This preview includes the contents, preface, first chapter, and the first 4 pages of each of the following chapters.

The Communal Universe

How things come together

Andrew McNeil

This book will take you on a journey through our physical universe, based on current, established science. The journey starts with the simplest fundamental particles, such as quarks and electrons, and ends with the most complex of all material objects – our human brains.

Our universe has evolved through forming communities of things, with simpler things coming together in new groupings to make more complex things. So, every "thing" in the universe is a community of things, and at every level a community is greater than the sum of its separate parts.

If we view the universe in terms of communities, it takes the form of a hierarchy of eight levels of communities, from protons and neutrons to human societies. And at every level in this universal hierarchy, the communities are bound together by ceaseless interactive exchanges.

So, our universe reveals itself as a dynamic hierarchy, sustained by endless exchanges between members of the communities at every level. Each of us is the universe in microcosm, for we each embody all eight levels of the universal hierarchy.

It is through things coming together and forming communities that the universe, with us now in it, has come to be what it is.

Andrew McNeil has a PhD in metallurgy. He first worked in university research and then, for twenty years, he taught secondary school science.

SCIENCE £16.99

ISBN 978-1-80514-257-7

01699

9 781805 142577

www.troubador.co.uk

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website: https://andrewmcneil.net/the-communal-universe/

First published 2025.

Troubador Publishing Ltd
Unit E2 Airfield Business Park,
Harrison Road, Market Harborough,
Leicestershire. LE16 7UL
Tel: 0116 2792299
Email: books@troubador.co.uk
Web: www.troubador.co.uk

ISBN 978 1805142 577

British Library Cataloguing in Publication Data.
A catalogue record for this book is available from the British Library.

The manufacturer's authorised representative in the EU for product safety is
Authorised Rep Compliance Ltd, 71 Lower Baggot Street, Dublin D02 P593 Ireland
(www.arccompliance.com)

Printed and bound by Imago in Turkey
Typeset in Times New Roman and Myriad Pro by
Troubador Publishing Ltd, Leicester, UK, and by Karen Hall.

This book is dedicated to all who ask, “How does *that* work?”.

Contents

Preface

This book is about the way things have come together to make our universe what it is. This preface outlines how its author has "come together" and how the book got written. After a somewhat unsettled time as an undergraduate, I received a very ordinary first degree in metallurgy and was very fortunate to be accepted to do a PhD. I then worked for several years as a university post-doctoral researcher and published a handful of specialist papers. I enjoyed experimenting and finding out how "stuff" works, but I became increasingly aware that I was working in a specialised area, just looking at details.

I wanted to share my knowledge and enthusiasm on a broader basis, so I left university research and worked for 20 years in an 11–18 secondary school. I taught all the sciences and electronics to all years. So, for example, I would teach the first ideas of chemical reactions to 12-year-old students through rôle play, with the students playing the parts of the reacting atoms; I taught genetics and the Big Bang theory of the expanding universe to 16-year-olds; and I introduced the quantum mechanics of particle-waves to 18-year-olds. Sometimes, I taught all these within the same week!

I started wondering how all these different aspects of our physical universe fit together. If our universe has its origins in a singular Big Bang, then they must all be part of a unified evolutionary narrative. We're familiar with the idea that all living things are connected through the genes in their DNA, in an unbroken chain that goes back to the very first biological ancestor. Similarly, every one of the atoms in our bodies and our physical world is connected in an unbroken chain of transformations to the very first particles created in the universe.

So, how did we get from there to here? By what processes have self-awareness, wonder and laughter emerged out of fundamental particles and forces and energy?

I had discovered that teaching science greatly improved my own understanding of the subject. It seemed that the best way – perhaps the only way – to understand something fully is to explain it to someone else. So, I decided that I would write my own account of the universe's evolution, and I started on this when I left teaching, with the distant idea that it might turn into a book. At first, the account was just a series of unconnected sections joined by "and then..." links, with no overall structure. But after a while, I realised that the whole scheme fitted a simple hierarchical pattern, and this is the basis of "The Communal Universe".

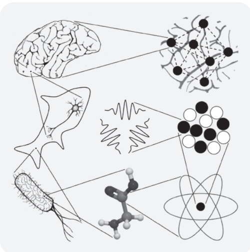
The remit is very broad, taking in disciplines such as particle and atomic physics, chemistry, biochemistry, cell biology, neuroscience, primatology, and anthropology. I have no particular expertise or authority in any of these specialist fields. I am a moderately literate practical scientist with a basic understanding of a fairly broad range of scientific disciplines, and a tendency to ask, "How does *that* work?".

A crime novel has many characters who interact in lots of ways, and in the end, you discover "whodunnit". Similarly, this account of the universe has many material "characters" that interact in a variety of ways, and we see that it's things coming together in communities over a series of levels that have "dunnit". My account of the universe's story is intricate and full of details – but I believe it can be understood by someone with a reasonable scientific education, say, a good pass in Science at 16+ level.

Our universe appears to have evolved by the formation of *communities* of things, whereby simpler things come together in new groupings to make more complex things. Every "thing" in the universe is, in fact, a community of things, and at every level, a community is greater than the sum of its separate parts, and so the universe has grown ever more complex. Everything is incessantly active, interacting with other things, creating and sustaining communities. The entirety of our universe, the vast, rich complexity of it all, fits into a scheme of a hierarchy of communities.

In this book, I will take you on a journey through our physical universe, from the simplest fundamental particles, such as quarks and electrons, to the most complex things – our human brains. It is through things coming together and forming communities that the universe, with us now in it, has come to be.

Chapter 0: introduction



0.1 what this book is about

This book is about our universe – what it is made of, how it works, and how it has come to be what it is. We now have a well-established scientific description of the universe, and its evolution from very shortly after the Big Bang to the present time. The breadth and detail of this description shows how much we have learned, but it's clear from the many loose ends and unanswered questions that there is much that we don't yet know. This book is based on the current scientific description, and introduces a new idea – the concept of *communities* as a fundamental principle in the universe's evolution and organisation.

If we follow the progress of the universe as it evolves, we see physical matter coming together in ever more complex communal arrangements. So, every "thing" in the universe is, in fact, a community of things. In this book, I present a view of the universe as a hierarchy of material communities, which rises in just eight levels from fundamental sub-atomic particles to human society.

The members of the communities at each level of the hierarchy are bound together by endless exchanges between themselves. Each successive level is then sustained by the activities in the levels below it. Our universe is not a static edifice, like stones piled one on top of another, but is a dynamically stable pattern of activity, in which nothing is ever still.

Every community is greater than the sum of its separate parts. And so, as we climb the universal hierarchy, level by level, we see new material communities emerge with new properties and powers. Thus, fundamental particles of mass-energy come together in a sequence of emergent transitions, each one creating a new level in the hierarchy, ultimately becoming human beings. We are complex material communities with our own thoughts and feelings, and we can empathise with the thoughts and feelings of others, and thereby sustain our human society.

It is through forming a sequence of eight levels of communities of increasing complexity that the universe has evolved from its origin to the present time. This book is a journey through those eight levels of the universal hierarchy.*

0.2 the universal hierarchy

0.2.1 taking things apart

You, the reader, are one individual in a global human society, connected to all other humans by shared thoughts and inherited DNA, and also by social and economic links. Someone who is with you from day to day would observe your empathy with others,

* The text is supported by a full set of notes and references; see the end of the book.

your rational behaviour, your emotions and your sense of humour. This behaviour is enabled by the coordinated activities of the billions of nerve cells in your brain, which are endlessly passing signals between themselves. You are a complex biological organism, with a body that is made of many types of specialist cells, such as muscle, bone, and nerve cells. When we look inside each one of your body's cells, we find many different types of molecules, such as carbohydrates and proteins.

Each of these molecules comprises a number of specific atoms in a particular configuration. When we take the atoms apart, we find that each one has a number of electrons gathered around a tiny central nucleus. The hydrogen atom's nucleus is a single proton, but in all other atoms, the nucleus is a cluster of protons and neutrons. Finally, when we look inside individual protons and neutrons, we find that each is made of a trio of quarks.

We can't take things apart any further because quarks are fundamental particles – they are "*substance without inside*". We have arrived at what appears to be the basic stuff of the universe – "*mass-energy*". Matter is, in a sense, "*frozen energy*", and so "*a material particle is nothing more than a highly concentrated and localized bundle of energy*". In short, energy *is* matter *is* energy.

We have "unpacked" physical matter like a set of Russian dolls, and have found a series of things made of smaller things, most of which are fairly familiar. But there appears to be no overall pattern or scheme.

0.2.2 the universe evolves by forming communities of things

However, we have been taking apart things that have already been created, and this is the reverse of how the universe has actually evolved. When we follow the universe's evolution, we see a simple, consistent pattern, in which things come together in communal groupings to make new things, with novel, emergent properties. A universal hierarchy of communities naturally emerges, in which everything has its own level – this is shown in figure 0.1. As we ascend this hierarchy, we follow the universe's evolution from its beginning to the present time. At each level, things become bound together to make a community that brings the next hierarchical level into being, and then sustains its existence.

So, a trio of fundamental quarks, shown as "wiggly" quantum particle-waves, come together to create and sustain a proton or a neutron (Level 1). A communal cluster of protons and neutrons create and sustain a nuclide, which is generally known as an atomic nucleus (Level 2). A nuclide becomes the centre for a community of electrons, which we know as an atom (Level 3). A community of specific atoms then bind together to create and sustain a molecule, such as the amino acid glycine that is shown in figure 0.1, at Level 4.

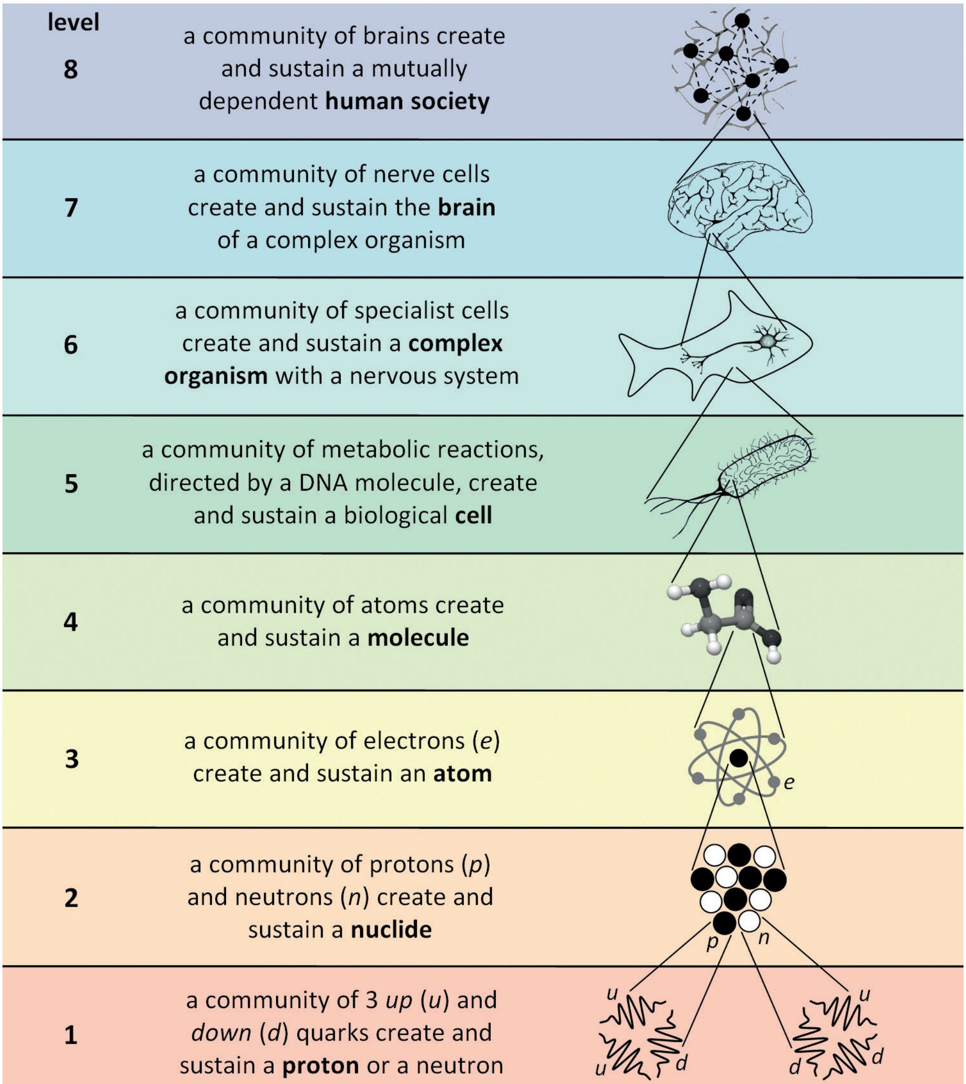
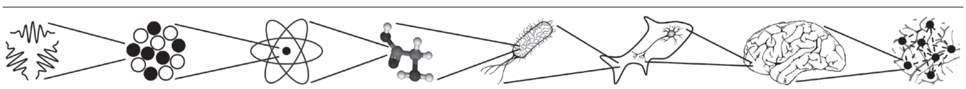


Figure 0.1. The eight levels of the universal hierarchy. Each level is defined and has a simple graphic icon. The hierarchy has built up, level by level, as the universe has evolved.

Inanimate matter does not progress beyond the 4th level, for while substances can aggregate on ever-larger scales, to make crystals, mountains, planets, and stars, none of these has the properties of the tiniest biological cell. However, the molecules at Level 4 are capable of endless chemical reactions with each other, and this activity sustains Levels 5–8, which are the biological world of "living" organisms.

Thus, a select community of chemical reactions between molecules, directed by a DNA molecule, create and sustain a self-sufficient biological cell, such as the



E. coli bacterium shown in the figure (Level 5). A community of specialised cells create and sustain a complex organism with a nervous system – represented by the enlarged neuron inside the fish outline (Level 6). A community of inter-connected neurons create and sustain a brain that controls an individual organism, such as the chimpanzee brain shown in the figure (Level 7). Finally, a community of empathic brains, each capable of accommodating diverse and conflicting individual perspectives, create and sustain a mutually dependent human society, in which people share their knowledge and feelings with each other (Level 8).

This is the universal hierarchy of communities in a nutshell, and in just eight levels, it goes from quarks to human consciousness. Each of us is a "*local embodiment of a Cosmos grown to self-awareness*", for we all have the eight levels of the evolved universal hierarchy within ourselves.

When we consider the ascent from Level 1 to Level 8, we can begin to comprehend the universe, not in terms of unitary things, but in terms of *communities* of things. Communities assemble into communities of communities, and so it goes on in a cumulative progression that builds up a hierarchy of communities. Each community is brought into existence and sustained by the community below, and in turn, creates and sustains the community above. This leads to a natural hierarchy of systems of matter, in which things are made of smaller things, and are themselves part of bigger things.

Each level of the universal hierarchy is sustained by the same principle – a group of matter systems exchange "things" between themselves, and so bind together in a stable community. The principle is simple, and perhaps it seems too simple to explain the complexity of our universe, but the natures of the matter systems, and the things they exchange are different at every level. For example, atoms bind themselves into a molecule at Level 4 by the exchange of light photons. At Level 6, biological cells bind themselves into a complex organism by the exchange of specific molecules. At Level 8, humans bind themselves into a shared society by the exchange of thoughts and feelings. Each level builds on the one below, and so, step by step, the universe becomes more complex.

Each of the eight communities is represented in figure 0.1 by a visual symbol or icon, and these also appear in the inset figure at the start of this chapter, and in the footer at the bottom of the right-hand pages of this chapter. Each of the following chapters has an inset icon and a footer that show the number of levels in the universe at that stage of its evolution. We won't see all eight symbols again until we reach chapter 8.

0.2.3 right here, right now

It is through forming a hierarchy of eight levels of material communities of ever-increasing complexity that the universe has evolved from its origin to the present time – with us now in it. A hierarchical scheme can lead one to think that higher, more complex levels are somehow better than lower, simpler levels. But a higher level is not inherently superior to the level below it. For example, Level 4 can only exist because it is sustained by the three levels below it; Level 4 then plays its part in sustaining the next level above. It could be argued that Level 1, the lowest level, is the most important because without it, none of the other levels can come into existence.

