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Liam Graham

PHYSICS FIXES ALL THE FACTS

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London, UK

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Advance Praise for This Book

"I wish I knew as much as Liam Graham. It would have enabled me to write a much more convincing and well informed book than *The Atheist's Guide to Reality*. Fortunately Graham has done it. My envy of Graham's erudition is only surpassed by my admiration of his achievement. This is the definitive guide to why the physical facts fix all the facts! It's also the definitive diagnosis of all the specious arguments against this simple truth."

—**Alex Rosenberg**, R. Taylor Cole Professor of Philosophy, Duke University, author of *The Atheist's Guide to Reality*

"Graham does an impressive job of advancing his vision of 'austere physicalism' as against non-reductionist views on which there are higher-level or 'emergent' phenomena. His lively, wide-ranging, detailed treatment of the relevant scientific case studies and philosophical positions is a tour-de-force, and his critical salvos and defensive strategies deserve further attention by scientists and philosophers alike. Anyone curious about the structure of natural reality will find this book to be a great read and a valuable resource."

—**Jessica Wilson**, Professor of Philosophy, University of Toronto, author of *Metaphysical Emergence*

"This well written book offers a balanced approach for those with interests in physics and/or metaphysics. It dismisses various forms of emergentism, arguing that these views wrongly project human cognitive limitations onto the world's ontology. It defends an austerely monistic version of physicalism according to which the world is a single entity—the ‘blobject’—with richly complex dynamic structure but without any constituent entities as proper parts. Diverse metaphysical topics are addressed, including free will and consciousness. Highly recommended.”

—**Matjaž Potrč**, Professor of Philosophy, Ljubljana University, author of *Austere Realism*

“Whatever you think about the nature of reality, there’s value in grappling with the idea that it may fundamentally be ‘all physics’! Liam Graham presents an engaging and well-researched argument, with some excellent examples drawn from across the sciences.”

—**Louis Barson**, Director of Science, Innovation and Skills, Institute of Physics

“This book is a thorough and critical examination of the idea of emergence arguing that the concept is so generic that it is useless. It provides a very good overview of emergent phenomena, particularly those from condensed matter physics, and is written in an entertaining, thought-provoking style.”

—**Ilias Amanatidis**, Ben-Gurion University of the Negev, Israel and **Ioannis Kleftogiannis**, National Center for Theoretical Sciences, Taiwan

“I have often puzzled over claims that emergent properties are ‘something else, something that cannot be explained by the elements of the system’. This splendid book shows why such claims are nonsense. And it helps us understand why, in a few years, that thesis will not be in the least controversial.”

—**Antonio Cabrales**, Professor of Economics, Universidad Carlos III, Madrid

For Axelle

Preface

Books in the humanities often begin with a statement of the author's position. Science books rarely do. Since this book involves as much philosophy as science, let me start by describing where I am coming from.

I have a long-standing dislike of mystical or magical thinking in all its forms. A dislike of thinking that avoids rigorously seeking a good explanation and opts instead for an attractive one. Of thinking that settles for a baroque explanation rather than accepting that some things are as yet unexplained. The usual suspects of free will and consciousness are fertile ground for such thinking, as is emergence, a term widely used to describe complex systems and a central topic of this book. This means I am an opinionated narrator. But I strive to be a reliable one and include extensive references and suggestions for further reading to help you make up your own mind.

Let me give an example of what motivates me. Later in the book I will cite a philosopher of science who argues that the placebo effect is evidence against physical causal closure. I find this deeply suspicious. Causal closure is right down at the fundamental level of quantum physics. The placebo effect, while well documented, is a property of the human brain, the most complex and poorly understood system we've come across. No evidence is given which links the two. Perhaps the philosopher will turn out to be right. But for now there is no reason to think that our lack of understanding of the brain should have any implications for physics.

Descriptions of emergent phenomena often convey little more than "Wow, that's so mind-blowingly complex it can't be just physics". For those who want to see more clearly, this book shows how emergence can be eliminated and presents an unflinching worldview in which everything, without exception, is physics.

