In Praise of Natural Philosophy: A Revolution for Thought and Life

Chapter One

Triumphs of Natural Philosophy

In this book I set out to expose an intellectual disaster at the heart of our culture – at the heart of our world. It has a multitude of adverse repercussions for the way we think and the way we live. Science and scholarship are adversely affected. Our understanding of our place in the universe is obscured. Our ability to see what is of value in life, and our ability to realize what is of value, are undermined. Peace, justice, liberty, democracy, sustainability are all compromised. The disaster obstructs attempts to develop institutions and social endeavours that work in our best interests. It sabotages our efforts to make progress towards a good world.

What is this malignant intellectual disaster that spreads its tentacles in such an abundant fashion throughout our world? It is, to begin with, a blunder about the nature of science. But it is also a long-standing blunder about how to understand our human world – the world as we experience it, imbued with consciousness, free will, meaning and value – given the new vision of the universe ushered in by modern science. It is a blunder about the nature of rational inquiry and, perhaps even more important, the nature and desirability of rational living, of rational institutions. Our very psyches are affected, the way we split off reason and intellect from feeling and desire, fact from value, science from art.

It is, at root, a philosophical blunder – or a series of philosophical blunders.[1] At once it will seem absurd to hold that philosophical blunders could have such dire, far-flung consequences. Everyone knows that philosophy is a dry, esoteric discipline, of absorbing interest no doubt to its academic practitioners, but otherwise devoid of any relevance to anything else whatsoever.

Academic philosophy as it exists today is however one of the products of the disaster I seek to expose, and correct. The very act of correcting it reveals that philosophy as it should be pursued is far too important, for thought and for life, to be left to its current academic practitioners.

The intellectual disaster that we shall be concerned with in this book threads its way far back into our history. It has its roots in the 17th century, with the birth of modern science. That is where we will begin.

I must stress, however, that what follows is only a sketch of those elements of the scientific revolution just sufficient to provide a historical background to the blunder about the nature of science (and inquiry more generally) that is the real theme of this book.[2] Towards the end of this first chapter, I make a few remarks about what historians of science have said about the scientific revolution, in recent decades.

Science Began as Natural Philosophy

Modern science began as natural philosophy – or “experimental philosophy” as it was sometimes called. In the time of Isaac Newton, in the 17th century, science was not only called “natural philosophy”. It was conceived of, and pursued, as a development of philosophy. It brought together physics, chemistry and other branches of natural science as we know it today, with diverse branches of philosophy: metaphysics, epistemology, methodology, philosophy of science – even theology. Science and philosophy, which we see today as distinct, in those days interacted with one another and formed the integrated enterprise of natural philosophy.[3] This had, as its basic aim, to improve our knowledge and understanding of the universe – and to improve our understanding of ourselves as a part of the universe. And around the time of Newton there was this great upsurge of excitement and confidence. For the first time ever, in the history of humanity, the secrets of the universe, hitherto wholly unknown, had been revealed and laid bare for all to understand – or at least, for all those who understood Latin and the intricate mathematics of Newton's *Principia*.[4]

Today we look back at the great intellectual figures associated with the birth of modern science and we unhesitatingly divide them up into scientists on the one hand, philosophers on the other. Galileo, Johannes Kepler, William Harvey, Robert Boyle, Christiaan Huygens, Robert Hooke, Edmond Halley, and of course Isaac Newton are all scientists; Francis Bacon, René Descartes, Thomas Hobbes, John Locke, Baruch Spinoza and Gottfried Leibniz are philosophers (see table 1 for dates). But this division is anachronistic. They did not see themselves in this fashion. Their work interacted in all sorts of ways, science with philosophy, philosophy with science. They all sought, in one way or another, to improve our knowledge and understanding of the universe, to improve our understanding of how we can acquire knowledge of the universe, and to work out the implications, for our understanding of ourselves, of the new view of the universe that the new natural philosophy had ushered in.

That the distinction we make between science and philosophy is anachronistic when projected back into the 16th and 17th century becomes all the more apparent when one considers the *philosophy* that was done by those natural philosophers we now consider to have been scientists, and the *science* done by those natural philosophers we now regard as philosophers. Thus Galileo, for us a scientist, made a substantial contribution to what we would now regard as philosophy when he drew the distinction between what came to be called "primary" and "secondary" qualities. He writes:

> whenever I conceive any material or corporal substance, I immediately feel the need to think of it as bounded, and as having this or that shape; as being large or small in relation to other things, and in some specific place at any given time; as being in motion or at rest; as touching or not touching some other body; and as being one in number, for few, or many. From these conditions I cannot separate such a substance by any stretch of my imagination. But that it must be white or red, bitter or sweet, noisy or silent, and of sweet or foul odour, my mind does not feel compelled to bring in as necessary accompaniments....Hence I think that tastes, odours, colours, and so on are no more than mere names so far as the object in which we place them is concerned, and they reside only in the consciousness. Hence if the living creature were removed, all these qualities would be wiped away and annihilated.[5]

Galileo goes on, delightfully, to consider a hand tickling a person and a statue, and points out that we would consider it ridiculous to hold that the tickling is a property of the hand in addition to its motion and touch. The tickling sensation is in us, not in the hand;

and so it is, Galileo argues, for colour, sound, taste, and odour. He adds, very significantly "To excite in us tastes, odours, and sounds I believe nothing is required in external bodies except shapes, numbers, and slow or rapid movements".[6] Galileo is here, of course, elaborating on what Democritus had asserted 2,000 years earlier: "Colour exists by convention; sweet and sour exist by convention: atoms and the void alone exist in reality".[7] Galileo is in effect affirming the key metaphysical tenet of the new natural philosophy: the universe is made up of atoms in motion or, more generally, of physical entities in motion whose physical properties can be depicted in mathematical terms. Galileo is also, implicitly, invoking a key paradox inherent in the new natural philosophy: on the one hand there is the appeal to observation and experiment, while on the other the new (or re-vitalized) metaphysical vision of the universe - atomism, or the corpuscular hypothesis - tells us that perception is profoundly delusive. This paradox, unresolved, played an important role in driving science and philosophy apart, as we shall see.

Newton, whom we undeniably deem to be a scientist, echoed Galileo's philosophical remarks concerning real physical properties and illusory perceptual qualities, in connection with light. He also put forward many metaphysical theses and speculations about such matters as space, time, the aether, and unknown forces governing physical and chemical phenomena. He engaged in philosophy of science in seeking to characterize scientific method by means of four "rules of reasoning in philosophy" as we shall see below. And he even engaged in theology in arguing that God played an important role in setting up the solar system, and in intervening from time to time to ensure its continuing existence.

Descartes, for us a philosopher, made a vital mathematical contribution to subsequent science by creating what we call "Cartesian coordinates". This made it possible to translate geometrical figures, curves and problems into algebraic equations, and vice versa, thus facilitating the mathematical treatment of motion. Descartes was the first person to formulate the correct version of the law of inertia.[8] He put forward laws of reflection and refraction, and proposed what we would call today a physical "theory of everything" intended to account for all phenomena, including those associated with the solar system. According to this theory, what seems to be empty space is really filled with invisible particles that possess extension and motion but no other property. Swirling vortices of these particles sweep the planets around the sun. That it turned out to be unworkable,[9] or at least false on empirical grounds, does not negate its scientific character, or its important role in the history of science.

Leibniz, another philosopher, made a vital contribution to science by inventing the integral and differential calculus, independently of Newton, his formulation being the one that was subsequently used.

Finally Locke, unquestionably for us a philosopher, declares in his "Epistle to the Reader" at the beginning of his *Essay Concerning Human Understanding* that he sees his task to be that of an under-labourer of the work of "such masters as the great Huygens and the incomparable Mr. Newton" in "clearing ground a little, and removing some of the rubbish that lies in the way of knowledge".[10]

There were good reasons why, in the 17th century, empirical science could not be split off from philosophy. Natural philosophers disagreed about crucial questions of method. Should evidence alone decide what theories are accepted and rejected, or does reason play a role as well? After the work of Galileo and Kepler, and with the work of

Descartes and, above all, Newton, it became apparent that mathematics had an important role to play in science, along with observation and experiment. But mathematical truths can be established by reason alone. Reason must therefore have an important role in science. But how? In what way? Some held that all knowledge comes to us via the senses, via experience. Reason, according to this kind of empiricist view, could not establish any knowledge at all independent of experience. The nature of mathematical knowledge became problematic. Others – most notably Descartes and Leibniz – held that reason plays a vital role in natural philosophy, in the enterprise, that is, of acquiring knowledge of the universe. These different views about the roles of experience and reason in science led to different methods in science, and thus had practical consequences for science itself: they had to be discussed as a part of science.

