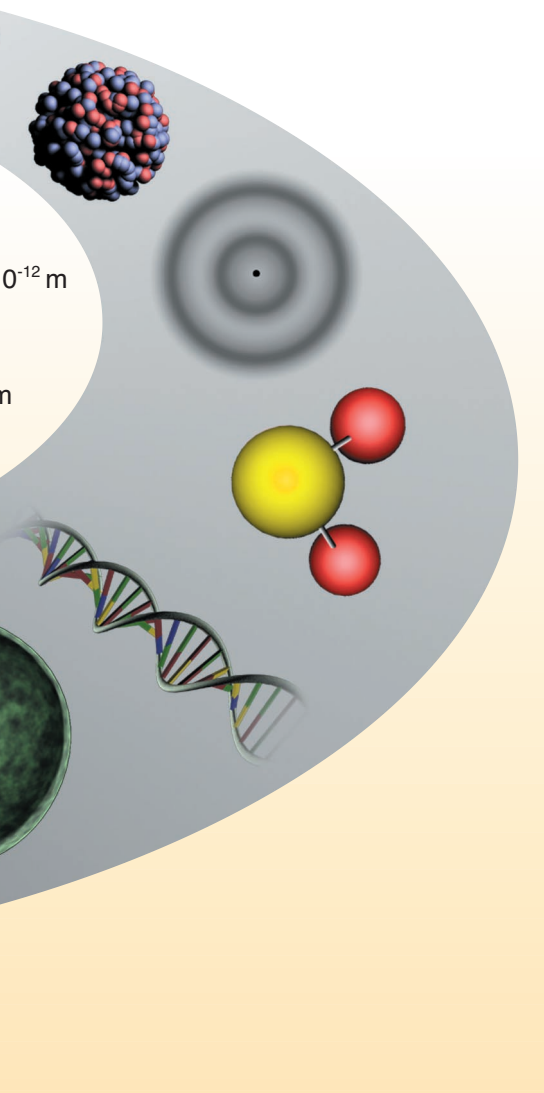
People stand midway between the immensity of the Universe and the unimaginable smallness of atomic nuclei and their building blocks. Yet what happened long ago involving these tiniest of objects set the entire Universe on its course. Today, we cannot understand the Universe as a whole without understanding Nature on the smallest scale. That is why the largest and the smallest meet in this picture.



Galileo, using his telescope in around 1610, took the first steps beyond what we can see with our eyes alone. This is his own sketch of sunspots. (Courtesy Royal Astronomical Society.)



In the mid 17th century, Robert Hooke and Antoni van Leeuwenhoek explored the world of the very small. Their discoveries, like this flea drawn by Hooke, astonished their contemporaries.



1 000 000 000 000 000 000 000 000 000	10^{24}	yotta	Y
1 000 000 000 000 000 000 000 000 000	10^{21}	zetta	Z
1 000 000 000 000 000 000 000 000 000	10^{18}	exa	E
1 000 000 000 000 000 000 000 000 000	10^{15}	peta	P
1 000 000 000 000 000 000 000 000 000	10^{12}	tera	T
1 000 000 000 000 000 000 000 000 000	10^9	giga	G
1 000 000 000 000 000 000 000 000 000	10^6	mega	M
1 000 000 000 000 000 000 000 000 000	10^3	kilo	k
1	10^0		
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	μ
0.000 000 001	10^{-9}	nano	n
0.000 000 000 001	10^{-12}	pico	p
0.000 000 000 000 001	10^{-15}	femto	f
0.000 000 000 000 000 001	10^{-18}	atto	a
0.000 000 000 000 000 000 001	10^{-21}	zepto	z
0.000 000 000 000 000 000 000 001	10^{-24}	yocto	y

The familiar 'kilometre' for thousand metres or 'millimetre', for a thousandth of a metre, do not help us much to talk about the really large or the very minute. This table presents the whole range of prefixes which apply not just to length (kilometre) but also to mass (kilogram) and other quantities.

understanding of the Universe involves both the unimaginably large and the unimaginably small. The nucleus is minuscule, but understanding its properties helps us to comprehend some of the ideas about matter on the greatest possible scale: the Universe itself.

