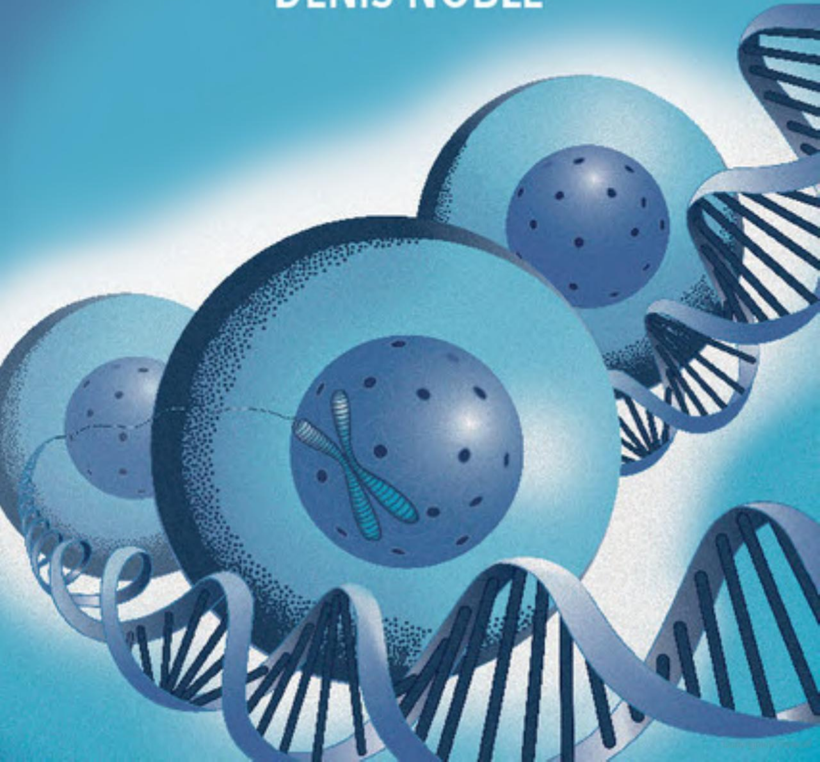
# DANCE TO THE TUNE OF LIFE

## BIOLOGICAL RELATIVITY

### DENIS NOBLE



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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 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.

# Acknowledgements

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.

**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.

**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

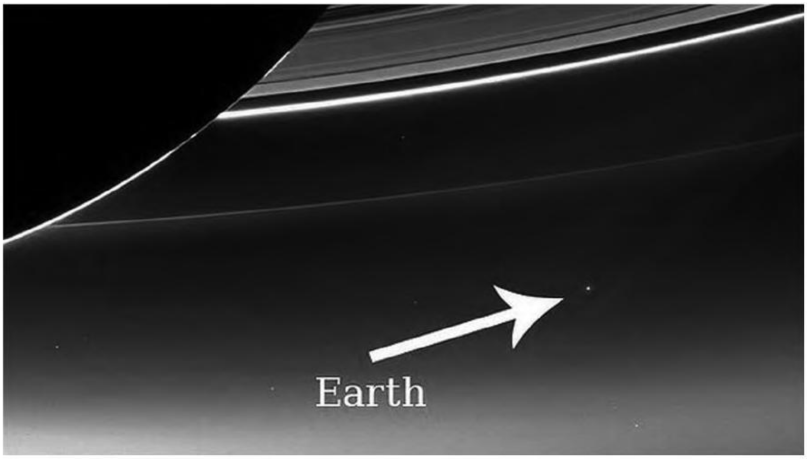

**Figure 1.3** The Earth (little blue dot) viewed from the spacecraft *Cassini* as it photographed the rings of Saturn during an eclipse of the sun by Saturn. *Cassini* was 900 million miles from Earth. Light takes over an hour to reach the Earth from Saturn. But this is minuscule compared to the more 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.

Newton must have realised that, of course, there is an everyday example of continual motion: a falling object does not stop until it hits the ground. On the contrary, it accelerates. There was therefore no need to suppose that the moon needs something to push it round the Earth. It just goes on falling. But because it already has lateral motion it will combine that motion with the fall due to gravity to produce overall motion in an orbit. If the moon was in deep space it would just travel indefinitely in a straight line.

