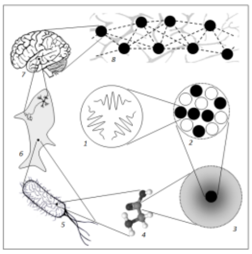


Chapter 0: Introduction

0.1 right here, right now

This book will take you, the reader, on a journey through the physical universe to see how it works.‡

As the first step on this journey, I would like you to think about your current position in the grand scheme of things. Observed from far away, as if from a satellite, you are one individual in a global human culture, connected to all other humans by inherited DNA and by social and economic links. Someone who sees you from day to day would observe your rational behaviour, your emotions, your humour and empathy. If this observer goes close enough to get under your skin, they would see your internal organs, such as liver, heart and brain, and that these are made of a variety of living biological cells, such as muscle cells, white blood cells and neurons, the nerve cells in your brain.

Closing in on the brain, the observer would see the individual neurons endlessly firing and passing signals between themselves, as you listen, think and speak. Within each neuron there are billions of molecules of glucose that provide the energy for it to function, and our observer sees that each glucose molecule comprises atoms of carbon, hydrogen and oxygen. Zooming in on one of the carbon atoms, the observer sees the electrons surrounding the protons and neutrons in its central nucleus, and going closer still, sees that each proton and neutron comprises three quarks.

In this short sequence, we have descended through the different systems of the physical universe – from the conscious human brain down to fundamental sub-atomic quarks. These material systems form a natural hierarchy, in which things are made of smaller things, and are themselves part of bigger things. So, a molecule is made of atoms, but is itself a part of a living cell. Each of us is, in effect, a universe in microcosm – quarks, protons, neutrons, electrons, molecules, body cells, tissues and organs – all playing their parts in sustaining our human consciousness.

Right here, right now, your muscles are holding you up, your stomach is digesting the last meal, your lungs are breathing in and out, your heart is pumping blood, while your eyes flick from one word to the next, so your brain can take in the meaning … of …… this ……… particular ………… sentence.

Each one of us is sustained by the ceaseless activity of our body cells and organs, and also by the activity of the molecules and atoms of which they are made, but we live our lives quite unaware of it.

when did you last think of an electron?

So, when did you last think of a proton, or an electron? Have you recently mentioned molecules or neurons in conversation? For just about all of us, the answer to these questions is probably, "No". It's likely that most of us last talked of things like electrons, molecules and chemical reactions in school lessons. We're not normally aware of the workings of our neurons unless there's a problem, like a toothache or a trapped nerve. Even professional scientists probably don't think of their specialisms while engaged in their everyday activities. The atomic physicist doesn't think of protons and electrons as she uses her smartphone. The biochemist doesn't think about molecules as he eats his breakfast.

We can get by perfectly well without knowing how things work. In fact, in our everyday life, it's better that we *don't* think about what's happening. If we had to think about what the atoms and molecules are doing when we make an omelette, then we'd never start. If we had to be aware of what the neurons in our brains are doing, then we'd never achieve a single thought.

If we were asked what the universe is made of, then most of us would think of things like atoms and molecules, protons and neutrons and electrons, and living biological cells. We're aware of some kind of hierarchy, in which things are made of smaller things, so cells comprise molecules, which are made of atoms, which contain protons, neutrons and electrons, and we may have heard of protons and neutrons being made of quarks. But how do these things relate to one another? Is this hierarchy just a random list of things, or does it follow any consistent pattern or scheme? And how do they sustain a conscious human being, capable of rational thought, empathy and laughter?

‡ **Footnote**: every chapter is supported by notes, which are at the end of each chapter.

This book is about the universal scheme of "things" – how "stuff" works, from quarks to human consciousness. In this book I show how everything fits into a hierarchy, in which "things" at lower levels support "things" at higher levels, with the whole system being sustained by ceaseless activity at every level. Moreover, the interactions between the "things" at each level vary from one level to the next, so each level has its own set of physical laws. Thus the principles governing the behaviour of protons underlie the principles governing the behaviour of electrons, which in turn underlie the principles governing the behaviour of biological cells.

The universe has evolved following the sequence of levels in the hierarchy, with higher levels emerging from the activities of lower ones. The principles of the hierarchical scheme are fairly simple (they are in figure 0.5 in this chapter); it's the details of the "things" and their activities at each level that are complex.

Carl Sagan once observed, "*If you wish to make an apple pie from scratch, you must first invent the universe*". However, the hierarchical nature of the physical universe and its laws means that we can, in practice, make an apple pie just by following a recipe, and without knowing anything of the biology of apples or the chemistry of cookery, or of the principles of protons in the pastry, or of the quarks in the custard. On a scale bigger than apple pies, "*the tendency of nature to form a hierarchical society of physical laws is why the world is knowable … It is the reason we can live without understanding the ultimate secrets of the universe*".

We can live happy, productive and creative lives without knowing anything much of electrons, chemical reactions or neurons. However, if you've sometimes wondered, "How does *that* work?", then maybe this book will be of interest to you.

0.2 the major systems of matter in our universe

0.2.1 the universe as a set of Russian dolls

Our physical universe is a series of systems of matter, stacked one inside another, like a set of Russian dolls. If we "open" one system of matter we find another system inside it. If we "unpack" this series of matter systems we find that the substances of our everyday world are made of molecules, which are made of atoms, within which are electrons and nuclei, which comprise protons and neutrons, and finally, we come to quarks, the innermost doll, which are not made of anything smaller. These matter systems are, like Russian dolls, successively smaller in size, but each system functions at a higher energy than the one before it.

Before we look at these matter systems we need to become familiar with the energies on the scale of atoms and molecules.

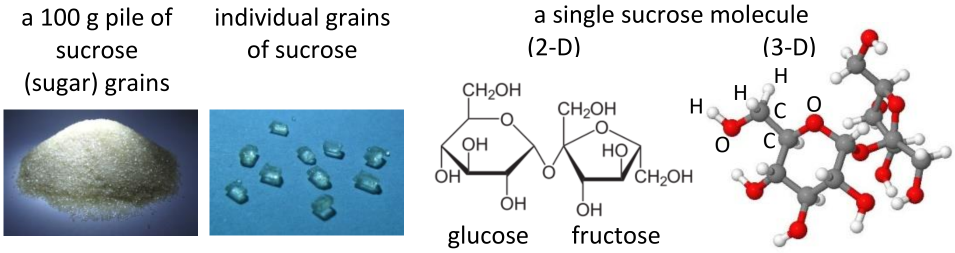
0.2.2 sugar and measuring energies in eV

We are made of molecules, but mentally we are so far removed from the molecular world, that it requires a rather elaborate and intellectual exercise to connect with it. I'll use the example of sugar, which is composed entirely of molecules of sucrose, as is shown in figure 0.1.

The label on a bag of sugar states that 100 g (about 14 heaped teaspoons) provide 1700 kJ of energy. This is obtained when the carbohydrate sugar molecules (formula $C_{12}H_{22}O_{11}$) are oxidised within the body to carbon dioxide (CO_2) and water (H_2O). There are about 1.8×10^{23} sucrose molecules in a 100 g pile of sugar grains, that is, about one million billion billion. If we divide the pile in two about sixteen times in succession, halving the number of grains each time, we end up with a single grain, roughly a 1 mm cube. Even this tiny amount of sugar, hard to see with the naked eye, and just about detectable on the tongue, contains 2.8×10^{18}, or nearly three billion billion molecules, and will yield 27 J of energy.

If we make a further series of about 61 cuts, halving the sugar grain each time, then we end up with just a single molecule of sucrose. The energy released by the oxidation of this molecule is a tiny figure when measured in Joules. We need another measure of energy that is more appropriate for the molecular world.

In the everyday macro-world, we define quantities like energy in terms of everyday objects and forces. We must distinguish between the mass of an object, the amount of matter in it, and the force needed to lift it in a gravity field. A 1 kg bag of sugar requires a force of about 10 Newtons (N) to lift it against the pull of Earth's gravity, but only about $1/6^{th}$ of this on the Moon. If we imagine an apple with a mass of 0.1 kg, then it will need a force of 1 N to pull it away from the Earth, and raising it by 1 m in the Earth's gravity field gives it a potential energy of 1 J.



number of molecules	1.8×10^{23}	2.8×10^{18}		1
number of halvings	-	16	+ 61 more	77
energy in Joules	1,700,000	27		10×10^{-18}
energy in eV	1×10^{25}	1.7×10^{20}		60

Figure 0.1. From the everyday world to the micro-world of molecules. A sequence of about 77 cuts, each halving the number of molecules present, will reduce a 100 g pile of sucrose grains to a single molecule. The energy released by the complete oxidation of this one molecule ($C_{12}H_{22}O_{11}$) to carbon dioxide (CO_2) and water (H_2O) is about 60 eV. Sucrose is a disaccharide, with each sucrose molecule comprising a molecule of glucose linked to a molecule of fructose by an oxygen atom. The 2-D view of the sucrose molecule shows the rings lying flat, and does not show the carbon atoms in the rings, or the hydrogen atoms attached to them. The rings are actually at an oblique angle to each other, and the 3-D view shows the glucose molecule face-on and the fructose molecule edge-on; some of the carbon (C), hydrogen (H) and oxygen (O) atoms have been labelled, and the rest can be identified by their colour-coding.

On the atomic scale we have charged particles like electrons and protons, and the dominant forces are electrical, not gravitational. We measure heights in a gravitational field in metres, and we measure “heights” in an electrical field in Volts. A positive electric charge creates an electric field around itself, which is attractive to a negatively charged electron. The electron has to be pulled away from the positive charge, and “raising” the electron by 1 V in the electric field gives it a potential energy of 1 electron-volt (1 eV).

There is an enormous difference between Joules and electron-volts: 1 eV = 1.6×10^{-19} J, so 1 J is equivalent to 6.3×10^{18} eV, or about six billion billion electron-volts. We can quantify energies with equal accuracy on both scales, just as you can write down the accurate dimensions of your kitchen in kilometres, but it’s much easier to work in millimetres. The electron-volt is a tiny amount of energy, that is useful in describing events on the molecular scale. We now have a useful measure of the energy provided by the combustion of one molecule of sucrose, and it is about 60 eV.

glucose and neurons

Humans with a size of about 1 m are about one billion times bigger than the molecules we are made of and whose chemical interactions sustain us. Consequently, we are incapable of detecting events at the level of individual molecules or atoms. A single grain of sugar, about one billion billion molecules, is perhaps the smallest number of sucrose molecules that we can taste. Just as we can only taste biological molecules like sucrose in their billions, so they are consumed in billions in our body’s daily processes.

For example, the human cortex contains over ten billion neurons, and a typical cortical neuron consumes about 600 million eV of energy when it “fires” and passes on a nerve impulse. Neurons have to be fed glucose molecules constantly in order to function. We have an approximate figure for the energy yield of a glucose molecule, for figure 0.1 tells us that it is about 30 eV, half the yield of a sucrose molecule. From this we know the neuron needs 20 million glucose molecules for each firing. Each of the ten billion or so neurons in the human cortex typically fires about 10 times each second, and so the cortex alone requires about 2 billion billion glucose molecules *every second*, in order to function.

This small example gives us one of the themes of this book – how enormous and endless activity on a lower level sustains a higher level.

0.2.3 *energy and temperature*

We can now go on to look at how the different matter systems "operate" at different energies and temperatures, and these are shown in figure 0.2, for the case of water. The different matter systems can be "unpacked" by heating them to higher temperatures, and thereby subjecting them to greater thermal energies. The different material systems are bound by different forces, and the general pattern that we find is that smaller systems are bound by more powerful forces, and "operate" at larger energies.

Broadly speaking, above absolute zero (0 K, or –273°C) the constituent atoms and molecules of all objects are not stationary, but ceaselessly moving and colliding, and transferring energy among themselves. On the microscopic scale, what we call "heat" or thermal energy is really the random motion of individual particles. Increasing the temperature of an object increases the average energy of motion of each particle in it, so "*turmoil and temperature go hand in hand*". Thus there is a profound connection between temperature and energy, and we can roughly equate a particle energy of 1 eV to a temperature of 10,000 K, or 10^4 K.

When we warm a substance we give its molecules more energy. For example, giving a water molecule an extra 0.001 eV of energy makes it about one degree "hotter". The molecules in bulk matter, such as solid ice and liquid water are in constant contact, and are randomly colliding and exchanging tiny amounts of energy with each other. A molecule that is one degree "hotter" will lose its extra 0.001 eV of energy in collisions with other molecules.