Leonardo da Vinci 1452 - 1519

Nicolaus Copernicus 1473 – 1543

William Gilbert 1544 - 1603

Tycho Brahe 1546 – 1601

Giordano Bruno 1548-1600

Francis Bacon 1561-1626

Galileo Galilei 1564 – 1642

Johannes Kepler 1571 – 1630

William Harvey 1578 – 1657

Thomas Hobbes 1588 – 1679

Pierre Gassendi 1592-1655

Rene Descartes 1596-1650

Robert Boyle 1627 – 1691

Christiaan Huygens 1629 – 1695

John Locke 1632-1704

Baruch Spinoza 1632 – 1677

Robert Hooke 1635-1702

Isaac Newton 1642-1727

Gottfried Wilhelm Leibniz 1646-1716

Edmond Halley 1656 – 1742

Table 1: Some Natural Philosophers of the Scientific Revolution

Again, the new natural philosophy ushered in a new vision of the universe: it is made up of colourless, soundless, odourless corpuscles which interact only by contact. This metaphysical view[11] had an impact on what scientific theories are to be accepted and rejected; natural philosophers held different versions of the view, and different attitudes to the influence the view should have on science: all this had to be discussed as an integral part of science. Physics and chemistry could hardly be pursued without some thought being given to the manner in which corpuscles might produce phenomena associated with light, combustion, heat, chemical reactions, gravitation.

In addition, the corpuscular hypothesis provoked profound philosophical problems about how it is possible for human beings to acquire knowledge of the universe, and how it is possible for people to be conscious, free and of value if immersed in the physical universe. If everything really is made up of colourless, soundless, odourless particles, how come roses are red, dogs bark, and sometimes smell? If our bodies and brains are made up exclusively of these particles, what becomes of our inner sensations, our consciousness? If all our knowledge of the world around us is based on particles of light entering our eyes, other particles bouncing against our eardrums or nostrils, how is it that we know anything about what we think we see, hear and smell? And if the corpuscles dart about and collide in accordance with precise, mathematical laws, how can we be responsible for our actions? What becomes of free will? Natural philosophers could hardly take the corpuscular theory seriously in what we might today regard as their "scientific" work and then just ignore the radical and disturbing implications this theory seems to have for human knowledge, consciousness and free will. They did not, as we shall see.

The new science did not just usher in a new vision of the universe. Its birth owed much to the advent of this new vision. One might have supposed, naively, that modern science began when people started to take evidence seriously. Is not modern science based on evidence? What more natural, then, to suppose that science began when people based the pursuit of knowledge, not on mere tradition or authority, but on evidence?

To be fair, there is an element of truth in the idea – but only an element. Appealing to evidence did not begin with the birth of modern science. And factors other than appealing to evidence were of even greater significance. A key factor was a revolution in philosophy – the downfall of Aristotelianism, and the creation – or recreation – of the corpuscular hypothesis, or the more general view that the universe has some kind of mathematical structure, or that "the book of nature is written in the language of mathematics" as Galileo put it. Kepler, Galileo, Descartes, Huygens and Hooke all held versions of this view. And their adoption of the view played an essential role in their scientific work – as we should call it today.

Aristotelianism is the view that change comes about because objects strive to actualize their inherent potentialities, much as an acorn strives to actualise its potential to become an oak tree. Objects fall because they have an inherent potential to seek the centre of the earth. The natural world is, in a sense, alive. Purpose, goal-seeking, is built into the constitution of things. According to Aristotelianism, a sharp distinction is to be made between terrestrial and heavenly phenomena. The earth is at the centre of the universe. On earth, there is imperfection, change, decay, and phenomena do not observe precise, mathematical laws. In the heavens, by contrast, there is perfection, no decay, and the motions of heavenly bodies observe precise mathematical laws.

Copernicus and the Downfall of Aristotelianism

The first step towards the overthrow of Aristotelianism was the Copernican revolution.[12] The earlier theory of Ptolemy put the earth at the centre of the universe, the sun, planets and stars rotating around the earth in uniform, circular motion. In order to account for deviations from uniform circular motion, Ptolemy was forced to postulate epicycles, and other devices. Thus planets move as if fixed to the rim of a uniformly rotating disk, the centre of which is fixed to the rim of a much bigger, uniformly rotating disk which has its centre at the centre of the earth. By means of a horrendously complex system of epicycles and other such devices, Ptolemy was able to account for the observed motions of the planets, the sun, and the stars.

Copernicus hesitated to publish his new theory of the cosmos (as the solar system was then thought to be) not, it seems, because he feared persecution from the Church, but rather because he feared ridicule from his fellow scholars. It was not until he lay on his death bed in 1543 that his book *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Celestial Spheres), setting out his new theory, was published.

It was not evidence that prompted Copernicus to put the sun at the centre of the solar system. He may have been influenced somewhat by a tendency towards sun-worship. And he may also have been influenced by Aristarchus, a 3rd century BC Greek who put forward the heliocentric view. The decisive factor however was simplicity. A sun-centred solar system promised to be much simpler than Ptolemy's complicated system. Evidence, if anything, told against Copernicus's theory. Both theories accounted equally well for observed astronomical motions, but Copernicus's theory faced additional empirical problems. First, there was the problem that if the earth rotates on its axis every 24 hours[13] and sweeps at vast speed around the sun, why is this motion not felt? Why does not a stone, thrown vertically into the air, fall some distance away because of the earth's motion during the stone's flight? And if the earth goes round the sun, why do the stars have the same, fixed relative positions at six month's intervals? Stars would have to be absurdly far away for no parallax to be observed.[14]

If planets moved in circles round the sun, Copernicus's theory would indeed have been much simpler than Ptolemy's. But, as Kepler subsequently discovered, they move in ellipses. In order to reduce the motions of the planets to uniform circular motion, Copernicus was obliged to introduce complicated epicycles of just the kind that bedevilled Ptolemy's theory. And in the end, in order to do justice to observations, Copernicus had to stipulate that the planets went round, not the sun, but a point in space some distance from the sun. The beautifully simple idea of Copernicus, or of Aristarchus before him, became somewhat complicated and ugly when developed in detail so as to do justice to observation - although, even in its final, complicated form, Copernicus's theory is still simpler than Ptolemy's.[15]

There is, nevertheless, a beautifully simple idea, which does not quite work, buried in the complexities of Copernicus's actual theory, which does work. It was this beautifully simple idea that subsequently inspired Galileo, Kepler, and a few others.

The Copernican revolution has dramatic implications for Aristotelianism. No longer is the earth at the centre of the cosmos, utterly distinct from the heavens. The earth is thrown into the heavens, a planet among the other planets that encircle the sun. This may be taken to mean, on the one hand, that the earth, now itself a part of the heavens, partakes of the mathematical precision of the heavens. Apparently wayward, haphazard terrestrial phenomena such as weather, growth and decay, all occur, perhaps, in accordance with unknown, mathematically precise law. On the other hand, the Copernican revolution may be taken to imply that since the earth is a part of the heavens, and imperfection, change, growth and decay are everywhere apparent on earth, all this obtains on other heavenly bodies too - the moon, the planets, even the sun. Both these implications came to dominate the thinking, and the work, of Galileo, Kepler, and those that came after them. The implications of the Copernican revolution only came to full fruition, however, with Newton. His laws of motion and law of gravitation apply with equal force to all phenomena, terrestrial and heavenly, to the motion of a stone thrown into the air on earth and to the motion of the earth and other planets around the sun.

There is a diagram in Newton's *Principia* which vividly depicts the point. It shows the earth. Projectiles are hurled horizontally from a mountain peak with greater and greater force. The projectiles travel further and further around the earth before they crash into the ground. But eventually a projectile is hurled with such force that it goes all the way round the earth and returns to the mountain peak from which its flight began. It is in orbit - like the moon or, more accurately, like today's satellites. Thus is continuity between the terrestrial and astronomical depicted in vivid, graphic terms. But we are getting ahead of ourselves!

