Why Beliefs Matter

Reflections on the Nature of Science

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The growth of science has depended more on
opportunity and vision than on method.

1.1 Early Memories

One of my clearest memories from my time at Cardiff High School for Boys is of my history master, Mr Riddell. At the start of every lesson he would come into the classroom and start dictating at high speed, with the expectation that everything that he said would be copied down faithfully. In the 1950s in that school there was no possibility of rebellion, but many of us could not keep up, and were forced to copy from the boy next to us. I soon learned that good marks in the examination depended on memorizing as long a list of dates as possible. I was therefore not sorry to give up history at the age of fourteen – I took it for granted that I would specialize in the sciences, because my father was the senior mathematics master in the same school. The result was that, like countless other children of that era, I left the school knowing nothing about British history after the death of Queen Elizabeth I in 1603, and nothing at all about the history of other countries.

My later appreciation of history and philosophy was at least partly the result of watching a 1950s television programme called *The Brains Trust*. This was a series of live discussions by a small group of intellectuals, who answered questions submitted by viewers on any topic, with the exception of politics and religion. The older of the two scientists in the group was Julian Huxley, a grandson of Thomas Huxley, also known as 'Darwin's bulldog'. The other was Jacob Bronowski, who later produced an ambitious television series called *The Ascent of Man*, covering the whole of human civilization and science in thirteen episodes. Whenever he spoke in *The Brains Trust* he would pause for several seconds and place the tips of his fingers together very precisely as though to emphasize the depth and precision of his thoughts. In retrospect, it is not clear whether this was a deliberate device to persuade his audience of his profundity, but it certainly succeeded.

The effect of these early influences, and of Bertrand Russell's *History of Western Philosophy*, was to persuade me that science must be understood in an historical context. Once one fully accepts that our ancestors four hundred years ago were just as intelligent as we are, one is forced to ask why their attitudes and beliefs were so different. One reason is our possession of scientific instruments that enable us to investigate in detail aspects of the world that they had no inkling of, ranging from ultraviolet light and radioactivity to the structure of DNA. We should try to keep in mind that much that is obscure to us will seem self-evident to our descendants in a few hundred years' time. We cannot begin to imagine their world-views, but they will be very different from ours.

The notion of a world-view is of fundamental importance in any discussion of people's beliefs, however rational they may appear on the surface. A world-view is a set of fundamental beliefs about reality used to evaluate a wide range of other, more particular, beliefs. World-views are often called metaphysical frameworks in academic circles.[1] Examples include religious belief, Platonism, scientific realism and the belief that other people have rights; we will discuss several of these below.

In 1962, the historian of science Thomas Kuhn published *The Structure of Scientific Revolutions*, which made him a household name in philosophy circles. In this book he introduced the term 'paradigm shift', referring to a fairly sudden change in an attitude or world-view, particularly one arising from a new scientific theory. He argued that paradigm shifts were not fully justifiable in rational terms, and defended this claim by detailed historical examples. Unfortunately his concept of incommensurability was used by others to argue that all world-views are equally valid, a development that Kuhn did not dissociate himself from for many years.

Describing alternative scientific theories as embodying different world-views sounds rather pompous. However, the conceptual revolutions involved in quantum theory and general relativity are so fundamental that the use of the term is perhaps justifiable in those cases. In most situations it is more appropriate to refer simply to the framework in which a discussion is taking place, because one may change from one framework to another with little difficulty.

Another term used in this context is the more literary ‘narrative’. The idea is that people create narratives that bind their lives, or some aspect of their lives, into coherent wholes and provide the bases on which they make their decisions. The consistency of one narrative does not imply the inconsistency of another. All narratives deal with some aspects of reality better than others, and some people manage to switch between them effortlessly depending on the context. Others regard this as dishonest.

There are people who react with extreme hostility to any mention of world-views. They appear to believe that even accepting the *existence of the notion* leads inevitably to cultural relativism. Indeed, a person’s world-view can be prejudiced and unreasonable. If the rational analysis of a world-view (or theory), taking as many considerations as possible into account, leads to bizarre consequences, this forcefully suggests that it should be abandoned, even though it does not *logically* compel one to do so.

> **World-views can be evaluated, compared and changed, but you cannot avoid having one.**

A world-view that depends on rejecting large amounts of evidence about natural processes may be rationally indefensible. For example, young Earth creationism (not exclusively a Christian phenomenon) implies that vast numbers of apparently ancient fossils were built into the strata only a few thousand years ago to deceive us (or test our faith). The logician, philosopher, aristocrat, and statesman Bertrand Russell once pointed out that, if this is accepted, it removes the basis for believing *anything* about the past, because any physical evidence might be a deception. Each of us might have been created five minutes ago, complete with all of our memories. Young Earth creationists may logically, but not reasonably, believe that events after God’s act of creation (often said to have been in 4004 BC) happened at the time they appear to have, while everything that appears to have happened before simply did not do so. Why they believe this is another question, whose answer has more to do with group cohesion than with rational argument.

The Catholic and Anglican churches accept that one should take seriously evidence about the natural world revealed by painstaking scientific investigations. If one rejects the possibility of deliberate deception by an effectively omnipotent superbeing, then it is hard to find reasons for rejecting Darwin’s account of the origin of species. The status of evolution is not diminished by the existence of controversies within the subject, for example about gradualism versus punctuationism. Nor is the acceptance of evolution dependent on explaining the origin of life itself, hidden in the mists of time almost four billion years ago. It is also possible to argue that evolution occurred over this enormous timescale but that its course was guided by God. Many biologists, including Darwin, find this argument unconvincing because of the extreme cruelty of the struggle for survival, but it could be argued that either argument is too anthropocentric.

In this chapter we will discuss two world-views that led to one of the most famous conflicts in the history of science; the traditional view that planets were points in the sky whose movements should be described mathematically by reference to celestial spheres and epicycles, and the new claim by Copernicus that they were physical objects orbiting around the Sun, as was the Earth. At the start of the seventeenth century both positions were reasonable, but today it would require extraordinary contortions to argue in favour of the former. When men have walked on the Moon and space probes have photographed most of the planets and their satellites in great detail, the only way of rejecting all the evidence is to claim a massive long-term fraud by all relevant scientific bodies and governments. Who can believe that the latter are capable of this when they are incompetent in so many other respects?

We will see in Chapter 5 that comparing the world-views of different religions and those of atheists is much harder than the above examples. However, trying to understand the point of view of others is surely a prerequisite for fruitful discussions between the various groups, and many of those involved are visibly not interested in doing so.

1.2 The Scientific Method

Over the last two hundred years science has transformed our everyday lives. We, or at least our children, take air travel, motor cars, mobile phones, refrigerators, computers, and anaesthetics for granted. I still remember my promise in the 1970s to buy a pocket calculator if the price ever fell below £100 – a possibility that I was sure would never materialize. About fifteen years later I was the owner of a calculator that had been given away free in a packet of breakfast cereal! It may have been puny by comparison with today's desktop computers, but it heralded a revolution in personal computing whose end is still nowhere in sight. Within twenty years people's watches may contain a terabyte of memory that will interface seamlessly with any computer that they sit in front of; more likely the future will bring something wholly unexpected – perhaps the replacement of desktop computers by an entirely different technology.

The positive results of the explosion of science and technology are supposedly the result of applying the 'scientific method' to the study of the world. The negative ones are 'of course' unfortunate consequences of human greed, to be resolved by ever more ingenious applications of science. But what exactly is the scientific method and how did it arise? Clearly science is not just another story – its impact is undeniable and huge – but we must avoid telling tales about it that are too simple. On the one hand science is a human creation, whose historical development has depended on the imagination of many brilliant individuals as well as the patient labour of countless others. On the other it has provided knowledge about the world that has survived the theories and even the philosophical outlooks of many of its creators. In spite of the fact that science has far more to offer than we have seen so far, it has little to say about large areas of human experience.

The scientific method is often said to have been the invention of Francis Bacon. He was born in 1561 to a privileged family and rose rapidly in political and legal circles. He gained the favour of King James I and was knighted in 1603. After becoming Lord Chancellor and Baron of Verulam in 1618, his public career suddenly ended in 1621 as the result of a (possibly politically motivated) conviction for accepting bribes. Bacon also wrote several works on science and philosophy, and these had a substantial influence, particularly on the Royal Society, founded in 1660. In these works he emphasized the importance of experiment and observation, as opposed to the scholastic philosophy, in which the truth about the world was supposed to be deducible by detailed argument based upon a few evident facts about the world. Bacon advocated the patient accumulation of quantities of information that could later be used as the foundation on which to build the next layer of knowledge. His idea that the acquisition of knowledge could be incremental and progressive was of great importance for the future of science. William Harvey's investigation into the circulation of blood provides a good example of this, although he owed nothing to Bacon – he announced his theory in 1616, before the publication of Bacons's *Novum Organum* in 1620. Harvey's conclusions were based on extensive dissections, vivisections and other experiments at a time when the existence of invisibly small capillary vessels was no more than a theory.

Bacon argued that science was the process of deriving the laws of nature from a body of observations by induction, the process of inferring a general law from a sufficiently large number of particular instances. While it has merits in some areas of science, in the eighteenth century David Hume pointed out that it was logically flawed. There is no *purely logical* way one can infer from a finite sequence of events in the past that similar events will occur in the future. Even an appeal to the uniformity of the laws of nature is logically flawed; their validity and uniformity in the past does not guarantee that they will remain valid in the future. We all assume this, but not for logical reasons.

