The Large Hadron Collider

Martin Beech

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Unraveling the Mysteries of the Universe

Springer

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This book is dedicated to my parents, Leonard and Irene Beech.

For their many years of patient support and encouragement, I am grateful.

Preface

The Discarded Image was the last book that C. S. Lewis, perhaps better known for his *Narnia* series of stories, wrote. In this final tome, published in 1964, Lewis reflected upon many decades of lecturing, scholarly research, and philosophical thought.

The "image" that Lewis was concerned with was that of the medieval universe, and specifically its complete, compact, and fully determined form. Indeed, the image of the medieval universe is the very antithesis of the one that we have today. Although our universe is inconceivably large, nowhere near fully surveyed, only partially explained, and full of surprises, it does have one parallel with the medieval image: all is connected, and as every medieval astronomer knew, within the microcosm is a reflection of the macrocosm and *visa versa*.

The Large Hadron Collider (LHC) experiment now under commission at CERN [Conseil Européen pour la Recherche Nucléair][1] is just a modern-day continuation of this basic ancient tenet, and even though conceived and constructed to test the best present theories of particle physics, the results from the LHC will provide fundamentally new insights into the origin of the universe and its observed large-scale structure. All is connected.

This book will be concerned with the fleshing out of a new image that binds together the macrocosm (the universe) and the microcosm (the world of elementary particles). Our task in the pages that follow will be to "un-weave" the fabric of the universe, and to thereby tease out the intricate strands that connect the Standard Model of particle physics (and its many present possible extensions) to the observed cosmos around us. For indeed, it is now abundantly clear that once in the deep past, some 14 billion years ago, the vast expanse of the observable universe (with a present diameter of order 93 billion light years) was minutely small – a compact cloud of raw bubbling energy, full of future potential, arguably quixotic, and evolving on a mercurial timescale faster than the blink of a tomcat's eye. Out of the

[1]This was the provisional title for the organization at its founding in 1952. In 1954, however, a name change to *Organisation Européenne pour la Recherche Nucléaire* – European Organization for Nuclear Research – was agreed, but the original acronym, for reasons that are not clear, was kept.

primordial microcosm grew the macrocosm that is the universe of today, with its associated flotsam of galaxies, stars, planets, and life.

Verily, since it seems only right to use exulted tones, science and the work of countless observers and cloistered theoreticians have brought us quite an image to deal with. The modern-day image of the universe is full of incredible and unknown wonders. It is an image that would have thoroughly appalled the medieval scholar, not least because of its vast emptiness but also because its dominant components are entirely unknown to us. The mystery of dark matter (most definitely detected, as we shall see in Chapter 5, yet entirely unseen) and the possible existence of dark energy (discussed in Chapter 6) represent the most profound scientific problems of our age. And although it is not known what physical effects underlie these phenomena (yet), the LHC, by smashing head-on the nuclei of two lead atoms, will transport our understanding back to those moments that prevailed just 10^{-25} s after the Big Bang occurred – back to a time before stable matter even existed. Indeed, The LHC, in addition to its many other incredible properties, is also, in essence, a time machine, and this massive collider will enable researchers to study, for the merest fraction of a second, the primordial fire (the so-called quark–gluon plasma) out of which everything that we can now see and feel initially appeared.

The LHC experiment will not only provide researchers with insights as to why the universe has the characteristic form that it does (being made of something rather than absolutely nothing), it will also look for signs of the much anticipated Higgs boson, one of the key theoretical components of the Standard Model of particle physics, since it is generally believed that it is through interactions with the Higgs field that the various elementary particles acquire their mass; and this is no mere ivory-towered problem – without the Higgs (or some similar such mass-generating process) there would be no matter and no us.

Although the history and origins of the LHC will be described in greater detail in Chapter 2, we should provide at least a few words about its incredible properties before moving into our discussion on the basic properties of matter. The LHC is a machine – perhaps symbiotic complex is a better term for it – that can only be described in superlatives. As the medieval astronomer would have marveled at the great cathedrals of Paris and Rome, so the LHC is the pinnacle of modern experimental physics writ large on the landscape (actually under the landscape, as we shall see). We can do little but wonder at the LHC; its intricate yet paradoxically parsimonious structure, along with its sheer scale, leaves us humbled.

Indeed, the mind reels at the very thought that such machines can even be constructed. The numbers speak for themselves: the main accelerator ring is 26,659 m in circumference; the particle beams are manipulated by 9,593 super-cooled magnets that operate at a temperature of –271.3°C (just 1.9° warmer than the coldest temperature that anything can possibly be in the universe); and the system contains about 7,600 km of electrical cable, using strands of wire that if unraveled and joined end to end would stretch to the Sun and back five times over. When fully operational the LHC experiments will generate about 700 MB of data per second, or some 15 petabytes of data per year – enough digital data, in fact, to produce a 20-km-high stack of CDs every year.

The scale is grand, the structure is colossal, the task is Herculean, but the results from the LHC experiment could confirm and also re-write particle physics as it is presently known. The past, present, and future story of the LHC is and will be a fascinating one to follow, and it is an unfolding epic that could conceivably be destined to change our understanding of both atomic structure and the cosmos. All is connected, and within the macrocosm resides the microcosm (Fig. 1).

