Matter and Meaning

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Matter and Meaning:
Is Matter Sacred or Profane?

Edited by

Michael Fuller

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PREFACE

THE RIGHT REVERED JAMES JONES, BISHOP OF LIVERPOOL

When the Science and Religion Forum met in conference at Liverpool Hope University I was honoured to be invited to address them after dinner on their final evening. I was deeply impressed by the scope and the expertise of the symposium, not just of those giving papers but of the members themselves. At a time when siren voices in the media want to polarise science and religion, it is immensely hopeful that we are served by scholars who are able not only to bridge that divide but also to show by example and research that there is a consonance and a correspondence between these two scholarly disciplines.

The symposium took place in Liverpool during its year as European Capital of Culture. Science and religion constitute two pillars of European civilisation; and this was illustrated shortly before the symposium took place. On the same evening in the City Professor Richard Dawkins packed the auditorium at the Philharmonic Hall, while a stone's throw down Hope Street an equally large audience had been enthralled by the world premiere of Sir John Tavener's 'Requiem' in the Metropolitan Cathedral. Whatever polarities were represented by these two events it was good then to welcome to the City the Science and Religion Forum for their symposium on 'Matter and Meaning: Is matter sacred or profane?'

I was particularly interested to engage with the Symposium on this subject because of my increasing conviction that Christianity has vitally important insights to share with the world in the face of the current ecological crisis. One of the reasons that the Christian faith has been slow off the starting blocks in raising awareness of our environmental responsibilities is because we have given priority to the spiritual over the material. Indeed, some would argue that allowing a division between the two, and failing to recognise that the material and spiritual are indivisible, marked the beginning of the retreat from engaging with the full reality of God's world.

The Lord’s Prayer is a petition for God’s will to be done on earth as it is done in heaven. This is a prayer for the earthing of heaven. I like the version from the Book of Common Prayer, which has us asking for God’s will to be done ‘in earth’. The preposition ‘in’ gives a depth to the meaning, and signifies that the spiritual work of God’s Kingdom, or bringing heaven down to earth, is fundamentally and essentially material.

There is a spiritual and material continuity from Genesis to the Gospels. At the outset God declares his world in all its dimensions to be ‘good’ and ‘very good’. The Resurrection of Jesus – his whole self, not just his soul – is the divine affirmation that God’s purposes include the material as well as the spiritual. The Resurrection of the body in the Gospels shows that matter matters to God, which is the creed to be found in Genesis.

If it were only the soul that continued after death there might be some excuse for relegating the physical to a place of less importance. One of the conundrums of the last century is why the evangelical tradition, which was so emphatic about the bodily dimension to the Resurrection of Jesus, was so suspicious of the social Gospel – and why the Liberal tradition, which sat so loose to the Resurrection of the body, was so strong about the material dimensions of the Kingdom. Fortunately, these separations are less fixed today; but they have dogged the mission of God in the not too distant past, and have frustrated those who long to see Science and Religion marching in step with each other.

The sacredness of matter has major repercussions on how religious believers engage with politics, sexuality and the arts as well as with the sciences. It also has an impact on attitudes to the environment. In this country, in America and in Africa, I’ve heard Christians suggest that we need not concern ourselves with what is happening to the earth because, according to the Bible, it will end up in a ball of flames. Some have even gone on to suggest that we might as well milk the earth for all it is worth while we have time!

These attitudes to the earth make the task of the environmentalist and the scientist more challenging, especially if they are people of faith. It suggests that within some quarters of the community of faith the priority lies in preparing people for what is to come beyond the consummation. It suggests that exploring, analysing, understanding and caring for the earth are secondary activities. Little wonder that scientists who are believers might find themselves undervalued within the community of faith.

What we need is a theology of the earth that recognises the Biblical vision of a world that is originally good, created by God and sustained by him; a world that has come into being through and for Christ, and that will be renewed and transformed for the glory of God. Such a world is the scientist’s laboratory, and the believer’s temple.

Recently, re-reading C.S. Lewis’ ‘The Last Battle’, I was struck by the depiction of devastation as old Narnia came to an end. It resembled a scene of deforestation.

> They went to and fro tearing up the trees by the roots and crunching them up as if they were sticks of rhubarb. Minute by minute the forests disappeared. The whole country became bare. The grass died. Soon Tirian found that he was looking at a world of bare rock and earth. You could hardly believe that anything had ever lived there.

The children are understandably distressed by all the destruction and turn to Lord Digory, who dismisses all that they had witnessed as ‘only a shadow or a copy of the real Narnia which has always been here and always will be here’. He differentiates the new Narnia from the old ‘as different as a real thing is from a shadow or as waking life is from a dream’. But what leapt off the page was the basis for Lord Digory’s explanation: ‘.... he added under his breath, “it’s all in Plato, all in Plato: bless me, what do they teach them at these schools!”’