The Copernican revolution was not the only reason for a re-awakening of the ancient Greek idea that the ultimate nature of the cosmos might be mathematical in character - or such that it could only be depicted employing mathematical ideas. This re-awakening came also from the Renaissance, and a renewed interest in the work of Plato, Pythagoras, Euclid and Archimedes, all of whom can be regarded as holding that the physical universe is mathematical in character. Leonardo, who died before Copernicus's great work was published, nevertheless became convinced that mathematics held the key to understanding nature.[16] Others convinced of the importance of mathematics in this respect include Roger Bacon (1214–1294), Nicholas of Cusa (1401–1464), and Giordano Bruno.

Bruno was an early convert to Copernicus's heliocentric view. Influenced possibly by Nicholas of Cusa, who held somewhat similar views, Bruno argued that the universe is infinite in extent, in both space and time, and homogeneous in that the same four elements (water, earth, fire, air) are present everywhere. He held that the stars are distant suns with their own planetary systems. Matter, Bruno held, is made up of atoms, but these are living, possessing a kind of intelligence (an idea which does not help much with the universe having a precise mathematical structure at a fundamental level).

In January 1600, after a protracted trial, Bruno was condemned as a heretic, partly for his religious views, partly for his cosmology, and on February 27th of that year he was burned at the stake.

William Gilbert was another early convert to Copernicus's theory. His great contribution to natural philosophy, however, was to investigate magnetism experimentally. He discovered many properties of the lodestone, and discovered, too, that the earth is a gigantic magnet. In life, he faired rather better than Bruno. He was a successful physician, and ended up chief physician to Queen Elizabeth and, briefly, to King James.

The full rich implications of Copernicus's theory only began to emerge, however, with the work of Kepler and Galileo.

Kepler

Kepler started out studying theology. It occurred to him that he could study God by studying His creation: the heavens. He decided to devote himself to astronomy. And in a flash of inspiration, he thought he might have discovered the secret of the cosmos. If one imagined the five Platonic solids - in a form both gigantic and invisible - being placed one inside the other, centred on the sun, then the planets could be understood as pursuing circular paths around the sun in the spaces within, between and around the five solids. Thus could one explain why there are only six planets (all that were known at the time), and why they are arranged as they are, with their various distances from the sun. (A great triumph of Euclidean geometry is the theorem that there are only five perfect solids - the so-called "Platonic" solids: the tetrahedron, the cube, the octahedron and so on.[17]) Even though Kepler discovered subsequently that the actual distances of the planets from the sun do not accord with those predicted by his great idea, he never altogether abandoned the idea.[18] What is really significant for the theme of this chapter is that the idea is a magnificent exemplification of the thesis that the universe has a mathematical structure. Kepler's first revelation into the structure of the universe amounts to a special (if false) case of the general, profound idea inherent in the birth of modern science, the scientific revolution, and the immense success of science ever since: some kind of beautiful mathematical structure is built into the universe, into the way all natural phenomena occur.

This general idea informed all of Kepler's subsequent great astronomical discoveries, his big contributions to science or, rather, to natural philosophy. In essence, these consist of the following three laws of planetary motion.

1. The planets orbit the sun in ellipses, with the sun at one of the two foci of each ellipse.
2. The planets move in such a way that a line joining any planet to the sun sweeps out equal areas in equal times.
3. The time taken for each planet to orbit the sun is such that the square of the time taken is proportional to the cube of the semi-major axis of the orbit.[19]

Kepler's works are packed with many additional numerical relationships concerning the solar system which he regarded as being of equal importance, but the above three laws embody Kepler's great contribution to science - to natural philosophy.

Accurate observation played a major role in Kepler's discovery of these three laws. Kepler was fortunate to meet and, for a time, work for Tycho Brahe, who had amassed a body of observations of the planets of great accuracy for the period.[20] When Tycho Brahe died, Kepler inherited his data, and was employed to work on them. It was Tycho Brahe's observational data that made it possible for Kepler to discover and confirm his three laws.

But if observational data were important, so too was Kepler's metaphysical view of the cosmos, his conviction that it had been created by God to exemplify a magnificent, harmonious mathematical structure. It was Kepler's conviction that the motions and distances of planets must exemplify simple and beautiful mathematical relationships that made it possible for him to discover his three laws, and accept them as representing genuine knowledge when they fitted the facts of observation.

Somewhat analogous considerations apply to Galileo, except that in Galileo's case what is most significant in his work depends even more on observation and experiment he carried out himself than is the case with Kepler.

Galileo

Galileo, more than any other single individual, was responsible for the demise of Aristotelianism, the adoption in its stead of Copernicanism and what might be called the "mathematical" view of nature, and the creation of the new natural philosophy - or what we now call "modern science". Galileo fruitfully developed both implications (mentioned above) of Copernicus's theory that result from the theory hurling the earth into the heavens: first, that heavenly phenomena exhibit change and imperfection just like phenomena on earth, and second, that apparently random, chaotic phenomena on earth actually occur in accordance with precise mathematical law - something hitherto associated with the heavens.[21]

The opportunity to develop the first implication arose when Galileo turned his newly invented telescope to view the skies.[22] He discovered that the moon has mountains and craters, and is far from the perfect sphere of Aristotelian orthodoxy. He discovered, most momentously perhaps, that Jupiter has four moons which rotate around it - an emblematic image of the Copernican vision of the solar system. He discovered that Saturn is not a perfect sphere - the first observational hint of Saturn's rings. He discovered that Venus has phases like the moon, an observation which can easily be explained given Copernicus's theory but which is almost impossible to explain given Ptolemy's. He discovered that the milky way is made up of a multitude of stars, an observation that supports the idea of Nicholas of Cusa, Bruno, Gilbert and others that stars are spread out in an immense space - perhaps an infinite space. And he discovered that the sun has dark spots on its surface which rotate with the rotation of the sun, and which come and go, a manifestation of imperfection and change.

Galileo reported these discoveries in *The Starry Messanger* - a book that made Galileo famous all over Europe - indeed, all over the educated world. A translation of the book appeared in China five years after its first publication in 1610.

Galileo worked on developing the second "implication" of Copernicus's theory, on and off, throughout much of his life. By far the most important of this work was his discovery of laws governing terrestrial motion.[23] His first discovery was made when he was 16 years old, soon after first becoming interested in mathematics. During a sermon in the cathedral in Pisa, he noticed, using his pulse to measure time, that a swinging chandelier took the same time to complete a swing however wide or gentle the swings of the chandelier might be. Some years later, Galileo confirmed by experiments that the time a pendulum takes to execute one cycle of swings depends only on the length of the pendulum, and is independent of the amplitude of the swinging or the weight of the bob.

Galileo's most famous discovery concerning terrestrial motion is probably that all objects near the earth fall at the same rate whatever their weight may be, and fall with constant acceleration. Legend has it that Galileo dropped balls of different weight from the leaning tower of Pisa to refute Aristotle's claim that the rate of fall is proportional to the weight of the object. There is no evidence that Galileo did drop balls from the leaning tower of Pisa. The experiment was performed rather by an Aristotelian opponent to refute Galileo and confirm Aristotle. And that was the result claimed for the experiment: the heavy weight did hit the ground a bit before the light one! Galileo was scornful in his dismissal of this conclusion.[24] Historians of science used to believe that Galileo never did perform the experiment anywhere. But more recently, examination of Galileo's papers has revealed that he performed the experiment many times, noting the results with considerable accuracy. Galileo also sought to confirm his discovery that objects fall with constant acceleration by measuring the time balls take to roll down inclined planes - experiments which again, it seems, Galileo really did perform.[25]

Another achievement of Galileo is his discovery of the law of inertia: in the absence of friction or other forces, a body continues in its state of uniform motion in a straight line (and does not gradually come to rest as Aristotelianism holds). Closely associated with this is Galileo's enunciation of what, today, is called "Galilean invariance": laws governing motion - or, more generally, all laws - are the same with respect to all bodies as long as they are moving with uniform velocity in a straight line. In his *Dialogue Concerning The Two Chief World Systems* published in 1632 (which in effect argued for Copernicus and against Ptolemy, and got Galileo into trouble with the Catholic Church), Galileo considers a ship travelling smoothly through a calm sea. He argues that no experiment performed in the cabin of the ship would be able to tell that the ship was in motion. Exactly the same results would be obtained as experiments performed at rest on land.

As I have indicated above, these Galilean laws of terrestrial motion are of decisive importance when it comes to rebutting what were, at the time, standard objections to the Copernican theory. These laws explain why, for example, a stone thrown vertically into the air returns to the point from which it was thrown even though the earth is hurtling through space round the sun.

The law of inertia and Galilean invariance subsequently become key components of Newtonian physics and are not revised until the advent of Einstein's theory of special relativity in 1905.[26]

Galileo made clear that his laws of terrestrial motion ignored air resistance and friction. And indeed a feather falls as fast as a lead shot in a vacuum.

