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Chapter 1

What is science?

What is science? This question may seem easy to answer: everybody knows that subjects such as physics, chemistry, and biology constitute science, while subjects such as art, music, and theology do not. But when as philosophers we ask what science is, that is not the sort of answer we want. We are not asking for a mere list of the activities that are usually called 'science'. Rather, we are asking what common feature all the things on that list share, i.e. what it is that *makes* something a science. Understood this way, our question is not so trivial.

But you may still think the question is relatively straightforward. Surely science is just the attempt to understand, explain, and predict the world we live in? This is certainly a reasonable answer. But is it the whole story? After all, the various religions also attempt to understand and explain the world, but religion is not usually regarded as a branch of science. Similarly, astrology and fortune-telling are attempts to predict the future, but most people would not describe these activities as science. Or consider history. Historians try to understand and explain what happened in the past, but history is usually classified as an arts subject not a science subject. As with many philosophical questions, the question 'what is science?' turns out to be trickier than it looks at first sight.

Many people believe that the distinguishing features of science lie in the particular methods scientists use to investigate the world. This suggestion is quite plausible. For many sciences do employ distinctive methods of enquiry that are not found in non-scientific disciplines. An obvious example is the use of experiments, which historically marks a turning-point in the development of modern science. Not all the sciences are experimental though – astronomers obviously cannot do experiments on the heavens, but have to content themselves with careful observation instead. The same is true of many social sciences. Another important feature of science is the construction of theories. Scientists do not simply record the results of experiment and observation in a log book – they usually want to explain those results in terms of a general theory. This is not always easy to do, but there have been some striking successes. One of the key problems in philosophy of science is to understand how techniques such as experimentation, observation, and theory-construction have enabled scientists to unravel so many of nature's secrets.

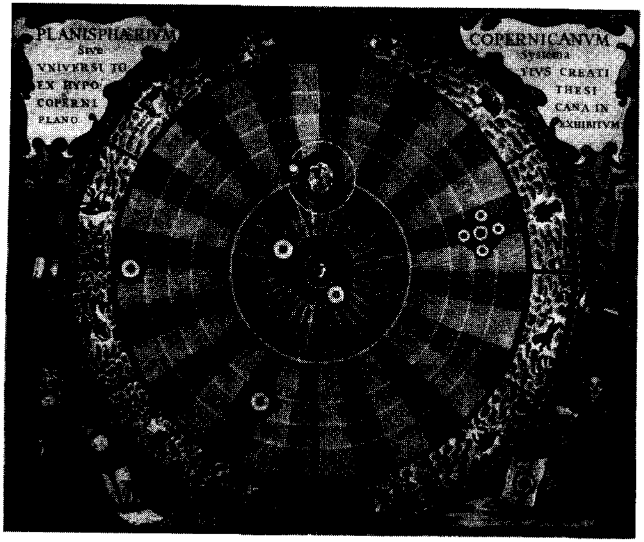
The origins of modern science

In today's schools and universities, science is taught in a largely ahistorical way. Textbooks present the key ideas of a scientific discipline in as convenient a form as possible, with little mention of the lengthy and often tortuous historical process that led to their discovery. As a pedagogical strategy, this makes good sense. But some appreciation of the history of scientific ideas is helpful for understanding the issues that interest philosophers of science. Indeed as we shall see in Chapter 5, it has been argued that close attention to the history of science is indispensable for doing good philosophy of science.

The origins of modern science lie in a period of rapid scientific development that occurred in Europe between the years 1500 and 1750, which we now refer to as the scientific revolution. Of course scientific investigations were pursued in ancient and medieval times too – the scientific revolution did not come from nowhere. In these earlier periods the dominant world-view was Aristotelianism, named after the ancient Greek philosopher Aristotle, who put forward detailed theories in physics, biology, astronomy, and cosmology. But Aristotle's ideas would seem very strange to a modern scientist, as would his methods of enquiry. To pick just one example, he believed that all earthly bodies are composed of just four elements: earth, fire, air, and water. This view is obviously at odds with what modern chemistry tells us.