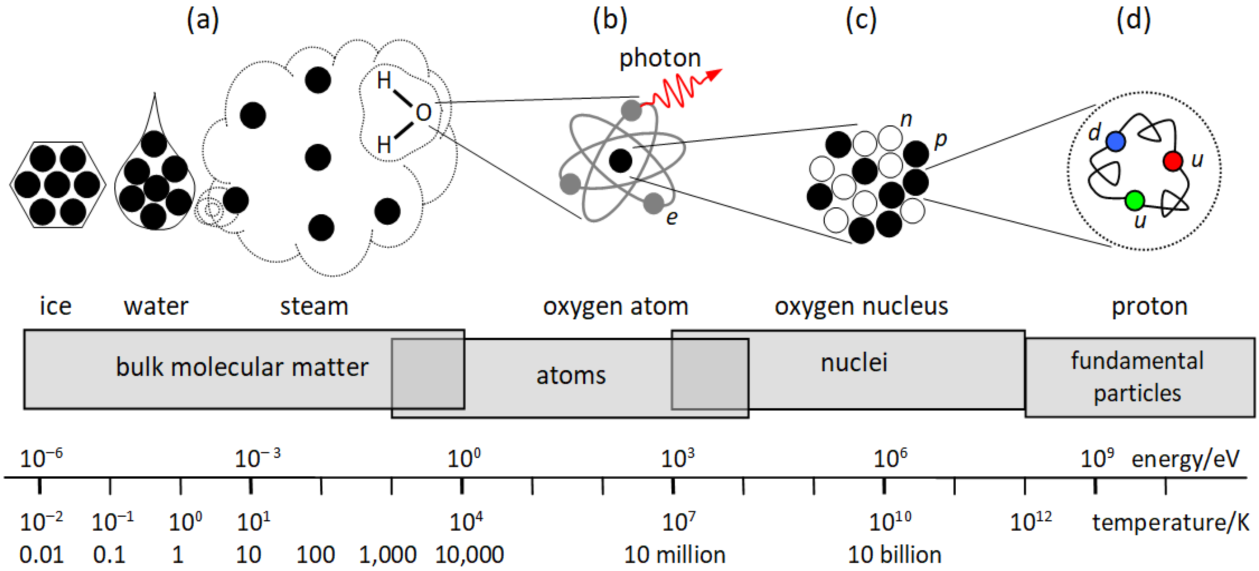


Figure 0.2. The energies and temperatures of matter systems in water: (a) the three states of bulk water (ice, liquid water and steam); (b) the oxygen atom in an H_2O molecule emitting a photon of red light; (c) the [8p,8n] nucleus of the oxygen atom, and (d) the quarks in one proton in the nucleus. Key: H = hydrogen, O = oxygen, e = electron, n = neutron, p= proton, u = up quark, d = down quark. Energies and temperatures are shown on the scale, with 1 eV being equivalent to 10^4 K, and the temperature scale is given in words and numbers. The energy and temperature scales are logarithmic, which means they count in powers of 10, and this lets us cover an enormous numerical range. So moving to the right we can look at very values of high energy and temperature, and moving to the left we look at smaller and smaller values, but never actually reach zero. A temperature of 10,000 K, or 1 followed by 4 zeroes, is written as 10^4 ; 10^0 represents a 1 followed by no zeros, which is just 1; and 0.01 K is $1/10^2$, or $10^0/10^2$, which is written as 10^{-2} K. The temperature scale starts at 0.01 K, one hundredth of a degree above absolute zero, and goes up to 10^{12} K, or 1,000 billion degrees.

We're familiar with the way water changes state as its temperature is raised, from solid ice, through liquid water to gaseous steam. The H_2O molecules remain the same, but the thermal energy overpowers the bonds holding the molecules together. In ice the H_2O molecules are bound tightly together in a rigid hexagonal crystal structure. Above the ice melting point (0°C, 273 K) the molecules have enough thermal energy to break out of this crystal structure, but not enough to separate from each other, so the molecules can tumble around as a liquid, but are held together in a drop with a fixed volume. When they are made one hundred degrees hotter, the H_2O molecules have enough thermal energy to separate from each other completely, and the drop of water becomes a cloud of steam.

Up to about 2,000 K the thermal energy is not enough to break the chemical bonds between the hydrogen and oxygen atoms in the H_2O molecule. But as steam is heated above this temperature the molecules start to split into their component atoms, and by about 4,000 K no H_2O molecules survive. The H_2O molecules in the ice, water and steam are shown just as black dots, except for one molecule in the cloud of steam, which is shown with its molecular structure, H—O—H. The H_2O molecule can't exist above about 4,000 K, and it splits into two atoms of hydrogen and one of oxygen, and the oxygen atom is shown in figure 0.2(b). So we can say that bulk molecular matter exists on the energy scale from very small energies up to about 1 eV, equivalent to about 10,000 K.

Isolated atoms can exchange energies of around 1 eV with each other by emitting and absorbing photons of light radiation. For example, the hot atoms in a candle flame provide illumination by emitting photons of visible light. Photon energies range from around 0.1 eV for infrared photons up to a few eV for ultraviolet photons.

Energies larger than this start to remove electrons from their atoms, for example, an energy of about 14 eV will remove one electron from an oxygen atom. Successive electrons need more energy to be removed, until about 870 eV is needed to remove the eighth and last electron, and leave the "bare" nucleus. An oxygen atom has only 8 electrons, and larger atoms need more energy for all their electrons to be removed, but an energy of 10,000 eV, corresponding to a temperature of about 100 million degrees, will strip all the electrons from the nucleus of any atom. So we can say that atoms function and "have their being" in the energy range 0.1-10,000 eV (10^{-1} to 10^4 eV on the scale in figure 0.2).

Nuclei carry positive electric charges, and so two nuclei will repel each other and stay apart. But if two nuclei collide head-on with enough speed, that is enough kinetic energy, then they can overcome the mutual repulsion and come together and make a larger nucleus, and the lowest energy for this is about 1,000 eV (1 keV in figure 0.2). This is equivalent to a temperature of about 10 million degrees, which is about the temperature at the centre of the Sun, where the nuclear reactions occur that generate heat and light for Earth and our solar system. In the very high temperatures in stars, from about 10^7 K up to about 10^{10} K, nuclei split, merge and rearrange themselves in a series of interactions that release enormous energies.

Whereas a few electron-volts will remove an electron from its atom, an energy of a few million electron-volts is needed to remove one proton or neutron from its nucleus. Protons and neutrons are bound together in a nucleus with an energy about one million times bigger than electrons are bound in an atom. Chemical reactions, such as the combustion of a sucrose molecule, involve the rearrangement of electrons, and yield only a few electron-volts of energy. In contrast, the nuclear reactions in stars involve the rearrangement of protons and neutrons, and yield energies of millions of electron-volts.

Nuclei operate on the part of the energy scale between about 10^3 and 10^8 eV. At this end of the energy scale matter can be created directly from energy, though the creation of matter must always be accompanied by the creation of anti-matter. For example, an energy of about one million eV can create an electron and its anti-matter counterpart, the positron.

Electrons appear to be fundamental, and not to be composed of anything smaller, but protons and neutrons are each composed of a trio of smaller fundamental particles called quarks, and these are shown in figure 0.2(d). The force that binds quarks into protons and neutrons is so strong that isolated quarks have never been observed.

The quark is the last Russian doll in the series, because we've reached the point where we can't take things apart any further, and we encounter the basic stuff of the physical universe – "*mass-energy*". Matter is, in a sense, "*frozen energy*", and "*a material particle is nothing more than a highly concentrated and localized bundle of energy*". I'll return to this point in section 0.6.

0.2.4 unpacking the universe

Figure 0.2 unpacked the matter system we know as water on the energy scale, but we know there's more to the physical universe than water, and that matter systems have different sizes. Figure 0.3 lays out the hierarchy of the matter systems of the universe, arranged by size and energy. In this wider view we find galaxies, stars and planets, and on at least one of these planets, we find living things of various sizes. We find that physical matter, both inanimate and living, is made of many different types of molecules, and we've already unpacked water molecules to atoms, nuclei, protons and neutrons and finally to quarks.

a range of sizes

A size of 10^2 metres is ten times bigger than a size of 10^1 metres, and we say the first size is bigger by one order of magnitude, or one power of ten. So we see that the sizes of the objects in figure 0.3 span around 24 orders of magnitude, with the Earth the largest object shown, with a diameter of about twelve million metres.

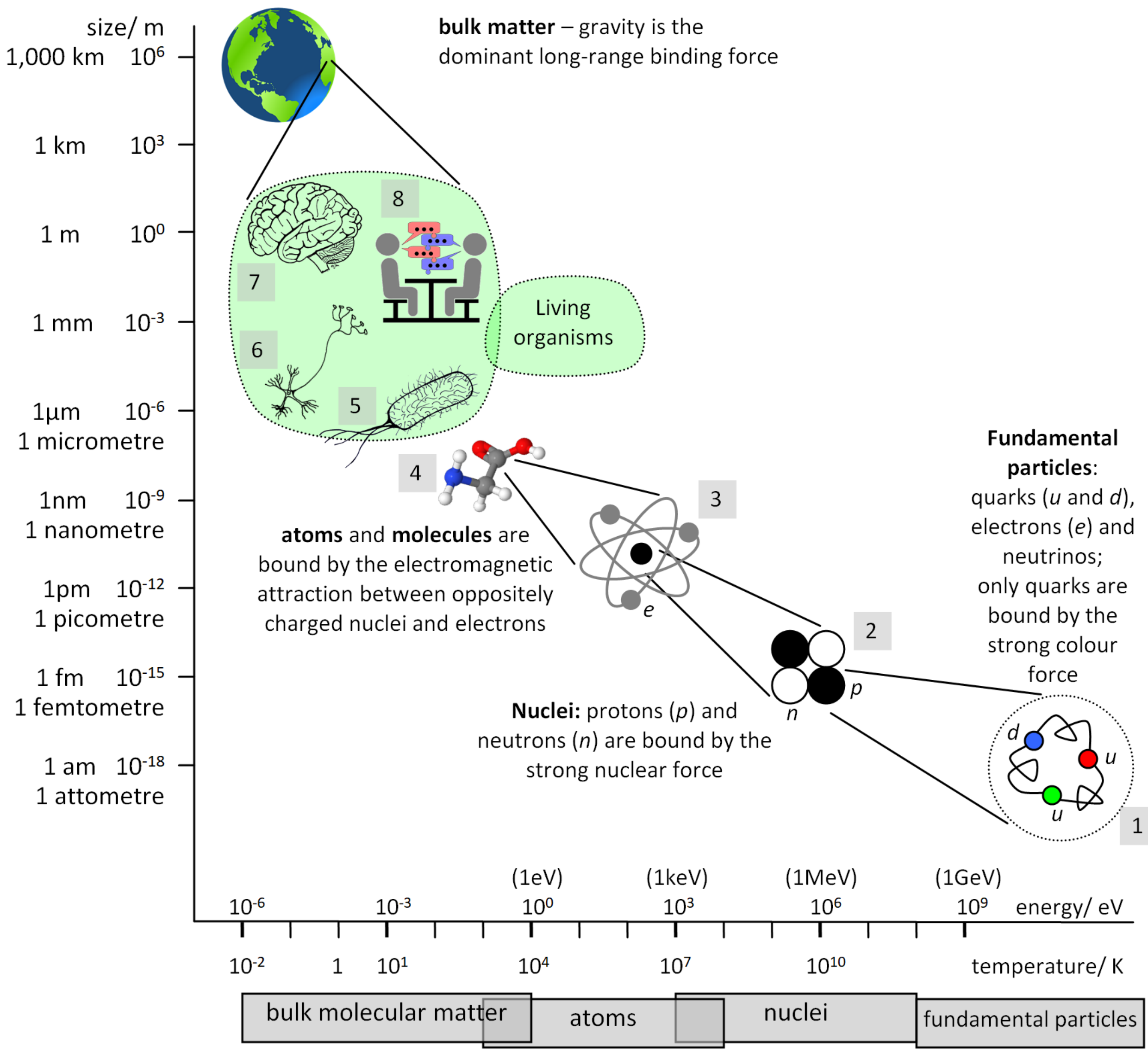


Figure 0.3. The range of material systems in our physical universe. Inanimate systems go from fundamental particles, through nuclei, atoms and molecules to larger structures such as planets. The green shaded region shows the bacterium E. coli, a neuron, a human brain and a conversation. The approximate physical size of systems is given on the vertical y-axis, and their energies are given on the horizontal x-axis, with units in electron-volts, eV. The approximate temperatures in Kelvin (K) are given below the energy scale. The matter systems are numbered with their level in the universal hierarchy.

Living things span nine orders of magnitude, from a giant redwood tree about 100 metres tall, to a bacterium, less than micrometre across. Molecules also span a large size range, for not all molecules are very small. For example, the glycine molecule shown in figure 0.3 is about 0.4 nanometres from end to end. Carbon is pre-eminently capable of potentially infinite links with itself, and so the largest molecules are carbon-based organic molecules. Fibrous proteins, such as cellulose and collagen, are linear molecules containing many thousands of atoms, and can be several thousands of nanometres long. DNA is an extreme example of a linear molecule. In a human chromosome it's coiled up inside the cell's nucleus, which is about 5 micrometres across, but if it is extracted and fully uncoiled it can be as much as 15 mm long.

Individual atoms range in size from about 100-400 picometres, and the nuclei at the centres of atoms are typically about 10 femtometres across, about four orders of magnitude smaller than atoms, while individual protons and neutrons within the nuclei are about 2 femtometres across. Individual quarks, the components of protons and neutrons, have never been observed, and their size is unknown, but less than 10^{-18} m, less than one thousandth the size of a proton.

0.2.5 a "scala naturae"

The systems shown in figure 0.3 form a "*scala naturae*", a natural hierarchy of systems of matter, in which things are made of smaller things, and are themselves part of bigger things.

a hierarchy of scientific specialisms

This is reflected in a hierarchy of scientific specialisms, where each specialism is an independent system of concepts, principles and terminology dealing with one particular matter system.

