DANCE TO THE TUNE OF LIFE

BIOLOGICAL RELATIVITY

DENIS NOBLE

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In this thought-provoking book, Denis Noble formulates the theory of biological relativity, emphasising that living organisms operate at multiple levels of complexity and must therefore be analysed from a multi-scale, relativistic perspective. Noble explains that all biological processes operate by means of molecular, cellular and organismal networks. The interactive nature of these fundamental processes is at the core of biological relativity and, as such, challenges simplified molecular reductionism. Noble shows that such an integrative view emerges as the necessary consequence of the rigorous application of mathematics to biology. Drawing on his pioneering work in the mathematical physics of biology, he shows that what emerges is a deeply humane picture of the role of the organism in constraining its chemistry, including its genes, to serve the organism as a whole, especially in the interaction with its social environment. This humanistic, holistic approach challenges the common gene-centred view held by many in modern biology and culture.

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A colour plate section can be found between pages 174 and 175.

Preface

The central message of this book is that living organisms are open systems. That refers to all parts of organisms. All the molecules, organs and systems dance to the tune of the organism and its social context. Those molecules include the sequences of DNA we now call genes.

- How do all these components of life dance together in harmony?
- When did their billion-year dance begin?
- What makes them dance?
- Why is their dance relativistic?
- What do we mean by a 'gene'?
- What do we mean by 'life'?
- How can 'life' depend on 'dead' molecules?
- And what is Biological Relativity?

The answers to these questions form the subject of this book. We will also address the question of meaning. Could all this really happen as a consequence of 'blind chance'? And what could that commonly used phrase possibly mean? What, indeed, do we mean by 'meaning'? Could meaning itself be subject to a relativity principle: a relativity of epistemology?

If these questions fascinate you, then read on.

You will not need to know a lot of science to understand the book: what you will need is a new set of eyes. I will encourage the reader to adopt the eyes and mind of an inquisitive explorer. The scientific knowledge you need to know will mostly be in the book. If you already know a lot of science, you may need to relearn what you thought you knew. Because the central message is that twentieth-century biology went up the wrong street in the interpretation and presentation of its many impressive discoveries.

The reason is that some very influential twentieth-century biologists presented a simplistic gene-centred view of biology using memorable metaphors and brilliant writing to encourage you to adopt their view. And in this they were very successful. Hardly any biological discovery today is presented in the popular media without reference to the discovery of this or that gene 'for' something or other.

This book will show you that there are no genes 'for' anything. Living organisms have functions which use genes to make the molecules they need. Genes are used. They are not active causes.

This book will show you that there is no complete programme in our DNA. Programmes, if useful at all as a concept in biology, are distributed across scales in the organism.

This book will show you that there is no privileged level of causation, which is a central statement of the theory of Biological Relativity.

It will also show you that we are now far from certain what a gene is, and that many of the confusions and misrepresentations of biology arise from mixing up different definitions of genes and genetics.

We don't know when DNA first evolved. But it is virtually certain that it already existed two billion years ago. It seems likely that it must have existed for at least a billion years before that. There are fossils of the simplest cells that go back to over three billion years ago.[1] So, if genes dance, then they have been doing so for billions of years, in fact for most of the period of the Earth's existence, which is about 4.5 billion years.

For the Fainthearted

In spite of the sub-title of this book, don't be afraid if you are not mathematically trained. I promise you that, with the sole exception of Einstein's iconic equation $e = mc^2$, there are absolutely no equations in the main body of the book. Science could not function properly without mathematics. But, even in the most mathematical areas of science, and biology is rapidly becoming one of those, it is usually possible to explain the concepts in common language, once they have been distilled down from the abstract world of equations.

To help you through some uncharted territory, like the Bellman in Lewis Carroll's nonsense poem *The Hunting of the Snark*, remember that 'what I tell you three times is true'. I have deliberately included a certain amount of repetition in the different chapters, usually by expressing the same concept from a different angle or in a different context. Don't be alarmed if you think you have read something before. I turn some basic ideas in biology upside down. That takes a certain amount of getting used to. As you read on you may come to welcome those nice reminders of a point that is already half-appreciated. We are all used to this phenomenon in other ways. When we first see an unfamiliar object we easily mistake it for something else, and have to look again. That is even more true for unfamiliar concepts.

As an example, the fact that organisms are what we call open systems is employed in several chapters, from different perspectives. It is by appreciating the full extent of the development of this concept that a reader can come to understand its profound significance.