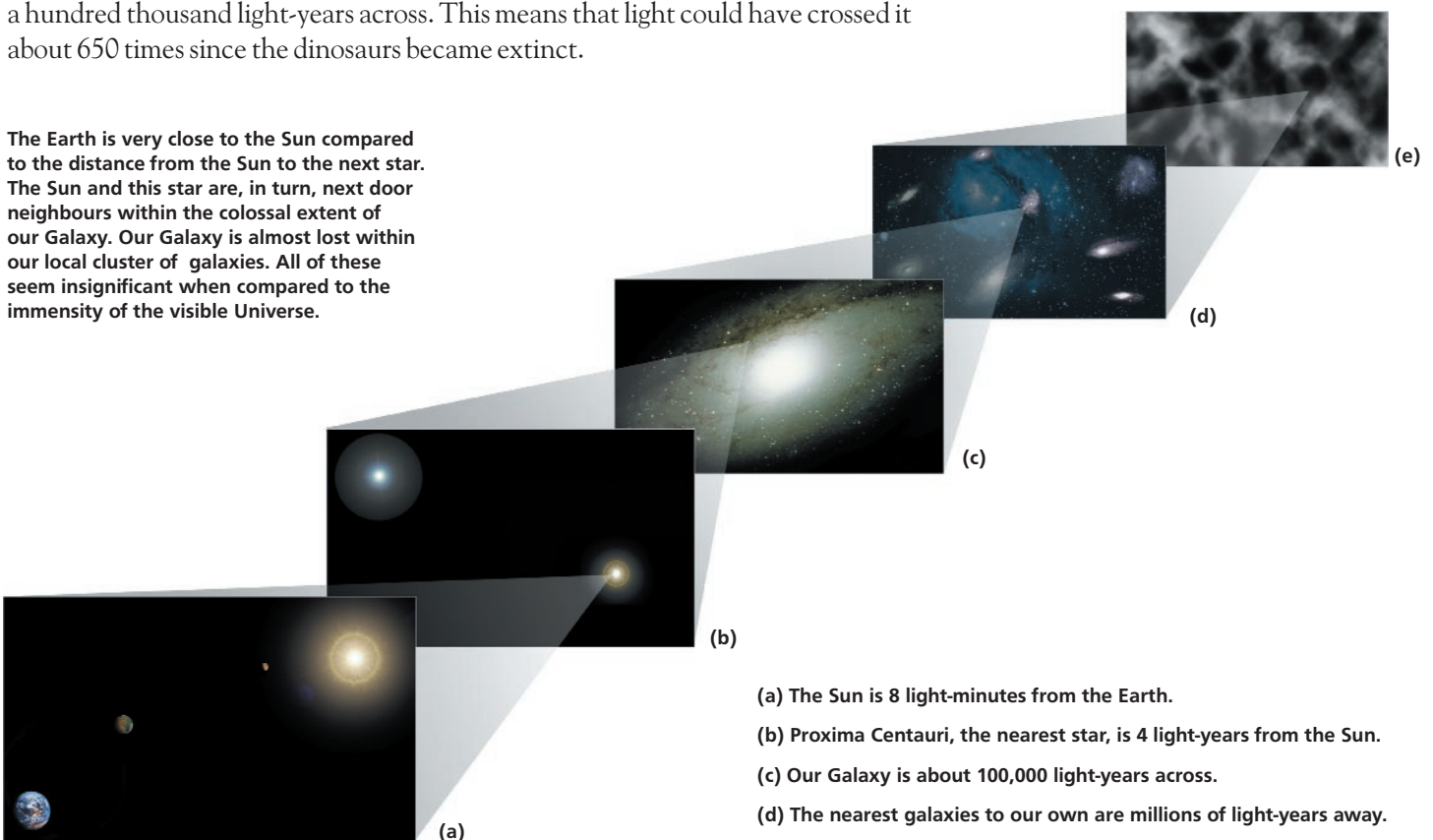
Towards infinity

We are all familiar with objects on a human scale, but gaining a feel for distances much larger than the size of the Earth can be difficult. The distance of the Earth from the Sun, for example, is already quite hard to grasp. It is about 150,000,000,000 metres (93 million miles); if you could fly it in Concorde, the flight time would be about seven years – definitely not good for the circulation in your legs.