This insight established several important things that are relevant to the principle of relativity and to our story. The first is that celestial objects experience the same forces and motions as those on Earth. We prove that today every time we send a satellite into orbit. If we give the satellite enough speed it will 'escape' the Earth's gravitational attraction and go into orbit. Actually, it never escapes gravity. It is rather that the force of gravity and the inertial motion we have given it combine, just as they do for the moon, to enable it to 'fall' continually in an orbit around the Earth. The second is that if we know the forces acting on objects, we could use calculus to predict their motions indefinitely.

There was, however, one problem relating to the principle of relativity that Newton had difficulty solving. Where was the centre of the universe? Could it be the sun? But he also understood that the centre of gravity (which might be a possible interpretation of 'centre') of the solar system was not precisely the sun. He decided that 'the common centre of gravity of the Earth, the Sun and all the Planets is to be esteem'd the Centre of the World'. If he had gone one step further and recognised, as Nicholas de Cusa had, that 'the world will have its centre everywhere' he would have made the next step into the fully relativistic idea that there is no centre, and that all movement is relative.

## Nineteenth-Century Certainties

With Newton's equations of motion and the idea that the universe, and perhaps everything in it, worked rather like clockwork, it seemed that in principle everything could be predicted with just the force of gravity and the laws of motion. The conviction that this must be so became very strong in the middle of the nineteenth century. Even the apparently

No single water molecule travels with the wave. The molecules simply bob up and down, much like a Mexican wave in a sports stadium. Similarly, a sound wave is the transmitted behaviour of large numbers of molecules in the medium, air or fluid or solid, that transmits it. The molecules of the medium oscillate back and forth but they do not travel with the wave. But a particle is a discrete object which should be part of an ensemble to allow a wave to form. How can it also be the wave itself? The particle that is itself the wave travels with the wave. And when it is behaving as a wave, what is the medium in which the wave occurs? As we will see, that question connects with Einstein's Special Theory of Relativity, discussed in the next section.

A further difficulty is that we can only say where the particle might be with a certain degree of probability. The same applies to its velocity. There is a fundamental degree of uncertainty such that the more accurately we try to determine position, the less certain we can be about velocity, and vice versa.

There are many other ways in which the features and consequences of quantum mechanics can be expressed, but this characterisation will suffice for the purposes of this chapter.

Physicists and philosophers have thought deeply about the implications of quantum mechanics. Early reactions were that this can't be true, or at least only provisionally true while waiting for something to replace it. Einstein was very sceptical; he said: 'God does not play dice.' Yet, she does! There seems to be no way around the shocking nature of this discovery. It shakes the very foundations of nineteenth-century confidence. People have therefore tried various ways of arguing for minimising the impact. One of these is to say that this uncertainty applies only at the micro level, the subatomic level. That is not entirely true. There are conditions, such as very low temperatures, under which quantum mechanical behaviour has been shown to exist at a macro level. And people are already using quantum mechanical properties to construct macro-level machines.

Quantum computers are a good example. They use quantal behaviour to implement more logical operations simultaneously than can be done with conventional computers, and experiments have already been done to demonstrate the feasibility.[18] But of course the machine itself must be usable by a human being. The quantal properties at the micro level will have consequences for what happens at the macro level. That has already been shown by maintaining quantal memory states that could be used in such a computer at room temperature for more than 30 minutes.[19] The first demonstrations of such effects were at exceedingly low temperatures, beyond the range of living organisms. Some have also speculated, perhaps wildly at this stage, that there could be features of our brains that allow quantum mechanical effects to play a role.[20]

Furthermore, this way of dealing with the problem is not really satisfactory to someone who wants to know what the world is really like. The best way, at present at least, to interpret the equations of quantum mechanics is to note that they work. In fact they work very well for describing what we see. But they don't provide a satisfactory explanation of the world 'as it really is'.

This returns us to the big 'why?' question posed at the beginning of this chapter. Possibly, it is the wrong question. There may be aspects of reality that we can never know. That is not a comfortable position to be in. Our predecessors asking the big 'why?' question on looking at the sky at night would hardly find this kind of answer satisfactory.

Another approach to this problem is to say that there must be more to be found out that may lead to a set of physical theories that are more satisfactory. That is the approach of those who note that there are also other unsatisfactory features about our present knowledge, not least that we use different theories for micro and macro levels. Perhaps we should just wait until another Einstein turns up to sort it all out.

I will return to these questions in the last chapter of the book. Meanwhile, our story moves on to Albert Einstein.