The first crucial step in the development of the modern scientific world-view was the Copernican revolution. In 1542 the Polish astronomer Nicolas Copernicus (1473–1543) published a book attacking the geocentric model of the universe, which placed the stationary earth at the centre of the universe with the planets and the sun in orbit around it. Geocentric astronomy, also known as Ptolemaic astronomy after the ancient Greek astronomer Ptolemy, lay at the heart of the Aristotelian world-view, and had gone largely unchallenged for 1,800 years. But Copernicus suggested an alternative: the *sun* was the fixed centre of the universe, and the planets, including the earth, were in orbit around the sun (Figure 1). On this heliocentric model the earth is regarded as just another planet, and so loses the unique status that tradition had accorded it. Copernicus' theory initially met with much resistance, not least from the Catholic Church who regarded it as contravening the Scriptures and in 1616 banned books advocating the earth's motion. But within 100 years Copernicanism had become established scientific orthodoxy.

Copernicus' innovation did not merely lead to a better astronomy. Indirectly, it led to the development of modern physics, through the work of Johannes Kepler (1571–1630) and Galileo Galilei (1564–1642). Kepler discovered that the planets do not move in circular orbits around the sun, as Copernicus thought, but rather in ellipses. This was his crucial 'first law' of planetary motion; his second and third laws specify the speeds at which the planets orbit the sun.



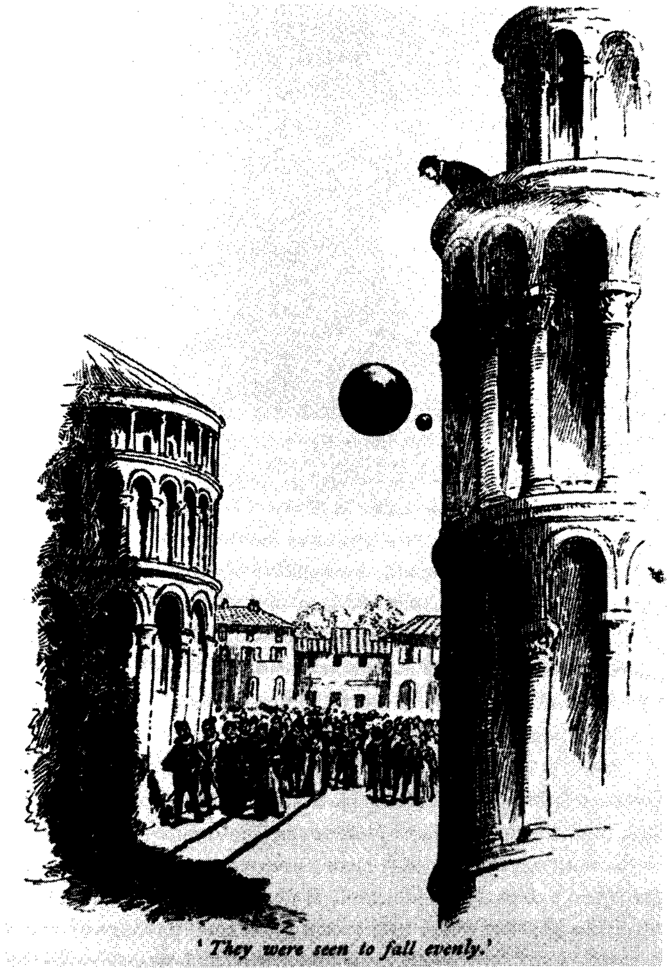
1. Copernicus' heliocentric model of the universe, showing the planets, including the earth, orbiting the sun.

Taken together, Kepler's laws provided a far superior planetary theory than had ever been advanced before, solving problems that had confounded astronomers for centuries. Galileo was a life-long supporter of Copernicanism, and one of the early pioneers of the telescope. When he pointed his telescope at the heavens, he made a wealth of amazing discoveries, including mountains on the moon, a vast array of stars, sun-spots, and Jupiter's moons. All of these conflicted thoroughly with Aristotelian cosmology, and played a pivotal role in converting the scientific community to Copernicanism.