Working with such large numbers can be quite unwieldy and 150,000,000,000 is more usually written as 1.5×10^{11} . Moving out into the Universe introduces even greater quantities and astronomers use a much larger unit to measure length, based on the speed of light, which is 299,792,458 metres per second (186,280 miles per second). The distance light can travel in a certain time provides a convenient unit of length. It takes light about eight minutes to reach us from the Sun, so we say that the Sun is eight 'light-minutes' away. The furthest planet from the Sun, Pluto, is about six light-hours away, but it is the light-year that is most useful for expressing the enormous distances to objects outside our solar system. Since the light from the nearest star beyond the solar system, Proxima Centauri, takes four years to reach us, we say that it is four light-years away. This is about 38,000,000,000,000,000 or 3.8×10^{16} metres (733 million million miles).

On a larger scale, the Sun is one of about a hundred billion (a billion is a thousand million, 10^9) stars in a gigantic rotating disk called the Milky Way Galaxy, which is a hundred thousand light-years across. This means that light could have crossed it about 650 times since the dinosaurs became extinct.

The Earth is very close to the Sun compared to the distance from the Sun to the next star. The Sun and this star are, in turn, next door neighbours within the colossal extent of our Galaxy. Our Galaxy is almost lost within our local cluster of galaxies. All of these seem insignificant when compared to the immensity of the visible Universe.



- (a) The Sun is 8 light-minutes from the Earth.
- (b) Proxima Centauri, the nearest star, is 4 light-years from the Sun.
- (c) Our Galaxy is about 100,000 light-years across.
- (d) The nearest galaxies to our own are millions of light-years away.
- (e) Distant clusters of galaxies are billions (10^9) of light-years away.

On an even larger scale, space is studded with galaxies. They are grouped into clusters, separated by vast empty regions. The nearest large galaxy outside our own is Andromeda, visible to the unaided eye on a very clear, dark night as a faint glow the size of the Moon. Andromeda is about two million light-years away and is a member of the Local Group, a small cluster of galaxies which includes the Milky Way.

With a very powerful telescope, a vast number of galaxies can be observed, stretching out to such distances that the light coming from the very furthest would have been travelling for most of the time since the Universe was born. That was about 15 billion years ago and so they are the better part of 15 billion light-years away. The furthest point in space that we can ever hope to see marks the limits of what is called the observable Universe.

The size of the Universe is a measure of matter on the greatest possible scale. We will now set off in the opposite direction towards the smallest.



The galaxy NGC 2997; our own galaxy would look something like this from outside, a view we shall never have.
(Courtesy European Southern Observatories.)

Under the microscope

The smallest unit of length with which most of us are familiar, is the millimetre (a thousandth of a metre), but for many objects which are only visible through a microscope, length scales are more sensibly expressed in terms of microns. A micron is a millionth of a metre, or a thousandth of a millimetre. A red blood cell inside your body is about seven microns in diameter; and a typical bacterium is only one micron across. Viruses, which are responsible for many diseases including the common cold, can range in size from a few tenths down to a hundredth of a micron.

Small as viruses are, they are not the smallest of objects; they are, in common with everything else, structures made of atoms. Everything is composed of a few types of atoms arranged in an uncountable number of different ways, and an atom is only about one ten-thousandth the size of a micron. Thus there are about a billion atoms in a typical virus and a single glass of water contains more atoms than there are glasses of water in all the seas and oceans on Earth.