Although this book is critical of the simplistic way in which twentieth-century biology was often presented, my purpose is certainly not to minimise the phenomenal experimental achievements. It is rather an appeal for scientific humility. We are all prisoners of the cultures in which we find ourselves. Particularly in its theoretical aspects, science cannot be immune from culture even though it often challenges common and received ideas. Perhaps the ultimate principle of relativity is the relativity of knowledge, of epistemology. That is the title of the last chapter. As you journey from chapter to chapter, fasten your intellectual seatbelts. The ride through the book may jolt many of your present assumptions about the nature of living organisms.

The Sub-Title of the Book: A Challenge for the Future

The first complete draft of this book was finished in 2015, the centenary year of Einstein's General Theory of Relativity. That was not the initial reason for the sub-title, but it is a nice and appropriate coincidence. But, before the reader should judge me for being so presumptuous, let me hasten to add that what is developed in this book is more like a sketch when compared to the beautiful mathematical expressions of Special and General Relativity. Furthermore, I very much doubt whether the principle of Biological Relativity could be so expressed. We may not have the appropriate mathematics for an evolutionary process that has been as much a history as a phenomenon that could be predicted mathematically, except over relatively short time scales. Many biologists follow the lead of Stephen J. Gould in thinking that if the evolutionary clock could be set back to any point in history, the process would not follow the path that it has.

The extension of the principle of relativity to biology, as outlined here, is therefore more a set of signposts to a path. It opens up vistas that others better equipped than I might follow wherever they may lead. This is a challenge to younger scientists. I wrote the book while having the privilege of being the President of the International Union of Physiological Sciences. I believe it could be the union of those sciences with the relevant branches of physics, engineering and mathematics that could lead the way forward in the future.

Chapter Guide

Chapter 1 introduces the general principle of relativity as it developed in the study of the universe. Understanding the steps by which the idea of relativity was reached will prepare you for application of the general principle to biology, which is the core of the book.

Chapters 2–4 contain the background knowledge of biology required to understand the later chapters. Chapter 2 is a complement to Chapter 1 since instead of reaching out to the larger scales of the universe as a whole it reaches down to the microscopic and molecular components of our bodies. It will guide you through the various levels of organisation from molecules to the whole organism. Chapter 3 then introduces the processes that characterise life in the form of networks of interactions. I will give some examples of networks that involve multiple levels. Multilevel interactions form a central aspect of Biological Relativity since causation is then not restricted to one level and is necessarily bi-directional. Chapter 4 shows how these components and processes work in the smallest living things – single cells. The great majority of organisms on Earth are unicellular, and even multicellular organisms go through a single-cell stage when they reproduce.

Chapter 5 outlines the current widely held theory of evolution (Neo-Darwinism) and analyses its main conceptual problems. You will learn that it is a gene-centric, molecular-oriented view of biology. By focusing on genes and molecules it cannot answer the question 'what is life?' Moreover, it was not Darwin's theory of evolution.

Chapter 6 explains the central principle of Biological Relativity. You will learn that organisms are alive precisely because their processes operate at and between many different scales and levels. The molecular and other components are constrained by all levels, including the environment.

Chapters 7 and 8 describe the experimental findings that enable an integrative relativistic theory of evolution to be developed to replace Neo-Darwinism. Chapter 7 focuses on the ways in which the genetic material, DNA, has been rearranged during evolution. Chapter 8 focuses on the epigenetic and related mechanisms by which the genome is controlled.

Chapter 9 returns to the questions asked in Chapter 1 and develops a form of relativity of our knowledge of the universe: a relativity of epistemology. It is through this idea that we arrive at answers that science can give to the big questions about the universe and ourselves and to an understanding of the limits of those answers.

Chapter 10 is written as a brief postscript that summarises the central argument of the book.

Each chapter begins with an easy way in, often using stories from my personal experience. As you read on, you will see the relevance of the story to the main message of the chapter.

You might initially wonder how such a diverse range of topics hangs together since the book begins with the fundamentals of physics and cosmology, yet ends with the fundamentals of biology and the limits to our knowledge. You will discover, perhaps surprisingly, that there are many links between these various threads. The insights of Chapter 1 inform important conclusions in many of the subsequent chapters, and the general principle of relativity informs the whole book.

It will be clear from this introduction to the various chapters, and how they link together, that this book is not a textbook of the systems approach to biology. My aim is rather different. It is to contribute to the new trends in biology that have become evident during the first decade or so of the twenty-first century by creating a coherent conceptual framework within which those trends and their experimental basis can be understood. In any case, there is no need for me to write a textbook since an excellent one has been published already: Capra and Luisi's (2014) *The Systems View of Life: A Unifying Vision* (Cambridge University Press, 2014). At various points in my book I will cross-reference this text to guide readers to the relevant parts of their book. Their vision of the systems approach is very similar to mine.