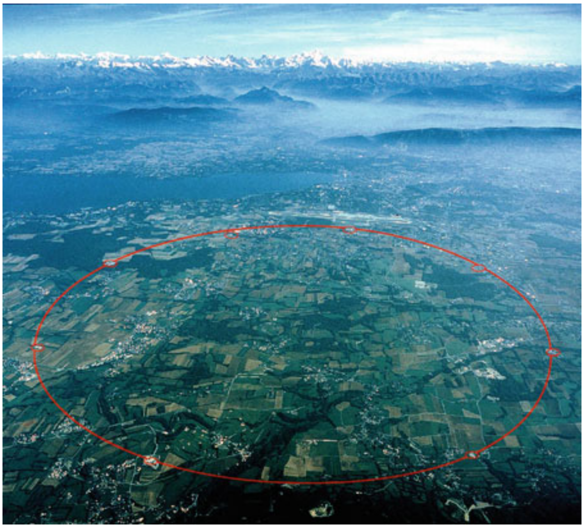

Fig. 1 An aerial view of the CERN complex. Set amidst the verdant fields of the French-Swiss border, the loop of the LHC collider ring is shown in the image center and foreground, with Lake Geneva and Mont Blanc, the tallest mountain in Europe, in the far distance. (Image courtesy of CERN)

The expectations of the medieval scholar were entirely different from those of today's scientist. Although our forebears would have held out zero expectation of discovering novelty within the universe (and within the properties of matter, for that matter), the modern observer fully expects to find new celestial objects and unexpected behaviors. The LHC is the tool that likely will reveal the new and the novel, and we can certainly expect that not only will our appreciation of the universe be very different a decade from now, but so, too, will our understanding of fundamental particle physics. It is almost certainly going to be a wonder-filled journey.

However, this journey has its associated risks. The LHC has been designed to explore the unknown, and some scientists have suggested that the CERN researchers may be on the verge of opening a veritable Pandora's Box of trouble. Literally, it has been argued that the LHC could release a host of exotic "demon" particles from beyond the borders of known physics – miniature black holes and so-called strangelets that some believe could pour from the LHC and potentially destroy Earth. These are frightening claims, and they must be considered carefully. How safe is the LHC, and how can we be sure that is doesn't pose a serious threat? These are questions that must be answered as we move forward, not only in the following pages of this book but also as we move into the future exploring the microcosm at ever higher energies.

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About the Author

Dr. Martin Beech is a full professor of astronomy at Campion College at The University of Regina in Saskatchewan, Canada. He has published many scientific research papers on stellar structure and evolution and several books on astronomy. Asteroid 12343 has been named in recognition of his research on meteors and meteorites. This is Beech's third book for Springer. He has already published *Rejuvenating the Sun and Avoiding Other Global Catastrophes* (2008) and *Terraforming: The Creating of Habitable Worlds* (2009).

Chapter 1
The Story of Matter

A Few Searching Questions

Science is all about asking questions and looking for logically consistent explanations of what is observed. But, more than simply the searching for and finding of answers, the quest of the scientist is never over. There is always another question that can be posed, and there is always a different way, perhaps a better way, of explaining an observation.

This ceaseless process of searching, testing, pushing, and pulling at an idea and questioning is exactly what makes science so powerful, and it is also what makes it so successful at explaining the world that we see around us. For the scientific approach is by far humanity's best choice if a meaningful understanding of the universe and how it works is ever to be achieved. All other approaches lead either to fantasy or dogma.

Certainly, wrong explanations have been, and no doubt are still being, proposed by scientists, and on occasion entirely wrong ideas have been accepted for long periods of time as realistic explanations to some phenomena. But eventually, inevitably, the scientific process is self correcting. Science is ultimately ruthless, totally impartial, and completely devoid of feeling, but for all this it allows us to creep forward, inching ever closer towards a finer and better understanding of the marvelous universe and the many wonders that reside within it.

Given science is concerned with asking questions, then let us search the depths of our human senses and ask what the limits of our perceptions are. What, for example, is the smallest thing that you can see with your unaided eye? Certainly a period (.) is visible, but what about something half its size? Perhaps this is still visible to some readers; the author's aged and far less than perfect eyesight, however, would struggle to pick out such a miniscule ink-speck. Certainly something, say, one-tenth the size of a period would be below the ability of the best human eye to detect with any certainty. For the unaided human eye, therefore, the limit of smallness is achieved at about 0.05 mm.

From the inanimate viewpoint of the electron located in the ground state of the hydrogen atom (the meaning of all this will be explained later), the naked-eye limit of human perception corresponds to a distance that is about 500,000 times larger

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than the orbit it occupies. The atom and the many exotic subatomic structures that will be described in this book are all entirely invisible to our naked eye, and yet science unequivocally tells us that they exist, and that they are real entities with measurable and understandable properties. Here, indeed, lies the power of scientific inquiry, since it can take us far beyond our body's ability to sense, and it affords us a deep and searching pair of artificial eyes with which to observe new and fantastic domains.

What is the most distant object that can be seen with the unaided eye? In the prairies of Canada, where this author lives, the distant horizon is about 33 km away when viewed from the top of the 25-story, 84-m-high Regina Delta Hotel. From the top of Chomolungma (Mt. Everest), the highest mountain in the world, the mountain climber's distant horizon (ignoring clouds and other mountains in the way) might stretch to 330 km.