Galileo did not succeed quite in enunciating the law of inertia in the form I have just stated it. He considered a ball rolling on a smooth plane and realized it would move in a giant circle as it travelled round the earth. For Galileo, inertial motion is circular motion, not motion in a straight line. It is possible that Galileo hoped that his version of the law of inertia would, somehow, explain what he took to be the circular motion of the planets round the sun, the motion of the moon round the earth, and the motion of the moons of Jupiter. But any such idea neglects, of course, that these bodies are subject to the force of gravitation, and thus are not exhibiting inertial motion.

The correct form of the law of inertia - bodies continue in their state of rest or uniform motion in a straight line unless a force is impressed upon them - was first enunciated by Descartes.[27]

Galileo also discovered that projectiles trace out parabolas as they fly through the air - neglecting air resistance. (A parabola is an ellipse with one focus moved to infinity.) That projectiles do move along parabolas is a consequence, as Galileo demonstrated, of two of his other discoveries: the law of inertia, and the law of free fall with constant acceleration. It is because a thrown stone continues to have the motion it acquired when it left the hand, and at the same time falls towards the earth with constant acceleration, that it executes the path of a parabola as it flies through the air.

Galileo's achievements are remarkable, both for *what* he achieved, and for *how* he achieved it. More than any other contemporary, Galileo strikes one as doing science in the way that scientists do it today. He is the first modern scientist - as well as a great natural philosopher! Not only does he exploit the telescope brilliantly to obtain observational results highly pertinent to the key cosmological problem of the time: Ptolemy or Copernicus? Even more strikingly, he performs experiments to test, to falsify or corroborate, theoretical conjectures. And he derives consequences from theories and tests them against the results of experiments.

Galileo was not, however, an out and out empiricist. He is quite clear that physical objects and natural phenomena exhibit mathematical structure. And not just any mathematics, but rather in essence *simple* mathematics. Thus it emerges that objects move in accordance with mathematically *simple* laws once one puts aside inessential complications due to friction and air resistance. The intrinsically simple mathematical structure of the universe makes it possible for us to discover what this structure is - as long as we acknowledge that it does have such a structure and develop, as a result, conjectures and theories that reflect this mathematical reality. There are, in short, two crucial components in Galileo's conception of scientific method. There is, on the one hand, the appeal to *observation* and *experiment*. But equally, there is the appeal to a quite definite metaphysical view of the universe: the book of nature is written in the language of mathematics - ultimately *simple* mathematics. Both play essential roles in Galileo's discoveries, not just psychologically, but methodologically.[28] As for Kepler, so for Galileo: *evidence* and *metaphysics* are both essential - the metaphysics being that the universe has some kind of underlying simple mathematical character.

One astonishing feature of Kepler's and Galileo's achievements is that the somewhat different astronomical and terrestrial motions that they discovered are both examples of conic sections. Conic sections are curves produced by the intersection of a plane with a circular cone. Imagine the cone stands upright on a table. If the intersecting plane is horizontal, the resulting curve of intersection is a circle. Tilt the plane, and the curve of intersection becomes an ellipse. Tilt the plane further so that its slope is as steep as the slope of the cone's side, and the curve of intersection becomes a parabola. Tilt the plane even further so that its slope is even steeper than the sides of the cone, and the curve of intersection becomes a hyperbola (or a pair of straight lines if the plane intersects the apex of the cone). The elliptical paths of planets, and the parabolic paths of stones thrown on earth, though different, nevertheless belong to a common class of curves. Even more astonishingly, conic sections were first identified and studied by ancient Greek mathematicians, Menaechmus, Apollonious and others, almost 2,000 years before Kepler and Galileo discovered that planets in the heavens and stones hurled on earth travel along conic sections. We have here a very dramatic example of something that has occurred on a number of occasions in the history of science: mathematicians exploring mathematical ideas with no thought whatsoever for applications to the physical universe nevertheless come up with discoveries which turn out to depict the way physical phenomena occur with incredible accuracy. It is as if mathematicians' minds are attuned, in some mysterious way, to the inner workings of nature. This capacity of pure mathematics to anticipate subsequent physics has baffled scientists and philosophers.[29] An explanation will be proposed in chapter five (note 17)!

Newton

The next great natural philosopher for us to consider is Isaac Newton. Building on the contributions of his great predecessors - Copernicus, Kepler, Galileo, and Descartes - Newton produced a kind of triumphant synthesis of their work. But it was much more than a synthesis of his predecessors. Newton laid the foundations for classical physics which met with ever expanding empirical success, until the 20th century and the advent of the theories of relativity of Einstein, and quantum theory. And even today, long after the advent of these 20th century theories, it is still Newtonian physics that is used to calculate the paths of spaceships and artificial satellites. Newton put forward the first fundamental dynamical theory of physics ever - his theory of gravitation.[30] There are only six successful fundamental dynamical theories in physics, and Newton put forward the first one.[31] To some of his contemporaries and immediate successors, it seemed that Newton had done something almost miraculous. He had discovered the secret of the universe. He had put his finger on what it is that causes the earth, the moon, the planets and the stars to move as they do throughout the universe, for all time. There is a sense in which, with Newton, modern science comes of age. But, as we shall see, though clearly a natural philosopher himself, Newton's work nevertheless played a key role in the demise of natural philosophy - its disintegration into science and philosophy.[32]

What, in a bit more detail, did Newton achieve? First, he created the differential and integral calculus, mathematics required to describe motion and change more generally, and absolutely essential for the subsequent development of physics.[33] But it is in the three Books of his *Principia*,[34] published in 1687, that Newton laid the foundations of classical physics and demonstrated how his universal law of gravitation was able to predict and explain the motions of the planets, moons and comets of the solar system together with a wealth of other phenomena as well. In the Preface to the first edition of the *Principia*, Newton makes clear what he sets out to do - and even specifies clearly the research programme for the future of physics:

> the whole burden of philosophy seems to consist in this - from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena; and to this end the general propositions in the first and second Books are directed. In the third Book I give an example of this in the explication of the System of the World; for by the propositions mathematically demonstrated in the former Books, in the third I derive from the celestial phenomena the forces of gravity with which bodies tend to the sun and the several planets. Then from these forces, by other propositions which are also mathematical, I deduce the motions of the planets, the comets, the moon, and the sea. I wish we could derive the rest of the phenomena of Nature by the same kind of reasoning from mechanical principles, for I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards one another, and cohere in regular figures, or are repelled and recede from one another. These forces being unknown, philosophers have hitherto attempted the search of Nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.[35]

Newton's suspicion - the conjecture he expresses here about the nature of the physical universe and the path physics would take in the future - has turned out to be substantially correct, even if Newtonian principles have had to be revised along the way. Three forces in addition to gravitation suffice in principle to account for all the known phenomena of Nature - properties of matter, electromagnetic, chemical and nuclear phenomena.[36]

In Book 1 of the *Principia*, after defining crucial notions such as "quantity of motion" (mass times velocity, or momentum), Newton formulates the following three laws of motion, the basis for classical mechanics:[37]

I Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

II The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

III To every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

The second of these laws in effect asserts that the force, F, on a body is equal to the mass, m, times the acceleration, a, of the body, that is: F = m.a.

Newton then goes on in Book 1 to prove a great number of propositions and theorems, many, but by no means all, related to the task of establishing his universal law of gravitation and using it to explain the System of the World - that is, the solar system - to be taken up in Book 3. Thus the first theorem proves that a body attracted by a force to a fixed point moves in such a way that the line joining the body to the fixed point sweeps out equal areas in equal times - echoes of Kepler's 2nd law! Theorem 2 established the converse: if a body moves so that a line joining it to a fixed point sweeps out equal areas in equal times then it is attracted to the fixed point by a force. Proposition 11 establishes that a body moving in an ellipse experiences a force directed at a focus of the ellipse, the strength of the force being inversely proportional to the square of the distance. Newton goes on to establish similar results for bodies moving in hyperbolas and parabolas. He then goes on, in proposition 17, to prove the converse of these results, namely that if a body moves under the influence of a force directed towards a fixed point, the force varying inversely as the square of the distance, then the body will move in a conic section - an ellipse, parabola or hyperbola.

Book 2 is in the main concerned with the motion of bodies through fluids. It may have been written in part to refute Descartes' vortex theory of the solar system, according to which invisible swirling matter in space sweeps the planets round the sun (a modified version of which was also held by Huygens).