London, UK — Liam Graham

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My thinking has been shaped over the years in discussions with friends and colleagues too numerous to mention. Let me thank those who shared their thoughts on this text: Ilias Amanatidis, Sue Arthur, Louis Barson, Alex Buell, Antonio Cabrales, Nigel Goldenfeld, Ioannis Kleftogiannis, Honor Klein, Paul Mans, Kanesh Rajani, Jessica Wilson and Stephen Wright. Special thanks to Nick Rimmer for his intuition, energy and remarkable attention to detail.

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About the Author

Liam Graham "Do we need more than physics to understand the world?" Liam first asked himself this question as a teenager and it has been the driving force behind his career ever since. After a degree in Theoretical Physics at Cambridge and a master's in Philosophy at Warwick, he eventually found economics to be an appealing middle ground and completed a Ph.D. at Birkbeck College, London. To pay the rent, he taught English, developed and sold trading software and was the numbers' guru for a boutique finance house.

Liam's 15-year academic career was mostly spent as an Associate Professor at University College London, working in one of Europe's top Economics departments. His research involved building mathematical models of an extremely complex system, the macroeconomy, and his work was published in all the top macroeconomics journals. Whether working on philosophy or economics, he never stopped reading science and exchanging with scientists. In 2018, he left UCL to concentrate on his original question and the wide-ranging, multidisciplinary and endlessly fascinating project it has become. His first book, *Molecular Storms: The Physics of Stars, Cells and the Origin of Life* was published by Springer Nature in 2023.

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Introduction

Hurricanes. Living cells. Flocks of birds. You yourself. Few would deny that these things are made of atoms. Yet they behave very differently from atoms. Fundamental physics might do a good job of explaining atoms, but such complex phenomena seem to lie outside its scope. This is the basic idea of emergence. Things emerge from physics but are beyond physics. The whole is greater than the sum of its parts. More is different.

Emergence is one way of understanding complexity. There are alternatives. You can be a dualist. Then some things are supernatural, in a different domain from physics. More is spooky. This might seem to apply only to the last item on my list, but it wasn't so long ago that hurricanes were seen as avenging ghosts and life as caused by a vital spirit.

Or you can be a physicalist. In this case, everything is physics. More may be different but more is always different. Physics explains the properties of the whole and the properties of the parts. The nature of quantum physics means the whole can influence the parts as well as the parts influencing the whole. If we don't fully understood things, this is a result of lack of knowledge or computing power.

Many find neither alternative attractive. Emergence promises a middle way. You can have your cake of not believing in the supernatural. And eat it with the pleasure of knowing that, while it is made of atoms, it is somehow more than those atoms. Stephen Hawking said in an interview:

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> The human race is just a chemical scum on a moderate-sized planet, orbiting around a very average star in the outer suburb of one among a hundred billion galaxies.[1]

Emergence allows us to accept we are a chemical scum while rejoicing in being more than just a chemical scum. This appeal is part of the reason for the remarkable spread of the term. It can be found everywhere, from fundamental physics to chemistry and biology, to sociology and economics.

However appealing, it is an illusion. Emergence is usually divided into two types according to its relation to physics. Weak emergence is consistent with current physics. Strong emergence is outside current physics. This book will argue that neither tells us anything useful about the world. Weak emergence turns out to be so weak that it can be applied to everything. And strong emergence is such a strong criterion that there is no evidence for it. The term emergence either refers to everything or to nothing. We think it tells us something about the nature of reality, but this is an illusion.

Fascinating phenomena exist at every scale but describing them as emergent adds nothing. Emergent behaviour. Emergent organisation. Emergent structure. Whenever you see the word you can simply discard it. You can discard its aura of mystery and its suggestion that some things will be forever beyond our understanding.

If you want to avoid the supernatural, you are left with physicalism. This book argues that the only possible physicalism is an austere physicalism that dissolves our commonsense understanding of the world. Physics fixes all the facts. Any description of the world that is not fundamental physics is at best an approximation. Such descriptions may be useful, they may be necessary but they are functions of our interests and our cognitive structure not properties of the world. This goes for everything that is not fundamental physics: the concepts which make thought possible, our intuitive notions and the rest of the sciences.

These things are illusions. Reality means having causal power. If everything is physics, only the entities of fundamental physics have causal power. Other things are therefore unreal, illusions. So there are no objects. No creatures, colours or concepts. Instead, there are arrangements of quantum fields.