Galileo's most enduring contribution, however, lay not in astronomy but in mechanics, where he refuted the Aristotelian theory that heavier bodies fall faster than lighter ones. In place of this theory, Galileo made the counter-intuitive suggestion that all freely falling bodies will fall towards the earth at the same rate, irrespective of their weight (Figure 2). (Of course in practice, if you drop a feather and a cannon-ball from the same height the cannon-ball will land first, but Galileo argued that this is simply due to air resistance – in a vacuum, they would land together.) Furthermore, he argued that freely falling bodies accelerate uniformly, i.e. gain equal increments of speed in equal times; this is known as Galileo's law of free-fall. Galileo provided persuasive though not totally conclusive evidence for this law, which formed the centrepiece of his theory of mechanics.

Galileo is generally regarded as the first truly modern physicist. He was the first to show that the language of mathematics could be used to describe the behaviour of actual objects in the material world, such as falling bodies, projectiles, etc. To us this seems obvious – today's scientific theories are routinely formulated in mathematical language, not only in the physical sciences but also in biology and economics. But in Galileo's day it was not obvious: mathematics was widely regarded as dealing with purely abstract entities, and hence inapplicable to physical reality. Another innovative aspect of Galileo's work was his emphasis on the importance of testing hypotheses experimentally. To the modern scientist, this may again seem obvious. But at the time that Galileo was working, experimentation was not generally regarded as a reliable means of gaining knowledge. Galileo's emphasis on experimental testing marks the beginning of an empirical approach to studying nature that continues to this day.

The period following Galileo's death saw the scientific revolution rapidly gain in momentum. The French philosopher, mathematician, and scientist René Descartes (1596–1650) developed a radical new 'mechanical philosophy', according to which the physical world consists simply of inert particles of matter interacting and colliding with one another. The laws governing the motion of these particles or 'corpuscles' held the key to understanding the structure of the Copernican universe, Descartes



2. Sketch of Galileo's mythical experiment on the velocity of objects dropped from the Leaning Tower of Pisa.

believed. The mechanical philosophy promised to explain all observable phenomena in terms of the motion of these inert, insensible corpuscles, and quickly became the dominant scientific vision of the second half of the 17th century; to some extent it is still with us today. Versions of the mechanical philosophy were espoused by figures such as Huygens, Gassendi, Hooke, Boyle, and others; its widespread acceptance marked the final downfall of the Aristotelian world-view.

The scientific revolution culminated in the work of Isaac Newton (1643–1727), whose achievements stand unparalleled in the history of science. Newton's masterpiece was his *Mathematical Principles of Natural Philosophy*, published in 1687. Newton agreed with the mechanical philosophers that the universe consists simply of particles in motion, but sought to improve on Descartes' laws of motion and rules of collision. The result was a dynamical and mechanical theory of great power, based around Newton's three laws of motion and his famous principle of universal gravitation. According to this principle, every body in the universe exerts a gravitational attraction on every other body; the strength of the attraction between two bodies depends on the product of their masses, and on the distance between them squared. The laws of motion then specify how this gravitational force affects the bodies' motions. Newton elaborated his theory with great mathematical precision and rigour, inventing the mathematical technique we now call 'calculus'. Strikingly, Newton was able to show that Kepler's laws of planetary motion and Galileo's law of free-fall (both with certain minor modifications) were logical consequences of his laws of motion and gravitation. In other words, the very same laws would explain the motions of bodies in both terrestrial and celestial domains, and were formulated by Newton in a precise quantitative form.

Newtonian physics provided the framework for science for the next 200 years or so, quickly replacing Cartesian physics. Scientific confidence grew rapidly in this period, due largely to the success of

Newton's theory, which was widely believed to have revealed the true workings of nature, and to be capable of explaining everything, in principle at least. Detailed attempts were made to extend the Newtonian mode of explanation to more and more phenomena. The 18th and 19th centuries both saw notable scientific advances, particularly in the study of chemistry, optics, energy, thermodynamics, and electromagnetism. But for the most part, these developments were regarded as falling within a broadly Newtonian conception of the universe. Scientists accepted Newton's conception as essentially correct; all that remained to be done was to fill in the details.

Confidence in the Newtonian picture was shattered in the early years of the 20th century, thanks to two revolutionary new developments in physics: relativity theory and quantum mechanics. Relativity theory, discovered by Einstein, showed that Newtonian mechanics does not give the right results when applied to very massive objects, or objects moving at very high velocities. Quantum mechanics, conversely, shows that the Newtonian theory does not work when applied on a very small scale, to subatomic particles. Both relativity theory and quantum mechanics, especially the latter, are very strange and radical theories, making claims about the nature of reality that many people find hard to accept or even understand. Their emergence caused considerable conceptual upheaval in physics, which continues to this day.