It made me wonder how much Platonic thought informed our present world view, and how much we need to affirm that the earth is indeed ‘the real thing’ and neither a dream nor a passing shadow. The earth is the Lord’s – and the place in which the believer prays for God’s will to be done, and in which the scientist explores the mysteries of the universe.

I ended my address to the Symposium with the beautiful imagery of Gerard Manley Hopkins’ poem ‘God’s Grandeur’.

> The world is charged with the grandeur of God.
> It will flame out, like shining from shook foil;
> It gathers to a greatness, like the ooze of oil
> Crushed. Why do men then now not reck his rod?
> Generations have trod, have trod, have trod;
> And all is seared with trade; bleared, smeared with toil;
> And wears man’s smudge and shares man’s smell: the soil
> Is bare now, nor can foot feel, being shod.
>
> And for all this, nature is never spent;
> There lives the dearest freshness deep down things;
> And though the last lights off the black West went
> Oh, morning, at the brown brink eastward, springs –
> Because the Holy Ghost over the bent
> World broods with warm breast and with ah! bright wings.

It was good to be in the company of those whose minds can span the disciplines of science and religion, and whose imaginations can behold the grandeur of God flowing out of the material world 'like shining from shook foil'.

CHAPTER ONE

INTRODUCTION: MATTER AND MEANING

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The title of this symposium may be seen to be a very conscious drawing-together of the worlds of science and theology. Scientists explore matter: they investigate the stuff of which the physical world is made, and the ways in which that stuff interacts and combines to form the things which we observe around us. Theologians explore issues of meaning, and of purpose. Put like this, we may initially suppose that our title confronts us with a classic case of the 'independence' model of science and theology, of Gould's 'non-overlapping magisteria' (cf. Barbour 1998, p. 84 ff; Gould 2001). But is this, in fact, a topic on which fruitful dialogue between these two areas of human endeavour can occur? The contributors to this volume certainly think so. Indeed, it would be odd for a theologian, at least, to think otherwise. One need not advocate a return to a Paleyesque natural theology to believe that, if our cosmos is in some sense the creation of God, then the matter from which that cosmos is constituted may have a story to tell other than simply that of what it is comprised.

But this is, of course, to beg the initial question: in what sense (if any) can matter be said to *mean* anything at all? Here, perhaps we may usefully distinguish between three approaches.

The first approach, which has characterised much Christian thinking down the centuries, is to see the material world as shot through with meaning. An exquisite example of this is afforded by Gerard Manley Hopkins' poem 'God's Grandeur', quoted in the preface to this volume, with its assertion that 'The world is charged with the grandeur of God'. Whilst the Bible is by no means univocal concerning the importance and value of material things, the psalmist's declaration that 'The heavens are telling the glory of God; and the firmament proclaims his handiwork' (Psalm 19:1), may be said to exemplify such a view. The material world has the power to inspire people to reflect upon the meanings it may have; and whilst evolutionary theorists have not been slow to speculate on why humans should possess such a capacity for feeling inspired (cf. Boyer 2002, Barrett 2009), such speculations scarcely negate that capacity.

The second approach would be to say that matter is inherently meaningless. This is part of a world-view characterised by Keith Ward as materialism: 'Materialism says that the only things that exist are material things in space. There is no purpose or meaning in the universe. Scientific principles are the only proper forms of explanation' (Ward 1996, p. 99). Ward associates this viewpoint with zoologist and scientific populariser Richard Dawkins, who writes that 'a body is really a machine blindly programmed by its selfish genes' (Dawkins 1989, p. 146). Genes, of course, are contained within the DNA found in living organisms; and Dawkins powerfully advocates the view that 'DNA just is' – that it, in common with other physical material, is simply a phenomenon found in a universe which he declares to consist of 'just electrons and selfish genes' (Dawkins 1996, p. 155). According to this viewpoint, then, matter 'just is': it is meaningless: it is simply something which is there to be studied (and science is the appropriate systematic method for such study).

The third approach would be somewhere in between these two. We may not wish simply to latch on to the insights of a particular set of texts affirmed as normative within a religious tradition, being conscious that such texts necessarily reflect the outlook of the age in which they were produced; but we may also feel unsatisfied with a Dawkinsian dismissal of meaning altogether. Rather, we might affirm that whilst the data of science in and of themselves may be 'meaningless', by placing them within the context of a narrative framework meaning may be made of them. This is, in fact, what Dawkins does: but the narrative within which he chooses to understand the raw data obtained by scientists is one which presumes a metaphysical materialist outlook, with its explicit denial of meaning. (For a discussion of narratives, including the Dawkinsian scientistic narrative, as conveyors of meaning, see Smith 2003, esp. chapter 4.) There can be no doubt that Dawkins tells his tale with skill and verve. But other narratives, other stories, might yet allow for understandings which would see matter as meaningful, without imposing any distortions on the data of science or their rigorous interpretation. The choice of which story to tell lies with the storyteller; and the choice of which narrative is to be believed lies with the hearer of the tale.

