John Gribbin

Science

JOHN GRIBBIN

SCIENCE

A HISTORY

1543–2001

PENGUIN BOOKS

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Both singular and plural forms of the personal pronoun appear in the text. ‘I’, of course, is used where my own opinion on a scientific matter is being presented; ‘we’ is used to include my writing partner, Mary Gribbin, where appropriate. Her help in ensuring that the words which follow are comprehensible to non-scientists is as essential to this as to all my books.

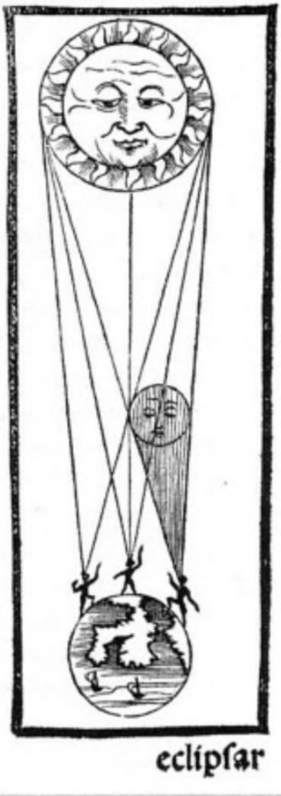
Introduction

The most important thing that science has taught us about our place in the Universe is that we are not special. The process began with the work of Nicolaus Copernicus in the sixteenth century, which suggested that the Earth is not at the centre of the Universe, and gained momentum after Galileo, early in the seventeenth century, used a telescope to obtain the crucial evidence that the Earth is indeed a planet orbiting the Sun. In successive waves of astronomical discovery in the centuries that followed, astronomers found that just as the Earth is an ordinary planet, the Sun is an ordinary star (one of several hundred billion stars in our Milky Way galaxy) and the Milky Way itself is just an ordinary galaxy (one of several hundred billion in the visible Universe). They even suggested, at the end of the twentieth century, that the Universe itself may not be unique.

While all this was going on, biologists tried and failed to find any evidence for a special 'life force' that distinguishes living matter from non-living matter, concluding that life is just a rather complicated form of chemistry. By a happy coincidence for the historian, one of the landmark events at the start of the biological investigation of the human body was the publication of *De Humani Corporis Fabrica* (*On the Structure of the Human Body*) by Andreas Vesalius in 1543, the same year that Copernicus eventually published *De Revolutionibus Orbium Coelestium* (*On the Revolutions of Celestial Bodies*). This coincidence makes 1543 a convenient marker for the start of the scientific revolution that would transform first Europe and then the world.

le faltaua poco para llegar ala cola/ d̄ manera q̄ touieſe latitud ſeptẽtrional/los q̄ eſtuuieſen enlos climas ſeptẽtrionales veriã la luna eclipſar a todo el ſol:y los d̄la eq̄nocial veriã eclipſada la pte ſeptẽtrional d̄l ſol:y los meridionales veriã el ſol ſin eclipſi. Aſi q̄ aunq̄ el eclipſi del ſol ſea total o particular no puede ſer vniuerſal en todo la tierra. Notaſe que para la quãtidad deſtos eclipſis el diametro aſi del ſol como dela luna diuidẽ los aſtrologos en doze ptes yguales: y a eſtas ptes llamã dedos/o pũtos. Y segũ los puntos del diametro de la luna que cubre la ſombra de la tierra/o las partes d̄l diametro del ſol que cubre la luna: tantos dedos/o pũtos ſe dira eclipſar. Si ſeis/ medio. Si tres quarto. ſi quatro/ tercio. ſi nueue/tres q̄rtos. ſi ocho/dos tercios.

Doze ptes del diametro llamados dedos o puntos.



Diametro viſual del ſol y d̄la luna.

¶ Ha ſe tambien d̄ notar que aun q̄ el ſol ſea mayor que la luna alas vezes pesce la luna mayor quel ſol: y eſto ſera q̄ndo el ſol eſtuuiere en el auge d̄l eſcẽtrico:y la luna en el oppoſito del auge del epiciclo. y quãdo aſſi parece lo puede

2. A plate from Martin Cortes de Albacar's Breve compendio de la esfera y de la arte de navigar, *1551.*

Of course, any choice of a starting date for the history of science is arbitrary, and my own account is restricted geographically, as well as in the time span it covers. My aim is to outline the development of *Western* science, from the Renaissance to (roughly) the end of the twentieth century. This means leaving to one side the achievements of the Ancient Greeks, the Chinese, and the Islamic scientists and philosophers who did so much to keep the search for knowledge about our world alive during the period that Europeans refer to as the Dark and Middle Ages. But it also means telling a coherent story, with a clear beginning in both space and time, of the development of the world view that lies at the heart of our understanding of the Universe, and our place in it today. For human life turned out to be no different from any other kind of life on Earth. As the work of Charles Darwin and Alfred Wallace established in the nineteenth century, all you need to make human beings out of amoebas is the process of evolution by natural selection, and plenty of time.

All the examples I have mentioned here highlight another feature of the story-telling process. It is natural to describe key events in terms of the work of individuals who made a mark in science – Copernicus, Vesalius, Darwin, Wallace and the rest. But this does not mean that science has progressed as a result of the work of a string of irreplaceable geniuses possessed of a special insight into how the world works. Geniuses maybe (though not always); but irreplaceable certainly not. Scientific progress builds step by step, and as the example of Darwin and Wallace shows, when the time is ripe, two or more individuals may make the next step independently of one another. It is the luck of the draw, or historical accident, whose name gets remembered as the discoverer of a new phenomenon. What is much more important than human genius is the development of technology, and it is no surprise that the start of the scientific revolution 'coincides' with the development of the telescope and the microscope.

I can think of only one partial exception to this situation, and even there I would qualify the exception more than most historians of science do. Isaac Newton was clearly something of a special case, both because of the breadth of his scientific achievements and in particular because of the clear way in which he laid down the ground rules on which science ought to operate. Even Newton, though, relied on his immediate predecessors, in particular Galileo Galilei and Rene Descartes, and in that sense his contributions followed naturally from what went before. If Newton had never lived, scientific progress might have been held back by a few decades. But *only* by a few decades. Edmond Halley or Robert Hooke might well have come up with the famous inverse square law of gravity; Gottfried Leibniz actually did invent calculus independently of Newton (and made a better job of it); and Christiaan Huygens's superior wave theory of light was held back by Newton's espousal of the rival particle theory.

None of this will stop me from telling much of my version of the history of science in terms of the people involved, including

Newton. My choice of individuals to highlight in this way is not intended to be comprehensive; nor are my discussions of their individual lives and work intended to be complete. I have chosen stories that represent the development of science in its historical context. Some of those stories, and the characters involved, may be familiar; others (I hope) less so. But the importance of the people and their lives is that they reflect the society in which they lived, and by discussing, for example, the way the work of one specific scientist followed from that of another, I mean to indicate the way in which one *generation* of scientists influenced the next. This might seem to beg the question of how the ball got rolling in the first place – the 'first cause'. But in this case it is easy to find the first cause – Western science got started because the Renaissance happened. And once it got started, by giving a boost to technology it ensured that it would keep on rolling, with new scientific ideas leading to improved technology, and improved technology providing the scientists with the means to test new ideas to greater and greater accuracy. Technology came first, because it is possible to make machines by trial and error without fully understanding the principles on which they operate. But once science and technology got together, progress really took off.

I will leave the debate about why the Renaissance happened when and where it did to the historians. If you want a definite date to mark the beginning of the revival of Western Europe, a convenient one is 1453, the year the Turks captured Constantinople (on 29 May). By then, many Greek-speaking scholars, seeing which way the wind was blowing, had already fled westwards (initially to Italy), taking their archives of documents with them. There, the study of those documents was taken up by the Italian humanist movement, who were interested in using the teaching found in classical literature to re-establish civilization along the lines that had existed before the Dark Ages. This does rather neatly tie the rise of modern Europe to the death of the last vestige of the old Roman Empire. But an equally important factor, as many people have argued, was the depopulation of Europe by the Black Death in the fourteenth century, which led the survivors to question the whole basis of society, made labour expensive and encouraged the invention of technological devices to replace manpower. Even this is not the whole story. Johann Gutenberg's development of moveable type in the mid-fifteenth century had an obvious impact on what was to become science, and discoveries brought back to Europe by another technological development, sailing ships capable of crossing the oceans, transformed society.

Dating the end of the Renaissance is no easier than dating the beginning – you could say that it is still going on. A convenient round number is 1700; but from the present perspective an even better choice of date might be 1687, the year Isaac Newton published his great work *Philosophiae Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*) and, in the words of Alexander Pope, 'all was light'.

The point I want to make is that the scientific revolution did not happen in isolation, and certainly did not start out as the mainspring of change, although in many ways science (through its influence on technology and on our world view) became the driving force of Western civilization. I want to show how science developed, but I don't have space to do justice to the full historical background, any more than most history books have space to do justice to the story of science. I don't even have space to do justice to all of the science here, so if you want the in-depth story of such key concepts as quantum theory, evolution by natural selection or plate tectonics, you will have to look in other books (including my own). My choice of events to highlight is necessarily incomplete, and therefore to some extent subjective, but my aim is to give a feel for the full sweep of science, which has taken us from the realization that the Earth is not at the centre of the Universe and that human beings are 'only' animals, to the theory of the Big Bang and a complete map of the human genome in just over 450 years.

In his *New Guide to Science* (a very different kind of book from anything I could ever hope to write), Isaac Asimov said that the reason for trying to explain the story of science to non-scientists is that:

> No one can really feel at home in the modern world and judge the nature of its problems – and the possible solutions to those problems – unless one has some intelligent notion of what science is up to. Furthermore, initiation into the magnificent world of science brings great esthetic satisfaction, inspiration to youth, fulfillment of the desire to know, and a deeper appreciation of the wonderful potentialities and achievements of the human mind.[1]

I couldn't put it better myself. Science is one of the greatest achievements (arguably *the* greatest achievement) of the human mind, and the fact that progress has actually been made, in the most part, by ordinarily clever people building step by step from the work of their predecessors makes the story more remarkable, not less. Almost any of the readers of this book, had they been in the right place at the right time, could have made the great discoveries described here. And since the progress of science has by no means come to a halt, some of you may yet be involved in the next step in the story.

