A Very Short Introduction to Philosophy of Science

Samar Okasha
Chapter 2
Scientific reasoning

Scientists often tell us things about the world that we would not otherwise have believed. For example, biologists tell us that we are closely related to chimpanzees, geologists tell us that Africa and South America used to be joined together, and cosmologists tell us that the universe is expanding. But how did scientists reach these unlikely-sounding conclusions? After all, no one has ever seen one species evolve from another, or a single continent split into two, or the universe getting bigger. The answer, of course, is that scientists arrived at these beliefs by a process of reasoning or inference. But it would be nice to know more about this process. What exactly is the nature of scientific reasoning? And how much confidence should we place in the inferences scientists make? These are the topics of this chapter.

Deduction and induction

Logicians make an important distinction between deductive and inductive patterns of reasoning. An example of a piece of deductive reasoning, or a deductive inference, is the following:

All Frenchmen like red wine
Pierre is a Frenchman

Therefore, Pierre likes red wine

The first two statements are called the premisses of the inference, while the third statement is called the conclusion. This is a deductive inference because it has the following property: if the premisses are true, then the conclusion must be true too. In other words, if it's true that all Frenchman like red wine, and if it's true that Pierre is a Frenchman, it follows that Pierre does indeed like red wine. This is sometimes expressed by saying that the premisses of the inference entail the conclusion. Of course, the premisses of this inference are almost certainly not true - there are bound to be Frenchmen who do not like red wine. But that is not the point. What makes the inference deductive is the existence of an appropriate relation between premisses and conclusion, namely that if the premisses are true, the conclusion must be true too. Whether the premisses are actually true is a different matter, which doesn't affect the status of the inference as deductive.

Not all inferences are deductive. Consider the following example:

The first five eggs in the box were rotten
All the eggs have the same best-before date stamped on them

Therefore, the sixth egg will be rotten too

This looks like a perfectly sensible piece of reasoning. But nonetheless it is not deductive, for the premisses do not entail the conclusion. Even if the first five eggs were indeed rotten, and even if all the eggs do have the same best-before date stamped on them, this does not guarantee that the sixth egg will be rotten too. It is quite conceivable that the sixth egg will be perfectly good. In other words, it is logically possible for the premisses of this inference to be true and yet the conclusion false, so the inference is not deductive. Instead it is known as an inductive inference. In inductive inference, or inductive reasoning, we move from premisses about objects we have examined to conclusions about objects we haven't examined – in this example, eggs.
Deductive reasoning is a much safer activity than inductive reasoning. When we reason deductively, we can be certain that if we start with true premises, we will end up with a true conclusion. But the same does not hold for inductive reasoning. On the contrary, inductive reasoning is quite capable of taking us from true premises to a false conclusion. Despite this defect, we seem to rely on inductive reasoning throughout our lives, often without even thinking about it. For example, when you turn on your computer in the morning, you are confident it will not explode in your face. Why? Because you turn on your computer every morning, and it has never exploded in your face up to now. But the inference from ‘up until now, my computer has not exploded when I turned it on’ to ‘my computer will not explode when I turn it on this time’ is inductive, not deductive. The premise of this inference does not entail the conclusion. It is logically possible that your computer will explode this time, even though it has never done so previously.

Other examples of inductive reasoning in everyday life can readily be found. When you turn the steering wheel of your car anticlockwise, you assume the car will go to the left, not the right. Whenever you drive in traffic, you effectively stake your life on this assumption. But what makes you so sure that it’s true? If someone asked you to justify your conviction, what would you say? Unless you are a mechanic, you would probably reply: ‘every time I’ve turned the steering wheel anticlockwise in the past, the car has gone to the left. Therefore, the same will happen when I turn the steering wheel anticlockwise this time.’ Again, this is an inductive inference, not a deductive one. Reasoning inductively seems to be an indispensable part of everyday life.