## Einstein's Special Theory of Relativity

A recurring problem with the various stages of application of the relativity principle has been the persistent idea that there must always be a medium in which movement occurs. Early objections to the view that the Earth rotates were based on the idea that this would be detectable, for example in the winds that it was thought such movement must create. At the equator, the speed of rotation is about 1000 miles per hour. If an aeroplane moves through the atmosphere at this supersonic speed, there is always a supersonic bang. So where is the bang that the Earth's movement should create? In fact, of course, there is no bang because the atmosphere rotates with the Earth. So, to a first approximation, there is no relative speed of the Earth with respect to its atmosphere. The problem seems even greater when we consider the speed with which the Earth is orbiting the sun, which is about 67,000 miles per hour. Again, the answer is that the atmosphere moves with us at this speed. In both cases, we don't notice the movement because there is no movement relative to what would make us feel the movement. Only when we compare the Earth's position relative to objects in the sky do we see the effect of the movement. These observations already take us well on the way to understanding Special Relativity. The key point is that we can only detect relative movement.

But consider this. It is nevertheless true that the Earth is moving through space. If space is the fixed structure that we learnt about in Euclidean geometry, then surely there must be a way of detecting whether or not we are moving through this structure. Since the atmosphere moves with us, we won't notice this by measuring the speed of sound. But what does light move through? Clearly it must be capable of moving through essentially empty space, otherwise we would not see the stars. Since we are moving with respect to space, we should be able to detect this movement by measuring how fast light travels when it moves with the Earth's movement compared to how fast it moves when travelling in the opposite direction. There should be a difference.

Another way to think of this is to imagine that space is filled with something through which objects travel. People called it the ether. If that was so, then there would be a privileged frame of reference in the universe: it would be the one in which movement through the ether is zero.

The experiment to test this idea was conducted by Albert Michelson and Edward Morley at Case Western Reserve University in the USA in 1887. The answer was a big surprise. There is no difference between the speed of light measured in any direction. The experiment has been repeated many times with ever-increasing accuracy and always with the same result. The conclusion is that there is no ether. There is therefore no privileged frame of reference.[21]

This is startling. Think about it and you will appreciate just how big a revolution this set in train. If space is not filled with anything that could form the basis of a frame of reference then the 'centre of the universe' is nowhere, or perhaps everywhere. Remember Cardinal Nicholas of Cusa, who as early as 1440 wrote: ‘Thus the fabric of the world will have its centre everywhere and circumference nowhere.’ It took more than 400 years for the world to catch up with his insight.

It is not certain whether this experiment was the trigger for Einstein’s Special Theory, but the theory certainly provides an explanation for the result and so it became a major experimental proof of the theory.[22]

The fact that the speed of light is the same in all directions and that there is no privileged frame of reference leads to some counterintuitive consequences. When two objects are moving with respect to each other, let’s call them A and B, distance and time in B must be perceived by A to be changed. Similarly, B will perceive A’s distances and times to be changed. This is the phenomenon that leads to the famous space traveller example. A space traveller leaves Earth and travels a long distance at a very high speed relative to the Earth, and then returns to Earth. The space traveller will have aged in what will seem to him to be a normal way, but he will find that people on Earth have aged even more. By contrast, people on Earth will have experienced ageing at a normal rate and will think that the space traveller has discovered the secret of longevity! To them he would appear young.

These consequences lead to the fact that there will be no absolute measure of simultaneity. If time seems to change at different speeds depending on the relative velocities of objects, then we no longer have a privileged frame of reference to which to refer all events in their time sequences. An event that precedes another one at a distance away from it can appear to follow it if we change our observer position and relative speed. Think of three objects all moving with respect to each other: A, B and C. Suppose also that events occur in B and C that seem to be at the same time to A. Depending on how they are moving with respect to each other, they will not appear to be simultaneous to B or C. Their order in time will be different to different observers. Time and space are therefore no longer absolutes. They can contract and dilate according to the position and velocity of who is observing the events that occur.

It is important to note that these contractions and dilations of space and time do not allow the central rule of causality to be broken, even though their order in time can appear differently to different observers. The distance between the two events will always be such that, if the event on B is the cause of the event on C, no observer could consider C to be the cause of B.

There are many other surprising consequences of Special Relativity. One of the most important is that the speed of light becomes an absolute limit. However much we accelerate an object with mass, it will never achieve the speed of light. Only an object without mass can do that. Mass and energy also become inter-convertible according to Einstein's famous equation: $e = mc^2$.