The relationship of human beings with matter, as investigators of it, as re-presenters of it, as interpreters of it, and as composers of narratives concerning it, is a complex one (cf. Polanyi 1958, Polkinghorne 1991). In a book titled 'Atoms and Icons', I noted that 'It is atoms which compose the face on an icon, and it is icons which are used to represent the invisible world of the atom' (Fuller 1995, p. 146). The symbolic creation of the icon-painter is clearly intended to be meaningful; yet it is a material object, albeit a carefully-crafted one. Conversely, the very description of material objects – particularly objects like atoms, the complexities of which may not be observed directly – may of necessity require symbolic representation; and symbols inevitably bring with them an epistemic flexibility which opens up the possibility of their conveying a variety of meanings, not solely those intended by the originator of the symbol.

It is here that we may see a possible ground for the interaction of scientists and theologians which is ripe with possibility. If we set to one side those narratives that preclude the involvement of one of those dialogical partners, be it the historical unpacking of a scriptural narrative in the absence of scientific insight or the materialist paradigm refusing to countenance meaning in a universe consisting solely of 'electrons and selfish genes', then many fruitful opportunities for conversation open up. And in fact, as contributors to this volume note, such dialogue would appear historically to have been the norm rather than the exception.

* * * *

The papers delivered at the Science and Religion Forum's 2008 conference at Liverpool Hope University have been gathered together in the present volume into three parts. Part One offers accounts of our current scientific understanding of what matter is. Ruth Gregory describes the remarkable developments in twentieth century science which have built up our current thinking regarding how matter at its most basic level is constituted, and how it behaves. She introduces the mathematical world underpinning and shaping our understanding of contemporary science, through a consideration of the ideas of those who were its founding fathers: Planck, Einstein and Dirac, amongst others. Gregory's paper also demonstrates something of the 'unreasonable effectiveness of mathematics', as Eugene Wigner put it, in enabling us to describe and account for the most remote material systems to which we can have access – those at the atomic and subatomic levels. Basil Ataie also offers some reflections on this historical account, and then explores some of the ways in which quantum measurement has been understood. He also proposes a novel understanding of quantum indeterminism, in terms of the physical properties of micro-systems being in a constant state of re-creation.

Part Two offers some historical perspectives on the ways in which we currently understand matter. Peter Harrison extends the historical canvas under consideration further back through history, to consider formative thinkers prior to the twentieth century. His paper focuses in particular on those classical thinkers who saw a dualism between what we would now term the world of matter and the world of ideas, or the world of spirit: thinking which has cast a highly significant shadow over subsequent centuries. Against this backdrop, Harrison suggests ways in which the corpuscular and mechanical views of nature, which gave rise to science in the early modern period, have tended to drain 'meaning' from the natural world. Given the explanatory power of the theories spawned by this understanding of nature, it is clear that the presumption of the meaninglessness of matter is now firmly engrained in the Western psyche, as a metaphysical assumption that can often be unquestioningly accepted by those who turn to the sciences for explanations of natural phenomena. John Henry, in a response to this paper, demonstrates the irony that these changes happened principally as a consequence of the attitude of the Church, rather than as a reaction against the Church's teachings.

Colin Russell's paper offers some further historical insights into the ways in which metaphors and models have been used and developed throughout history to generate explanations of the understandings of matter current at particular times. In a valuable 'case study' illustrating this, he draws attention to the present global warming crisis; and he suggests that this is the point as which theological thinking might intervene. Thinking of matter not as something objective, which is there to be exploited, but rather as something subjective, to which we can relate, assists us in facing up to incipient climate change; and, Russell adds, it may enable us also to re-introduce the idea of sacredness into our understanding of matter. Russell's clear inference is that this is an understanding that serves us rather better than ones which have prevailed during the post-Enlightenment centuries: centuries which, famously, have seen a desacralisation of nature.

Michael Poole responds directly to a number of points made in Russell's paper, commenting on and drawing out some of the ideas found there. Concluding this section, Basil Altaie offers a valuable view from an Islamic perspective, reminding us that scientific thinking flourished within this tradition for centuries before the development of Western science as we know it today. Altaie also points out some of the ways in which insights from Islamic thought can feed directly into 'hot' topics in today's dialogue of science and theology.

In Part Three, contributors present some theological perspectives which explore the interpretation of matter as meaningful. Niels Gregersen's paper reflects on contemporary understandings of matter, and draws on information theory and on logos-theology in noting some fascinating parallels between theological and scientific enquiry – in particular, that the natural 'triad' of mass, energy and information suggests constructive parallels with traditional Christian Trinitarian thinking about God, as Father, Son and Holy Spirit. Kenneth Wilson, responding to Gregersen's paper, draws on Wittgenstein and others in unpacking further some of the points being made. Hilary Martin explores a Roman Catholic understanding of the way in which the relationship of nature and grace may provide a perspective on the created order, which in turn promotes a greater integration of divine grace and earthly reality. Daniel Scott explores the radically anti-materialist thinking of Mary Baker Eddy, and examines the ways in which this has found expression in the outlook of the Christian Science movement. Finally, Peter Barrett draws on the writings of John Polkinghorne, Anthony Monti and others in developing a 'New Natural Theology' which includes the insights of the arts.

