Our microworld

1.1 Microcosmos and cosmos

The panorama of the night sky is very inspiring to the human mind; indeed stars were considered divine by ancient thinkers. Nowadays, sophisticated tools are used to detect and record visible light and other forms of radiation from the cosmos. The study of the composition of cosmic radiation tells us that the Universe contains the same molecules, atoms and nuclei as found here on Earth. It also provides evidence that the Universe was created by a gigantic explosion, known as the ‘big bang’, some 15 billion \((1.5 \times 10^{10})\) years ago. After the creation of Earth, five billion years ago, it took between one and two billion years for the first traces of life to appear. Now, after the relatively brief million-year existence of human beings, we are able to observe the Earth from satellites. This view of the Earth has opened up a new dimension in our thinking. Our blue and green planet appears to be unique in an otherwise apparently lifeless cosmic environment.

If we now view our World from an atomic perspective, we can see that our experiences can be explained in terms of the behaviour of atoms. For example, it takes two oxygen atoms to form an oxygen molecule, and two nitrogen atoms to form a nitrogen molecule. These two molecular species constitute 99% of the air that we breathe. Carbon, perhaps the most spectacular of the 92 naturally occurring atoms, defines the chemistry of life. Carbon and nitrogen atoms bind to form the long-chain backbone of the protein molecules that are the ubiquitous building blocks of living matter. The largest molecule of the living cell is deoxyribo-nucleic acid, DNA, which is composed, in higher organisms, of more than one thousand million atoms, of carbon, nitrogen, oxygen, phosphorus and hydrogen. It looks like a twisted ladder, or ‘double helix’. DNA contains all the instructions for the ordered growth of cells, and can be thought of as the ‘recipe for life’.

There are many different types of carbon compounds. The thing that makes them different is that the atoms are joined together in a variety
of ways. Living matter is based on one-dimensional chains of atoms, whereas inorganic carbon materials may have their atoms arranged in two or three spatial dimensions. Graphite is a two-dimensional structure and an excellent lubricant since the carbon planes glide easily over each other. Diamond is a three-dimensional structure in which the atoms are arranged regularly in a crystal lattice. It is remarkable that the basic atomic building blocks of life are also building blocks of the hardest substance we know.

In viewing matter from the inside, we are able to make a unifying description of processes on Earth and in the Universe. This projection of events and things from a large scale world onto a microworld, the microcosmos, was practised in many ancient cultures. For example, the Chinese of 600 BC regarded the human being as a miniature universe; stars were thought of not only as navigational aids, but also as bodies which facilitated the circulation of universal air in a gigantic organism representing the heavens. Guided by their view of man as a miniature universe, the Chinese assumed that air must be present also in man, and they formed a theory of respiration. Acupuncture needles put into the human skin were thought to act in the same way as stars in the sky, to facilitate the motion of air that they thought of as a ‘vital spirit’.

Like the Chinese, Plato in the fourth century BC regarded man as a miniature universe. Essential to Plato’s philosophy were ‘immortal souls’, which were thought to be present in the Universe as well as in living bodies. The soul was a basic entity in the ‘world of Ideas’, an abstract concept and one of Plato’s most important contributions to philosophy. Here, the idea of an object rather than the object itself was considered to represent true reality. The objects themselves were seen as ‘shadows’ of the Ideas. To Plato, the Idea represented the basic form of an object, and the purest way of expressing it was by mathematics and geometry. Plato developed the Ideas by reasoning, and he did not believe that true knowledge could be obtained through direct sensory observations. In his view, full understanding of the world of Ideas could be reached only through philosophy.