For example, particle physics deals with fundamental particles such as quarks in protons (object 1 in figure 0.3), while nuclear physics deals with protons and neutrons clustered together in nuclei (object 2), and atomic physics covers the behaviour of electrons clustered round these nuclei (object 3). Chemistry covers physical matter's interactions with itself, and with the structures that it makes, such as the glycine molecule, which is object 4. Organic chemistry deals specifically with carbon-based molecules, such as glycine, and biochemistry deals with the molecules and reactions in living cells, such as the *E. coli* bacterium that is object 5. The glycine molecule is one of the 20 amino acids found in proteins, and so it is half in and half out of the group of living things in figure 0.3. While the *E. coli* bacterium would be the speciality of a biochemist or cell biologist, neuroscience deals with the behaviour of neurons, either singly (object 6), or interconnected in brains (object 7). The two people having a conversation (object 8) would be of interest to a wide range of specialisms, including neuroscience, psychology, sociology and economics.

Each specialism draws on principles and concepts from disciplines a little way below, and lays the basis for disciplines a little way above. For example, cell biology draws on the principles of biochemistry but not of nuclear physics, and can usefully contribute to neuroscience but not to economics.

the reductionist approach

We follow a reductionist approach when we describe the behaviour of matter systems in terms of their constituents. For example, we describe thoughts in terms of signals between neurons, biological cell function in terms of molecular interactions, and the behaviour of gases in terms of atoms and molecules. Our understanding of the physical universe can be organised in a reductionist sequence of levels, that might go like this:

social and cultural values → mental processes → living cells → molecules → atoms → protons, neutrons and electrons → quarks.

The current scientific description of our universe in terms of hierarchies of matter systems resembles a set of Russian dolls, as I mentioned at the start of this chapter. We can unpack the separate dolls, and lay them out, and describe each one well in its own terms, but we have no overall pattern or scheme for how they all relate to each other.

0.3 the universal hierarchy of communities

0.3.1 an unbroken chain

We're familiar with the idea that all living things are connected through their molecular DNA, in an unbroken chain of inheritance to the very first living cell. If we extend this idea, then there must be a similarly continuous narrative that takes things from the beginning of the universe in the Big Bang to the present time.

Every particle in our bodies and our physical world is connected in an unbroken chain of transformations to the very first discrete particles created in the universe. So, how did we get from *there* to *here*? By what processes have empathy and laughter, music and mathematics, emerged from fundamental particles, forces and energy?

0.3.2 the universe evolves by forming communities of things

The reductionist approach has brought enormous understanding, but it is retrospective, for it takes apart things that have already been created. The evolution of the physical universe has broadly followed the reverse of the reductionist sequence. If we follow the universe forwards as it evolves, then what we see is things coming together in new groupings to make new things, with the emergence of novel entities with new properties. We can begin to see the universe, not in terms of unitary things, but in terms of *communities* of things.

The physical universe that we can perceive, from space-dust to brain tissue, is made from just four types of fundamental particles – *up* and *down* quarks, electrons and neutrinos. These are assembled, first into communities, then into communities of these communities, and so on in a cumulative progression, that builds up a hierarchy of communities. Each community is brought into existence and sustained by the communities below, and in turn creates and sustains the community above. We can follow this sequence in figure 0.3, starting at the bottom right and working towards the top left.

So …

1) a community of fundamental quarks form a proton or a neutron (object 1),

2) a community of protons and neutrons form a nucleus (object 2),

3) a nucleus becomes the centre for a community of electrons – an atom (object 3),

4) a community of atoms become a molecule (object 4), which is capable of chemical reactions with other molecules,

5) a community of biochemical reactions between molecules become an individual living cell (object 5),

6) a community of specialised cells become a complex organism, with a nervous system composed of neurons (object 6),

7) a community of neurons become a brain (object 7), which controls an individual organism, and finally,

8) a community of brains become a society of cooperative individuals, sharing their ideas and feelings (object 8).

This is the universal hierarchy of communities in a nutshell, and in just eight levels it goes from quarks to consciousness. Each of these eight levels is represented by a graphic element in figure 0.3. The first four communities are inanimate, and the second four are living systems. Inanimate matter does not progress beyond the fourth level, for while matter can aggregate on larger and larger scales, such as crystals, mountains, oceans, planets and stars, none of these has the properties of the tiniest living cell.

0.3.3 the emergence of novelty

As we ascend the universal hierarchy, we see simpler entities come together to become parts of a more complex whole with novel properties, that can then act as a unitary entity in its own right. For example, a nucleus and a cluster of electrons together make an atom; atoms can combine to make molecules; molecules interact in life processes; life processes can sustain a self-conscious mind. At each stage a new whole emerges, with novel properties that transcend their separate parts. Earlier I used water to illustrate the reductionist unpacking of the universe; now we can use water to illustrate the emergence of novel properties of a community.

water – from molecule to liquid

A single molecule of water is not wet; it cannot flow or freeze, boil or evaporate, and it is incapable of dissolving anything. These are all emergent properties, that arise from the interactions between large numbers of water molecules. The flow of water in a river, the skin of ice on a puddle, the bubbling of soup simmering in a saucepan, the chill of sweat drying and the saltiness of blood are all bulk properties of large ensembles of water molecules. These bulk properties only emerge when large numbers of water molecules come together, and introduce a new "*physical principle of organization*", and this is shown in figure 0.4.

Every molecule is moving and spinning, and colliding with other molecules. The outcome of each interaction between a pair of molecules is determined by their specific properties. Figure 0.4 shows the interactions in a very general way, and in fact a pair of molecules may attract or repel each other, and may also set each other spinning in the process. But in even a tiny drop of water there are billions of random interactions in every second, and water's bulk properties are the sum of all of them.

The point is not whether water's bulk properties can be predicted or explained in terms of the properties of an individual molecule. The point is that the bulk properties only emerge and have any meaning when large numbers of individual molecules come together.

a hierarchy of physical laws

The principle of hierarchical organization generates a hierarchy of physical laws and concepts, So, the "*laws of electron motion beget the laws of thermodynamics and chemistry, which beget the laws of crystallization, which beget the laws of rigidity and plasticity, which beget the laws of engineering*".

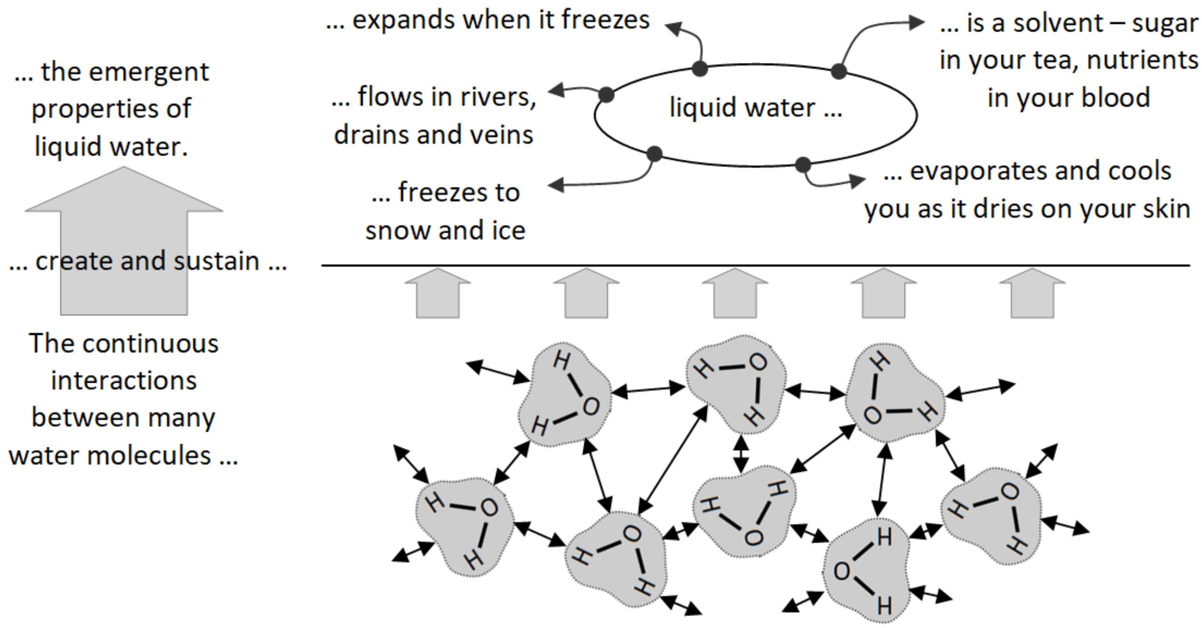


Figure 0.4. The emergence of the properties of liquid water from the ceaseless interactions between individual H_2O molecules. The interactions are shown as double-headed arrows, which can be attractions or repulsions.

So, rather than a single Theory of Everything, "*we appear to face a hierarchy of Theories of Things, each emerging from its parent and evolving into its children as the energy scale is lowered*". Most of us live successful daily lives with a working knowledge of only a few specialisms, for example, materials science (wood, metals, plastics), biochemistry (food and nutrition) and psychology (social behaviour and relationships).

0.3.4 communities are bound together by exchanges

What binds communities together on every level of the universal hierarchy is a process of exchange. Science recognises and can quantify the forces between inanimate matter systems as due to the exchange of particular particles. For example, quarks are bound together in a proton by the exchange of particles called gluons, and the electromagnetic forces between charged particles such as protons and electrons are due to the exchange of photons.

The communities on each of the four animate levels are also bound together by ceaseless exchanges. We usually think of a biological cell as a "community of molecules" undergoing a set of metabolic reactions. But it is more useful to turn this around and see a cell as a metabolic ensemble of biochemical reactions that process a set of molecules, directed by proteins, for it is the reactions that are constant, and the molecules that are transient, and are just passing through. So we can see a cell as a community of chemical reactions, in which proteins exchange molecules between themselves, thereby sustaining the cell's overall metabolism.

In complex living organisms that comprise specialist cells, the cells are in constant communication by the exchange of specific messenger molecules, and if a cell does not receive these molecules, then it may die. In organisms with nervous systems, neurons are cells that are specialised for relaying signals, and a brain is a community of interconnected neurons that are ceaselessly exchanging signals between themselves. And finally, our human culture is sustained by the constant exchange of thoughts and feelings through language, mediated by books and magazines, the broadcast media (such as tv and radio), and the social media (such as Twitter and Facebook), as well as by the economic exchanges of goods and services.

8: a community of brains, exchanging thoughts and feelings using symbolic language, and also material goods and services, create and sustain a mutually dependent social and economic culture.

7: a community of inter-connected neurons, exchanging neurotransmitter molecules, create and sustain the brain of a social individual.

6: a community of specialist cells, bound by sharing the same DNA, and exchanging messenger molecules, create and sustain a complex organism with a nervous system.

5: a community of metabolic reactions, mediated by protein catalysts and directed by a single DNA molecule, create and sustain a living cell.

4: a community of atoms, bound by shared electrons, create and sustain a molecule.

3: a community of electrons, bound to a nucleus by electrostatic attraction, which is mediated by the exchange of photons, create and sustain an atom.

2: a community of protons and neutrons, bound by the strong nuclear force, which is mediated by the exchange of pions, create and sustain a nuclide.

1: a community of quarks, bound together by the strong colour force, which is mediated by exchanging gluons, create and sustain a proton (*uud*) or a neutron (*udd*).

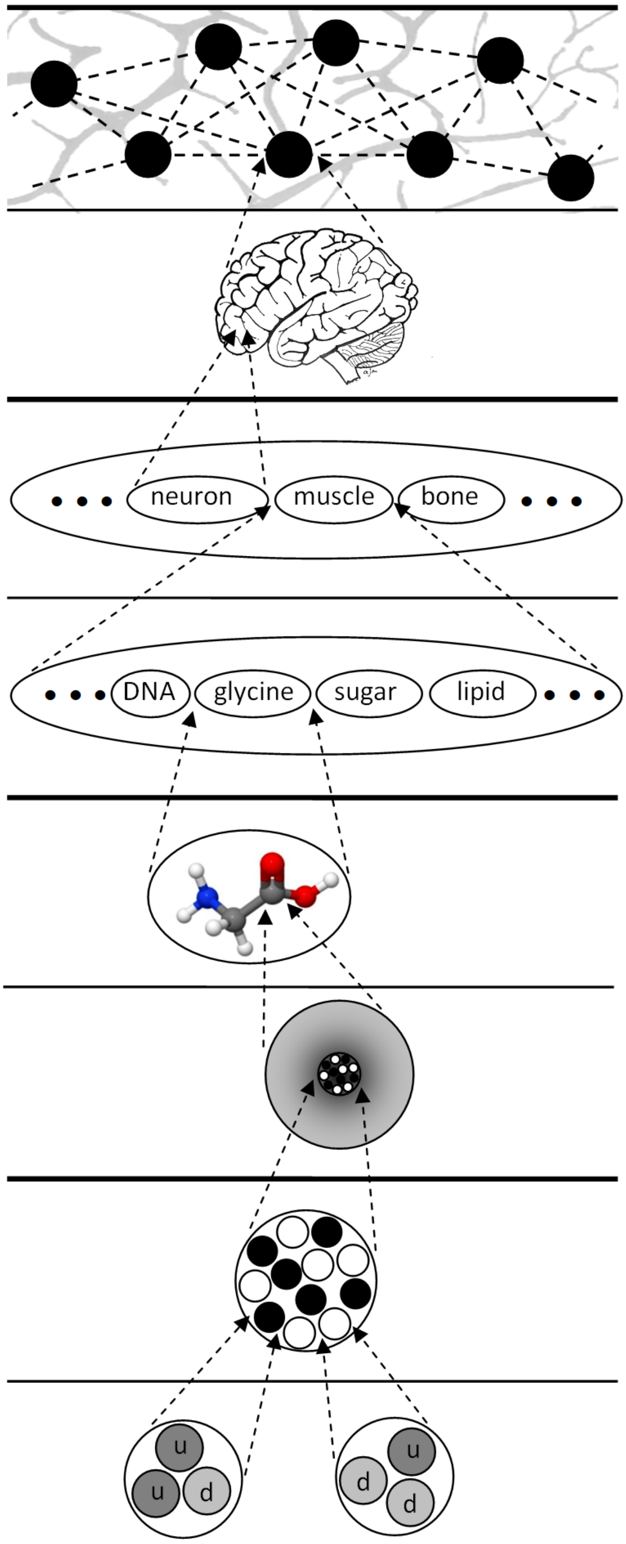


Figure 0.5. The eight levels of the universal hierarchy of our physical universe.