Notes and glossary. The glossary is an important part of the book. Some key words have significantly different interpretations and definitions used by different writers. These include reductionism, Neo-Darwinism, Darwinism, Lamarckism and epigenetics. When you first encounter these words, you may benefit from consulting the glossary entries on them.

Note

1 Fossils of microbes metabolising sulphur have been identified in rocks dating from 3.4 billion years ago: Wacey, D., M.R. Kilburn, M. Saunders, J. Cliff and M.D. Brasier (2011) Microfossils of sulphur-metabolizing cells in 3.4 billion-year-old rocks of Western Australia. *Nature Geoscience* 4:698–702.

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Working towards writing this book has been a very long journey. Many colleagues, friends and critics have been companions on that journey.

First, both in time and in what I owe him, is my PhD supervisor, Otto Hutter, who first set me out on the journey at University College London way back in 1958. Even nearly 60 years later he is still my best critic, and kindly read many of the draft chapters.

Second is my brother, Ray, who has inspired many of the ideas of this book ever since his undergraduate days in zoology at Manchester University and more recently as a medical ethicist at University College London. He spotted the problems with gene-centric accounts of biology well before I did.

Third are the innumerable students who have studied with me and, in the process, often taught me their own wisdom over a period of 50 years. Nothing can prepare you for the 'wow' moment when a student brings a razor sharp new mind to an old problem and cuts through the standard textbook guff.

Fourth are fellow academics from all over the world who have criticised and helped to smooth the wilder aspects of my journey. They have particularly included scientists and philosophers at Balliol College over many years. I am deeply privileged to have worked in such a richly interdisciplinary Oxford college.[1] Some of the lectures and videos referred to in this book were recorded by *Voices from Oxford*, based at Balliol College, and I am very grateful to the Director, Professor SungHee Kim, for all the advice and help she and the *Voices from Oxford* team have given.

Finally, I especially thank those who have trenchantly disagreed with me. Some of them may well say that I didn't take much notice of them. Not really true. But it is true that often enough they influenced me in ways that they might not recognise.

An intellectual journey in which you end up in a place very different from your starting point can often be lonely, a kind of pilgrim's progress with many doubts on the way. To all who have helped, hindered or just lent a kindly ear, I thank you.

The full technical details for parts of this book were first published as invited articles in *Science*, *Molecular Systems Biology*, *Philosophical*

Transactions of the Royal Society, *Interface Focus*, *Journal of Experimental Biology*, *Journal of Physiology*, *Experimental Physiology*, *Physiology News* and other journals and books published between 2008 and 2015. I am grateful to the editors of these journals and books and to the referees for many valuable comments and criticisms. The ideas in this book have been through extensive peer review.[2]

Finally, I thank those who kindly read and criticised early drafts of particular chapters or of the whole book. I am particularly grateful to Geoffrey Bamford, Sir Patrick Bateson, Nicholas Beale, Steven Bergman, Dario DiFrancesco, Yung Earm, Martin Fink, Otto Hutter, Eva Jablonka, Mike Joyner, Sir Anthony Kenny, Ard Louis, Colin Meyer, Derek Moulton, Raymond Noble, Susan Noble, Kazuyo Tasaki, Toshiaki Tasaki, David Vines and Michael Yudkin, many of whom gave me valuable feedback and detailed corrections. I also thank the Press reviewers for very helpful feedback.

Notes

1 The philosophers include particularly Stuart Hampshire, Charles Taylor, Alan Montefiore, Anthony Kenny and Peter Hacker.

2 The full list of these publications for those who want to study the technical detail is as follows, with the key publications starred:

Systems biology:

* Noble, D. (2008) Claude Bernard, the first Systems Biologist, and the future of Physiology. *Experimental Physiology* 93:16–26.

Auffray, C. and D. Noble (2009) Conceptual and experimental origins of integrative systems biology in William Harvey's masterpiece on the movement of the heart and the blood in animals. *International Journal of Molecular Sciences* 10:1658–1669.

Kohl, P. and D. Noble (2009) Systems biology and the virtual physiological human. *Molecular Systems Biology* 5:291–296.

* Kohl, P., E. Crampin, T.A. Quinn and D. Noble (2010) Systems biology: an approach. *Clinical Pharmacology and Therapeutics* 88:25–33.

Noble, D. (2010) Mind over molecule: systems biology for neuroscience and psychiatry. In *Systems Biology in Psychiatric Research*. F. Tretter, G. Winterer, J. Gebicke-Haerter and E.R. Mendoza, editors (Wiley-VCH, Weinheim; pp. 97–109).

Noble, D. (2010) Biophysics and systems biology. *Philosophical Transactions of the Royal Society A* 368:1125–1139.