Many people in the twenty-first century West doubtless continue to think of matter as the inert 'stuff' of the universe, no longer 'sacred' in a way in which it might have been understood in the past, and belonging to a category of existent for which the term 'profane' would be equally inappropriate. The historical studies presented here trace something of the story by which this understanding of matter has arisen. But the contributors to this volume suggest that this is not the end of the story; and Russell's writing of a *resacralisation* of matter, together with Gregersen's invitation to think of modern relativistic and quantum theories in terms of their *dematerialisation* of matter, suggest that other understandings of the 'stuff' of our universe are possible. Perhaps the materialist metaphysic which has become habitual for many in the twenty-first century West is better exchanged for a rather different view. This view would see matter as imbued with the sacred (which, for believers in God, will mean that it has some capabilities for revealing to us something about the divine nature – and which for everyone, believers in God or not, will serve as a reminder of the ethical responsibilities which we bear when we manipulate it). And this view would see matter as something of which the absolute nature eludes us more and more the deeper it is studied – and would hence urge humility on those who seek to understand it further.

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PART I:

SCIENTIFIC PERSPECTIVES ON MATTER

CHAPTER TWO

WHY MATTER? A SCIENTIFIC PERSPECTIVE

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The recent switching on of the Large Hadron Collider (LHC) at CERN in Geneva makes my topic particularly timely: the physics of matter, or, for fans of *Angels and Demons*, antimatter. The experiments in Geneva are aimed both at verifying our theories of how matter works, and also at pushing forward the frontiers of our understanding and hopefully uncovering something new and, maybe, something unexpected. Although I will not cover some of the more technical aspects of our theory of particle physics, the *Standard Model* as it is known, I will discuss the underlying physical principles that lead to it. Like many scientists, I concern myself largely with the question of *how* the universe works, rather than *why*. Nevertheless, our struggle to understand the 'how' often leads us to some very interesting 'why's!

The foundation for understanding what we mean by matter is Quantum Mechanics. Even those who developed it considered this theory paradoxical: Niels Bohr said, 'Anyone who is not shocked by Quantum Mechanics has not understood it'. It touches almost every aspect of our modern daily life. Imagine no TV, computers, iPods, or Nintendo; nor any medical diagnostics and, some would argue, no free will. Quantum Mechanics is inherently paradoxical from a non-scientific standpoint. It explains how the atom splits, and yet how it is stable; it gives us uncertainty, yet also makes predictions for experiments. So how did we get to Quantum Mechanics?

Democritus, the laughing philosopher, believed that matter could not be subdivided *ad infinitum*, but that there had to be a 'smallest unit' – the atom. His basic philosophy was that the continuum (as we now call it) did not exist. To a large extent, this must have been a matter of faith, as there was no empirical evidence at the time for either finite or infinitesimal subdivisions. It is remarkable that, in the absence of experiment, he could have intuited the essence of matter. Although we often focus on its shortcomings, the scientific world view of the Greeks was breathtakingly successful in its reach, and indeed, based as it was on aesthetics, is very analogous to fundamental high energy physics today

The concept of an atom was formalized by John Dalton around 200 years ago. He laid down a set of hypotheses governing the nature of matter, and how it interacted chemically. At that time, chemical reactions were the only scientific basis for experiment. His definitions are recognizable to any student of chemistry these days:

> Matter is made up of **atoms**, which are **indivisible**.
>
> All atoms of a given element are **identical**, but different elements have different atoms.
>
> Atoms cannot be created or destroyed, only rearranged in chemical reactions.

Later in the nineteenth century, Dmitri Mendeleev classified the elements by the nature of their chemical interactions. The great significance of this work was that it showed patterns in the atoms of nature. We now understand the periodic table in terms of the structure of electron orbits around the atomic nucleus; but this understanding took a great deal of time to dawn.

The first step on the road to quantum mechanics started with the theory of heat, developed towards the end of the nineteenth century. James Clerk Maxwell and Ludwig Boltzmann developed the theory of *Statistical Mechanics*, whereby heat (and all other thermodynamical quantities) was described in terms of bulk motion of the constituent particles. Thus heat was simply atomic or molecular motion: the hotter the gas, for example, the more energy the molecules had. The statistical aspect comes because there are such large numbers of molecules, and we do not need to know the detail of their behaviour, just the overall net effect.

