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PHILOSOPHY OF SCIENCE

A Very Short Introduction

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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 a humanities subject not a science subject. As with many philosophical questions, the question 'what is science?' is 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 scientific disciplines do employ distinctive methods of enquiry that are not used in non-scientific enterprises. 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 main tasks of 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.

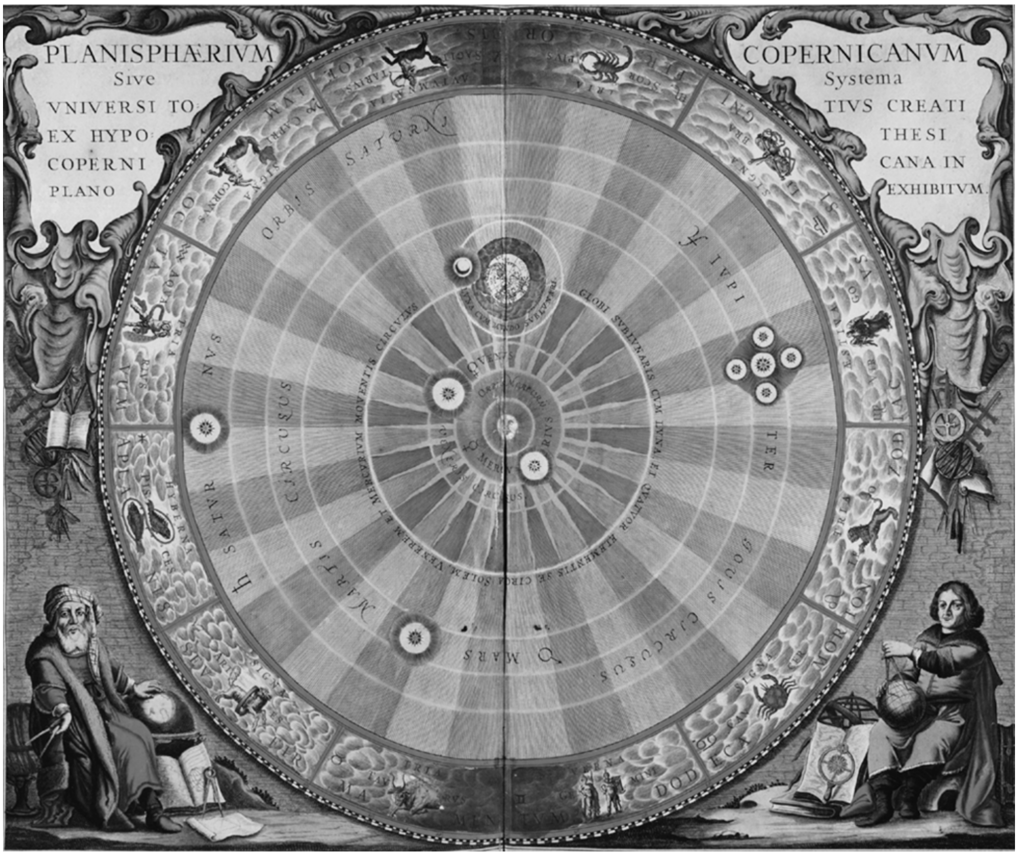
The origins of modern science

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 which 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 about 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 worldview 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 worldview 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 worldview, 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 it (see 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 'first law' of planetary motion; his second



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

and third laws specify the speeds at which the planets orbit the sun. Taken together, Kepler's laws provided a successful planetary theory, solving problems that had confounded astronomers for centuries. Galileo was a lifelong 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: mountains on the moon, a vast array of stars, sun-spots, Jupiter's moons, and more. All of these conflicted 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. (Of course in practice, if you drop a feather and a cannonball from the same height the cannonball 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 conclusive evidence for this law, which formed the centrepiece of his mechanics.

Galileo is generally regarded as the first modern physicist. He was the first to show that the language of mathematics could be used to describe the behaviour of material objects, such as falling bodies and projectiles. To us this seems obvious—today's scientific theories are routinely formulated in mathematical language, not only in physics but also in the biological and social sciences. But in Galileo's day it was not obvious: mathematics was widely regarded as dealing with purely abstract entities, hence inapplicable to physical reality. Another innovative aspect was Galileo's emphasis on testing hypotheses experimentally. To the modern scientist this may again seem obvious. But in Galileo's day experimentation was not generally regarded as a reliable means of gaining knowledge. Galileo's emphasis on experiment 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-scientist René Descartes (1596–1650) developed a radical new 'mechanical philosophy', according to which the physical world consists 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 universe, Descartes believed. The mechanical philosophy promised to explain all observable phenomena in terms of the motions of these corpuscles, and quickly became the dominant scientific vision of the late 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, and Boyle; its acceptance marked the final downfall of the Aristotelian worldview.