Much more recently the philosopher Karl Popper claimed that basing science on induction misrepresents the scientific process and tried to lay down principles governing the way that scientists did or should behave. He argued that intuitive breakthroughs were beyond explanation, but, once obtained, the process of assessment could be carried out rationally, not by the discredited method of induction, but by attempts at refutation. He considered that a scientific theory can never be proved true and that science advances by carrying out critical tests which may prove its falsity, and hence the need for a better theory. Many people still hail Popper as the true prophet of the scientific method, not knowing that serious flaws in his analysis were eventually revealed. The problem was not his insistence that all theories should be regarded as provisional, but the fact that his system gave no basis for using scientific theories with confidence, as in fact we do. If one does not rely on induction what basis can there be for believing that the sun will rise tomorrow or that opening your eyes is necessary to see things? Both beliefs can be justified by scientific theories, but why do we believe that those theories will continue to hold in the future, if not by induction? Another problem is that Popper was unduly concerned with logic – truth and falsity. All current theories are known to be inadequate in certain situations. In real life a failed prediction is often regarded as reducing or clarifying the domain of applicability of a theoretical model, rather than refuting it in an absolute sense.

The weakness of Popper's ideas about refutation may be illustrated by small anomalies in the orbits of Mercury and Uranus that occupied some astronomers in the nineteenth century. According to Popper both should have led to the abandonment of Newton's theory of gravitation. In fact the problem relating to Uranus motivated astronomers to seek a further planet, leading to the discovery of Neptune in 1846 and then Pluto in 1930. In 1859, the French astronomer Le Verrier proposed that the anomalies in the orbit of Mercury could also be explained by the gravitational influence of a small planet, which he named Vulcan, orbiting even closer to the Sun than Mercury did. Sporadic observations of this hypothetical planet over half a century failed to determine consistent orbital parameters – unsurprisingly, since it did not exist. Eventually the anomalies were only resolved by the introduction of general relativity. This example is typical: the failure of a mature theory is usually *but not always* explicable within the framework of the theory itself by the introduction of new considerations that had not previously been thought necessary. Whether or not a new theory is needed can only be decided by the passage of time, possibly after many decades.

The most extreme example of different reactions to radically new theories might be Einstein's theory of general relativity and Wegener's theory of continental drift, both published in 1915. The first was accepted within a very few years even though the evidence supporting it was very slight. Wegener's theory was more or less universally dismissed in spite of the wealth of detailed evidence that he produced in support of it. There seemed to be no mechanism that allowed continents to move and, without this, his theory was rejected as a mere list of coincidences. If Popper's views about the correct way of assessing science had been in vogue at the time, Wegener's theory might have been accepted and Einstein's regarded as very weak. However, the key issue in both cases was not the quantity of relevant evidence but whether the theory could be fitted into a credible general framework. When the framework was forthcoming, as a result of surveys of the ocean floors in the 1960s, attitudes towards Wegener's theory changed very rapidly.

We turn to Paul Feyerabend, a philosopher of science whose views lay far from the main stream of the subject. He was born in Vienna in 1924, but moved from one country to another frequently during his life. He studied under Popper in the 1950s, but later renounced Popper's views as mere propaganda. Feyerabend's first book *Against Method* was published in 1975, and contained two major arguments, which we discuss below in turn. Both arguments were anarchistic in character, but they were not equally good.

A large part of *Against Method* was a sustained argument against the existence of something called 'the scientific method'. Feyerabend concluded from his analysis of a variety of particular cases that 'the only principle that does not inhibit progress is: *anything goes*'. In other words scientific progress is measured by its eventual success, not by the nature or quality of the reasoning used *en route*. This was totally out of line with the views of Popper, Lakatos, and most other philosophers at the time that Feyerabend was writing. In true anarchistic style, he later denied that it was a valid principle. Since I agree to a substantial extent with this aspect of *Against Method*, I should emphasize that I strongly disagree with his other major thesis.

This was to be further developed in *Science in a Free Society*, which Feyerabend published in 1978 as a reply to the critics of 'Against Method'. Here he endorsed the notion of cultural relativism, that conventional science was just one way of looking at the world, and that it was being imposed on Western society for no good reason. (He later denied being a relativist.) The following is typical of many statements of a similar type in *Against Method*.

> *The theoretical authority of science is much smaller than it is supposed to be. Its social authority, on the other hand, has by now become so overpowering* that political interference is necessary to restore a balanced development. . . . *Such a balanced presentation of the evidence may even convince us that the time is overdue for adding the separation of state and science to the separation of state and church.*[2]

He went on to applaud the actions of the Chinese communists in acting against this scientific chauvinism and in the process (supposedly) improving the practice of medicine. This statement must be taken as support for the so-called 'Cultural Revolution' of Mao Zedong in China between 1966 and 1976, generally regarded as a major disaster. Later he wrote that, objectively speaking, i.e. independently of participation in a tradition, there is not much to choose between humanitarianism and anti-Semitism. It is easy to dismiss such views as ridiculous, or worse, but Feyerabend later said that he was trying to provoke debate and to free up people's minds; he even accused his critics of not having a sense of humour. While there might be an element of truth in this claim, the only response left when someone feels free to disown his own arguments is, ultimately, to ignore him.

Cultural relativism depends on the belief that our interpretations of the world are almost entirely dependent on the cultural context in which we view it. This idea provides some insights, but it is based on the 'blank slate' theory of the mind, in which our responses to situations have no inborn components. In Chapter 2 we will provide evidence that the blank slate theory is simply false. The same criticism applies to what is called postmodernism in literary circles, in which 'deconstruction' of the written word tells one a lot about the intentions of the person writing it but much less about the ostensible topic.

The theoretical physicist Sheldon Glashow has also endorsed the view that scientific progress does not fit neatly into a single pattern, but he has little else in common with Feyerabend. In 2003 he went on a lecture tour of Japan, during which he described a series of important discoveries that arose from chance observations, rather than by the more systematic approach favoured by methodologists. One of these involved Sir William Herschel, best known for his discovery of Uranus in 1781. In 1800 he carried out several experiments to try to understand the heating effect of different colours of light, by using a prism to separate the sun's light into its spectrum. He found that the rays of sunlight at the red end of the spectrum produced a greater heating effect on carefully placed thermometers than did the violet rays at the other end. By chance he noticed that a thermometer placed outside the visible spectrum, beyond the red end, was heated up even more, even though no light was apparently falling on it. This led him to the discovery of infrared light, apparent by its heating effect even though our eyes are not sensitive to it. Herschel's discovery only happened in the context of his enquiry into the heating effect of different colours of light. In the process he revealed a completely unexpected phenomenon that transformed our understanding of light and emphasized the inadequacy of our senses.

The importance of their world-view to scientists is not an accident. Science is a human activity. Scientists, like everyone else, have beliefs, and then try to find evidence to support them. They often persuade others that their discoveries are valid by recasting the process of discovery in the Baconian mold, because scientific journals prefer this. But in fact the beliefs often come first. The obvious example is that of Copernicus, who provided no new observational evidence to support his heliocentric theory; its merit was an economy of description, but this was not initially enough to persuade many to abandon the well entrenched Ptolemaic system. The battles between science and religion have often been about competing world-views, rather than facts. Some now maintain that different world-views can be complementary, but others disagree even about this. Their world-view excludes the possibility that complementary world-views could exist!

1.3 The New Astronomy

When people talk about the 'scientific revolution' they are not referring to the deliberate actions of a group of revolutionaries. They hardly could be when the changes happened over a period of a hundred and fifty years that is traditionally said to start in 1543. Many of the main participants in the events that unfolded, including Newton, had attitudes that were a strange mixture of the old and the new. Nevertheless, whatever they intended, it is now considered that the developments in physics and astronomy during this period were of fundamental importance. The separate revolution that replaced the spiritually loaded alchemy by quantitative chemistry was equally fundamental, but it was not to happen until the end of the eighteenth century.

The scientific revolution is often described without mentioning its heavy dependence on major scientific advances made in the Islamic world over a period of several hundred years, following the foundation of Baghdad in 724. The golden age of science and literature under the Abbasid Caliphate was important for many reasons, but one was the sustained effort to collect books from all over the known world and translate then into Arabic, after which they were made available in many libraries throughout the Islamic empire. Without this, the works of Aristotle would not have become known in the West and the foundations for the scientific revolution there would not have existed. But Islamic scholars did far more than just transmit knowledge from earlier times. At around 1000, al-Biruni used Greek advances in geometry and trigonometry in an original way to measure the size of the earth to an accuracy of better than 1%, five hundred years before comparable accuracy was achieved in the West. Many other advances were made during this period, including the invention of algebra, but we will have to pass them by.

Apart from Copernicus, the leading figures in the scientific revolution of Christian Europe must include Brahe, Kepler, Galileo, Descartes, Newton, and Leibniz. But to restrict it to this short list does a major injustice to many others, including Torricelli, Boyle, Bacon, Hooke, and Huygens. If one includes the biological sciences the list expands even further. The causes and nature of the revolution have been debated for decades, and most of the explanations probably have some degree of truth. The development of printing, the telescope, the microscope, and the pendulum clock were surely important. So was the existence of a decentralized system of city states in Europe, whose wealthy rulers gained prestige by promoting the development of culture, both in the arts and sciences. The voyages of discovery encouraged individual enterprise, while the Reformation decreased the authority of the hierarchical Catholic church. But whatever range of factors was responsible, the development of science during the revolution changed the course of Western civilization profoundly.