However, a problem arises, in that according to statistical mechanics, all the energy is divided democratically between the available states; and for a hot radiating body, this means that light of all wavelengths should be radiated. But there are infinitely many wavelengths! This means that the amount of energy radiated in visible light should be zero – but we know this isn't true. In fact, a sharp cut-off in the ultraviolet is seen in the spectrum from a hot body, and no light is radiated at very short wavelengths. This paradox (or rather, the failure of otherwise good scientific theories to explain a known phenomenon) became known as the *ultraviolet catastrophe.*

Meanwhile, J. J. Thomson had discovered the electron, so physicists now knew that in fact atoms were not indivisible. Even worse – when he repeated his experiment to try to observe positively charged ions, which should be the parts of the atom identifiable with the chemical element, he found that they were not in fact identical. Rather, ions of the same element could have different masses (Thomson called these *isotopes*). The simplest example is hydrogen, which has three isotopes: hydrogen, deuterium and tritium.

Finally, the discovery of radioactivity showed that atoms could transmute into other atoms. It seemed that all of Dalton's hypotheses had fallen: atoms were not identical, indivisible or fundamental. So, what was 'matter' now?

Once it was realized that atoms had structure, the next aim was to determine what that structure was. In 1908, Rutherford was firing alpha particles (these are helium nuclei: small positively charged objects emitted during radioactive decay) at gold film to prove his 'plum pudding' atomic model. He believed that atoms were structured as a globule of positive material, with negatively charged electrons embedded in them like plums in a pudding. He expected to see the alpha particles deflected by the positive pudding, emerging at a variety of different angles. Instead, he found that most of the alpha particles went straight through the gold film, with just a few bouncing back. This was only possible if the positive part of the atom was tiny and concentrated, and Rutherford deduced that the structure of the atom was more like a mini solar system: a tiny positively-charged nucleus surrounded by electrons orbiting around this centre. Rutherford could estimate the size of the nucleus from the scattering, and found it was less than one millionth of a millionth of a centimeter – roughly the equivalent of a pinhead in the centre of a football field. This was a complete shock: the plum pudding had been replaced by empty space! This immediately led to another problem: electrons in orbit around a positive charge will radiate by Maxwell's theory of electromagnetism – so how was the atom stable?

Fortunately, as is often the case when ideas and understanding are developing so rapidly, the tools which could supply an answer were already on the shelf. Six years previously, Max Planck had provided a solution to the ultraviolet catastrophe. He noticed that if you assumed that energy came in lumps, rather than being continuous, and moreover if you assumed that those units of energy increased as the wavelength of light decreased, the black body spectrum could be explained. He proposed the following equation:

$$E = h / \lambda$$

where E is the energy contained in the little lump of light (known as a *photon*), λ is its wavelength, and h is a constant of proportionality, now known as Planck's constant.

It is worth just taking a moment to reflect on Planck's equation, as this is absolutely central to the development of quantum mechanics. His claim was that light at a particular wavelength (or frequency, the two being related through the speed of light) could only contain multiples of a fundamental unit or *quantum*. Since light can only be emitted with *at least* this quantum of energy, which increases with decreasing wavelength, a radiating body will not have enough energy to radiate at very short wavelength; hence the cut-off of the black body spectrum in the ultraviolet.

Planck at first did not believe his idea was fundamental, corresponding to some underlying reality, since what it actually says is that light comes in units – it is a *particle*. But everyone knew light was a wave: James Clerk Maxwell had demonstrated that with his theory of electromagnetism forty years earlier. Indeed, some two centuries earlier Huygens had correctly explained refraction and polarization in terms of wavefronts of light. However, another physicist at the time was prepared to believe Planck.

1905 was an amazing year for physics: it was the year that Albert Einstein emerged onto the scene. Even the least of Einstein's papers that year would be a feather in the cap of most physicists today. Yet, as well as ultimately overturning our concepts of space and time, and explaining Brownian motion (the random motion of larger particles in a fluid) and other statistical properties of matter, Einstein set a revolution in motion. He took Planck seriously, and by assuming the quantization of light he was able to explain the photoelectric effect. In the photoelectric effect, light shining on certain metals releases electrons of the same velocity, independent of the intensity of the light: increasing the light intensity leads to more electrons, not more energetic electrons. At the time, this was a puzzle – after all, if you hit something harder it tends to move faster, so why were the electrons all emerging with the same speed? Einstein explained this by supposing that the light consisted of Planck's light quanta – the photons – and that only a photon of the right wavelength could knock an electron out of the metal. Adding more photons would not make the electron move any faster: it could only release more electrons.

At first the scientific community was skeptical, but in 1913 Niels Bohr realized that this quantization could explain both atomic structure and stability. Bohr suggested that the energy of orbiting electrons was quantized, and that the electron could jump between orbits if given the right ‘kick’ from a photon. In particular, this meant there was a lowest orbit, which was stable, and it also explained *and predicted* characteristic lines in the spectrum of the hydrogen atom. It was not a perfect description, since Bohr assumed that orbits were circular, and this does not work so well for electrons in higher orbits, or for elements with a higher atomic number than Hydrogen. However, it did capture the idea of the quantum atom, rather like Ptolemy’s universe captures the idea of the solar system, and this model is still taught to students today to illustrate the application of quantum mechanics to the atom.