We should not be so parochial in our views, however, as the painter John Ruskin reminds us that "mountains are the beginning and end of all natural scenery." The Moon, the Sun, and the planets out to distant Uranus are all visible to the unaided eye. Although discovered fortuitously by William Herschel and first recognized as a planet in 1782, Uranus is just visible to the unaided eye if one knows where to look. At closest approach to Earth, Uranus is about 18 astronomical units (AU) away, a distance equivalent to about 2.7 billion kilometers, or over 8 million times further away from us than the most distant horizon (that from Mt. Everest) visible on Earth. The nearest star, next to the Sun, of course, that is visible to the unaided eye is Alpha Centauri (which is actually a binary star; see Fig. 1.1), and it is 1.35 parsecs away, or about 41.5 million million kilometers. We are now 126 billion Everest horizons away from Earth.

We can search for stars fainter than Alpha Centauri in the sky, and these will mostly be further away, but the ultimate span over which our unaided eye can see is to a distance beyond any star in our Milky Way Galaxy and even beyond the stars in the nearest dwarf galaxies. The depth of human eye perception stretches all of the way to the spiral-shaped Andromeda Galaxy. Located in the constellation of Andromeda (Fig. 1.2), what looks like a faint fuzzy patch of light to our eye is about 736 kiloparsecs distant. Andromeda probably affords us a doppelganger image of our Milky Way Galaxy, and by viewing it (Fig. 1.3) we get a proxy grandstand view of our galactic home, a home that we will have much more to say about in Chapter 5.

The distance estimate for the Andromeda Galaxy completely escapes our sense of scale. It is 23 billion billion kilometers away, or equivalent to 69 million billion Mt. Everest horizons. It is remote on a scale that leaves us almost breathless and reeling. It takes light about 2.4 million years to traverse the distance between Andromeda and Earth, and the light that we see from the Andromeda Galaxy today started on its journey long before we, as *homo erectus*, had even evolved.

The world of human perception is sandwiched between the limits set by the tiny period and the Andromeda Galaxy, limits corresponding to about 5×10^{-5} m on the small side and 2.3×10^{22} m on the long. But the limits of our human senses are dwarfed by the atomic and universal scales that science allows us to explore;

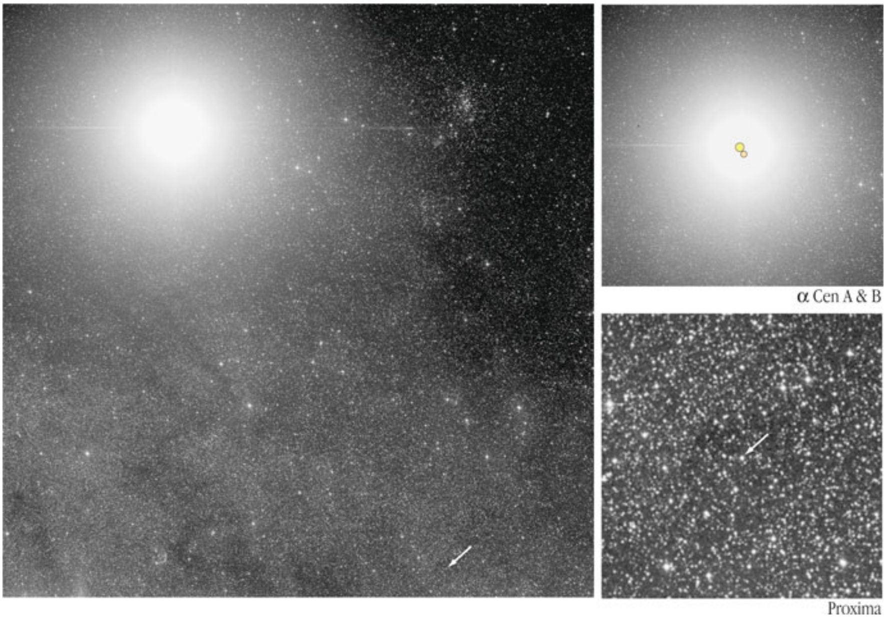

Fig. 1.1 Alpha Centauri, the nearest star, after the Sun, visible to the unaided eye. The "star" is part of a binary system in which two stars orbit each other at a distance of about 24 Astronomical Unites (AU), with a period of about 80 years. The star Proxima Centauri is actually closer to us than Alpha Centauri, but it is not visible to the unaided eye. The images shown here were obtained with the European Southern Observatory's 1-m Schmidt Telescope. (Image courtesy of ESO)

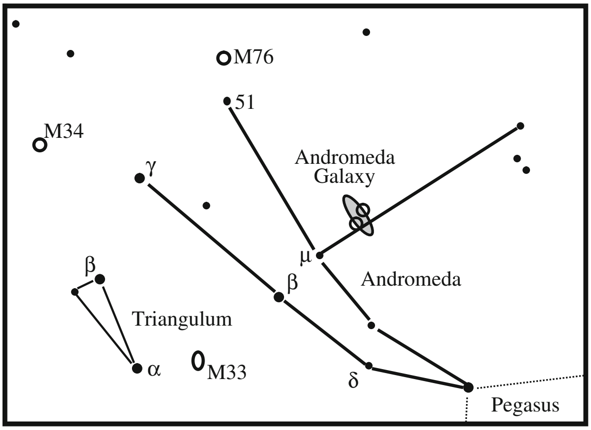

Fig. 1.2 A star map indicating the sky location of the Andromeda Galaxy, the most distant object visible to the unaided human eye

Fig. 1.3 The Andromeda Galaxy. (Image courtesy of NASA)

indeed, as Blaise Pascal was to reflect with both wonderment and vertiginous fear, we occupy that region that teeters between the two abysses of the infinitely large and the infinitely small.