I have summarised rapidly some of the main consequences of the Special Theory of Relativity. But this is not intended to be a textbook on the theory itself. Readers who wish to understand more deeply should read other texts – as suggested at the end of this book. The real purpose of this chapter is to prepare you for the rest of this book. Just as Einstein's relativity theories upset some common perceptions about space and time, mass and energy, light and gravity, so we will find that the consequences of extending the principle of relativity to biological processes also upsets many common ideas about causation and the relations between genes and organisms and their environments. If you find some of the consequences of the principle of relativity to be surprising or even shocking, you are not alone. Most people found the consequences of each stage of applying the principle to be surprising. The important point is the recommendation I made at the beginning of this chapter. Adopt the eyes of an inquisitive explorer. Don't hold on to your pre-conceptions unnecessarily.

## Einstein's General Theory of Relativity

The Special Theory applies to the 'special' case of frames of reference moving at a constant speed with respect to each other. Each frame of reference can obey the rules of Euclidean geometry. In the special theory what we are abandoning is the idea that space is filled with something, the ether, that enables us to know whether we are at absolute rest or moving. But for each frame of reference, space can be treated successfully with the usual (which means Euclidean) rules of geometry. The angles of a triangle, for example, will always add up to 180°. A right-angled triangle will always obey the square rule for the lengths of its sides – the sum of the squares of the short sides equals the square of the long side.

In his General Theory, Einstein incorporated gravity. In doing so he also abandoned the assumption that space must be Euclidean. In this distant blue galaxy, the red galaxy and the Earth to enable the distortion to produce an almost perfect circle. More frequently, the alignment is not that perfect and the result is a number of smeared arcs. A full horseshoe shape is itself rare. But had the alignment been even more perfect we would have seen a full circle (Figure 1.4).

There are even more wonderful discoveries that have come from the Hubble Space Telescope. The last section of this chapter concerns the Hubble deep field views of the distant universe and how they may be used to estimate the size of the visible universe. That estimate will prove very useful to our story in Chapter 3.

## Hubble's Deep Field Views

This chapter began with the star constellation *Ursa Major*, and it ends with it. When astronomers were choosing a part of the sky to enable the Hubble to look at the very distant universe, they chose a very tiny region (only one-24-millionth of the whole sky) in order to point the Hubble at it to collect the light for a period of ten days. There are only four stars from our galaxy in this area, so to the naked eye and even most telescopes, the area seems empty, completely black. The Hubble was therefore looking all the way through our galaxy into far deep space. The area chosen is just above the 'plough' of *Ursa Major*, near where the bear's tail joins its back, which is the part of the formation that resembles a plough. The resulting image is amazing. Far from the sky being empty, it shows at least 3000 galaxies, many of them extremely faint and distant. The light from some of them has taken around 13 billion years to reach the Earth. In fact, the Earth did not exist when the light set out on its journey. The Earth is estimated to have been formed about 4.5 billion years ago (Figure 1.5).

Hubble's fabulous views take us to near the edge of the visible universe. They also enable a calculation to be made. If the universe looks roughly the same everywhere, which seems to be true, then by calculating the amount of matter from the total number of galaxies in the field of view and then multiplying it by 24 million we can estimate the total number of galaxies in the visible universe. That gives about 200 billion. Estimating the number of particles (e.g. protons, which form the hydrogen atom nucleus) in a galaxy at about $10^{69}$, the total number of particles

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**Figure 1.5** The Hubble deep field view of one-24-millionth of the sky showing numerous galaxies right to the edge of the visible universe (source: apod.nasa.gov/apod/ap140605.html). For a colour version of this figure, please see the plate section.

in the universe turns out to be about $10^{80}$ particles.[25] That is a huge number, which would take most of this paragraph to write out fully, with 80 zeros. In Chapter 3 we will compare this number to the number of possible interactions in biological systems.

## Conclusions

Relativity theory is inevitably associated with the name of Einstein – correctly so, although others, notably Poincaré, Lorentz, Gauss and Riemann, also developed many of the key mathematical ideas, and many others have done so since. Physicists, however, also refer to the general *principle* of relativity. By this they mean the distancing of our ideas from presumptions for which there is insufficient justification. So, many physicists also talk, completely correctly, about Galilean relativity or Newtonian relativity. Both Galileo and Newton were applying relativistic ideas, although they did not use the word relativity.

I think we should go even further. As shown in this chapter, each of the stages of trying to find the centre of the universe was an application of this very general principle of relativity. The stages are: first, abandon the idea of the Earth as flat while all the rest of the universe is spherical; second, abandon the idea that the Earth is the centre; third, abandon the idea that the sun is the centre; fourth, abandon the idea of any privileged frames for movement – movement is always relative; fifth, abandon the idea that there could be a centre – all frames of reference are equivalent; sixth, abandon the assumption that space-time is Euclidean.