Our sensory limitations mean we can't see quantum fields. Our cognitive limitations mean we can't intuitively understand them. Yet despite these limitations we perceive a world full of structure and meaning. From a physicalist perspective, this leads to fascinating questions. Why do we perceive creatures, colours and concepts? Why does a quantum field arranged in a particular

[1] Stephen Hawking, interviewed by Ken Campbell in Dugan (1995), 50′00″.

way interact with another arranged as a human brain so that it adopts a state which corresponds to creature, colour or concept?

More specifically, a physicalist approach allows us to unpack the term emergence and show how it lumps together disparate ideas about the limits of our thought. Emergence may be no more than an assertion that there are interesting questions at every scale. It may be a way of describing phenomena yet to be explained. Or it may be about the distinction between understanding and prediction. Sometimes its use is a result of projecting our cognitive limitations onto the world. Sometimes a result of a failure to distinguish between the nature of reality and the language, models and approximations that scientists use.

Let me now turn to the structure of the book. To start, Chap. 2 gives a broad overview of the sort of phenomena that can be described as emergent. The examples are chosen to cover a wide range of scales and sciences, starting inside the nucleus of an atom and working up through chemistry and biology to mental causation and its place in the universe. These will help illustrate the subsequent arguments and also give an excuse for a romp through some of the most fascinating parts of physics.

Part I presents three general frameworks which will be used throughout the book. Chapter 3 turns to philosophy and identifies six positions: dualism, weak emergence, strong emergence and three varieties of physicalism. Each of these can be understood in terms of where what matters happens. For physicalism, everything that matters happens at the level of fundamental physics. All causation is at the lowest level. For dualism and strong emergence, on the other hand, the system as a whole is what matters. There is downward causation from the whole to the parts and this must contradict physics. Weak emergence describes a precarious middle ground where downward causation is somehow consistent with physics.

One thread of my argument is that the concept of emergence is a consequence of our cognitive limitations, so Chap. 4 describes aspects of human cognitive evolution. Partly this is about understanding our commonsense models of the world, partly about understanding how we transcend them. How can brains that evolved to survive and thrive on the African savannah roam from quarks to quasars? How do they create and take part in the system of distributed cognition which is science? Chapter 5 turns to role of simulations in science and the theory of computation. There are many links to the discussion of emergence and physicalism. The most interesting is the way that quantum computers will radically transform how we simulate systems from the bottom up. Our ability to simulate and hence to understand physical systems may only be limited by the size of the quantum computers we can build.

Part II contains the case against emergence. Chapters 6–9 discuss four forms of weak emergence. The central argument of each of these chapters is the same: weak emergence applies to every real system. If all physical systems can be called weakly emergent, the definitions are empty and the term redundant. Studying these forms of emergence tells us little about the world but much about our cognitive structure.

Underlying all four senses of weak emergence is a basic confusion between the nature of the models scientists use and the nature of reality. Chapter 10 addresses this in the context of three common modelling strategies: the thermodynamic limit, effective theories and the renormalization group. All of these have features which fit one or more of the definitions of emergence. But this tells us nothing about the world, only about the models we use to explain the world.

Next, strong emergence. Chapter 11 discusses possible mechanisms ranging from quantum physics to non-computability. All are logically possible. But there is not a shred of convincing evidence for any of them. Believing in strong emergence is equivalent to believing there are pixies in your garden. Impossible to disprove, but not worth spending your time on until there's some solid evidence. Even if there were such evidence, it would support either an extended physicalism or dualism. As a term, strong emergence is also redundant.

Chapter 12 is a brief summary of the previous chapters. For each type of emergence, it gives a one line answer to three questions: what it is; why it applies to everything and why it is not a challenge to physicalism.

So much for emergence. Part III turns to the alternative. Chapter 13 presents the argument for austere physicalism. It is an easy position to state, but one that some may find self-evidently absurd and most of the chapter is spent dealing with potential objections. Chapter 14 applies it to emergence. If you've discarded the word emergence, what can you replace it with? What becomes of our intuition that more is different?