Noble, D., R. Noble and J. Schwaber (2014) What is it to be conscious? In *The Claustrum*. J. Smythies, V.S. Ramachandran and L. Edelstein, editors (Academic Press, San Diego, CA; pp. 353–364).

Genes and causation:

* Noble, D. (2008) Genes and causation. *Philosophical Transactions of the Royal Society A* 366:3001–3015.

Noble, D. (2008) For a redefinition of god. *Science* 320:1590–1591.

* Noble, D. (2011) Editorial. *Interface Focus* 1:1–2.

Noble, D. (2011) Differential and integral views of genetics in computational systems biology. *Interface Focus* 1:7–15.

Ellis, G.F.R., D. Noble and T. O'Connor (2012) Top-down causation: an integrating theme within and across the sciences. *Interface Focus* 2:1–3.

* Noble, D. (2012) A theory of biological relativity: no privileged level of causation. *Interface Focus* 2:55–64.

Noble, D. (2013) A biological relativity view of the relationships between genomes and phenotypes. *Progress in Biophysics and Molecular Biology* 111:59–65.

Evolution:

Noble, D. (2010) Letter from Lamarck. *Physiology News* 78:31.

Noble, D. (2011) Book review: Evolution. A view from the 21st century. *Physiology News* 85:40–41.

* Noble, D. (2011) Neo-Darwinism, the modern synthesis, and selfish genes: are they of use in physiology? *Journal of Physiology* 589:1007–1015.

Noble, D. (2013) Life changes itself via genetic engineering. Comment on 'How Life Changes Itself: The Read-Write (RW) Genome' by James Shapiro. *Physics of Life Reviews* 10:344–346.

* Noble, D. (2013) Physiology is rocking the foundations of evolutionary biology. *Experimental Physiology* 98:1235–1243.

Noble, D. (2014) Secrets of life from beyond the grave. *Physiology News* 97:34–35.

* Noble, D., E. Jablonka, M.M. Joyner, G.B. Müller and S.W. Omholt (2014) Evolution evolves: physiology returns to centre stage. *Journal of Physiology* 592:2237–2244.

* Noble, D. (2015) Evolution beyond neo-Darwinism. *Journal of Experimental Biology* 218:7–13.

Noble, D. (2015) Conrad Waddington and the origin of epigenetics. *Journal of Experimental Biology*, 218:816–818.

Noble, D. (2015) Central tenets of neo-Darwinism broken: response to 'Neo-Darwinism is just fine'. *Journal of Experimental Biology* 218:2659.

1

The Universe and the Principle of Relativity

'Let there be light, and there was light'
יהי אור ויהי אור
(Genesis 1:3) (Figure 1.1)

The Sky at Night

Now that most of humanity lives in cities, it has become rare for us to experience the full extent of the wonder that our predecessors must have felt as they saw the night sky from open country or from their unlit dwelling places. On every clear moonless night they would have experienced what we can do only by going to remote parts of the countryside far away from the city lights. They would have noticed that as dusk gives way to night, more and more stars appear. And as their eyes slowly adapted to the dark, even more would appear until they became uncountable. On a really clear, cold night they would also experience the feeling that the universe is somehow alive with activity as the faintest stars seem to appear and disappear depending on whether one looks directly at them or at a slight angle. There is a depth also to the sheer blackness of space between the stars that contrasts so markedly with its light blue during the day. The sky at night viewed in this way, when there is little or no moonlight, is a miracle, with a giant belt (the Milky Way) running across it, with countless stars appearing, more the longer we look, and with the occasional larger movement as a meteor appears. To crown the spectacle, it moves slowly and majestically throughout the night.

Figure 1.1 A view of the Milky Way towards the Constellation Sagittarius (including the Galactic Centre) as seen from a non-light polluted area (the Black Rock Desert, Nevada) (courtesy of Steve Jurvetson). For a colour version of this figure, please see the plate section.

Faced with such glory and spectacular beauty, we are forced to ask a question. Why?

The question pushes its way before us. And the human response to this question has always been the same: to propose an answer. We find it difficult to live without answers. That is what drives our metaphysical instincts, which in turn create our systems of religious and scientific thought. They are not so far apart as many might think. The quest for meaning can be seen as the religious instinct. The quest for explanation in terms of cause can be seen as the scientific instinct. But the two connect through the fact that we cannot even begin to develop an explanation without making some meaningful assumptions about the framework within which we can interpret what we see, feel and hear. We need a metaphysics within which we can develop our physics. That is as true today as it was in the earliest scientific discoveries, as we will see as the story in this book develops. Science also contributes to understanding meaning through identifying what we call function. It is too simplistic to say that science deals only with 'how?', while religion deals only with 'why?'. The two questions intertwine.