I also imply that there are more applications of the principle to come in the future. Some physicists have already proposed extensions of the principle of relativity – for example, to the relativity of scales, a theory proposed by the French astrophysicist Laurent Nottale. The rest of this book explores applications of the principle of relativity in what I call Biological Relativity, which shares important ideas with the scale relativity theory of Nottale.

A second implication of this chapter is that there is also a philosophical principle of relativity. The discoveries of quantum mechanics forced us to distance ourselves from the idea that the universe is a vast piece of determinate clockwork. It has also forced some re-thinking concerning how we can know the world 'as it really is'. These implications will be explored more fully in the last chapter. But the lesson is worth bearing in mind throughout the book.[26]

## Notes

1 Job 9:9.

2 http://en.wikipedia.org/wiki/Chinese_constellations

3 The seven stars of the big dipper are sometimes taken to be the *Septarishi* (seven sages) in Indian literature.

4 http://en.wikipedia.org/wiki/Principle_of_relativity

5 The first ‘cosmological constant’ was introduced by Einstein to enable his equations to produce a steady-state universe. If he had not done this he would have predicted an expanding universe. For a readable review of this problem and the cosmological parameters in general see Penrose, R. (2004) *The Road to Reality: A Complete Guide to the Laws of the Universe* (Jonathan Cape, London; pp. 772–778). Also, the wonderful little book by the Astronomer Royal: Rees, Martin (1999) *Just Six Numbers: The Deep Forces that Shape the Universe* (Weidenfeld and Nicolson, London).

6 Einstein, Albert (2010) *Relativity: The Special and the General Theory* (trans. Robert Lawson) (Ancient Wisdom Publications, Peoria, AZ).

7 In this case I have used the word ‘uniquely’ because ‘privileged’ would give the wrong impression. The idea was not that the Earth was a privileged ‘centre’ of the universe. On the contrary, the flat Earth was regarded as at the *bottom* of the universe, with an even worse place, Hell, below it.

8 See Cormack, L.B. (2015) Myth 2: that before Columbus, geographers and other educated people thought the earth was flat. In *Newton’s Apple and Other Myths About Science*. R.L. Numbers and K. Kampourakis, editors (Harvard University Press, Cambridge, MA; pp. 16–22). The Wikipedia entry on this issue is also very clear: https://en.wikipedia.org/wiki/Myth_of_the_Flat_Earth

9 Rosen, Edward (trans) (2004) [1939] *Three Copernican Treatises: The Commentariolus of Copernicus; The Letter against Werner; The Narratio Prima of Rheticus* (second edition, revised) (Dover Publications, New York).

10 An epicycle is a circle whose centre moves round the circumference of another circle. If movement around this smaller circle is faster than the movement around the main circle then it would be possible to explain why some planets seem to travel backwards compared to their expected path.

11 Nicholas of Cusa, *De docta ignorantia*, 2.12, p. 103, cited in Koyré, A. (1957) *From the Closed World to the Infinite Universe* (Johns Hopkins Press, Baltimore, MD; p. 17).

12 *Dialogo sopra i due massimi sistemi del mondo* 1632.

13 Drake, Stillman (1978) *Galileo At Work* (University of Chicago Press, Chicago).

14 http://en.wikipedia.org/wiki/Laplace%27s_demon

15 Quoted and referenced in Fara, P. (2015) Myth 6: that the apple fell and Newton invented the law of gravity, thus removing God from the Cosmos. In *Newton's Apple and Other Myths About Science*. R.L. Numbers and K. Kampourakis, editors (Harvard University Press, Cambridge, MA; pp. 48–56).

16 Address to the British Association for the Advancement of Science.

17 Dirac, Paul (1930) *Lectures on Quantum Mechanics* (Princeton University Press, Princeton, NJ). Cox, Brian and Jeff Forshaw (2011) *The Quantum Universe: Everything That Can Happen Does Happen* (Allen Lane, London).