John Gribbin

June 2001

Book One

OUT OF THE DARK AGES

1

Renaissance Men

Emerging from the dark – The elegance of Copernicus – The Earth moves! – The orbits of the planets – Leonard Digges and the telescope – Thomas Digges and the infinite Universe – Bruno: a martyr for science? – Copernican model banned by Catholic Church – Vesalius: surgeon, dissector and grave-robber – Fallopio and Fabricius – William Harvey and the circulation of the blood

Emerging from the dark

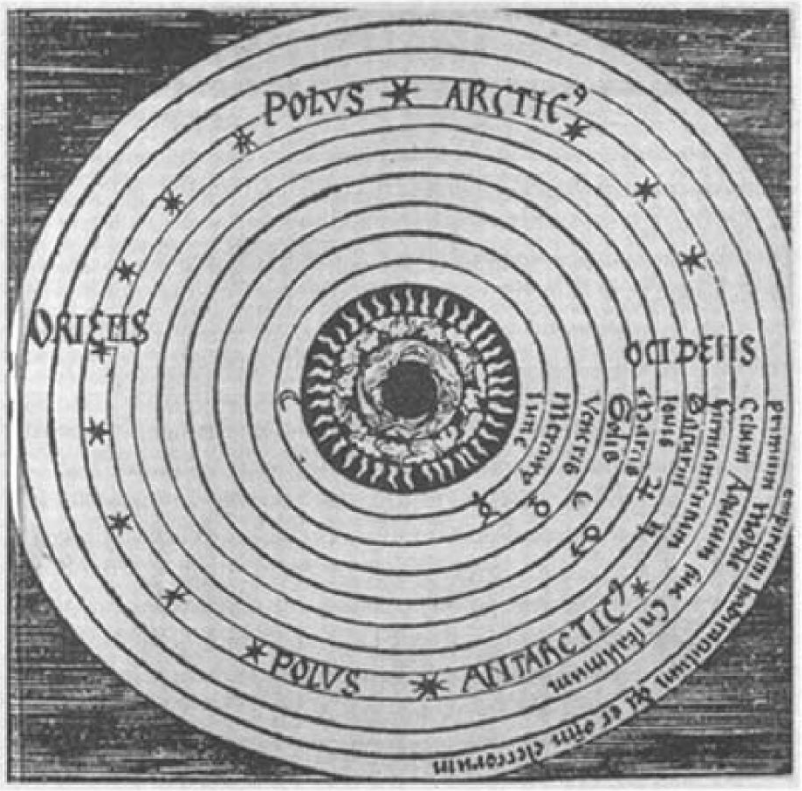
The Renaissance was the time when Western Europeans lost their awe of the Ancients and realized that they had as much to contribute to civilization and society as the Greeks and Romans had contributed. To modern eyes, the puzzle is not that this should have occurred, but that it should have taken so long for people to lose their inferiority complex. The detailed reasons for the hiatus are outside the scope of this book. But anyone who has visited the sites of classical civilization around the

Mediterranean can get a glimpse of why the people of the Dark Ages (in round terms, roughly from AD 400 to 900) and even those of the Middle Ages (roughly from AD 900 to 1400) felt that way. Structures such as the Pantheon and the Colosseum in Rome still inspire awe today, and at a time when all knowledge of how to build such structures had been lost, it must have seemed that they were the work almost of a different species – or of gods. With so much physical evidence of the seemingly god-like prowess of the Ancients around, and with newly discovered texts demonstrating the intellectual prowess of the Ancients emerging from Byzantium, it would have been natural to accept that they were intellectually far superior to the ordinary people who had followed them, and to accept the teaching of ancient philosophers such as Aristotle and Euclid as a kind of Holy Writ, which could not be questioned. This was, indeed, the way things were at the start of the Renaissance. Since the Romans contributed very little to the discussion of what might now be called a scientific view of the world, this meant that by the time of the Renaissance the received wisdom about the nature of the Universe had been essentially unchanged since the great days of Ancient Greece, some 1500 years before Copernicus came on the scene. Yet, once those ideas were challenged, progress was breathtakingly rapid – after fifteen centuries of stagnation, there have been fewer than another five centuries from the time of Copernicus to the present day. It is something of a cliché, but nonetheless true, that a typical Italian from the tenth century would have felt pretty much at home in the fifteenth century, but a typical Italian from the fifteenth century would find the twenty-first century more unfamiliar than he or she would have found the Italy of the Caesars.

The elegance of Copernicus

Copernicus himself was an intermediate figure in the scientific revolution, and in one important way he resembled the Ancient Greek philosophers rather than the modern scientist. He did not carry out experiments, or even make his own observations of the heavens (at least, not to any significant degree), and did not expect anyone else to try to test his ideas. His great idea was purely that – an idea, or what is today sometimes called a ‘thought experiment’, which presented a new and simpler way of explaining the same pattern of behaviour of heavenly bodies that was explained by the more complicated system devised (or publicized) by Ptolemy. If a modern scientist has a bright idea about the way the Universe works, his or her first objective is to find a way to test the idea by experiment or observation, to find out how good it is as a description of the world. But this key step in developing the scientific method had not been taken in the fifteenth century, and it never occurred to Copernicus to test his idea – his mental model of how the Universe works – by making new observations himself, or by encouraging others to make new observations. To Copernicus, his model was better than that of Ptolemy because it was, in modern parlance, more elegant. Elegance is often a reliable guide to the usefulness of a model, but not an infallible one. In this case, though, it eventually turned out that Copernicus’s intuition was right.

Certainly, the Ptolemaic system lacked elegance. Ptolemy (sometimes known as Ptolemy of Alexandria) lived in the second century AD, and was brought up in an Egypt that had long since come under the cultural influence of Greece (as the very name of the city he lived in records). Very little is known about his life, but among the works he left for posterity there was a great summary of astronomy, based on 500 years of Greek astronomical and cosmological thinking. The book is usually known by its Arabic title, the *Almagest*, which means ‘the Greatest’, and gives you some idea of how it was regarded in the centuries that followed; its original Greek title simply describes it as ‘The Mathematical Compilation’. The astronomical system it described was far from being Ptolemy’s own idea, although he seems to have tweaked and developed the ideas of the Ancient Greeks. Unlike Copernicus, however, Ptolemy does seem to have carried out his own major observations of the movements of the planets, as well as drawing on those of his predecessors (he also compiled important star maps).



3. *The Earth-centred Ptolemaic model of the Universe. From Reisch's* Margarita Philosophica, *1503.*

The basis of the Ptolemaic system was the notion that heavenly objects must move in perfect circles, simply because circles are perfect (this is an example of how elegance does not necessarily lead to truth!). At that time, there were five known planets to worry about (Mercury, Venus, Mars, Saturn and Jupiter), plus the Sun and Moon, and the stars. In order to make the observed movements of these objects fit the requirement of always involving perfect circles, Ptolemy had to make two major adjustments to the basic notion that the Earth lay at the centre of the Universe and everything else revolved around it. The first (which had been thought of long before) was that the motion of a particular planet could be described by saying that it revolved in a perfect little circle around a point which itself revolved in a perfect big circle around the Earth. The little circle (a ‘wheel within a wheel’, in a sense) is called an epicycle. The second adjustment, which Ptolemy seems to have refined himself, was that the large crystal spheres, as they became known (‘crystal’ just means ‘invisible’ in this context), which carry the heavenly bodies round in circles, didn’t actually revolve around the Earth, but around a set of points slightly offset from the Earth, called ‘equant points’ (around different equant points, to explain details of the motion of each individual object). The Earth was still regarded as the central object in the Universe, but everything else revolved around the equant points, not around the Earth itself. The big circle centred on the equant point is called a deferent.

The model worked, in the sense that you could use it to describe the way the Sun, Moon and planets seem to move against the background of fixed stars (fixed in the sense that they all kept the same pattern while moving together around the Earth), which were themselves thought to be attached to a crystal sphere just outside the set of nested crystal spheres that carried the other objects around the relevant equant points. But there was no attempt to explain the physical processes that kept everything moving in this way, nor to explain the nature of the crystal spheres. Furthermore, the system was often criticized as being unduly complicated, while the need for equant points made many thinkers uneasy – it raised doubts about whether the Earth ought really to be regarded as the centre of the Universe. There was even speculation (going right back to Aristarchus, in the third century BC, and revived occasionally in the centuries after Ptolemy) that the Sun might be at the centre of the Universe, with the Earth moving around it. But such ideas failed to find favour, largely because they flew in the face of 'common sense'. Obviously, the solid Earth could not be moving! This is one of the prime examples of the need to avoid acting on the basis of common sense if you want to know how the world works.

There were two specific triggers that encouraged Copernicus to come up with something better than the Ptolemaic model. First, that each planet, plus the Sun and Moon, had to be treated separately in the model, with its own offset from the Earth and its own epicycles. There was no coherent overall description of things to explain what was going on. Second, there was a specific problem which people had long been aware of but which was usually brushed under the carpet. The offset of the Moon's orbit from the Earth, required to account for changes in the speed with which the Moon seems to move across the sky, was so big that the Moon ought to be significantly closer to the Earth at some times of the month than at others – so its apparent size ought to change noticeably (and by a calculable amount), which it clearly did not. In a sense, the Ptolemaic system *does* make a prediction that can be tested by observation. It fails that test, so it is not a good description of the Universe. Copernicus didn't think quite like that, but the problem of the Moon certainly made him uneasy about the Ptolemaic model.

Nicolaus Copernicus came on the scene at the end of the fifteenth century. He was born in Torun, a Polish town on the Vistula, on 19 February 1473, and was originally known as Mikolaj Kopernik, but later Latinized his name (a common practice at the time, particularly among the Renaissance humanists). His father, a wealthy merchant, died in 1483 or 1484, and Nicolaus was brought up in the household of his mother's brother, Lucas Waczenrode, who became the bishop of Ermeland. In 1491 (just a year before Christopher Columbus set off on his first voyage to the Americas), Nicolaus began his studies at the University of Krakow, where he seems to have first become seriously interested in astronomy. In 1496, he moved on to Italy, where he studied law and medicine, as well as the usual classics and mathematics, in Bologna and Padua, before receiving a doctorate in canon law from the University of Ferrara in 1503. Very much a man of his time, Copernicus was strongly influenced by the humanist movement in Italy and studied the classics associated with that movement. Indeed, in 1519, he published a collection of poetic letters by the writer Theophylus Simokatta (a seventh-century Byzantine), which he had translated from the original Greek into Latin.

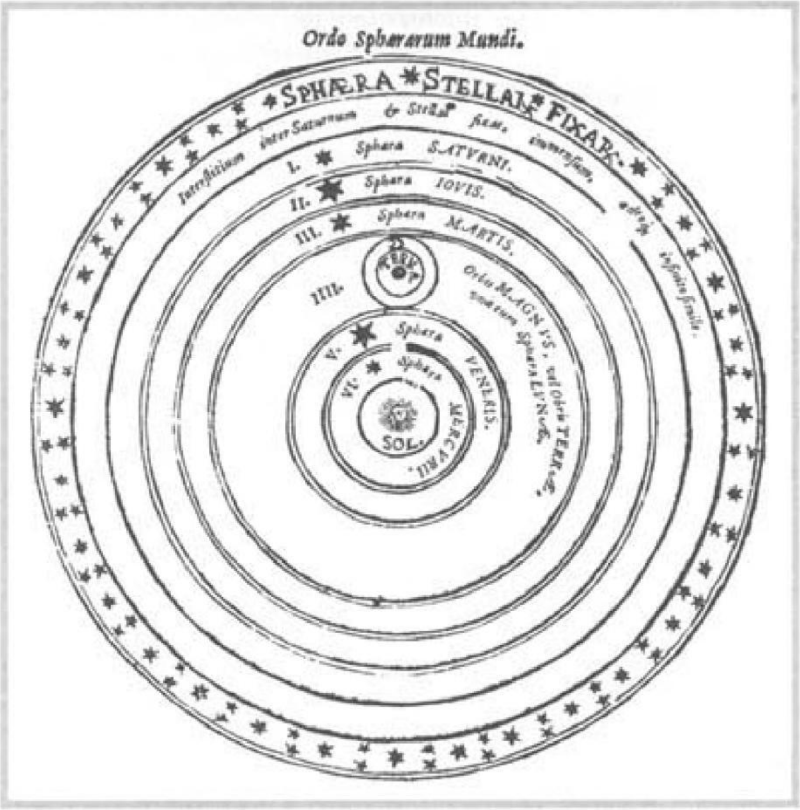
By the time he completed his doctorate, Copernicus had already been appointed as canon at Frombork Cathedral in Poland by his uncle Lucas – a literal case of nepotism that gave him a post amounting to a sinecure, which he held for the rest of his life. But it was not until 1506 that he returned permanently to Poland (giving you some idea of just how undemanding the post was), where he worked as his uncle's physician and secretary until Lucas died in 1512. After his uncle's death, Copernicus gave more attention to his duties as a canon, practised medicine and held various minor civil offices, all of which gave him plenty of time to maintain his interest in astronomy. But his revolutionary ideas about the place of the Earth in the Universe had already been formulated by the end of the first decade of the sixteenth century.

The Earth moves!