So, what did our ancestors do to make sense of what they saw in the darkest of nights in the deep countryside? They saw groups of stars, what we today call constellations. They also imagined that these groups had meaning and so they gave them names. There is one particular constellation, the one we now call the Big Dipper or The Plough, which received names in all the main historical traditions we know about. Many saw a bear, which is why its Latin name is *Ursa Major*, the great bear. It appears in Babylonian and Egyptian astronomy, leading to the Greek system, and in the Jewish system which leads to its reference in the Bible.[1] It appears in ancient Chinese[2] and Indian[3] astronomy, and in every other traditional system. In fact, this constellation is only one of two (the other is *Orion*) that appear as such in both the Western and Eastern astronomical traditions. The Chinese divided the sky up in a different way, based on the pole star, Polaris, whereas the Greeks thought in terms of the relationship of the constellations to the way the sun appears to move amongst them during the year, which is what gave us the signs of the zodiac.

Dividing up the sky into constellations was very practical. Relating them to the pole star was particularly helpful to travellers and mariners. *Ursa Major* points towards the pole star and could therefore be used to find north. It was also possible to use the sky as a timekeeper since it rotates smoothly throughout the night. If one knows the constellations well and how their movements change during the year, one can work out what time of night it is. All of this was important to people navigating through open seas and deserts. The sky was their signpost and clock. Those highly practical results arose from the smooth circular movement of the heaven above us as it rotates around the Earth.

Or does it? Today, we know that assumption is wrong. But it is instructive to understand the steps by which we came to that conclusion. Therein lies the origin of the principle of relativity.[4] Most people think that the principle applies only to physics. One of the purposes of this book is to show that, in its widest sense, it must apply also to biology. First we must understand its use in physics, which is the purpose of this chapter. We will then be able to explore its impact on biology.

Before I outline the steps by which the fundamental principle of relativity developed, I would like to ask the reader to adopt the attitude of an inquiring explorer. It is easy for us to laugh at what we see as the misunderstandings of the past. A flat earth? Absurd! A heavenly globe containing the stars? Ridiculous! With that attitude, it is also easy to forget that we will be seen as ancestors in the future. How do we know that we, and we alone amongst the tens of thousands of years of human thought, have at last got the answers right? Many thoughtful scientists today are convinced that there are more revolutions to come and are not at all happy with our current models of nature.

Those models are brilliantly successful at prediction, much more so than ever before. But as a basis for understanding, for feeling certain that we have 'got it', they leave much to be desired. We find it difficult, for example, to unify the physics of the smallest scales, where quantum mechanics is relevant, and the physics of large scales, where general relativity dominates. Nor do we know how to explain the apparently arbitrary nature of the constants of the universe,[5] although we know that they need to be within narrow limits for our universe to exist and for living systems to be possible. In biology, there are many more puzzles calling out for answers: what is life? How did we as a species get to be the way we are? What is a gene? And many more. In the search for those answers, we followed a largely blind alley during the twentieth century. The blind alley is the idea that the genome is the 'book of life', a blueprint from which you and me, and all other living creatures, were made.

We have more to learn from the history of thought about the universe than we might think. If we take each step seriously and understand why it was taken, we will then understand better what steps we can take in the future to distance ourselves from our own misunderstandings. This book is also an appeal for humility in scientific thought. It occupies an intellectual space billions of miles from the naive certainties that many popular science writers portray. We advance in understanding by first coming to know what we don't understand. That kind of knowledge requires hard work. We have to undo some of our cherished basic beliefs.

So, join me on a thoughtful and provocative journey through the questions that we can't help asking. We begin in this chapter by asking how to interpret the sky at night, how that question led to the principle of relativity, and to the Special Relativity and General Relativity forms of the theory proposed by Einstein.[6]

Early Cosmologies

The oldest Hebrew sources represented the Earth as a flat disc floating in a huge sea. Since no one could consider the possibility of going completely round the Earth, the idea that the habitable Earth must have an edge, beyond which was a sea, was a reasonable assumption. The heavens were then represented as a hollow sphere with the stars set in the surface of the sphere as points of light in what could be viewed as a massive celestial candelabrum. Clearly the sphere must move, which creates the difficult question of where it goes when it moves below the horizon. And there must be several such spheres since the sun moves separately, and so do the 'stars' that we now know are planets.

One way to think about such a universe is that, since it consists of concentric spheres, perhaps its centre is also a sphere. That makes it easier to answer the question of where the spheres go when they disappear below the horizon. They just go round the central sphere, which must be the Earth. We don't know when exactly the idea that the Earth too was a sphere first arose, but we do know that it was a central idea for the astronomer Claudius Ptolemy, who lived around CE 90 to about CE 168. As his given name, Claudius, suggests, he was a Roman citizen, although he lived in Egypt when it was ruled from Rome, and his family name, Ptolemy, is Greek. He wrote in classical Greek.