Book 3, exploiting the results of Book 1, sets out to establish Newton's universal law of gravitation and explain the System of the World. First, Newton makes explicit his conception of what we would today call "scientific method" in what he calls "Rules of Reasoning in Philosophy":

Rule 1: We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

Rule 2: Therefore to the same natural effects we must, as far as possible, assign the same causes.

Rule 3: The qualities of bodies, which admit neither intensification now remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.

Rule 4: In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypothesis that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.[38]

Newton goes on to specify six "phenomena" - six regularities of the solar system - that form the empirical basis for arriving at the law of gravitation. These are that the moons of Jupiter and Saturn obey Kepler's 2nd and 3rd laws of planetary motion, and so too do the planets other than the earth in their motion round the sun; and our moon, in its motion round the earth, obeys Kepler's 2nd law. Newton then goes on, in a number of propositions and theorems, to establish his universal law of gravitation by means of his laws of motion and mathematical theorems of Book I, and the six phenomena just indicated - the above four rules of reasoning being appealed to at various points. Thus Newton first proves, in Proposition 1, that the moons of Jupiter move subject to a force directed towards the centre of the planet that is inversely proportional to the square of the distance to the centre (i.e. $F \alpha 1/D^2$, where D is the distance from the centre of the moon to the centre of Jupiter). He goes on to establish the same for the moons of Saturn and, in Proposition 2, the same for the planets (D in this case, of course, being the distance to the centre of the sun). The moon too is shown to obey the inverse square law (in Proposition 3). Then, invoking rules 1 and 2, Newton argues, in Proposition 4, that the force to which the moon is subject is the force of gravity - the very same force we feel on earth and call gravity, responsible for bodies falling near the earth's surface. Likewise (Proposition 5), the moons of Jupiter are drawn towards Jupiter by the force of gravitation - as are the moons of Saturn towards Saturn. And indeed "there is a power of gravity tending towards all the planets". "And", Newton goes on "since all attraction (by Law III) is mutual, Jupiter will therefore gravitate towards all his satellites, Saturn towards his, and the earth towards the moon, and the sun towards the planets". And "All the planets do gravitate towards one another" which means, Newton points out, that Jupiter and Saturn, when closest together, will sensibly disturb each other's motion, as the sun disturbs our moon's motion, and the sun and moon disturb our sea (causing the tides). Then (in Proposition 6), Newton sets out to establish that "all bodies gravitate towards every planet", weights of bodies, at any given distance from the centre of the planet, being proportional to the quantity matter (i.e. the mass). Newton then establishes that "there is a power of gravity pertaining to all bodies, that is proportional to several quantities of matter which they contain". Then, in Proposition 8, we have the theorem that two homogeneous spheres attracting each other by gravitation, the weight of either will be inversely as the square of the distance between their centres". Newton then establishes that the centre of the solar system is, not the centre of the sun, but rather the centre of gravity of the solar system, the sun being somewhat in motion with respect to this centre as it is tugged this way and that by the gravitational attraction of the planets. Newton then derives Kepler's laws for the planets *a priori* as he puts it, the planets only moving precisely in ellipses, however, if gravitational forces between planets are neglected, and the sun is assumed not to move.[39]

Newton goes on to derive various consequences from his law of gravitation and what has been established so far. He discusses the flattening of the earth and other planets at the poles because of their rotation; variation in weight at different latitudes on earth; gravitational attraction of the moon and sun producing the tides; the motion of the moon, affected by gravitational attraction of both earth and sun - a difficult 3-body problem which cannot be solved exactly; the motion of comets, which are shown to be along conic sections (approximately parabolas close to the sun).

What Newton does in the *Principia* is extraordinarily impressive. It really does seem that Newton derives his universal law of gravitation from the phenomena, just as he claimed he had done. First, there are the purely mathematical theorems: bodies that move so as to obey Kepler's laws must be deflected from uniform motion in a straight line by a force that varies inversely as the square of the distance. Then, observation tells us that moons and planets do actually move so as to obey Kepler's laws. Therefore they must be subject to a force that varies inversely as the square of the distance. And since we can move, by degrees, from the motion of a stone thrown on earth to the motion of the moon round the earth, this force must be the force of gravitation, of which we are so familiar here on earth. Granted that every body in the universe gravitationally attracts every other body, it is clear that the motions of the moons and planets must deviate slightly from perfect Keplerian motion due to mutual gravitational attraction - the final, devastatingly convincing evidence in support of Newtonian theory.

The contrast with Kepler and Galileo is striking. Newton does not appeal to the metaphysical thesis that the universe has some kind of mathematical structure - or does not do so explicitly. He is quite clear. In a famous passage in the *Principia* he declares: "I have not been able to discover the cause of [the] properties of gravity from the phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called an hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy. In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction."[40]

Newton, subsequently, was taken at his word. He became a hero of the Enlightenment. The *Principia* was taken to reveal what one has to do to secure knowledge. First, phenomena have to be reduced to precise regularities; then laws and theories can be inferred by induction, just as Newton had done, and had himself affirmed. No longer do natural philosophers need to engage in fruitless debate about metaphysics, philosophy, epistemology and methodology. That could be left to the philosophers.

Newton's *Principia*, the moment of high triumph of the new natural philosophy also, paradoxically, spelled its downfall. It was Newton's *Principia* that led, eventually, to a decisive split between science and philosophy, and thus to the death of natural philosophy.

Epilogue

In this chapter I have argued that science began as natural philosophy, and this brings together two crucial elements: first, a new metaphysical vision of the universe (it is made up of atoms; it is governed by precise mathematical laws) and, second, associated with this, the empirical method of careful observation and experimentation. Both are essential. The second element stems, in part, from the first. New theories, in order to be acceptable, must meet two requirements: they must accord sufficiently well with the new metaphysical view of the universe, and they must meet with sufficient empirical success.

This picture of the origins of science and the scientific revolution has been expounded and defended by a number of notable historians of science: A. E. Burtt, Alexandre Koyré, Herbert Butterfield, Richard Westfall,[41] and others. But other historians of science have called aspects of this orthodox picture into question. Pierre Duhem[42] argued that there is far more continuity in the development of science than the orthodox picture allows;

research conducted in medieval times anticipated aspects of the work of Galileo and his contemporaries. Other historians of science have pointed out that some of those who contributed to natural philosophy around the time of Galileo did not accept atomism or the mathematical view of nature, and may have seen the world in Aristotelian terms. This is true of both William Gilbert and William Harvey. Others have denied that there is anything unique or distinctive about the scientific revolution, or even that it existed at all.

Burtt and Koyré seem to be out of fashion. This may be, in part, because both stressed the importance of so-called "internal" factors - intellectual and methodological factors - in the emergence of modern science. These days, "external" factors - social, institutional, cultural, economic, political - are all the fashion among many historians of science, and internal factors are regarded as somewhat passé. In fact we need to attend to both.[43] Modern science has institutional, social, cultural, economic and political aspects: in order to tell how it arose and evolved, all these features need to be appealed to. But science is also an intellectual endeavour; it seeks to improve our knowledge and understanding of the universe, and of ourselves and other living things as a part of the universe, and in that endeavour it has met with astonishing success. In order to understand how that intellectual success has come about, we need to attend to the intellectual and methodological aspects of science just as much as its social, political and economic aspects. Indeed, there are grounds for holding that the intellectual leads the way. It was because natural philosophy began to be astonishingly successful *intellectually*, that it was able to attract support, social status and funds.

Many contemporary historians of science seem incapable of doing intellectual history of science because such history would be of an enterprise that seeks, and achieves, intellectual progress, which in turn would mean, they believe, that it would inevitably be disreputable "Whiggish" history.[44] But that is nonsense. As Popper argued decisively long ago, all history is of something more or less specific: "the history of art; or of language; or of feeding habits; or of typhus fever".[45] There is no such thing as "total" history - history of everything that has happened. One entirely legitimate specific kind of topic for history is any endeavour that seeks to make progress or, more specifically, *science construed as an endeavour that seeks to make progress in knowledge.* In writing history of science so construed one should not, of course, just assume that progress is inevitable, or even that it has occurred; nor should one write propaganda on behalf of science and its claims to have made progress. It does mean, however, that one selects out for attention those past episodes, contributions, events, that in retrospect constitute steps in the progress of scientific knowledge and understanding. In order to tell the history of science properly, it is vital to consider blind alleys, failed efforts, theories and research that may have seemed promising at the time but led nowhere. And it is important to consider what past contributions, research and debates meant at the time, not just what they mean to us today. The crucial point to appreciate, however, is that intellectual history of science as an endeavour that seeks, and achieves, progress in knowledge lies at the heart of the discipline of history of science. The idea that such history must be "Whiggish" in some intellectually disreputable sense is an elementary blunder. Those who make the blunder render themselves incapable of writing history of science as a progress-achieving endeavour. The fundamental problem of the history of science - how and why scientific progress has come about - disappears from view.[46]

There is a more specific reason why Burtt and Koyré are out of fashion. Both held, I think it is fair to say, that modern science emerged from a new, significant intellectual and methodological discovery: *how to do science*.[47] This tends to be denied by a number of contemporary historians of science. I now consider the views of two such historians: Steven Shapin and Stephen Gaukroger.