These ideas did not appear out of thin air, and even in his major contribution to scientific thought (sometimes regarded as *the* major contribution to scientific thought) Copernicus was still a man of his time. The continuity of science (and the arbitrariness of starting dates for histories) is clearly highlighted by the fact that Copernicus was strongly influenced by a book published in 1496, the exact time when the 23-year-old student was becoming interested in astronomy. The book had been written by the German Johannes Mueller (born in Königsberg in 1436, and also known as Regiomontanus, a Latinized version of the name of his birthplace), and it developed the ideas of his older colleague and teacher Georg Peuerbach (born in 1423), who had (of course) been influenced by other people, and so on back into the mists of time. Peuerbach had set out to produce a modern (that is, fifteenth-century) abridgement of Ptolemy's *Almagest.* The most up-to-date version available was a Latin translation made in the twelfth century by Gerard of Cremona, which was translated from an Arabic text which had itself been translated from the Greek long before. Peuerbach's dream was to update this work by going back to the earliest available Greek texts (some of which were now in Italy following the fall of Constantinople). Unfortunately, he died in 1461, before he could carry out the task, although he had begun a preliminary book summarizing the edition of the *Almagest* that was available. On his deathbed, Peuerbach made Regiomontanus promise to complete the work, which he did, although the new translation of Ptolemy was not carried out. But Regiomontanus did something that was in many ways even better, producing his book the *Epitome*, which not only summarized the contents of the *Almagest*, but added details of later observations of the heavens, revised some of the calculations Ptolemy had carried out and included some critical commentary in the text (in itself a sign of the confidence of Renaissance man in his own place as an equal of the Ancients). This commentary included a passage drawing attention to a key point that we have already mentioned, the fact that the apparent size of the Moon on the sky does not change in the way that the Ptolemaic system requires. Although Regiomontanus died in 1476, the *Epitome* was not published for another twenty years, when it set the young Copernicus thinking. Had it appeared before Regiomontanus died, there is every likelihood that someone else, rather than Copernicus (who was only three in 1476), would have picked up the baton.

Copernicus himself did not exactly rush into print with his ideas. We know that his model of the Universe was essentially complete by 1510, because not long after that he circulated a summary of those ideas to a few close friends, in a manuscript called the *Commentariolus (Little Commentary).* There is no evidence that Copernicus was greatly concerned about the risk of persecution by the Church if he published his ideas more formally – indeed, the *Commentariolus* was described in a lecture at the Vatican attended by Pope Clement VII and several cardinals, given by the papal secretary Johan Widmanstadt. One of the cardinals, Nicholas von Schönberg, wrote to Copernicus urging him to publish, and the letter was included at the beginning of his masterwork, *De Revolutionibus Orbium Coelestium (On the Revolution of the Celestial Spheres)*, when Copernicus did eventually publish his ideas, in 1543.

So why did he delay? There were two factors. First, Copernicus was rather busy. Reference to his post as canon as a sinecure may be accurate, but it doesn't mean that he was willing to sit back and enjoy the income, dabble in astronomy and let the world outside go by. As a doctor, Copernicus worked both for the religious community around Frombork Cathedral and (unpaid, of course) for the poor. As a mathematician, he worked on a plan for the reform of the currency (not the last time a famous scientist would take on such a role), and his training in law was put to good use by the diocese. He was also pressed into unexpected service when the Teutonic Knights (a religious-military order, akin to the Crusaders, who controlled the eastern Baltic states and Prussia) invaded the region in 1520. Copernicus was given command of a castle at Allenstein, and held the town against the invaders for several months. He was, indeed, a busy man.



4. *An early version of a Sun-centred Universe, from Rheticus's* Narratio Prima, 1596

But there was a second reason for his reluctance to publish. Copernicus knew that his model of the Universe raised new questions, even if it did answer old puzzles – and he knew that it didn't answer all of the old puzzles. As we have said, Copernicus didn't do much observing (although he did oversee the construction of a roofless tower to use as an observatory). He was a thinker and philosopher more in the style of the Ancient

Greeks than a modern scientist. The thing that most worried him about the Ptolemaic system, typified by the puzzle of the Moon, was the business of equants. He couldn't accept the idea, not least because it needed different equants for different planets. Where, in that case, was the true centre of the Universe? He wanted a model in which everything moved around a single centre at an unvarying rate, and he wanted this for aesthetic reasons as much as anything else. His model was intended as a way of achieving that and, on its own terms, it failed. Putting the Sun at the centre of the Universe was a big step. But you still had to have the Moon orbiting around the Earth, and you still needed epicycles to explain why the planets seem to slow down and speed up in their orbits.

Epicycles were a way of having deviations from perfectly circular motion while pretending that there were no deviations from perfectly circular motion. But the biggest problem with the Copernican world view was the stars. If the Earth were orbiting around the Sun and the stars were fixed to a crystal sphere just outside the sphere carrying the most distant planet, then the motion of the Earth should cause an apparent motion in the stars themselves – a phenomenon known as parallax. If you sit in a car travelling down a road, you seem to see the world outside moving past you. If you sit on a moving Earth, why don't you see the stars move? The only explanation seemed to be that the stars must be very much further away than the planets, at least hundreds of times further away, so that the parallax effect is too small to see. But why should God leave a huge empty space, at least hundreds of times bigger than the gaps between the planets, between the outermost planet and the stars?

There were other troubling problems with a moving Earth. If the Earth moves, why isn't there a constant gale of wind blowing past, like the wind in your hair that rushes past if you are in an open-topped car travelling on a motorway? Why doesn't the motion cause the oceans to slop about, producing great tidal waves? Indeed, why doesn't the motion shake the Earth to bits? Remember that in the sixteenth century, motion meant riding on a galloping horse or in a carriage being pulled over rutted roads. The notion of smooth motion (even as smooth as a car on a motorway) must have been very difficult to grasp without any direct experience of it – as late as the nineteenth century there were serious concerns that travelling at the speed of a railway train, maybe as high as 15 miles per hour, might be damaging to human health. Copernicus was no physicist and didn't even attempt to answer these questions, but he knew they cast doubts (from the perspective of the sixteenth century) on his ideas.

There was another problem, which lay completely outside the scope of sixteenth-century knowledge. If the Sun lay at the centre of the Universe, why didn't everything fall into it? All Copernicus could say was that 'Earthy' things tended to fall to Earth, solar things tended to fall to the Sun, things with an affinity for Mars would fall to Mars, and so on. What he really meant was, 'we don't know'. But one of the most important lessons learned in the centuries since Copernicus is that a scientific model doesn't have to explain everything to be a good model.

After the arrival of Georg Joachim von Lauchen (also known as Rheticus) in Frombork in the spring of 1539, Copernicus, despite his doubts and his busy life, was persuaded to put his thoughts into a form that could be published. Rheticus, who was the professor of mathematics at the University of Wittenberg, knew of Copernicus's work, and had come to Frombork specifically to learn more about it; he realized its importance, and was determined to get the master to publish it. They got on well together, and in 1540, Rheticus published a pamphlet *Narratio Prima de Libtus Revolutionum Copernici* (*The First Account of the Revolutionary Book by Copernicus*, usually referred to simply as the *First Account*) summarizing the key feature of the Copernican model, the motion of the Earth around the Sun. At last, Copernicus agreed to publish his great book, although (or perhaps because) he was now an old man. Rheticus undertook to oversee the printing of the book in Nuremberg, where he was based, but (as has often been told) things didn't quite work out as intended. Rheticus had to leave to take up a new post in Leipzig before the book was completely ready to go to press and deputed the task to Andreas Osiander, a Lutheran minister, who took it upon himself to add an unsigned preface explaining that the model described in the book was not intended as a description of the way the Universe really is, but as a mathematical device to simplify calculations involving the movements of the planets. As a Lutheran, Osiander had every reason to fear that the book might not be well received, because even before it was published Martin Luther himself (an almost exact contemporary of Copernicus – he lived from 1483 to 1546) had objected to the

Copernican model, thundering that the Bible tells us that it was the Sun, not the Earth, that Joshua commanded to stand still.

Copernicus had no chance to complain about the preface because he died in 1543, the year his great work was published. There is a touching, but probably apocryphal, tale that he received a copy on his deathbed, but whether he did or not, the book was left without a champion except for the indefatigable Rheticus (who died in 1576).

The irony is that Osiander's view is quite in keeping with the modern scientific world view. All of our ideas about the way the Universe works are now accepted as simply models which are put forward to explain observations and the results of experiments as best we can. There is a sense in which it is acceptable to describe the Earth as the centre of the Universe, and to make all measurements relative to the Earth. This works rather well, for example, when planning the flight of a rocket to the Moon. But such a model becomes increasingly complicated as we try to describe the behaviour of things further and further away from Earth, across the Solar System. When calculating the flight of a spaceprobe to, say, Saturn, NASA scientists in effect treat the Sun as being at the centre of the Universe, even though they know that the Sun itself is in orbit around the centre of our galaxy, the Milky Way. By and large, scientists use the simplest model they can which is consistent with all the facts relevant to a particular set of circumstances, and they don't all use the same model all the time. To say that the idea of the Sun being at the centre of the Universe is just a model which aids calculations involving planetary orbits, is to say what any planetary scientist today would agree with. The difference is that Osiander was not expecting his readers (or rather, Copernicus's readers) to accept the equally valid view that to say that the Earth is at the centre of the Universe is just a model which is useful when calculating the apparent motion of the Moon.

It is impossible to tell whether Osiander's preface soothed any ruffled feathers at the Vatican, but the evidence suggests that there were no ruffled feathers there to soothe. The publication of *De Revolutionibus* was accepted essentially without a murmur by the Catholic Church, and the book was largely ignored by Rome for the rest of the sixteenth century. Indeed, it was largely ignored by most people at first – the original edition of 400 copies didn't even sell out. Osiander's preface certainly didn't soothe the Lutherans, and the book was roundly condemned by the European protestant movement. But there was one place where *De Revolutionibus* was well received and its full implications appreciated, at least by the cognoscenti – England, where Henry VIII married his last wife, Catherine Parr, the year the book was published.

The orbits of the planets

What was particularly impressive about the full Copernican model of the Universe was that by putting the Earth in orbit around the Sun it automatically put the planets into a logical sequence. Since ancient times, it had been a puzzle that Mercury and Venus could only be seen from Earth around dawn and dusk, while the other three known planets could be seen at any time of the night. Ptolemy's explanation (rather, the established explanation that he summarized in the *Almagest)* was that

Mercury and Venus ‘kept company’ with the Sun as the Sun travelled once around the Earth each year. But in the Copernican system, it was the Earth that travelled once around the Sun each year, and the explanation for the two kinds of planetary motion was simply that the orbits of Mercury and Venus lay inside the orbit of the Earth (closer to the Sun than we are), while the orbits of Mars, Jupiter and Saturn lay outside the orbit of the Earth (further from the Sun than we are). By making allowance for the Earth’s motion, Copernicus could work out the length of time it took each planet to orbit once around the Sun, and these periods formed a neat sequence from Mercury, with the shortest ‘year’, through Venus, Earth, Mars and Jupiter to Saturn, with the longest ‘year’.

But this wasn’t all. The observed pattern of behaviour of the planets is also linked, in the Copernican model, to their distances from the Sun relative to the distance of the Earth from the Sun. Even without knowing any of the distances in absolute terms, he could place the planets in order of increasing distance from the Sun. The order was the same – Mercury, Venus, Earth, Mars, Jupiter and Saturn. This clearly indicated a deep truth about the nature of the Universe. There was much more to Copernican astronomy, for those with eyes to see, than the simple claim that the Earth orbits around the Sun.