18 This is a highly technical field of research using several approaches to the question of how to harness quantum states effectively for computer memory and logical operations. See, for example, Harty, T.P., D.T.C. Allcock, C.J. Balance, *et al.* (2014) High-fidelity preparation, gates, memory, and readout of a trapped-ion quantum bit. *Physical Review Letters* 113; DOI: 10.1103/PhysRevLett.113.220501, which achieves the longest coherence time for a single physical qubit, together with highest precision manipulations of a single qubit. Also see Ballance, C.J., V.M. Schafer, J.P. Home, *et al.* (2015) Hybrid quantum logic and a test of Bell's inequality using two different atomic isotopes. *Nature* 528:384–386; DOI: 10.1038/nature16184, which achieves highest precision 'quantum logic gate' between two qubits, and a test of the quantum mechanical 'Bell's inequality' for different-species of atoms. These results are important steps on the way to the construction of practical quantum computers.

19 Saeedi, K., S. Simmons, J.Z. Salvail, *et al.* (2013) Room-temperature quantum bit storage exceeding 39 minutes using ionized donors in silicon-28. *Science* 342:830–833.

20 For a review of possible quantum mechanical effects in biological systems, see Melkikh, A.V. and A. Khrennikov (2015) Non-trivial quantum and quantum-like effects in biosystems: unsolved questions and paradoxes. *Progress in Biophysics and Molecular Biology* 119:137–161.

21 Over a century later, there is a fascinating twist to this story. A modern variation of the Michelson–Morley experiment has been developed in attempts to test an important prediction of Einstein's General Theory of Relativity. This is that light should be influenced by gravitational waves when objects of large mass distort space-time.

# 2

# Biological Scales and Levels

*There are only molecules – everything else is sociology.*
Jim Watson (Nobel Laureate, author of *The Double Helix*)[1]

## The Sense of Scale

In Chapter 1 we got a sense of the immensity of the known universe. Let's now go in the opposite direction, down towards the smallest scale in living organisms. We will see that it takes almost as many scale changes to go down to the lowest level as it did to go all the way up to the whole visible universe.

I was a student in the 1950s when the first electron microscopes were introduced in biological research. A normal light microscope can magnify up to about 2000 times.[2] By using electrons as the beam instead of photons we can increase this magnification to at least ten million. To enable the electrons to form a meaningful image they must pass through only very thin sections of material, so we cannot use electron microscopes for living cells. That is a serious limitation, but it is balanced by the fact that we can drill down to the molecular level. This is the way in which the British scientist Hugh Huxley saw for the first time the individual molecules called actin and myosin. These are long protein filaments, and he showed that they must slide over each other when a muscle contracts. He was even able to see the small molecular protrusions called cross-bridges that enable this sliding movement to occur. Another Huxley, Andrew Huxley (not related), was able to make the same

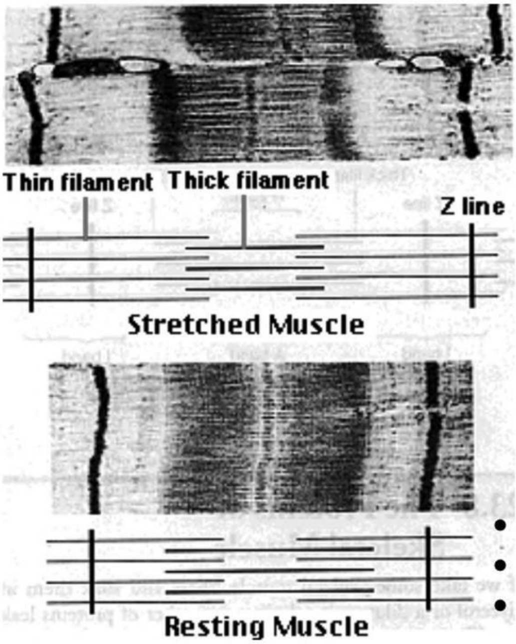

**Figure 2.1** The first electron micrograph images of the arrangement of protein filaments in skeletal muscle, together with diagrams showing how the filaments slide along each other when the muscle changes length (Huxley and Hansen, 1954).[3]

deduction from experiments using clever light microscopy. These discoveries led to the famous sliding filament model of muscle contraction (Figure 2.1).

As medical students at University College London, where Hugh Huxley was working, we had the opportunity to see where he had his electron microscope. It felt like entering a holy of holies. We were allowed to enter one by one through a sliding door into the dark room where the precious instrument was housed to see for ourselves the beautiful arrays of the filaments. It has always seemed to me surprising that this work was not honoured with a Nobel Prize. Andrew Huxley did receive one, but for his work with Alan Hodgkin on nerves.

At the magnification required to see the muscle filaments the cell that housed them would have covered the whole of the square mile or