Nicolaus Copernicus does not fit the conventional image of a revolutionary. Born in Torun, Poland in 1473, he became a canon at Frauenburg and gradually came to the attention of the Church authorities as an astronomer. But this was only one of many of his activities, which included reform of the coinage in Poland and other administrative, legal and diplomatic duties. In 1514 he was invited to participate in the reform of the calendar, but made little or no contribution. He communicated his idea that the Sun might be the centre of the world (the heliocentric theory) to a number of friends, but delayed publication of his famous book *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Heavenly Spheres) until the year of his death, 1543. The book did not, initially, have a substantial impact. One reason for this was its massive break with accepted conventions. Copernicus proposed a completely new way of thinking about the planets, but it was not based on new observations and did not result in more accurate predictions of their movements in the heavens than did the well-established Ptolemaic system. It also conflicted with the Bible and with Church doctrine at a time when the Church was heavily involved with fighting the Protestant movement. His ideas were by no means ignored, but they did not attract enough support, even among astronomers, for the Church to bother to condemn them until 1616, when *De Revolutionibus* was put on their Index of Forbidden Books.

Tycho Brahe, the most important observational astronomer of the sixteenth century, was among those who did not accept the heliocentric theory of Copernicus. However, two of his discoveries tended to undermine the medieval picture of the heavens.[3] In November 1572 he was among the first to observe a supernova in the constellation Cassiopeia. His systematic observations of this, published a few years later, proved that the supernova was much further away than the moon, contradicting the scholastic view that all transient phenomena were confined to the sub-lunar sphere and that the heavens were perfect and unchangeable. (Note, however, that several previous supernovae had been observed and described in some detail by Chinese, Japanese and Arab astronomers.) His observations of a comet over a period of two months in 1577–78 led him to conclude that it was also considerably further away than the Moon. The movement of the comet through the heavens, watched by people throughout Europe, seemed to be unimpeded by the heavenly spheres, and Brahe came to doubt that the spheres existed.

Johannes Kepler, who was born in 1571 close to Stuttgart, was among the first to support Copernicus openly. In 1589 he went to the nearby University of Tübingen to study theology, but quickly established himself as a mathematician of unusual ability. Michael Mästlin, an astronomy professor in Tübingen, introduced Kepler to the Copernican theory; Mästlin was one of a fairly small number of astronomers who came to support the theory, although cautiously and away from the public eye. Kepler was bolder, and in 1596 published *Mysterium Cosmographicum* (The Cosmic Mystery), supporting the Copernican theory publicly. In 1600 he became an assistant of Brahe. The following year Brahe died rather suddenly, apparently of a urinary infection. However, a recent analysis of a sample of his hair has proved that his death was caused by massive mercury poisoning a day or so before his death. Recent speculations that he might have been murdered, even by Kepler, are almost certain to remain no more than that, because of the extreme unlikelihood of finding any corroborating evidence; Brahe might also have taken medicine containing excessive quantities of mercury. After his death Kepler inherited Brahe's position as Imperial Mathematician in Prague. Equally importantly he obtained full access to Brahe's observational data for the first time, and spent much of the next decade analyzing them.

Kepler's career over the next ten years owed a lot to the liberal attitudes of the Holy Roman Emperor, Rudolf II, in Prague. Although a Catholic, Rudolf tolerated Protestants and supported a wide range of arts and sciences. He also built up a spectacular collection of scientific instruments and other objects. He may have been inadequate politically, but he was a key figure in the Renaissance, allowing a degree of intellectual freedom in his court that was unthinkable in Rome. When Rudolf died in 1612, Kepler was forced to leave Prague and moved frequently from city to city in order to avoid religious persecution. He even had to spend time defending his mother against a charge of witchcraft.

In 1609 Kepler formulated the first ever unification law in physics. In his fundamental treatise *Astronomia Nova* (New Astronomy) he asserted that all bodies, earthly and heavenly, were of one kind, and that their motions should be described by the same laws of physics. He wrote:

> *Indeed all things are so interconnected, involved, and intertwined with one another that after trying many different approaches to the reform of astronomical calculations, some well trodden by the ancients and others constructed in emulation of them and by their example, none other could succeed than are founded upon the motions' physical causes themselves, which I establish in this work.*

This might seem obvious to us, because we have a mass of evidence to support it. Kepler and his contemporaries had almost none when *Astronomia Nova* appeared, and Copernicus had not addressed the issue at all. The prevailing view was that astronomy and mechanics were quite different subjects, which should not be confused with each other. The first described the mathematical form of the orbits of the planets in the sky, while the second attempted to describe the physical motions of bodies on the Earth. Nor was it clear what the laws of motion were, even when applied to earthly bodies. Nevertheless, Kepler used the notion of centre of gravity, taken from mechanics, in his discussion of the effects of gravity on the Moon and

Earth. Although he had no observational evidence to support his conclusions, they were qualitatively completely right.

> *If the Moon and the Earth were not each held back in its own circuit by an animate force or something else equivalent to it, the Earth would ascend towards the Moon by one fifty-fourth part of the interval, and the Moon would descend towards the Earth about fifty three parts of the interval, and there they would be joined together; provided, that is, that the substance of each is of the same density.*

It appears from these passages that he considered that an explanation of the orbits of the primary and secondary planets was needed, but he did not identify gravity as providing this. He supposed that the Sun emitted an immaterial species (somewhat like light) that was dispersed as it got further away from the Sun. This species rotated around the Sun as a result of the Sun's own rotation, and the planets were impelled by it to move in orbits around the Sun. He also argued that the species might well be magnetic in nature.

Kepler's ignorance of the laws of motion gave him no chance of reaching his goal, but he did formulate three rules, each of which made an important statement about planetary orbits. Two of his rules, only called laws much later, were accepted quite quickly, but the most famous one, stating that planets moved in elliptical orbits, was not. The problem was that ellipses had no other role in astronomy, and existing descriptions of the planetary orbits fitted the facts equally well. Moreover Kepler's claim that the Sun was at one focus of each planetary orbit, rather than at its centre, immediately led to questions about the role of the other focus, to which no answer was forthcoming.

Kepler's three rules did not explain the motion of the planets in terms of any laws of motion, but the rules were all eventually incorporated into Newton's theory of gravitation. Contrary to popular belief Newton did not base his theory on the ellipticity of the planetary orbits: he deduced the ellipticity from his theory. Kepler's vision, however, cannot be represented as just a lucky guess. It was based on a deeply felt conviction about the unity of the world and was the key to the Scientific Revolution in physics and astronomy.

The other important astronomer of this period was Galileo Galilei. Born in Pisa in 1564, he spent his adult life in Padua and later in Florence. All three cities were in the direct sphere of influence of Rome, which claimed the right to control what could be said about matters touching on religion; unfortunately Galileo had the courage, or possibly foolishness, to think that he could ignore this fact. He had known about the Copernican theory from quite early in his life, but he taught and defended the Ptolemaic system until after 1600. His public support for the Copernican theory followed the discoveries that he made with his new telescope from 1609 onwards, but a letter to Kepler shows that he was already privately convinced that the theory was correct in 1597.

Galileo's observations were of crucial importance in undermining the Ptolemaic theory. The existence of mountains and craters on the Moon soon came to be accepted, in spite of the very poor optics of the first telescopes. His discovery of sunspots was a further blow to the scholastic belief that heavenly objects were perfect and incorruptible. (Actually the Chinese had been recording sunspots systematically for more than one and a half millennia.) The observation of satellites orbiting around Jupiter, just as the Moon orbited around the Earth, suggested that the Earth and Jupiter might be the same kind of object. The strongest support for the Copernican theory was provided by observations of Venus. If this shone by its own light, as was wrongly thought by Kepler, then it should always appear as a full, circular disc. If, on the other hand, it shone by reflected light, then according to the Ptolemaic theory it would never appear as a full disc. According to the Copernican theory it should appear to be a small, full disc at superior conjunction, when it was close to the Sun in the sky, as a medium sized half disc when it had the greatest angular separation from the Sun in the sky and as a larger thin crescent at inferior conjunction. This is exactly what Galileo saw through his telescope. Interpreting the size of the disc as caused by the distance of Venus from the Earth, he concluded in letters written in December 1610 to Kepler and to Clavius, an elderly and respected German astronomer, that Venus orbited around the Sun.

Galileo's discoveries and his skillful self-promotion made him famous, but also brought his beliefs to the attention of the Church, with results that he did not anticipate. His advocacy was brilliant, but his arguments were regarded as indecisive by the Church because he was not able to provide a direct *physical* proof that the Earth rotated or that it moved around the Sun. Galileo tried hard to detect annual stellar parallaxes – small apparent shifts in the positions of the stars as the Earth moved around the Sun, but he failed – the effect existed but it was much too small to be detectable using the telescopes that he had. The fact that no parallaxes could be observed implied that the stars were *far more* distant than many people were willing to contemplate, if the heliocentric theory was correct. Feyerabend argued at length in *Against Method* that Galileo should not have convinced people according to the 'canons of scientific method' as they existed at that time.

Nevertheless by 1660 the Ptolemaic world-view had been abandoned by most serious astronomers, particularly those outside Italy. There were several reasons for this, one of which is described in more detail on page 22.

The to and fro swinging of a long pendulum actually provides a simple physical proof of the Earth's rotation, but its significance was not appreciated until 1851, when Foucault described the effect. He observed that the plane in which a pendulum swings turns slowly, the precise rate depending on the latitude at which the pendulum is swinging. The effect is perfectly described by Newton's laws of motion, which were not known to Galileo, provided the rotation of the Earth is taken into account. Another effect of the rotation of the Earth was first described by Coriolis in 1835 and was of importance in naval battles during the First World War. When firing shells distances of several kilometres, it was found that, unless adjustments for the Earth's rotation were made, they fell far enough away from the expected position that they missed their target. Whatever Feyerabend and the Church might have thought, the fact that the Earth rotated was believed by everyone long before this physical evidence was forthcoming; the *observational* evidence was regarded as overwhelming long before the nineteenth century.