The scientific revolution culminated in the work of Isaac Newton (1643–1727), whose masterpiece, *Mathematical Principles of Natural Philosophy*, was published in 1687.

Newton agreed with the mechanical philosophers that the universe consists simply of particles in motion, and sought to improve on Descartes's theory. 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 remarkable precision and rigour, inventing the mathematical techniques 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. So a single set of laws could explain the motions of bodies in both terrestrial and celestial domains, and were formulated by Newton in a precise quantitative form.

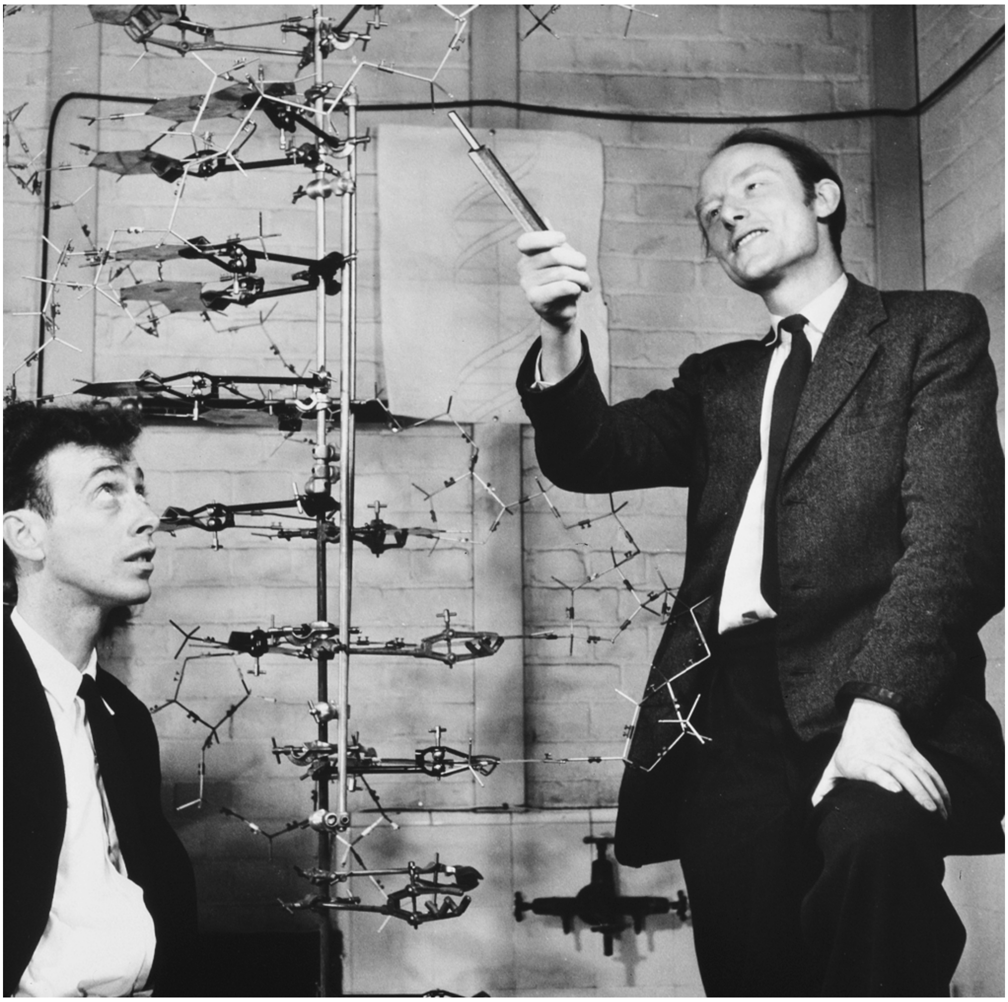
Newtonian physics provided the framework for science for the next 200 years, quickly replacing Cartesian physics. Scientific confidence grew rapidly in this period, due largely to the success of Newton's theory, which was widely believed to have revealed the true workings of nature, and to be capable 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 chemistry, optics, 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; what 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 strange and radical theories, making claims about the nature of reality which conflict with common sense, and which 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 important and in a sense the most fundamental scientific discipline. For the objects that other sciences study are themselves made up of physical entities, but not vice versa. Consider botany, for example. Botanists study plants, which are composed of cells, which are themselves composed of bio-molecules, which are ultimately made up of atoms, which are physical particles. So botany deals with entities that are less 'fundamental' than does physics—though that is not to say it is 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. Subsequent work has provided striking confirmation of Darwin's theory, which forms the centrepiece of the modern biological worldview.