The communities at every level in the universal hierarchy are bound together by endless exchanges between their members, and every exchange renews and reaffirms the bond between them. From the lowest level to the highest, the universe is sustained by this unceasing activity, and nothing is ever still or at rest. The universe is not a static thing like the stones stacked into an arch, but it is more like the array of balls kept aloft by the ceaseless motions of a juggler's hands.

0.4 the universal hierarchy of communities

The "*scala naturae*" of matter systems, that was listed in section 0.3.2, is shown arranged into the universal hierarchy of communities in figure 0.5. This should be read from the bottom to the top, following the evolutionary sequence, and reflecting the way that higher levels are sustained by lower levels. Each level of the hierarchy is summarised on the left, with a particular example given on the right. The universal hierarchy can be set against the unpacked universe, shown in figure 0.3, and each of the eight levels in the hierarchy is represented by a numbered graphic element in the figure.

following the fundamental particles

If we could be present in the very early universe, when it was less than about 100 microseconds old, then we would see free *up* and *down* quarks and electrons. Imagine that we take a handful of these quarks and electrons and tag them, so they can be distinguished from all the others. If we follow these tagged particles through the universe's evolution to the present time, then we might see some of them in living systems in levels 5-8 in figure 0.5. Quarks would be sustaining the protons and neutrons in atomic nuclei, and electrons would be involved in the unceasing biochemical interactions that sustain all living organisms, including the endless shared thoughts of the humans in level 8.

Each of us is represented by one black circle in level 8, and is sustained by the hierarchy of physical systems in the seven levels below. In figure 0.5 we see the emergence, level by hierarchical level, of the human qualities of abstract thought and empathy from the most basic fundamental particles in the universe.

explanations at their appropriate levels

As human beings, at the top and most recent level, we can look within ourselves and see all the way down to the quarks at the bottom, as we saw in the first section of this chapter. But each level has its own particular laws and principles. So, we explain our actions in terms of thoughts, ideas and feelings, and also in terms of molecules like neurotransmitters or alcohol or drugs, but not in terms of protons and neutrons. Our existence as conscious human beings rests ultimately on quarks, but is not explained by them. So, "*if neuroscientists someday decode the entire wiring diagram of the brain, human behavior makes the most sense when it is explained in terms of beliefs and desires, not in terms of volts and grams. Physics provides no insight into the machinations of a crafty lawyer, and even fails to enlighten us about many simpler acts of living things*".

We have seen that we cannot explain the bulk properties of water just in terms of the nature of a single molecule, but we have to consider the sum of all molecular interactions. Similarly, we cannot reduce the workings of each level of community to the workings of the lowest. We can *describe* thoughts and feelings in terms of the collective actions of atoms, for the thoughts and feelings arise from what the matter at the lower levels is doing. But we cannot *explain* thoughts in terms of atoms, for thoughts only arise at the level of a community of interconnected neurons.

So, if we could observe a thought enacted in the brain, we would see a pattern of coordinated activities of atoms. If we could recreate the activities of these atoms, then we could recreate the thought. But while each atom plays its part in the overall pattern, a collection of atoms will not spontaneously enact this pattern of coordinated activities. To do this, they must be organised into molecules, then into specialised neurons, and then into a specifically connected community of neurons, a brain – and then it must be a brain that has been shaped by a particular genetic inheritance and environmental experiences.

So, a thought, a collective event arising from the coordinated behaviour of a great number of atoms, can only be explained in terms of the level of the hierarchy on which it occurs. In short, we can break down a thought into a pattern of actions of individual atoms, but we can't go the other way and explain a thought in terms of the properties of an individual atom.

0.5 the two themes of this book

This book has two themes: first, that our physical universe has evolved as an emergent hierarchy of eight levels of communities; and second, that on each level, communities are bound together and sustained by ceaseless processes of exchange. The next eight chapters describe how communities work at each of the universal hierarchy. This introductory chapter is given the number zero, to bring subsequent chapter and level numbers into line.

But first, we need to look at the quantum mechanical foundations of the physical universe, which we could perhaps call level 0.

0.6 the quantum entity

Our everyday experiences are with macroscopic objects, made of large numbers of atoms, which stay in the same place when we put them down, and move when we push them about. We also recognise that these objects are influenced by fields, so a compass needle will rotate to align with the Earth's magnetic field, and the compass will fall in the Earth's gravity field when we let it go. Classical mechanics recognises particles as point-like objects with a definite location and motion in space, and fields as spreading throughout space, and having a particular value at every location, and when a field oscillates across space and time, it's called a wave. Particles and fields are opposites in that a particle has a unique precise location, while a field is everywhere, and so particles interact through the influence of fields. Taking a rock as a typical particle, to determine "*the entire trajectory of the rock, you need to tell me its position, its velocity, and what forces are acting on it. Newton's equations tell you the rest*". A profound consequence is that "*Newtonian mechanics describes a deterministic, clockwork universe*". Newton's laws of motion work perfectly well in describing the motions of objects over a huge range of sizes, explaining gas pressure in terms of molecular collisions, enabling us to land men on the Moon, and explaining the orbits of the planets around the sun.

But things that appear to be waves have particle-like properties, and so a light wave is actually a stream of photons, each of which has a definite energy and momentum. Conversely, things that appear to be particles, like electrons, show wave-like properties, which explains electron diffraction and the stability of atoms and molecules. These are examples of "*the breakdown of classical mechanics – not merely an inaccuracy in its laws of motion, but an inadequacy of its concepts to supply us with a description of atomic events*". This has brought us to quantum mechanics, which has "*unified particles and fields into a single entity, the wave function*". In quantum mechanics "*the world is fundamentally wavy; its apparent quantum discreteness comes from the particular way those waves are able to vibrate … Things like "space" and "fields" and "particles" are useful ways of talking about that wave function in an appropriately classical limit*".

In a classical universe a particle is of a lump of "matter-stuff", containing a certain amount of matter, with a fixed size and sharp boundary, and a precise position and state of motion at any moment in time, and this is the classical particle shown in figure 0.6(a). But the particles of our universe are not like this at all, and are more like the quantum entity shown in figure 0.6(b).

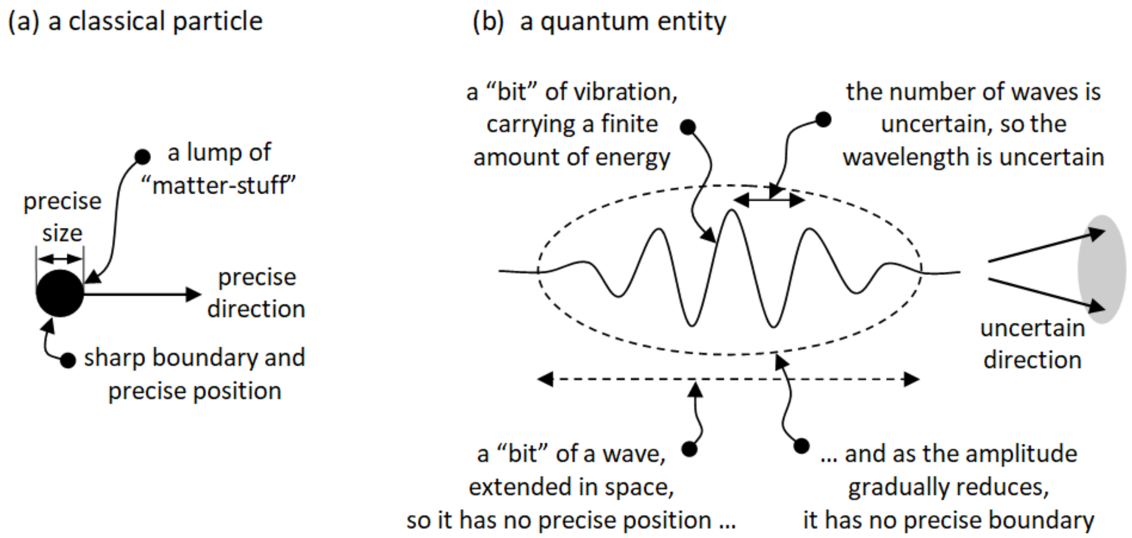


Figure 0.6. A classical particle and a quantum entity.

How can we comprehend the nature of this wiggly "thing"? It is a brief vibration, an "*isolated piece of a wave*", that arises from nothing, vibrates a bit, then returns to nothing, and this is represented visually as the wiggly waveform shown in the figure. This finite presence makes it a discrete thing like a particle, so the quantum entity is often called a "particle-wave", because it can be seen as having a dual nature.

The quantum entity is not a discrete lump of immutable "matter-stuff", but more like an action or a gesture – the trace of an infinitely pliable form. It is a holistic entity that is seamless and continuous, because if we remove even the smallest part of it, then we destroy the whole. If we peer into it we see only the pulse of its intrinsic energy, so it is created and sustained by ceaseless activity, and is never still or at rest, for "o*scillatory waves go through cycles in time and space; their essence is repetition*". A quantum entity unites space and time; its sequence of waves occupy space, and its ceaseless oscillations occupy time.

a world of happenings, not of things

We need to think in a profoundly different way if we are to understand the physical universe in terms of quantum entities and not classical particles.

A classical particle is inherently immutable; it is a discontinuity in the universe, making it a binary thing, that is either completely present or totally absent, and we must think in terms of certainties. If a classical particle is set down in a state of rest, then it will stay as it is, unchanging; if it's set moving, it follows a single precise path, like a bullet. The interactions between two classical particles are deterministic, resembling collisions between snooker balls, in which the particles remain essentially unchanged, and there is only one outcome.

A quantum entity is inherently active and pliable; it is a seamless continuous whole, with no discontinuity, and with an amplitude that varies, so it is more "present" in some places than in others, and we now have to think in terms of probabilities. A quantum entity can't be set down in a state of rest; if it's set moving, it travels as a wave that is extended in space, and does not follow a precise, pre-determined path. The interactions between two quantum entities can be more like the meeting of two sets of waves than like collisions between snooker balls, so there can be a range of outcomes, with different probabilities.

Quantum mechanics shows us that the physical world is fundamentally composed, not of bits of "matter-stuff", but of wiggly quantum entities, like the one shown in figure 0.6. We don't live in a world where "*minute cold stones* … [travel] … *on long precise trajectories in geometrically immutable space*". On the contrary, "*the world is a continuous, restless swarming of things; a continuous coming to light and disappearance of ephemeral entities*. … *A world of happenings, not of things*".

0.6.1 uncertainty

The classical particle embodies certainty; it has a precise location and direction of motion. In contrast, the quantum entity is a fundamentally uncertain thing. It is a "bit" of vibration, carrying a certain amount of energy, comprising a finite number of waves, which extend in space and gradually fade away. We "*cannot define a unique wavelength for a short wave train*", so we can't be sure of its wavelength, and nor can we be sure of its position, or even its direction of motion.

A classical particle is an unchanging thing; you see all there is to see in the briefest of glances, and observing it for longer will show you nothing new. But the quantum entity is not a thing, it is a cyclic action, and the longer you observe it, the more accurately you perceive it.

A bird flies by the cycle of its wing beats, and a high-speed photograph of a bird in flight shows it "frozen" in one part of this cycle, perhaps with wings outstretched. To see the complete flying action we have to observe the bird for at least one cycle of its wingbeat. Likewise, a high-speed photograph of a wave may show it poised, about to crash on to the beach, and to see the wave in its entirety, you have to observe it for at least one cycle. Like the bird and the wave, a high-speed "snapshot" of a quantum entity gives only a very vague indication of its form and the energy it carries, and the longer you observe it, the more precisely you can measure this energy.

There are two major uncertainties that are fundamental to the quantum entity, and each of these uncertainties involves a pair of parameters where we have to accept a degree of imprecision. The more precisely we know one of the pair of parameters, the less certain we are of the other.

The first pair of parameters are energy and time; the shorter the time that we observe a quantum entity, the less certain we are about how much energy it has. The second pair of parameters are momentum and position; the more precisely we know the quantum entity's momentum, that is, how fast it's going and in what direction, the less certain we are about where it is. These are two versions of Heisenberg's uncertainty principle, which he summarised as "*We cannot know, as a matter of principle, the present in all its details*".