Leonard Digges and the telescope

One of the few people whose eyes clearly saw the implications of the Copernican model soon after the publication of *De Revolutionibus* was the English astronomer Thomas Digges. Digges was not only a scientist, but one of the first popularizers of science – not quite *the* first, since he followed, to some extent, in the footsteps of his father, Leonard. Leonard Digges was born around 1520, but very little is known about his early life. He was educated at the University of Oxford and became well known as a mathematician and surveyor. He was also the author of several books, which were written in English – very unusual at the time. The first of his books, *A General Prognostication*, was published in 1553, ten years after *De Revolutionibus*, and partly thanks to its accessibility in the vernacular it became a best seller, even though in one crucial respect it was already out of date. Leonard Digges provided in his book a perpetual calendar, collections of weather lore and a wealth of astronomical material, including a description of the Ptolemaic model of the Universe – in some ways, the book was not unlike the kind of farmers' almanacs that were popular in later centuries.

In connection with his surveying work, Leonard Digges invented the theodolite around 1551. About the same time, his interest in seeing accurately over long distances led him to invent the reflecting telescope (and almost certainly the refracting telescope as well), although no publicity was given to these inventions at the time. One reason for the lack of development of these ideas was that the elder Digges's career was brought to an abrupt end in 1554, when he took part in the unsuccessful rebellion led by the Protestant Sir Thomas Wyatt against England's new (Catholic) Queen Mary, who had come to the throne in 1553 on the death of her father, Henry VIII. Originally condemned to death for his part in the rebellion, Leonard Digges had his sentence commuted, but he forfeited all his estates and spent what was left of his life (he died in 1559) struggling unsuccessfully to regain them.

When Leonard Digges died, his son Thomas was about 13 years old (we don't know his exact date of birth), and was looked after by his guardian, John Dee. Dee was a typical Renaissance 'natural philosopher'; a good mathematician, student of alchemy, philosopher and (not quite typical!) astrologer to Queen Elizabeth I (who came to the throne in 1558). He may, like Christopher Marlowe, have been a secret agent for the Crown. He was also, reputedly, an early enthusiast for the Copernican model, although he published nothing on the subject himself. Growing up in Dee's household, Thomas Digges had access to a library containing more than a thousand manuscripts, which he devoured before publishing his own first mathematical work in 1571, the same year that he saw to publication a posthumous book by his father *(Pantometria)*, which gave the first public discussion of Leonard Digges's invention of the telescope. In the preface to the book, Thomas Digges describes how:

> My father, by his continuall painfull practises, assisted with demonstrations mathematicall, was able, and sundry times hath, by proportionall glasses duely situate in convenient angles, not onely discovered things farre off, read letters, numbred peeces of money with the very coyne and superscription thereof cast by some of his freends on purpose upon downes in open fields but also seven miles off declared what hath been doone at that instant in private places.

Thomas also studied the heavens himself, and made observations of a supernova seen in 1572, some of which were used by Tycho Brahe in his analysis of that event.

Thomas Digges and the infinite Universe

Thomas Digges's most important publication, though, appeared in 1576. It was a new and greatly revised edition of his father's first book, now titled *Prognostication Everlasting*, and it included a detailed discussion of the Copernican model of the Universe – the first such description in English. But Digges went further than Copernicus. He stated in the book that the Universe is infinite, and included a diagram which showed the Sun at the centre, with the planets in orbit around it, and indicated a multitude of stars extending to infinity in all directions. This was an astonishing leap into the unknown. Digges gave no reason for this assertion, but it seems highly likely that he had been looking at the Milky Way with a telescope, and that the multitude of stars he saw there convinced him that the stars are other suns spread in profusion throughout an infinite Universe.

But Digges did not devote his life to science any more than Copernicus did, and he didn't follow up these ideas. With his background as the son of a prominent Protestant who had suffered at the hands of Queen Mary, and his links with the Dee household (under the protection of Queen Elizabeth), Thomas Digges became a Member of Parliament (serving on two separate occasions) and adviser to the government. He also served as Muster-Master General to the English forces in The Netherlands between 1586 and 1593, where they were helping the Protestant Dutch to free themselves from the rule of Catholic Spain. He died in 1595. By that time, Galileo Galilei was already an established professor of mathematics in Padua and the Catholic Church was turning against the Copernican model of the Universe because it had been taken up by the heretic Giordano

Bruno, who was embroiled in a long trial which would end with him being burned at the stake in 1600.

Bruno: a martyr for science?

It's worth mentioning Bruno here, before we go back to pick up the threads of the work of Tycho, Johannes Kepler and Galileo, which followed on from the work of Copernicus, because it is often thought that Bruno was burned because of his support for the Copernican model. The truth is that he really *was* a heretic and was burned for his religious beliefs; it was just unfortunate that the Copernican model got tangled up in the whole business.

The principal reason that Bruno, who was born in 1548, came into conflict with the Church was because he was a follower of a movement known as Hermetism. This cult based its beliefs on their equivalent of holy scripture, documents which were thought in the fifteenth and sixteenth centuries to have originated in Egypt at the time of Moses, and were linked with the teaching of the Egyptian god Thoth (the god of learning). Hermes was the Greek equivalent of Thoth (hence Hermetism), and to followers of the cult he was Hermes Trismegistus, or Hermes the Thrice Great. The Sun, of course, was also a god to the Egyptians, and there have been suggestions that Copernicus himself may have been influenced by Hermetism in putting the Sun at the centre of the Universe, although there is no strong evidence for this.

This is no place to go into the details of Hermetism (especially since the documents on which it was based later turned out not to originate from Ancient Egypt), but to fifteenth-century believers the documents were interpreted as, among other things, predicting the birth of Christ. In the 1460s, copies of the material on which Hermetism was based were brought to Italy from Macedonia and stirred great interest for well over a century, until it was established (in 1614) that they had been written long after the start of the Christian era and so their 'prophecies' were produced very much with the benefit of hindsight.

The Catholic Church of the late sixteenth century was able to tolerate ancient texts that predicted the birth of Jesus, and such thoroughly respectable Catholics as Philip II of Spain (who reigned from 1556 to 1598, married England's Queen Mary and was a staunch opponent of Protestantism) subscribed to these beliefs (as, incidentally, did John Dee, Thomas Digges's guardian). But Bruno took the extreme view that the old Egyptian religion was the true faith and that the Catholic Church should find a way of returning to those old ways. This, needless to say, did not go down too well in Rome, and after a chequered career wandering around Europe (including a spell in England from 1583 to 1585) and stirring up trouble (he joined the Dominicans in 1565 but was expelled from the order in 1576, and while in England he made so many enemies he had to take refuge in the French Embassy), he made the mistake of visiting Venice in 1591, where he was arrested and handed over to the Inquisition. After a long imprisonment and trial, it seems that Bruno was finally condemned on the specific charges of Arianism (the belief that Christ had been created by God and was not God incarnate) and carrying out occult magical practices. We cannot be absolutely sure, because the records of the trial have been lost; but rather than being a martyr for science, as he is occasionally represented, Bruno was actually a martyr for magic.

Copernican model banned by Catholic Church

Although his fate may seem harsh by modern standards, like many martyrs, Bruno to some extent brought it on himself, since he was given every opportunity to recant (one reason why he was held for so long before being condemned). There is no evidence that his support for Copernicanism featured in the trial at all, but it is clear that Bruno was a keen supporter of the idea of a Sun-centred Universe (because it fitted with the Egyptian view of the world), and that he also enthusiastically espoused Thomas Digges's idea that the Universe is filled with an infinite array of stars, each one like the Sun, and argued that there must be life elsewhere in the Universe. Because Bruno's ideas made such a splash at the time, and because he was condemned by the Church, all these ideas got tarred with the same brush. Moving with its customary slowness, it still took the Church until 1616 to place *De Revolutionibus* on the Index of banned books (and until 1835 to take it off the Index again!). But after 1600 Copernicanism was distinctly frowned upon by the Church, and the fact that Bruno was a Copernican and had been burned as a heretic was hardly encouraging for anyone, like Galileo, who lived in Italy in the early 1600s and was interested in how the world worked. If it hadn't been for Bruno, Copernicanism might never have received such adverse attention from the authorities, Galileo might not have been persecuted and scientific progress in Italy might have proceeded more smoothly.

But Galileo's story will have to wait, while we catch up with the other great development in science in the Renaissance, the study of the human body.

Vesalius: surgeon, dissector and grave-robber

Just as the work of Copernicus built on the rediscovery by Western Europeans of the work of Ptolemy, so the work of Andreas Vesalius of Brussels built on the rediscovery of the work of Galen (Claudius Galenus). Of course, neither of these great works from ancient times was ever really lost, and they were known to the Byzantine and Arabic civilizations even during the Dark Ages in Western Europe; but it was the resurgence of interest in all such writings (typified by the humanist movement in Italy and linked with the fall of Constantinople and the spread of original documents and translations westwards into Italy and beyond associated with the Renaissance) that helped to stir the beginnings of the scientific revolution. Not that this seemed like a revolution to those taking part in its early stages – Copernicus himself, and Vesalius, saw themselves as picking up the threads of ancient knowledge and building from it, rather than overturning the teaching of the Ancients and starting anew. The whole process was much more evolutionary than revolutionary, especially during the sixteenth century. The real revolution, as I have mentioned, lay in the change of mentality which saw Renaissance scholars regarding themselves as the equals of the Ancients, competent to move forward from the teachings of the likes of Ptolemy and Galen – the realization that the likes of

Ptolemy and Galen were themselves only human. It was only with the work of Galileo and in particular Newton that, as we shall see, the whole process of investigation of the world really changed in a revolutionary sense from the ways of the ancient philosophers to the ways of modern science.

Galen was a Greek physician born around AD 130 in Pergamum (now Bergama), in the part of Asia Minor that is now Turkey. He lived until the end of the second century AD, or possibly just into the beginning of the third century. As the son of a wealthy architect and farmer living in one of the richest cities in the Greek-speaking part of the Roman Empire, Galen had every advantage in life and received the finest education, which was steered towards medicine after his father had a dream when the boy was 16, foretelling his success in the field. He studied medicine at various centres of learning, including Corinth and Alexandria, was chief physician to the gladiators at Pergamum for five years from AD 157, then moved to Rome, where he eventually became both the personal physician and friend of the emperor Marcus Aurelius. He also served Commodus, who was the son of Marcus Aurelius and became emperor when his father died in AD 180. These were turbulent times for Rome, with more or less constant warfare on the borders of the Empire (Hadrian's Wall was built a few years before Galen was born), but it was still long before the Empire went into serious decline (the Empire was not divided into Eastern and Western parts until AD 286, and Constantinople wasn't founded until AD 330). Galen, secure at the heart of the Empire, whatever the troubles on its borders, was a prolific writer and, like Ptolemy, summed up the teachings of earlier men who he admired, notably Hippocrates (indeed, the modern idea of Hippocrates as the father of medicine is almost entirely a result of Galen's writings). He was also an obnoxious self-publicist and plagiarist – one of the kindest things he says about his fellow physicians in Rome is to refer to them as 'snotty-nosed individuals'.[1] But his unpleasant personality shouldn't be allowed to obscure his real achievements, and Galen's greatest claim to fame lay in his skill at dissection and the books he wrote about the structure of the human body. Unfortunately (and bizarrely, given the attitude to slaves and gladiatorial games), human dissection was frowned upon at the time, and most of Galen's work was carried out on dogs, pigs and monkeys (although there is evidence that he did dissect a few human subjects). So his conclusions about the human body were mostly based on studies of other animals and were incorrect in many ways. Since nobody seems to have done any serious research in anatomy for the next twelve or thirteen centuries, Galen's work was regarded as the last word in human anatomy until well into the sixteenth century.