He is said to have used Babylonian astronomical data to construct an elaborate set of tables and mathematical calculations brought together in the first surviving textbook of astronomy, called the *Almagest*. It includes ingenious geometrical calculations from a Greek mathematician, Hipparchus, which allowed estimations of the distances from the Earth to the sun and the moon. These calculations enabled the celestial spheres to be given dimensions and distances. In addition to the sphere carrying the sun, additional spheres carried the planets, and of course the outermost sphere carried the stars. In addition to the Earth, there were eight spheres carrying the sun, the moon, five known planets (Mercury, Venus, Mars, Jupiter, Saturn) and the fixed stars.

This shift in perception about the Earth and the universe can be represented as the first stage in developing the principle of relativity. As I will use this principle in this book it consists of distancing ourselves from privileged viewpoints for which there is insufficient justification. There are no absolutes – rather, even in science things can only be understood in a relative sense: relative to the question we ask; relative to the scale at which we ask the question; relative to our present knowledge of a universe of which we will always have questions remaining. In this sense, a privileged position is akin to an absolute.

Coming to view the Earth as yet another sphere was precisely such a use of relativity. The Earth was no longer viewed as a uniquely flat object.[7] Like the rest of the universe, it became a sphere. You will learn how this very general principle of distancing ourselves from supposedly unique or privileged viewpoints leads to the more familiar theories of relativity later in this chapter, and then to the theory of Biological Relativity in Chapter 6.

Distancing ourselves from viewing the Earth as a flat object may not have been easy. Many nineteenth-century writers thought that the idea of a flat Earth was originally so convincing that when Christopher Columbus set off in 1492 to sail west in order to arrive at the east, uneducated people still feared that he might reach the edge of the Earth, and perhaps never be seen again. This is a modern myth.[8] Medieval scholars were quite clear that the Earth was round. The mistake Columbus made was to calculate that East Asia was much closer. Finding the Caribbean islands saved him and his crew, and he still believed he had found the East.

The Copernican Revolution

Distancing ourselves from the geocentric view takes us to another great astronomer, Nicolaus Copernicus. Copernicus was born in 1473 in the Kingdom of Poland, and studied first at the Jagiellonian University in the then capital, Krakow. Later he moved to Italy and the famous universities of Bologna, Padua and Ferrara. Along with the anatomist Vesalius, he became one of the great polymaths of the Renaissance and a trigger of the Scientific Revolution. His book on the universe, *De revolutionibus orbium coelestium* (on the revolutions of the heavenly spheres) was published just before his death in 1543.[9]

The idea that the sun might be the centre of the universe was not entirely new. Similar ideas had been proposed in the third century BC by Aristarchus. We know this because Archimedes describes how Aristarchus thought that the fixed stars and the sun are unmoved, while the Earth revolves around the sun. Aristarchus also correctly thought that the fixed stars were very far away.

Copernicus, though, deserves the credit for providing the mathematical basis to show that the idea was predictive, and that it explained the strange fact that on the geocentric view the planets seem sometimes to move backwards. The Ptolemaic system had been made more complex in order to deal with this problem by postulating the existence of further epicycles.[10] This illustrates a pattern that is often repeated in science. Well-loved theories do not usually die suddenly. People try to find ways of retaining the central ideas of the theory while adding complexity to the explanations to accommodate observations that do not seem to fit the theory. Sometimes, the adoption of a new theory depends more on the overall weight of evidence, rather than on a single knock-down observation. We will have the opportunity to observe this process in science in later chapters of this book.

The clarity with which Copernicus stated the heliocentric view was impressive. He expressed his ideas as seven assumptions. First, that there is not one centre. This was to allow him to retain one aspect of geocentrism, which is that the moon orbits the Earth. This was explicitly stated in his second assumption, together with the statement that the Earth is not the centre of the universe. Instead, in assumption three he stated that the sun is or is near the centre of the universe. He then made a remarkable deduction. From observations of distances, he concluded that the distance to the stars is much greater than the distance of the Earth from the sun. His fifth assumption is also remarkable. This is that the motion of the stars represents simply the spinning motion of the Earth. The fixed stars are just that: fixed, immoveable. Assumption six gives the Earth an additional motion, that of orbiting the sun. Finally, he explained the Ptolemaic apparently 'backwards' movements of the planets as due to the Earth's motion.