We'll look at the energy/time uncertainty in chapter 2, on nuclide communities, and see how this enables the existence of virtual particles. The momentum/position uncertainty comes up in chapter 3, and we'll see how this enables quantum tunnelling and diffraction, and determines the sizes of atoms.

0.6.2 the wavefunction

To describe the behaviour of a quantum entity, the "*isolated piece of a wave*" shown in figure 0.6, we need an equation that describes how a wave evolves as it moves, and this is Schrödinger's wave equation. Solving the Schrödinger equation gives us a mathematical quantity called the wavefunction. "*The wavefunction contains all the dynamical information about the system it describes*", and it replaces the concept of a classical particle's trajectory.

In everyday examples of physical waves, there is always something that is "waving". With waves in a rope, like a washing line, the rope moves from side to side; with waves on puddles, the water surface moves up and down; and sound waves are transmitted by vibrating air molecules. The wavefunction for waves in a rope is the sideways displacement, in water waves it is the height of the surface, and in a sound wave it is the displacement of the air molecules.

The wavefunction that emerges from the solution of the Schrödinger equation is a "*mathematical function rather than a physical object*", and wavefunctions have been called "*oscillations of possibility*". "*At any instant in time it has a value for each point in space. So, unlike the position in space of a classical particle, the wavefunction is spread out over all of space – hence the term 'wave'*". We can use the mathematical wavefunction to predict the values of quantities that have physical meaning, but we cannot directly observe the wavefunction itself. Where the quantum entity is a material object, like an electron, then it is often called a "matter wave".

The wavefunction is not a physical entity, but is the representation of one. Hence, we have to view a wavefunction as "*one entire thing*", and think of it as "*describing (or 'being') just a single particle*", so that wavefunctions are "*completely holistic entities*". A wavefunction can have a quite complicated shape, depending on the system it is describing. A single electron will have a rather simple wavefunction, but "*the wavefunction describing the structure of an atomic nucleus, with its many protons and neutrons obeying complicated rules, is much more complicated*".

The wiggly quantum entity in figure 0.6 is not a single wave, but a "wave packet", which is "*an isolated piece of a wave, like a pulse, that can be constructed by superimposing many different waves of varying wavelengths and amplitudes in such a way that they interfere and cancel each other out everywhere apart from the tiny localized region where the particle happens to be*". In quantum mechanics "*a localised particle is represented by a wave packet, which has a maximum at the most probable position of the particle*". So, we can't view the interactions between quantum entities like collisions between snooker balls, instead we must see them as the overlapping and interference of wavefunctions. In this sense, quantum mechanics "*regards the world as made out of waves rather than out of things*".

particle-wave

The quantum entity has the particle property of mass, so it has momentum when it moves. It also has the wave property of intrinsic vibration, so it has a wavelength, and is extended in space. These apparently conflicting "particle" and "wave" qualities co-exist in complete harmony, so that there is "*no distinction between a wave and a particle*", and a quantum entity is both a particle and a wave at the same time, and all the time.

0.6.3 mass-energy

We are now in a position to see a fundamental particle, such as a quark or an electron, not as a lump of matter-stuff, but as "*a highly concentrated and localized bundle of energy*". The quantum entity can, in principle, take the form of any fundamental particle at all, and can be seen as the "incarnation" of a finite amount of energy as physical matter, possessing mass as the "*energy of being*". At the lowest, fundamental level in our physical universe "*mass is energy and energy has mass*", and everything consists of "*the same basic stuff, 'mass-energy', transfigured in time from one form into another*".

Energy (E, J) and mass (m, kg), are equivalent, linked by the speed of light (c, m/s), as expressed by Einstein's equation:

$E = mc^2$ *(equation 0.1)*

so Joules and kilograms are two units for the same quantity – mass-energy.

formless energy takes physical form

The first and lowest level in the emergent hierarchy starts with the undifferentiated energy from the big bang becoming 'centred', localised as individual quantum entities. Formless energy takes its first physical form in discrete structures that we know as the fundamental particles. We can now look at the first level in the universal hierarchy – the communities of quarks that create and sustain protons and neutrons, and this is the subject of chapter 1.

0.7 Notes

Each note starts with the first few words of the sentence or quotation to which it relates.

0.1 right here, right now

"**This book will take you**", there are a lot of notes, for a number of reasons: (1) to substantiate statements made in the text, (2) to explain the calculations, (3) to add a bit more information, and (4) to let the reader follow up anything of interest. The notes have been gathered here so as not to disturb the flow of the text.

I thought about indicating which sentences are supported by a note by putting a "double dagger" sign (‡) at the end of the sentence, like this.‡ But when I tried it out with this introduction, even this minimal indication felt intrusive. So, there's nothing to indicate which sentences have supporting notes. However, a useful guide is that every "*quote*" and every statement of fact is supported by a reference.

Scientific books and research papers often have many authors, and some authors have many publications to their name. To keep references both simple and precise I give every reference in the same format, as "first author (year):page number". The year is followed by a letter, such as a, b, c, if I make use of more than one publication from that author in that year. Page references are by far the most common, and these are referred to just by number, while chapters, sections and tables are individually mentioned.

All internet links were accessible in July 2019.

The small inset figure at the start of this chapter is a very simple representation of the 8 levels of the universal hierarchy, using elements from figures 0.3, 0.5, and 0.6.

0.1 right here, right now

"**Observed from far away**", for a comprehensive look at the scale of objects in the universe, see Morrison 1982. This presents the same series of views as the classic book by Eames 1997, but with a helpful commentary.

For a comparable look at the scale of time for events and processes in the universe, see 't Hooft 2014.

when did you last think of an electron?

"***If you wish to make an apple pie***", Sagan 1980:218.

"***the tendency of nature***", Laughlin 2006:8.

0.2 The major systems of matter in our universe

0.2.1 the universe as a set of Russian dolls

0.2.2 sugar and measuring energies in eV

Figure 0.1: the pictures of sugar were taken with a Canon PowerShot A640. The 2-D sucrose molecule is from the Wikipedia article on sucrose, and the 3-D molecule is from http://www.chemtube3d.com/ClaydenSucrose.html, and can also be seen at Chemspider (ID 5768) at http://www.chemspider.com/.

"**The label on a bag of sugar**", halving a pile of sugar divides the number of grains by two, which we can write as 2^1, so two halvings divides the number of grains by 2^2, three halvings divides the number by 2^3, and so *n* halvings divides the original number by 2^n.

I'll treat the sucrose grains as 1 mm cubes, because this makes the maths easier, and figure 0.1 shows they are not too far off this shape.

The density of sucrose is about 1.6 g/cm^3, so a 1 mm cube weighs $1.6/1{,}000 = 1.6 \times 10^{-3}$ g, and this means there are about $100/1.6 \times 10^{-3} = 62{,}000$ grains of sucrose in a 100 g pile. If we halve this pile 16 times in succession, then we end up with $62{,}000/2^{16} = 0.95$ grains, in effect a single grain.

Calculating the number of sucrose molecules involves moles, and is easier than it might seem (see Atkins 2002:F47, or any GCSE chemistry textbook). One mole of any "thing" is simply 6.0×10^{23} "things", and this number is known as Avogadro's constant.

One mole of sucrose molecules, that is 6.0×10^{23} molecules, has a mass of 342 g. So one grain of sucrose, taken as a 1mm cube with a mass of 1.6×10^{-3} g, contains about $6.0 \times 10^{23} \times 1.6 \times 10^{-3}/342 = 2.8 \times 10^{18}$ molecules.

If we cut this grain in half 61 times, then we reduce the number of molecules to $2.8 \times 10^{18}/2^{61} = 1.2$ molecules, very close to a single molecule. So a series of 16 + 61 = 77 halvings will reduce a 100 g pile of sugar to a single sucrose molecule.

The combustion of a 100 g pile of sucrose releases 1,700 kJ of energy. So, the energy released by the combustion of a single grain of sucrose will release $1.7 \times 10^6 \times 1.6 \times 10^{-3}/100 = 27$ J of energy.

This 100 g pile of sucrose contains about 6.0 x 10^{23} x 100/342 = 1.75 x 10^{23} molecules, and so the energy provided by one molecule of sucrose = 1.7 x 10^{6}/1.75 x 10^{23} = 9.7 x 10^{-18} J (the figures have been rounded in the table).

An energy of 1 eV equals 1.6 x 10^{-19} J, so 1 J = 1/1.6 x 10^{-19} = 6.25 x 10^{18} eV. So, the energy provided by the 100 g pile is 1.7 x 10^{6} x 6.25 x 10^{18} = 1 x 10^{25} J, and the energy provided by a single molecule of sucrose is 9.7 x 10^{-18} x 6.25 x 10^{18} = 61 eV.

Sucrose is a disaccharide, with a molecule that comprises two simple sugars, glucose and fructose, linked by an oxygen atom (Garrett 2005:217, Purves 1998:49). The electron-volt: converting Joules to electron-volts, see Close 2007a:11.

glucose and neurons

"**For example, the human cortex**", neurons are "*probably the most fastidious cells in the body*", and rely almost entirely on a constant supply of glucose from the bloodstream (Alberts 2008:102). For a typical neuron in the cortex to "fire" and pass on a nerve impulse, requires about 1.2 x 10^{9} ATP molecules, the cell's energy "currency" (Lennie 2003). Each ATP molecule releases about 0.5 eV (Alberts 2008:825), so one firing consumes 6 x 10^{8} or 600 million eV. Since one molecule of glucose provides about 30 eV (see section 5.5.1), a neuron consumes about 20 million glucose molecules each time it fires. There are some 12-16 billion neurons in the average human cortex (Roth 2005, Herculano-Houzel 2009). Cortical neuron firing rates vary widely, but firing rates between 5 and 25 "spikes" per second is fairly representative (Shafi 2007, O'Connor 2010). So, every second the cortex requires around 10 x 10^{9} x 10 x 20 x 10^{6} = 2 x 10^{18} glucose molecules.

The combustion of a glucose molecule yields about 30 eV of energy, of which half is lost as heat, and only 15 eV is in the form of ATP molecules, that the neuron can use. This doubles the rate of consumption of glucose, so a neuron uses about 40 million glucose molecules in each firing. This is explained in section 5.5.1, on the metabolism of glucose.

The calculation above is simplified, and glosses over the rôle of ATP as the cell's energy currency, which is covered in chapter 5, but all we need at the moment is an idea of the vast numbers involved on the molecular scale.

0.2.3 energy and temperature

"**On the microscopic scale**", Close 2007a:11.

"***turmoil and temperature go hand in hand***", quote from Atkins 2007:19 and also see his chapters 1 and 2, and see Cotterill 2008:chapter 3 on the connection between "heat" and motion.

"**Thus there is a profound connection**", Close 2007a:11, who describes the changes in matter as its temperature increases. Allday 2002:257 gives a bit more explanation of the link between particle energy and temperature. The relation between energy and temperature is covered in the notes on section 2.10.1.

"**For example, giving a water molecule**", liquid water has a molar heat capacity of about 75 J/K/mol, so one mole of water molecules, requires about 75 J of energy to raise its temperature by 1°C. But one mole is 6 x 10^{23} molecules, so in getting one degree "hotter" each molecule gains about 75/6 x 10^{23} = 1.3 x 10^{-22} J = 0.0008 eV – a bit less than 0.001 eV.

Figure 0.2 is based on Heyde 1994, figures I.1 and I.3, and Heyde 1998, figures 1.1-1.3. The sharp-eyed reader will have spotted that the H_2O molecules shown in (a) are packed less closely in the ice crystal than in the water drop, and this anomalous behaviour is why ice floats on water (Cotterill 2008:84). The "atom" shown in (b) is the "Rutherford" atom (Carroll 2019:45), which is a misrepresentation, but one that is universally recognised; the nuclide in (c) is the cluster of 8 protons and 8 neutrons that comprise the nucleus of oxygen-16; the cluster of quarks in (d) comprise a proton.

"**We're familiar with the way water changes state**", see Cotterill 2008:82 for a description of boiling water in a kettle.

"**But as steam is heated**", water molecules gradually dissociate as the temperature is raised from 2,000-4,000 K, mostly into a mixture of atoms and molecules of hydrogen and oxygen (H, H_2, O, O_2) – Steinfeld 2003:7, Tsutsumi 2019.

"**So we can say that bulk molecular matter**", the metal tungsten has the highest boiling point of all the elements, about 6,200 K, and this sets the upper energy limit for bulk matter at around 1 eV.

"**Energies larger than this**", the energy required to remove an electron from its atom is the ionisation energy, and values are widely available (for example, Atkins 2002:chapter 1). Values are often given in kJ/mole by chemists, and in eV/particle by physicists (1 kJ/mole is about equivalent to 0.01 eV/particle).

The successive ionization energies of the atoms of the elements are given at https://en.wikipedia.org/wiki/Ionization_energies_of_the_elements_(data_page). The nucleus of the iron atom has 26 protons, and an energy of about 9,300 eV is needed to strip all 26 electrons from it.

"**In the very high temperatures in stars**", Williams 2001:350, and this is covered in chapter 2 of this book.