Do scientists use inductive reasoning too? The answer seems to be yes. Consider the genetic disease known as Down’s syndrome (DS for short). Geneticists tell us that DS sufferers have an additional chromosome – they have 47 instead of the normal 46 (Figure 5). How do they know this? The answer, of course, is that they

5. A representation of the complete set of chromosomes – or karyotype – of a person with Down’s syndrome. There are three copies of chromosome 21, as opposed to the two copies most people have, giving 47 chromosomes in total.
examined a large number of DS sufferers and found that each had an additional chromosome. They then reasoned inductively to the conclusion that all DS sufferers, including ones they hadn’t examined, have an additional chromosome. It is easy to see that this inference is inductive. The fact that the DS sufferers in the sample studied had 47 chromosomes doesn’t prove that all DS sufferers do. It is possible, though unlikely, that the sample was an unrepresentative one.

This example is by no means an isolated one. In effect, scientists use inductive reasoning whenever they move from limited data to a more general conclusion, which they do all the time. Consider, for example, Newton’s principle of universal gravitation, encountered in the last chapter, which says that every body in the universe exerts a gravitational attraction on every other body. Now obviously, Newton did not arrive at this principle by examining every single body in the whole universe – he couldn’t possibly have. Rather, he saw that the principle held true for the planets and the sun, and for objects of various sorts moving near the earth’s surface. From this data, he inferred that the principle held true for all bodies. Again, this inference was obviously an inductive one: the fact that Newton’s principle holds true for some bodies doesn’t guarantee that it holds true for all bodies.

The central role of induction in science is sometimes obscured by the way we talk. For example, you might read a newspaper report that says that scientists have found ‘experimental proof’ that genetically modified maize is safe for humans. What this means is that the scientists have tested the maize on a large number of humans, and none of them have come to any harm. But strictly speaking this doesn’t prove that the maize is safe, in the sense in which mathematicians can prove Pythagoras’ theorem, say. For the inference from ‘the maize didn’t harm any of the people on whom it was tested’ to ‘the maize will not harm anyone’ is inductive, not deductive. The newspaper report should really have said that scientists have found extremely good evidence that the maize is safe for humans. The word ‘proof’ should strictly only be used when we are dealing with deductive inferences. In this strict sense of the word, scientific hypotheses can rarely, if ever, be proved true by the data.

Most philosophers think it’s obvious that science relies heavily on inductive reasoning, indeed so obvious that it hardly needs arguing for. But, remarkably, this was denied by the philosopher Karl Popper, who we met in the last chapter. Popper claimed that scientists only need to use deductive inferences. This would be nice if it were true, for deductive inferences are much safer than inductive ones, as we have seen.

Popper’s basic argument was this. Although it is not possible to prove that a scientific theory is true from a limited data sample, it is possible to prove that a theory is false. Suppose a scientist is considering the theory that all pieces of metal conduct electricity. Even if every piece of metal she examines does conduct electricity, this doesn’t prove that the theory is true, for reasons that we’ve seen. But if she finds even one piece of metal that does not conduct electricity, this does prove that the theory is false. For the inference from ‘this piece of metal does not conduct electricity’ to ‘it is false that all pieces of metal conduct electricity’ is a deductive inference – the premiss entails the conclusion. So if a scientist is only interested in demonstrating that a given theory is false, she may be able to accomplish her goal without the use of inductive inferences.

The weakness of Popper’s argument is obvious. For scientists are not only interested in showing that certain theories are false. When a scientist collects experimental data, her aim might be to show that a particular theory – her arch-rival’s theory perhaps – is false. But much more likely, she is trying to convince people that her own theory is true. And in order to do that, she will have to resort to inductive reasoning of some sort. So Popper’s attempt to show that science can get by without induction does not succeed.
Hume's problem

Although inductive reasoning is not logically watertight, it nonetheless seems like a perfectly sensible way of forming beliefs about the world. The fact that the sun has risen every day up until now may not prove that it will rise tomorrow, but surely it gives us very good reason to think it will? If you came across someone who professed to be entirely agnostic about whether the sun will rise tomorrow or not, you would regard them as very strange indeed, if not irrational.

But what justifies this faith we place in induction? How should we go about persuading someone who refuses to reason inductively that they are wrong? The 18th-century Scottish philosopher David Hume (1711–1776) gave a simple but radical answer to this question. He argued that the use of induction cannot be rationally justified at all. Hume admitted that we use induction all the time, in everyday life and in science, but he insisted this was just a matter of brute animal habit. If challenged to provide a good reason for using induction, we can give no satisfactory answer, he thought.