Humanity is at the 8th and highest level of the hierarchy, and it is tempting to think of ourselves as superior to all the "lower" levels of creation. But if we're inclined to see ourselves as lofty intellectual beings, distinct from and greater than everything else in the created universe, then we need the humility to accept that our existence at the 8th level depends utterly on the ceaseless activities of the seven underlying levels.

For example, right here, right now, millions of cells in your body are dividing, your muscles are holding you up, your stomach is digesting your 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 that your brain can take in the meaning of … this … particular … sentence. Your existence, from moment to moment, is sustained by the activities of your body's organs and cells, and by the molecules and atoms of which they are made.

Each of us can function as an independent consciousness at the 8th level of the hierarchy only because this level is sustained by the ceaseless activities of the seven levels below. We live our daily lives almost totally unaware of this.

0.3 the emergence of new properties and powers

We're familiar with the idea that there is a chain of genetic inheritance from the first biological cells to every organism alive today. If we extend this idea, there must be a continuous narrative that links events at the beginning of the universe 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 Big Bang. So, how did we get from *there* to *here*? How have empathy, laughter, music and mathematics emerged from raw energy and fundamental particles?

As we ascend the universal hierarchy in figure 0.1, we see simpler entities come together to become parts of a more complex whole with novel properties, which can then act as a unitary entity in its own right. Thus, a nucleus and a cluster of electrons come together to make an atom; atoms can combine to make molecules; molecules interact in biological processes; and biological processes can sustain a self-conscious mind. At each stage, a new whole emerges, with new properties that transcend the separate parts.

0.3.1 the emergent properties of water

We can use water as an example that illustrates how totally novel properties can emerge when a large number of single molecules come together. A single molecule of water is not wet; it cannot flow or freeze, boil or evaporate, and it's incapable of dissolving anything. All these are bulk properties of large numbers of water molecules, from a teardrop to an ocean.

These bulk properties emerge naturally from the interactions between water molecules, and this is illustrated in figure 0.2. All the water molecules are attracting or repelling each other as they randomly spin, move around and collide within the liquid. In even the tiniest droplet of water, there are billions upon billions of interactions every second, and the water's overall, bulk properties are the sum of them all. The surging ocean waves crashing on a beach, the skin of ice on a puddle, the bubbling of soup simmering in a saucepan, the chill of sweat drying, and the saltiness of tears – these properties only emerge and have any meaning when large numbers of water molecules come together.

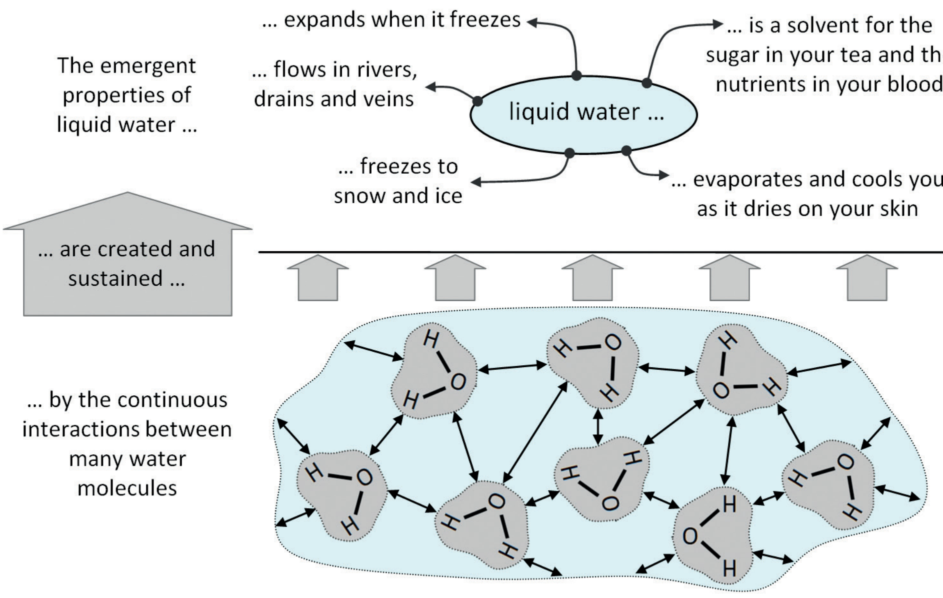


Figure 0.2. The emergence of the bulk properties of liquid water from the ceaseless interactions between individual H_2O molecules. The interactions are shown simply as double-headed arrows, which can be attractions or repulsions.

In the following chapters, we'll see how, as the universe evolves, new and more complex communities emerge at each level, with ever greater capabilities, properties, and powers.

0.4 communities are bound by endless exchanges

Figure 0.1 shows the eight communities that comprise our universe, but says nothing about the exchange processes that sustain each community. We can gain some idea of how the members of a community are bound together by continuous exchanges by looking at our human society at Level 8.

We live in a social and economic culture that encompasses the whole Earth. Materially, there is not one of us that is truly self-sufficient, and we support ourselves collectively by exchanging goods and services with each other. We also share and exchange our thoughts and feelings in various ways. We talk to and about each other, and share our responses to the books we read, the TV programs we watch, the video clips we like, and often, we just chat about the news and weather. For a sizeable portion of our waking moments, we are engaged with someone else's actions and thoughts, so that each of us lives as much in the minds of others as in our own.

For humans at Level 8, meaningful exchanges can involve physical objects, such as gifts and purchases, or they can make use of a shared symbolic language, which may be spoken or written. The communities at levels 1–7 are all bound together by the exchange of physical objects, which are different at each level; they can be photons (particles of light), sub-atomic particles, or whole molecules.

0.5 explanations at their appropriate levels

Because the communities and their exchange processes are different at each level of the hierarchy, each level has its own particular laws and principles. So, there is no all-encompassing explanation that covers all levels, and rather than a single "*Theory of Everything we appear to face a hierarchy of Theories of Things*". This means that we can only explain events at their appropriate level.

For example, we can *describe* thoughts and feelings in terms of the collective actions of atoms, for thoughts and feelings arise from what the matter at the lower levels is doing. But we can't *explain* thoughts in terms of atoms, for thoughts only arise at the level of a community of interconnected neurons.

If we could observe a thought enacted in the brain, we would see a pattern of coordinated activities of atoms. If we could recreate this pattern of activities, 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 finally, it must be a brain that has been shaped by a particular genetic inheritance and environmental experience.

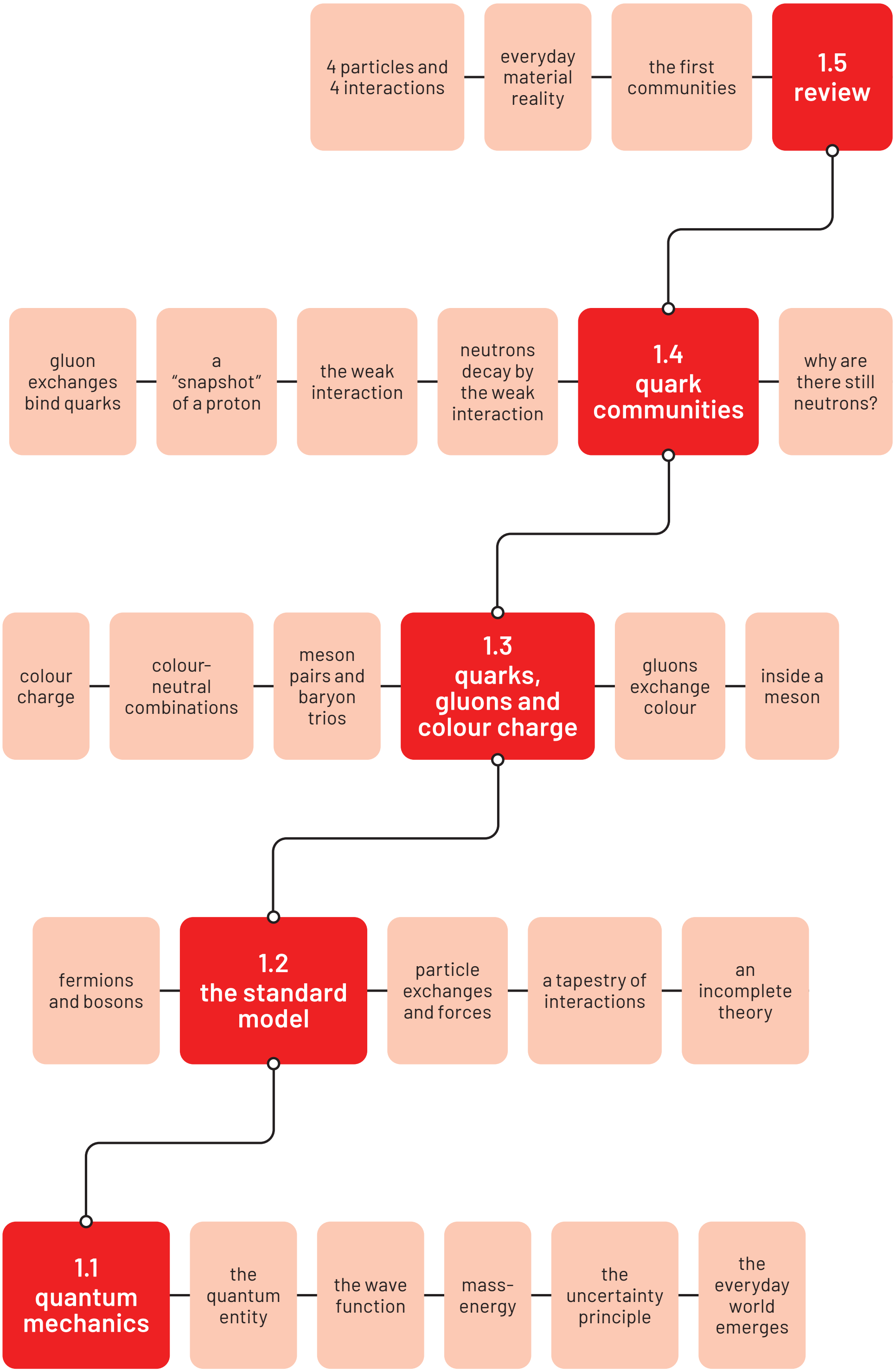
So, a thought, a collective event arising from the coordinated behaviour of a great number of atoms, can only be explained in terms of the level of the universal hierarchy at which it occurs. In short, we can break down a thought into a pattern of actions of individual atoms, but we can't go the other way and explain a thought in terms of the properties of those atoms. Our existence as conscious human beings rests ultimately on quarks, but our actions are not explained by them.

0.6 our journey begins

Our universe has evolved to become a hierarchy of eight levels of material communities of increasing complexity. This book is an account of that evolution in terms of the emergence of a series of communities with increasingly complex properties, rather than being a history of a series of unconnected events. So, there is no timeline, and only an occasional reference to when things occurred. The universe evolved when it was ready, in its own time, and we will follow its progress accordingly.

The following eight chapters will describe how physical matter evolves, level by level, from wiggly particle-waves, which are the merest gestures in space-time, to become capable of holding independent thoughts, and empathising with the thoughts of others.

Each chapter is a journey through one level of the hierarchy, and describes the matter systems and their exchanges, and how they naturally create the community at that level. Each chapter starts with a chapter map, which outlines the journey through that chapter. Just as you might use a geographical map to monitor your progress through unfamiliar terrain, you can use the chapter maps to monitor your progress through each chapter.


4 particles and 4 interactions
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1.5 review
gluon exchanges bind quarks
a "snapshot" of a proton
the weak interaction
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why are there still neutrons?
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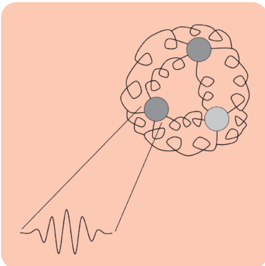
a tapestry of interactions
an incomplete theory
1.1 quantum mechanics
the quantum entity
the wave function
mass-energy
the uncertainty principle
the everyday world emerges

Chapter 1: protons and neutrons – communities of quarks



In this chapter, we will meet the ensemble of 16 fundamental particles that are collectively known as the standard model. Of those 16, just 8 make up our everyday world, and 2 of those 8 – the *up* and *down* quarks – come together to make protons and neutrons, the universe's first communities at Level 1.

We're starting with the fundamental particles from which the known universe is made. These microscopic particles aren't made of anything smaller; they can't be taken apart because they have nothing inside. In our macroscopic, everyday world, we think of particles as being like grains of sand or sugar – discrete objects that have a distinct presence at a particular location – but a fundamental particle is not anything like this at all. Instead, we must think of it simply as a bundle of energy, which can only be understood using quantum mechanics, and this is the subject of the first section.

1.1 quantum mechanics – the foundations of reality

1.1.1 the cosmic fireball

Our universe started as "*an immensely hot, immensely dense fireball of pure energy*" in the event we call the Big Bang. It's very difficult to imagine this state of things, but we can perhaps represent the formless energy of the Big Bang as a collection of waves of all sizes, as shown in figure 1.1. This formless, undifferentiated energy is always on the move and never at rest. We can think of a stormy sea, with waves of different heights and wavelengths, moving endlessly in all directions, passing through each other. Where the crests of two or more waves meet, there is an enormous surge of water. In other places, where the crest of one wave meets and "cancels" the trough of another, there can be a brief, local moment of calm.

Figure 1.1. A restless "sea" of formless, undifferentiated energy that is always on the move.

1.1.2 the quantum entity

The particles of physical matter that emerge from the bottomless chaos are tiny, individualised portions of this vast sea of energy. Each particle is "*nothing more than a highly concentrated and localized bundle of energy*", a discrete "quantum entity", which is sketched in figure 1.2.

The quantum entity shown here 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 in 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*".

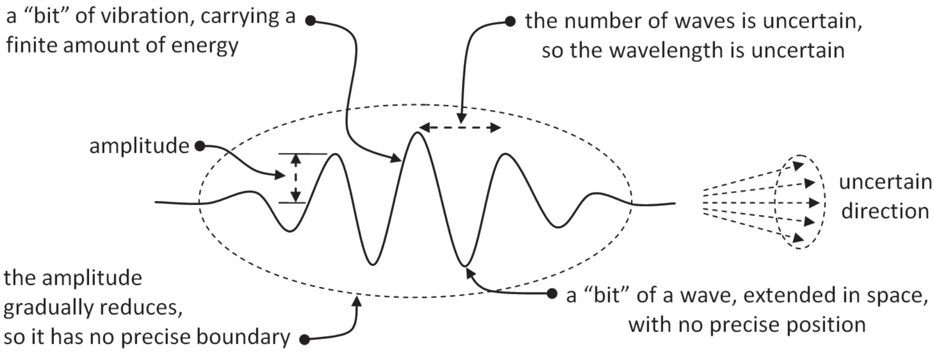


Figure 1.2. A quantum entity, a localised bundle of energy, and the embodiment of action, with all the uncertainties indicated by the dashed lines.

How can we comprehend the nature of this "wiggly" thing? It has the wave property of intrinsic vibration, so it has a wavelength and is extended in space. However, it is only a brief vibration, so it is an "*isolated piece of a wave*", which arises from nothing, vibrates a bit, and then returns to nothing. This finite presence makes it a discrete thing, like a particle. These apparently conflicting "wave" and "particle" qualities co-exist in complete harmony; there is "*no distinction between a wave and a particle*". The quantum entity shown in figure 1.2 is both a particle and a wave at the same time and all the time, and is commonly called a "particle-wave" because of its dual nature. The natures of particles and waves seem to be contradictory, but "*everything in the universe somehow manages to be both a particle and a wave*".

A quantum entity is not a discrete lump of immutable "matter-stuff", but is more like an action or a gesture – the trace of an infinitely pliable form. It is a holistic thing that is seamless and continuous; if we remove even the smallest part of it, then we destroy the whole. Its amplitude varies, so it is more "present" in some places than in others, and we now have to think in terms of varying probabilities rather than binary certainties/impossibilities.