Galileo made a fatal mistake when he employed his rhetorical skills to ridicule his opponents. Since these included important Jesuit figures and even Pope Urban VIII, his eventual fate was hardly surprising. The Catholic Church was more concerned with maintaining its authority during the Thirty Years War, which raged across Europe between 1618 and 1648, than with engaging in a theological debate with a troublemaker. Eventually the Peace of Westphalia in 1648 heralded the decline of the political influence of the papacy. The steady expansion of trade, newspapers and books made it easier for toleration to grow, particularly in Holland and England; both countries were major maritime trading nations with growing merchant classes. By 1670 it was possible for Newton, Huygens, Hooke, and others to discuss the Earth's motion around the Sun openly, without any fear of being persecuted. Indeed, John Wilkins, later to become one of the founders of the Royal Society and Bishop of Chester, had already published an introduction to the Copernican system in 1640 without affecting his close links with leading Republicans or Royalists.

The growth of religious toleration in England in the 1660s was aided by the fact that Charles II had liberal values and Catholic sympathies even though the country was officially Protestant. In 1656, Oliver Cromwell had decided to re-admit Jews (or at least rich Jewish merchants) into England more than three hundred years after they they had been banished by Edward I, and in 1664 Charles II affirmed their right to worship by exercising his royal prerogative. There were, however, limits to toleration even in England. In 1666 a House of Commons Bill against atheism specifically criticized Thomas Hobbes' book *Leviathan*, which expounded his secular political philosophy; Charles II interceded on his behalf, but Hobbes was forbidden from publishing any further work in England. More importantly the entire Quaker community was persecuted vigorously in England between its formation in the 1650s and the Act of Toleration in 1689.

Today the Catholic Church is usually criticized not for having disagreed with Galileo, but for forcibly preventing him from expressing his views on the Copernican theory; after his trial in 1633, he was confined to house arrest in his villa in Arcetri, near Florence, until his death in 1642. By comparison with the fate of Giordano Bruno, burned at the stake for his heretical religious beliefs rather than for his Copernicanism in 1600, this might be regarded as a moderate punishment. The Inquisition was a Catholic invention, but witches were being put to death in both Catholic and Protestant countries throughout the seventeenth century. We like to think of tolerance and free speech as basic human rights, but the twentieth century shows that these virtues are still practised less than they are preached even in Western democracies.

The treatment of Galileo is still a controversial matter. In 1990 Cardinal Ratzinger, now Pope Benedict XVI, quoted Paul Feyerabend as saying that the 'verdict against Galileo was rational and just'. This statement took a very narrow view of the trial and of the right of the Church to prevent people from expressing seriously held views. A pontifical commission set up by Pope John Paul II adopted a very different attitude from both Feyerabend and Ratzinger when Cardinal Poupard delivered its final report in 1992.

> *It is in that historical and cultural framework, far removed from our own times, that Galileo's judges, unable to dissociate faith from an age-old cosmology, believed quite wrongly that the adoption of the Copernican revolution, in fact not yet definitively proven, was such as to undermine Catholic tradition, and that it was their duty to forbid its being taught. This subjective error of judgment, so clear to us today, led them to a disciplinary measure from which Galileo had much to suffer. These mistakes must be frankly recognized, as you, Holy Father, have requested.*

Pope Benedict's retrogressive statements about a number of similar issues have been criticized widely, and in January 2008 his visit to La Sapienza University in Rome was cancelled as a result of strong protests about his anti-science attitudes by some of the academic staff and students. This prompted a backlash about the denial of free speech in the university. In

March 2008 the Vatican announced that it was to erect a statue of Galileo inside the Vatican walls, finally accepting a judgement that the rest of the world had made centuries before.

1.4 The Mechanical Philosophy

Although Copernicus initiated a new way of thinking about the Sun and planets, he did not contribute any ideas about the physics that maintained the planets in their orbits. On the other hand Galileo made fundamental advances in the new science of mechanics, but never integrated this into his advocacy of the Copernican system. Indeed, while promoting the idea that earthly bodies fell in parabolic paths under the influence of gravity, or moved in straight lines on a horizontal surface, he saw no need for an explanation of the approximately circular orbits of the planets around the Sun. In his view planets moved in circular orbits because circular motion was a natural form. Gravity was not involved. His consequent rejection of any influence of the Moon on the tides convinced almost nobody. Kepler was the first person to see that physics and astronomy should be integrated, but the time was not ripe for his ideas to be implemented.

The first person to make a serious attempt to do this was René Descartes. He was born near Tours in France in 1596 and educated at the Jesuit College of La Flèche in Anjou, but spent the later part of his life in Holland. One of his greatest achievements was to unify algebra and geometry, two subjects that had previously developed largely independently. This synthesis, often called coordinate geometry, would have assured his fame even if he had done nothing else. We have to pass this by and focus on his foundational contributions to philosophy and science. The condemnation of Galileo in 1633 led him to withdraw his treatise *The World* about physics and astronomy from publication. When his more ambitious book *Principles of Philosophy* appeared in 1644, he was careful not to claim that the Earth moved. All motion was relative to some body, so the Earth could be considered to be stationary in the relevant coordinates. But the Sun was also described as a fixed star.

Descartes' main philosophical works were published in the ten years before his death in 1650. These included his *Meditations*, which appeared in several editions. His work led to immediate objections in Holland as well as in France; it was criticized for undermining both the Aristotelean, scholastic philosophy and accepted Christian beliefs. In 1663 his work was put on the Catholic Index of Forbidden Books and in 1671 teaching his philosophy was banned throughout France by order of Louis XIV. In spite of this his ideas were discussed widely and were very influential in demolishing the scholastic system.

The starting point of Descartes' philosophy was his unshakeable conviction in his own existence, expressed in the immortal phrase 'cogito, ergo sum' (I think, therefore I am). From this minimalist position he tried to argue that true knowledge about the world could be obtained because of God's undeceitful nature.

> *Hence you see that once we have become aware that God exists it is necessary for us to imagine that he is a deceiver if we wish to cast doubt on what we clearly and distinctly perceive. And since it is impossible to imagine he is a deceiver, whatever we clearly and distinctly perceive must be completely accepted as true or certain.*

Leibniz was later to mock this claim by pointing out that Descartes' physics was so full of errors that his criterion for truth, 'clear and distinct perception', was, in practice, useless. Modern philosophers agree that this aspect of Descartes' philosophy cannot be taken seriously. In spite of this, his work was of tremendous importance, by posing many of the fundamental questions that were to occupy later generations of philosophers and scientists.

Descartes' mechanical philosophy was based on the idea that the behaviour of all physical bodies could be explained by analyzing them into very small and simple component parts, which moved and interacted according to physical laws. In particular he believed that almost all bodily functions of both animals and people were controlled by physical mechanisms that were capable of being investigated and explained without reference to final causes. These included the digestion of food, the processing of sensations, the formation of memories, even walking and singing when they occurred without the mind attending to them. His mechanical philosophy was to receive powerful support when Robert Hooke published his *Micrographia* in 1665. His microscopic observations revealed the cellular nature of cork, the compound eyes of insects and many other previously unsuspected structures in living beings.

In spite of the above, Descartes allowed one crucial exception. He contrasted the limited capacities of most bodily organs with the open-ended nature of our rational faculties. He considered that the latter could only be explained by our possession of an immaterial soul and supposed that this interacted with the body at the pineal gland, because of its location at the very centre of the brain.

> *Since reason is a universal instrument which can be used in all kinds of situations, whereas organs need some particular disposition for each*

> *particular action, it is morally impossible for a machine to have enough different organs to make it act in all the contingencies of life in the way in which our reason makes us act.*[4]

It is easy to see flaws in his argument today. We know far more than Descartes did about the incredible complexity of the brain, and have not found any structure in it that might allow the 'soul' to influence its operation. Cartesian mind–body dualism might appear to have been abandoned by modern philosophers, but many are still discussing the nature of subjective consciousness and what they called 'qualia' – the difference between sense perceptions as described scientifically and as experienced.

In physics, Descartes proposed the important idea that all bodies continued in motion in a straight line unless acted on by an external force. Circular motion was abolished as a natural kind, and had to be explained by a particular cause. Kepler had said much the same, but both of them proposed explanations of the planetary orbits that only survived as long as they did because nobody before Newton had any better theory. Descartes' laws governing collisions between bodies were so far from the truth that he could not have based them on experimental observations, but they spurred the Dutch polymath Christiaan Huygens and the English mathematician John Wallis to provide the correct laws some decades later.

The applicability of the laws of motion to the planets depended on the gradually strengthening belief, and eventually the conviction, that the celestial bodies were ordinary material objects. In 1672, Giovanni Cassini (who had just become the director of the new Paris observatory) made a major advance by using a parallax measurement of Mars to determine the Earth–Sun distance as 140 million kilometres, tolerably close to the correct value of 149.6 million kilometres; this distance is now called the Astronomical Unit. He probably knew that John Flamsteed in England had obtained a similar value in October 1672, but their relationship was always strained, and he did not refer to this. By settling the absolute scale of the Solar System, the measurements of Cassini and Flamsteed implied that Venus and Mars were similar in size to the Earth, that Jupiter and Saturn were much bigger, and that the Sun was enormous. After Cassini and Hooke had observed the rotation of Jupiter in 1664–1665, it became easier to believe that the Earth also rotated. Wallis regarded this as settled in 1666 and was confident enough to write the following:

> *Now supposing the Earth and Moon, jointly as one Body, carried about by the Sun in the great Orb of the Annual motion; this motion is to be estimated, (according to the Laws of Staticks, in other cases,) by the*

> *motion of the common Center of Gravity of both Bodies. For we use in Staticks, to estimate a Body, or Aggregate of Bodies, to be moved upwards, downwards, or otherwise, so much as its Common Center of Gravity is so moved, howsoever the parts may change places amongst themselves.*

In this passage Wallis was asserting that, as well as moving around the Sun, the Earth must be orbiting around the centre of gravity of the Earth–Moon system. Since he calculated that this centre of gravity was just outside the surface of the Earth, the Earth's monthly wobble would be small. Nevertheless the law of conservation of momentum, if it applied to heavenly bodies as it did to those on the Earth, implied that the wobble must exist. This prediction was particularly remarkable in the light of the fact that he admitted to having no idea what the cause of the constant association of the Earth and Moon might be, and no observational evidence that the conclusion was true.