"**Whereas a few electron-volts**", it requires an energy of about 8 MeV to remove a proton from a typical nucleus": Heyde 1994:217, Williams 2001:56.

"**The force that binds quarks**", isolated quarks have not been observed (Han 1999:chapter 10, Close 2007a:103), and Duff 1986:chapter 6 explains how the energy to pull two quarks apart is so big that it is enough to create a new quark-antiquark pair.

"***mass-energy***", Hogan 1998:chapter 3 gives a concise and accessible explanation of "*mass-energy*".

"***frozen energy***", Close 2004a:68.

"a material particle", Ford 1991:27.

0.2.4 unpacking the universe

Figure 0.3 is based on Close 2007a:figure 1.2, Duff 1986:figure 1.1, Heyde 1994:figures I.1 to I.3 and Heyde 1998:figures. 1.1 to 1.3. The hierarchies of scientific disciplines are based on Ellis 2006 and 2011. The molecule shown is the amino acid glycine (Chemspider ID 730), from Chemspider at http://www.chemspider.com and depicted using JSmol: an open-source HTML5 viewer for chemical structures in 3-D; http://wiki.jmol.org/index.php/JSmol. Atoms are colour-coded following the standard JSmol convention: carbon = grey, oxygen = red, nitrogen = blue and hydrogen = white.

3-D molecular structures are available at a number of websites, including http://www.chemspider.com/, and http://www.chemtube3d.com/Organic%20Structures%20and%20Bonding.html, http://www.biotopics.co.uk/jsmol/jscontents.html, and https://chemapps.stolaf.edu/jmol/jsmol/jsmol.htm.

The items shown in the living systems shape in figure 0.3 are chosen to illustrate different levels in the universal hierarchy: a molecule of the amino acid glycine (level 4); the bacterium *E. coli* (level 5), a neuron (level 6), a brain (level 7), and a conversation (level 8).

a range of sizes

For an overview of the sizes of living things see Campbell 2008:figure 6.2; for the size of the giant redwood, see Purves 1998:597; for proteins, see Alberts 2008:chapter3 and figure 3-23, Garrett 2005:chapter 5; for cellulose, see Alberts 2008:1197, Cotterill 2008:438; for DNA, Alberts 2008:210. The human chromosome number 22 has about 48 million nucleotide pairs, and the single molecule would be about 15 mm (15,000 µm) long if it were laid out, but the molecule is coiled and compacted to be only 2 µm across when the cell divides. The nucleus in most animal cells is about 5 µm across (Purves 1998:74). For the sizes of atoms, see Atkins and Jones:chapter 1, and Mark Winter's Webelements, at https://www.webelements.com/. For atomic nuclei, see Mackintosh 2001:50; the size of protons and neutrons is about 2-fm, based on the average separation of nucleons in a nucleus, Williams 2001:63, and also see Smith 2003:figure 3.1; quarks are considered to be smaller than 10^{-18} m (Heyde 1998:figure1.3, Smith 2003:50).

The living things are grouped within the rough size range of about 1 micrometre (a bacterium) to 100 m (a redwood tree), and within the energy range of 10^{-6} eV up to about 10^{-1} eV (about 100°C for thermophiles that live in hot springs).

0.2.5 a "scala naturae"

"***scala naturae***", this term was coined by Needham 1968:xii, and also see Needham 1968:chapter3, Needham 1986:184, 193 and 234. Many scientists, from a range of disciplines, have commented on the natural hierarchy of physical systems and their levels of organisation, for example, Bronowski 1977:chapter 13, Koestler 1979:chapter 1, Holland 2000:chapter 1, Morowitz 2002, Calvin 1997:34, Laughlin 2006:chapter 1, and Feynman 1992:124. Each level has its own principles and laws, and Laughlin and Feynman write of hierarchies of laws of behaviour.

a hierarchy of scientific specialisms

"**The glycine molecule**", Alberts 2008:127.

the reductionist approach

"**We follow a reductionist approach**", this is not a discussion of the nature and principles of the reductionist approach; see, for example, Anderson 1972, Davies 2006, Dennett 1996:80, and Weinberg 1993b:chapter 3.

0.3 The universal hierarchy of communities

0.3.1 an unbroken chain

"**We're familiar**", Dawkins 2005.

"**If we extend this idea**", the Big Bang is now generally accepted as the origin of the physical universe (Weinberg 1993b, Hogan 1998, Allday 2002, Gribbin 2008).

0.3.2 the universe evolves by forming communities of things

"**The evolution of the physical universe**", see, for example, Freedman 2002, Gribbin 2008, Hogan 1998, and Weinberg 1993a on the creation of the inanimate universe, and also Purves 1998, Dawkins 2005, Margulis 1997, Morowitz 2002, Fortey 1997, and Rutherford 2014 on the origin and evolution of living things.

A growing number of authors are providing comprehensive accounts of the evolution of the physical universe; see for example, Calvin 1986, Delsemme 1998, Jastrow 2008, Morowitz 2002, Smith 2000, and Bryson 2003.

"**The physical universe that we can perceive**", Lincoln 2009:22; and see also Han 1999:121.

0.3.3 the emergence of novelty

"**At each stage a new whole emerges**", see Morowitz 2002:13, Feynman 1992:124 and Ellis 2006:80. The appearance of novelty has led to the common observation that an emergent whole is more than the sum of its parts (Holland 2000:14, Morowitz 2002:20).

water – from molecule to liquid

"**A single molecule of water is not wet**", see Martin Chaplin's web-site on the properties of water, at http://www1.lsbu.ac.uk/water/. There are many of water's bulk properties that can be utilised without thinking of molecules at all – such as buoyancy, viscosity and turbulence (Tipler 1999:chapter 13, Bolton 2000:chapter 4). Similarly, Ohm's Law is meaningless for a single copper atom and the Pauli exclusion principle does not apply to a single electron (Davies 2006:36).

"**physical principle of organization**", Laughlin 2006:6.

In figure 0.4, the interactions between the water molecules can be attractive or repulsive, depending on their relative orientations, but for the sake of simplicity they are shown as double-headed arrows.

a hierarchy of physical laws

"**laws of electron motion**", Laughlin 2006:7.

"***we appear to face a hierarchy of Theories***", Laughlin 2000 has observed that it is generally impossible to deduce the higher organising principles from the underlying behaviour of systems at a lower level.

0.3.4 communities are bound together by exchanges

"**So we can see a cell as a community of reactions**", this is a "protein-centric" view that Gerrard has described as "*turning biochemistry inside out*" (Gerrard 2001, 2002 and 2005).

"**In complex living organisms**", many, maybe all, cells in a multicellular organism require signals from other cells in order to survive, and if deprived of these they can undergo a form of programmed cell death known as apoptosis (Purves 1998:213, Lodish 2000:1044).

0.4 the universal hierarchy of communities

following the fundamental particles

"**If we could be present**", Hogan 1998:chapter 2, Gribbin 2008:chapter 4.

"**If we follow these tagged particles**", Krauss 2002 has done this for an oxygen atom, and Levi 1990 has done it for a carbon atom.

Figure 0.5: the universe as a whole is a nested hierarchy, within which are innumerable branched hierarchies. A nested hierarchy resembles the concentric layers of an onion, and is a "bottom-up" hierarchy, in which each level is subsumed or contained by the next higher level, and the lower/inner levels sustain the higher/outer levels. A branched hierarchy is a "top-down" hierarchy, consistent with command and control from higher levels to lower levels.

Figure 0.5 summarises the nested hierarchy (on the left), and one possible branched hierarchy (on the right), that connects all eight levels of the universal hierarchy, from quark trios in level 1 up to the neurally connected human society in level 8. The inter-connected brains in level 8 can be regarded as one giant brain, for we all draw on the knowledge and expertise of others. Koestler (1967:chapter 4 and 1979:chapter 1) discusses types of hierarchies.

The 3-D representation of the molecule glycine (ID 730) is from Chemspider, available from http://www.chemspider.com/Chemical-Structure.730.html.

explanations at their appropriate levels

"**if neuroscientists someday**", Pinker 1998:314.

"**So, if we could observe a thought**", the brain operates as a hierarchy of systems, in which higher cognitive brain functions are carried out by bringing together sub-functions, so "*perception, language, thought, and memory are all made possible by the serial and parallel interlinking of several brain regions, each with specific functions*" (Kandel 2000:15).

0.5 the two themes of this book

0.6 the quantum entity

"**Our everyday experiences**", this is not an attempt to summarise the key points of quantum mechanics – for that see, for example, Al-Khalili 2008, Atkins 2006:chapters 8-10, Ball 2018, Carroll 2019, Coughlan 2006:chapter 3, Cox 2011, Feynman 1965:chapter 16, Herbert 1987, Hey 2003, Penrose 2004:chapter 21, Rae 1996, 2004 and 2005, Susskind 2014, Tipler 1999. What follows in this and subsequent chapters is an attempt simply to describe some key features of the quantum mechanical nature of the physical universe, and some of their consequences.

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minimalism and meaning in quantum mechanics

Sean Carroll has considered what quantum mechanics actually *means*, something that is not usually covered in textbook expositions. The following section is based on Carroll 2019, and page references are to that book.

"*Every version of quantum mechanics (and there are plenty) employs a wave function or something equivalent, and posits that the wave function obeys Schrödinger's equation, at least most of the time*" (p. 32).

In constructing a quantum mechanical description, "*physicists generally start by taking a classical theory and quantizing it*" (p. 231). But "*Nature is simply quantum from the start; classical physics … is an approximation that is useful in the right circumstances*" (p. 231). In Sean Carroll's view, we have "*reached a point where it is no longer practical to draw a bright line between the quantum and classical realms. Everything is quantum*" (p. 311).

But our everyday experience is of a classical world, and it's very hard to break away from this, and so we tend to have a split view: classical mechanics for big things, and quantum mechanics for small things. "*We use quantum mechanics to design new technologies and predict the outcomes of experiments. But honest physicists admit that we don't truly understand quantum mechanics*" (p. 2).

If we take a minimalist approach to quantum mechanics, then (*1*) we take the wave function as a direct representation of reality, with no added or hidden features, and (*2*) we assume that the wave function evolves smoothly in accordance with the Schrödinger equation. In this simple paradigm, "*there is a wave function, and it evolves according to a deterministic rule*" (p. 32). Sean Carroll suggests that "*we might call this proposal "austere quantum mechanics", or AQM for short. It stands in contrast with textbook quantum mechanics, where we appeal to collapsing wave functions, and try to avoid talking about the fundamental nature of reality altogether*" (p. 32).

If we start with the concept of a wave function for an individual object like an electron, then we can extend this to think of wave functions for progressively larger objects, such as atoms, molecules, rocks and planets, all the way up to the universe itself. In this view, "*the world is a wave function, nothing more or less. We can use the phrase "quantum state" as a synonym for "wave function", in direct parallel with calling a set of positions and velocities a "classical state"*" (p. 33).

To break out of our everyday classical viewpoint, we have to abandon the idea that the electron has some particular location. "*An electron is in a superposition of every possible location we could see it in, and it doesn't snap into any one specific location until we actually observe it to be there. "Superposition" is the word physicists use to emphasize that the electron exists in a combination of all positions, with a particular amplitude for each one. Quantum reality is a wave function; classical positions and velocities are merely what we are able to observe when we probe that function*" (p. 34).

A profound feature of the quantum world is entanglement, and this arises because "*there is only one wave function for the entire universe, not separate wave functions for each piece of it*" (p. 91). For example, if two electrons are fired directly at each other with the same velocity, then they will repel each other and rebound in different directions (p. 91). But momentum must be conserved in the collision, and this means that these directions are related, so that whatever direction one electron takes, the other electron takes the opposite direction. If we measure the speed and direction of one electron, then we know the speed and direction of the other. This is because the two electrons have become entangled by colliding, and their separate wave functions have become a combined wave function, which is part of the wave function of the universe.

The process of a macroscopic object becoming entangled with its environment in ways that we can't keep track of is known as decoherence, and it "*causes the wave function to split, or branch, into multiple worlds. Any observer branches into multiple copies along with the rest of the universe. After branching, each copy of the original observer finds themselves in a world with some measurement outcome. To them, the wave function seems to have collapsed. We know better; the collapse is only apparent, due to decoherence splitting the wave function*" (p. 119). This description is more commonly known as the Everett, or Many-Worlds formulation of quantum mechanics (chapter 6), and while it offers a simpler "bare-bones" formalism, it "*describes many copies of what we think of as "the universe", each slightly different, but each truly real in some sense*" (p. 39).

To illustrate this minimalist quantum mechanical thinking, imagine measuring the position of an electron, using a camera with ideal resolution, that can photograph a single electron. The camera interacts with the electron and shows on its viewing screen where it "saw" the electron. Textbook quantum mechanics treats the electron as a microscopic quantum system, and the camera as a macroscopic classical system, and that the electron's wave function collapses as a result of the interaction between the two.

But a camera is made of atoms, and it has a wave function of its own. So when the electron and camera interact in the process of observation, their separate wave functions become entangled in a single wave function for the (electron+camera) system. The camera itself now becomes entangled with the environment, because it emits light photons from its screen showing where the electron was observed, and some of these photons go into the observer's eye. "*There's nothing special about what constitutes "a measurement" or "an observer" – a measurement is any interaction that causes a quantum system to become entangled with the environment, creating decoherence and a branching into separate worlds, and an observer is any system that brings such an interaction about*" (p. 122). After the measurement the observer and camera are in a superposition, in each part of which the observer has seen the electron in a slightly different location (p. 38). The Everett formalism views this "*not as one person with multiple ideas about where the electron was seen, but as multiple worlds, each of which contains a single person with a very definite idea about where the electron was seen*" (p. 39).