If we peer into it, we see only the pulse of its intrinsic energy for it is created and sustained by ceaseless activity. It is never still or at rest, and its "*oscillatory 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 quantum entity is the embodiment of dynamic uncertainty. It is a bit of a wave that gradually comes into existence and then gradually disappears, so it merges seamlessly with the universe. It has an uncertain boundary, so its location is uncertain. It can't be set down in a state of rest. If it's set moving, it travels as a "wiggly" wave that is extended in space and does not follow a precise, pre-determined path. The interaction between two quantum entities is more like the meeting of two sets of waves than the collision of two discrete objects, such as snooker balls, so there can be a range of outcomes, each with a different probability. For example, if two waves line up so that their crests and troughs coincide, then they "add up" to make a single bigger wave, but if the crests of one coincide with the troughs of the other, then they "cancel", and both waves disappear.

The fundamental fabric of our physical reality is not bits of "matter-stuff", but wiggly quantum entities, like the one shown in figure 1.2. At its most basic level, the world is "*a continuous, restless swarming of things; a continuous coming to light and disappearance of ephemeral entities. A set of vibrations … A world of happenings, not of things*".

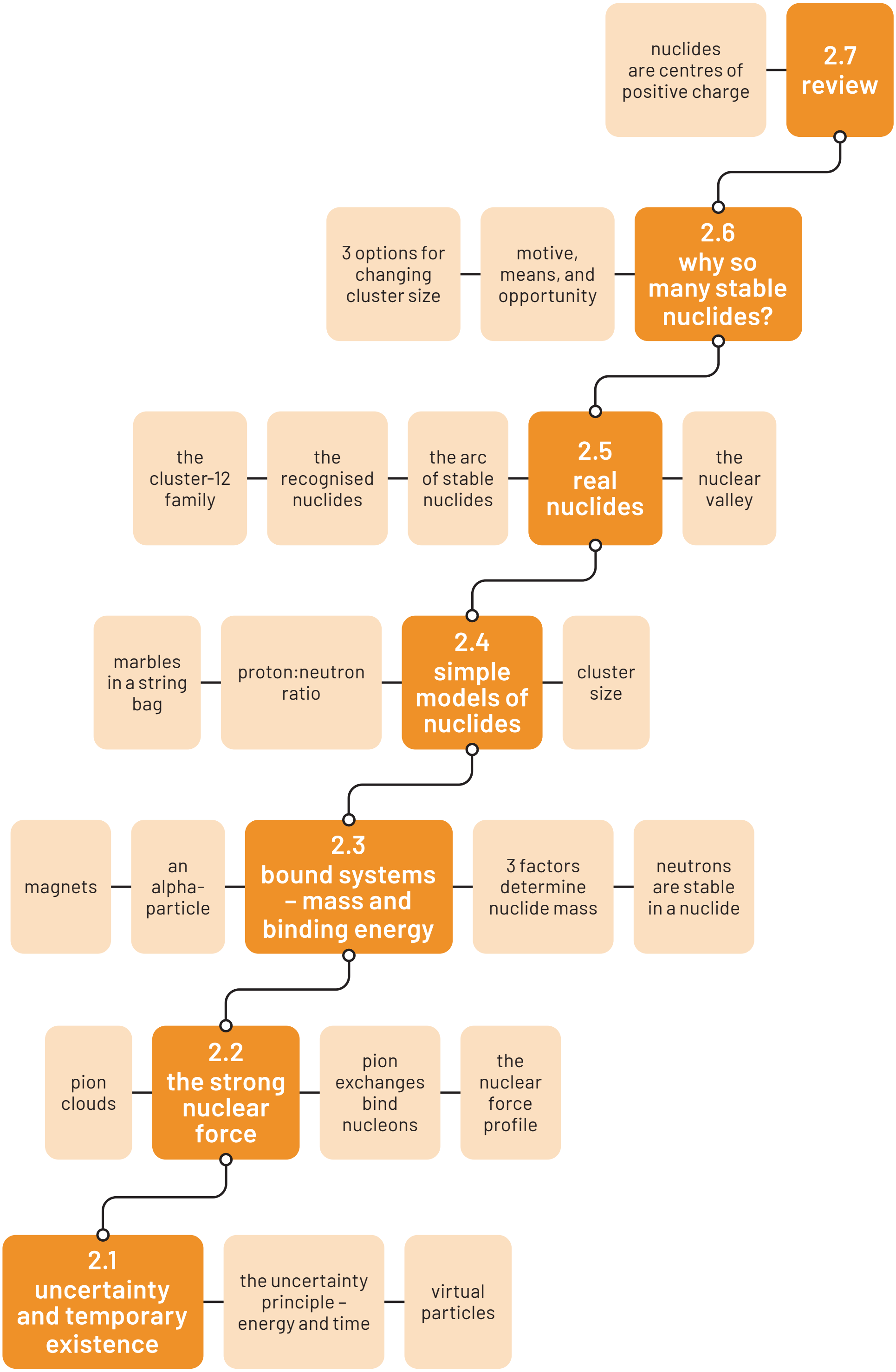
1.1.3 the wavefunction

To describe the behaviour of a quantum entity, the "*isolated piece of a wave*" shown in figure 1.2, 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 of a matter system "*contains all the dynamical information about the system it describes*".

In everyday examples of physical waves, there is always something that is "waving"; a washing line moves from side to side, the surface of a puddle moves up and down as a ripple passes across it, and air molecules vibrate to and fro as a sound wave passes through them. 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, … 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 can't directly observe the wavefunction itself.

This is because the wavefunction is not a physical entity but is the representation of one. When physicists refer to particles, "*they actually mean a mathematical object called the wave function, which is neither a particle nor a wave but has properties*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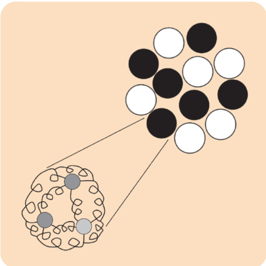
virtual particles

Chapter 2: nuclide – a community of protons and neutrons



At the end of Level 1, the universe has just two communities, both trios of *up* (*u*) and *down* (*d*) quarks. The lighter proton (*uud*) is stable, while the slightly heavier neutron (*udd*) is unstable – although with a very long half-life for a sub-atomic particle.

In this chapter, we will see how protons and neutrons assemble themselves into nuclide communities and bring the next level of the universal hierarchy into being. Neither protons nor neutrons can do this on their own, but together, they can create around a hundred different nuclides. These are the foundations of the atomic chemical elements that will emerge in Level 3 – our everyday world is beginning to come into view.

I will use the generic term *nucleon* to refer to both protons and neutrons, the term *cluster* for a group of unspecified nucleons, and the term *nuclide* for a specific combination of protons (p) and neutrons (n), such as [6p,6n]. This nuclide will become the central nucleus of a carbon atom in Level 3. However, there are no atoms yet, and therefore no nuclei, so none of the familiar chemical elements will appear in this chapter.

This might appear pedantic, but there is a good practical reason for taking this approach. In this chapter, we'll see that nuclides are dynamic communities of nucleons, which can either split into smaller nuclides, or fuse together to make bigger nuclides. Also, protons and neutrons within a nucleon community can interchange their identities, so that one nuclide can change into another. For example, the transformation of a neutron to a proton changes the nuclide [5p,7n], which is the nucleus of boron-12, into the nuclide [6p,6n], which is the nucleus of carbon-12. We can readily understand this change in terms of nucleons, but not when stated just in terms of atomic elements.

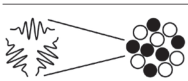
2.1 uncertainty and temporary existence

2.1.1 the uncertainty principle – energy and time

In chapter 1, we met the particle-wave quantum entity and saw the uncertainty that lies at its heart. We are now going to look at how this uncertainty enables the creation of short-lived virtual particles, which bind nucleons together into nuclides.

determining musical pitch

It's well known that the shorter the time a musical note is heard, the less certain one can be about its frequency, and this has been called the "musician's uncertainty principle". The time "pips" used on BBC radio in the UK illustrate this. These pips are a series of six 1 kHz tones, with the first five having a duration of 0.1 s and the final tone lasting 0.5 s. The precise time when the hour changes is at the start of the final pip. The point here is that all the tones have the same 1 kHz frequency, but it is almost impossible to



discern this frequency in the first five short pips, and only in the final long pip does the musical pitch become apparent.

the energy-time uncertainty relation

We saw in section 1.1.5 that a classical particle is a static thing, so a brief glimpse tells you everything about it; looking for a longer time does not add any more detail. In contrast, a quantum particle is a dynamic entity that is always vibrating in real time. Like the musical note, if it is observed on a shorter time-scale then its properties become more uncertain, and this is shown in figure 2.1.

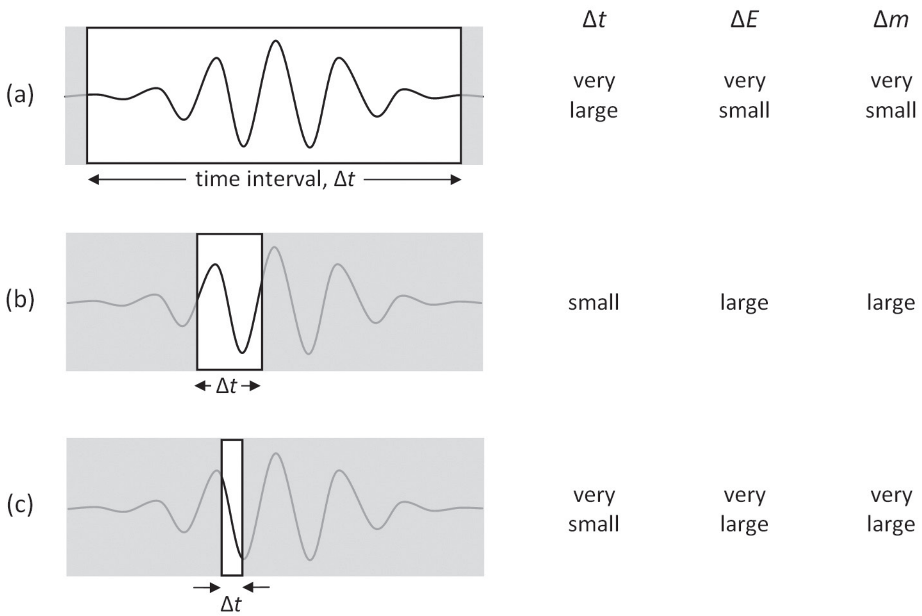


Figure 2.1. The energy-time uncertainty principle. Observing the quantum entity at a more precise time, hence for a shorter time interval (Δt), leads to a bigger uncertainty in its energy (ΔE) and mass (Δm).

This figure shows the same quantum entity that we saw in figure 1.2, but now observed in progressively shorter time intervals. The time interval, Δt, is a measure of the uncertainty in the time of the observation; the smaller the value of Δt, the more certain we can be about exactly when the quantum entity was observed.

With a long time interval, shown in part (a), we're not certain exactly when the quantum entity was observed, but its full waveform is apparent, and from this we can get an accurate measure of its energy. Because of the equivalence of energy and mass, whereby $E = mc^2$, if we know the particle's energy then we also know its mass. If the waveform is observed for a shorter time, as shown in part (b), then the time of observation is more certain, but now only part of the waveform is apparent, such as a peak and a trough, and this allows only a rough estimate of its energy and mass. On an even shorter time-scale, shown in part (c), we may see no peak or trough, but only that there is some sort of oscillation, and this permits only the vaguest estimate of its energy and mass.

So, the energy and mass of a quantum particle become more uncertain on shorter time-scales. This is the energy-time uncertainty relation, one form of Heisenberg's uncertainty principle. This states …

uncertainty in energy x uncertainty in time ≥ Planck's constant/2π

$$\Delta E \quad \times \quad \Delta t \quad \geq \quad h/2\pi \qquad \text{(equation 2.1)}$$

The energy-time uncertainty relation tells us that if we have a long time to observe a quantum entity, the time interval Δt is large, which makes ΔE small, and so we can measure its energy accurately. Conversely, if we can only observe the quantum entity for a short time, then ΔE is large and its actual energy is very uncertain.

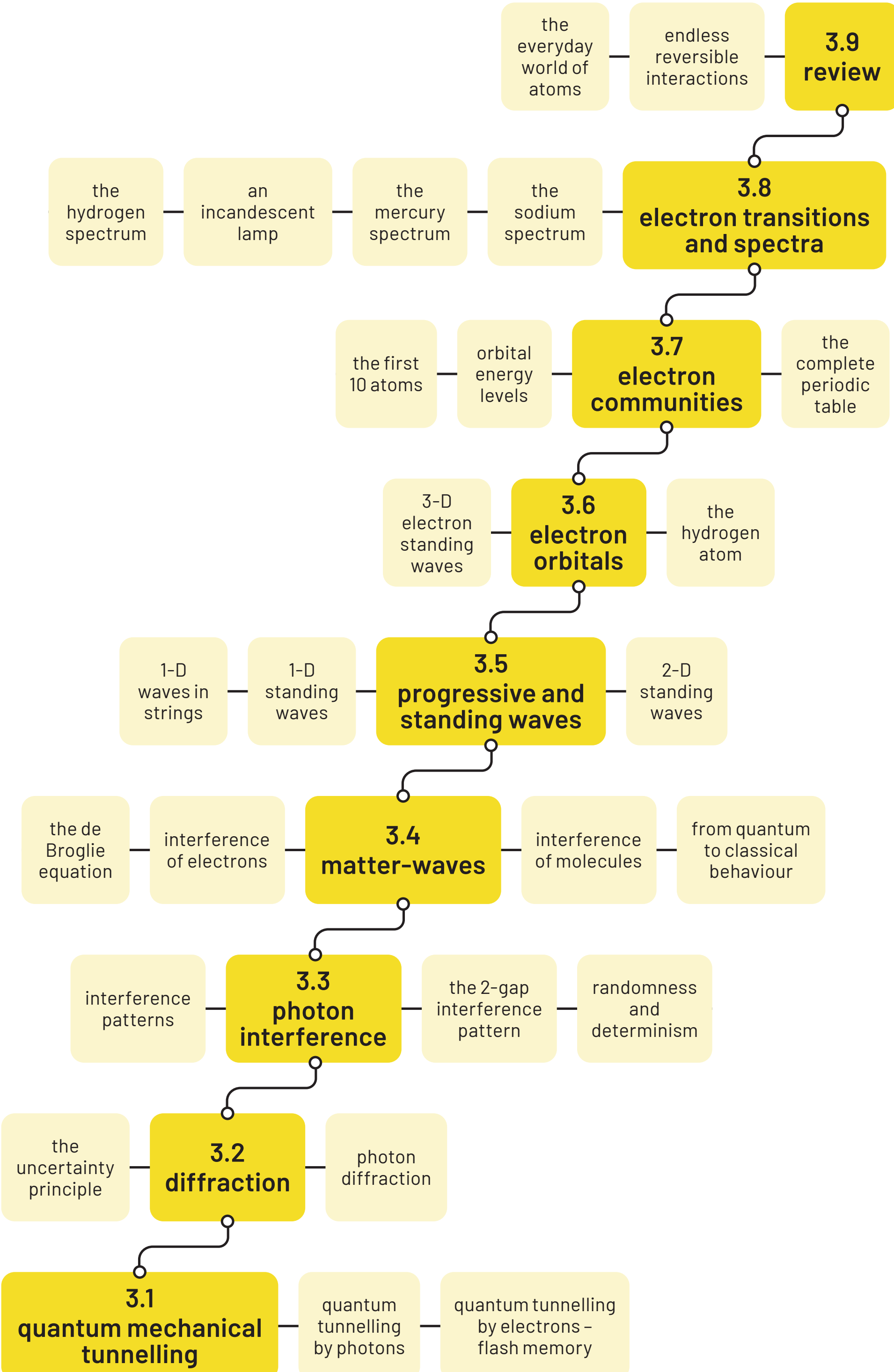
This tells us that we can't be sure at any moment in time how much energy is present, with Planck's constant setting the limit on the uncertainty. On a short time-scale (small Δt), there can be large fluctuations in energy (large ΔE). Therefore, it is possible for energy not to be conserved in the short term, as long as the non-conservation doesn't persist for too long.