To wrap up, Chap. 15 returns to the examples, describing them without using the concept of emergence and showing that none represent challenges to physicalism. The chapter ends by throwing down a gauntlet. If you think you have a system which is emergent in the sense that it cannot be explained by physics, there is a simple procedure you can follow to convince a hard-nosed physicalist of your case.

Throughout, I do my best to avoid discussing free will and consciousness. Partly this is because they merit a book of their own. Partly it is a rhetorical choice. If you concede that they are the only place left for emergence, I will consider my job done. But in the Epilogue, I show that there is no reason to think that they cannot be given a physicalist explanation. The chapter ends by revealing the meaning of life.

This book is part of a larger project to investigate the limits of physics. My first book[2] explored thermodynamics and its application to questions ranging from the formation of stars to the inner workings of cells to the origin of life. It concluded that there is no reason why physics shouldn't one day explain all of this. My next book will take the same approach to cognition and consciousness, starting with the simplest systems and working up through cognitive evolution to human subjective experience.

Emergence claims to put some things beyond physics. Addressing this claim is central to the physicalist project. The past decade has seen a dozen or so monographs and collections about emergence. Apart from the odd article, they are all resolutely supportive. This book aims to redress the balance by showing that emergence is an empty concept and providing an alternative framework with which to understand the world.

Humanity starts in a world of incomprehension. Magic and deities are everywhere. The scientific project chips away at this. Replacing intuitions with scientific concepts. Gradually withdrawing magic from the world. Emergence is a last refuge from this process. It promises to rescue the world from the austerity of physicalism. It puts humans and the concepts we use right at the heart of everything. It allows mind, consciousness and humanity to retain something of their previous dignity. It's not so much that more is different, but that I'm different and I know I'm different.

All this is an artefact of our cognitive limitations, an arbitrary way of slicing up the complex physical reality in which we exist, physical systems among others. Emergence is pessimistic and projects our limitations onto the world. Austere physicalism is modest and profoundly optimistic. There are unanswered questions everywhere. But the system of distributed cognition that is science transcends individual cognitive limits. There is no reason to think that we, and the machines we build, shouldn't continue to give us answers.

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[2] Graham (2023).

2

More Seems Different

Summary This chapter introduces the concept of emergence using a broad range of examples. These start from inside the atomic nucleus and work up through chemistry and biology to evolution and mind. While exploring these examples, many concepts that will play an important role in the remainder of the book make their first appearance.

What is emergence? One way of answering this question is by giving examples of physical systems which can be described as emergent. This chapter presents fifteen such examples, chosen to give a broad sweep from the smallest to the largest and across different sciences. There is no shortage of candidates, I could easily have included ten times as many. This means that it is likely your favourite example will not be here.

As a working definition of emergence, let's use the one we've already seen in the introduction: more is different. It comes from a 1972 paper[1] by Philip Anderson (Nobel Prize for Physics, 1977) which is often credited with reintroducing the term emergence into the mainstream. The definition is about composition. Emergence is when the properties of the whole are different from the properties of the parts. It also implies that you cannot understand the behaviour of the parts without understanding the behaviour of the whole.

[1] Anderson (1972).

L. Graham, *Physics Fixes All the Facts*, The Frontiers Collection,
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A toy example illustrates this. Take some Lego pieces and build a car. This car is emergent. It has properties that the parts don't have: looking like a car, capable of rolling in straight lines or turning corners. More is different. By itself, a single piece of Lego cannot move in a straight line, suspended a few centimetres above the ground. But that's exactly what it does when it's part of the car. To understand the motion of one of the parts, you need to understand the car as a whole.

For the moment, more is different will do as a rough and ready definition of emergence. While working through the examples, I will bring out other senses of the term. These are summarised in the final section and will be discussed in subsequent chapters.

My descriptions of the examples are brief, no more than a handful of paragraphs for each one. For some, there won't be enough physics. If this describes you, the material I present is standard and you can find more in-depth treatments in textbooks or in the suggestions for further reading at the end of the chapter. For others, there will be too much physics. In this case, I suggest you start this chapter in the middle, with the section "Ordinary objects".

One of the aims of this book is to show that the concept of emergence is redundant. So in Chap. 15, I return to these examples and show how they can be understood in a physicalist framework without a mention of emergence.