Shapin begins his book *The Scientific Revolution* (1998) with the inflammatory sentence "There was no such thing as the Scientific Revolution, and this is a book about it". He goes on to claim that science did not exist in the 17th century. Instead, there was "a diverse array of cultural practices aimed at understanding, explaining and controlling the natural world". It is doubtful, Shapin declares, that there is any such thing as scientific method, and even more doubtful that its origins are in the 17th century. There was no revolution in knowledge and understanding. On the contrary, natural philosophy displays continuity "with its medieval past" (pp. 3-4). In opposition to most of this, in this book I argue that natural philosophy, if not science, certainly did exist in the 17th century. There may well have been "a diverse array" of approaches to understanding nature, but this does not in any way challenge the profound significance of the work of Galileo, Kepler, Newton and others associated with the new natural philosophy that led eventually to modern science. No one, surely, has thought that *everyone* was doing the new natural philosophy! In chapters 3 and 5 we will see that there very definitely *is* such a thing as scientific method, and its roots are to be found, above all, in the work of Galileo and Newton. A profound revolution in our knowledge and understanding of Nature took place in the 16th and 17th centuries, associated with the work of Copernicus, Kepler, Galileo, Newton and others. Continuity with medieval science is only apparent if we ignore the revolutionary character of the discoveries and methods of 17th century natural philosophy.

Lurking behind Shapin's claims there is perhaps the "social constructivist" view that there is no such thing as scientific progress - or at least history of science must be conducted as if it does not exist.[48] If scientific progress does not exist, then of course the unprecedented progress made by Galileo, Newton and others disappears, and *the* reason to acclaim their work by calling it "the scientific revolution" disappears as well. Take scientific progress seriously, and it is at once obvious that the scientific revolution exists and is of profound significance.

The idea that there is no such thing as scientific progress may gain sustenance from the long-standing failure of philosophers to explain how it is possible. That source of sustenance is removed by this book. As my argument unfolds, it will become abundantly clear, I trust, how progress in science - or rather in natural philosophy - is to be understood.

Stephen Gaukroger is more modest in his denial of the profound intellectual significance of the scientific revolution. He does not deny it exists, but holds that it was just the latest in a series of similar earlier revolutions. In his *The Emergence of a Scientific Culture* (2006) - a work of magnificent sweep and scope, rich in detail - he declares "There have been a number of civilizations that have witnessed a form of 'scientific revolution'". What distinguishes *the* scientific revolution from these earlier ones is its "uninterrupted and cumulative growth that constitutes the general rule for scientific developments in the West since that time" (pp. 17-18). It is the *persistence* of the science that emerged from *the* scientific revolution that distinguishes it, in

Gaukroger's view, from earlier scientific revolutions in Europe, China and the Islamic world. These earlier revolutions all exhibit a "pattern of slow, irregular, intermittent growth, alternating with substantial periods of stagnation, in which interest shifts to political, economic, technological, moral, or other questions". Thus the persistent, accumulative character of modern science, stemming from *the* scientific revolution, does not come, for Gaukroger, from any new intellectual or methodological discovery; it comes, one might say, from persistent effort, a refusal to be distracted.

But all this is a mistake. Modern science does emerge from a new intellectual and methodological discovery: how to marry metaphysics and method, a specific view of the universe and a method of experiment and observation - experimentation linked to the new metaphysical view. (This has antecedents, of course, that go back to the ancient Greeks, to Democritus, Aristarchus, Eratosthenes, Archimedes and Euclid.) This idea is all but encapsulated in the title of one of Koyré's books: *Metaphysics and Measurement*. There is a reason why *the* scientific revolution led to "uninterrupted and cumulative growth": a key discovery had been made about how to acquire knowledge progressively, not made by earlier "scientific revolutions".

In one respect I may differ from the views of Burtt and Koyré. I hold that the new methodological discovery, that led to modern science, never got properly articulated and understood. The natural philosophers who created modern science made a crucial discovery in scientific *practice*, but failed to make this discovery lucidly explicit. And this failure lingers on down to the present. Scientists today take for granted an untenable view of science that fails to do justice to what actually goes on in scientific practice - fails to do justice to what is responsible for the growth of scientific knowledge.[49]

It may be that it is this long-standing failure to get the progress-achieving methods of science properly into focus that is in part responsible for the failure of many historians of science to see that there is anything novel, methodologically, about the new natural philosophy. If *empiricism* is all that characterizes the methods of modern science then one may well hold that there is nothing especially distinctive *methodologically* about *the* scientific revolution, or the science that came from it.

A central concern of this book is to demonstrate that *empiricism* is not enough. Science needs evidence *and metaphysics*. Once this is appreciated, it becomes clear that we need a new conception of science which acknowledges explicitly metaphysical assumptions of science so that they can be critically assessed and, we may hope, improved. In chapters three and five I expound, argue for, and spell out implications of, this new conception of science, which I call *aim-oriented empiricism*. This view provides methods designed to facilitate the articulation, critical assessment, and improvement of metaphysical assumptions of science.[50] It is the methodological framework for synthesizing metaphysics and empiricism, science and philosophy, and thus recreating something close to 17th century natural philosophy.

Scientific progress has been possible because scientists have managed to come close to implementing aim-oriented empiricism in scientific practice, even though they have not understood their scientific work in this way. Science would become even more successful, in both intellectual and humanitarian terms, I shall argue, in chapters five, six and eight, if it put aim-oriented empiricism consciously and explicitly into practice.

But is it conceivable that *what scientists do* is at odds with *what they think they are doing*? One rather well known scientist thought so - a scientist who made profound contributions to science as a result of implementing methods close to those of aim-oriented empiricism, and came close to *advocating* aim-oriented empiricism explicitly. That scientist is Albert Einstein.[51] And he remarked on one occasion "If you want to find out anything from the theoretical physicists about the methods they use, I advise you to stick closely to one principle: don't listen to their words, fix your attention on their deeds."[52]

In this chapter and the next I attend only to the bare minimum I need to attend to in order to sketch the story of the fundamental *intellectual* blunder inherent in our current conceptions of science which can be traced all the way back to Newton - a blunder all historians of science known to me ignore. I might add that histories of science which ignore the intellectual and methodological aspects of science thereby deprive themselves of even the possibility of uncovering damaging intellectual blunders inherent in the birth and evolution of modern science. The very possibility of *criticizing* aspects of modern science disappears. The fundamental *problem* of the history of science disappears as well - the problem of improving our understanding of how science has made such astonishing intellectual progress.

Fortunately, there is a recent, magnificent account of the rise of modern science that does do justice to the intellectual and methodological issues involved, and explores them in rich and fascinating detail: H. Floris Cohen's *How Modern Science Came into the World* (2010). Cohen fully appreciates just how extraordinary the great discoveries of the scientific revolution are - and how astonishing subsequent scientific progress has proved to be. But Cohen, along with all other historians of science known to me, fails to point out that the scientific community even today still fails to get the nature of the progress-achieving methods of science sharply into focus. We are not really in a position to tell the story properly of how humanity discovered how to do science until we get clear about *what it was that humanity did discover*!

Notes

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[1] Aspects of these philosophical blunders are discussed in Maxwell (1984 or 2007a; 2004a; 2014a; 2014b and 2017). See also Maxwell (2009a; and 2010).

[2] For an excellent recent detailed account of the origins of modern science see Cohen (2010). Classic works on the scientific revolution include Burtt (1980); Koyré (1957); Butterfield (1949); Dijksterhuis (1969); Westfall (1977). See Cohen (1994) for a fascinating, comprehensive discussion of various approaches of historians of science to the scientific revolution up to around 1991. More recent works on the scientific revolution include: Lindberg and Westman (1990); Shapin (1998); Rossi (2001); Henry (2002); Gaukroger (2006 and 2010); and Cohen (2015).