2.1.2 virtual particles and the quantum vacuum

Since energy and mass are equivalent, an energy fluctuation allows the brief creation of matter and so, over a brief interval of time (Δt), we can't be sure how much matter (Δm) there is at a location, even in the vacuum of "empty space". An energy fluctuation can cause a small amount of matter to appear spontaneously, exist for a short time and then disappear. The greater the amount of matter that appears, the shorter the time interval it can exist before disappearing back into nothingness.

Quantum mechanics tells us that if a process is not specifically forbidden, then it will occur. This opens the way for the creation of virtual particles, which have brief lives within the constraints of the energy-time uncertainty relation. Virtual particles are created in particle-anti-particle pairs, so the creation of matter is always balanced by the creation of an equal amount of anti-matter. "*This result is astonishing. It means that over a very brief interval Δt of time, we cannot be sure how much matter there is in a particular location, even in "empty space". During this brief moment, matter can spontaneously appear and then disappear. The greater the amount of matter (Δm) that appears spontaneously, the shorter the time interval (Δt) it can exist before disappearing into nothingness. … Pairs of every conceivable particle and antiparticle are constantly being created and destroyed at every location across the universe*".

The nothingness from which virtual particles come, and to which they return, is the quantum vacuum. The quantum vacuum has no real particles in it, but it is full of quantum energy fluctuations and these sustain a "*flickering froth*" of virtual particles. The quantum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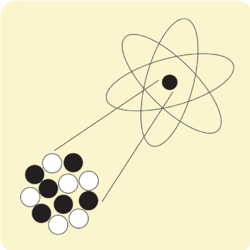
Chapter 3: atom – a community of electrons



the atom – a conflict of inclinations

Level 2 is complete with the emergence of a series of nuclides carrying up to about 100 units of positive electric charge. Every electron carries a negative electrical charge, so they repel each other and would never come together of their own accord. However, each positively charged nuclide attracts a number of negatively charged electrons to itself, equal to its positive charge. So, the nuclide becomes a nucleus, the centre of a community of electrons. Together, a nucleus and its electron community comprise an electrically neutral atom.

We probably include the central nucleus in our mental picture of an atom. But the only rôle of the nucleus is to gather a specific number of electrons around itself; the electrons then organise themselves into a structured atomic community. Thus, nuclides at Level 2 enable the existence of electron communities at Level 3.

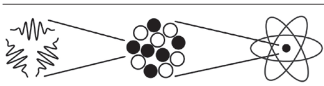
We are familiar with electric charge, and the electromagnetic force, whereby like charges repel each other, while opposite charges attract. In the Standard Model, summarised in figure 1.5, electrically charged particles exert forces on each other by exchanging photons. Through their exchange, "*photons transmit, or mediate, a force*", which may be attractive or repulsive. An atomic electron community is tethered to its nucleus by the continual exchange of photons. The simplest atom is hydrogen, comprising one proton and one electron, and by "*exchanging photons, the proton keeps the electron nearby, dancing around it*". So, at Level 3, we have an atom, a conflict of inclinations, because it is a community of electrons whose attraction to a shared nucleus overcomes their mutual repulsion.

In this chapter, we'll see how the hundred or so species of atoms build up the periodic table of the elements, and thus our everyday atomic world emerges.

the electron – both particle and wave

We've seen that a nuclide is a roughly spherical cluster of nucleons, rather like marbles in a string bag; this is because the nucleons all attract each other strongly, as shown in figure 2.7. But the electrons in an atomic community all repel each other, and they are confined together by their stronger attraction to their nucleus. So, how do these electrons manage to occupy the same small volume of space and yet keep out of each other's way?

The answer is that the electron is a quantum entity, as shown in figure 1.2, and is capable of behaviours that are quite beyond a classical particle. We'll look at three of these behaviours: quantum mechanical tunnelling, diffraction, and interference.



3.1 quantum mechanical tunnelling

3.1.1 principles

A quantum entity can pass through a barrier by quantum mechanical tunnelling – something that is quite impossible for a classical particle, and this is illustrated in figure 3.1. The classical particle, with its clearly defined boundary, will stop abruptly at a barrier, as shown in part (a). But the wavefunction of a quantum entity, with its smooth continuity, will only change gradually. So, a quantum entity encountering a barrier penetrates a little way inside it, as shown in part (b), because the amplitude of the wavefunction does not fall immediately to zero.

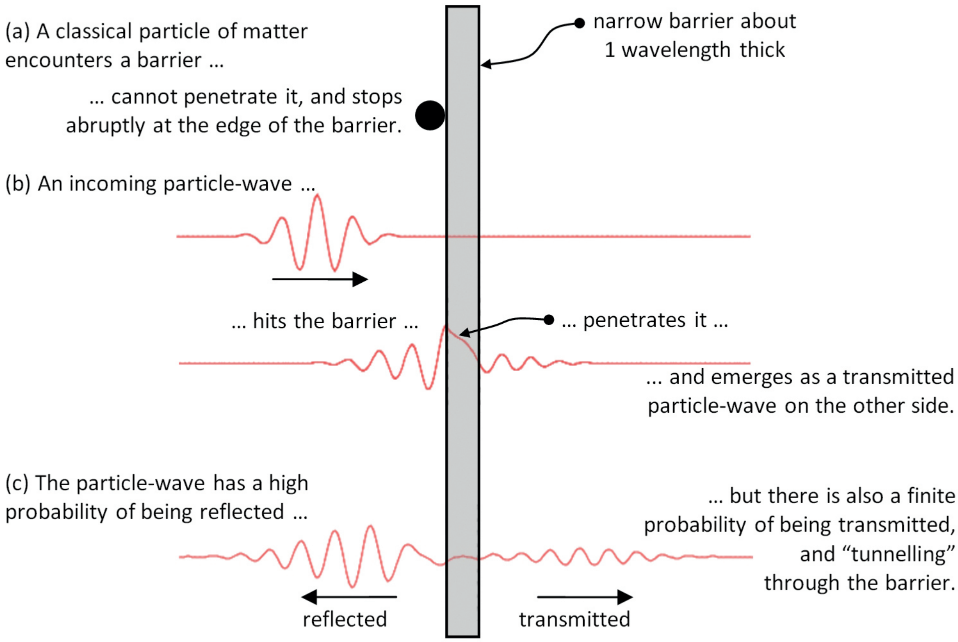


Figure 3.1. (a) A classical "lump" of matter is abruptly stopped by a thin barrier, but a quantum entity has a finite probability of (b) penetrating it, and (c) tunnelling through it.

If the barrier is narrow enough, then there will be a wave with a small but finite amplitude on the other side. The quantum entity is reflected by the barrier, and *also* penetrates through it. In physical terms, there is a small probability that an object approaching the barrier from the left will not bounce back but will appear on the other side, as shown in part (c). This is known as quantum mechanical tunnelling because the quantum particle can pass through a barrier that is impenetrable by a classical particle.

3.1.2 quantum tunnelling by photons

Figure 3.2 shows a simple optical analogue of quantum tunnelling. We can see a pair of binocular glass prisms pressed together, and a ray of laser light shining into the left-hand prism. The polished glass prisms are very flat and smooth, but there is a distinct air gap between their faces, whose width depends on how hard the prisms are pressed together.

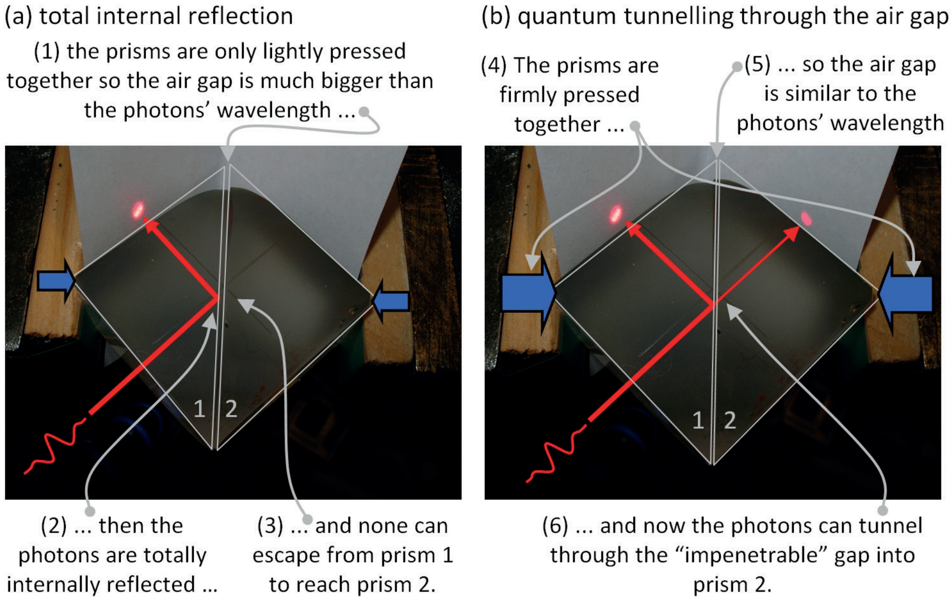
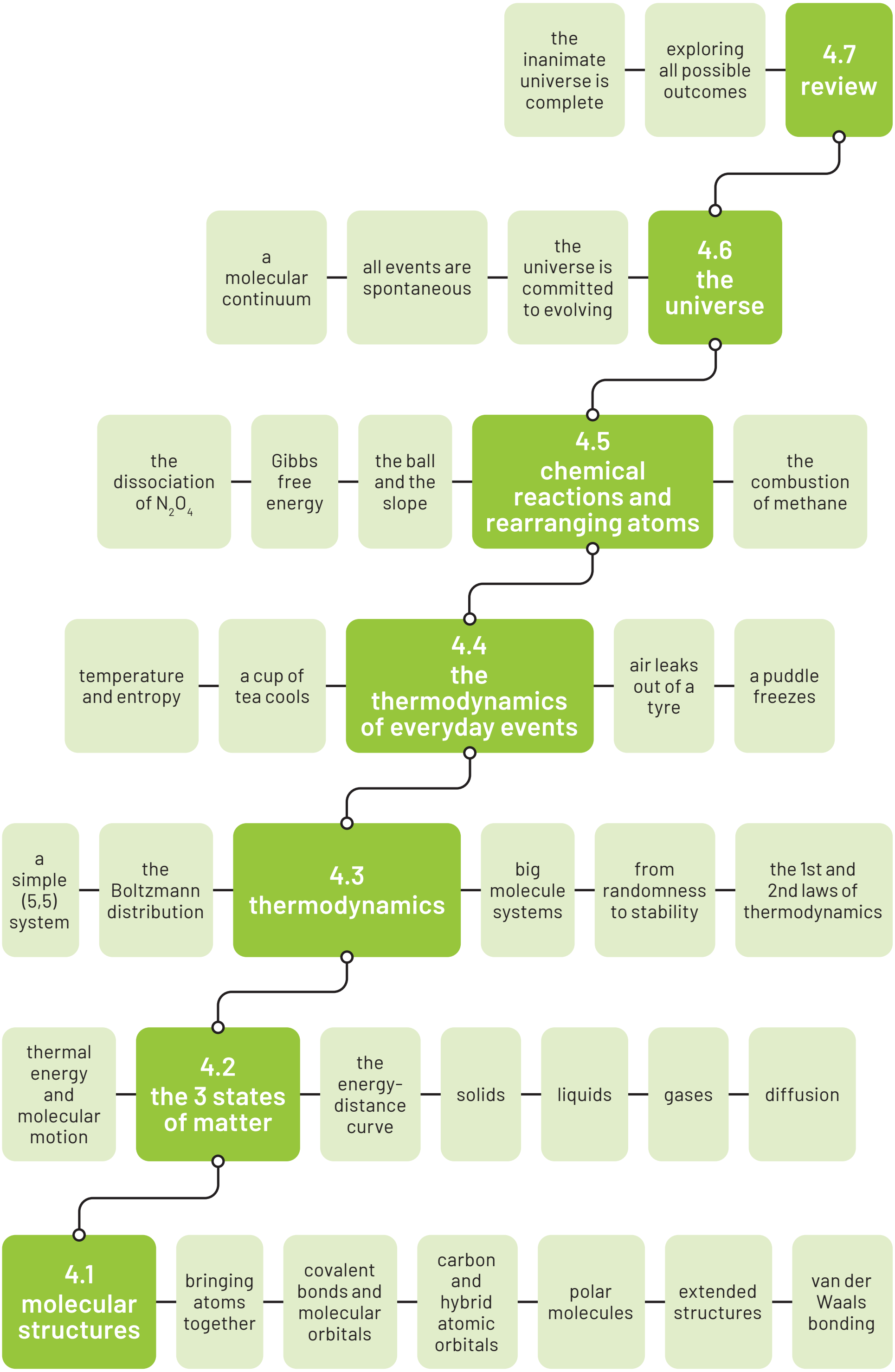


Figure 3.2. (a) light photons are trapped inside prism 1 by total internal reflection if the air gap to prism 2 is larger than the photon wavelength, but (b) some photons can tunnel through the air gap if it is about the same size as the wavelength. The red lines have been added to show the paths of the photons, and the blue arrows show the forces pushing the prisms together. The outlines of the prisms are shown in grey, and the sizes of the air gaps are exaggerated.

In part (a), the prisms are only gently pressed together, and the width of the air gap is much larger than the wavelength of the light photons. This wide air gap acts as an impenetrable barrier for the photons, so they all undergo total internal reflection at the glass/air interface, and appear on the left-hand screen. In part (b), the prisms have been firmly pressed together, which has reduced the width of the air gap to become comparable to each photon's wavelength. Now, a small proportion of the photons have been able to tunnel through the narrow air gap, enter prism 2, and travel on to appear on the right-hand screen. Reduce the pressure on the prisms, and the red spot on the right-hand screen disappears.

3.1.3 quantum tunnelling by electrons – flash memory

Quantum tunnelling is well-known and understood, but it might seem to be an arcane phenomenon of little practical use. However, we all use quantum tunnelling billions of times every day in flash memory, whereby we store data in a microcircuit. This might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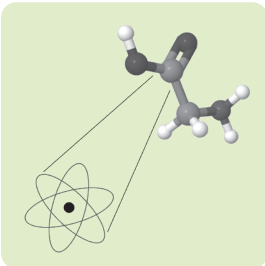
Chapter 4: molecule – a community of atoms



Chapter 3 ended with an atom, a community of electrons that are bound to a central nucleus and occupy a sequence of orbitals at different energy levels. In this chapter, we'll see how these independent electron communities join up to make extended communities and bring into being all the diverse substances of the everyday world.

Just as a limited range of LEGO™ bricks can be combined to make a vast number of diverse structures, so the limited range of atomic elements in the periodic table can be combined to create the enormous variety of the material world. And just as LEGO structures can be disassembled and the bricks re-used to build new and different structures, so all atomic interactions are reversible, and atoms can be endlessly re-used to make new molecules and materials.

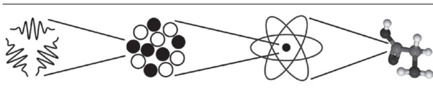
In the first part of this chapter, we will look at the molecular and larger structures that atoms make. In the second part, we'll look at the dynamic interactions between atoms and molecules, and we will see how all change in the universe is driven by the ever-increasing dispersal of matter and energy.

perceiving the atomic nature of the everyday world

We have been taught that everything is made of discrete atoms and molecules, so the world must be granular – atomically "pixelated". But there is actually very little in our everyday experience that tells us this. The materials of our everyday world are largely stone and ceramics, wood, metals, plastics and rubber, and watery and oily fluids. These appear to be continuous, rather than granular, and show no signs of being made of tiny particles. But it is possible to perceive the atomic nature of substance by focusing on two aspects of the behaviour of matter.

First, there are slow processes that occur in tiny increments over a long time-scale. So, Lucretius, in about 50 BCE, observed how "*a ring is worn thin next to the finger with continued rubbing. Dripping water hollows a stone. A curved ploughshare, iron though it is, dwindles imperceptibly in the furrow. … The bronze statues by the city gates show their right hands worn thin by the touch of travellers who have greeted them in passing*". We ourselves can observe the pattern of decades of wear on old stone steps and how the edges of kitchen knives gradually become concave with repeated whetting. In all these cases, a perceptible change has been produced by an immense number of microscopic steps, each of which removes an imperceptibly small amount of matter.