How did Hume arrive at this startling conclusion? He began by noting that whenever we make inductive inferences, we seem to presuppose what he called the 'uniformity of nature' (UN). To see what Hume means by this, recall some of the inductive inferences from the last section. We had the inference from 'my computer hasn't exploded up to now' to 'my computer won't explode today'; from 'all examined DS sufferers have an extra chromosome' to 'all DS sufferers have an extra chromosome'; from 'all bodies observed so far obey Newton's law of gravity' to 'all bodies obey Newton's law of gravity'; and so on. In each of these cases, our reasoning seems to depend on the assumption that objects we haven't examined will be similar, in the relevant respects, to objects of the same sort that we have examined. That assumption is what Hume means by the uniformity of nature.

But how do we know that the UN assumption is actually true, Hume asks? Can we perhaps prove its truth somehow (in the strict sense of proof)? No, says Hume, we cannot. For it is easy to imagine a universe where nature is not uniform, but changes its course randomly from day to day. In such a universe, computers might sometimes explode for no reason, water might sometimes intoxicate us without warning, billiard balls might sometimes stop dead on colliding, and so on. Since such a 'non-uniform' universe is conceivable, it follows that we cannot strictly prove the truth of UN. For if we could prove that UN is true, then the non-uniform universe would be a logical impossibility.

Granted that we cannot prove UN, we might nonetheless hope to find good empirical evidence for its truth. After all, since UN has always held true up to now, surely that gives us good reason for thinking it is true? But this argument begs the question, says Hume! For it is itself an inductive argument, and so itself depends on the UN assumption. An argument that assumes UN from the outset clearly cannot be used to show that UN is true. To put the point another way, it is certainly an established fact that nature has behaved largely uniformly up to now. But we cannot appeal to this fact to argue that nature will continue to be uniform, because this assumes that what has happened in the past is a reliable guide to what will happen in the future – which is the uniformity of nature assumption. If we try to argue for UN on empirical grounds, we end up reasoning in a circle.

The force of Hume's point can be appreciated by imagining how you would go about persuading someone who doesn't trust inductive reasoning that they should. You would probably say: 'look, inductive reasoning has worked pretty well up until now. By using induction scientists have split the atom, landed men on the moon, invented computers, and so on. Whereas people who haven't used induction have tended to die nasty deaths. They have eaten arsenic believing that it would nourish them, jumped off tall buildings believing that they would fly, and so on (Figure 6). Therefore it will clearly pay you
to reason inductively.' But of course this wouldn't convince the doubter. For to argue that induction is trustworthy because it has worked well up to now is to reason in an inductive way. Such an argument would carry no weight with someone who doesn't already trust induction. That is Hume's fundamental point.

So the position is this. Hume points out that our inductive inferences rest on the UN assumption. But we cannot prove that UN is true, and we cannot produce empirical evidence for its truth without begging the question. So our inductive inferences rest on an assumption about the world for which we have no good grounds. Hume concludes that our confidence in induction is just blind faith – it admits of no rational justification whatever.

This intriguing argument has exerted a powerful influence on the philosophy of science, and continues to do so today. (Popper's unsuccessful attempt to show that scientists need only use deductive inferences was motivated by his belief that Hume had shown the total irrationality of inductive reasoning.) The influence of Hume's argument is not hard to understand. For normally we think of science as the very paradigm of rational enquiry. We place great faith in what scientists tell us about the world. Every time we travel by aeroplane, we put our lives in the hands of the scientists who designed the plane. But science relies on induction, and Hume's argument seems to show that induction cannot be rationally justified. If Hume is right, the foundations on which science is built do not look quite as solid as we might have hoped. This puzzling state of affairs is known as Hume's problem of induction.

Philosophers have responded to Hume's problem in literally dozens of different ways; this is still an active area of research today. Some people believe the key lies in the concept of probability. This suggestion is quite plausible. For it is natural to think that although the premises of an inductive inference do not guarantee the truth of the conclusion, they do make it quite probable. So even if

6. What happens to people who don't trust induction.
scientific knowledge cannot be certain, it may nonetheless be highly probable. But this response to Hume’s problem generates difficulties of its own, and is by no means universally accepted; we will return to it in due course.