It's justifiable in the Everett formalism to talk of branching into separate worlds, "*because what happens on each branch doesn't affect what happens on the others*", and it's helpful, because it simplifies a very complex situation (p. 234). But "*characterizing the quantum state in terms of multiple worlds isn't necessary – it just gives us an enormously useful handle on an incredibly complex situation*" (p. 234). In every case it's the universe interacting with itself, and this is reflected in the change in the universal wave function, and "*the theory just cares about the wave function as a whole*" (p. 234).

Relativity is a "*theory of spacetime rather than a theory of stuff within spacetime*" (p. 270), and rather than taking classical general relativity and quantizing it, Sean Carroll has outlined the opposite approach of looking for space and gravity within quantum mechanics (p. 268). Our thinking is shaped by our macroscopic experience, and so we take a pre-existing space for granted, measure distances within it, and think of particles moving through it. A wave function would not seem to provide a basis for measuring distances, but Carroll shows how the concept of entanglement between sub-systems can perhaps provide a metric for space.

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"**Classical mechanics recognises**", Carroll 2019:44.

"**Particles and fields are opposites**", Carroll 2019:47.

"**the entire trajectory of the rock**", Carroll 2019:15.

"**Newtonian mechanics describes**", Carroll 2019:16.

"**Newton's laws of motion**", see Tipler 1999 on the kinetic theory of gases (p.550), and on Kepler's laws of planetary motion (p. 321).

"**But things that appear to be waves**", Tipler 1999:chapters 17 and 33.

"**Conversely, things that appear to be particles**", Dirac 1981:2, Tipler 1999:509, Carroll 2019:chapter 3.

"**the breakdown of classical mechanics**", Dirac 1981:3.

"**unified particles and fields**", Carroll 2019:44.

"***the world is fundamentally wavy***", the first quote is from Carroll 2019:61 and the second is from p. 275.

"**In a classical universe**", Dirac 1981:vii and 98, Carroll 2019:21.

"**But the particles of our universe**", normally, we learn classical mechanics first, and then have to "unlearn" some of it in order to tackle quantum mechanics. This encourages the view that quantum mechanics is basically "*classical mechanics with a couple of new gimmicks thrown in*" (Susskind 2014:xx). However, it is now accepted that quantum physics is more fundamental than classical physics, and that classical physics is a useful approximation in certain situations (Carroll 2019:chapter 3 and p. 231). "*We've reached a point where it is no longer practical to draw a bright line between the quantum and classical realms. Everything is quantum.*" (Carroll 2019:311).

Figure 0.6 is based on Feynman 1965:figure 2-1, Susskind 2014:figure 9.1, Penrose 2004:figure 21.10, and Carroll 2019:figure on p.20.

"**How can we comprehend**", Paul Dirac wrote, "*The new theories … are built up from physical concepts which cannot be explained in terms of things previously known to the student, which cannot even be explained adequately in words at all*" (Dirac 1981:vii).

"***isolated piece of a wave***", Al-Khalili 2008:50.

“**This finite presence**“, the term “particle-wave” is commonly used to try to capture its apparently contradictory, dual nature. Herbert uses a made-up term, “quon”, for a quantum object and Penrose uses the term “quantum particle”. I would like to avoid made-up words and any mention of “particle” or “wave”, with their powerful prior associations. I will use the term “quantum entity”; it sounds heavy-handed and over-formal, but it emphasises its seamless, holistic nature, and I’ll try not to use it too often.

“**It is a holistic entity**”, I’ve based this on Dirac 1981:2, who wrote “*A fraction of a photon is never observed*”.

“***oscillatory waves go through cycles***”, Herbert 1987:72.

“**A quantum entity unites space and time**”, Carroll sketches out how space and time might emerge from quantum mechanical wave functions (chapter 13). “*Change is the manifestation of time, and regular oscillations are a clear manifestation of change*” (Scales 1999:740).

a world of happenings, not of things

“**…a seamless continuous whole…**”, Atkins 2006:260, and “**…with an amplitude that varies…**”, Tipler 1999:section 36.4

“**A quantum entity can’t be set down in a state of rest**”, Paul Dirac wrote, “*while there exists a classical state with zero amplitude of oscillation everywhere, namely the state of rest, there does not exist any corresponding state for a quantum system*” (Dirac 1981:17-18).

“**…if it’s set moving, it travels as a wave…**”, Atkins 2006:254.

“**The interactions between two quantum entities**”, Coughlan 2006:21.

“***minute cold stones***” and “***the world is a continuous***”, both from Rovelli 2015:31.

0.6.1 Uncertainty

“**It is a “bit” of vibration**”, and “***cannot define a unique wavelength***”, Feynman 1965:2-2.

“**There are two major uncertainties**”, there are pairs of variables, called conjugate variables, for which one can’t know the precise values of both at the same time (Gribbin 1998:417). The more certain one is of the value of one conjugate variable, the less certain is the value of the other. This is a matter of fundamental principle, and not one of difficulties in experimental measurement.

There are two important and well known of these conjugate pairs; the first pair links momentum and position, and concerns the uncertainty in where a “particle” is and what it’s doing. The second pair links energy and time, and concerns the uncertainty in the quantum particle’s existence. In each of these two pairs of variables, one variable of the pair concerns the energy or momentum of the quantum entity, that is, its “*dynamical state*”, and the other variable of the pair concerns space or time (de Broglie 1939:254).

De Broglie links the uncertainty principle to Zeno’s paradoxes of motion. “*The impossibility of giving an exact description of the spatio-temporal localization, and of the dynamical state, simultaneously, may perhaps be connected with one of the difficulties which troubled ancient philosophers. Let us take an arrow in flight, said Zeno. At any given moment it is motionless in a certain position. How then can it follow a certain trajectory? How – that is to say – can motion be constructed out of a series of immobilities?*” (de Broglie 1939:254).

The derivation of these conjugate pairs is quite beyond the remit of this book, but we can understand them to some extent by looking at the units of the quantities involved.

We’re familiar with doing calculations involving units and balancing the units on each side of the equation. For example, we know that if we drive at a steady 50 miles/hour for 4 hours then we’ll travel 200 miles. We’ve done the mental calculation:

200	=	50	x	4
distance (miles)		speed (miles/hour)		time (hours)

When we do the mental calculation we don’t think about the units, but multiplying the unit “miles/hour” by the unit “hours” gives the unit “miles” on the right, and this matches the unit “miles” on the left. The equation is valid because it has the same unit, “miles”, on both sides. Similarly, we calculate the cost of buying apples (£) by multiplying their price (£/kg) by their weight (kg).

We’ll see in chapters 2 and 3 that the balance in uncertainties between pairs of conjugate variables, momentum and position and between energy and time, is set by the value of Planck’s constant, h, which has the unit *Js*, representing energy x time. The product of the conjugate variables energy and time have the unit *Js*, which is the same as the unit of Planck’s constant.

The energy unit *J* can be written as kgm^2/s^2 (from the formula for kinetic energy, $½mv^2$), and so the unit for Planck's constant can be written as kgm^2/s. The product of momentum ($p = mv$, with the unit *kgm/s*) and position (*x*, with the unit *m*) is also kgm^2/s.

So, the product of the two pairs of conjugate variables have the same unit as Planck's constant, *Js*, and so we have two forms of the uncertainty principle.

These two forms of the uncertainty principle have to be derived differently. The derivation of the momentum/position version is fairly straightforward, but this is not the case for the energy/time version (Briggs 2008). This simplistic approach is based on Thayer Watkins, at http://www.sjsu.edu/faculty/watkins/UncertaintyTE.htm.

"***We cannot know, as a matter of principle***", quoted in Gribbin 1998:418.

0.6.2 the wavefunction

"**Solving the Schrödinger equation**", Al-Khalili 2008:64.

There are several mathematical ways to describe the behaviour of a quantum entity, and Schrödinger's approach is the one generally used in teaching quantum mechanics (Al-Khalili 2008:64).

There are restrictions on possible wavefunctions. A wavefunction must be continuous, it must be finite and have only one value at each point in space. These restrictions mean that a quantum entity can have only certain energies, that is, its energy is quantized (Atkins 2006:260).

"*In principle, Schrödinger's equation is capable of explaining all atomic phenomena except those involving magnetism and relativity. It explains the energy levels of an atom, and all the facts of chemical binding. This is, however, true only in principle – the mathematics soon becomes too complicated to solve exactly any but the simplest problems. Only the hydrogen and helium atoms have been calculated to a high accuracy. However, with various approximations, some fairly sloppy, many of the facts of more complicated atoms and of the binding of molecules can be understood*" (Feynman 1965:16-13).

Feynman goes on to show how Schrödinger's equation, involving only continuous functions of continuous variables in space, gives rise to quantised energy levels in an atom (Feynman 1965:16-14).

"**The wavefunction contains all the dynamical information**", Atkins 2006:254 and 256.

"**In everyday examples of waves**" Rae 2005:41-42.

"**The wavefunction for waves in a rope**", Tipler 1999:520.

"***mathematical function***", Rae 2005:42.

"***oscillations of possibility***", Herbert 1987:72.

"***At any instant in time***", Al-Khalili 2008:66.

"**We can use the mathematical wavefunction**", Rae 2005:41.

For sound or light waves, the energy per unit volume of the wave is proportional to the square of the wave function. We know that a light "wave" is actually a stream of photons, so the energy per unit volume (such as one cubic millimetre) is proportional to the number of photons per unit volume. So we can think of the square of each photon's wavefunction as being proportional to the number of photons per unit volume in the light wave. But if we imagine a very weak light source that emits just one photon at a time, then in any unit volume there can be either one photon or none at all. The Schrödinger equation describes a single quantum particle, and so the square of the wavefunction gives the probability of finding the particle in some unit volume (Tipler 1999:520). This is the widely accepted Born interpretation of the wavefunction, and it states that the probability of finding the quantum particle in any particular location is proportional to the square of the wavefunction at that location (Atkins 2006:256). So it doesn't matter if the wavefunction has a positive or negative value, for they both will give a positive probability when squared. Strictly speaking, the square of the wavefunction gives the probability density, the probability of finding the particle in a small volume. To obtain the probability, the probability density must be multiplied by the volume chosen.

"***one entire thing***", "**describing (or 'being') just a single particle**" and "**completely holistic entities**", all from Penrose 2004:512.

"***the wavefunction describing the structure***", Al-Khalili 2008:68.

"***an isolated piece of a wave***", Al-Khalili 2008:50, and also see Atkins 2006:270.

"***a localised particle is represented by a wave packet***", Tipler 1999:1152, and also see Coughlan 2006:23.

A wave packet is a localised wavefunction, formed from a combination of wavefunctions that correspond to different values of linear momentum (Atkins 2006:270). The more wavefunctions that are combined to make the wave packet, the more the wave packet is localised in space. A wave packet composed of an infinite number of wavefunctions is a sharp infinitely narrow spike, corresponding to a particle of no measurable size. Now the particle is perfectly localised, so its position is known exactly, but its momentum is unknown, because it comprises wavefunctions with an infinite range of momentum values. Hence "*if we know the location of the particle precisely … then its momentum is completely unpredictable*" (Atkins 2006:270). This is the uncertainty principle, which will be covered in chapter 3, section 3.5.

Position and momentum are an example of a pair of complementary variables, and this takes us to "*the heart of the difference between classical and quantum mechanics. Classical mechanics supposed, falsely as we now know, that the position and momentum of a particle could be specified simultaneously with arbitrary precision. However, quantum mechanics shows that position and momentum are complementary, and that we have to make a choice: we can specify position at the expense of momentum, or momentum at the expense of position*" (Atkins 2006:272).

"**We can't view the interactions**", Coughlan 2006:21.

"***regards the world as made out of waves***", Herbert 1987:73.

particle-wave

"***no distinction between a wave and a particle***", Feynman1963:2-7, and Feynman 1998:36.

0.6.3 mass-energy

"**We are now in a position**", we are very successful at treating energy as an abstract construct, a numerical quantity that remains constant in a diversity of natural processes (Arons 1965:391), but Richard Feynman reminds us that "*we have no knowledge of what energy is*" (Feynman 1963:4-2). For the creation of matter from energy see Freedman 2002:674, Gribbin 2008:63, and chapter 2, section 2.9.

"***a highly concentrated and localized bundle of energy***" and "***energy of being***" both in Ford in Ferris 1991:27. Matter has been described as "***frozen energy***" (Close 2004a:68), but this static likeness does not begin to capture the ceaseless activity of the quantum entity.

"***mass is energy and energy has mass***", Davies 2006:49.

"***the same basic stuff***", Hogan 1998:25.

"**Energy (*E*, J) and mass (*m*, kg)**", Einstein's mass-energy equation, $E = mc^2$, summarises the relation between the two (Freedman 2002:392, Cox 2010, Bodanis 2001). See Ohanian 2008:chapter 7 for a discussion of Einstein's original work and mistakes. This is an extension of the concept of the equivalence of mechanical energy and heat (Einstein 1950 and 1991).