Second, there are dynamic processes in which matter is allowed to move and associate freely. We're familiar with snowflakes that have a common hexagonal symmetry, and with other mineral crystals that have regular geometric shapes. It may be that



we've grown crystals of chemicals, like copper sulphate, from their solutions. In these cases, large, macroscopic objects have been assembled by an immense number of microscopic steps, each of which adds an imperceptibly small amount of matter. We can infer the existence of tiny units of matter, which can move around independently and come together in regular spatial arrangements.

We're also familiar with the experience of knowing that dinner is nearly ready because we can smell it even if we are in a distant part of the house. From this, we can infer that there are tiny "dinner" particles, which are small enough to float unseen through the air, yet elaborate enough that they carry an identifiable smell.

4.1 molecular structures

4.1.1 bringing atoms together

In the last chapter, we saw that an atom comprises a central nucleus surrounded by a number of electrons, which are arranged in a series of orbitals, and that we can think of an orbital as a "cloud" of electric charge. If we imagine bringing a number of atoms together, the electron clouds will start to impinge on each other and each atom's outer valence electrons will become increasingly attracted to the nuclei in nearby atoms. In this very simple scenario, there are four basic options; these are illustrated in figure 4.1.

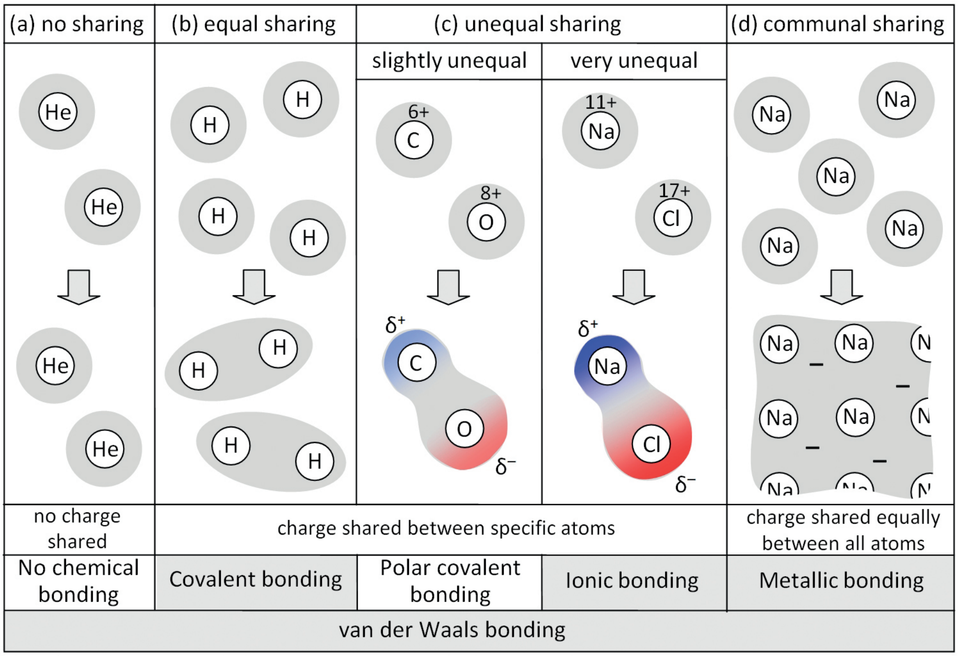


Figure 4.1. The four major options for atoms to share their electron charge. The clouds of electron charge are all shaded grey. Partial charges are indicated by the Greek letter δ ("delta"), and colour-coded – red for negative, and blue for positive. The four major types of bonding are shaded grey.

First, there are some atoms with full outer shells that don't share any of their electron charge with other atoms; this is illustrated by the helium atoms (He) in part (a). Each separate helium atom is shown simply as a nucleus surrounded by a grey cloud of electron charge. If these atoms are brought together (shown below the arrow), each atom holds on to its own electron charge and does not share it with any other atom. Consequently, helium forms no molecules with itself or any other elements, and exists only as individual, isolated atoms.

The second option is illustrated by the hydrogen atoms (H) in part (b). The atoms are distinct entities when far apart, but as they are brought together, their electron clouds merge so that a pair of nuclei become surrounded by a single cloud of electron charge, which is shared equally between them.

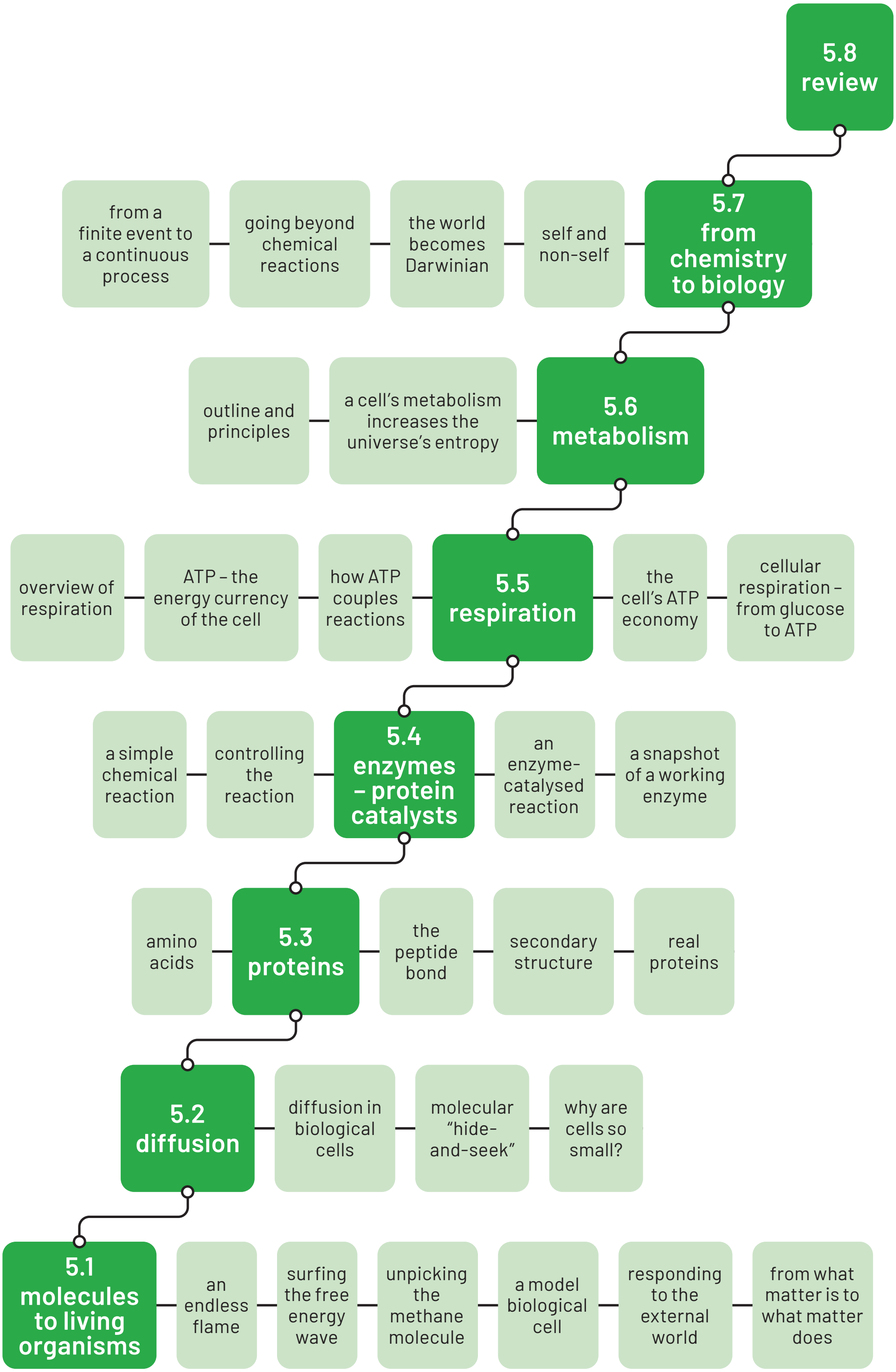
Our look at electron orbitals in chapter 3 might lead us to think of these as being inflexible, with fixed shapes. But we've seen how 1–D and 2–D standing waves will fully occupy the available space in a string or a membrane, and the same is true for 3–D electron standing waves. An electron will form an orbital around two or more nuclei as readily as around a single nucleus, so we see the two separate atomic orbitals fuse into a single shared orbital that holds both electrons, and encompasses both nuclei.

Each nucleus is attracted to this shared electron cloud, and the cloud also shields each nucleus from the other, thus reducing their mutual repulsion. This is a hydrogen molecule (H_2), and the shared electron charge is the essence of the covalent bond that binds the two H atoms together. Each H atom forms a covalent bond with one other H atom so that four H atoms produce two H_2 molecules.

The third option is illustrated by the two molecules in part (c), carbon monoxide (CO) and sodium chloride (NaCl). These comprise different atoms, with different numbers of protons in their nuclei.

We'll start with carbon monoxide (CO). The carbon atom in CO has 6 protons in its nucleus, so it is atom **6** in the periodic table (figure 3.20). However, the oxygen atom has 8 protons, so the oxygen attracts the shared electron cloud more strongly. We use the term "electronegativity" to describe "*the power of an atom when in a molecule to attract electrons to itself*". Oxygen is more electronegative than carbon, so it attracts the greater part of the shared electron charge towards itself. The result is a polar covalent bond, in which the two atoms are bound by shared electron charge, but the charge is shared unequally.

The CO molecule is a polar molecule. It is electrically neutral overall, but the shared electron charge is shifted towards the oxygen "end", so it carries a partial negative charge, while the carbon "end" carries a corresponding partial positive charge. In the figure, the partial charges are indicated by the Greek letter δ, pronounced "delta", and by colour-coding negative charge as red and positive charge as blue. The CO molecule is slightly polar, so its ends are tinged red and blue.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an endless flame
surfing the free energy wave
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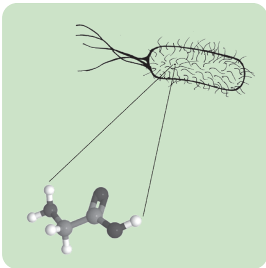
responding to the external world
from what matter is to what matter does

Chapter 5: cell – a community of chemical reactions



We have completed the first half of our journey up the universal hierarchy, and we can see physical matter as a hierarchy of four levels of communities: protons and neutrons, nuclides, atoms, and finally, molecules and extended structures, like crystals and metals. This is what physical matter *is*.

We have also seen that molecules can be endlessly un-made and re-made and that this is thermodynamically favoured if the rearrangement increases the universe's entropy. This is what physical matter can *do*, and in the second half of our journey, we will see that it creates and sustains levels 5–8 of the universal hierarchy. We will see that what matter *does* becomes increasingly complex, level by level. Finally, at Level 8, we will see matter systems capable of self-consciousness and of comprehending the diverse perspectives of others.

5.1 from molecules to living organisms

So far, the transition from one level in the universal hierarchy to the next has been fairly straightforward, and the community at each successive level emerges naturally from the previous one. But now things appear to have changed; something "special" seems to have happened, and matter has somehow become "alive". I want to avoid the idea that a biological cell is "special", and so, as far as possible, I will try to avoid the terms "life" and "living" and use the term "biological".

In this chapter, we will see the emergence of biological cells as thermodynamic communities, sustained by molecules engaging in endless free energy-dispersing interactions. The purpose of the first section of this chapter is to show how biological "life" emerges naturally and spontaneously in a universe with an inexhaustible thermal energy, which drives mutable molecules to engage in endless random interactions.

5.1.1 an endless flame

We've seen in figure 4.25 that the atoms in methane and oxygen will rearrange themselves through the combustion reaction into molecules of carbon dioxide and water because this increases the universe's entropy. The Earth's atmosphere has methane and oxygen molecules bumping into each other, and their reaction is thermodynamically favourable – we might say simply that it "wants" to occur. So why does combustion not occur naturally? Is there any way that the combustion of methane could be enabled to proceed?

To enable methane and oxygen to interact, we need to bring their molecules together and keep them together – this requires some kind of container. This arrangement is shown in figure 5.1(a), which shows the system in three states: before, during, and after combustion. No molecules can enter or leave this isolated system, though it can exchange energy with its surroundings. In this closed system, combustion is finite and ends with the consumption of either oxygen or methane, or the build-up of carbon dioxide and water, and the system reaching equilibrium.

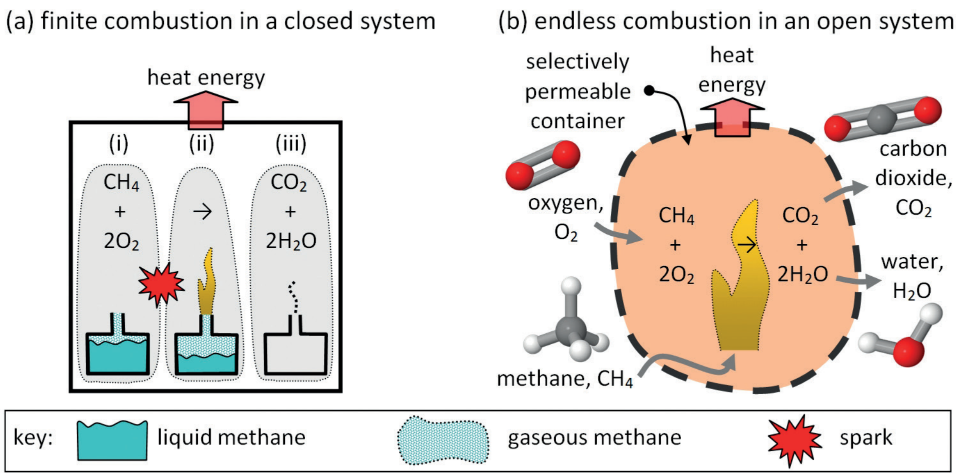


Figure 5.1. (a) the brief "lifetime" of a methane flame in a closed system; (i) before the flame is lit, (ii) the spark ignites the methane, and (iii) when all the oxygen or methane has been consumed, and the flame has gone out; (b) the endless "lifetime" of a methane flame in an open system, in a permeable container that allows selected molecules to pass in and out, and heat to escape.

How could we enable the flame to continue to burn? If we had an endless supply of methane and oxygen and could also remove the carbon dioxide, water and heat energy, then the flame's "lifetime" would be extended indefinitely. This is shown schematically in part (b). The combustion reaction is confined within a selectively permeable container, which allows particular molecules to pass in or out, and also allows the generated heat to escape. This arrangement ensures that the reacting molecules, methane and oxygen, are replenished as they are consumed and that the waste molecules, carbon dioxide and water, are removed after they are produced. The combustion reaction, represented by the flame, is spatially confined within the container. But it's not isolated from its surroundings because selected molecules can pass in and out, and heat energy can escape. This is an open system that exchanges both molecules and energy with its surroundings, so it can never attain equilibrium and be chemically at rest.

The one constant in this system is the combustion reaction, which we see as the flame in the figure. The molecules are transient because they just pass through the system, and sustain the constant flame while they are briefly present and interacting.

5.1.2 *"thermodynamic gravity" – surfing the free energy wave*

In section 4.5.2, we encountered the Gibbs free energy of an isolated chemical system as a measure of "*the energy that can be dispersed to the universe*". We saw that in spontaneous changes, such as a ball rolling down a hill (figure 4.24), and the combustion of a methane molecule (figure 4.25), the system's free energy is dispersed to the surroundings, thereby increasing the universe's entropy.

Figure 5.2(a) shows the free energy change in the combustion of one molecule of methane. After ignition by the spark, we see the unstable ensemble of C, H, and O atoms "fall" down the free energy slope as they rearrange themselves into molecules of CO_2 and H_2O. The process takes a small but definite amount of time for the atoms to move about and rearrange themselves, so time is plotted along the *x*-axis. The reaction is complete when all the reactant molecules are consumed and transformed into waste product molecules, and the system is in equilibrium at the bottom of the free energy slope.

Part (b) shows the combustion reaction taking place in the permeable container that was shown in the previous figure. Now the reactant CH_4 and O_2 molecules are replaced as fast as they are consumed, and the waste CO_2 and H_2O molecules are removed as fast as they are produced, so the system can never reach equilibrium. The result is that there is a new free energy slope for the combustion of every CH_4 molecule, and the chemical system is endlessly falling down it but never reaching the bottom, because the free energy slope is always being recreated, moment by moment.