Another popular response is to admit that induction cannot be rationally justified, but to argue that this is not really so problematic after all. How might one defend such a position? Some philosophers have argued that induction is so fundamental to how we think and reason that it’s not the sort of thing that could be justified. Peter Strawson, an influential contemporary philosopher, defended this view with the following analogy. If someone worried about whether a particular action was legal, they could consult the law-books and compare the action with what the law-books say. But suppose someone worried about whether the law itself was legal. This is an odd worry indeed. For the law is the standard against which the legality of other things is judged, and it makes little sense to enquire whether the standard itself is legal. The same applies to induction, Strawson argued. Induction is one of the standards we use to decide whether claims about the world are justified. For example, we use induction to judge whether a pharmaceutical company’s claim about the amazing benefits of its new drug are justified. So it makes little sense to ask whether induction itself is justified.

Has Strawson really succeeded in defusing Hume’s problem? Some philosophers say yes, others say no. But most people agree that it is very hard to see how there could be a satisfactory justification of induction. (Frank Ramsey, a Cambridge philosopher from the 1920s, said that to ask for a justification of induction was ‘to cry for the moon.’) Whether this is something that should worry us, or shake our faith in science, is a difficult question that you should ponder for yourself.

Inference to the best explanation

The inductive inferences we’ve examined so far have all had essentially the same structure. In each case, the premiss of the inference has had the form ‘all x’s examined so far have been y’, and the conclusion has had the form ‘the next x to be examined will be y’, or sometimes, ‘all x’s are y’. In other words, these inferences take us from examined to unexamined instances of a given kind.

Such inferences are widely used in everyday life and in science, as we have seen. However, there is another common type of non-deductive inference that doesn’t fit this simple pattern. Consider the following example:

The cheese in the larder has disappeared, apart from a few crumbs
Scratching noises were heard coming from the larder last night

Therefore, the cheese was eaten by a mouse

It is obvious that this inference is non-deductive: the premisses do not entail the conclusion. For the cheese could have been stolen by the maid, who cleverly left a few crumbs to make it look like the handiwork of a mouse (Figure 7). And the scratching noises could have been caused in any number of ways – perhaps they were due to the boiler overheating. Nonetheless, the inference is clearly a reasonable one. For the hypothesis that a mouse ate the cheese seems to provide a better explanation of the data than do the various alternative explanations. After all, maids do not normally steal cheese, and modern boilers do not tend to overheat. Whereas mice do normally eat cheese when they get the chance, and do tend to make scratching sounds. So although we cannot be certain that the mouse hypothesis is true, on balance it looks quite plausible: it is the best way of accounting for the available data.
different types of non-deductive inference. Nothing hangs on which choice of terminology we favour, so long as we stick to it consistently.

Scientists frequently use IBE. For example, Darwin argued for his theory of evolution by calling attention to various facts about the living world which are hard to explain if we assume that current species have been separately created, but which make perfect sense if current species have descended from common ancestors, as his theory held. For example, there are close anatomical similarities between the legs of horses and zebras. How do we explain this, if God created horses and zebras separately? Presumably he could have made their legs as different as he pleased. But if horses and zebras have both descended from a recent common ancestor, this provides an obvious explanation of their anatomical similarity. Darwin argued that the ability of his theory to explain facts of this sort, and of many other sorts too, constituted strong evidence for its truth.

Another example of IBE is Einstein’s famous work on Brownian motion. Brownian motion refers to the chaotic, zig-zag motion of microscopic particles suspended in a liquid or gas. It was discovered in 1827 by the Scottish botanist Robert Brown (1713–1858), while examining pollen grains floating in water. A number of attempted explanations of Brownian motion were advanced in the 19th century. One theory attributed the motion to electrical attraction between particles, another to agitation from external surroundings, and another to convection currents in the fluid. The correct explanation is based on the kinetic theory of matter, which says that liquids and gases are made up of atoms or molecules in motion. The suspended particles collide with the surrounding molecules, causing the erratic, random movements that Brown first observed. This theory was first proposed in the late 19th century but was not widely accepted, not least because many scientists didn’t believe that atoms and molecules were real physical entities. But in 1905, Einstein provided an ingenious mathematical treatment of
Brownian motion, making a number of precise, quantitative predictions which were later confirmed experimentally. After Einstein’s work, the kinetic theory was quickly agreed to provide a far better explanation of Brownian motion than any of the alternatives, and scepticism about the existence of atoms and molecules rapidly subsided.