Plato adopted the theory of Empedocles to identify the four ‘elements’ then classifying the material world: earth, water, air and fire; along with the two ‘forces’: love and strife. The elements and forces, although remote from the ideas, helped the philosophers to interpret the ‘shadows’. The stars and planets, because of their permanence and regular behaviour, were the most sublime representations of Ideas, and so were musical forms.
Plato’s Idea concept is illustrated by a particular object, the cat Allison. In our material world, Allison is a cat that may be running, resting, eating or drinking. In time, it develops from a small kitten to a mature cat and will finally age and die. To us the word ‘cat’ means merely a
form of life at the present state of evolution; but to Plato, the Idea of cat was an absolute and invariant entity which gave rise to worldly cats such as the specific cat, Allison. It may seem strange to us that the idea of an object rather than the object itself was thought to represent the highest degree of truth. Is this because we tend to consider knowledge of direct appearances in our daily world most important, and forget to reflect upon ‘la raison d'être’? Do we emphasize materialism too much and philosophy too little in our sphere of thinking?

Plato’s student, the Greek philosopher Aristotle, laid down laws for reasoning, performed experiments, and contributed greatly to the development of the natural sciences. In fact he was so successful in explaining natural phenomena that other philosophers refrained from doing experimental work. Aristotle accepted Plato’s idea that the soul is immortal, and the divine laws that determine the motion of planets, but regarded the planets themselves as tangible and not abstract bodies. In Aristotle’s philosophy, matter is as significant as the idea of matter, and knowledge of the material world can be derived only from truly scientific observations.

Plato’s views influenced philosophers for nearly 2000 years, and the search for knowledge was inspired by questions of why things exist and why events occur, rather than by questions of how things are and how events develop. Plato’s authoritative view was liked by leaders of the Church and rulers of the state, but was challenged in late medieval physical studies. The Renaissance brought a scientific revolution that led to a completely new idea of the world in which the Sun, and not the Earth, was the centre of the Universe. This idea came from Copernicus, and was a result of observations with the naked eye and reasoning. Later, in the 17th century, Galileo Galilei used the newly invented telescope to verify the Copernican view. He was arraigned before the Inquisition in 1633 because of his support of the idea that the Earth moves around the Sun and is not the centre of the Universe. This event was the culmination of a struggle that separated knowledge from faith, and Academy from Church. Galileo died in 1642, the year that Isaac Newton was born.

Newton developed an observational and rational approach to philosophy. In 1687, the science of moving bodies was laid out with unprecedented precision in his famous book *Principia*. In this masterpiece, Newton suggested that the gravitational force holding the planets in orbit is the same as the gravity acting on earthly objects. The descriptions of the motion of falling bodies and planetary motion due to Galileo Galilei and Johannes Kepler had thus been unified.

Plato’s philosophy is still interesting as it distinguishes an imperfect
material world experienced by our senses from a pure world of Ideas. Plato’s immaterial world of Ideas was, however, stereotypical and pre-determined, whereas scientists today have ideas of a microworld, of cells, molecules and atoms, which is successively modified when observations so require. In fact, most important to scientists is not whether an atom ‘exists’ but how observations can be explained by models (ideas) based on atomic constituents of matter.

Our idea of the microworld has evolved through experience and observation. The concept of the atom was introduced in the 5th century BC, by Leucippos and Democritos, who suggested that matter is composed of small indivisible constituents. The word ‘atom’ is derived from the Greek word meaning indivisible. More than 2000 years later, in the early part of the 19th century, the atomic concept was adopted for scientific use by John Dalton, an English teacher. He was interested in meteorology, and studied the composition of the atmosphere, which was already known to contain at least two gases of different weight. By studying the partial pressures of oxygen and nitrogen, he concluded that air is a mixture of gases, not a chemical compound. Dalton thought that heat separated the individual gas particles and prevented them from joining together. He concluded that every gas is composed of a given kind of atom; the heavier the gas, the heavier its constituent atoms. Dalton’s theory means that a chemical element is defined by its own specific kind of atom, and that chemical reactions do not destroy but merely separate and unite atoms.

In 1869, the Russian Dmitri Ivanovitz Mendeleev arranged the elements from hydrogen to uranium according to their weights. His well-known periodic table displays the elements in horizontal rows and vertical columns. The vertical columns contain elements with similar chemical properties. The regular increase in mass of consecutive elements in the periodic table suggested that atoms are built of even smaller constituents with a weight equal to the average mass difference between neighbouring elements.