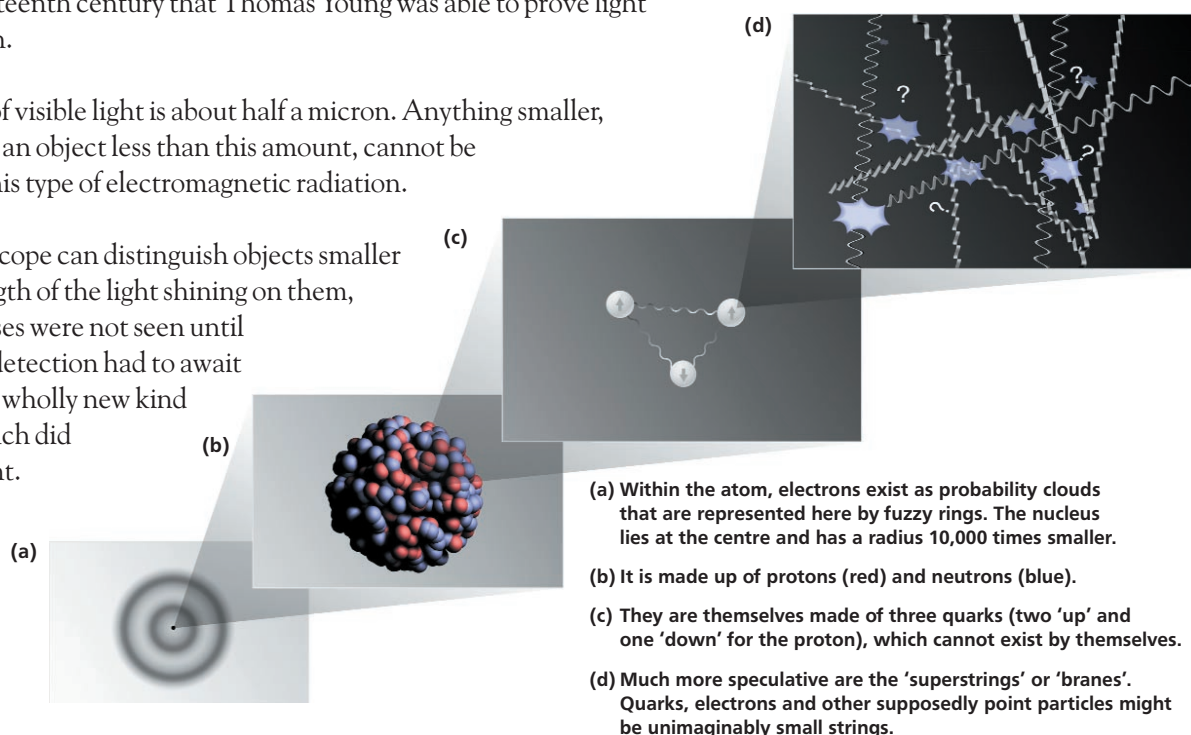
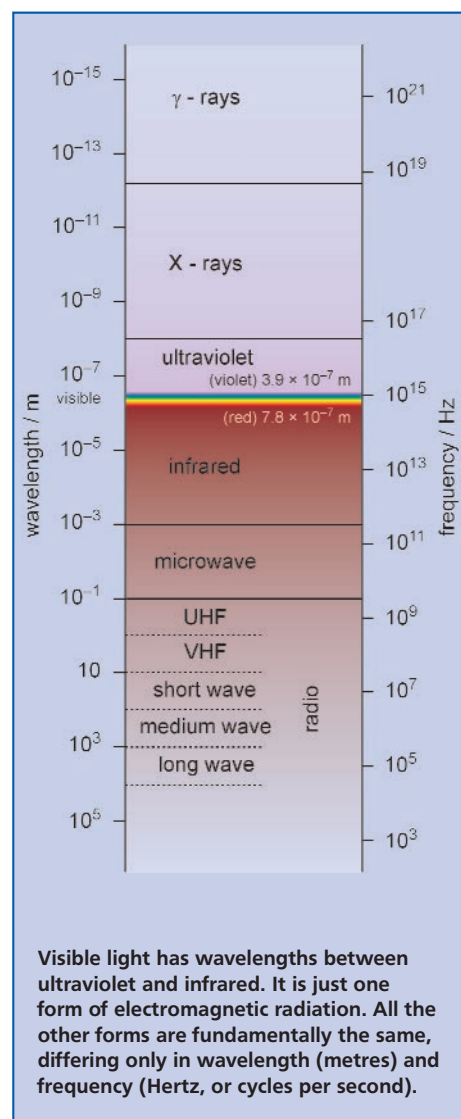
This book is about entities much smaller even than atoms. Each atom has a nucleus at its centre that is typically about ten thousand times smaller still – a tiny bundle of concentrated mass and energy. The question of whether we have reached the limit of smallness with atomic nuclei is addressed later.