2.1 Protons and Neutrons

Let's start right down at the bottom, inside the atomic nucleus. While this is a natural place to begin, it involves some of the most complex physics discussed in the whole book. I invite readers unfamiliar with these ideas to skip this and the next couple of examples.

Atomic nuclei are composed of protons and neutrons, called collectively *nucleons*. These are not fundamental particles but are made of quarks. A proton is made of two up quarks and one down quark. A neutron is made of one up quark and two down quarks. An up quark has a positive charge equal to two thirds the charge of an electron. A down quark has a negative charge of one-third the charge of an electron. Combined, these give the charge of a proton equal and opposite to that of an electron and the zero charge of the neutron.

Forces are mediated by particles. The electromagnetic force between charged particles is carried by photons. When two electrons approach each other, the electronic repulsion between their negative charges occurs via the exchange of a photon. The theory describing this is Quantum Electrodynamics (QED).

A further fundamental force is the strong interaction, described by Quantum Chromodynamics (QCD). Quarks experience both electromagnetism and the strong interaction. The equivalent of electronic charge for the strong interaction is known as color. The force is carried by gluons which are electrically neutral but have color so are themselves subject to the strong interaction. This is an important difference from electromagnetism. Photons, the carriers of the electromagnetic force, have no charge so are not affected by the force. When two charged particles interact, they exchange a photon and that is the end of the story.

Things are more complicated for the strong interaction. Quarks can emit or absorb gluons. Gluons can emit or absorb gluons. Gluons can split into virtual quark-antiquark pairs. These virtual particles can undergo further interactions. This leads to wild tangle of gluons, quarks and their antiparticles flickering in and out of existence as they are emitted and reabsorbed.

The left panel of Fig. 2.1 shows a proton and the middle panel a neutron. The coloured circles represent the quarks (the colours are arbitrary, all that matters is all three are present so overall nucleons are color neutral) and the curly lines represent gluons carrying the strong interaction. For clarity, these two diagrams only show direct interactions between the quarks. The right panel includes some of the other possible types of interactions. Now imagine an endless avalanche of these interactions and you can see the challenge of solving QCD problems.[2]

What does all this have to do with emergence? Quarks have fractional charge. Protons have integer charge. Quarks have color and experience the strong interaction directly. Nucleons are color neutral. In these senses, more is different. But that's not all. Unless you are a high energy physicist, none of

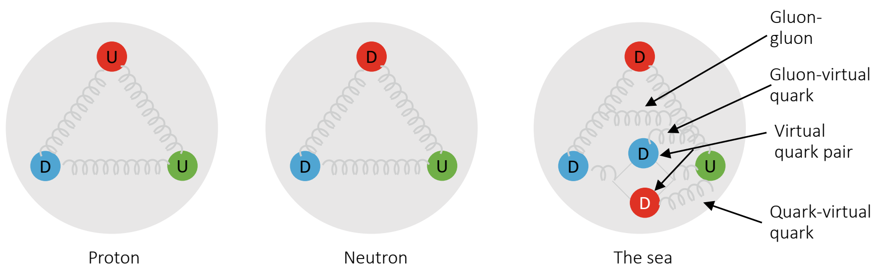

Fig. 2.1 Three quarks for Muster Mark!

[2] For a beautiful visual representation, see https://arts.mit.edu/projects/visualizing-the-proton/.

this matters. You can do everything you need to do, including nuclear fission and fusion, while treating protons and neutrons as fundamental particles, as the featureless grey circles in the figure. The approximation involved only breaks down at high energy levels. This is why nucleons were thought to be fundamental right up to the 1960s. Nucleons are nothing more than their components, yet for all practical purposes they are independent of them.

There are two further senses in which the interactions of quarks lead to emergence. Atomic nuclei are bound together by the nuclear force which overcomes the electromagnetic repulsion between positive protons. Yet this force is just a residual of the strong interaction between quarks, orders of magnitude weaker than the strong interaction itself. The nuclear force is emergent.