Twenty-one years later Newton went even further, stating that the motion of the Earth around the centre of gravity of the Earth and Moon was 'sensible'. The fact that he made no attempt to demonstrate it suggests that he knew that it was actually too small to be observable with the telescopes of the day. Eventually they became accurate enough for the monthly wobble to be observed, but its existence had been regarded as settled long before that. A direct physical proof that the gravitation between pairs of astronomical bodies was mutual followed painstaking observations of the orbits of a steadily increasing number of visual binary stars in the nineteenth century, following the pioneering work of William Herschel.

1.5 The Impact of Technology

Christian theologians sometimes claim credit for the scientific revolution, on the grounds that the very notion of the world being governed by laws depends on the previous idea of God as a law-giver. While this has an element of truth, it is far from being the whole story. Historically, a large factor behind the revolution was the diffusion of Islamic scientific advances from Sicily and Andalusia in Spain into Christian Europe, starting in the twelfth century. The Islamic advances themselves depended on the insights of Plato, Socrates, Aristotle, Euclid, Archimedes, and others of the Greek classical period, which owed nothing to the Abrahamic God. One also has to remember the enormous influences of India and China on the development of mathematics and technology. In this section we present an alternative explanation of the scientific revolution; there are several others and their relative importance cannot be quantified in a simple formula.

Scientific advances are not always the result of asking new questions or thinking of new answers to old ones. They have frequently grown out of advances in technology – new instruments often reveal wholly unexpected aspects of the world. Indeed a case could be made that science has largely been a response to advances in technology, and that it only started driving technology in the twentieth century. Obvious examples are the telescope, first exploited by Galileo, and the microscope, by means of which Robert Hooke revealed the wholly unexpected existence of cells in cork and many other fascinating things. Much more recently the invention of photography has had a huge impact, for example by enabling scientists to observe processes that occur much too rapidly for the human eye to be able to follow them.

The Printing Press

The introduction of movable type printing into Europe is usually credited to one man, Johannes Gutenberg, but this is perhaps unfair to some of his contemporaries. The idea of printing had existed for centuries and was highly developed in China, where printers had normally used wooden blocks that were preserved for decades or even centuries. Gutenberg realized that the mass production of individual letters, cast in metal and then assembled into the desired text, would transform printing, and spent years perfecting the technique before he was ready to print the Gutenberg Bible in Mainz, Germany in 1455.

Gutenberg's printing process was soon copied throughout Europe and by the end of the fifteenth century there were about a thousand printing shops in Europe, and tens of thousands of different titles had been printed, each one with many copies; by 1600 it is estimated that about two hundred thousand different titles had been published. The invention steadily undermined the control of knowledge by the Catholic Church. Its response was typically authoritarian; the first Roman Index of Forbidden Books was produced in 1559 and banned the entire output of hundreds of authors as well as numerous individual books. In the event these attempts at control failed as authors with unwelcome ideas started to smuggle their manuscripts to other countries to be printed there. Nevertheless, the Index substantially reduced the freedom of expression, particularly in Italy.

The impact of printing steadily increased, and by the seventeenth century large numbers of pamphlets were already being circulated in the vernacular languages. Many of these were announcements of recent news stories, and in the seventeenth century the regular publication of newspapers started, initially under strict licences. The first scientific journals were the *Journal des Sçavans* followed closely by the *Philosophical Transactions of the Royal Society*, both of which started publication in 1665. These had an important effect on the development of science by expediting the publication of small additions to knowledge and allowing criticism of it by others. Of course this did not happen overnight; many scientists continued to keep their hard won expertise to themselves for many decades after that.

The effect of printing on the development of Western civilization, and in particular of science, was so great that one has to ask why the same did not happen in China, which was far in advance of Europe scientifically in the first half of the millennium. There must be many answers to such a complex question. One is that the Chinese writing system was not well adapted to movable type printing, while the small number of letters in European languages made movable type extremely easy to use once the technology had been developed. Another answer is that Chinese society was highly centralized around the court of the Emperor, while the fragmented city states of Europe encouraged entrepreneurial activity. Particular entrepreneurs were often ruined or cheated of their just rewards, as was Gutenberg, but his invention lived on after him to everyone's benefit.

The printing press affected the development of science because it increased the level of literacy, promoted independent thinking and facilitated general communication. The developments described below are more specifically scientific. Nevertheless, they have been important philosophically as well as scientifically, as we will explain at the end of this section.

Lenses

The development of the microscope disproves the frequent claims of philosophers that scientific research always proceeds in the context of some explanatory theory, which dictates experiments that might test it. It had been known for many centuries that glass of varying thickness could make objects behind it look larger, and spectacles with convex lenses exploiting this fact were being made in the thirteenth century. Early in the seventeenth century improvements in the manufacture of lenses and the crucial discovery of the effect of using two lenses together led to the first telescopes. These discoveries did not depend on a proper theory of lenses – the law governing the refraction of light at a surface was discovered some years later in 1621 by Willebrord Snell in Leiden and independently by Descartes in 1637. Terrestrial objects that one 'saw' using a telescope could be inspected at close quarters to confirm that they did have the stated features. The same applied to microscopes. With small magnifications it was obvious that the object seen through the lens was the same as one could see using one's bare eyes. There was no reason to doubt the existence of new structures that became visible as the magnification was slowly increased. The only 'theory' involved was the assumption that a continuous change of apparent size does not suddenly lead to the appearance of unreal objects, but we have always taken that for granted as we walk through the countryside. The subsequent history of the microscope has involved steadily more detailed attention to the laws of optics, but that is not how it started.

Logarithm Tables

We are now so accustomed to scientific calculators and computers that it is difficult to remember that astronomical calculations were all carried out by hand until the twentieth century. Even multiplying two numbers, a process that needed to be done thousands of times by astronomers when analyzing planetary orbits, was a time-consuming process requiring great care, because any error could propagate and render the rest of a lengthy calculation worthless.

The tedium of these calculations was greatly reduced when John Napier, Laird of Merchistoun near Edinburgh, introduced logarithms. In 1614, after years of work, he published a book called *Mirifici Logarithmorum Canonis Descriptio*, containing ninety pages of tables that made multiplication almost as simple as addition. Although he died in 1617 his achievement was recognized immediately. Henry Briggs, who had become the first Professor of Geometry at Gresham College, London in 1596, travelled from London to Edinburgh twice to discuss the tables with him, and in 1624 he published *Arithmetica Logarithmica*, which contained new and more extensive tables in a form that was more readily applicable.

Kepler realized the significance of Napier's tables very quickly and used them systematically to produce his important *Rudolphine Tables*, published after years of hard work in 1627. These were named after the Emperor Rudolf II, although he was by then long dead. The tables provided detailed positions of over a thousand stars based on Brahe's observations, but more importantly provided a procedure and the relevant data for calculating the positions of the planets at any chosen time. The Rudolphine tables were much more accurate than those in any previous publications. The calculations were carried out in the heliocentric framework, and this was undoubtedly a factor in the general acceptance of the latter by 1660.

Napier's tables and the earlier publication in 1585 by Simon Stevin of *The Tenth* both encouraged another computational revolution, the use of the decimal notation (for example the replacement of $14\frac{3}{8}$; by 14.375). This shift of notation took longer to complete, and Newton was still using both notations haphazardly when he wrote *The Principia* in 1687.

The tedium involved in producing log tables can hardly be imagined today. Briggs' *Arithmetica Logarithmica* tabulated the logarithms of 30,000 numbers, each result being accurate to 14 digits. A willingness to undertake such Herculean tasks remained necessary in astronomy and other areas of physics until the 1960s, when computers started to penetrate the industrial and university sectors. In the 1980s pocket calculators became cheap enough for children in Western countries to have one for their personal use. Books of log tables were removed from school classrooms, first to cupboards and then to dustbins. The revolution started by Napier was over.

Since the use of log tables has not been taught in schools or even universities for many years, two simple examples are given below. The accuracy obtained depends on the number of digits provided by the log tables. The calculation proceeds as suggested by the arrows.

Number		**Logarithm**
9.000123	→	0.9542484
8.000321	→	0.9031074
product = 72.00386	←	sum of above = 1.8573558

Number		**Logarithm**
16.00022	→	1.204126
square root = 4.000028	←	half of above = 0.602063

Time

In ancient times there were two methods of measuring time, sundials and water clocks. The first were much simpler but suffered the disadvantage of only working during the day and, even then, only if it was sunny. The second tended to be inaccurate or cumbersome, but they were developed to a high level of sophistication, particularly by the Chinese. They were widely used for many centuries, but were eventually superseded by the invention of the pendulum clock in the seventeenth century. Two people should be given the main credit for this. Galileo carried out extensive observations of pendulums, and proposed that they could be used as the basis for a clock. He produced a design for a pendulum clock in 1641, by which time he was blind, but it was never constructed. In 1657 Huygens actually manufactured a pendulum clock, and started a revolution in the measurement of time. The idea quickly spread around Europe, and many technical modifications and improvements were forthcoming. Huygens' first clock was *far* better than its predecessors, being accurate to a minute per day; he later improved this to ten seconds per day. By 1721 George Graham had achieved an accuracy of one second per day by using temperature compensation.