The 20th century witnessed another revolution in biology that is not yet complete: the emergence of molecular biology and 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 (see Figure 2). 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 known as molecular biology, which studies the molecular basis of biological phenomena. In the sixty years since Watson and Crick's work, molecular biology has grown fast, transforming our understanding of heredity, development, and other core biological processes. In 2003, the decade-long attempt to provide a molecular-level description of the complete set of genes in a human being, known as the Human Genome Project, was finally



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

completed; the implications for medicine and biotechnology have only begun to be explored. The 21st century will most likely see further exciting developments in this field.

More resources have been devoted to scientific research in the last sixty years than ever before. One result has been an explosion of new scientific disciplines, such as computer science, artificial intelligence, and neuroscience. The late 20th century witnessed the rise of cognitive science, which studies aspects of human cognition including perception, memory, 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 that human mental processes can be understood by comparing them to the operations computers carry out. By contrast, the field of neuroscience studies how the brain itself works. Thanks to technological advances in brain scanning, neuroscientists are beginning to understand the underlying neural basis of human (and animal) cognition. This enterprise is of great intrinsic interest and may also lead to improved treatments for mental disorders.

The social sciences, such as economics, anthropology, and sociology, also flourished in the 20th century, though some believe they lag behind the natural sciences in terms of sophistication and predictive power. This raises an interesting methodological question. Should social scientists try to use the same methods as natural scientists, or does their subject matter call for a different approach? We return to this issue 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 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 philosophical reflection can uncover assumptions that are implicit in scientific enquiry. To illustrate, consider experimental practice. Suppose a scientist does an experiment and gets a particular result. They repeat the experiment a few times and keep getting the same result. After that they will probably stop, confident that were the experiment repeated again under exactly the same conditions, the same result would obtain. 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 much time puzzling over this: they probably have better things to do. It is a quintessentially philosophical question.

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, scientists have played a key role in the development of philosophy of science. Descartes, Newton, and Einstein are prominent examples. Each was deeply interested in questions about how science should proceed, what methods of enquiry it should use, and whether there are limits to scientific knowledge. These questions still lie at the heart of contemporary philosophy of science. So the issues that concern philosophers of science have engaged the attention of some of the greatest scientists. That being 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 much modern education.

You may still be wondering exactly what philosophy of science is all about. For to say that it 'studies the methods of science' is not really to say very much. Rather than try to provide a more informative definition, we will instead examine a classic issue 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 which 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 which 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; 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 had 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 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, 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 shown 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 surely something suspicious about a theory that can be made to fit any empirical data whatsoever. But many philosophers regard Popper's criterion as overly simplistic. Popper criticized Freudians and Marxists for explaining away any data which appeared to conflict with their theories, rather than accepting that the theories had been refuted. This certainly looks like a dubious 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 predicted.

Now clearly we should not criticize Adams's 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; see Chapter 5. Also, it is worth remembering that virtually every scientific theory 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 way of explaining away the conflict is 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 and only the things we call 'science'? Popper assumed that the answer was yes. He felt that Freud's and Marx's theories were clearly unscientific, so there must be some feature which they lack and which 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 disciplines and theories. It may be that they share some fixed set of features which 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.

Further reading

Chapter 1: What is science?

A good discussion of the scientific revolution is Steven Shapin, *The Scientific Revolution* (University of Chicago Press, 1998). Detailed treatment of topics in the history of science can be found in J. L. Heilbron (ed.), *The Oxford Companion to the History of Modern Science* (Oxford University Press, 2003). There are many good introductions to philosophy of science, including Alexander Rosenberg, *The Philosophy of Science* (Routledge, 2011) and Peter Godfrey-Smith, *Theory and Reality* (University of Chicago Press, 2003). An excellent collection of papers on general philosophy of science, with extensive commentaries by the editors, is Martin Curd, J. A. Cover, and Christopher Pincock (eds), *Philosophy of Science: The Central Issues* (W. W. Norton, 2012). Popper's attempt to demarcate science from pseudo-science can be found in his *Conjectures and Refutations* (Routledge, 1963). A good discussion of Popper's demarcation criterion is in Donald Gillies, *Philosophy of Science in the 20th Century* (Blackwell, 1993). A good introduction to Popper's philosophy is Stephen Thornton's article 'Karl Popper', in Edward N. Zalta (ed.), *The Stanford Encyclopedia of Philosophy*, <http://plato.stanford.edu/archives/sum2014/entries/popper/>.

Chapter 2: Scientific inference

A clear discussion of induction and scientific inference is Wesley Salmon, *The Foundations of Scientific Inference* (University of Pittsburgh Press, 1967). David Hume's reflections on induction can be