So far our brief account of the history of science has focused mainly on physics. This is no accident, as physics is both historically very important and in a sense the most fundamental of all scientific disciplines. For the objects that other sciences study are themselves made up of physical entities. Consider botany, for example. Botanists study plants, which are ultimately composed of molecules and atoms, which are physical particles. So botany is obviously less fundamental than physics – though that is not to say it is any less important. This is a point we shall return to in Chapter 3. But even a brief description of modern science's origins would be incomplete if it omitted all mention of the non-physical sciences.

In biology, the event that stands out is Charles Darwin's discovery of the theory of evolution by natural selection, published in *The Origin of Species* in 1859. Until then it was widely believed that the different species had been separately created by God, as the Book of Genesis teaches. But Darwin argued that contemporary species have actually evolved from ancestral ones, through a process known as natural selection. Natural selection occurs when some organisms leave more offspring than others, depending on their physical characteristics; if these characteristics are then inherited by their offspring, over time the population will become better and better adapted to the environment. Simple though this process is, over a large number of generations it can cause one species to evolve into a wholly new one, Darwin argued. So persuasive was the evidence Darwin adduced for his theory that by the start of the 20th century it was accepted as scientific orthodoxy, despite considerable theological opposition (Figure 3). Subsequent work has provided striking confirmation of Darwin's theory, which forms the centrepiece of the modern biological world-view.

The 20th century witnessed another revolution in biology that is not yet complete: the emergence of molecular biology, in particular molecular genetics. In 1953 Watson and Crick discovered the structure of DNA, the hereditary material that makes up the genes in the cells of living creatures (Figure 4). Watson and Crick's discovery explained how genetic information can be copied from one cell to another, and thus passed down from parent to offspring, thereby explaining why offspring tend to resemble their parents. Their discovery opened up an exciting new area of biological research. In the 50 years since Watson and Crick's work, molecular biology has grown fast, transforming our understanding of heredity and of how genes build organisms. The recent attempt to provide a molecular-level description of the complete set of genes in a human

MR. BERGH TO THE RESCUE.

THE DEFRAUDED GORILLA. "That *Man* wants to claim my Pedigree. He says he is one of my Descendants."

MR. BERGH. "Now, Mr. DARWIN, how could you insult him so?"

3. Darwin's suggestion that humans and apes have descended from common ancestors caused consternation in Victorian England.

4. James Watson and Francis Crick with the famous 'double helix' – their molecular model of the structure of DNA, discovered in 1953.

being, known as the Human Genome Project, is an indication of how far molecular biology has come. The 21st century will see further exciting developments in this field.

More resources have been devoted to scientific research in the last hundred years than ever before. One result has been an explosion of new scientific disciplines, such as computer science, artificial intelligence, linguistics, and neuroscience. Possibly the most significant event of the last 30 years is the rise of cognitive science, which studies various aspects of human cognition such as perception, memory, learning, and reasoning, and has transformed traditional psychology. Much of the impetus for cognitive science comes from the idea that the human mind is in some respects similar to a computer, and thus that human mental processes can be understood by comparing them to the operations computers carry out. Cognitive science is still in its infancy, but promises to reveal much about the workings of the mind. The social sciences, especially economics and sociology, have also flourished in the 20th century, though many people believe they still lag behind the natural sciences in terms of sophistication and rigour. This is an issue we shall return to in Chapter 7.

What is philosophy of science?

The principal task of philosophy of science is to analyse the methods of enquiry used in the various sciences. You may wonder why this task should fall to philosophers, rather than to the scientists themselves. This is a good question. Part of the answer is that looking at science from a philosophical perspective allows us to probe deeper – to uncover assumptions that are implicit in scientific practice, but which scientists do not explicitly discuss. To illustrate, consider scientific experimentation. Suppose a scientist does an experiment and gets a particular result. He repeats the experiment a few times and keeps getting the same result. After that he will probably stop, confident that were he to keep repeating the experiment, under exactly the same conditions, he would continue to get the same result. This assumption may seem obvious, but as philosophers we want to question it. *Why* assume that future repetitions of the experiment will yield the same result? How do we know this is true? The scientist is unlikely to spend too much time puzzling over these somewhat curious questions: he probably has better things to do. They are quintessentially philosophical questions, to which we return in the next chapter.