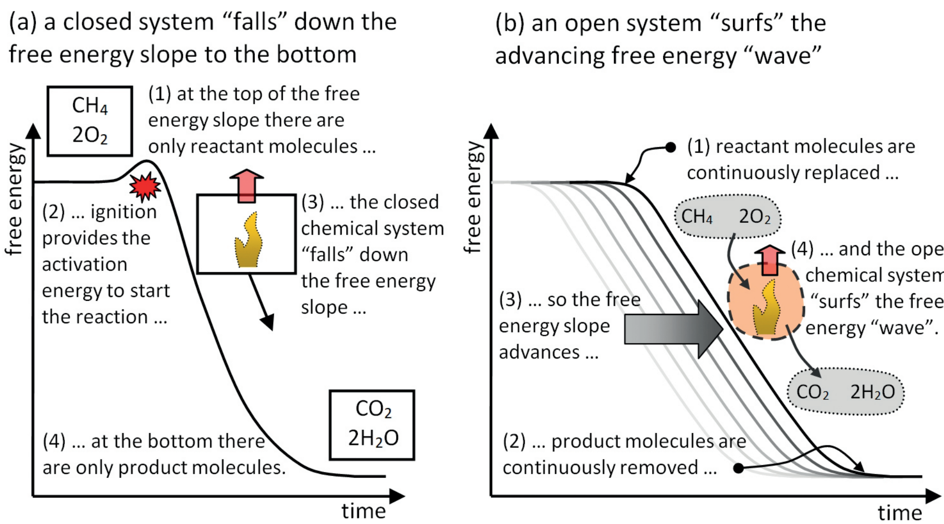
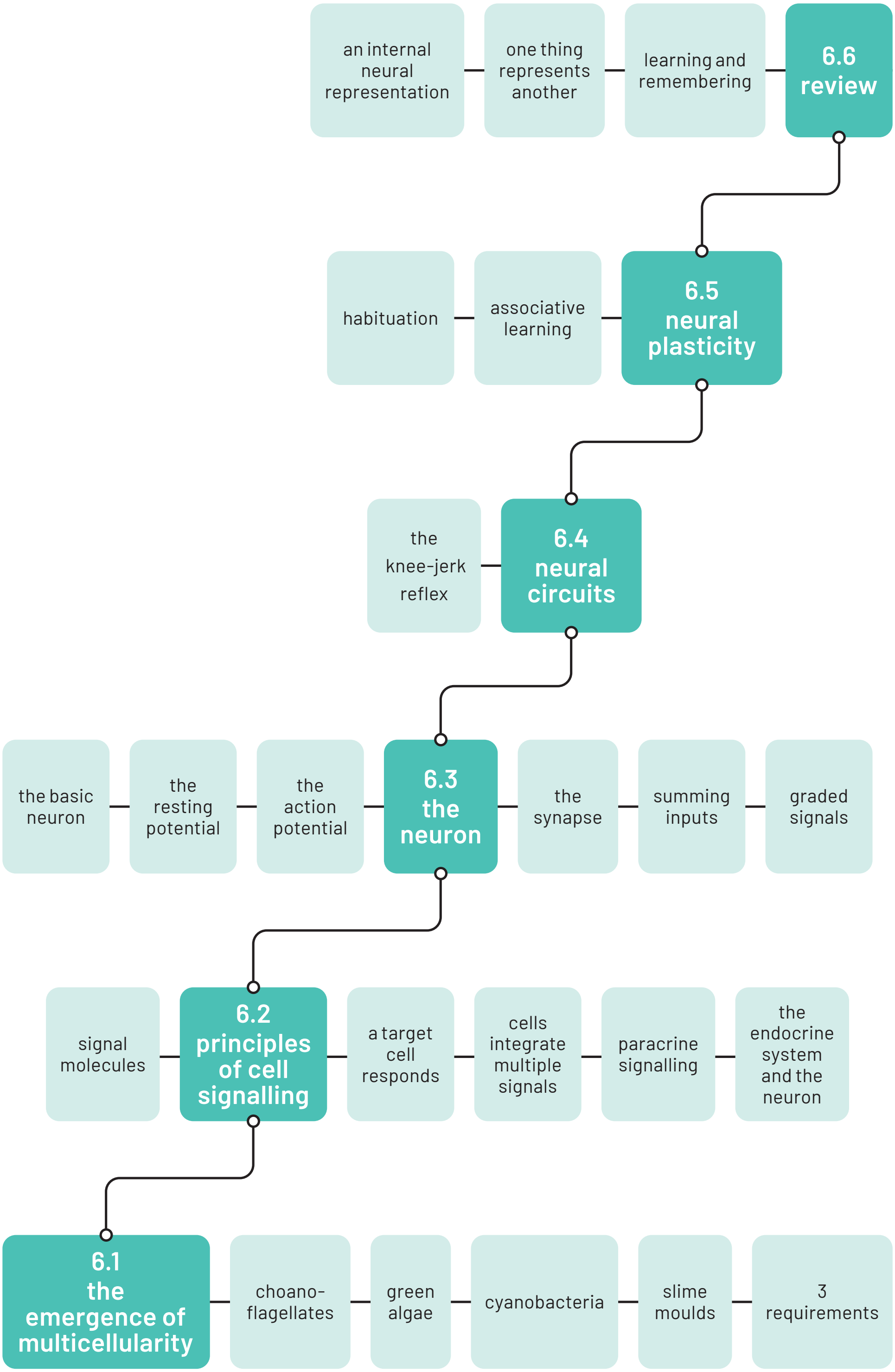
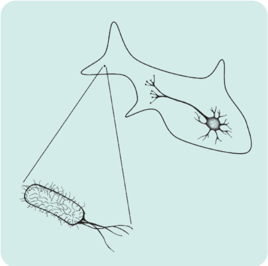


Figure 5.2. (a) the finite combustion of a single methane molecule, in which the chemical system "falls" down to the bottom of the free energy slope; (b) the endless combustion of methane is sustained by the supply of reactants and the removal of waste products, so the free energy slope is always being recreated, moment by moment, and the system never reaches the bottom.


an internal neural representation
one thing represents another
learning and remembering
6.6 review
habituation
associative learning
6.5 neural plasticity
the knee-jerk reflex
6.4 neural circuits
the basic neuron
the resting potential
the action potential
6.3 the neuron
the synapse
summing inputs
graded signals
signal molecules
6.2 principles of cell signalling
a target cell responds
cells integrate multiple signals
paracrine signalling
the endocrine system and the neuron
6.1 the emergence of multicellularity
choano-flagellates
green algae
cyanobacteria
slime moulds
3 requirements

Chapter 6: a complex organism – the neuron



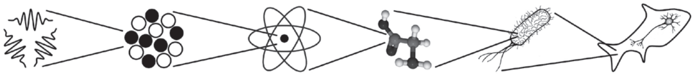
The last chapter ended with the emergence of single-celled biological organisms. Each organism functions as an independent metabolic "self", sustained by a closed set of chemical reactions that disperse energy to the wider surroundings.

Unicellular organisms must be totally self-sufficient and carry all their metabolic "baggage" with them. A single cell can "*make weapons, catch food, digest it, get rid of wastes, move around* [and] *engage in sexual activity*"; this means it must be a generalist that can do many things but not specialise in any of them. In contrast, "*a whole range of ways of life are open to big creatures, whether trees or people, that small ones cannot aspire to. To become large, organisms must become 'multicellular' … At its simplest, a multicellular 'organism' is little more than a collection of cells that have divided, but failed to separate. The real transition comes about when the different cells in the bunch begin to take on specialist functions … then we see real division of labour and real teamwork … with each cell dependent on all the rest, and groups of cells cooperating to form organs, such as lungs and livers, or leaves and flowers. This degree of collaboration requires enormous self-sacrifice: to be a member of a bona-fide organism, each cell must give up some of its own ability to live by itself. Each cell has to 'trust' the others … True multicellularity is possible only because the individual cells give up their autonomy, each relying on the rest for its survival, and for the replication of its genes*".

In this chapter, we will see how individual generalist cells come together to make a complex multicellular organism composed of specialist cells, which must now cooperate for their collective survival. These simple cellular communities have evolved to become the diversity of complex living things we see today.

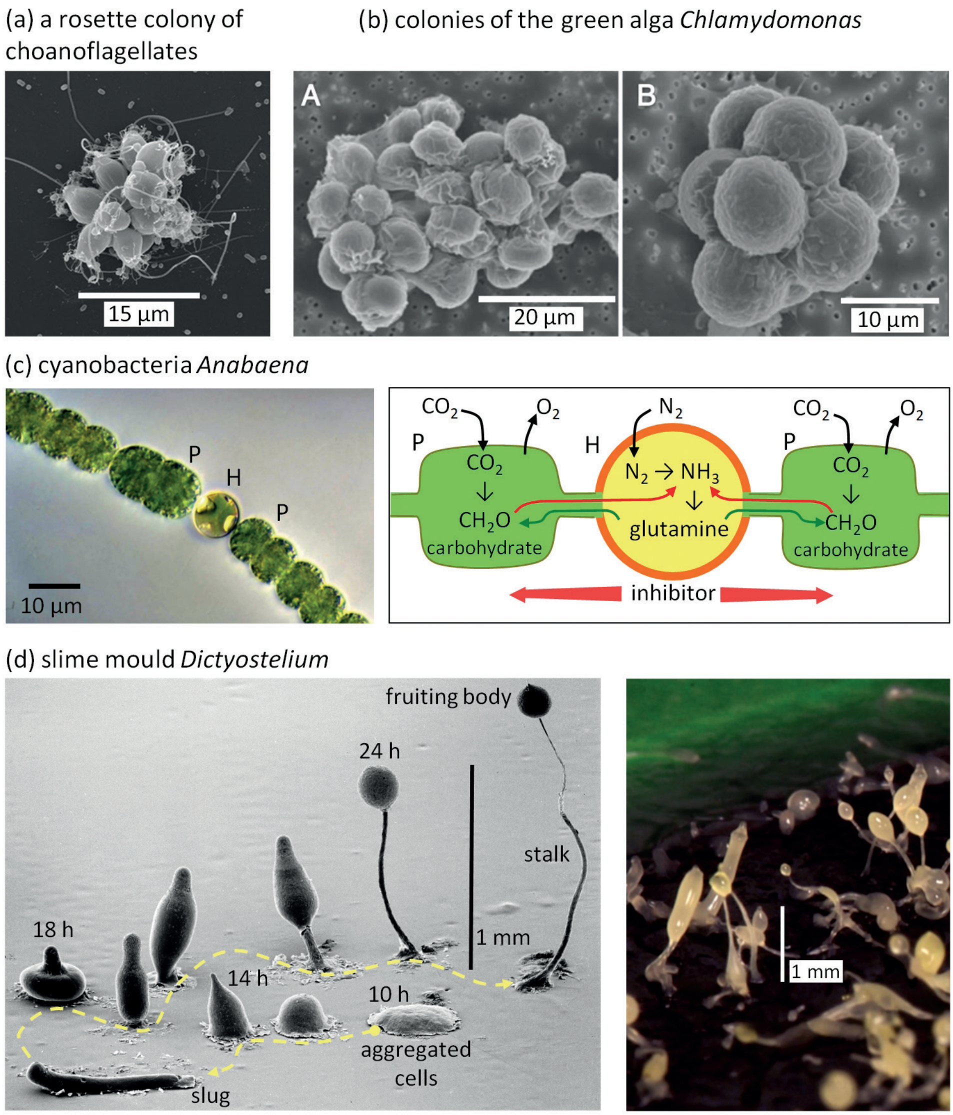
All organisms inhabit a changeable and competitive environment, so they must be able to make constructive responses to external events to stay alive. For example, if the environment changes $X \rightarrow Y$, then an organism might need to respond by changing $A \rightarrow B$, but not C. Thus, each organism needs some internal model of the environment, which shapes its responses to external events. We've seen two simple internal models in bacteria: first, hunting for food by chemotaxis, and second, in the tryptophan repressor (section 5.1.7).

The specialist cells in a complex organism need to coordinate their diverse activities so the organism can make a unified response to external events. This requires communication between cells, and the neuron is the specialised cell that has evolved



to relay signals between cells in animals. Neurons are also experientially plastic – that is, they are changed by their experiences. The universe now has a material community that can learn and remember.

In this chapter, we will progress from single cells to communities of cells. We will first look at the emergence of multicellularity, using some very simple multicellular organisms as examples. Next, we'll look at how cells in a multicellular organism can communicate. The main part of this chapter describes the cell that is specialised for communication – the neuron. We will look at how individual neurons "work" and relay signals between cells. Finally, we'll see how a simple neural circuit, comprising only a few connected neurons, is capable of learning about its environment.



6.1 the emergence of multicellularity

There are a number of organisms whose lifestyles show us the foundations of multicellularity; these are shown in figure 6.1.

6.1.1 choanoflagellates

Choanoflagellates are small aquatic organisms that can live as independent single cells and can also form small colonies. They get their unwieldy name from having a single whip-like flagellum surrounded by a collar (*choanos* in Greek, so they are, in effect, called "collared whippers"). The beating of the flagellum generates water currents that draw prey bacteria into the collar, where they are consumed. Some choanoflagellate species differentiate into different cell types during their life cycle. For example, they can function as independent cells that can swim at a range of speeds and can also attach themselves to a solid surface.

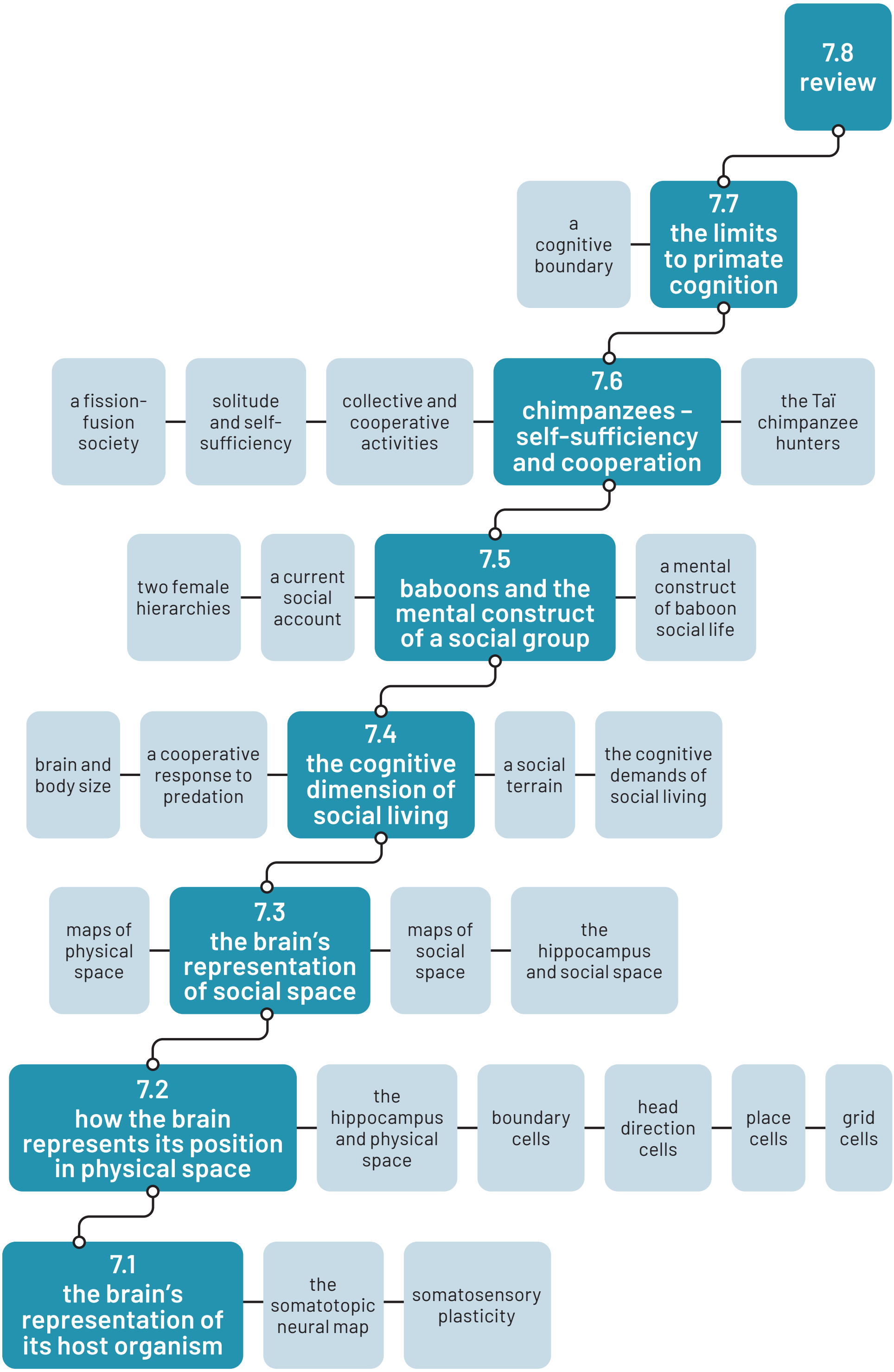
However, when they detect prey bacteria in their watery environment, they come together in small clusters, one of which is shown in part (a). We can see all the organisms facing outwards, ready to act together to draw in and catch bacteria coming from any direction.