The pendulum clock brought the measurement of time to the same level of accuracy as measurements of length, mass (or weight) and of sidereal coordinates. By 1700 all of the fundamental quantities of physics could be measured to better than one part in a thousand, and the mathematization of the physical sciences became a real possibility. The immediate impact of this was in astronomy. As soon as it was possible to measure time with an accuracy comparable to that of sidereal latitude and longitude, Newton's theory could be tested in some detail. Its success came to be regarded as the standard to which other sciences should aspire.

The first pocket watches were made by Peter Henlein in the sixteenth century and were powered by coiled springs. They could not be regulated by pendulums and the first watch to use a spiral balance spring for this purpose was made for Huygens in 1675. Unfortunately the invention provoked claims by others that they had thought of a similar idea earlier, but the strongest was by Hooke. He had indeed demonstrated some such mechanism to the Royal Society in 1668, but the record is absent from the Society's minutes. The watch that he constructed did not function well and he did not pursue the idea. As happened on many other occasions, the demands on his time by his masters in the Royal Society prevented him from carrying the project through to fruition.

Huygens' ideas for regulating clocks were steadily refined until the twentieth century, when they were finally replaced by quartz clocks and watches for everyday use and atomic clocks when extreme accuracy was needed.

The Vacuum

Until the seventeenth century ideas about the vacuum depended more on the preconceptions of the philosophers involved than on experiment. Aristotle rejected the vacuum as inconsistent with his concept of place, and his views were adopted by the medieval scholastic philosophers. Although Descartes' approach to natural science was a decisive break from the scholastic school, to which he owed his education, he agreed with them in this respect. Space, even the parts of it that appeared empty, must be filled with some ethereal substance, because there could not be a vacuum. Descartes' grounds for this were philosophical and difficult to understand, because our thoughts are shaped by a quite different world-view. He delayed publication of his ideas until 1644 because of fears about the reaction of the Church. By this time his ideas had already been superseded by the invention of the barometer, which, for the first time, allowed the measurement of air pressure.

The person responsible was Evangelista Torricelli. Following Galileo's death in 1642, still under house arrest, Torricelli was offered the position of court mathematician to Grand Duke Ferdinand II of Tuscany. This was a natural choice: Torricelli was already an accomplished mathematician and had studied with Galileo for a few months before the latter's death. In 1643, he constructed the first barometer in Florence, creating a vacuum at the top of an eleven-metre column of water. He quickly switched to the much more practical mercury barometers, with a height of less than two metres. In 1644 he wrote to Michelangelo Ricci in Rome to tell him about his experiments, declaring 'we live submerged at the bottom of an ocean of the element air, that by unquestioned experiments is known to have weight.' He commented that his discoveries supported the observation that the atmosphere appeared to come to an end at a height of fifty miles (eighty kilometres) or less. Torricelli's work created considerable controversy, but in 1647, with the help of Perier, Pascal confirmed his ideas by showing that air pressure decreased as one goes up a mountain.

In 1660 Robert Boyle published his *New Experiments Physio-Mechanicall, Touching the Spring of the Air and its Effects*, describing a series of experiments performed in a 38 cm glass chamber that had been evacuated using an air pump designed by Robert Hooke, then his assistant. His discovery of the relationship between pressure and volume (Boyle's Law) reinforced the idea that air was a material substance that could be understood within the framework of the mechanical philosophy.

Philosophical Implications

Descartes argued that we could acquire true knowledge of the world because of God's undeceitful nature, but his argument was not accepted and the problem was put aside. It seemed evident that we did have such knowledge and an explanation of this was not the most pressing issue. It was much more interesting and productive to study the physical sciences by following his mechanical philosophy. Developments in experimental psychology over the last few decades have shown that Descartes' problem was far harder than he had appreciated. We now know that the stimuli that impact on our sense organs are analyzed at an unconscious level into fragments which are then combined in ways which depend, not only on what is there, but on our previous experiences and current preoccupations. It is amazing that the end result is the feeling that we are perceiving the real world as it actually is.

It can be argued that our scientific progress since the time of Galileo has depended on finding ways of reducing our dependence on our sense organs. The point of scientific instruments is that they replace our direct appreciation of the quantities in which we are interested by something else that we can observe with much greater reliability and accuracy. By virtue of the pendulum, measuring the passage of time was replaced by counting its swings to and fro. By virtue of the balance, weighing objects was reduced to observing whether a balance tipped one way or the other and counting the number of standard weights involved. By virtue of instruments with graded scales, measuring the size of objects or the angles between stars was again reduced to counting. In the process of reducing our reliance on our unaided senses we discovered that some measured quantities did not change over long periods of time, and that different methods of measuring quantities were often remarkably consistent with each other. The motions of the stars in the heavens, the flow of water in a water clock, the beat of a pendulum, and the mechanism of a spring-regulated watch give almost the same measures of time, and their deviations from complete consistency turned out to be explicable. Although we take this for granted, the world did not have to be like that. If it had not exhibited these long term regularities, mathematics could not have become one of our main methods of understanding it.

Our memories are as unreliable as our senses. When walking (or even driving!) along a familiar route one may literally have no memory of large sections of the journey, even at the moment of arrival. Controlled experiments show that long-term memory is a matter of creating a plausible story around a few essential details, and that people can create convincing false memories based on stories that they have been told about their childhood. By virtue of the development of writing and then printing and photography, our memories have been replaced by records that can be re-examined many years later. In a scientific context laboratory notebooks provide the best method of avoiding self-deception later in life.

Although there is no logical proof that we can escape from the subjectivity of our own sense impressions and memories, in fact we have done so, and the route was by finding many alternative ways of analyzing the world around us and discovering that they could be made consistent with each other. The world-view of physicists and chemists is now that dictated by their instruments, which reveal aspects of reality that we could not know about without them. The astonishing thing is that this process works. Eventually it led us to understand how limited our own sense organs and brains are, and how lucky we were to have found more reliable, although indirect, ways of understanding the world.

1.6 The Laws of Motion

As we have seen, Kepler insisted that earthly and heavenly bodies should obey the same laws of motion, whatever they were. The eventual elucidation of these laws is usually attributed to Newton, because of the Matthew effect. (The Gospel of Matthew Ch. 25, v. 29 says 'for unto every one that hath shall be given, and he shall have abundance; but from him that hath not, even that which he hath shall be taken away'.) In fact the history of the laws is much more complex and interesting.[5]

The law of conservation of momentum was formulated by Descartes in 1644. His laws describing the collisions of two bodies were, however, misconceived, and Huygens set to work to replace them. He completed his fundamental treatise *De motu corporum ex percussione* (On the Motion of Bodies as the Result of an Impact) laying out the final form of these laws in 1656, while still only 27 years old. At this point he seems to have lost his self-confidence: although the manuscript was circulated to a few chosen scientists, he never published *De motu*. However, he must surely have discussed his results with Wallis, Wren, Boyle, Hooke, and others during his visits to London in 1661 and 1663. Newton, still a very young man at that time, was not to meet Huygens until 1689, and his knowledge of Huygens' work on mechanics during the 1660s is not easy to determine. They did correspond to a limited extent about optics early in the 1670s and Huygens sent him a copy of his long delayed and very important *Horologium Oscillatorium* (The Pendulum Clock) when it was published in 1673.

In 1668 the Secretary of the Royal Society, Henry Oldenburg, invited Huygens, Wren and Wallis to submit articles about the laws of motion, which were published in the *Philosophical Transactions* in 1669. The first article, by Wallis, was excessively brief, but he was presumably too busy writing his magnum opus on the subject to want to make it longer. One has to infer his knowledge of the laws from detailed mathematical calculations involving a variety of examples. The article of Wallis was followed immediately by that of Wren, in which several of the key notions were not defined. However, it was agreed by all concerned that its contents agreed with the other two papers.

The publication of Huygens' article was preceded by several exchanges between him and Oldenburg. Huygens knew that he had scientific priority over Wren and Wallis, and was angry that his article was not published alongside the others. As a result he decided to submit a French version of his article to the *Journal des sçavans*. His article appeared a few months later in the *Philosophical Transactions*, and was preceded by a placatory statement by Oldenburg:

> *Before these Rules of Motion be here deliver'd, 'tis necessary to preface something, whereby the worthy Author of them may receive what is unquestionably due to him, yet without derogating from others, with whom in substance he agreeth.*

After a preamble describing the history of the Laws, Huygens listed the laws of motion, more or less as they were in *De Motu*. In our language these included laws for the conservation of momentum and of kinetic energy in elastic collisions. He also provided a graphical procedure for determining the outcome of a collision between two elastic bodies.