So part of the job of philosophy of science is to question assumptions that scientists take for granted. But it would be wrong to imply that scientists never discuss philosophical issues themselves. Indeed, historically, many scientists have played an important role in the development of philosophy of science. Descartes, Newton, and Einstein are prominent examples. Each was deeply interested in philosophical questions about how science should proceed, what methods of enquiry it should use, how much confidence we should place in those methods, whether there are limits to scientific knowledge, and so on. As we shall see, these questions still lie at the heart of contemporary philosophy of science. So the issues that interest philosophers of science are not 'merely philosophical'; on the contrary, they have engaged the attention of some of the greatest scientists of all. That having been said, it must be admitted that many scientists today take little interest in philosophy of science, and know little about it. While this is unfortunate, it is not an indication that philosophical issues are no longer relevant. Rather, it is a consequence of the increasingly specialized nature of science, and of the polarization between the sciences and the humanities that characterizes the modern education system.

You may still be wondering exactly what philosophy of science is all about. For to say that it 'studies the methods of science', as we did above, is not really to say very much. Rather than try to provide a more informative definition, we will proceed straight to consider a typical problem in the philosophy of science.

Science and pseudo-science

Recall the question with which we began: what is science? Karl Popper, an influential 20th-century philosopher of science, thought that the fundamental feature of a scientific theory is that it should be falsifiable. To call a theory falsifiable is not to say that it is false. Rather, it means that the theory makes some definite predictions that are capable of being tested against experience. If these predictions turn out to be wrong, then the theory has been falsified, or disproved. So a falsifiable theory is one that we might discover to be false – it is not compatible with every possible course of experience. Popper thought that some supposedly scientific theories did not satisfy this condition and thus did not deserve to be called science at all; rather they were merely pseudo-science.

Freud's psychoanalytic theory was one of Popper's favourite examples of pseudo-science. According to Popper, Freud's theory could be reconciled with any empirical findings whatsoever. Whatever a patient's behaviour, Freudians could find an explanation of it in terms of their theory – they would never admit that their theory was wrong. Popper illustrated his point with the following example. Imagine a man who pushes a child into a river with the intention of murdering him, and another man who sacrifices his life in order to save the child. Freudians can explain both men's behaviour with equal ease: the first was repressed, and the second had achieved sublimation. Popper argued that through the use of such concepts as repression, sublimation, and unconscious desires, Freud's theory could be rendered compatible with any clinical data whatever; it was thus unfalsifiable.

The same was true of Marx's theory of history, Popper maintained. Marx claimed that in industrialized societies around the world, capitalism would give way to socialism and ultimately to communism. But when this didn't happen, instead of admitting that Marx's theory was wrong, Marxists would invent an *ad hoc* explanation for why what happened was actually perfectly consistent with their theory. For example, they might say that the inevitable progress to communism had been temporarily slowed by the rise of the welfare state, which 'softened' the proletariat and weakened their revolutionary zeal. In this sort of way, Marx's theory could be made compatible with any possible course of events, just like Freud's. Therefore neither theory qualifies as genuinely scientific, according to Popper's criterion.

Popper contrasted Freud's and Marx's theories with Einstein's theory of gravitation, also known as general relativity. Unlike Freud's and Marx's theories, Einstein's theory made a very definite prediction: that light rays from distant stars would be deflected by the gravitational field of the sun. Normally this effect would be impossible to observe – except during a solar eclipse. In 1919 the English astrophysicist Sir Arthur Eddington organized two expeditions to observe the solar eclipse of that year, one to Brazil and one to the island of Principe off the Atlantic coast of Africa, with the aim of testing Einstein's prediction. The expeditions found that starlight was indeed deflected by the sun, by almost exactly the amount Einstein had predicted. Popper was very impressed by this. Einstein's theory had made a definite, precise prediction, which was confirmed by observations. Had it turned out that starlight was not deflected by the sun, this would have showed that Einstein was wrong. So Einstein's theory satisfies the criterion of falsifiability.