The smallest size that physicists believe to be meaningful, by which it is meant that known physical theories should apply, is that of the Planck length. Named in honor of German physicist Max Planck, one of the pioneering founders of quantum mechanics in the early twentieth century, the Planck length corresponds to a minuscule distance of some 1.6×10^{-35} m.

The Planck length is a rather curious number, composed as it is from a combination of the universal gravitational constant G, Planck's constant h, and the speed of light c. For all this apparently abstract construction, however, the Planck length is the fundamental scale below which known physics no longer applies, and it is the new realm of the presently unrealized, but greatly sought after, domain of quantum gravity.

Between the domains of the world observable to humans and the world over which known physics applies we encounter a mind-numbing scale of magnitudes. The realm of known physics operates over scales 30 orders of magnitude smaller than our eyes can see. The observable universe also swamps our human eye limit to Andromeda by a factor of about 40,000. Remarkably, on the scale of our human senses, the domain of the inner, atomic realm outstrips that of the greater universal one.

The Smallest of Things

The philosophers of ancient Greece began the long struggle that has become modern science. The struggle, then and now, was not one relating to existence, but was rather the struggle to tease from nature a rational understanding of its properties. Their ideas on how the universe was ordered and how it came into being were no less remarkable than our own, but the modern-day concepts are more rigorously based upon observations and experimental measurements – observations and experiments, of course, that the ancient philosophers had no way of making.

Similar to the situation that prevails today, the ancient Greek philosophers did not want for theoretical ideas about the origin of the heavens; the problem then, as now, was rather one of differentiating between rival possibilities and agreeing upon an underlying physical theory of how nature works. By circa 400 B.C. it was generally agreed, however, that a spherical Earth was located at the center of a spherical cosmos, and that there were two types of celestial motion, that of the stars and that of the planets. In each case the motion was taken to be circular, and eternal, but the rate of motion was different in each case. Likewise, by about the same time it was generally agreed that objects in nature were composed of atoms, or elemental building blocks that were extremely small and that could not be further subdivided. One of the greatest (but perhaps more difficult to decipher) accounts of nature and the origins of cosmic order is that given by Plato in his speculative dialog *Timaeus* written circa 300 B.C.

The key to understanding nature, according to Plato, was one of identifying the good or benefit in its arrangement. This rationale stemmed from Plato's philosophical dictate that the universe had been brought into existence by a benevolent demiurge who had strived throughout to make its construction as near perfect as possible. According to Plato, therefore, things happen in the universe because the various objects within it are seeking to find their best possible configuration. Plato's cosmology is accordingly teleological and yet fully consistent with Socrates's (Plato's great teacher and mentor) mandate that a cosmological model should seek to explain why the cosmos is so structured and why its contents are so arranged in the best possible way.

To Plato it was in the nature of solid, earthy matter, for example, to fall or move towards the center of the universe, and by this reasoning he explained why Earth was spherical, since this corresponded to the tightest, most even packing of all the earthly material, and it also explains why Earth was centrally located within the cosmos – the reason being that Earth is made up of earthy matter. In this latter sense, for Plato, Earth is located at the center of the universe not because it is special, but because of what it is made of. Plato also considered the universe to be alive, an idea echoed, in some sense, in more recent times in the writings of James Lovelock and the Gaia hypothesis in which Earth is considered to be a large-scale, self-regulating, living organism. Here, in fact, is a nice example of an old, discarded idea being re-invigorated in the modern era.

Although we no longer give credence to Plato's living universe (because of our better understanding of what the expression "being alive" actually means and entails), Lovelock's Gaia hypothesis is much more rigorously defined and also much more restricted in its scope than Plato's world as described in the *Timaeus*. Not only do we continue to find the microcosm reflected in the macrocosm in the modern era, we also continue to find old ideas reflected and re-invented in the new.

Plato's living cosmos was infused with what he called the world-soul, which can be thought of as an animating force and intelligence that guides change to work towards the better good. Plato's spherical universe was essentially divided into two realms, that of the heavens and that of Earth. Above the spherical Earth's upper fiery-air region (the atmosphere to us) resided the perfect realm of the planets and the celestial sphere. The planets, which to the ancient Greeks constituted the Moon, Venus, Mercury, the Sun, Mars, Jupiter, and Saturn, were deemed to move along perfectly circular paths around the center of the universe and from Earth were observed to move within the zodiacal band of constellations wrapped around the celestial sphere. The celestial sphere had its own perpetual motion, and it was this primary motion that caused the stars, considered by Plato to be living entities that were divine and eternal, to move around a stationary Earth.