Wallis's magnum opus *Mechanica*: *sive De Motu, Tractatus Geometricus* was published in three parts, dated 1669, 1670 and 1671, and provided the first comprehensive account of the laws of motion, as well as illustrating their application in a variety of contexts. When Newton published *Principia* in 1687, he acknowledged the contributions of Wallis, Wren, and Huygens to the elucidation of the laws, and referred to their papers of 1668–9. However his own law governing the interactions of two bodies had one very significant novelty. His law of conservation of momentum stated:

> *The quantity of motion, which is determined by adding the motions made in one direction and subtracting the motions made in the opposite direction, is not changed by the action of bodies on one another.*

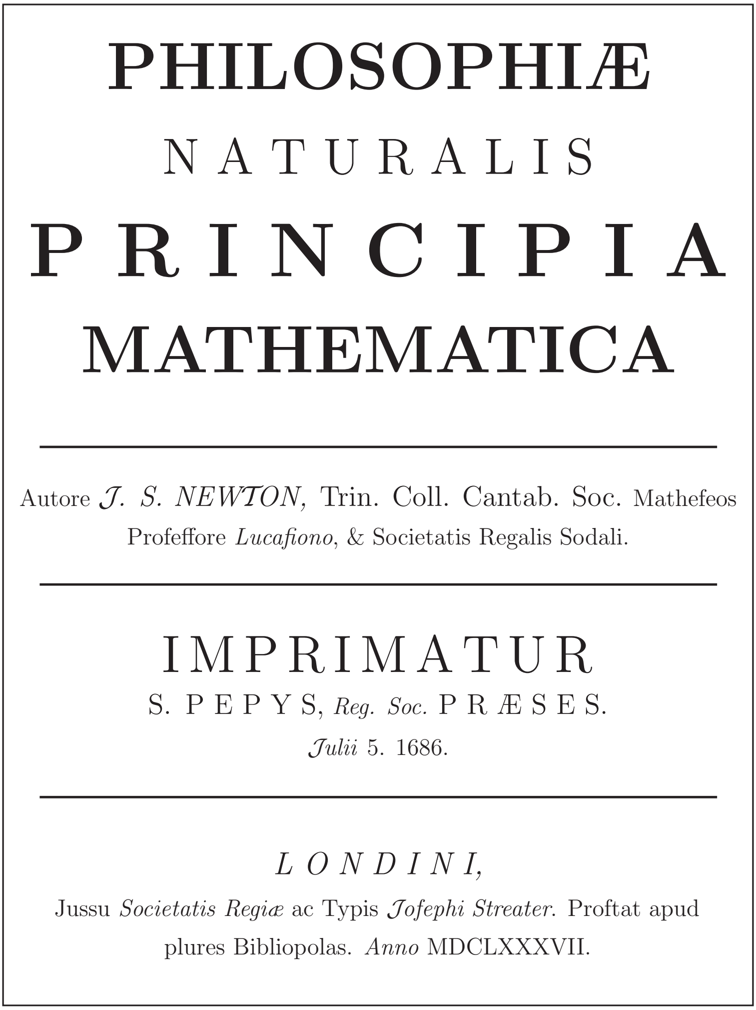
The use of the word 'action' implied the extension of the law to remotely acting forces – Wallis, Wren, and Huygens had only considered collisions. Newton was to apply his extended law to gravity, even though he had no direct evidence that this was appropriate. In the following pages of *Principia* he described experiments which confirmed that the law applied to magnets, which also interacted remotely. Nevertheless, his extraordinary attention to detail strongly suggests that he deliberately chose not to draw attention to his *assumption* that the law applied to gravity.

1.7 Universal Gravitation

Isaac Newton (1643–1727) is regularly voted one of the three most important scientists of all time, the others being Darwin and Einstein. Unfortunately he might also come near the top of a poll for sheer nastiness. Most of his crucial scientific discoveries were made at Trinity College, Cambridge, where he had few close relationships and often shunned contacts with the outside world. In later life he engaged in long and bitter disputes with Flamsteed and Leibniz, and almost succeeded in writing Hooke's existence out of the historical record. Only recently have Hooke's many important contributions to science been recognized.

Nevertheless, Newton's *Principia* is one of the most amazing and important books ever to have been written. Its central achievement was to lay out a Universal Law of Gravitation that was to survive unchanged for over two centuries. Indeed it is still used just as widely today in spite of Einstein's subsequent discoveries. Anyone who reads more than a few pages of *Principia* can only be astonished at the subtlety of its reasoning and the genius with which Newton resolved the many difficulties that he encountered. Unfortunately it is also very hard reading, except for a few sections near the start and end. The final section, at least in the second and third editions, is called the 'General Scholium' and is polemical in character. Moreover it does not represent the main body of the text accurately. It gives the impression that Newton followed the Baconian, or inductive, method throughout. (We discuss this further on page 35.) Historians and philosophers of science soon agreed that this was not the case, but they struggled to identify a 'Newtonian method' that would explain his success. In fact he used a great variety of methods, choosing the most appropriate one in each context. His success was a function of his genius and of being in the right place at the right time, not of having a special method.

It is difficult to absorb the fact that, without the intervention of Edmond Halley, *Principia* might well never have appeared in print, with unknowable consequences for the future development of science. Newton started working on the theory of gravitation seriously in 1684, as the result of questions about the motions of the planets put to him in Cambridge by Halley. Newton had written most of *Principia* in an astonishing burst of creative energy by 1686, but then a dispute relating to a much earlier suggestion by Hooke that gravity obeyed an inverse square law provoked Newton to threaten to withdraw his work. Although Halley eventually persuaded him to continue, Newton removed almost every reference to Hooke from his manuscript as a result. There were also financial troubles at the



PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA

Autore *J. S. NEWTON,* Trin. Coll. Cantab. Soc. Mathefeos
Profeffore *Lucafiono*, & Societatis Regalis Sodali.

IMPRIMATUR
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu *Societatis Regiæ* ac Typis *Jofephi Streater.* Proftat apud
plures Bibliopolas. *Anno* MDCLXXXVII.

Fig. 1.1 Title Page of Newton's *Principia*

Royal Society, which had committed itself to the publication of several volumes of an expensively illustrated work on the *History of Fishes*, and in the end Halley had to provide the resources to support its publication out of his own, not very deep, pocket.

Book 1 of *Principia* lays down the laws of motion and then develops their consequences in far greater depth than anyone had previously attempted. In particular he uses a geometrical version of calculus to determine the orbit of a body under a variety of *hypothetical* force laws.

This book is full of mathematical proofs and is the backbone of his analysis of the *actual* orbits of the planets in Book 3. One of the opening sections of this final book is entitled 'Phenomena'. Almost inevitably, the contents of this section are not actually phenomena; they are descriptions of the planetary motions that had been obtained before Newton started writing *Principia* by Brahe, Kepler, Cassini, Römer, Flamsteed, and other astronomers. In particular Kepler's formula relating the orbital period of a planet to its distance from the Sun would not have made sense to anyone before Copernicus, because the concept of an orbital radius did not exist. It is a derived concept rather than a measured phenomenon. Nevertheless Newton's judgement that the items in his list of phenomena were reliable has been amply justified by history. Now that we have space probes travelling around the Solar System on a regular basis, it has become impossible to think about the Solar System any other way.

A large part of Book 3 of *Principia* is devoted to the motions of the comets. Although many people had studied these previously and knew that their orbits were far from circular, nobody had a plausible method for computing the actual orbits. Newton's theory of gravitation suggested that the orbits were parabolic, and he was able to find the orbital parameters and confirm his parabolic assumption by a completely new and very difficult method. Although his analysis was later refined by Halley and others, Newton's solution of this problem was of major importance.

Newton infers his famous Universal Law of Gravitation by induction from the phenomena *provided* one accepts his starting point. The Law is obtained by combining a series of theorems, of which the following is typical:

> **Proposition 2** *The forces by which the primary planets are continually drawn away from rectilinear motions and are maintained in their respective orbits are directed to the sun and are inversely as the squares of their distances from its centre.*
>
> *The first part of the proposition is evident from phen. 5 and from prop. 2 of book 1, and the latter part from phen. 4 and from prop. 4 of the same book. But this second part of the proposition is proved with the greatest exactness from the fact that the aphelia are at rest. For the slightest departure from the ratio of the square would (by book 1, prop. 45, corol. 1) necessarily result in a noticeable motion of the apsides in a single revolution and an immense such motion in many revolutions.*

The fact that the aphelia – the points on their orbits at which the planets were furthest from the Sun – did not move sensibly over many orbits was of much greater importance in the deductive process than the ellipticity of the planetary orbits.

Newton took the Phenomena and Rules of Inference from the start of Book 3 and the laws of motion from the opening Axioms section of *Principia*. Almost nobody seems to have commented on Newton's claim in the General Scholium that the laws of motion *including their applicability to the heavenly bodies* had been obtained by induction from the phenomena. (The italicized part of the last sentence is not to be found in the General Scholium, but it was absolutely essential to Newton's application of the laws of motion in the main text.) Everyone at that time agreed that the laws of motion applied to the heavenly bodies, but there was *no evidence for this* before *Principia*.

One can resolve this problem by presenting the applicability of the laws of motion to the heavenly bodies and the Universal Law of Gravitation as a composite hypothesis, with all of the observational evidence that Newton used as evidence in support of it (or, as Popper would have said, failing to refute it). Newton would have disagreed with this. Everyone at that time took it for granted that the first issue had already been settled, not by quantitative evidence, but on general, intuitive grounds. The scholastic system was already dead and the mechanical philosophy had replaced it long before Newton started his investigations.

Newton did not confine himself to the inductive method. In fact he used a wide variety of different methods. For example, *Principia* describes a series of experiments that he performed to demonstrate that the inertial masses of a variety of substances were proportional to their gravitational masses. (He did not express it this way.) By showing that two pendulums of equal length but with bobs made of different materials swung next to each other with the same period, his experiment tested the above hypothesis in a truly Popperian fashion. In his account of the tides, he abandoned the precise language of the earlier text, and indulged in an entirely appropriate and open-ended discussion of the difficulties of taking account of the effects of coastal topography. *Principia* even contains a thought experiment as a part of the argument identifying the force acting on the Moon and planets with terrestrial gravity.