At the beginning of the 20th century, the atom was found to be divisible, consisting of electrons in orbit around a small nucleus in which most of the atomic mass is concentrated. Later, it was found that the atomic nucleus consists of protons and neutrons, which in turn are formed of even smaller particles called quarks. The present idea of the subatomic microworld is based on the notions of electrons and quarks, which appear to be pointlike particles and whose rapid motion determines the shapes of molecules, atoms, protons and neutrons.
1.2 Our senses

From childhood, our mind develops from experiences gained through the senses. We begin to learn by imitating our family and friends, and continue learning at school. These impressions provide us with good judgement and common sense, but our mind and ‘true’ reality are clearly separated. Take the song of a bird as an example. The ‘social’ message may be understood only by another bird of the same species and not by a human mind. However, the sound can be superficially understood by knowledge of the bird’s anatomy, the propagation of the sound waves through the air, and the function of the human ear. To interpret events in the material world, it is essential to consider all physical and chemical events in the microworld, even those that are not accessible directly through the senses. The limitations of the senses really make the definition of true reality meaningless.

Our vision lets us appreciate blue sky, green trees, and all colours of the rainbow. Form and colour appear as a result of the interaction of sunlight with air molecules in the atmosphere, with cells of plants, and with rain-drops. Light patterns so formed are absorbed in the retinal cells of the eye, where chemical reactions generate nerve signals which lead to perception of form and colour in the rear portion of the brain.

Our auditory system opens up the world of sound, including those sounds created by instruments such as the violin, harp or horn; or song and speech by the human larynx. The resulting motion of the air molecules constitutes an acoustic wave which hits the ear drum and causes the three small bones of the middle ear to vibrate and transmit the signal to the cells in the inner ear. There, the vibrations convert to nerve signals in cells of the cochlea, and these signals stimulate regions in the brain. A human being may perceive up to 20,000 vibrations per second, a dog up to 35,000, and a bat up to 100,000.

The sense of smell allows us to identify algae on the sea shore, brandy from the Cognac district, and the lily of the valley, all scents as fragrant as any perfume produced artificially. The sensation of smell is induced by volatile molecules which affect the nerve endings of specialized cells in the nose.

The cells of the taste buds, which convert stimuli to nerve signals, allow us to recognize bitter, sour, salt and sweet chemical compounds. These four basic flavours are perceived, respectively, when tonic water, vinegar, sea water and honey, stimulate the tongue. Different parts of the tongue are best adapted to the different flavours; the tip to sweetness,
Fig. 1.2. In the upper part of the nose, inhaled molecules stimulate the terminal filaments of the nerves, which conduct signals of smell to the brain.

the sides to sour and salt, and the base to bitter. The sensation of taste is also assisted by the sense of smell.

Nerve endings in the skin convey the impression of touch. This sense also detects the temperature of a medium, reflecting the motion of molecules bombarding our skin. Water heats us intensely in the steam of a sauna, but cools us decidedly in a cold shower, both because of the way water molecules at different temperatures interact with our skin. Pain is due to an even more intense sense of touch such as that experienced owing to molecular motion in a flame. Nerve signals may also occur as a result of tension induced through cells situated not only in the skin but also in tendons and muscles.

Sensory impressions depend not only on the characteristics of the sensory cells but also on the chemical and physical properties of the stimulating agent. Consider, for example, light. Visual sensations are a result of light being absorbed on the cells of the retina. Because this
light has been emitted or scattered by surrounding objects, knowledge of the interaction of light is important in assessing the picture we observe. If the rays of light, like the longer radio waves, were reflected on the upper ionized layer of the atmosphere, this layer would appear visible to us. On the other hand, if light had a similar penetrating power to that of X-rays, our bodies would appear transparent! So the properties of visible light determine our visual perception of the material world.