[3] This point was well made long ago by Burtt (1932).

[4] Aspects of the picture of the scientific revolution I depict in this chapter have been called into question by some historians of science in recent decades. I discuss this issue briefly in the final section of this chapter.

[5] Galileo, *The Assayer* (1623): see Drake (1957, p. 274).

[6] Drake (1957, p. 276).

[7] A slightly modified version of a translation quoted in Guthrie (1978, p. 440), where an account of Democritus' life and work is to be found.

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[8] The first person to publish the correct version of the law of inertia was Pierre Gassendi, who also tested it experimentally by dropping weights on moving ships and carriages. Descartes formulated the law earlier in a treatise on natural philosophy called *Le Monde* which he decided not to publish at the last minute because he received news of Galileo's trial. *Le Monde* defended a Copernican theory. Descartes finally published the law in his *Principia Philosophiae* (*Principles of Philosophy*) which appeared in 1644, published after Gassendi: see Cohen (1985, pp. 210-211).

[9] That the particles fill all of space and are rigid creates a problem for motion.

[10] Locke (1961, p. xxxv).

[11] A thesis that is *metaphysical*, as I use the term, is one that is not testable empirically. It is neither verifiable nor falsifiable by means of observation or experiment. This definition is not entirely satisfactory. One might well hold that the corpuscular hypothesis - the doctrine that matter is made up of minute, invisible, rigid corpuscles - is a metaphysical doctrine. But versions of the corpuscular hypothesis that hold that corpuscles interact only by colliding – there thus being only repulsive forces in the world – can be regarded as being not just falsifiable empirically, but falsified by the observation that there are cohesive and attractive forces in nature (forces that hold pieces of rock and metal together, for example, and magnetic and gravitational forces). In the 17th century, attempts were made to explain cohesive and attractive forces within the framework of the corpuscular hypothesis, but these attempts were not very successful! The metaphysical theses that we will be concerned with in this book are all theses put forward in an attempt to anticipate what theoretical physics may subsequently discover. Examples of such theses from the history of physics and its associated metaphysics are: the corpuscular hypothesis just mentioned; the thesis that the world is made up of point-particles that have mass and are surrounded by a centrally directed, rigid, spherically symmetric field of force that varies from the repulsive to the attractive as one moves away from the point-particle. For further examples, see chapter 5, section 5.

[12] In what follows I give a very brief account of the contributions of Copernicus, Kepler, Galileo and Newton, not with the intention of saying anything new about these contributions, but rather to highlight the vital role that a certain metaphysical view about the nature of the universe played in these discoveries - the view, as Galileo put it, that "the book of nature is written in the language of mathematics". This metaphysical view is not just psychologically important, important in suggesting fruitful hypotheses - important in the context of discovery, as philosophers of science would put it. The view is *methodologically* important - indeed essential. It is vital in the context of verification, the context of accepting and rejecting hypotheses. It is as important as *evidence* is - observation and experiment. There were two vital ingredients in the new natural philosophy: the appeal to *observation* and *experiment*; and the appeal to the metaphysical thesis that the universe has some kind of mathematical structure or reality. A new hypothesis in physics or astronomy, in order to be acceptable as new knowledge, had to satisfy *both*.

[13] Copernicus differs from Ptolemy, not only in holding that the earth goes round the sun every year, but also in holding that the earth rotates on its axis every 24 hours - instead of the heavens rotating every 24 hours around a stationary earth.

[14] Galileo cleared up the first of these two empirical problems facing Copernicus's theory.

A stone thrown into the air continues to possess the motion of the earth it had before it was thrown. The second empirical problem was not cleared up until 1838, when Friedrich Bessel, a German mathematician and astronomer, observed stellar parallax predicted by Copernican theory.

[15] Ptolemy's theory postulated some 80 epicycles (plus other devices), whereas Copernicus postulated only 34.

[16] Burtt (1932, pp. 42-43).

[17] The Platonic, regular or perfect solids are polyhedra whose faces are all the same, edges all the same length. Thus the cube has 6 faces, each face a square. The tetrahedron has 4 faces, each an equilateral triangle; the octahedron has 8 faces, each also an equilateral triangle; the dodecahedron 12 faces each with 5 edges; and the icosahedron has 20 faces each an equilateral triangle. And these are all that there are, granted that space is Euclidean and 3 dimensional.

[18] From a modern perspective, of course, Kepler's idea faces the further difficulty that there are nine planets (taking Pluto to be a planet), not five. In addition, we have no particular reason to suppose that the distances planets have from the sun will obey any precise law. There is, however, Bode's law, which states that the distance from sun to planet is 4 + N, where 10 is taken to be the distance from the sun to the earth, and $N = 0, 3, 6, 12, 24, 48, \ldots$, where for $N \geq 3$ each value of N is twice the previous value. This rule works quite well, as long as we take Ceres in the asteroid belt to be a planet (or failed planet) until we get to the two final planets, Neptune and Pluto, when it goes badly astray.

[19] A few words of explanation. In order to draw an ellipse, fix the ends of a piece of string to two drawing pins stuck into a board, and trace out a curve with a pencil pressed hard against the string so as to keep the string taught. The drawing pins are at the two foci of the ellipse that results. The ellipse, it should be noted, is a generalization of the circle. As the drawing pins are put closer and closer together, so the ellipse tends towards the circle. Kepler's second law amounts to a generalization, for the ellipse, of the statement that planets move uniformly in circles round the sun. The semi-major axis of an ellipse is the line drawn from the centre of the ellipse, half way between the foci, through one focus and on to the ellipse itself. It is, as it were, the longest radius of the ellipse, as opposed to the shortest radius, the "semi-minor" axis. (The difference between these two axes becomes less and less as the two foci are put closer and closer together.) Kepler's third law can be formulated thus: $T^2 = kR^3$, where T is the time it takes for the planet in question to orbit the sun, R is the length of the semi-major axis of the ellipse the planet traces out on its journey round the sun, and k is a constant.

[20] Tycho Brahe's theory of the solar system was a compromise between Ptolemy and Copernicus. He held that the sun goes round the earth, but all the other planets go round the sun.

[21] I should make clear that "implications" of Copernicus's theory here means no more than "what might be taken to be reasonable modifications of Aristotelianism in the light of Copernicus's theory". The Aristotelian contrast between the unchanging mathematical perfection of the heavens and the rather more arbitrary processes of change, growth and decay here on earth can hardly be maintained once it is acknowledged that the earth is, as it were, in the heavens itself as it goes round the sun with the other planets. It is not

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unreasonable to conclude that other planets, other heavenly bodies, exhibit change, imperfection, growth and decay just as the earth does. And, on the other hand, if we hold onto the Platonic and Aristotelian idea that mathematics governs what goes on in the heavens, and we hold that the earth is now itself in the heavens, it is reasonable to conclude that phenomena on earth occur in accordance with (unknown) mathematical laws.

[22] An Englishman called Leonard Digges seems to have been the first person to invent the telescope around 1551. His son, Thomas Digges, was the first person to give an account of Copernicus's theory in English in 1576: see Gribbin (2003, pp. 15-17). The telescope was reinvented by accident by a Dutch spectacle maker, Hans Lipershey, in 1608. Galileo on hearing of the invention, reinvented an improved telescope, one which included a convex lens, and thus kept the image upright instead of inverting it as Lipershey's telescope did.

[23] For a summary of Galileo's discoveries concerning terrestrial motion see Cohen (1985, pp. 214-217).

[24] Galileo wrote: "Aristotle says that a hundred-pound ball falling from a height of one hundred cubits hits the ground before a one-pound ball has fallen one cubit. I say they arrive at the same time. You find, on making the test, that the larger ball beats the smaller ball by two inches. Now, behind those two inches you want to hide Aristotle's ninety-nine cubits and, speaking only of my tiny error, remain silent about his enormous mistake."

[25] For discussion of the grounds for holding that Galileo really did perform experiments he claimed to have performed, and further references, see Cohen (1985, pp. 188-209 and 212-213).