Then there's the question of mass. If you're up to speed on physics and are asked where mass comes from, you would probably answer that it's to do with the Higgs field. But you'd be mostly wrong. The mass of a proton is around 140 times the mass that the Higgs field produces for its three quarks. The rest of the mass comes from the energy of the cloud of virtual particles shown in the right panel of Fig. 2.1. This is known as emergent hadron mass. Pause for a minute to think about this. Around 98% of the mass of the visible universe is emergent in this sense.[3]

Right down at the heart of matter, we've already got three emergent phenomena. Nucleons emerge from their component quarks. Their masses emerge from the interaction between these quarks. And the nuclear force which holds nuclei together emerges from the strong interaction.[4]

2.2 The Classical World

Quantum physics describes systems by a wave function. One implication of this is that quantum systems are simultaneously in all their possible states. This is known as a superposition of states, or simply a superposition. The wave function can be interpreted as the probability of each state.

Imagine a quantum coin. It can be placed in a superposition where it is simultaneously heads and tails, with a probability of one half attached to each.

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[3] Binosi (2022).

[4] In fact, all the properties of nucleons are emergent. The figure shows them as shaded grey circles, but their measurable radius is a consequence of the nature of the strong interaction. Their spin also emerges in some complex way from the spin of their component quarks and gluons.

The better-known example is Schrödinger's cat which is in a superposed state consisting of awake and asleep.[5]

We never observe such superpositions. Instead, we experience a world where objects are in one state at a time. When we toss a coin, we see heads or tails. Cats are either awake or asleep. How can we reconcile this classical world with the quantum world that underlies it?

One answer is quantum decoherence. Let me illustrate it by continuing with the example of a coin. The left panel of Fig. 2.2 shows a classical coin, either heads or tails. In the middle is a quantum coin, prepared in a superposition between heads and tails. The quantum coin is shown inside a perfectly empty box. To preserve the superposition, or more precisely to preserve its coherence, the coin must be kept isolated from its environment. Coherent superpositions are extremely fragile.

In the world, quantum systems are not isolated but in environments full of particles and radiation. These scatter off the quantum coin, become entangled with it and the coherence of the superposition leaks away into the environment. This is shown in the right panel of the figure.

For macroscopic objects, decoherence happens extremely quickly.[6] Due to the effects of sunlight alone, a speck of dust would decohere in 10^{-12}s and a bowling ball in 10^{-20}s. Even in the ultra-pure vacuum of deep space, the photons of the cosmic microwave background would cause decoherence of dust in 10^{-4}s and the ball in 10^{-15}s. This is why we never observe superpositions. It is also one of the reasons why quantum computing, which depends on such superpositions being maintained, is a challenge.

A quantum system open to its environment behaves dramatically differently from an isolated quantum system. More is different. The classical world

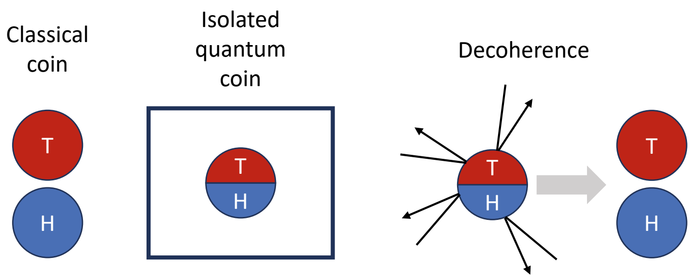

Fig. 2.2 Decoherence

[5] I borrow this gentle formulation from Rovelli (2021).

[6] See Appendix A.2 for details of the calculation.

we experience is emergent and decoherence explains how it dynamically emerges from the quantum world.

2.3 Atoms and Molecules

The properties of nucleons depend on their environment. Isolated neutrons are unstable. Due to the weak interaction, they decay with a half-life of around 15 min into a proton, an electron and an antineutrino. Isolated protons, on the other hand, are either stable or have extremely long half lives. Inside light nuclei, protons and neutrons are both stable. Inside heavier nuclei, protons can decay by positron emission, again due to the weak interaction. This is emergence. You cannot understand the properties of a nucleon without understanding its environment.

Now let's turn to atoms. The simplest atom is hydrogen, consisting of a proton and an electron. By themselves, these particles just get on and do their own thing. Combined, they give the atom a whole range of interesting new properties. Most notably, the electron becomes confined in what are known as orbitals. Some of these are illustrated in Fig. 2.3.