The penultimate piece of the quantum puzzle was put in place by Louis de Broglie in 1924, when he proposed wave-particle duality. Just as the ideas of Planck and Einstein show that light can have a particle-like nature, de Broglie suggested that particles like electrons could have a wave-like nature. He inverted Planck’s equation to say that a *particle* would have a fundamental *wavelength*, the de Broglie wavelength as it is now known. Again, the amazing feat here was not that de Broglie reversed the order of an equation, but that he reversed the *interpretation*, and drew a far-reaching and revolutionary conclusion from this hypothesis. Not only could light, a wave, behave like a particle, but also particles could behave like waves. Using Einstein’s relation between energy and momentum for a photon, the de Broglie wavelength is defined as

$$\lambda = h / p.$$

Here, h is Planck’s constant as before, and p is the momentum of the particle. (Recall that momentum, which is conserved in collisions, is the combination of mass and velocity: p = mv). Why had nobody noticed this extraordinary conclusion before? The reason we are not aware of our wave-like nature is that the wavelength is so small. Planck’s constant is an extremely tiny number, and so the de Broglie wavelength of a human would be one million billion billion billionth of a centimeter (10^{-33} cm)! However, the de Broglie wavelength of an electron is the size of an atomic radius, so the size of the atom emerges naturally from this description. Moreover, de Broglie could explain why Bohr’s electrons orbited the way they did. They were simply standing waves, with each orbit a given ‘multiple’ of the electron’s wavelength.

At this stage, everything was conceptually in place; the fundamental nature of matter was more or less understood, at least in essence. However, science is not about general descriptions or conceptual understanding, essential though these things are. Science is about making predictions, quantifying results, and measuring the outcomes of an experiment. Science is about the construction and verification of a mathematical model of nature: in other words, a theory.

In 1926, Erwin Schrödinger presented his ‘wave equation’. This was a theory of how quantum particles behave. It incorporated de Broglie’s idea of waves by replacing the electron by a *wave function*, a number at every point in space and in time. In a similar way to Maxwell’s equations for the propagation of light, Schrödinger gave an equation for the way this wave function evolved. However, this wave function was something very different from the usual expressions used in physics. Not only was it a complex number, but also it did not directly correspond to anything concrete, such as the size of an electric field. Instead, Schrödinger’s wave function encodes the *probability* of finding the electron at a particular point in space (and time). It does not represent the electron as we might visualize it in our minds, but more the electron in its full generality. Thus, Schrödinger had made the final conceptual leap from the classical predictability of Newton and Maxwell, and introduced a quantum world: a place of probability, uncertainty and chance.

Complex numbers are a tool by which scientists generalize the real, or ordinary, numbers. They have a ‘phase’ as well as a ‘size’. They not only allow you to take roots of negative numbers, but they are also very powerful mathematically. From another perspective, they contain more information than you can actually ‘see’. There is a reason that counting or number systems have been with us for millennia, but complex numbers for only a few centuries: our perception of the world is real. In part because of the extra hidden information in complex numbers, but also because we have replaced a concrete thing with a probability, we are led to a property known as *uncertainty*. If we observe a particle, we interact with it, which changes it. We can never know exactly where it is without completely destroying our knowledge of where it is going. In other words, we no longer know where we are, where we are going, how much we’ve got and when we are going to get there – at least, not all at the same time!

It is worth pausing for a moment to reflect on where our journey into the quantum world has led us. We have, step by logical step, been forced to blur the distinction between forces, like electromagnetism, and the objects those forces act on, like electrons. In the 19th century, these were either waves or particles, and real. Now, we see they are each both wave-like and particle-like, and possibly complex. We find that our description of nature includes not only things that we do not see, but also things that we can *never* see.

Einstein found this deeply disturbing, and felt that nature could not be fundamentally indeterministic. ‘God does not play at dice’, was his famous complaint: ‘Stop telling God what to do’, was Bohr’s laconic response! In many ways, Quantum Mechanics was Einstein’s unruly child. Although he had fathered the theory, it had become something with which he could not reconcile himself. Yet we now know that this understanding of nature is absolutely right.

However, the Schrödinger equation was not the final word. As Schrödinger was well aware, it was not directly compatible with Einstein’s Special Relativity, a well-verified theory. Schrödinger in fact had initially derived his wave equation in a more conventional form. To understand how he did this, we can think of the equation as a sum of energies, which reads much as a classical Newtonian relation: the total energy is a sum of kinetic and potential parts. However, Newton thought time was absolute, and certainly separate from space. From Einstein, we know that space and time have to be on the same footing. This means that every time we see a length, we need a time to balance it. For the energy relation, it actually means it is a sum of squares, like Pythagoras:

$$E^2 = m_o^2\, c^4 + p^2\, c^2$$

Here, we see the famous $E = mc^2$ relation of Einstein, the energy contained in matter. We also see the kinetic energy, contained in p, the momentum. Translating this into our wave function, we relate E to a rate of change in time, and p to a gradient in space. This gives a relativistic equation, the one Schrödinger originally obtained, with time and space appearing on the same footing. Schrödinger abandoned this original form because the square of the energy appeared. This meant that the energy was given by a square, and hence there could be negative as well as positive energy solutions; but how could energy be negative?