6.1.2 green algae

Aquatic green algae normally live as independent single cells and maintain this form for thousands of generations in continuous laboratory cultures. Single cells have full access to nutrients in their aquatic environment, whereas cells in a clustered group

Figure 6.1. (a) choanoflagellates: a rosette cluster, with an approximate scale added; (b) green algae: two colonies of the alga Chlamydomonas, a large amorphous cluster (A) and an eight-cell cluster (B), with approximate scales added; (c) cyanobacteria Anabaena: (left) a light microscope view, with an approximate scale, and with the heterocyst (H) and photosynthetic cells (P) labelled; (right) a schematic view of a heterocyst and adjacent photosynthetic cells, and showing the diffusing inhibitor; (d) slime mould Dictyostelium: (left) a scanning electron microscope composite view of the life cycle, with the dashed line showing the sequence of stages, and approximate timings and scale bar; (right) a light microscope side view, with an approximate scale bar. The image on the left pre-dates the digital manipulation of images, and the ensembles of cells were individually placed in their positions by hand, using an eyelash.

The image in (a) is courtesy of Dr. Mark Dayel, and with kind permission from Professor Nicole King, University of California, Berkeley. The image in (b) is from "De novo origins of multicellularity in response to predation" by Matthew D. Herron et al., in Scientific Reports, volume 9, p. 2328, licensed under Creative Commons License, CC BY 4.0, at https://creativecommons.org/licenses/by/4.0/. The image in (c) is courtesy of Professor Alan Baker, University of New Hampshire. The image in (d-left) is courtesy of Professor Richard Blanton, NC State University. The image in (d-right) is courtesy of Dr. Fernando Rossine, Harvard Medical School, and Professor Corina Tarnita, Princeton University.


7.8
review
a cognitive boundary
7.7
the limits to primate cognition
a fission-fusion society
solitude and self-sufficiency
collective and cooperative activities
7.6
chimpanzees – self-sufficiency and cooperation
the Taï chimpanzee hunters
two female hierarchies
a current social account
7.5
baboons and the mental construct of a social group
a mental construct of baboon social life
brain and body size
a cooperative response to predation
7.4
the cognitive dimension of social living
a social terrain
the cognitive demands of social living
maps of physical space
7.3
the brain's representation of social space
maps of social space
the hippocampus and social space
7.2
how the brain represents its position in physical space
the hippocampus and physical space
boundary cells
head direction cells
place cells
grid cells
7.1
the brain's representation of its host organism
the somatotopic neural map
somatosensory plasticity

Chapter 7: brain – a community of neurons

The last chapter ended with a community of specialised cells in a complex organism with a simple nervous system. The neural circuits in this nervous system learn the causal relationships between events in the physical environment so the organism can function as a "causal self". In this chapter, we will see how a community of neurons in the brain of a social animal, such as a chimpanzee, knows all the members of its group and the relationships between them so the animal can function as a "social self".

Because the animal is a physical organism, it must be able to find its way around its spatial environment, so it must know its location in physical space. Similarly, to sustain its membership of the group, it must be able to find its way around its social environment, so it must know its location in "social space".

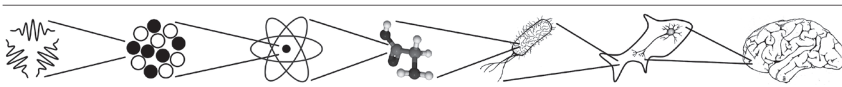
This chapter starts by looking at how a brain constructs a set of neural maps of its environment: first, of the body of its host organism; second, of its location in physical space, relative to other objects; and third, of its location in social space, relative to other individuals. Then, we will look at the cognitive demand of social living and see that it can only be sustained by creatures with sufficiently large brains. Finally, we will look at the complex social systems of primates, such as baboons and chimpanzees, and see high-level behaviours, such as deception and cooperative group hunting.

7.1 the brain's representation of its host organism

7.1.1 the somatotopic neural map of the body

The human brain is divided into two hemispheres, left and right, and each hemisphere has a highly folded outer layer about 4 mm thick, known as the cortex (from the Latin *cortex* = bark), which comprises densely packed neurons and their dendrites. The cortex is highly folded, and this increases its area and the number of cortical neurons that can be accommodated within the skull's fixed volume.

Figure 7.1(a) shows the four lobes in the cortex of the left hemisphere of a human brain, each of which is named after a bone in the skull – frontal, temporal, occipital, and parietal. Three of these lobes have primary sensory areas that deal directly with incoming stimuli: the auditory cortex in the temporal lobe, the visual cortex in the occipital lobe, and the somatosensory cortex in the parietal lobe, which receives information about the body (from the Greek *soma* = body). The frontal lobe has no sensory cortex but has an area called the primary motor cortex, which controls the muscles in the body.



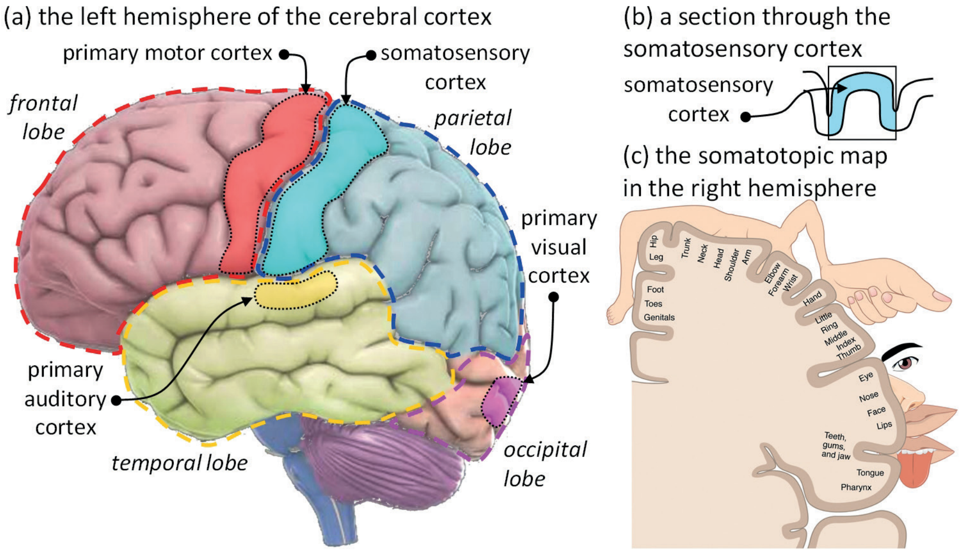


Figure 7.1. (a) an external view of the left hemisphere of the human brain, showing the four lobes and the primary sensory and motor cortices in each lobe; (b) a transverse section through the folded somatosensory cortex, as seen from the left side; (c) a transverse section of the right hemisphere of the brain, as seen from behind, showing the left-hand side of the body represented as a somatotopic map.

The image of the human brain in (a) is from "3D Brain", an online resource provided by the Cold Spring Harbor Laboratory, at http://www.g2conline.org/3dbrain/.

These sensory and motor areas take up only a small fraction of the cortex in each of the lobes they are in. The remaining area of each of the four lobes is association cortex, which processes the sensory information and integrates it with information from other regions of the brain. The temporal association cortex processes sound stimuli and also recognises objects and conditions. The occipital association cortex processes visual stimuli. The parietal association cortex attends to body awareness and responds to signals coming from inside the body and to stimuli from the external environment. The frontal association cortex is especially important for decision-making, and planning actions and behavioural responses.

The size of the cortex in some mammals has increased significantly during their evolution, and this is largely due to the expansion of the association areas. For example, the cerebral cortex of a rat comprises mainly primary sensory areas, whereas the much larger human cerebral cortex comprises mostly association areas, which enable more complex behaviour and learning.

the primary somatosensory cortex

Lying along the front edge of the parietal lobe is the primary somatosensory cortex, which "*integrates tactile information from specific body regions*"; this is shown in figure 7.1(a). The somatosensory cortex is a long strip of cortex that is deeply folded, as shown in part (b). Each primary somatosensory cortex contains a complete representation of the opposite side of the body, organised as a somatotopic map, so the cortex in the right hemisphere, shown in part (c), maps the left-hand side of the body.

The representation of each part of the body is not in proportion to its physical size but to its "*importance to the sense of touch*". Humans need fine discrimination of touch in our hands and faces, and this requires many neurons, so these small parts of the physical body are represented by extra-large areas of cortex. We need fine discrimination in our lips and tongue, so the area of cortex representing them is larger than for the rest of the face.

The somatotopic maps in different animal species are proportioned according to the relative importance of the different types of sensory input to each species. For example, a large part of a rat's somatotopic map is devoted to its whiskers, with which it probes its local environment, and each whisker has its own distinct area of cortex. In a digging raccoon, it's the paws that take up a large area of the somatotopic map; in a burrowing platypus, it's the bill.

7.1.2 plasticity in the somatosensory cortex

An animal has a dynamic neural representation of its external world, which is constantly being adjusted to its changing experiences. So, if an animal's pattern of sensory experience changes, then its somatotopic map alters to adapt; this is shown in figure 7.2. Part (a) shows a detail of the somatotopic map of an owl monkey, showing all five digits represented fairly equally, from the thumb (digit 1) to the little finger (digit 5). Each digit is mapped in an orderly way on the cortical surface.

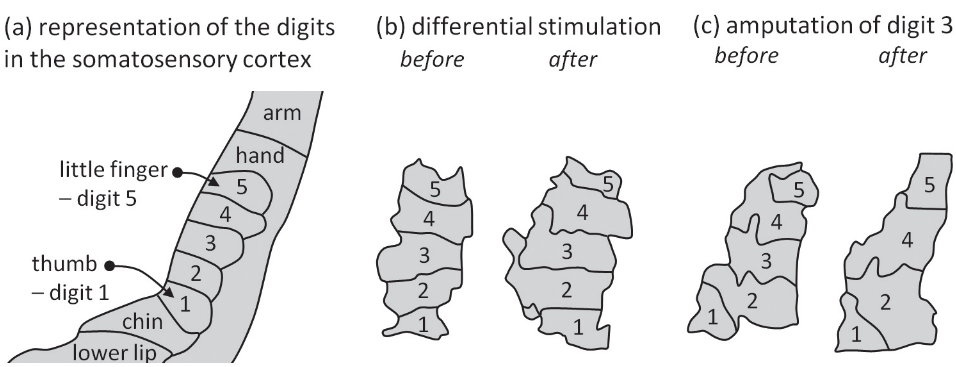
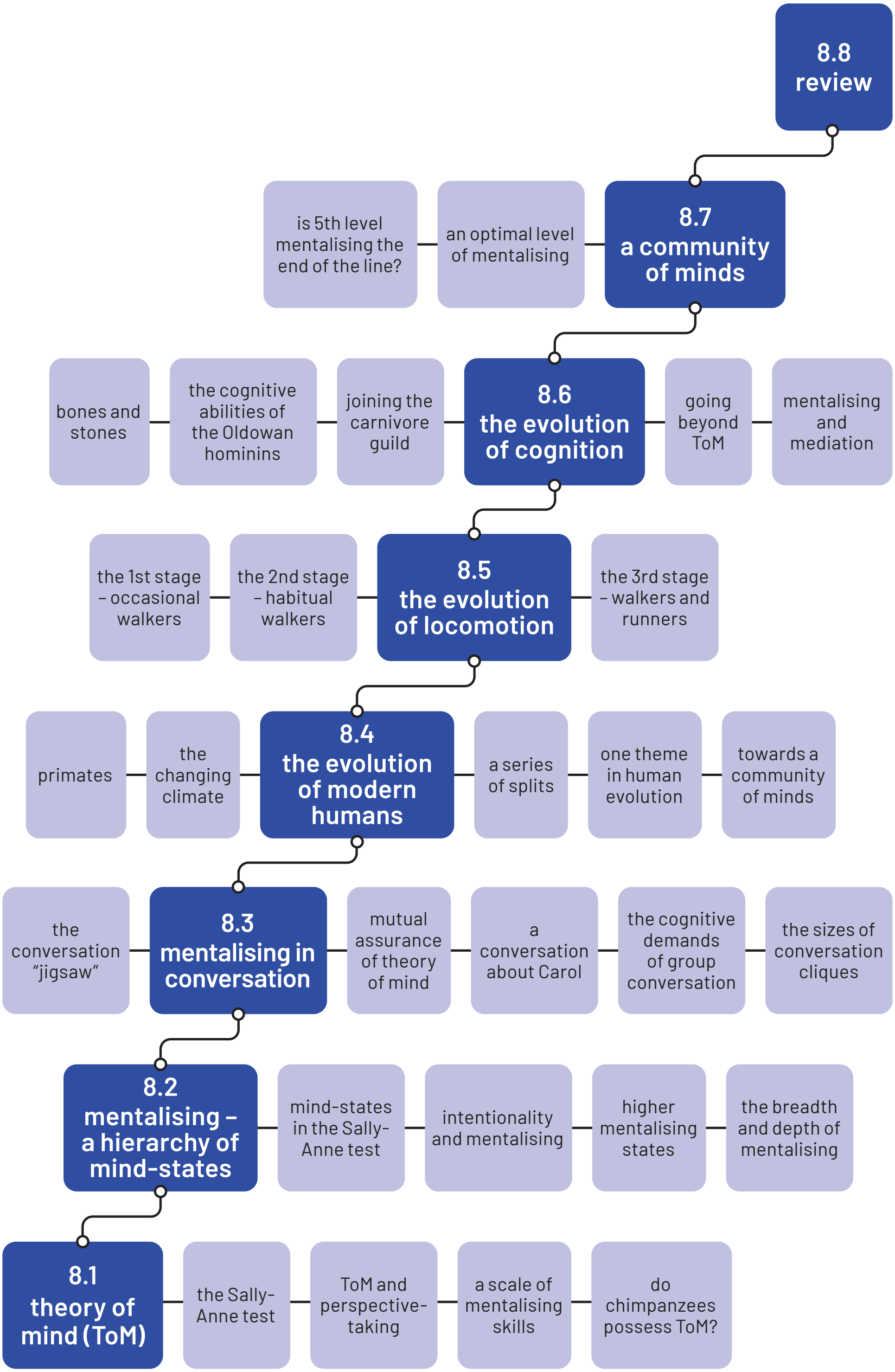
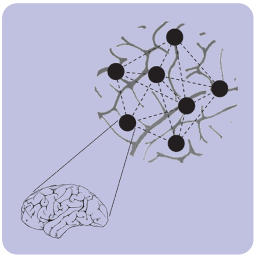


Figure 7.2. The plasticity of the somatosensory cortex in two owl monkeys in response to differential stimulation and to amputation: (a) a schematic view of a section of the sensory cortex, showing the representation of the five digits of the hand; (b) the representation of the five digits before and after several months of stimulation of digits 2, 3, and 4; (c) the representation of the five digits before amputation of digit 3, and two months after amputation.