The revival of Galen was part of the humanist obsession with all things Greek. In religion, not only the Protestant movement of the sixteenth century but also some Catholics believed that the teaching of God had been corrupted by centuries of interpretation and amendment to Biblical writing since the time of Jesus, and there was a fundamentalist move to return to the Bible itself as the ultimate authority. Part of this involved studying the earliest Greek versions of the Bible rather than translations into Latin. Although the suggestion that nothing worthwhile had happened since ancient times was a little extreme, there was certainly some truth in the idea that a medical text that had been corrupted by passing through several translations (some of those translations had been made from Arabic texts translated from the Greek) and copied by many scribes might be less accurate than one might wish, and it was a landmark event in medicine when Galen’s works were published in the original Greek in 1525. Ironically, since hardly any medical men could read Greek, what they actually studied were new Latin translations of the 1525 edition. But, thanks to these translations and the printing press, Galen’s work was disseminated more widely than ever before over the next ten years or so. Just at this time, the young Andreas Vesalius was completing his medical education and beginning to make a name for himself.

Vesalius was born in Brussels on 31 December 1514, a member of a family with a tradition of medicine – his father was the royal pharmacist to Charles V, the so-called Holy Roman Emperor (actually a German prince). Following in the family tradition, Vesalius went first to the University of Louvain then, in 1533, enrolled to study medicine in Paris. Paris was at the centre of the revival of Galenism, and as well as being taught the works of the master, Vesalius also learned his skill at dissection during his time there. His time in Paris came to an abrupt end in 1536, because of war between France and the Holy Roman Empire (which, as historians are fond of pointing out, was neither holy, Roman, nor an empire; but the name has passed into history), and he returned to Louvain, where he graduated in medicine in 1537. His enthusiasm for dissection and interest in the human body are attested by a well-documented occasion in the autumn of 1536, when he stole a body (or what was left of it) from a gibbet outside Louvain and took it home for study.

5. *Andreas Vesalius. From Vesalius's De Humani* Corporis Fabrica, *1543.*

By the standards of the day, the medical faculty at Louvain was conservative and backward (certainly compared with Paris), but with the war still going on, Vesalius could not return to France. Instead, soon after he graduated, Vesalius went to Italy, where he enrolled as a graduate student at the University of Padua at the end of 1537. This seems to have been merely a formality though, since after being given an initial examination which he passed with flying colours, Vesalius was almost immediately awarded the degree of doctor of medicine and appointed to the faculty at Padua. Vesalius was a popular and successful teacher in the still-new Galenic 'tradition'. But, unlike Galen, he was also an able and enthusiastic dissector of human beings, and in striking contrast to his grave-robbing activities in Louvain, these researches were aided by the authorities in Padua, notably the judge Marcantonio Contarini, who not only supplied him with the bodies of executed criminals, but sometimes delayed the time of execution to fit in with Vesalius's schedule and need for fresh bodies. It was this work that soon convinced Vesalius that Galen had had little or no experience of human dissection and encouraged him to prepare his own book on human anatomy.

The whole approach of Vesalius to his subject was, if not exactly revolutionary, a profound step forward from what had gone before. In the Middle Ages, actual dissections, when undertaken at all, would be carried out for demonstration purposes by surgeons, who were regarded as inferior medical practitioners, while the learned professor would lecture on the subject from a safe distance, literally without getting his hands dirty. Vesalius performed his dissection demonstrations himself, while also explaining to his students the significance of what was being uncovered, and thereby raised the status of surgery first at Padua and gradually elsewhere as the practice spread. He also employed superb artists to prepare large diagrams used in his teaching. Six of these drawings were published in 1538 as the *Tabulae Anatomica Sex (Six Anatomical Pictures)* after one of the demonstration diagrams had been stolen and plagiarized. Three of the six drawings were by Vesalius himself; the other three were by John Stephen of Kalkar, a highly respected pupil of Titian, which gives you some idea of their quality. It is not known for sure, but Stephen was probably also the main illustrator used for the masterwork *De Humani Corporis Fabrica* (usually known as the *Fabrica)*, published in 1543.

6. *A page from Vesalius's* Tabulae Sex, *1538.*

Apart from the accuracy of its description of the human body, the importance of the *Fabrica* was that it emphasized the need for the professor to do the dirty work himself, instead of delegating the nitty gritty of the subject to an underling. In the same vein, it stressed the importance of accepting the evidence of your own eyes, rather than believing implicitly the words handed down from past generations – the Ancients were not infallible. It took a long time for the study of human anatomy to become fully respectable – there remained a lingering disquiet about the whole business of cutting people up. But the process of establishing that the proper study of man is man, in the wider sense, began with the work of Vesalius and the publication of the *Fabrica.* The *Fabrica* was a book for the established experts in medicine, but Vesalius also wanted to reach a wider audience. He produced alongside it a summary for students, the *Epitome*, which was also published in 1543. But having made this mark on medicine and laid down a marker for the scientific approach in general, Vesalius suddenly abandoned his academic career although still not 30 years old.

He had already been away from Padua for a considerable time in 1542 and 1543 (mostly in Basle) preparing his two books for publication, and although this seems to have been an officially sanctioned leave of absence, he never returned to his post. It is not entirely clear whether he had simply had enough of the criticisms his work had drawn from unreconstructed Galenists, or whether he wanted to practise medicine rather than teach it (or a combination of these factors), but armed with copies of his two books Vesalius approached Charles V and was appointed as court physician – a prestigious post which had one principal disadvantage in that there was no provision for the physician to resign during the lifetime of the Emperor. But Vesalius can hardly have regretted his decision, since when Charles V allowed him to leave his service in 1556 (shortly before Charles abdicated) and granted him a pension, Vesalius promptly took up a similar post with Philip II of Spain, the son of Charles V (the same Philip who later sent the Armada to attack England). This turned out not to be such a good idea. Spanish physicians lacked the competence that Vesalius was used to, and initial hostility to him as a foreigner became exacerbated by the growth of the independence movement in the Netherlands, then ruled by Spain. In 1564, Vesalius obtained permission from Philip to go on a pilgrimage to Jerusalem, but this seems to have been an excuse to stop off in Italy and open negotiations with the University of Padua, with a view to taking up his old post there once again. But on his way back from the Holy Land, the ship Vesalius was travelling in encountered severe storms and was delayed sufficiently for supplies to run low, while the passengers also suffered severe seasickness. Vesalius became ill (we don't know exactly what with) and died on the Greek island of Zante, where the ship ran aground, in October 1564, in his fiftieth year. But although Vesalius himself contributed little directly to the achievements of science after 1543, he had a profound influence through his successors in Padua, which led directly to one of the greatest insights of the seventeenth century, William Harvey's discovery of the circulation of the blood.

In a way, Harvey's story belongs in the next chapter. But the line from Vesalius to Harvey is so clear that it makes more sense to follow it to its logical conclusion now, before returning to the development of astronomy in the sixteenth century. Just as this is not a book about technology, I do not intend to dwell on the strictly medical implications of the investigation of the human body. But Harvey's special contribution was not what he discovered (though that was impressive enough) but the way in which he proved that the discovery was real.

Fallopio and Fabricius

The direct line from Vesalius to Harvey involves just two other people. The first was Gabriele Fallopio (also known as Gabriel Fallopius), who was a student of Vesalius in Padua, became professor of anatomy in Pisa in 1548 and came back to Padua as professor of anatomy – Vesalius's old post – in 1551. Although he died in 1562 at the early age of 39, he made his mark on human biology in two ways. First, he carried out his own research on the systems of the human body, very much in the spirit of Vesalius, which, among other things, led to him discovering the 'Fallopian tubes' which still bear his name. Fallopio described these links between the uterus and the ovaries as flaring out at the end like a 'brass trumpet' – a *tuba.* This accurate description somehow got mistranslated as 'tube', but modern medicine seems to be stuck with the inaccurate version of the term.[1] But perhaps Fallopio's greatest contribution to anatomy was his role as the teacher of Girolamo Fabrizio, who became known as Hieronymous Fabricius ab Aquapendente, and succeeded Fallopio to the chair in Padua when Fallopio died.

Fabricius was born on 20 May 1537, in the town of Aquapendente, and graduated from Padua in 1559. He worked as a surgeon and taught anatomy privately until he was appointed to the chair in Padua in 1565 – the post had been left vacant for three years following Fallopio's death, so Fabricius was Fallopio's direct successor, in spite of the gap. It was during this gap that Vesalius opened negotiations to take up the post, and if it hadn't been for his ill-fated trip to Jerusalem he would probably have got the job ahead of Fabricius. A lot of Fabricius's work concerned embryology and the development of the foetus, which he studied in hens' eggs, but with the benefit of hindsight we can see that his most important contribution to science was the first accurate and detailed description of the valves in the veins. The valves were already known, but Fabricius investigated them thoroughly and described them in detail, first in public demonstrations in 1579 and later in an accurately illustrated book published in 1603. But his skill as an anatomist in describing the valves was not matched by any notable insight into their purpose – he thought they were there to slow down the flow of blood from the liver to allow it to be absorbed by the tissues of the body. Fabricius retired in 1613, because of ill health, and died in 1619. By then, however, William Harvey, who studied under Fabricius in Padua from some time in the late 1590s to 1602, was well on the way to explaining how the blood circulation system really worked.

William Harvey and the circulation of the blood

Before Harvey, the received wisdom (going right back to Galen and earlier times) was that blood was manufactured in the liver and carried by the veins throughout the body to provide nourishment to the tissues, getting used up in the process, so that new blood was constantly being manufactured. The role of the arterial system was seen as carrying 'vital spirit' from the lungs and spreading it through the body (actually, not so far from the truth given that oxygen would not be discovered until 1774). In 1553, the Spanish theologian and physician Michael Servetus (born in 1511, and christened Miguel Serveto) referred in his book *Christianismi Restitutio* to the 'lesser' circulation of the blood (as it was later known) in which blood travels from the right-hand side of the heart to the left-hand side of the heart via the lungs, and not through tiny holes in the dividing wall of the heart, as Galen had taught. Servetus reached his conclusion largely on theological grounds, not through dissection, and presented them almost as an aside in a theological treatise. Unfortunately for Servetus, the theological views he expressed here (and in earlier writings) were anti-Trinitarian. Like Giordano Bruno, he did not believe that Jesus Christ was God incarnate and he suffered the same fate as Bruno for his beliefs, but at different hands. John Calvin was at the height of his reforming activity at the time, and Servetus had written to him (in Geneva) about his ideas. When Calvin stopped replying to his letters, Servetus, based in Vienna, continued to send a stream of increasingly vituperative correspondence. This was a big mistake. When the book was published Calvin contacted the authorities in Vienna and had the heretic imprisoned. Servetus escaped and headed for Italy, but made the further mistake of taking the direct route through Geneva (you would have thought he would have had more sense), where he was recognized, recaptured and burned at the stake by the Calvinists on 27 October 1553. His books were also burned, and only three copies of *Christianismi Restitutio* survive. Servetus had no influence on the science of his times, and Harvey knew nothing of his work, Even the way Harvey became interested in the problem shows how things had changed since the days when philosophers would dream up abstract hypotheses about the workings of the natural world based on principles of perfection rather than on observation and experience. Harvey actually measured the capacity of the heart, which he described as being like an inflated glove, and worked out how much blood it was pumping into the arteries each minute. His estimates were a little inaccurate, but good enough to make the point. In modern units, he worked out that, on average, the human heart pumped out 60 cubic centimetres of blood with every beat, adding up to a flow of almost 260 litres an hour – an amount of blood that would weigh three times as much as an average man. Clearly, the body could not be manufacturing that much blood and there must really be a lot less continuously circling through the veins and arteries of the body. Harvey then built up his case, using a combination of experiments and observation. Even though he could not see the tiny connections between the veins and the arteries, he proved they must exist by tightening a cord (or ligature) around an arm. Arteries lie deeper below the surface of the arm than veins, so by loosening the ligature slightly he allowed blood to flow down the arm through the arteries while the cord was still too tight to allow blood to flow back up the arm through the veins, and so the veins below the ligature became swollen. He pointed out that the rapidity with which poisons can spread throughout the entire body fitted in with the idea that the blood is continually circulating. And he drew attention to the fact that the arteries near the heart are thicker than those further away from the heart, just as would be required to withstand the greater pressure produced near the heart by the powerful ejection of blood through its pumping action.