Schrödinger believed that a negative energy solution to his wave equation was a disaster. The equation would then predict that negative energy particles would be produced, which would actually lower the energy further, so more would be produced, leading to a runaway instability of the vacuum. He could find no satisfactory way to avoid this negative energy solution, and so he abandoned the relativistic equation, taking an approximation for low kinetic energy. It is not the first time in physics that a rough and ready working model has turned out to be more valuable than the ‘Rolls Royce’ version. The Schrödinger equation is used in most modern atomic physics and nanotechnology.

A theoretical particle physicist, however, seeks to describe nature as accurately as possible; and since nature is relativistic, it was essential to understand what happened to the negative root. Paul Dirac, a Cambridge mathematical physicist, believed that if we could take the square root of the equation directly, then the problem of negativity would go away. The trouble was, relativity implied that space and time should be on the same footing; but there are three dimensions of space and only one of time. Dirac had a moment of inspiration when he realized that by mopping up these single gradients by an array, or matrix, of other numbers, he could take a meaningful relativistic square root. He wrote down his ‘gamma matrices’, deriving the relations they had to satisfy, and he then had the insight that indeed they could satisfy those relations if the wave function became a more complicated expression known as a *spinor*.

While working through his theory, Dirac found that he had not removed the negative energy. Rather, he had simply given it a new place to hide in the extra information contained in the wave function. By this point, however, he was sure he was on the right track, and sought an alternative explanation. He theorized that there were negative energy solutions, but that they would in fact be full of electrons. Electrons were known to obey the Pauli exclusion principle, which states that no two electrons can occupy the same state. (This principle ultimately has a neat explanation from the Dirac equation.) It was therefore quite possible for these negative states all to be filled. The true vacuum was then a state in which all the negative energy solutions were populated. Dirac interpreted a hole in the ‘sea’ of negative energy states as a positive-energy, positively-charged particle, which would form if an electron were kicked out of a negative state. This new particle would therefore have the *same* mass but *opposite* charge as the electron.

Dirac thus predicted a new particle. Four years later this was observed by Carl Anderson, who christened it the ‘positron’, thus heralding a new era of particle prediction and discovery in high energy particle physics. We now have the idea of an anti-particle to every particle, which is essentially ‘the same but opposite’ to the particle. An anti-particle has all the same charges as the particle, but with the opposite sign. The only thing a particle and anti-particle do not possess in opposite degree is their energy, which is positive. What this means is that when a particle meets its anti-particle, there is nothing to stop them from unravelling each other, i.e. they annihilate.

This is what is used in the positron emission tomography (PET) scanner; the precisely collinear photons produced from such annihilations give a precise location of the decay, which allows for extremely accurate imaging. The energy released in a single decay is tiny, which is why it is a safe diagnostic tool, but if we had even a small amount (by everyday standards) of antimatter, the corresponding release of energy would be huge. For example, one kilogram of matter and antimatter would release 270 *billion* kWh of energy!

The Dirac equation underlies the basic description of most ‘matter’. But what do we mean by ‘matter’? From a particle physics point of view, matter is something which we can describe by the Dirac (or other appropriate) equation, where we identify the particle through its charges: most particles carry not just electric charge, but also other hidden charges which we do not see at our macroscopic level. The antiparticle then has the opposite charges. This is the particle physics picture, but from a more mundane point of view we imagine matter to be the stuff we are made of – something with mass, and possibly with some electric charge. Why therefore do we not see other charges, why is matter massive, and why do we not see anti-matter? These are the issues I now briefly explore in the closing part of this chapter.

Most familiar (and less familiar) particles have a property known as spin, which can be thought of as the particle spinning on its axis rather like the earth or the sun. With one rather high profile exception, all known particles have spin, that exception being the Higgs boson, which has no spin at all. The Large Hadron Collider (LHC) has been built primarily to find this final piece of the Standard Model of particle physics, as well as looking for clues beyond the Standard Model. What makes the Standard Model so elegant is that is encodes the known quantum interactions of nature in an economical description, with a relatively small number of fields. The model has hidden symmetries relating different particles through this as yet unobserved Higgs scalar. Observing the Higgs boson would tell us that we have the right picture of nature and also confirm our theories of how particles get their masses, and how these masses relate to each other. But of course that is not the whole story. We want to push our theories beyond this Standard Model, because like Einstein we want to incorporate gravity into particle physics. This very interesting story is too long to review here, so I would like to finish off with a few remarks about the Universe, cosmology, and what we do not know – which is how matter got here in the first place.