8.8 review
is 5th level mentalising the end of the line?
an optimal level of mentalising
8.7 a community of minds
bones and stones
the cognitive abilities of the Oldowan hominins
joining the carnivore guild
8.6 the evolution of cognition
going beyond ToM
mentalising and mediation
the 1st stage – occasional walkers
the 2nd stage – habitual walkers
8.5 the evolution of locomotion
the 3rd stage – walkers and runners
primates
the changing climate
8.4 the evolution of modern humans
a series of splits
one theme in human evolution
towards a community of minds
the conversation "jigsaw"
8.3 mentalising in conversation
mutual assurance of theory of mind
a conversation about Carol
the cognitive demands of group conversation
the sizes of conversation cliques
8.2 mentalising – a hierarchy of mind-states
mind-states in the Sally-Anne test
intentionality and mentalising
higher mentalising states
the breadth and depth of mentalising
8.1 theory of mind (ToM)
the Sally-Anne test
ToM and perspective-taking
a scale of mentalising skills
do chimpanzees possess ToM?

Chapter 8: society – a community of brains



The last level ended with the emergence of a brain that can sustain a complex society and be aware of the state of knowledge or ignorance of others. But this brain can't understand that other individuals have different perspectives on reality, so it can't recognise false beliefs. The cooperative hunting behaviour of the Taï chimpanzees appears to represent the highest level of primate cognition in the wild.

In the final level of the hierarchy, we will see that the human brain is capable of "mentalising" to a high level. This enables an "empathic self" that can understand someone else's false belief and also comprehend the disparate viewpoints of others. Thus, human society emerges as a neural community of "empathic selves" whose members transfer "mind-states" among themselves. I use the term "mind-state" as a general name for all thoughts, feelings, ideas, and knowledge – anything that is a construct or outcome of some pattern of neural activity.

However, human society is not just a neural community; it is also an economic community in which inter-dependent specialists exchange goods and services between themselves. It is also an altruistic, practical community in which individuals provide assistance and support, even to complete strangers. This "*collectivism of thought … effectively turns us into a new kind of organism. Each of us has become a neurone in a global brain – a brain that thinks across time as well as space*".

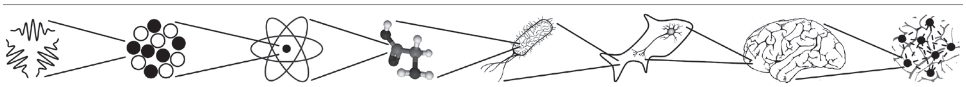
In this chapter, I will first look at the different levels of mentalising, and at the cognitive demands of conversation, from pairs to small groups. Then, I will survey the evolution of humans and show how the advantages of being able to "read" the minds of others drove our ancestors to develop ever-higher mentalising powers.

8.1 theory of mind

living in a mental environment

We think of the "outside" world in terms of physical objects like houses and shops, cars and roads, wind and rain, and so on, but we also inhabit and negotiate a cognitive terrain, which is made of other people's minds, with their thoughts, feelings, and intentions. As a fish is immersed in water, we live "*immersed in a constant process of reading other people's minds*" because the "*very world we tread is already a mentally generated, social, cultural, intersubjective world … a mental landscape we take for granted*".

In our everyday social interactions with other adults, we recognise that each of us lives in "*a mental world as much as in a world of real situations and occurrences*". We see ourselves and others in terms of "*mental states – the desires, emotions, beliefs, intentions, and other inner experiences that result in, and are manifested in human*



action". This sentence may read oddly, but a little reflection makes it clear that, without being aware of it, we routinely "read the minds" of others and infer their mental states – a process known as mentalising. We take this mentalising ability for granted and don't realise what a remarkable ability it is. To understand the importance of mentalising, it's worth thinking about what our social experiences might be without it.

So, "*imagine a hypothetical being who knows nothing of internal mental states … Such a being might be able to know, and learn, but it would possess no understanding of these activities. ... Persons would be seen and heard but there would be no notion of … ideas and beliefs organizing their actions and personalities. … The concept of a lie would be inconceivable, as would ... notions such as illusions, beliefs, hunches, mistakes, guesses, or deceptions. It is almost impossible to imagine what such a perspective would be like, how such a creature would view the world*". This is a brief description of the very real life-experience of a person with autism, which is a condition that affects around 4–15 children in every 10,000.

In stark contrast, by the time they are 1 year old, most children "*can read people's actions as directed at goals and as driven by desires. As toddlers, they can pretend and understand pretense. And by the time they begin school, around the age 4, they can work out what people might know, think, and believe*". It's around the age of 4–5 years that the great majority of children come to understand the concept of belief. They understand that every person has an inner mental world that holds a representation of the external world, but is quite independent of it, and may even be in conflict with the external world. A person with a mental state that conflicts with reality is said to hold a false belief. Someone who understands how others can hold false beliefs is said to possess "theory of mind". With the mentalising capability of theory of mind, a person is able to "*make inferences about what other people believe to be the case in a given situation*" and can predict what they will do.

8.1.1 the Sally-Anne test for theory of mind

There are numerous tests for theory of mind, and one of the best known is the Sally-Anne test, shown in figure 8.1.

The Sally-Anne test is presented as a scenario with two dolls: Sally, who has a ball and a basket, and Anne, who has only a box. Sally puts her ball in her basket, covers it and then goes away. In her absence, naughty Anne takes the ball and puts it in her box. The question is then asked: when Sally comes back, where will she look for her ball? Up to the age of about 4–5 years, children say that Sally will look in the box because "that's where the ball is". They cannot comprehend that Sally does not know what they know to be true – that the ball is now in the box. Between the ages of 4 and 5, children start to say something like: "Sally thinks the ball is in the basket, but I know that's not true". These children have understood that other people have inner mental worlds of their own and can have different views of the same situation. The children know that these views may be untrue, so the Sally-Anne test is also known as a "false-belief" test.

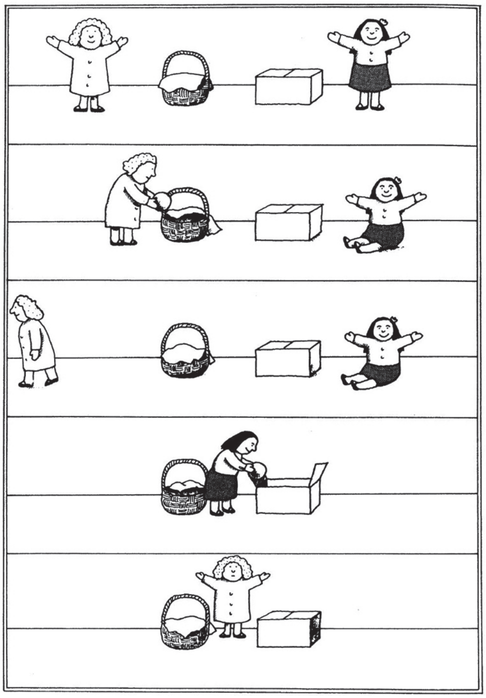
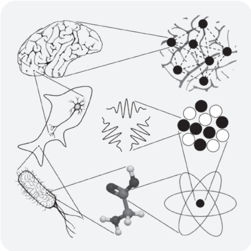


Figure 8.1. The Sally-Anne test for theory of mind. This illustration is reproduced here by kind permission from Axel Scheffler.

The false-belief test is the formal test for full theory of mind, in which the subject predicts what another person will do on the basis of a false belief – where the other's belief does not match reality. To predict what another will do on the basis of a true belief is not a sufficient test for theory of mind. In this case, the other person's mental state corresponds with reality, and the predictions of behaviour based on their mental state and on reality will be the same. The full mentalising ability of theory of mind rests on understanding that people act according to their beliefs, which may not match reality. Comprehending a false belief, in contrast to a true belief, "*requires the representation of a person's mental state independently of reality, i.e., a decoupling of mental representation and reality*".

We have seen, at Level 6, how an organism with a simple nervous system can learn the causal relationships between objects and events in its physical environment, so it can function as a "causal self". At Level 7, an organism with a brain can learn the causal relationships between individuals and their actions in its social environment, so it can function as a "social self". Now, at Level 8, we see how someone who possesses theory of mind can learn the causal relationship between personal experience and belief in

Chapter 9: conclusion



The hierarchy that we have explored in chapters 1 to 8 – summarised in figures 0.1 and 8.20 – connects fundamental particles, the simplest entities that have a detectable physical presence, to human culture and our shared mental world. This is a hierarchy, not just of physical "things", but also their communal interactions, which together create and sustain every level of the hierarchy. I have called this the universal hierarchy because it appears to be universal and fundamental. In this final chapter, I will look at its underlying themes and patterns.

9.1 themes and patterns in the universal hierarchy

9.1.1 a hierarchy of communities on eight levels

If we follow the universe as it evolves in time, then we see a repeated pattern of things coming together. Thus, we can see the universe as a series of emergent communities that are bound together by ceaseless exchange processes, as introduced in section 0.2.2.

a community of A, bound by B, exchanging C, create and sustain D

Using the ideas of communities and exchanges, we can characterise every level of the universal hierarchy with the phrase, "a community of ***A***, bound by ***B***, exchanging ***C***, create and sustain ***D***", changing only the identities of ***A***, ***B***, ***C*** and ***D***. This is summarised in table 9.1.

Table 9.1 A common description of each level

level	a community of ***A*** …	… bound by ***B*** …	… exchanging ***C*** …	… create and sustain ***D***
8	- social individuals	- shared mind-states	- individual mind-states	- a cognitive community
7	- neurons	- a set of synaptic connections	- neurotransmitter molecules	- a social individual
6	- specialist cells	- shared DNA	- signal molecules	- a complex organism
5	- chemical reactions	- a DNA molecule	- metabolite molecules	- a biological cell
4	- atoms	- molecular electron orbitals	- photons	- a molecule
3	- electrons	- electrical attraction to a nucleus	- photons	- an atom
2	- nucleons	- the strong nuclear force	- pions	- a nuclide with a + electric charge
1	- quarks	- the strong colour force	- gluons carrying colour charge	- a nucleon (proton or neutron)

From the bottom to the top of the hierarchy, the transitions between levels follow the same pattern: existing "things" interact through an exchange process and create a new community, which is subject to new organising principles, and so the next level appears. The "things" that interact and come together range from quarks at Level 1 to empathic social individuals at Level 8, and the pattern seems to apply just as well to the highest level as to the lowest.

many become one

It is a fundamental feature of the hierarchy that a composite community at one level becomes a component part of another, more complex community at the next level. At every transition between levels, we can look two ways. If we look down, we see a community of interacting component "things"; if we look up, we see this community become a component "thing" in a more complex community. What were many at the lower level become one at the higher level.

exchange processes at every level

There are exchange processes that bind things together in communities at every level of the hierarchy. Gluon exchanges bind quarks into protons and neutrons (Level 1). Pion exchanges bind protons and neutrons into nuclides (Level 2). Photon exchanges bind electrons to nuclei to create atoms (Level 3) and molecules (Level 4).

Exchange processes are also at work, binding the "living" communities above Level 4. At Level 5, large biomolecules exchange smaller molecules and ions between themselves to sustain a living cell. Specialised cells in complex organisms exchange a variety of signal molecules in order to function cooperatively (Level 6), and neurons exchange a variety of neurotransmitter molecules at their synapses and thereby sustain brain function (Level 7).

Up to this point, communities are sustained by the exchange of "bits" of matter. However, at Level 8, communities of brains are bound together by the exchange of non-material thoughts and feelings. These can be transmitted by words in a complex symbolic language and also by a variety of non-verbal experiences such as music, paintings, dance, architecture, and embroidery. These are not bits of matter, though they certainly induce changes in the configurations of matter in the brain of the receiver. There seem to be parallels between the words of a language and the particles exchanged at lower levels. Like pions and signal molecules, spoken words have a short lifetime – the time for the sound to travel from speaker to listener.

Thus, every level in the hierarchy is characterised by a community of things, engaged in ceaseless interactive exchanges. From the vibration inherent in every quantum particle-wave to the exchange of ideas and information between each of us in human society, the physical universe is incessantly, dizzyingly active.

the exchange process can change the receiver

Nucleons and biological cells are changed by the exchange particles they receive. We've seen in figure 2.3 that when a proton and a neutron exchange a charged pion, they interchange their identities, so the proton becomes a neutron, and *vice versa*. We've also seen in figures 6.2 and 6.3 how a specialised cell's function is changed when it receives a signal molecule. Similarly, every day, we experience being changed by hearing the words spoken by others. Spoken words represent a part of the mind-state of the speaker, which is received by the listener and incorporated into their own mind-state. A conversation can enable each person to see the world from the other's point of view so that, for a brief time, each can, to some degree, "become" the other, as was shown in figures 8.6 and 8.7.

interactions are specific to each level

The interactions between the "things" at each level are highly specific. Nucleons communicate only in "pion-language", and cells communicate with specific signal molecules. Our verbal interactions are also "particle-specific". For example, we don't understand words from a foreign language, or technical terms in our own language that are outside our experience. Also, we don't engage with someone talking about a topic that doesn't interest us. In such a case, we might say that we weren't "in sync", or we didn't "connect".

In this respect, the transfer of thoughts and feelings seems to resemble resonance (described in section 3.5.2), whereby an object can be set vibrating by a vibration with the right frequency, such as repeated pushes on a swing or a sound wave acting on a guitar string.

no theory of everything

Because interactions in the universal hierarchy are level-specific, there is a hierarchy of physical laws and concepts that we have to understand. So, rather than there being 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*".

open and closed systems

We have seen that the inanimate communities at levels 1–4 can exist as both open and closed systems. Their continued existence does not depend on whether they exchange energy or substance with their surroundings. In contrast, the living communities at levels 5–8 depend completely on exchanges with their surroundings. The biological communities at levels 5 and 6 cease to function if they are denied energy or nutrients, and if they can't excrete, they poison themselves with their own waste products. At Level 8, the communities express themselves in the exchange of neural patterns and belief states via language. Put simply, communities at levels 5 and 6 engage in juggling matter, and communities at levels 7 and 8 engage in juggling neural mind-states. The existence of communities at all these levels is founded on their engagement with their respective material and neural environments.

branched and nested hierarchies

We have journeyed through all eight levels of the universal hierarchy, but we have not considered what type of hierarchy this might be. There are two fundamental types of hierarchy, and these are shown schematically in figure 9.1. We're familiar with the linear, branched hierarchy – shown in part (a) – and may associate this with "top-down" control, from higher levels to lower levels. The concentric, nested hierarchy – shown in part (b) – 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.

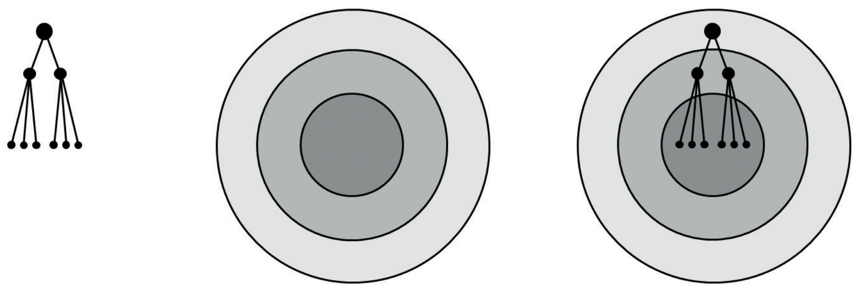


Figure 9.1. Schematic representations of (a) a linear, branched hierarchy and (b) a concentric, nested hierarchy, while (c) shows a branched hierarchy within a nested hierarchy.

The universal hierarchy, as shown in figures 0.1 and 8.20, has features of both types of hierarchy. It is a linear hierarchy because we can take a particular proton at Level 1 and track it through ascending levels to find it in the brain of someone at Level 8. This hierarchy is branched because at each level we find things coming together to make a new community at the next level. This branching becomes more obvious when we work downwards, and encounter innumerable splits as each community at one level divides into many communities at the level below. For example, a molecule can be divided into many atoms, and the nucleus of each atom can then be divided into many protons and neutrons, and each of these nucleons comprises three quarks.

However, the universal hierarchy is also concentric because each level is hidden within the level above it, like a set of Russian dolls – as was discussed in section 0.2.1. Thus, we "see" the proton, but not the quarks inside it; we "see" the electrons in the atom, but not the nucleus; and we "see" the cell, but not the constant