But don’t run away with the idea that Harvey invented the scientific method. He was, in truth, more of a Renaissance man than a modern scientist, and still thought in terms of vital forces, an abstract conception of perfection and spirits that kept the body alive. In his own words (from the 1653 English translation of his book):

> In all likelihood it comes to pass in the body, that all the parts are nourished, cherished, and quickned with blood, which is warm, perfect, vaporous, full of spirit, and, that I may so say, alimentative: in the parts the blood is refrigerated, coagulated, and made as it were barren, from thence it returns to the heart, as to the fountain or dwelling-house of the body, to recover its perfection, and there again by natural heat, powerful and vehement, it is melted, and is dispens’d again through the body from thence, being fraught with spirits, as with balsam, and that all things do depend upon the motional pulsation of the heart: So the heart is the beginning of life, the Sun of the Microcosm, as proportionably the Sun deserves to be call’d the heart of the world, by whose virtue, and pulsation, the blood is mov’d perfected, made vegetable, and is defended from corruption, and mattering: and this familiar household-god doth his duty to the whole body, by nourishing, cherishing, and vegetating, being the foundation of life, and author of all.

This is very far from the common misconception that Harvey was the person who first described the heart as *only* a pump that keeps the blood circulating around (it was actually René Descartes who took that step, suggesting in his *Discourse on Method*, published in 1637, that the heart is a purely mechanical pump). Nor is it the whole truth simply to say, as many books do, that Harvey saw the heart as the source of the blood’s heat. His views were more mystical than that. But Harvey’s work was still a profound step forward, and throughout his surviving writings (many of his papers were lost, unfortunately, when his London rooms were ransacked by Parliamentary troops in 1642) there is a repeated emphasis on the importance of knowledge derived from personal observation and experience. He specifically pointed out that we should not deny that phenomena exist just because we do not know what causes them, so it is appropriate to look kindly on his own incorrect ‘explanations’ for the circulation of the blood and to focus on his real achievement in discovering that the blood does circulate. Although Harvey’s idea was by no means universally accepted at first, within a few years of his death, thanks to the development of the microscope in the 1650s, the one gap in his argument was plugged by the discovery of the tiny connections between arteries and veins – a powerful example of the connection between progress in science and progress in technology.

But if Harvey was, as far as scientific history is concerned, one of the last of the Renaissance men, that doesn’t mean we can draw a neat line on the calendar after his work and say that proper science began then, in spite of the neat coincidence of the timing of his death and the rise of microscopy. As the example of the overlap of his publications with those of Descartes highlights, history doesn’t come in neat sections, and the person who best fits the description of the first scientist was already at work before Harvey had even completed his studies in Padua. It’s time to go back to the sixteenth century and pick up the threads of the developments in astronomy and the mechanical sciences which followed on from the work of Copernicus.

2

The Last Mystics

The movement of the planets – Tycho Brahe – Measuring star positions – Tycho's supernova – Tycho observes comet – His model of the Universe – Johannes Kepler: Tycho's assistant and inheritor – Kepler's geometrical model of the Universe – New thoughts on the motion of planets: Kepler's first and second laws – Kepler's third law – Publication of the Rudolphine star tables – Kepler's death

The movement of the planets

The person who most deserves the title or 'first scientist' was Galileo Galilei, who not only applied what is essentially the modern scientific method to his work, but fully understood what he was doing and laid down the ground rules clearly for others to follow. In addition, the work he did following those ground rules was of immense importance. In the late sixteenth century, there were others who met some of these criteria – but the ones who devoted their lives to what we now call science were often still stuck with a medieval mindset about the relevance of all or part of their work, while the ones who most clearly saw the, for want of a better word, philosophical significance of the new way of looking at the world were usually only part-time scientists and had little influence on the way others approached the

the eclipse, but the fact that the event had been predicted long before, from the tables of observations of the way the Moon seems to move among the stars – tables going back to ancient times but modified by later observations, particularly by Arabian astronomers. It seemed to him 'as something divine that men could know the motions of the stars so accurately that they could long before foretell their places and relative positions'.[1]

Tycho spent most of the rest of his time in Copenhagen (just over eighteen months) studying astronomy and mathematics, apparently indulged by his uncle as a phase he would grow out of. Among other things, he bought a copy of a Latin edition of the works of Ptolemy and made many notes in it (including one on the title page recording that he purchased the book, on the last day of November 1560, for two thaler).

In February 1562, Tycho left Denmark to complete his education abroad, part of the usual process intended to turn him into an adult fit for his position in society. He went to the University of Leipzig, where he arrived on 24 March, accompanied by a respectable young man called Anders Vedel, who was only four years older than Tycho but was appointed by Joergen as his tutor, to act as a companion and (it was clearly understood) to keep the younger man out of mischief. Vedel was partly successful. Tycho was supposed to study law in Leipzig, and he did this work with reasonable diligence. But his great academic love was still astronomy. He spent all his spare money on astronomical instruments and books, and stayed up late making his own observations of the heavens (conveniently, when Vedel was asleep). Even though Vedel held the purse strings, and

Tycho had to account to him for all his expenditure, there was little the elder man could do to curb this enthusiasm, and Tycho's skill as an observer and knowledge of astronomy increased more rapidly than his knowledge of law.

Measuring star positions

When Tycho became more knowledgeable about astronomy, though, he realized that the accuracy with which men seemed to 'know the positions of the stars' was much less impressive than he had thought at first. In August 1563, for example, a conjunction of Saturn and Jupiter took place – a rare astronomical event in which the two planets are so close together on the sky that they seem to merge. This had great significance for astrologers,[1] had been widely predicted and was eagerly anticipated. But while the actual event occurred on 24 August, one set of tables was a whole month late in its prediction and even the best was several days in error. At the very start of his career in astronomy, Tycho took on board the point which his immediate predecessors and contemporaries seemed unwilling to accept (either out of laziness or too great a respect for the Ancients) – that a proper understanding of the movement of the planets and their nature would be impossible without a long series of painstaking observations of their motions relative to the fixed stars, carried out to a better accuracy than any such study had been carried out before. At the age of 16, Tycho's mission in life was already clear to him. The only way to produce correct tables of the motions of the planets was by a prolonged series of observations, not (as Copernicus had) by taking the odd observation now and then and adding them more or less willy-nilly to the observations of the Ancients.

Remember that the instruments used to make observations in those days, before the development of the astronomical telescope, required great skill in their construction and even greater skill in their use (with modern telescopes and their computers, it is the other way around). One of the simplest techniques used by Tycho in 1563 was to hold a pair of compasses close to his eye, with the point of one leg of the pair on a star and the other point on a planet of interest – say, Jupiter. By using the compasses set with this separation to step off distances marked on paper, he could estimate the angular separation of the two objects on the sky at that time.[2] But he needed much better accuracy than this could provide. Although the details of the instruments he used are not crucial to my story, it is worth mentioning one, called a cross-staff or radius, which Tycho had made for him early in 1564. This was a standard kind of instrument used in navigation and astronomy in those days, consisting basically of two rods forming a cross, sliding at right angles to one another, graduated and subdivided into intervals so that by lining up stars or planets with the ends of the cross pieces it was possible to read off their angular separation from the scale. It turned out that Tycho's cross-staff had not been marked up correctly, and he had no money to get it recalibrated (Vedel was still trying to do his duty by Joergen Brahe and keep Tycho from spending all of his time and money on astronomy). So Tycho worked out a table of corrections for the instrument from which he could read off the correct measurement corresponding supported by a wealth of observational facts, his writing style was largely impenetrable, although the book did contain a few striking examples. One of the best of these concerns the Roman roads still visible in Europe some 2000 years after they were laid down, in spite of the natural processes of erosion going on all that time. Clearly, Hutton pointed out, the time required for natural processes to carve the face of the Earth into its modern appearance must be vastly longer – certainly much longer than the 6000 years or so allowed by the then-standard interpretation of the Bible. Hutton regarded the age of the Earth as beyond comprehension, and in his most telling line wrote ‘we find no vestige of a beginning – no prospect of an end’.

Such flashes of clarity were rare in the book, though, and with Hutton dead and no longer around to promote his ideas, which came under renewed and vigorous attack from the Neptunists and Wernerians, they might have languished if it had not been for his friend John Playfair (1748–1819), then professor of mathematics at Edinburgh University (and later professor of natural philosophy there). Picking up the baton, Playfair wrote a masterly, clear summary of Hutton’s work, which was published in 1802 as *Illustrations of the Huttonian Theory of the Earth.* It was through this book that the principle of uniformitarianism first reached a wide audience, convincing all those with wit to see the evidence that here was an idea that had to be taken seriously. But it literally took a generation for the seed planted by Hutton and Playfair to flower, since the person who picked up the baton of uniformitarianism from Playfair was born just eight months after Hutton died.

Book Four

THE BIG PICTURE

9

The ‘Darwinian Revolution’

Charles Lyell: his life – His travels in Europe and study of geology – He publishes the Principles of Geology – Lyell’s thoughts on species – Theories of evolution: Erasmus Darwin and Zoonomia *– Jean-Baptiste Lamarck: the Lamarckian theory of evolution – Charles Darwin: his life – The voyage of the Beagle – Darwin develops his theory of evolution by natural selection – Alfred Russel Wallace – The publication of Darwin’s* Origin of Species.

There were many dramatic developments in science in the nineteenth century, but undoubtedly the most important of these in terms of understanding the place of humankind in the Universe (and arguably the most important idea in the whole of science) was the theory of natural selection, which, for the first time, offered a scientific explanation of the fact of evolution. The name of Charles Darwin is forever linked with the idea of natural selection, and rightly so; but two other names, Charles Lyell and Alfred Russel Wallace, deserve to stand either side of his at the centre of the evolutionary stage.

Charles Lyell came from a well-off family, but the wealth was scarcely two generations old. It originated with his grandfather, also Charles Lyell, who had been born in Forfarshire, Scotland, in 1734. This Charles Lyell was the son of a farmer, but after his father died he was apprenticed as a book-keeper before joining the Royal Navy in 1756 as an able-bodied seaman. His former training helped him to become successively a captain's clerk, gunner's mate and then midshipman, the first step on the road to becoming an officer. But he was not to be another Nelson, and in 1766 he became purser of HMS *Romney.* Fans of Horatio Hornblower and the novels of Patrick O'Brien will appreciate that the job of purser gave opportunities for even an honest man to line his pockets – the purser was responsible for purchasing supplies for his ship, which he sold at a profit to the Navy; grandfather Lyell went even further than most by joining a business partnership to supply Navy ships in the ports of North America. In 1767, he married Mary Beale, a Cornish girl, and in 1769 she gave birth (in London) to another Charles Lyell, who was to become the father of the geologist. By 1778, the elder Charles Lyell was secretary to Admiral John Byron and purser of his flagship, HMS *Princess Royal.* As a result of the action which Byron's fleet saw against the French during the American War of Independence (the French navy's assistance to the rebel cause was instrumental in ensuring that the British lost that war), Lyell received so much prize money[1] that, combining it with his other earnings, in 1782, three years after retiring from the Navy, he was able to buy estates in Scotland running to 5000 acres and including a fine house at Kinnordy, in Forfarshire (now Angus). His son had been educated in a manner fitting the elder Lyell's growing status and spent just over a year at St Andrews University before moving to Peterhouse, Cambridge, in 1787.

The second Charles Lyell was well educated (he graduated in 1791 and then studied law in London) and well travelled, including a long tour of Europe carried out in 1792, visiting Paris when France was in the turmoil of Revolution. In 1794, he became a Fellow of Peterhouse, a useful connection for an aspiring lawyer, but he remained based in London until his father died in January 1796, in his sixty-second year. With no need now to practise law, the second Charles Lyell married a Miss Frances Smith later that year, and moved to Kinnordy, where Charles Lyell the geologist was born on 14 November 1797.