One interesting question is whether IBE or ordinary induction is a more fundamental pattern of inference. The philosopher Gilbert Harman has argued that IBE is more fundamental. According to this view, whenever we make an ordinary inductive inference such as ‘all pieces of metal examined so far conduct electricity, therefore all pieces of metal conduct electricity’ we are implicitly appealing to explanatory considerations. We assume that the correct explanation for why the pieces of metal in our sample conducted electricity, whatever it is, entails that all pieces of metal will conduct electricity; that is why we make the inductive inference. But if we believed, for example, that the explanation for why the pieces of metal in our sample conducted electricity was that a laboratory technician had tinkered with them, we would not infer that all pieces of metal conduct electricity. Proponents of this view do not say there is no difference between IBE and ordinary induction – there clearly is. Rather, they think that ordinary induction is ultimately dependent on IBE.

However, other philosophers argue that this gets things backwards: IBE is itself parasitic on ordinary induction, they say. To see the grounds for this view, think back to the cheese-in-the-larder example above. Why do we regard the mouse hypothesis as a better explanation of the data than the maid hypothesis? Presumably, because we know that maids do not normally steal cheese, whereas mice do. But this is knowledge that we have gained through ordinary inductive reasoning, based on our previous observations of the behaviour of mice and maids. So according to this view, when we try to decide which of a group of competing hypotheses provides the best explanation of our data, we invariably appeal to knowledge that has been gained through ordinary induction. Thus it is incorrect to regard IBE as a more fundamental mode of inference.

Whichever of these opposing views we favour, one issue clearly demands more attention. If we want to use IBE, we need some way of deciding which of the competing hypotheses provides the best explanation of the data. But what criteria determine this? A popular answer is that the best explanation is the simplest or the most parsimonious one. Consider again the cheese-in-the-larder example. There are two pieces of data that need explaining: the missing cheese and the scratching noises. The mouse hypothesis postulates just one cause – a mouse – to explain both pieces of data. But the maid hypothesis must postulate two causes – a dishonest maid and an overheating boiler – to explain the same data. So the mouse hypothesis is more parsimonious, hence better. Similarly in the Darwin example. Darwin’s theory could explain a very diverse range of facts about the living world, not just anatomical similarities between species. Each of these facts could be explained in other ways, as Darwin knew. But the theory of evolution explained all the facts in one go – that is what made it the best explanation of the data.

The idea that simplicity or parsimony is the mark of a good explanation is quite appealing, and certainly helps flesh out the idea of IBE. But if scientists use simplicity as a guide to inference, this raises a problem. For how do we know that the universe is simple rather than complex? Preferring a theory that explains the data in terms of the fewest number of causes does seem sensible. But is there any objective reason for thinking that such a theory is more likely to be true than a less simple theory? Philosophers of science do not agree on the answer to this difficult question.

Probability and induction

The concept of probability is philosophically puzzling. Part of the puzzle is that the word ‘probability’ seems to have more than one
meaning. If you read that the probability of an Englishwoman living to 100 years of age is 1 in 10, you would understand this as saying that one-tenth of all Englishwomen live to the age of 100. Similarly, if you read that the probability of a male smoker developing lung cancer is 1 in 4, you would take this to mean that a quarter of all male smokers develop lung cancer. This is known as the frequency interpretation of probability: it equates probabilities with proportions, or frequencies. But what if you read that the probability of finding life on Mars is 1 in 1,000? Does this mean that one out of every thousand planets in our solar system contains life? Clearly it does not. For one thing, there are only nine planets in our solar system. So a different notion of probability must be at work here.