It is fascinating to explore how we can possibly know anything about things as tiny as nuclei. Microscopes have extended the range of our vision enormously, allowing bacteria to be observed, but no ordinary microscope will ever let us see a virus and they certainly will not work for atoms or nuclei. The reason for this is the nature of light.

Light is a form of electromagnetic radiation; the same type of phenomenon as radio waves, infrared, ultraviolet, X-rays and gamma rays. Electromagnetic radiation travels as a wave; the different types vary according to their wavelength, which depends upon the amount of energy the radiation possesses. It was not until the nineteenth century that Thomas Young was able to prove light has a wave motion.

The wavelength of visible light is about half a micron. Anything smaller, or any features on an object less than this amount, cannot be discerned using this type of electromagnetic radiation.

No optical microscope can distinguish objects smaller than the wavelength of the light shining on them, which is why viruses were not seen until the 1940s. Their detection had to await the invention of a wholly new kind of microscope which did not use visible light.



Seeing with electrons



Here is a modern electron microscope flanked by an image of a human hair and, on the right and some 10,000 times smaller, a hepatitis B virus, showing its outer protein capsule which both protects it and provides the key which unlocks the defences of liver cells. (Courtesy LEO microscopes/John Berriman/MRC Cambridge.)

The revolutionary new instrument, an electron microscope, uses electron waves which have a much smaller wavelength. Electrons are the particles of electric charge that are present in every atom and which carry electric currents, but they can also behave as though they are spread-out waves. The wave character of electrons was the great discovery of a French prince Louis duc de Broglie. This discovery was a key step towards the understanding of the structure and properties of the subatomic world.