In the Earthly, sub-lunar realm conditions were much less pristine than those encountered in the greater cosmos and certainly not eternal. With respect to matter, Plato argued in the same vain of Empedocles, who lived circa 450 B.C., positing the existence of four basic elements: earth, air, fire, and water. All matter in the sub-lunar region was made up of combinations of these basic elements. Objects in the celestial realm were composed of a special pure and incorruptible substance called quintessence. In turn the basic elements were composed of minute particles (atoms), each of which had a special three-dimensional form. Indeed, Plato described the elemental atoms in terms of the regular or Platonic solids (Fig. 1.4).

The Platonic solids are special in that they are the only solids (or more correctly polyhedra) that can be made with the same generating shape for all of their faces. The hexahedron (or cube), for example, is made up of six squares, while the octahedron is made up of eight equilateral triangles (see Table 1.1). What Plato knew and presumably liked about these polyhedra, apart from their visual appeal, was that only five of them can possibly exist; there are no other regular polyhedra composed of more complex face panels. By associating the elemental atoms with the regular polyhedra, therefore, Plato was assured of there being a finite generating set of atoms. In this manner, each of Plato's six atomic polyhedra had an associated elemental composition (Table 1.1, last column). The element of earth, for example, corresponded to the cube, while that of water corresponded to the 20-sided icosahedrons, and so on.

As we shall see towards the end of this chapter Plato's list of atoms (just 5) is very small compared to our modern-day list. His list, however, is nonetheless a matter

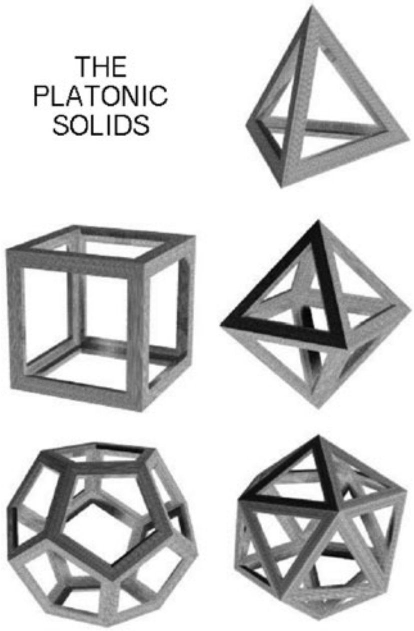

Fig. 1.4 The platonic (also regular) solids. These are the only five polyhedra that can be made entirely of similar-shaped polygonal faces

Table 1.1 Characteristic properties of the Platonic solids. The first column gives the name for each of the polyhedra. The second identifies the generating polygon, and the third shows how many faces each polyhedron has. The last column is the element association given by Plato

Polyhedron	Generating Shape	Faces	Association
Tetrahedron	△	4	Fire
Hexahedron	□	6	Earth
Octahedron	△	8	Air
Dodecahedron	⬠	12	Quintessence
Icosahedron	△	20	Water

alphabet that describes how all possible substances can be put together, and it also enables a basic alchemy (chemistry is far too grand a word for it) to be described.

Transformation of one element into another was possible, Plato argued, provided the generating faces of the various participating polyhedra were the same. One could take two atoms of fire, for example, and break them down into 8 equilateral triangles (each tetrahedron having 4 triangular faces), and then reassemble them as an octahedron, thus creating an air atom. We could write this reaction as 2Fire ⇒ 1Air. Many other transformation are possible, with, for example, 3Fire + 1Air ⇒ 1Water, or 2Water ⇒ 5Air.

Now, although Plato, as far as we know, didn't perform any experiments to see if such transformations could really come about, his basic outlook was not greatly dissimilar to that of today's chemist. Indeed, the science of chemistry is concerned with understanding the relationships and interactions between molecules, which are made up of atoms, with the atoms being from the Periodic Table of Elements. Once one type of molecule has been produced, then under specific conditions it can interact with a second type of molecule to generate a third type of molecule, and so on. In this basic manner all of the various solids, liquids, and gases can be built up and explained as being vast collections of specific atoms, with the different kinds of atoms being derived from a finite list.

In Plato's transformation theory, just as in the case of modern chemistry, some reactions are not allowed. A glance at Table 1.1 indicates the problem. Only the elements fire, air, and water could undergo transformations because the generating faces of their associated polyhedra were triangles. The earthly elements, in contrast, could not be transformed directly into fire, air, or water since they were composed of hexaheda that were generated by squares. Likewise quintessence, associated with the 12 pentagram-faced dodecahedron, cannot be transformed into any other form of matter. Within Plato's alchemical theory of atoms and elements, therefore, there are some forms that are stable, apparently forever, while others are more mutable and can switch form from one to another.

The idea of the basic elements was further expanded upon, especially in the medieval era, to include additional qualities such as being hot, dry, cold, or moist. These additional attributes resulted in the development of a diagnostic medicine, with the human body being brought into the cosmic fold. Indeed, the human body was deemed to be under the influence of four humors: *cholericus* (hot + fire), *melancholicus* (dry + earth), *phlegmaticus* (cold + water), and *sangineus* (moist + air). In a healthy body these four humors would be in balance, but in an unhealthy body one or more of the humors were held to be out of balance, and an appropriate medicinal step was required to restore both equilibrium and health. Bloodletting, for example, might follow a diagnosis of an excess of the sanguine humor – the moist + air combination that resulted in the formation of blood. Since, however, the flow of blood was deemed to be influenced by the lunar phase, a doctor might be reluctant to let blood in a specific region of the body at the time of a full Moon, and this accordingly introduced a role for the various planets. (The Moon, you'll recall, was considered a planet at that time.)