When photons scatter off the atom, transitions between these orbitals give characteristic spectral lines. All these properties are dramatically different from those of an isolated proton or electron. Understanding the behaviour of the particles without taking into account the atomic environment is impossible.

Atoms combine to form molecules and the molecules have properties different from their components. Let's take water as an example. The water molecule is composed of two hydrogen atoms bound to one oxygen atom. This is shown in the inset of Fig. 2.4. The nucleus of an oxygen atom contains eight protons compared to the single proton of hydrogen. This means that the molecule's eight electrons, six from oxygen and one from each of the hydrogens, shown as black dots on the figure, tend to be closer to the oxygen nucleus. This, when combined with the bond angle of around 105°, means charge is distributed asymmetrically across the molecule. There is a net positive charge on the side of the hydrogen atoms, a net negative charge on the side of the oxygen atom.

This allows water molecules to form bonds with each other, the negative charge on the oxygen atom in one molecule being attracted to the positive charge on the hydrogen atom in another molecule. This is shown in the main part of the figure. The oxygen atoms are in red, the hydrogen atoms are in grey. The dotted lines representing the electronic attraction between them.

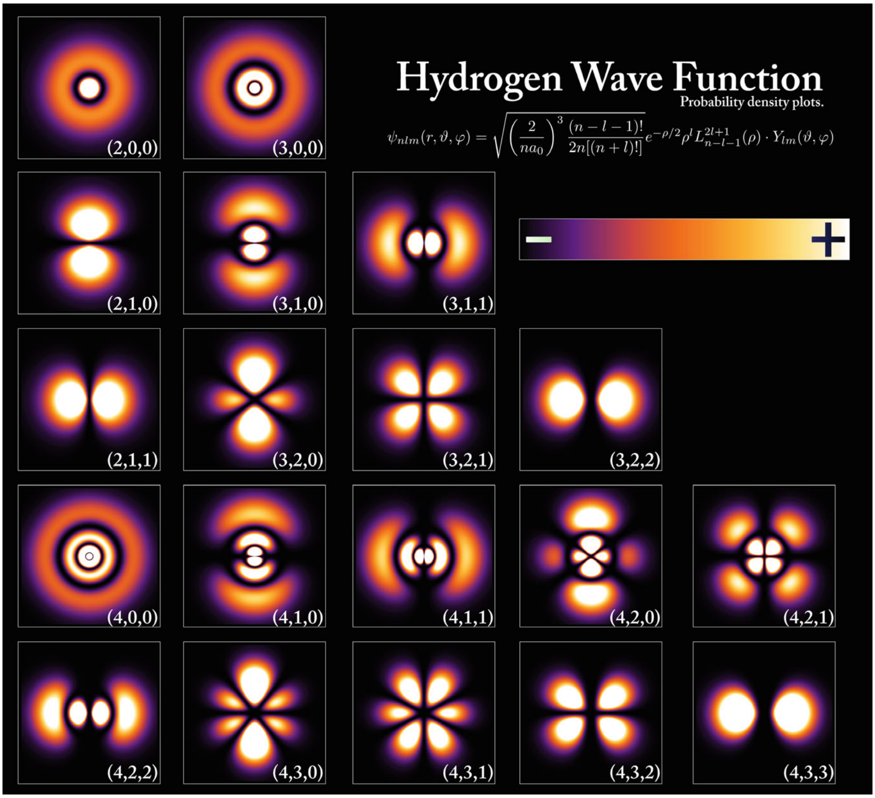

Fig. 2.3 Hydrogen orbitals[7]

Such bonds are known as hydrogen bonds and are responsible for many of the unique properties of water. Hydrogen bonds and the properties of water are emergent.

And so on to the rest of chemistry. Here we've seen three levels of emergence, three levels at which more is different: in the nucleus, in the atom and in molecules.

2.4 Chemical Oscillators

Mix most chemicals and, if they react at all, they will rapidly reach equilibrium. In 1951, Russian chemist Boris Belousov showed that if a particular set of chemicals are mixed in a beaker, the liquid starts off colourless, changes

[7] Source: https://commons.wikimedia.org/wiki/File:Hydrogen_Density_Plots.png. License: Public domain.