Charles and Frances Lyell never settled in Scotland, however, and before baby Charles was a year old they had moved to the south of England,[2] renting a large house and some land in the New Forest, not far from Southampton. It was there that young Charles grew up, surrounded by younger siblings (eventually, two brothers and no less than seven sisters). The New Forest provided a backdrop for the boy to develop an interest in botany and insects while attending school locally, but in 1810 he moved on to a minor public school at Midhurst, together with his younger brother Tom. Tom left in 1813 to become a midshipman, but Charles, as the eldest son, was groomed to follow in his father's footsteps.

After visiting Scotland in 1815 with his parents and sister Fanny (an extended tour, but taking in the family estates he would one day inherit), Charles went up to Oxford in February 1816, joining Exeter College as a gentleman commoner, the most prestigious (and expensive) ‘rank’ of undergraduate. He took with him a reputation for academic excellence in the traditional arts-oriented subjects, and arrived at a university that was just (only just) beginning to shake off its well-deserved reputation as an institution only fit for the education of country parsons.[1] Lyell found in himself an unsuspected mathematical ability and became interested in geology after he read a book in his father’s library, Robert Bakewell’s *Introduction to Geology*, either late in 1816 or early in 1817. Bakewell was an advocate of Hutton’s ideas, and it was through reading Bakewell that Lyell was introduced to Hutton’s work and went on to read Playfair’s book. This was the first time he had any clue that a subject like geology existed, and he then attended some lectures on mineralogy given by William Buckland (1784–1856) at Oxford in the summer term of 1817. Buckland in his turn had been inspired by the pioneering work of William Smith (1769–1839), a surveyor whose work on canals in the late eighteenth and early nineteenth centuries made him familiar with the rock strata of England and an expert in the use of fossils to indicate the relative ages of different strata (which were older and which were younger), even though there was no way at that time to tell their absolute ages. It was Smith, now regarded as the ‘father of English geology’, who produced the first geological map of England, which was published in 1815, although much of his material had already been circulated to colleagues such as Buckland. Buckland himself had been on a long geological expedition features into France was also being mapped), and it was obvious that rock layers had been twisted and bent, after they were laid down, by immense forces. It was natural to suppose that these forces, and the forces which had lifted what were clearly once sea beds high above sea level, were associated with earthquakes. But in spite of Hutton's insight, the widely held opinion, championed by geologists such as William Conybeare (1787–1857), was that the changes had been brought about by short-lived, violent convulsions, and that the kind of processes now seen at work on the surface of the Earth were inadequate for the task. In the early 1820s, Lyell was intrigued by these arguments, though still more impressed by Hutton's ideas, and learned a great deal about cutting-edge geology from Conybeare's writings.

Lyell did actually keep up his legal studies just enough to be called to the Bar in May 1822, and later he did practise (for a short time and in a rather desultory fashion) as a barrister. But in 1823 he not only visited Paris once again (this time meeting Cuvier, still a confirmed catastrophist) but became involved in the running of the Geological Society, first as Secretary and later as Foreign Secretary; much later, he also served two terms as President. Apart from its scientific importance (Lyell attended several lectures at the Jardin, as well as meeting French scientists), the 1823 trip is significant historically because it was the first time that Lyell crossed the English channel in a steamship, the packet *Earl of Liverpool*, which took him direct from London to Calais in just eleven hours, with no need to wait for a fair wind. A small technological step, to be sure, but one of the first signs of the speeding up of global communications that was about to change the world.

Lyell's own world began to change in 1825, the year that he began his practice as a barrister. He was asked to write for the *Quarterly Review*, a magazine published by John Murray, and began to contribute essays and book reviews (themselves really an excuse for an essay) on scientific topics and issues such as the proposal for a new university in London. He turned out to have a talent for writing, and, even better, the *Quarterly* paid for its contributions. Lyell's legal work brought him very little income (it is not clear whether he actually earned enough to cover his expenses in the profession) and writing enabled him, for the first time, to achieve a degree of financial independence from his father – not that there was any pressure on him from his father to do so, but still a significant step for the young man. The *Quarterly* also brought Lyell's name to the attention of a wider circle of educated people, which opened up other prospects. Having discovered his talent as a writer, early in 1827 he decided to write a book about geology and began to gather material for this project. So the idea for the book already existed, and Lyell had already proved his worth as a writer, before he set out on his most important, and famous, geological expedition, in 1828.

His travels in Europe and study of geology

The expedition has echoes of John Ray's great botanical expedition of the previous century, showing how little things had yet changed in spite of the steam packet. In May 1828, Lyell travelled first to Paris, where he had arranged to meet the geologist Roderick Murchison (1792–1871), and together they then travelled south through the Auvergne and along the Mediterranean coast to northern Italy, with Lyell making extensive notes on the geological features that they encountered. Murchison (who was accompanied by his wife) set off back to England from Padua at the end of September, while Lyell pressed on towards Sicily, the nearest location of volcanic and earthquake activity to mainland Europe. It was what Lyell saw in Sicily, in particular, that convinced him that the Earth had indeed been formed by the same processes that are at work today, operating over immense spans of time. It was Lyell's field work that put flesh on the bones of the idea outlined by Hutton. On Etna, among other things, he found raised sea beds '700 feet & more' above sea level, separated with lava flows, and in one place:

> A very strong illustration of the length of the intervals which occasionally separated the flows of distinct lava currents. A bed of [fossilized] oysters, perfectly identifiable with our common eatable species, no less than *twenty feet in thickness*, is there seen resting on a current of basaltic lava; upon the oyster bed again is superimposed a second mass of lava, together with tuff or peperino.
>
> ... we cannot fail to form the most exalted conception of the antiquity of this mountain [Etna], when we consider that its base is about ninety miles in circumference; so that it would require ninety flows of lava, each a mile in breadth at their termination, to raise the present foot of the volcano as much as the average height of one lava-current.[1]

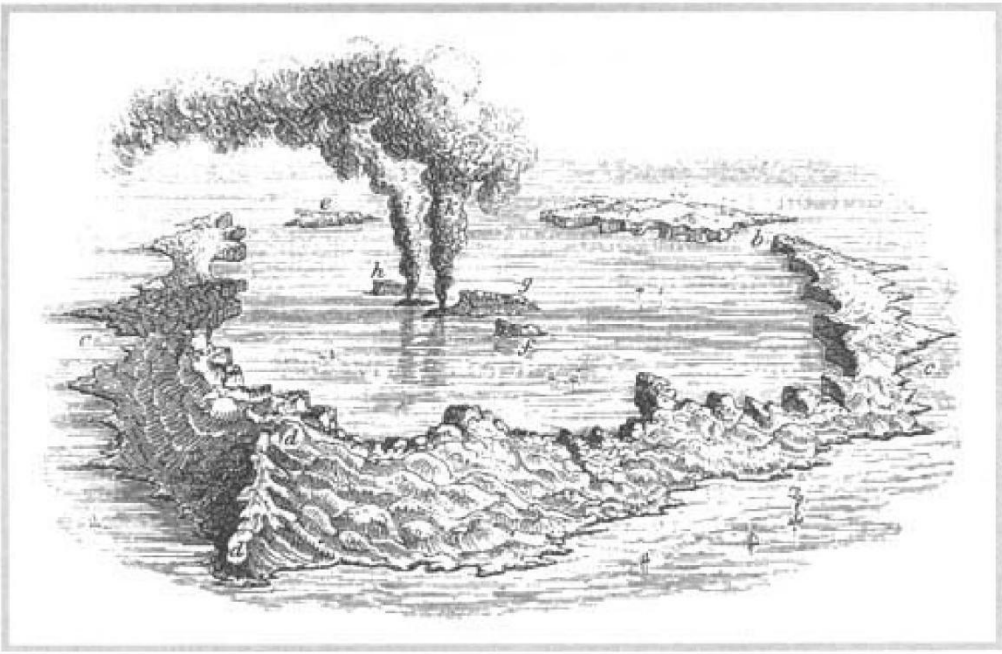
It was this kind of clear writing, as well as the weight of evidence he gathered in support of his case, that made Lyell's book such an eye-opener, both to geologists and to the educated public.

Lyell also realized that since Etna (and, indeed, the whole of Sicily) was relatively young, the plants and animals found there must be species that had migrated from Africa or Europe and adapted to the conditions they found. By adapting to the changing environments of our planet, life itself must be moulded in some way by geological forces, although he was unable to say just how this happened.

He publishes the Principles of Geology

By February 1829, Lyell was back in London and, with his eyesight as good as it had ever been after his long journey away from his legal documents and enjoying a great deal of physical activity, he lost no time in getting down to work on his book. As well as his own field studies, Lyell drew extensively on the work of geologists from across continental Europe, producing by far the most thorough overview of the subject that anyone had yet written. John Murray, the publisher of the *Quarterly*, was the obvious choice to put the material before the public, and although Lyell kept rewriting his work even after it had been sent to the printers, the first volume of the *Principles of Geology* (a name deliberately chosen to echo Newton's *Principia)* appeared in July 1830, and was an immediate success.[2] Although Lyell often bickered with Murray about the financial side, the publisher actually treated his author well, by the standards of the day, and it was Lyell's income from the book that eventually made him financially independent, although his father continued to provide an allowance. After more field work (this time chiefly in Spain), the second volume of the *Principles* appeared in January

1832 and was not only a success in its own right, but revived the sales of the first volume.



28. *Sketch of Santorini, from Lyell's* Principles of Geology, Volume 2., 1868.

The delay between the publication of the two volumes wasn't just caused by the field work. In 1831, a chair of geology was established at King's College in London, and Lyell successfully sought the appointment (in spite of some opposition by Church representatives concerned about his views on the age of the Earth), giving a series of highly successful lectures (in a daring innovation, women were allowed to attend some of them), but resigning in 1833 to devote himself to his writing, which he with the spirit of his times, though, Lyell reserved a special place for humankind, regarding our species as unique and distinct from the animal kingdom. But he *did* suggest that the reason why species went extinct was because of competition for resources, such as food, from other species.

The third volume of the *Principles* appeared in April 1833. Lyell's work for the rest of his life revolved around keeping the massive book up to date, rewriting it and bringing out new editions hot on the heels of one another – the twelfth and final edition appeared posthumously in 1875, Lyell having died in London on 22 February that year (less than two years after the death of his wife), while working on what turned out to be his last revisions for the book. His *Elements of Geology*, which appeared in 1838 and is regarded as the first modern textbook of geology, was based on the *Principles*, and itself underwent refinements. This eagerness for revision wasn't just because geology really was a fast-moving subject at the time;[1] Lyell's obsession with keeping the book bang up to date derived from the fact that it was his main source of income (certainly until his father died in 1849, the year of the California Gold Rush), both from its own sales and in terms of maintaining his profile as a science writer and, by general acclaim, the leading geologist of his time. Lyell was knighted in 1848 and became a baronet (a kind of hereditary knight) in 1864. Although he by no means ceased to be an active field geologist after 1833, he was then in his mid-thirties, and it was with the *Principles* and the *Elements* that he made his mark on science; there is no need to say much here about his later life, except (as we shall see) in the context of his relationship with

Charles Darwin. But it is worth mentioning one of Lyell's later geological field trips, which shows how the world was changing in the nineteenth century. In the summer of 1841, he went on a year-long visit to North America (by steamship, of course), where he not only encountered new geological evidence for the antiquity of the Earth and saw the forces of nature at work in such places as Niagara Falls, but was pleasantly surprised by the ease with which the new railways made it possible to travel across what had until very recently been unknown territory. He also gave hugely popular public lectures and boosted the sales of his books in the New World. Lyell enjoyed the experience so much that he returned for three later visits, and as a result of his first-hand knowledge of the United States became an outspoken supporter of the Union during the American Civil War (when most people of his social position in Britain supported the Confederates). But everything that Lyell did in later life was overshadowed by the *Principles*, and even the *Principles* has tended to be overshadowed in the eyes of many people by a book which, its author acknowledged, owed an enormous debt to Lyell's book – Charles Darwin's *Origin of Species.* Darwin was the right man, in the right place, at the right time to gain the maximum benefit from the *Principles.* But, as we shall see, this was not entirely the lucky fluke that it is sometimes made out to be.