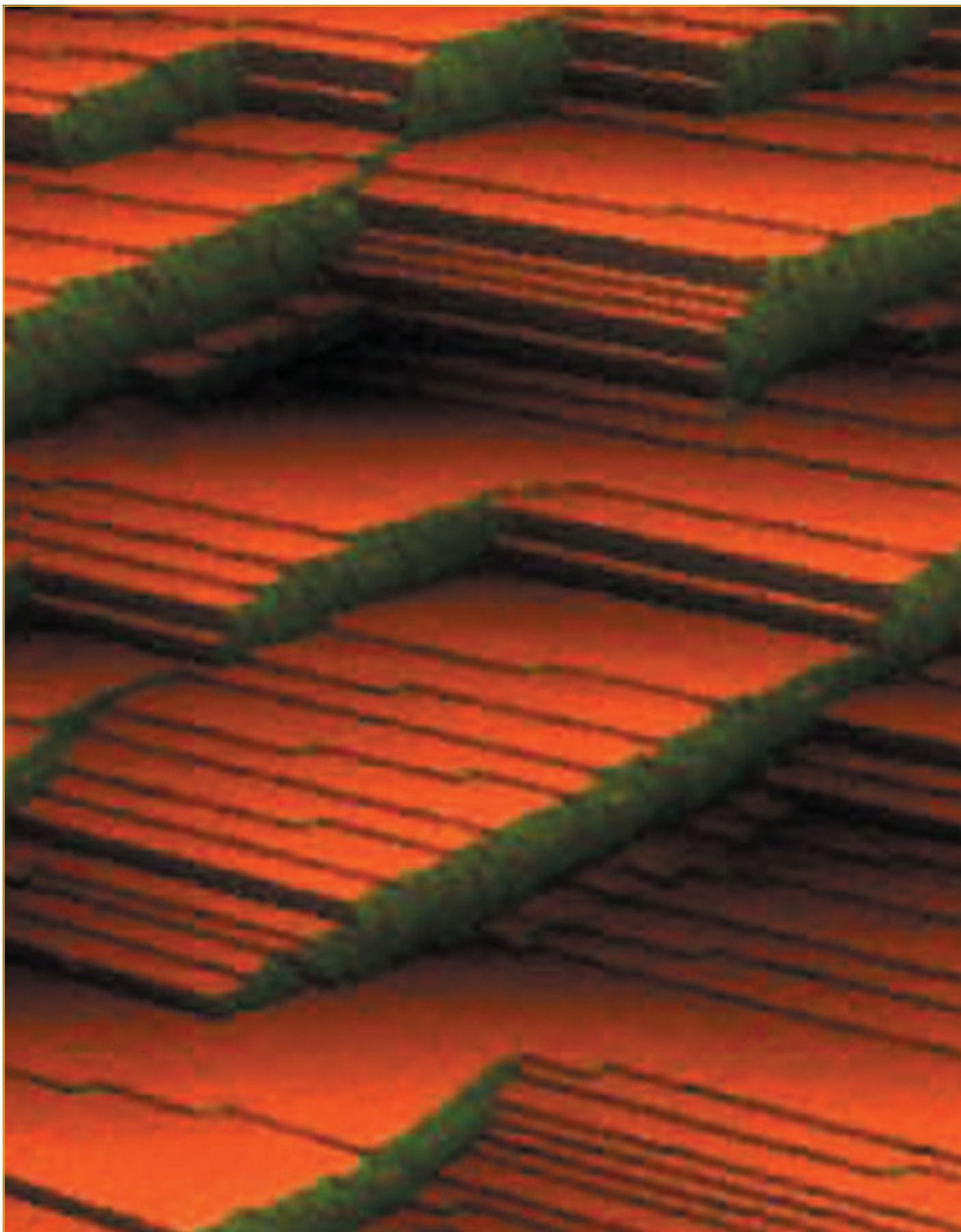
It sounds contradictory to describe electrons both as particles and as behaving like waves. This is the language of quantum mechanics, the physical theory in which electrons sometimes behave like waves and sometimes like particles. It is also the theory of the world of atoms and nuclei. For many purposes, electrons can be considered to be waves with a well-defined wavelength and this wavelength becomes shorter as the energy of the electrons is increased. Being waves, and also electrically charged, magnetic lenses can be made for beams of electrons and this allows the construction of electron microscopes. The limit of resolution is the same as for ordinary microscopes: the wavelength of the beam, but electrons have much shorter wavelengths than ordinary light. The shorter the wavelength of the electrons, the finer the detail that can be revealed.

In order to see smaller and smaller things we use electrons with higher and higher energies because higher energies mean shorter wavelengths. As electrons are charged particles, they will feel a force if put into a vacuum with an electrical voltage across it. This force causes them to accelerate. This is the manner in which electrons are accelerated in ordinary television tubes or computer monitors. In such applications, the electrons are focused to a point which moves over the screen, tracing out the picture. Electron microscopes generally accelerate electrons to energies ten or more times higher than in a television tube in order to get the wavelength small enough to see viruses.

Atoms are much smaller still than viruses. Today it is understood how they are arranged in most materials, but as late as the first decade of the twentieth century the very existence of atoms was seriously doubted by many scientists. It is truly remarkable that we are able to learn anything at all about things so small.