Indeed, each part of the body was associated with one of the 12 zodiacal constellations; the heart, for example, was ruled over by the constellation of Leo, while the knees were ruled over by Capricorn. With these associations having being adopted, an illness could be treated according to which planets were in which specific constellation. It is for this very reason that one of the most important courses that a medieval doctor would take during his university training was astrology. Remarkably, the four elements and four humors model brought the very universe into the workings of the human body, and, once again, we find the idea that within the microcosm is the macrocosm.

Clearly much has changed in our understanding since the time of the ancient Greek philosophers, but some of their essential outlook is very familiar to us in the modern era. The idea that matter is composed of extremely large numbers of very small basic building block, or atoms, that can bond together and turn into other forms under certain circumstances is exactly what we call chemistry. Our modern rules for transformation are more clearly defined and understood, but the basic idea is the same. This constancy of an underlying idea (with numerous modifications, admittedly) over many hundreds, even thousands, of years of human history is very rare, and the same cannot be said for our understanding of the cosmos.

Mysterium Cosmographicum

The *Mystery of the Heavens* was Johannes Kepler's first book, and it was written with a fearless passion and the energetic enthusiasm of youth. While historically this text, published in 1596, is less well known than his other great works relating to the refinement of Copernicus's heliocentric cosmology (to be discussed in Chapter 4), it is a wonderful book crammed full of mathematical insight and speculation.

Remarkably, we know exactly when Kepler had the seed idea that resulted in the new cosmological model presented in the *Mysterium*. The flash of insight occurred on July 19, 1595, during an astronomy class in which Kepler was talking about triangles and the properties of their inscribed and circumscribed circles (Fig. 1.5). The example that Kepler was considering during that fateful July class concerned the motion of Jupiter and Saturn around the zodiac, and being the great mathematician that he was he noticed that the ratio of the orbit radii for Saturn and Jupiter was the same (well, nearly so) as that corresponding to the radii of the circumscribed and inscribed circles of an equilateral triangle. This observation relating to the spacing of the obits of Saturn and Jupiter set his mind reeling, and he reasoned that perhaps the other planets are spaced according to the circumscribed circles that can be

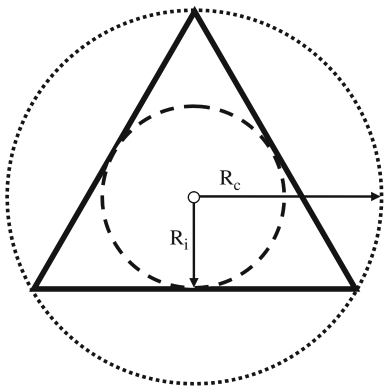

Fig. 1.5 The circumscribed and inscribed circles to an equilateral triangle. The ratio of the radii of these two circles is almost identical to the ratio of the orbits of Saturn and Jupiter

constructed around other plane figures such as the square or pentagon. He enthusiastically worked through the calculations but soon came up short. The ratios just didn't work out as an explanation for the observed spacing of the planets. Undaunted, however, and giving clear testament to his skill as a mathematician, Kepler was soon able to show that the orbital spacing of the planets could very nearly be explained according to the nesting, not of plane figures such as the square and triangle but according to the three-dimensional spheres that can be inscribed and circumscribed around the Platonic solids (Fig. 1.6).

The idea was beautiful, and the harmony exceptionally pleasing to Kepler, and in spite of his other great contributions to astronomy he never quite gave up on this early idea; it was his *idee fixe*. How could something so mathematically delightful, he reasoned, not be the true model upon which the universe (the planetary system as we would now call it) have been constructed by the great and omnipotent maker?

The problem with Kepler's cosmology, however, is that it just doesn't quite agree with the observed spacing of the actual planetary orbits, and as Kepler was to reveal a few years later in his life, it did not account for the fact that planetary orbits are elliptical and not circular (Table 1.2). One point that Kepler felt was particularly elegant and compelling about his new cosmological model, however, was that it offered a clear explanation as to why there were only six planets (the planets Mercury through to Saturn; the next planet outwards, Uranus, wasn't to be discovered until 146 years after Kepler's death). Given that there are five Platonic solids,

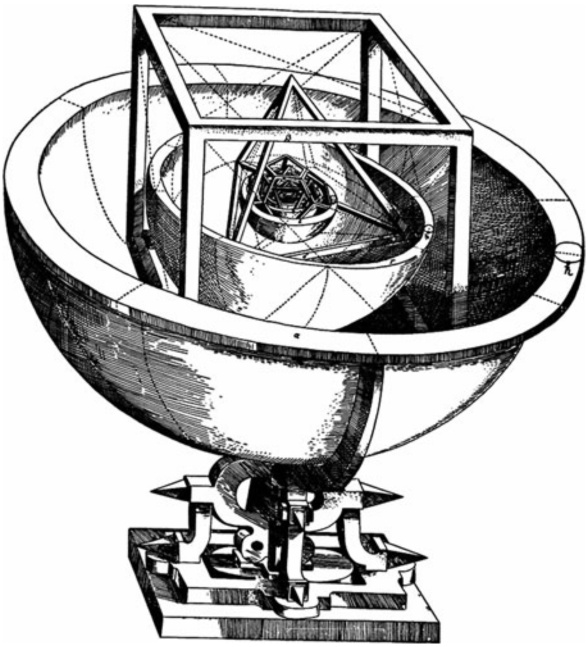

Fig. 1.6 Kepler's cosmological model designed according to the nesting of the Platonic solids