One interpretation of the statement 'the probability of life on Mars is 1 in 1,000' is that the person who utters it is simply reporting a subjective fact about themselves — they are telling us how likely they think life on Mars is. This is the subjective interpretation of probability. It takes probability to be a measure of the strength of our personal opinions. Clearly, we hold some of our opinions more strongly than others. I am very confident that Brazil will win the World Cup, reasonably confident that Jesus Christ existed, and rather less confident that global environmental disaster can be averted. This could be expressed by saying that I assign a high probability to the statement 'Brazil will win the World Cup', a fairly high probability to 'Jesus Christ existed', and a low probability to 'global environmental disaster can be averted'. Of course, to put an exact number on the strength of my conviction in these statements would be hard, but advocates of the subjective interpretation regard this as a merely practical limitation. In principle, we should be able to assign a precise numerical probability to each of the statements about which we have an opinion, reflecting how strongly we believe or disbelieve them, they say.

The subjective interpretation of probability implies that there are no objective facts about probability, independently of what people believe. If I say that the probability of finding life on Mars is high and you say that it is very low, neither of us is right or wrong — we are both simply stating how strongly we believe the statement in question. Of course, there is an objective fact about whether there is life on Mars or not; there is just no objective fact about how probable it is that there is life on Mars, according to the subjective interpretation.

The logical interpretation of probability rejects this position. It holds that a statement such as 'the probability of life on Mars is high' is objectively true or false, relative to a specified body of evidence. A statement's probability is the measure of the strength of evidence in its favour, on this view. Advocates of the logical interpretation think that for any two statements in our language, we can in principle discover the probability of one, given the other as evidence. For example, we might want to discover the probability that there will be an ice age within 10,000 years, given the current rate of global warming. The subjective interpretation says there is no objective fact about this probability. But the logical interpretation insists that there is: the current rate of global warming confers a definite numerical probability on the occurrence of an ice age within 10,000 years, say 0.9 for example. A probability of 0.9 clearly counts as a high probability — for the maximum is 1 — so the statement 'the probability that there will be an ice age within 10,000 years is high' would then be objectively true, given the evidence about global warming.

If you have studied probability or statistics, you may be puzzled by this talk of different interpretations of probability. How do these interpretations tie in with what you learned? The answer is that the mathematical study of probability does not by itself tell us what probability means, which is what we have been examining above. Most statisticians would in fact favour the frequency interpretation, but the problem of how to interpret probability, like most philosophical problems, cannot be resolved mathematically. The
mathematical formulae for working out probabilities remain the same, whichever interpretation we adopt.

Philosophers of science are interested in probability for two main reasons. The first is that in many branches of science, especially physics and biology, we find laws and theories that are formulated using the notion of probability. Consider, for example, the theory known as Mendelian genetics, which deals with the transmission of genes from one generation to another in sexually reproducing populations. One of the most important principles of Mendelian genetics is that every gene in an organism has a 50% chance of making it into any one of the organism's gametes (sperm or egg cells). Hence there is a 50% chance that any gene found in your mother will also be in you, and likewise for the genes in your father. Using this principle and others, geneticists can provide detailed explanations for why particular characteristics (e.g., eye colour) are distributed across the generations of a family in the way that they are. Now 'chance' is just another word for probability, so it is obvious that our Mendelian principle makes essential use of the concept of probability. Many other examples could be given of scientific laws and principles that are expressed in terms of probability. The need to understand these laws and principles is an important motivation for the philosophical study of probability.

The second reason why philosophers of science are interested in the concept of probability is the hope that it might shed some light on inductive inference, in particular on Hume’s problem; this shall be our focus here. At the root of Hume’s problem is the fact that the premisses of an inductive inference do not guarantee the truth of its conclusion. But it is tempting to suggest that the premisses of a typical inductive inference do make the conclusion highly probable. Although the fact that all objects examined so far obey Newton’s law of gravity doesn’t prove that all objects do, surely it does make it very probable? So surely Hume’s problem can be answered quite easily after all?

However, matters are not quite so simple. For we must ask what interpretation of probability this response to Hume assumes. On the frequency interpretation, to say it is highly probable that all objects obey Newton’s law is to say that a very high proportion of all objects obey the law. But there is no way we can know that, unless we use induction! For we have only examined a tiny fraction of all the objects in the universe. So Hume’s problem remains.