This was the second application of the general principle of relativity. Arguably, it may have been the most important one since abandoning the privileged position of the Earth as the centre of the universe was a first step. That idea leads inevitably to the more familiar theories of relativity since, once we abandon the idea that our home, the Earth, is in any way special, why should we be convinced that anything else is the centre of the universe?

But it did not do so immediately. In fact, the ideas of Copernicus did not initially create any great waves of controversy. Significantly, there was no dramatic argument with religious thinkers. This fact is very important in the story of this book. Religious thinkers treated Copernicus as they treated themselves: as metaphysical theorists struggling to make sense of the world and the universe. This is hardly surprising since he was also a canon of the Catholic Church. Moreover, other church leaders had also proposed ideas similar to those of Copernicus. Two centuries earlier the French bishop Nicole Oresme had considered the proposition that the Earth rotates. In fact, his *Livre du ciel et du monde* contains the spirit of relativity, since he showed that to assume that the Earth is rotating rather than the heavens would not change any of the astronomical calculations. He appreciated the fact that different metaphysical standpoints can lead to the same conclusions concerning relative movements. His work did not, however, lead to a revolution of thought in the way that Copernicus' work did. In fact, he concluded that there was no proof that the Earth rotates – and no disproof either!

In the fifteenth century, the German Cardinal Nicholas of Cusa had expressed in a book called *De Docta Ignorantia* (roughly translated as 'On scientific ignorance') a viewpoint that is infused with the central idea of relativity: 'Thus the fabric of the world will have its centre everywhere and circumference nowhere.' This is remarkable since it also anticipates the later stage of questioning whether even the sun (or any other point)

Figure 1.2 Jupiter and the four Galilean moons observed through a Meade "10" LX200 telescope, i.e. ten times more magnification than was available to Galileo (Jan Sandberg, Wikimedia). For a colour version of this figure, please see the plate section.

could be the centre of the universe. Not surprisingly, he also developed a sophisticated, some would say mystical, concept of god.[11]

These historical facts are important. They show that the widely held view that every major advance in science has provoked reaction from conservative religious thinkers is far too simplistic. The more accurate historical view is that these debates about the nature of the universe occurred as much within the Church as outside it. Arguably, Nicholas of Cusa was the greater revolutionary than Nicolaus Copernicus since he was way ahead in questioning even the idea of giving a privileged position to the sun, *or any other celestial object*.

As to opposition to Copernicus, there were opponents both within and without the Church. Wider scientific acceptance of his ideas had to wait for more experimental proof anyway. This came with the work of Galileo and the first use of the telescope (Figure 1.2).

Galileo: Father of Modern Science

Galileo Galilei was born in 1564 and studied medicine at the University of Pisa. It was Einstein who called him the 'father of modern science'. He transformed our study of the universe. He did so using his own early telescope of very limited power (magnification about ×20), so with even a modest modern telescope you can easily repeat some of Galileo's key observations, which he made on 7 January 1610.

The planet Jupiter can often be seen as a bright object. Amongst the planets, only Venus is brighter. Its position in the sky depends of course on its movements, so you need to consult a guide to its position on any given night. It is easily the largest planet, a gas giant 11 times the Earth's diameter. Unless there can be living systems very different from what we know, it could not support life. However, it has many moons and four of these are so large that they could be observed by Galileo. You can also see them. They are arranged on the same plane so you will see them strung out on either side of Jupiter. They orbit Jupiter in a matter of days, so you can also repeat another of Galileo's observations, which is to see that they are in different positions every night. Galileo, of course, saw the point. Here is a miniature solar system with Jupiter acting as the attraction in place of the sun and the moons playing the role of the planets. It is hard to make these observations without realising that the Earth must also go round the sun. And that the planets that do so can have moons just as the Earth has a moon. While Jupiter itself is very unlikely to harbour life, its moons might do so. Europa has a surface of ice and water which might well support life.

Galileo's observations and his defence of the heliocentric idea came about 60 years after Copernicus' publication of his work. This time, the mood within the Church was different. Some, notably amongst the Jesuits, supported him. But it is thought that intrigue at the Vatican led to Urban VIII, who had been a supportive friend, even encouraging him to publish his work, becoming offended by what could be seen to be mockery of him and the geocentric view in Galileo's book *Dialogue Concerning the Two Chief World Systems.*[12] The defender of the geocentric view was a character called Simplicio, which carries the connotation of simpleton. Offending friends by mocking them may not be wise. Perhaps Galileo meant no offence. Simplicio was simply a literary device.

There have been many books and articles written on these events and the subsequent famous 'recantation' of Galileo.[13] It is true that Galileo was found guilty of heresy by the inquisition and put under house arrest, while his books were banned. The ban on his books was not lifted until the eighteenth century. Famously, in 1992 Pope John Paul II expressed regret for the events that led to the Church accusing him of heresy and subjecting him to house arrest.