Let me first explain in a nutshell the standard cosmological model. This is an astonishing achievement of 20th century physics, using rather broad and basic theories and models to achieve a staggeringly successful description of the cosmos. Once again, we start with Einstein, and his ‘unification’ of space and time. We in fact are used to this type of visualization of time as a dimension, as we often use it to draw graphs of the behaviour of various quantities in time – the downward curve of a recession is sadly all too familiar! In Special Relativity, we draw time as an extra axis, and have rather bizarre rules for changing our velocity, called Lorentz transformations, which tell us how space and time are related.

Einstein's theory of General Relativity then does a rather sneaky thing: it curves those dimensions of space and time. When thinking of the curve of a thrown ball in the Earth's gravitational field, Einstein realized that these apparently curved paths were in fact inertial, or straight. This meant that the space around the Earth must be curved! General Relativity relates matter to curvature, and then inertial motion in this curved space translates to gravity. By doing this in a mathematically consistent way (and it took Einstein several years to assimilate the mathematics he needed), he correctly reflected the fact that gravity is just another sort of acceleration, but one in which tidal forces are real.

The largest possible canvas for Einstein's relativity is of course our universe. When we apply general relativity to the universe as a whole, we obtain a surprisingly simple model for the universe, which turns out to have one of three basic shapes, which grow in time. These shapes are a flat infinite space, a three-dimensional sphere, and what is known as a hyperbolic space. The universe is completely determined by only one varying quantity: the scale factor $a(t)$. This scale factor tells us how big the universe is, or was, at a certain time. Moreover, $a(t)$ satisfies a relatively simple equation from which a great deal of information may be inferred.

The main features of our universe turn out to be that it is dynamic (it tends to expand or contract), hotter at earlier times (the temperature drops along with expansion), and that it had a beginning, which we now call the *Big Bang*. While we cannot concretely describe the beginning (yet – another story!), we can describe the effect of the temperature evolution on the constituents of the universe.

The main huge success of the Big Bang model, and the principal reason it is the accepted model of the universe, is *nucleosynthesis,* or the process in which light nuclei are formed. We know that the universe comprises roughly a quarter helium, together with smaller abundances of other light elements such as lithium, and helium-3 (a lighter isotope of helium). Most heavy elements are synthesized in stars, but there is not enough time for this large percentage of helium-4 ('normal' helium) to have been produced in stellar cores. It must therefore have been formed in the early, hot, universe.

Fortunately, nuclear physics tells us which reactions can produce helium-4, and also how to calculate the reaction rates to compute the proportion of helium in the universe. Helium is formed in a chain of reactions, in which protons and neutrons combine to form deuterium (heavy hydrogen) and thence helium. It turns out that there is a subtle interplay between the rate at which neutrons get bound, and their decay rate (for the neutron is not a stable particle, and it decays into an electron, proton and antineutrino with a half-life of around 15 minutes). In order to get the proportion of helium we observe in our universe, we need to delay the formation of deuterium so that some neutrons can decay. This means that we need a huge bath of photons around to retard this nuclear reaction.

Alpher, Bethe and Gamow predicted this ‘microwave background’ – the afterglow of the Big Bang – back in the 1940s, although it was not seen until 1965 by Penzias and Wilson. The observation of this radiation background is what makes us sure that the general description of the Big Bang is correct.

We can try to apply the same ideas to calculating the abundance of matter in the early universe, which should have resulted from some earlier, higher energy reaction. However, within the Standard Model, we find we cannot. *A priori*, we expect as much matter as antimatter at the Big Bang, so we need to explain how an excess of matter was created. The problem is that any thermal process will produce equal amounts of matter and anti-matter, since they have equal mass and equal (but opposite) charge. Sakharov summed up this problem with three conditions, stating that we needed a theory of particle physics which allowed the amount of matter to change, and violated underlying symmetries, as well as a period in the early universe that was out of thermal equilibrium. So far, in spite of a great deal of effort, we do yet have a scientific theory of *baryogenesis*, the creation of matter.

Thus we have come full circle. From the ancient Greeks applying their ideas of aesthetics and deduction to the natural world around them, through the renaissance of scientific measurement, the development of the mathematical tools to describe nature, the explosion (unfortunately rather too literal) of our understanding of the very small scale and quantum nature of our world, we have arrived once again at the edge of our testable knowledge. However, we have a far better understanding of the universe, and of how it came to evolve into the rich structure we see around us today. We also have many ideas and theories which take us beyond the Standard Model, some of which include Einstein’s gravity as part of their goal. However, we are stymied in our progress of picking out the correct theories because, like the ancient Greeks, our reasoning has taken us beyond our capability of testing the ideas it has generated.

In my description of the physics behind our theories of matter I have tried to explain not only the physics, but also to give an insight into the flow of ideas or the way in which the scientific community has grappled with the issues it faced. Most of science is about finding a concrete truth, yet our motivation for seeking out facts can sometimes be more an act of faith. So perhaps Einstein was right when he said: ‘Science without religion is lame, religion without science is blind’.