There was nothing new about the idea of evolution by the time Charles Darwin came on the scene. Evolutionary ideas of a sort can be traced back to the Ancient Greeks, and even within the time frame covered by this book, there were notable discussions about the way species change by Francis Bacon in 1620 and a little later by the mathematician Gottfried Wilhelm Leibnitz; while in the eighteenth century, Buffon, puzzling over the way similar but subtly different species occur in different regions of the globe, speculated that North American bison might be descended from an ancestral form of European ox that migrated there, where ‘they received the impression of the climate and in time became bisons’. What was different about Charles Darwin (and Alfred Russel Wallace) was that he came up with a sound scientific theory to explain why evolution occurred, instead of resorting to vague suggestions such as the idea that it might be due to ‘the impression of the climate’. Before Darwin and Wallace, the best idea about how evolution might work (and it really was a good idea, given the state of knowledge at the time, although it has sometimes been ridiculed by those who have the benefit of hindsight) was thought up by Charles Darwin’s grandfather, Erasmus, at the end of the eighteenth century, and (independently) by the Frenchman Jean-Baptiste Lamarck at the beginning of the nineteenth century.

Theories of evolution: Erasmus Darwin and Zoonomia

The association between the Darwin family and the mystery of life on Earth actually goes back one generation further still, to the time of Isaac Newton. Robert Darwin, the father or Erasmus, lived from 1682 to 1754 and was a barrister who retired from his profession and settled in the family home at Elston, in the English midlands, at the age of 42. He married the same year and Erasmus, the youngest of seven children, was born on 12 December 1731. Several years before settling into domestic bliss, however, in 1718, Robert had noticed an unusual fossil embedded in a stone slab in the village of Elston. The find is now known to be part of a plesiosaur from the Jurassic period; thanks to Robert Darwin, the fossil was presented to the Royal Society, and as a thank you, Robert was invited to attend a meeting of the Royal on 18 December that year, where he met Newton, then President of the Royal Society. Little is known about Robert Darwin's life, but his children (three girls and four boys) were clearly brought up in a household where there was more than average curiosity about science and the natural world.

Erasmus was educated at Chesterfield School (where one of his friends was Lord George Cavendish, second son of the then Duke of Devonshire) before moving on to St John's College, Cambridge, in 1750, partly financed by a scholarship which brought in £16 per year. In spite of the dire state of the university at the time, Erasmus did well, initially in classics, and also gained a reputation as a poet. But his father was not a rich man and Erasmus had to choose a profession where he could make a living. After his first year in Cambridge he began to study medicine; he also became a friend of John Michell, who was then a tutor at Queen's College. His medical studies continued in Edinburgh in 1753 and 1754 (the year his father died), then he went back to Cambridge to obtain his MB in 1755. He may have spent more time in Edinburgh after that, but there is no record of him ever receiving an MD there, although this didn't stop him from adding those letters to his list of qualifications.

Whatever his paper qualifications, Erasmus Darwin was a successful doctor who soon established a flourishing practice at

Lichfield, 24 kilometres north of Birmingham. He also began to publish scientific papers (he was especially interested at the time in steam, the possibilities of steam engines and the way clouds form), and on 30 December 1757, a few weeks after his twenty-seventh birthday, he married Mary Howard (known as Polly), who was herself a few weeks short of her eighteenth birthday. All of this activity, on several fronts simultaneously, is typical of Erasmus Darwin, who certainly lived life to the full. The couple had three children who survived to adulthood (Charles, Erasmus and Robert) and two who died in infancy (Elizabeth and William). The only one who married was Robert (1766–1848), the father of Charles Robert Darwin, of evolution fame. The Charles Darwin who was Erasmus's son was his eldest child, a brilliant student who was the apple of his father's eye and seemed to have a glittering career ahead of him in medicine when, at the age of 20, as a medical student in Edinburgh he cut his finger during a dissection and acquired an infection (septicaemia) from which he died. By then, in 1778, Erasmus junior was already set on the path to becoming a lawyer, but young Robert was still at school and was strongly influenced by his father to become a doctor, which he did successfully, even though he lacked the brilliance of his brother and hated the sight of blood. Erasmus junior also died relatively young, drowned at the age of 40 in what may have been an accident or may have been suicide.

Polly herself had died, after a long and painful illness, in 1770. Although there is no doubt that Erasmus loved his first wife and was deeply affected by her death, when 17-year-old handicapped by the limited state of knowledge at the time. He details the evidence that species have changed in the past, and draws particular attention to the way in which changes have been produced in both plants and animals by deliberate human intervention, for example breeding faster racehorses or developing more productive crops by the process of artificial selection – something that was to be a key feature in the theory developed by his grandson. He also points out the way in which characteristics are inherited by offspring from their parents, drawing attention to, among other things, ‘a breed of cats with an additional claw on every foot’ that he has come across. He elaborates on the way different adaptations enable different species to obtain food, mentioning (in another pre-echo of Charles Darwin) that ‘some birds have acquired harder beaks to crack nuts, as the parrot. Others have acquired beaks adapted to break the harder seeds, as sparrows. Others for the softer seeds…’. Most dramatically of all, Erasmus (clearly a Huttonian!) comes out with his belief that all of life on Earth (by implication including humankind) may be descended from a common source:

> Would it be too bold to imagine, that in the great length of time since the earth began to exist, perhaps millions of ages[1] before the commencement of the history of mankind, would it be too bold to imagine, that all warm-blooded animals have arisen from one living filament, which THE GREAT FIRST CAUSE endued with animality, with the power of acquiring new parts, attended with new propensities …

God still exists for Erasmus, but only as the first cause who set the processes of life on Earth working; there is no place here for a God who intervenes to create new species from time to time, but a clear sense that whatever the origins of life itself, once life existed it evolved and adapted in accordance with natural laws, with no outside intervention.[2] But Erasmus did not know what those natural laws that govern evolution were. His speculation was that changes were brought about in the bodies of living animals and plants by their striving for something they needed (food, say) or to escape from predators. This would be rather like the way in which a weight lifter puts on muscle. But Erasmus thought that these acquired characteristics would then be passed on to the offspring of the individual that acquired them, leading to evolutionary change. A wading bird that didn't like getting its feathers wet, for example, would constantly be stretching up as high as possible to avoid contact with the water, and thereby stretch its legs a tiny bit. The slightly longer legs would be inherited by its offspring, and over many generations this repeating process could turn a bird with legs like a swan into one with legs like a flamingo.

Although this idea was wrong, it was not crazy, given the state of knowledge at the end of the eighteenth century, and Erasmus Darwin deserves credit for at least trying to come up with a scientific explanation for the fact of evolution. He continued (along with many other activities) to develop his ideas for the rest of his life, and 1803 saw the publication of *The Temple of Nature*, which told in verse of the evolution of life from a microscopic speck to the diversity of the present day. Once again, the verse is accompanied by copious notes that amount to a book in their own right. But this time Erasmus did not meet with publishing success; his near atheism and evolutionary ideas were condemned, and were clearly out of step with a society at normal conditions in the late 1940s. But these studies then benefited enormously from the wartime effort to understand nuclear interactions in connection with research into nuclear weapons and the development of the first nuclear reactors. As the appropriate information was declassified, it helped astrophysicists to work out the rates at which interactions like the ones we have just described could go on inside the stars. And, as the work by Alpher, Herman and Gamow highlighted, the problem of the 'mass gaps' for the manufacture of heavier elements step by step from hydrogen and helium, in the 1950s several astronomers looked at the problem of how the heavy elements (which, after all, had to come from somewhere) might be manufactured inside stars. One idea that was aired was the possibility that three helium-4 nuclei (three alpha particles) could come together essentially simultaneously, forming a stable nucleus of carbon-12 without having to manufacture the highly unstable beryllium-8 as an intermediate step. The key insight came from the British astronomer Fred Hoyle in 1953. Rather in the way that 'classical' physics said that two protons could not fuse under the conditions inside a star like the Sun, the simplest understanding of nuclear physics said that such 'triple-alpha' interactions could occur, but would be far too rare to make sufficient amounts of carbon during the lifetime of a star. In most cases, such triple collisions ought to smash the particles apart, not combine them in a single nucleus.

The concept of 'resonances'

The proton fusion puzzle was solved by quantum tunnelling; Hoyle suggested, on the basis of no other evidence than the fact

Atkinson and Houtermans and, in a different context, by Alpher and Herman (this kind of process is also at work in the carbon cycle). Hoyle, Fowler and their British-born colleagues Geoffrey Burbidge (1925–) and Margaret Burbidge (1922–) produced the definitive account of how the elements are built up in this way inside stars in a paper published in 1957.[2] Following this work, astrophysicists were able to model in detail the internal workings of the stars, and by comparing these models with observations of real stars, to determine the life cycles of stars and work out, among other things, the ages of the oldest stars in our Galaxy.

This understanding of nuclear fusion processes operating inside stars explained how all the elements up to iron can be manufactured from the hydrogen and helium produced in the Big Bang. Even better, the proportions of the different elements predicted to be produced in this way match the proportions seen in the Universe at large – the amount of carbon relative to oxygen, or neon relative to calcium, or whatever. But it cannot explain the existence of elements heavier than iron, because iron nuclei represent the most stable form of everyday matter, with the least energy. To make nuclei of even heavier elements – such as gold, or uranium, or lead – energy has to be put in to force the nuclei to fuse together. This happens when stars rather more massive than the Sun reach the end of their lives and run out of nuclear fuel which can generate heat (by the kind of interactions we have just described) to hold them up. When their fuel runs out, such stars collapse dramatically in upon themselves, and as they do so, enormous amounts of

Coda: The Pleasure of Finding Things Out

Science is a personal activity. With very few exceptions, scientists throughout history have plied their craft not through a lust for glory or material reward, but in order to satisfy their own curiosity about the way the world works. Some, as we have seen, have taken this to such extremes that they have kept their discoveries to themselves, happy in the knowledge that they have found the solution to some particular puzzle, but feeling no need to boast about the achievement. Although each scientist – and each generation of scientists – exists and works in the context of their time, building on what has gone before with the aid of the technology available to them, it is as individual people that they make their own contribution. It has therefore seemed natural to me to use an essentially biographical approach to the history of science (at least, for my first attempt at such a history), in the hope of teasing out something of what makes a scientist tick, as well as revealing how one scientific advance led to another. I am aware that this is not an approach that is much favoured by historians today, and that any professional historians who have read this far may accuse me of being old-fashioned, or even reactionary. But if I am old-fashioned, it is because I choose to be so, not because I am unaware that I am out of step. I am also aware that there are almost as many approaches to the study of history as there are historians, and each approach can shed light on the subject. Few, if any, historians would claim that one person's view (or interpretation)

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1. Quoted by Vivian Nutton, in Conrad *et al.* See Bibliography.

1. Quoted by Dreyer, from Gassendi's biography of Tycho, first published in 1654, which drew on Tycho's personal papers.

1. The original peripatetics were the followers (literally!) of Aristotle, but the name was also used by the Italian philosophers of the late sixteenth century.

1. In a letter to his friend Conrad Habicht. See John Stachel, *Einstein's Miraculous Year.*
2. See John Stachel, Einstein's Miraculous Year.