To see how Einstein's equation for the equivalence of mass and energy, $E = mc^2$, gives the familiar equation for kinetic energy, see http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/releng.html#c1.

"**so Joules and kilograms**", Taylor 1966:137.

formless energy takes physical form

0.8 References

Where there are more than three authors I give the lead author, followed by “et al.” – meaning “and others”.

Al-Khalili, J. (2008), *Quantum*, Phoenix, London.

Alberts, B. et al. (2008), *Molecular Biology of the Cell*, Garland Science, New York, 5th edition.

Anderson, P. (1972), “More is Different”, *Science*, volume 177, p. 393-396.

Allday, J. (2002), *Quarks, Leptons and the Big Bang*, Institute of Physics Publishing, Bristol, 2nd edition.

Arons, A. B. (1965), *Development of Concepts of Physics*, Addison-Wesley, Reading, MA.

Atkins, P. and Jones, L. (2002), *Chemical Principles: the quest for insight*, W.H.Freeman, New York, 2nd edition.

Atkins, P. and de Paula, J. (2006), *Atkins’ Physical Chemistry*, Oxford University Press, Oxford, 8th edition.

Atkins, P. (2007), *Four Laws that drive the universe,* Oxford University Press.

Ball, P. (2018), *Beyond Weird,* The Bodley Head, London.

Bodanis, D. (2001), *$E=mc^2$: a biography of the world’s most famous equation*, Pan, London.

Bolton, J., editor (2000), *Classical Physics of Matter*, Institute of Physics Publishing, Bristol, in association with the Open University, Milton Keynes.

Briggs, J. S. (2008), “A derivation of the time-energy uncertainty relation”, *Journal of Physics: Conference series*, volume 99, 012002.

de Broglie, L. (1939), *Matter and Light – the New Physics*, W. W. Norton, New York.

Bronowski, J. (1977), *A Sense of the Future.* MIT Press, Cambridge, MA.

Bryson, B. (2003), *A short History of Nearly Everything*, Doubleday, London.

Calvin, W. (1986), *The River that flows Uphill: a journey from the big bang to the big brain*, Sierra Club Books, San Francisco.

Calvin, W. (1997), *How Brains Think*, Weidenfeld and Nicolson, London.

Campbell, N. et al. (2008), *Biology*, Pearson, San Francisco, 8th edition.

Carroll, A. and Heiser, G. (2010), “An analysis of power consumption in a smartphone”, *Proceedings of the 2010 USENIX Annual Technical Conference*, available at https://www.usenix.org/legacy/event/usenix10/tech/full_papers/Carroll.pdf.

Carroll, S. (2019), *Something Deeply Hidden: quantum worlds and the emergence of spacetime*, Oneworld Publications, London.

Clayton, P. and Davies, P., editors (2006), *The Re-Emergence of Emergence: the emergentist hypothesis from Science to religion*, Oxford University Press.

Close, F., Marten, M. and Sutton, C. (2004a), *The Particle Odyssey: a journey to the heart of matter*, Oxford University Press, paperback edition.

Close, F. (2007a), *The New Cosmic Onion: quarks and the nature of the universe*, Taylor and Francis, Boca Raton, Florida.

Cotterill, R. (2008), *The Material World*, Cambridge University Press.

Coughlan, G., Dodd, J. and Gripaios, B. (2006), *The Ideas of Particle Physics: an introduction for scientists*, Cambridge University press, 3rd edition.

Cox, B. and Forshaw, J. (2010), *Why does $E = mc^2$?*, Da Capo Press, Perseus Books Group, Philadelphia.

Cox, B. and Forshaw, J. (2011), *The Quantum Universe: everything that can happen does happen*, Allen Lane, London.

Davies, P. (2006), “Preface”, in Clayton and Davies (2006).

Dawkins, R. (2005), *The Ancestor's Tale: a pilgrimage to the dawn of life*, Phoenix, London.

Delsemme, A. (1998), *Our Cosmic Origins: from the big bang to the emergence of life and intelligence*, Cambridge University Press.

Dennett, D. (1996), *Darwin's dangerous Idea*, Penguin, London.

Dirac, P. (1981), *The Principles of Quantum Mechanics*, Clarendon Press, Oxford, 4th edition, revised.

Duff, B. (1986), *Fundamental Particles: an introduction to quarks and leptons*, Taylor and Francis, London.

Durrant, A., editor (2000), *Quantum Physics of Matter*, Institute of Physics Publishing, Bristol, in association with the Open University, Milton Keynes.

Eames, C. and Eames, R. (1997), *Powers of Ten: a flipbook*, Eames Office, and also available to view as a video at https://www.eamesoffice.com/the-work/powers-of-ten/ .

Einstein, A. (1950), *The Theory of relativity and other essays*, MJF Books, New York.

Einstein, A. (1991), $E=mc^2$, in Ferris (1991).

Ellis, G. (2006), "On the Nature of Emergent Reality", chapter 4 in Clayton and Davies (2006).

Ellis, G. (2011), "Top-down causation and emergence: some comments on mechanisms", *Interface Focus*, vol. 2, pp. 126-140.

Ferris, T., editor (1991), *The World Treasury of Physics, Astronomy and Mathematics*, Little, Brown and Company, Boston, MA.

Feynman, R., Leighton, R. and Sands, M. (1963), *Lectures on Physics: volume I*, Addison-Wesley, Reading, Massachusetts, 6th printing.

Feynman, R., Leighton, R. and Sands, M. (1965), *Lectures on Physics: volume III*, Addison-Wesley, Reading, Massachusetts, 3rd printing.

Feynman, R. (1992), *The Character of Physical Law*, Penguin, London.

Feynman, R. (1998), *Six Easy Pieces: the fundamentals of physics explained*, Penguin, London.

Ford, K. (1991), "The Large and the Small", in Ferris (1991).

Fortey, R. (1997), *Life: an Unauthorised Biography*, HarperCollins, London.

Freedman, R. and Kaufmann, W. (2002), *Universe*, W. H. Freeman, New York, 6th edition.

Garrett, R. and Grisham, C. (2005), *Biochemistry*, Thomson Brooks/Cole, Belmont, California, 3rd edition.

Gerrard, J., Sparrow, A. and Wells, J. (2001), "Metabolic databases – what next?", *Trends in Biochemical Sciences*, vol. 26, pp. 137-140.

Gerrard, J. and Sparrow, A. (2002), "Turning biochemistry inside out", *Biochemistry and Molecular Biology Education*, vol. 30, pp. 293-295.

Gerrard, J. (2005), "Metabolism: chemistry of Life or Biology of Molecules?", page 536 in Garrett and Grisham (2005).

Gribbin, J. (1998), *Q is for Quantum: an encyclopedia of particle physics*, The Free press, New York.

Gribbin, J. (2008), *The Universe: a biography*, Penguin, London.

Han, M. Y. (1999), *Quarks and Gluons: a century of particle charges*, World Scientific, Singapore.

Herbert, N. (1987), *Quantum Reality: beyond the new physics*, Anchor Books, New York.

Herculano-Houzel, S. (2009), "The human brain in numbers: a linearly scaled-up primate brain", *Frontiers in Human Neuroscience*, vol. 3, pp. 1-11.

Hey, T. and Walters, P. (2003), *The New Quantum Universe*, Cambridge University Press.

Heyde, K. (1994), *Basic Ideas and Concepts in Nuclear Physics*, Institute of Physics Publishing, Bristol.

Heyde, K. (1998), *From Nucleons to the Atomic Nucleus: perspectives in nuclear physics*, Springer-Verlag, Berlin.

Hogan, C. (1998), *The Little Book of the Big Bang: a cosmic primer*, Copernicus, New York, 2nd printing.

Hogle, J., Chow, M. and Filman, D. (1985), “Three-dimensional structure of Poliovirus at 2.9 Å resolution”, *Science*, vol. 29, pp. 1358-1365.

Holland, J. (2000), *Emergence: from Chaos to order*, Oxford University Press.

Jastrow, R. and Rampino, M. (2008), *Origins of Life in the Universe*, Cambridge University Press.

Kandel, E. (2000), *Principles of Neural Science*, McGraw-Hill, New York, 4th edition.

Keeler, J. and Wothers, P. (2006), *why chemical reactions happen*, Oxford University Press, reprinted with corrections.

Koestler, A. (1967), *The Ghost in the Machine*, Hutchinson, London.

Koestler, A. (1979), *Janus: a summing up*, Pan, London.

Krauss, L. (2002), *Atom: an odyssey from the big bang to life on earth…and beyond*, Abacus, London.

Laughlin, R. and Pines, D. (2000), “The Theory of Everything”, *Proceedings of the National Academy of Sciences*, volume 97, p. 28-31.

Laughlin, R. (2006), *A Different Universe: reinventing physics from the bottom down*, Basic Books, New York.

Lennie, P. (2003), “The cost of cortical computation”, *Current Biology*, vol. 13, pp. 493-497.

Levi, P. (1986), *The Periodic Table*, Abacus, Sphere Books, London.

Lincoln, D. (2009), *The Quantum Frontier*, The Johns Hopkins University Press, Baltimore.

Lodish, H. et al. (2000), *Molecular Cell Biology*, W. H. Freeman, New York, 4th edition.

Mackintosh, R. et al. (2001), *Nucleus: a trip into the heart of matter*, The Johns Hopkins University Press, Baltimore, Maryland.

Margulis, L. and Sagan, D. (1997), *Microcosmos: four billion years of evolution from our microbial ancestors*, University of California Press, Berkeley, California.

McMurry, J. (2000), *Organic Chemistry*, Brooks/Cole, Pacific grove, California, 5th edition.

Morowitz, H. (2002), *The Emergence of Everything: how the world became complex*, Oxford University Press.

Morrison, P. and Morrison, P. (1982), *Powers of Ten*, Scientific American Library, New York.

Needham, J. (1968), *Order and Life*, The M.I.T. Press, Cambridge, Massachusetts.

Needham, J. (1986), *Time the Refreshing River,* Spokesman, Nottingham, England.

O’Connor, D. et al. (2010), “Neural activity in barrel cortex underlying vibrissa-based object localization in mice”, *Neuron*, vol. 67, pp. 1048-1061.

Ohanian, H. (2008), *Einstein’s mistakes: the human failings of genius*, W. W. Norton, New York.

Penrose, R. (2004), *The Road to reality: a complete guide to the physical universe*, BCA by arrangement with Jonathan Cape, London.

Pinker, S. (1998), *How the Mind Works*, Penguin, London.

Purves, W. et al. (1998), *Life: the science of biology*, Sinauer, Sunderland, Massachusetts, 5th edition.

Rae, A. (1996), *Quantum Mechanics*, Institute of Physics Publishing, Bristol and Philadelphia, 3rd edition, with corrections.

Rae, A. (2004), *Quantum Physics: illusion or reality?*, Cambridge University Press, 2nd Canto edition.

Rae, A. (2005), *Quantum Physics: a beginner’s guide*, Oneworld Publications, Oxford.

Roth, G. and Dicke, U. (2005), “Evolution of the brain and intelligence”, *Trends in Cognitive Sciences*, vol. 9, pp. 250-257.

Rovelli, C. (2015), *Seven Brief lessons on Physics*, Allen Lane, London.

Rutherford, A. (2014), *Creation: the origin of life*, Penguin, London.

Sagan, C. (1981), *Cosmos*, Book Club Associates, London.

Scales, J. and Snieder, R. (1999), “What is a wave?”, *Nature*, volume 401, p. 739-740.

Shafi, M. et al. (2007), ”Variability in neuronal activity in primary cortex during working memory tasks”, *Neuroscience*, vol. 146, pp. 1082-1108.

Simon, S. (2013), *The Oxford Solid State Basics*, Oxford University Press.

Smith, J. M. and Szathmáry, E. (2000), *The Origins of Life: from the birth of life to the origins of language*, Oxford University Press.

Smith, T. (2003), *Hidden Worlds: hunting for quarks in ordinary matter*, Princeton University Press, Princeton, New Jersey.

Steinfeld, A.(2003), “Solar Power and Fuels”, available at https://forumvera.info/jwa/VFS-DFA-690179-Solarenergie__Aldo_Steinfeld.pdf.

Susskind, L. and Friedman, A. (2014), *Quantum Mechanics: the theoretical minimum*, Allen Lane, London.

‘t Hooft, G. and Vandoren, S. (2014), *Time in Powers of Ten: natural phenomena and their timescales*, World Scientific, Singapore.

Taylor, E. and Wheeler, A. (1966), *Spacetime Physics*, W. H. Freeman, New York.

Tipler, P. (1999), *Physics for Scientists and Engineers,* W. H. Freeman, New York, 4th edition.

Tsutsumi, A. (2019), “Thermodynamics of water splitting”, in “Energy Carriers and Conversion Systems”, which is part of the Encyclopedia of Life Support Systems, and is available at https://www.eolss.net/Sample-Chapters/C08/E3-13-03-01.pdf .

Weinberg, S. (1993a), *The First Three Minutes: a modern view of the origin of the universe*, Basic Books, New York, revised 2nd edition.

Weinberg, S. (1993b), *Dreams of a Final Theory*, Hutchinson Radius, London.

Williams, W. (2001), *Nuclear and Particle Physics*, Clarendon Press, Oxford, reprinted with corrections and data updates.