Popper's attempt to demarcate science from pseudo-science is intuitively quite plausible. There is certainly something fishy about a theory that can be made to fit any empirical data whatsoever. But some philosophers regard Popper's criterion as overly simplistic. Popper criticized Freudians and Marxists for explaining away any data that appeared to conflict with their theories, rather than accepting that the theories had been refuted. This certainly looks like a suspicious procedure. However, there is some evidence that this very procedure is routinely used by 'respectable' scientists – whom Popper would not want to accuse of engaging in pseudo-science – and has led to important scientific discoveries.

Another astronomical example can illustrate this. Newton's gravitational theory, which we encountered earlier, made predictions about the paths the planets should follow as they orbit the sun. For the most part, these predictions were borne out by observation. However, the observed orbit of Uranus consistently differed from what Newton's theory predicted. This puzzle was solved in 1846 by two scientists, Adams in England and Leverrier in France, working independently. They suggested that there was another planet, as yet undiscovered, exerting an additional gravitational force on Uranus. Adams and Leverrier were able to calculate the mass and position that this planet would have to have, if its gravitational pull was indeed responsible for Uranus' strange behaviour. Shortly afterwards the planet Neptune was discovered, almost exactly where Adams and Leverrier had predicted.

Now clearly we should not criticize Adams' and Leverrier's behaviour as 'unscientific' – after all, it led to the discovery of a new planet. But they did precisely what Popper criticized the Marxists for doing. They began with a theory – Newton's theory of gravity – which made an incorrect prediction about Uranus' orbit. Rather than concluding that Newton's theory must be wrong, they stuck by *the theory and attempted to explain away the conflicting observations by postulating a new planet. Similarly, when* capitalism showed no signs of giving way to communism, Marxists did not conclude that Marx's theory must be wrong, but stuck by the theory and tried to explain away the conflicting observations in other ways. So surely it is unfair to accuse Marxists of engaging in pseudo-science if we allow that what Adams and Leverrier did counted as good, indeed exemplary, science?

This suggests that Popper's attempt to demarcate science from pseudo-science cannot be quite right, despite its initial plausibility. For the Adams/Leverrier example is by no means atypical. In general, scientists do not just abandon their theories whenever they conflict with the observational data. Usually they look for ways of eliminating the conflict without having to give up their theory; this is a point we shall return to in Chapter 5. And it is worth remembering that virtually every theory in science conflicts with some observations – finding a theory that fits all the data perfectly is extremely difficult. Obviously if a theory persistently conflicts with more and more data, and no plausible ways of explaining away the conflict are found, it will eventually have to be rejected. But little progress would be made if scientists simply abandoned their theories at the first sign of trouble.

The failure of Popper's demarcation criterion throws up an important question. Is it actually possible to find some common feature shared by all the things we call 'science', and not shared by anything else? Popper assumed that the answer to this question was yes. He felt that Freud's and Marx's theories were clearly unscientific, so there must be some feature that they lack and that genuine scientific theories possess. But whether or not we accept Popper's negative assessment of Freud and Marx, his assumption that science has an 'essential nature' is questionable. After all, science is a heterogeneous activity, encompassing a wide range of different disciplines and theories. It may be that they share some fixed set of features that define what it is to be a science, but it may not. The philosopher Ludwig Wittgenstein argued that there is no fixed set of features that define what it is to be a 'game'. Rather, there is a loose cluster of features most of which are possessed by most games. But any particular game may lack any of the features in the cluster and still be a game. The same may be true of science. If so, a simple criterion for demarcating science from pseudo-science is unlikely to be found.

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Great Clarendon Street, Oxford OX2 6DP

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Published in the United States
by Oxford University Press Inc., New York

First published as a Very Short Introduction 2002

British Library Cataloguing in Publication Data
Data available

Library of Congress Cataloging in Publication Data
Data available

ISBN 0-19-280283-6

5 7 9 10 8 6 4

Typeset by RefineCatch Ltd, Bungay, Suffolk
Printed in Great Britain by
TJ International Ltd., Padstow, Cornwall

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