Newton's intellectual brilliance could not be challenged after the publication of *Principia*, but his theory was not accepted by everyone as a *physical* explanation of the motions of the planets. The criticisms of *Principia* by Huygens and Leibniz were based upon their allegation that he allowed interactions at a distance as a *fundamental ingredient* of his natural philosophy. This was the obvious conclusion to draw from the structure of the main body of *Principia*, but there is plenty of evidence that it was not his position, and that he tried hard to find a 'mechanical' cause for gravity. In the General Scholium, added when the second edition was published in 1713, he stated:

> *Thus far I have explained the phenomena of the heavens and of our sea by the force of gravity, but I have not yet assigned a cause to gravity. Indeed this force arises from some cause that penetrates as far as the centres of the sun and planets without any diminution of its power to act…I have not yet been able to deduce from phenomena the reason for these properties of gravity, and I do not feign hypotheses.*

Readers at that time would have understood that his unwillingness to feign hypotheses was a criticism of the Cartesian philosophy. Here and elsewhere Newton makes clear that when referring to the force of gravity he is interposing the notion of a mathematical explanation between the phenomena and an unknown physical explanation.[6]

Principia was an extraordinary advance on previous studies of the Solar System, and established that elucidating the laws of nature might need mathematics of a much more sophisticated character than anyone had previously tried to use in this context. But it was far from complete. Newton tried to explain the tides, and approached the problem correctly, but it was far too complex a phenomenon for him to succeed in his goal. His attempts to explain the anomalies in the orbit of the Moon were not successful because of his inadequate mathematical technique. In 1752, over sixty years after Principia was published, Alexis Clairaut eventually justified Newton's confidence that the anomalies could be explained by a careful analysis of the Earth–Moon–Sun three-body problem. By 1800 the mechanical philosophy was starting to be replaced by the mathematical philosophy, in which finding the equations that 'controlled' some phenomenon was considered to be the real goal. Maxwell's discovery of the equations governing electricity and magnetism in 1864 was a decisive step in this process. The failure of attempts to explain the propagation of these by the ether (in the same way as sound is propagated by the air) eventually led to people accepting that the ether did not exist. The new orthodoxy was that there was no mechanical explanation for electromagnetism – the fields existed in their own right, whatever that meant. We have now got to the position in which fundamental physics is entirely based on quantum fields and the mechanical philosophy is only relevant for bodies as large as molecules, which are huge by the standards of particle physicists.

The gradual mathematization of fundamental physics has been accompanied by the disappearance of the distinction between explanation and understanding in that field. Understanding the physics is more or less identified with understanding the mathematics, and this means having some intuitions about the form of the solutions of the relevant equations. This process has been taken to its logical conclusion in superstring theory, a subject disliked by some experimentally oriented physicists. We will discuss whether this is justified in Chapter 4.

1.8 Induction

In spite of David Hume's criticism of the logical flaw in the inductive law, it seems impossible to make progress in science without a belief in the uniformity of nature – that patterns in past events provide some guidance about what is likely to happen in the future. In my book *Science in the Looking Glass* I included a discussion of induction, concentrating on the period between Hume and Karl Popper, both of whom regarded it as logically unsound. Although they were right as far as *their own definition* of induction was concerned, Newton had already anticipated the difficulties that they pointed out. His formulation of the law of induction is not based on logical deduction and is difficult to fault. Once again, a careful analysis of what he wrote provides impressive evidence of the depth and subtlety of his thought.

Book 3 of *Principia* starts with a section entitled Rules for the Study of Natural Philosophy.[7] This section is methodological. Each of the rules refers to how one *should* behave as a scientist, not to how the world actually is or to any logical argument. Rule 1, for example, states:

> *No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena.*

This advice is sound even if the subject matter is extremely complicated, as biology is – deliberately seeking a complicated explanation of some phenomenon without a good reason is hardly sensible. Following his Rule 1, Newton then declares 'nature is simple'. This belief is shared by many physicists today, in spite of the advent of quantum theory, a subject so difficult that even the experts do not claim to understand it at an intuitive level; see page 130.

The most important of Newton's rules, Rule 4, states:

> *In experimental philosophy, propositions gathered from phenomena by induction should be considered either exactly or very nearly true notwithstanding any contrary hypotheses, until yet other phenomena make such propositions either more exact or liable to exceptions.*

Note again the use of the word ‘should’. Newton emphasizes that the conclusion is provisional – the phrase ‘more exact’ indicates that he is not using the word ‘exact’ in a logical sense. When discussing the orbit of the Moon, he argued that gravity obeyed an inverse square law in spite of the fact that the best match to the data was obtained by replacing the power 2 by $2\frac{4}{243}$. One might conclude that this indicates his preference for the ‘exact’ number 2 over the ‘non-exact’ number $2\frac{4}{243}$. However, his preference was justified. The power 2 gave a much better fit between theory and data for all bodies except the Moon, and in that case he was aware that the effect of the Sun on the orbit of the Moon around the Earth was important. In spite of much effort, he did not resolve this issue, but he was correct to believe that it would one day be resolved.

A fuller statement of Rule 4 may be found in the following extract from Query 31 of *Opticks*, published in 1704, seventeen years after *Principia*:

> *And although the arguing from Experiments and Observations by Induction be no Demonstration of general Conclusions; yet it is the best way of arguing which the Nature of Things admits of, and may be looked upon as so much the stronger, by how much the Induction is more general. And if no Exception occur from Phenomena, the Conclusion may be pronounced generally. But if at any time afterwards any Exception shall occur from Experiments, it may then begin to be pronounced with such exceptions as occur.*

This explicitly denies that induction provides a *logical proof*, or, in his words, a ‘Demonstration’, but argues that one should nevertheless use it, while accepting its provisional basis. Newton allows the possibility that the induction may have to be revised, and that the conclusion reached may turn out to be only approximate. He applies Rule 4 with these reservations in mind in the main body of *Principia*. The fact that he proves the inverse square law for two-body systems but applies it to planets in a multi-body Solar System does not invalidate the proof, because the derivation is stable under small perturbations. Popper and others could only accuse him of serious error because they they did not appreciate that his induction was not intended to be a logical proof.

The obsession with logic was characteristic of British philosophy in the middle of the twentieth century. Logical positivists and linguistic analysts were no doubt influenced by the rapid advances in mathematical logic that started with Frege towards the end of the nineteenth century. Other schools of philosophy always understood that logic cannot adjudicate between differences in world-views, and that human beliefs are influenced by a huge variety of experiences. This is not to say that logic is worthless, far from it, but it is only one among many considerations that scientists, like other human beings, use to create their theories.

Popper's charge could be made more fairly against Laplace, who rewrote *Principia* in the form of a mathematical treatise, but Laplace was also a creature of his time. By 1800 the successes of Newton's laws were so sweeping that everyone had come to believe that they represented the final truth about the world. Kant had the same problem as Laplace, with the consequence that a good part of what he wrote about science looked obviously foolish after Einstein. But Newton's caution in his Rule 4 provided him with a strong defence against such accusations. His laws, although approximate, are still much more widely used than Einstein's general relativity.

1.9 Conclusions

The Baconian account of scientific method had a metaphysical aspect – it suggested that human input into science could be minimized if one focused on the phenomena and used the method of induction. In the eighteenth century Hume correctly argued that induction, *as he understood the term*, had an unavoidable philosophical content, and could not be logically justified. Newton used induction, but his version drew people into the picture by formulating it as a regulative or methodological principle rather than as a rule of logic.

Popper did not understand, and probably had not read with any attention, what Newton had written about induction, and replaced it by his own theory, based solely on refutation.[8] This has substantial merits, but it disregards the initiative and imagination involved in scientific research. It also does not admit that certain theories have gone beyond any reasonable prospect of refutation. If the Copernican theory, atomic theory and the existence of viruses are to be regarded as provisional, perhaps our belief that the world is round is also provisional. Popper's philosophy does not give any account of major revolutions in scientific outlook, which sometimes occur long before significant supporting evidence is available. Nor does it mention the many important discoveries that have been direct consequences of the invention of new scientific instruments.

The unification of different theories has been a major goal in science, but neither Bacon nor Popper had any explanation for its successes, often after many decades of effort. During the seventeenth century, physical and mechanical explanations came to be regarded as superior to descriptions 'of the appearances' and the scholastic philosophy withered because it did not have the potential for providing the former. Definitive evidence for the correctness of Kepler's vision only appeared long after he had died, and by the time Newton provided a correct account of the planetary motions the philosophical issues about the form, and indeed nature, of the Solar System were already regarded as settled.

All of this supports Feyerabend's criticisms of the scientific method. However, his argument that science is no more than a cultural phenomenon is absurd. Newton's laws worked in the context that he discovered them, but they are also used in many other situations that he could not have imagined. A few centuries ago machines were designed by heuristic methods that did not owe much to scientific progress, but the huge range of sophisticated machines that are now a part of our lives only work as advertised because engineers have used scientific laws, *discovered in laboratories*, to design them. Ultimately, science is important because it works, not because it has advocates in high places.

Notes and References

[1] For a further discussion of world-views, see Ward, K. (2006), *Is Religion Dangerous?*, Chapter 4, Lion Hudson plc., Oxford.

[2] Feyerabend, Paul K. (1975). *Against Method, Outline of an Anarchistic Theory of Knowledge*, p.160. NLB, London.

[3] Astronomy in the medieval period was much more complex and fluid than this paragraph suggests. See Grant, E. (1994), *Planets, Stars and Orbs, the Medieval Cosmos 1200–1687*, Camb. Univ. Press.

[4] Cottingham, John (1992). Cartesian dualism: theology, metaphysics and science. In John Cottingham, ed. *The Cambridge Companion to Descartes*, p.249. Camb. Univ. Press.

[5] A detailed account of the material here appears in Davies, E. B. (2009), Reflections on Newton's 'Principia'. *British. J. Hist. Sci.* **42**, 211–24.

[6] Cohen, I. B. and Whitman, A. (1999). *Isaac Newton, The Principia, a New Translation*, pp. 408, 588, 943. Berkeley.

[7] A detailed discussion of the status of the rules may be found in Davies, E. B. (2003), The Newtonian myth. *Stud. Hist. Phil. Sci.* **34**, 763–80.

[8] See Davies (2003), *Stud. Hist. Phil. Sci.* **34**.