Louis Victor Pierre Raymond duc de Broglie, 1892–1987, the first person to glimpse the wave nature of matter. (Copyright the Nobel Foundation.)

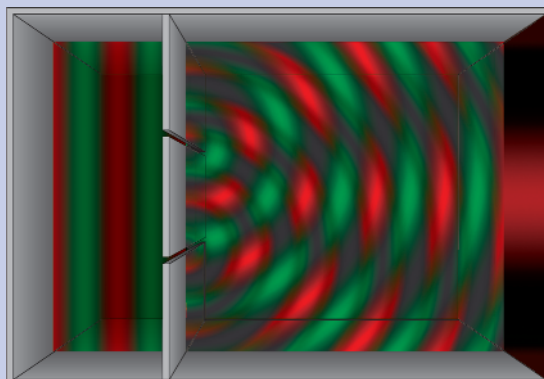


Imaging sheets of atoms: this is the surface of a crystal of iron silicide as seen using a device called a scanning tunnelling microscope. The smallest step corresponds to a layer one atom thick. (Courtesy Nanoscale Science Laboratory, Cambridge.)

How do we know that light is waves?

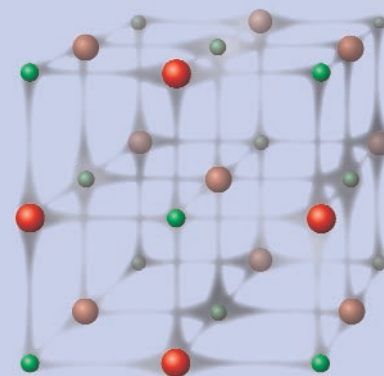
When light falls on a barrier with tiny holes or slits in it, a pattern of light and dark can be found on a screen placed on the far side. The same sort of thing happens with any waves, including water waves where it is easier to see what is happening.

Waves spread out when they encounter objects, something most easily observed when their wavelength is comparable to the size of the object. This spreading out is known as diffraction. Waves from different holes interfere with each other and where a trough arriving from one hole meets a crest from another they can cancel each other out. For light waves this means there are dark patches at such places, as Thomas Young discovered.



Another type of electromagnetic radiation is X-rays. These have wavelengths typically a thousand times smaller than visible light. Unfortunately it is not possible to build X-ray microscopes because there is no suitable system of lenses that can bring X-rays to a focus within such an instrument. Nevertheless, almost as soon as they were discovered, X-rays were used to study the structure of matter. The secret is to use a universal property of all waves: diffraction.

Early in the nineteenth century Thomas Young demonstrated how a grating creates an interference pattern using visible light. Working backwards from complicated diffraction patterns allows scientists to determine what sort of 'grating' gave rise to those particular patterns, and atoms in a crystal are, in effect, a grating. This method was used to determine, for example, how far apart the sodium and chlorine ions are in a crystal of common salt. Much more interesting crystals than common salt have been studied with X-ray diffraction. It was by looking at the way X-rays were diffracted by DNA that Francis Crick and James Watson unravelled the double helix structure of this key molecule of life.



A crystal of common salt consists of alternating sodium and chlorine atoms arranged in a regular cubic array. The spacing between the atoms can be worked out from the way X-rays diffract from the crystal.

The method of diffraction, applied to electron waves rather than X-rays, allows the size and shape of atomic nuclei to be measured. Real images of atoms in the surface of a crystal can be obtained, taken using a particular type of electron microscope called a scanning tunnelling microscope.

We now leave the realm of atoms for the realm of nuclei, ten thousand times smaller. There was no reason to suspect that Nature had structures on such a small scale. Clues of this 'sub'-atomic world came in the shape of a wholly unexpected new phenomenon: radioactivity.



Thomas Young, 1773–1829, polymath. It was Young who first provided convincing evidence of the wave nature of light. (AIP Emilio Segrè Visual Archives.)