[26] The law of inertia and Galilean invariance may be understood to be consequences of, or at least closely related to, the idea that all motion is relative, there being no such thing as motion relative to space itself but only relative to some other body. If this is the case, then whether a body is at rest or in motion depends solely on one's frame of reference. So, if we agree that a body at rest stays at rest unless a force impressed on it causes it to move, it follows from this that a body in motion will continue in that state of motion unless a force impressed on it changes its state of motion. For the body at rest with respect to another body A, is also in motion with respect to another body, B, in motion with respect to A. Even though all this can be regarded as key components of Newtonian theory, Newton himself would have disagreed. Newton held that there is such a thing as absolute space, and absolute motion with respect to it. And there is the following consideration ostensibly in favour of this view. Even though there is no way of measuring whether one is in uniform motion or at rest with respect to absolute space, one can, it seems, determine whether one is accelerating or not - without it being necessary to refer to any external body. If you are travelling in a train that hits the buffers as it comes into the station, what you experience inside the train tells you that you have experienced a sudden de-acceleration. Only with Einstein's general theory of relativity is there a suggested explanation as to why you may not know whether you have suffered a sudden de-acceleration or not. At first sight it seems impossible to declare, in the spirit of the relativity of motion, that the train is stationary throughout and it is the platform and station (and earth) which come hurtling towards the train, to suffer sudden de-

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acceleration when the buffers hit the train. It is only people in the train who feel the effects of sudden de-acceleration; people on the platform feel no effects whatsoever. But Einstein suggests a way in which it is possible to declare that the train is stationary throughout and it is the station that de-accelerates. At the very moment that the station buffers hit the stationary train, a powerful gravitational field comes into existence for the brief period of the collision. This exactly cancels out the effects of de-acceleration of the platform and the people on it. Acceleration due to the gravitational field and de-acceleration due to the collision with the train cancel each other out, and people on the platform feel nothing. But people in the train, being stationary (according to this surreal account), feel powerfully the effects of the sudden gravitational field at the moment of impact. They are thrown forward, and cups of coffee fly off tables. It is just as if the train has come to an abrupt halt, even though it has been stationary throughout. All the effects of acceleration, in other words, can be mimicked by gravitational forces appropriately switched on and off, and *vice versa*. No experiment performed in a lift can distinguish between effects of (a) acceleration or (b) appropriate gravitational field. But all this lies far into the future of Galileo. Nevertheless, that Galileo's work prompts such reflections is an indication of just how fundamental his contribution is.

[27] The first to publish the correct form of the law was Pierre Gassendi: see note 8.

[28] Gary Hatfield has argued that Galileo adopted, and argued for, a mathematical approach to nature, but this does not amount to adopting a metaphysical view of nature: see Hatfield (1990). But Hatfield's argument strikes me as unconvincing. There is, implicit in Galileo's methods and approach, a view of the natural world dramatically different from Aristotle's - a view that becomes explicit in Galileo's remark about "the book of nature", and in the distinction he draws between what came to be called after Locke "primary" and "secondary" qualities, only the former being real.

[29] For a famous articulation of this sense of bafflement see Eugene Wigner's essay "The Unreasonable Effectiveness of Mathematics in the Natural Sciences": Wigner (1967, ch. 17). Related is Einstein's pronouncement "The eternal mystery of the world is its comprehensibility": Einstein (1973, p. 292).

[30] A "dynamical" theory, as I use the term, is a theory that provides a law for the operations of a *force.*

[31] The other five are classic electrodynamics, general relativity, quantum electrodynamics, quantum electroweak theory, and quantum chromodynamics. Classical electrodynamics is the theory of the electromagnetic field. It was created by James Clerk Maxwell in the 19th century, building on the work of Michael Faraday and others. General relativity is Einstein's theory of gravitation, put forward in 1915. It holds, roughly, that matter (or energy more generally) curves space-time, and bodies then move along what is nearest to straight lines (called geodesics) in the resulting curved space-time. Quantum electrodynamics, as its name suggests, is the quantum version of Maxwell's classical electrodynamics. It was created by Paul Dirac, Richard Feynman and others in the 20th century. Quantum electroweak theory unifies the electromagnetic and so-called "weak" forces (the latter a nuclear force). And chromodynamics is the quantum field theory of the so-called "strong" nuclear force.

[32] For a recent, detailed and very impressive analysis of and, in a way, defence of, Newton's achievement, see Harper (2011).

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[33] As I have already mentioned, the calculus was also invented independently by Leibniz. Newton invented his version of the calculus first in 1666 when he was 23, but did not publish at the time. Leibniz invented his version later and published before Newton. Newton's supporters accused Leibniz of stealing Newton's work from unpublished letters and manuscripts.

[34] Full title: Philosophiae naturalis principia mathematica (Mathematical Principles of Natural Philosophy).

[35] Newton (1962, pp. xvii-xviii) - first published 1687.

[36] One needs of course the physical theories of these forces to predict phenomena - the theories mentioned in note 31. And in practice only the simplest phenomena can be predicted because of the extreme difficulty of solving the equations of the theories. The nature of dark matter remains a mystery - a form of matter conjectured to exist on the basis of its gravitational effects on the rotation of stars in galaxies.

[37] Newton (1962, vol. 1, p. 13).

[38] Newton (1962, vol. 2, pp. 398-400). These rules were modified, and even added to, by Newton in successive editions of the *Principia*, as we shall see in chapter two.

[39] All this is established in the first 24 pages of Book 3 of the *Principia*: see Newton (1962, vol 2, pp. 399-422).

[40] Newton (1962, vol. 2, p. 547).

[41] See Burtt (1980); Koyré (1957; 1965; 1968); Butterfield (1949); Westfall (1977)..

[42] Duhem (1954-58; 1991).

[43] The very distinction, as customarily drawn - factors "internal" to the discipline versus "external" social factors: see, for example, Henry (2002, p. 7) - is doubly misconceived. In the first place, the rationality, the scientific character, of science depends crucially on its *social* character (Popper, 1962, Vol II, pp. 217-220), and on having the right kind of *institutional* structure (Popper, 1961, pp. 154-159). In ignoring *methodological* aspects of science (as "internalist"), social constructivists ignore vital *social* and *institutional* aspects of science! Secondly, it is absurd to hold that *intellectual* aspects of science are *internal* to it. Very crudely, we might say that the intellectual aspects of the social phenomenon that is science are those aspects that have to do with fact, truth, knowledge and explanation, and methods relevant to the assessment of these things. But it is quite wrong to characterize these as "internal" to science: they are of concern throughout the social world, in courts of law, in journalism, and throughout social life quite generally. Whether a statement or belief is true or not - or whether there are good grounds to hold it to be true or not - can be a matter of great concern in all sorts of social contexts. It is an aspect of social life that no social scientist can ignore - including, of course, sociologists and historians of science.

[44] The notion of "Whiggish" history as something intellectually disreputable comes from Butterfield (1951) - a rather bad book that ignores that history is always about something more or less specific, and may, quite legitimately, be about the more or less specific topic of an endeavour that seeks to make progress towards some aim, and may even achieve it.

[45] Popper (1962, p. 270).

[46] For a more detailed refutation of the idea that history that sees science as a progress-achieving endeavour must be Whiggish history in an intellectually disreputable sense, see Maxwell (2014b, pp. 65-85).

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[47] We need to distinguish two kinds of discovery associated with the birth of modern science: (i) discoveries about the world, such Kepler's, Galileo's and Newton's laws, and Harvey's discovery of the function of the heart, and (ii) the discovery of how to do science. If (ii) is to be attributed to any one individual - and of course it cannot be - that individual would be Galileo. But Galileo made the discovery primarily *in practice*, in the way he *did* natural philosophy, not in a formulated view as to how natural philosophy ought to be pursued.

[48] For a decisive criticism of social constructivism see Maxwell (2014b, ch. 4).

[49] The view I have in mind is that *evidence* decides what theories are accepted and rejected in science, metaphysical assumptions playing no role. This orthodox view of *standard empiricism*, as I call it, is expounded and refuted in chapter three.

[50] How are metaphysical theses associated with physics to be assessed and improved even though they are not empirically testable? First, there are theses which are required to be true if science is to be possible at all: these deserve to be accepted even though we have no grounds to hold that they are true. An example is the thesis: the universe is such that it is possible for us to acquire some knowledge of our local circumstances. If this thesis is false, we have had it, whatever we assume. Nothing can ever be gained by rejecting this thesis. Second, from a number of candidates, we accept that thesis which (a) best accords with theses of the type just mentioned, and (b) is associated with the most empirically successful research programme in physics, or at least holds out the best hope of leading to such an empirically successful research programme. For details, see chapter 3, appendix 2, and above all chapter 5, section 5.

[51] See Maxwell (1993a, part III).

[52] Einstein (1973, p. 270).