It is right to condemn the seventeenth-century Vatican inquisitors. They were certain they were right and Galileo was wrong, so wrong that

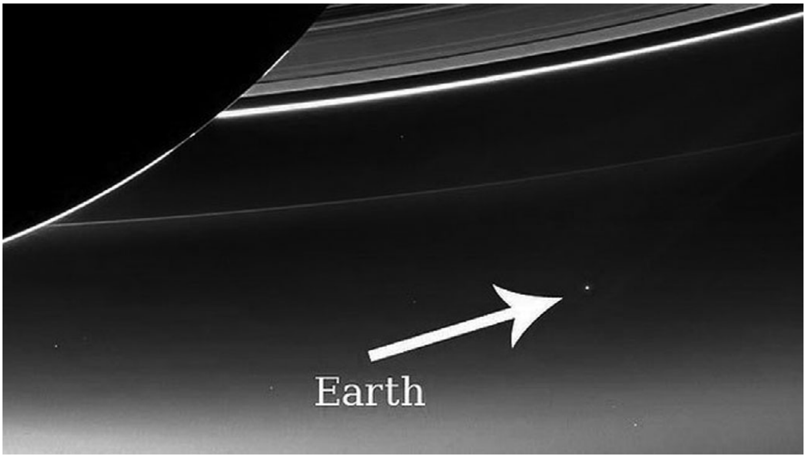

Figure 1.3 The Earth (little blue dot) viewed from the spacecraft *Cassini* as it photographed the rings of Saturn during an eclipse of the sun by Saturn. *Cassini* was 900 million miles from Earth. Light takes over an hour to reach the Earth from Saturn. But this is minuscule compared to the more than 13 billion years for light to reach us from the edge of the observable universe (source: NASA/JPL-Caltech/Space Science Institute (www.nasa.gov/mission_pages/cassini/multimedia/pia17171.html)). For a colour version of this figure, please see the plate section.

he had to be humiliated and punished. It took nearly four centuries for the injustice to be openly acknowledged. It is one of the strange characteristics of metaphysics that, while its very speculative nature should convince people to be cautious, even humble, it often does just the reverse. Perhaps the very uncertainty creates the inner wish for certainty. That, after all, is also part of the religious instinct – the search for the certainty of faith. Scientists, even atheistic scientists, are not immune to the same problem. If you think that could not happen, that scientists could not be so cruel, wait until you read in later chapters the way in which twentieth-century scientists ridiculed the great French biologist Jean-Baptiste Lamarck and sidelined almost completely the brilliant developmental biologist and polymath Conrad Waddington.

The Earth from a Billion Miles (Figure 1.3)

Galileo would surely have been delighted to see the Earth from the giant planet Saturn, as we can now do thanks to the voyage of the spacecraft

Cassini. He would have seen the Earth as a tiny blue dot just as we view other planets as small objects in the solar system. Hardly a candidate for the centre of the universe! Outside our solar system the Earth would not even be directly visible. Its presence could be detected only indirectly, just as we now detect what are called exoplanets, planets circling other stars to produce a tiny fluctuation in the light from them, and the tiny perturbations of the star's position.

Newton's Laws of Motion

It is one thing to show that planets orbit the sun, and moons orbit the planets. It is quite another thing to show how those motions could be explained. Our own experience teaches us that for something to move continually there must be a force making it do so. Mechanics before Newton adopted the same common sense view. Without a force, an object would stop moving. Newton reversed that. Without a force it would continue moving! Not just temporarily, like the supermarket trolley after a brief push, but *permanently*. It would never stop. Imagine the trolley continuing on its motion until it goes right around the Earth and returns to you! A satellite in orbit does precisely that.

Newton's laws are so familiar to us now that it is difficult to imagine how counterintuitive they must have seemed in his day. People were so used to the idea that hard work had to be done to move anything around, whether on a farm, in the house or along the streets. If the planets moved indefinitely then something (angels?) had to be moving them.

Newton was born in 1643 and had quite a difficult childhood. He studied at Trinity College Cambridge and graduated in 1665 just before the university closed because of the plague. It was while at home for two years that he developed his brilliant mathematics. This included calculus, his optics and the law of gravitation. Not bad for a two-year stint at home! He returned to Cambridge in 1667 to become a Fellow, and only two years later was given the prestigious Lucasian Chair. He was unorthodox enough to avoid the rules that, at that time, required all the Fellows and Professors to be ordained. One can speculate that it was his very unorthodoxy that stood him in good stead in challenging so many ideas of his time.