Television can be used to show us images from all over the world, and even from outer space, thereby widening dramatically our knowledge of the visible world. Images may also be stored and manipulated on video tape. We may, if we wish, use slow motion to examine details of an image forwards or backwards in time. We are often unsure, when watching television, if the images represent an on-going event or a recording. Our own vision is artificial in a somewhat similar sense. The nerve signals, when arriving at the brain, convey an image of some reality that may have changed by the time of registration in the brain. The delay may be unimportant when considering the events of every day, but consider the light coming from a star. This light has had to travel so far before reaching our eyes that the star itself will be considerably older than it appears at the moment of observation. It is even conceivable that a star being observed today does not still exist! Indeed by observing stars we are truly looking back into the past.

Our understanding of the material world has progressed greatly thanks to sophisticated tools of observation. Such tools are used nowadays to measure and record phenomena around us, but in the end our senses and brains must interpret the findings and form an idea of the world.

### 1.3 Exploration of the microcosmos

For centuries, the material world was explored using visible light and the unaided human eye as detector. The telescope and the microscope, invented around AD 1600, improved the observations significantly since light could then be collected and focused. In 1888, radio waves, a new type of radiation, invisible to the human eye, were discovered by the German Heinrich Hertz. This discovery has been very important for wireless communication and for radioastronomy.

More energetic types of invisible radiation were soon to be discovered. In 1895, the German Wilhelm Konrad Röntgen performed various experiments using evacuated glass tubes, and studied how an electric
tension across a gas at reduced pressure could lead to conduction of an electric current. When the glass tube was covered with black cardboard, a paper coated with platino-cyanide, which happened to be nearby, appeared to glow in the dark. When the voltage was switched off, the glow disappeared. Röntgen concluded that very energetic ‘rays’ had penetrated the walls of the glass tube. The nature of these rays is different from that of visible rays because, unlike visible light, they are not refracted in lenses. Röntgen thought that the new rays were of very short wavelength, and because of their mysterious behaviour he named them X-rays. They are electrically neutral and are produced when ‘cathode rays’ – the rays emitted from an electrode with negative potential, the cathode – are absorbed on an electrode with positive potential, the anode. The discovery gained Röntgen the first Nobel Prize in 1901.

In Great Britain, soon after Röntgen’s discovery, Joseph John Thomson started research on X-rays, but his interest soon focused on cathode rays, which were found to be electrically charged. Their charge-to-mass ratio was found to be independent of the kind of gas in which the glow discharges developed. Cathode rays were renamed electrons, and were found to be smaller and lighter than atoms, the hitherto smallest known particles of matter.

Radioactivity, a third major discovery of this era, was revealed by the Frenchman Henri Becquerel. He discovered that minerals containing uranium caused blackening of photographic plates which had not been exposed to light. Apparently some kind of invisible radiation affected the plate, so liberating silver atoms. Continued research on radioactivity revealed that three different types of radiation can be emitted from radioactive substances: alpha particles, identical to the nuclei of helium atoms; beta particles, identified to be high-velocity electrons; and gamma rays, similar to, but more penetrating than Röntgen’s X-rays. Becquerel was awarded the 1903 Nobel Prize for his discovery of spontaneous radioactivity, together with Pierre and Marie Curie for their joint research on radiation phenomena.

At the beginning of the 20th century, the new types of radiation were used for several important experiments. One of the most important was in 1909 in Manchester, UK, by Hans Geiger and Ernest Marsden, who irradiated a thin gold foil with alpha particles. They expected the electrically charged alpha particles to be only slightly deflected by the positive and negative electric charges which then were thought to be evenly distributed in a gold atom. To their surprise, they found that some alpha particles were deflected at unexpectedly large angles. Ernest Rutherford,
who was in charge of the Manchester laboratory at the time, interpreted the large deflections as scattering of the alpha particles by dense clusters of positive charge, since identified as the nuclei of the gold atoms. The nuclei are now known to contain most of the weight of the gold atom,