Table 1.2 Kepler's cosmological model based upon the nesting of spheres set between the Platonic solids. The fourth column shows the ratio of the radii corresponding to the circumscribed and inscribed spheres generated by the various polyhedra (third column). The last column shows the actual ratio of orbital radii

N	Planet	Circumscribed Polyhedron	R_C/R_I	R_N/R_{N-1}
1	Mercury	–	–	–
2	Venus	Octahedron	1.73	1.868
3	Earth	Icosahedron	1.26	1.383
4	Mars	Dodecahedron	1.26	1.523
5	Jupiter	Tetrahedron	3.00	3.416
6	Saturn	Cube	1.73	1.833

Kepler reasoned, there are a maximum of six possible spheres that can be nested among them.

Within the framework of Plato's atomic and Kepler's cosmological models we find a remarkable mathematical synergy (albeit an historically contrived one) between the microcosm and macrocosm. Sadly, perhaps – for they are beautiful ideas – the Platonic description of atomic structure and atomic transformation, along with Kepler's explanation for planetary spacing, are simply wrong. The observations do not support the predictions, and the theories must accordingly be discarded (but not forgotten). Such is the working of science, and scientists must take all such realties within their stride and soldier on. Indeed, just like Plato and Kepler before them, present-day physicists, astronomers, chemists, and mathematicians are still trying to annotate the connections between the very smallest of entities, the atoms, and the largest of all structures, the universe.

A Particle Primer

An outline of the Standard Model of particle physics will be given in Chapter 3. It is a remarkable model, as you will see, but for the moment let us simply look at a few of its key elements.

It has already been stated that all matter is made up of atoms, but it turns out that atoms can be subdivided into even smaller entities – just as Plato allowed the faces of his polyhedral atoms to be subdivided into smaller two-dimensional triangles. The Standard Model describes the essential building blocks of matter and the atom, and it tells us that all stable matter in the universe is made up of just two fundamental particle types: leptons and quarks. There are, in fact, just two leptons and two quarks of interest to the material world. The lepton group is made up of the electron and the electron neutrino, while the quark group is composed of the up quark and the down quark and their antiparticles. All matter that we, as human beings, can see, feel, and experience directly is made up of electrons and combinations of the up and down quarks. The atoms themselves have a centrally concentrated massive nucleus made up of protons and neutrons (each of which is composed of combinations of

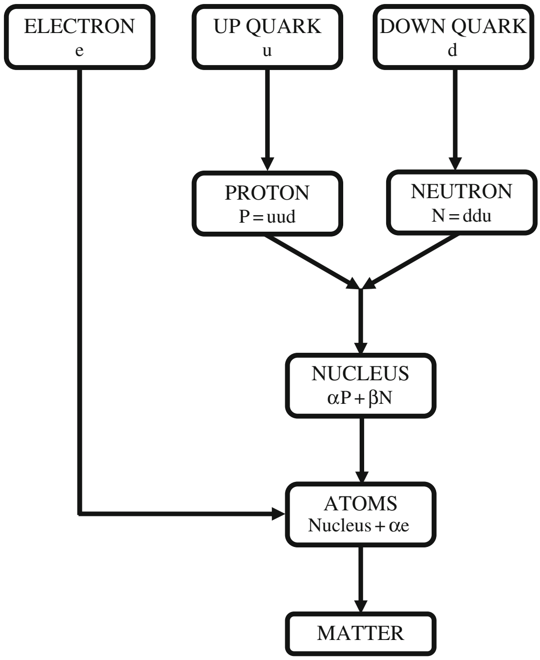

Fig. 1.7 The fundamental building blocks of our material world. The nucleus of an atom contains protons and neutrons, and a neutral atom (that is, one with no net charge) will have an associated cloud of electrons

up and down quarks – Fig. 1.7), around which is located a cloud-like structure of electrons.

How all these combinations of quarks, nuclei, electrons, and electron neutrinos and their anti-particles interact will be described in Chapter 3. What follows below is a very brief history of how all this basic understanding came about. It is a remarkable history and one that has been forged by some of the most bright, charismatic, and insightful of beings to have ever lived.

Thomson's Plum Pudding and an Unexpected Rebound

Jumping forward some two and half centuries from the time of Kepler's death, we find ourselves amidst the gentlemanly world of late Victorian science. This was a time of incredible advancement and growing confidence. The world of classical, deterministic physics was at its zenith, and it was beginning to seem that the job of future physicists would soon be reduced to simply finding better and more accurate numbers for experimental constants. The boundaries of physical knowledge had, for so it seemed, been reached.

Nature, however, has a much greater girth than can be encompassed by the iron-clad equations of classical physics, and as the twentieth century approached, the august world of Victorian science was about to be rudely shaken.

The challenge to the systematic rigidity of classical physics came from two fronts. Indeed, it was an overpowering pincer movement, which brought into play experiments relating to the details of atomic structure and observations of the manner in which hot objects radiate energy into space.

The first subatomic particle to be discovered was the negatively charged electron. Building upon earlier experiments relating to cathode rays, Joseph John Thomson, then director of the Cavendish Laboratory at Cambridge University in England, along with his collaborators and students were able to show experimentally, in the late 1890s, that the atom must be able to be subdivided, and that part of its structure was a small, low mass, negatively charged component. These corpuscles, or primordial atoms, as Thomson initially called them, were soon identified with electrons (a name coined by Irish physicist Johnstone Stoney) and associated with the flow of electricity.

Thomson's experiments revealed that the electron mass was very small, and equal to about one one-thousandth the mass of the hydrogen atom. In the wake of Thomson's work a new picture of the atom emerged, and it was reasoned that there must be at least two atomic components – the electrons that carried a negative charge and a confining component that carried a positive charge. Likened by British physicist William Thomson (better known now as Lord Kelvin) to a plum pudding, the image of the atom was that of a positively charged, elemental atomic fluid in the shape of a sphere (the pudding) containing a random distribution of small, negatively charged electrons (the plums).

Ernst Rutherford (Fig. 1.8) was a man with a big, booming voice. Born in New Zealand in 1871, he conducted seminal research at universities in both England and Canada, and while at the Cavendish Laboratory in Cambridge, he acquired the

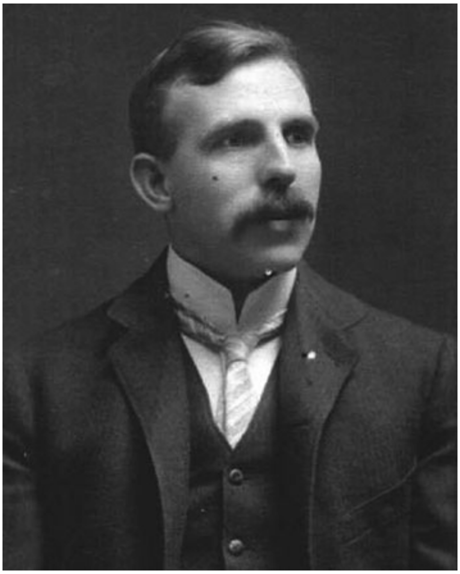

Fig. 1.8 Ernst Rutherford, 1st Baron Rutherford of Nelson (1871–1937)

nickname "The Crocodile."[1] It was Rutherford who succeeded Thomson as director of the Cavendish in 1919, and it was Rutherford who re-worked Thomson's dense plum-pudding into a more airy and centrally condensed, dare one say soufflé form. Specifically, Rutherford re-defined the positively charged fluid, or pudding, part of Thomson's model.

Rutherford's early research was related to the study of radioactive decay – a phenomenon first described by Antoine Henri Becquerel and the Curie husband and wife team in the late 1890s. While working at McGill University in Montreal, Canada, Rutherford discovered that two types of particles were emitted during the decay of radioactive material: alpha particles, which have a positive charge and weighed in at four times the mass of the hydrogen atom (what we would now call a helium atom nucleus), and beta particles, which in fact are electrons. It was for this pioneering work that Rutherford won the Nobel Prize for Chemistry in 1908.

Further, it was through an experiment devised by Rutherford, while resident at the University of Manchester in England, to study the properties of alpha particles that the nature of the atomic nucleus was revealed. Rutherford didn't actually perform the experiment that is named in his honor; rather, he turned the idea over to his research assistant Hans Geiger (who co-invented the Geiger counter with Rutherford in 1908) and an undergraduate student Ernst Marsden.

The Rutherford scattering experiment (Fig. 1.9) has since become a classic of its kind, and it is now the familiar training apparatus upon which many a present-day atomic physicist has proven his or her experimental mettle. The idea of the experiment is (partly) to see what affect the tightly packed atoms in a gold foil target have upon the direction of flight of alpha particles. If the Thomson plum-pudding model were true, Rutherford argued, then it would be expected that very little scattering away from the central axis would take place, since the electrons, being much less massive than the alpha particles, shouldn't be able to significantly change the latter's path.

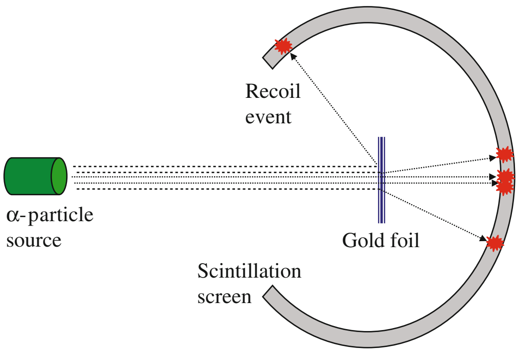

Fig. 1.9 A schematic outline of Rutherford's scattering experiment

[1] A crocodile, in veneration of Rutherford, was carved into the wall of the Mond Laboratory building at Cambridge University, during its construction in 1933.