Another way to see the point is this. We began with the inference from ‘all examined objects obey Newton’s law’ to ‘all objects obey Newton’s law’. In response to Hume’s worry that the premisses of this inference doesn’t guarantee the truth of the conclusion, we suggested that it might nonetheless make the conclusion highly probable. But the inference from ‘all examined objects obey Newton’s law’ to ‘it is highly probable that all objects obey Newton’s law’ is still an inductive inference, given that the latter means ‘a very high proportion of all objects obey Newton’s law’, as it does according to the frequency interpretation. So appealing to the concept of probability does not take the sting out of Hume’s argument, if we adopt a frequency interpretation of probability. For knowledge of probabilities then becomes itself dependent on induction.

The subjective interpretation of probability is also powerless to solve Hume’s problem, though for a different reason. Suppose John believes that the sun will rise tomorrow and Jack believes it will not. They both accept the evidence that the sun has risen every day in the past. Intuitively, we want to say that John is rational and Jack isn’t, because the evidence makes John’s belief more probable. But if probability is simply a matter of subjective opinion, we cannot say this. All we can say is that John assigns a high probability to ‘the sun will rise tomorrow’ and Jack does not. If there are no objective facts about probability, then we cannot say that the conclusions of inductive inferences are objectively probable. So we have no explanation of why someone like Jack, who declines to use induction, is irrational. But Hume’s problem is precisely the demand for such an explanation.
The logical interpretation of probability holds more promise of a satisfactory response to Hume. Suppose there is an objective fact about the probability that the sun will rise tomorrow, given that it has risen every day in the past. Suppose this probability is very high. Then we have an explanation of why John is rational and Jack isn't. For John and Jack both accept the evidence that the sun has risen every day in the past, but Jack fails to realize that this evidence makes it highly probable that the sun will rise tomorrow, while John does realize this. Regarding a statement's probability as a measure of the evidence in its favour, as the logical interpretation recommends, tallies neatly with our intuitive feeling that the premises of an inductive inference can make the conclusion highly probable, even if they cannot guarantee its truth.

Unsurprisingly, therefore, those philosophers who have tried to solve Hume's problem via the concept of probability have tended to favour the logical interpretation. (One of these was the famous economist John Maynard Keynes, whose early interests were in logic and philosophy.) Unfortunately, most people today believe that the logical interpretation of probability faces very serious, probably insuperable, difficulties. This is because all the attempts to work out the logical interpretation of probability in any detail have run up against a host of problems, both mathematical and philosophical. As a result, many philosophers today are inclined to reject outright the underlying assumption of the logical interpretation – that there are objective facts about the probability of one statement, given another. Rejecting this assumption leads naturally to the subjective interpretation of probability, but that, as we have seen, offers scant hope of a satisfactory response to Hume.

Even if Hume's problem is ultimately insoluble, as seems likely, thinking about the problem is still a valuable exercise. For reflecting on the problem of induction leads us into a thicket of interesting questions about the structure of scientific reasoning, the nature of rationality, the appropriate degree of confidence to place in science,
Chapter 3
Explanation in science

One of the most important aims of science is to try and explain what happens in the world around us. Sometimes we seek explanations for practical ends. For example, we might want to know why the ozone layer is being depleted so quickly, in order to try and do something about it. In other cases we seek scientific explanations simply to satisfy our intellectual curiosity – we want to understand more about how the world works. Historically, the pursuit of scientific explanation has been motivated by both goals.

Quite often, modern science is successful in its aim of supplying explanations. For example, chemists can explain why sodium turns yellow when it burns. Astronomers can explain why solar eclipses occur when they do. Economists can explain why the yen declined in value in the 1980s. Geneticists can explain why male baldness tends to run in families. Neurophysiologists can explain why extreme oxygen deprivation leads to brain damage. You can probably think of many other examples of successful scientific explanations.

But what exactly is scientific explanation? What exactly does it mean to say that a phenomenon can be ‘explained’ by science? This is a question that has exercised philosophers since Aristotle, but our starting point will be a famous account of scientific explanation put forward in the 1950s by the American philosopher Carl Hempel.

Hempel’s account is known as the covering law model of explanation, for reasons that will become clear.

Hempel’s covering law model of explanation

The basic idea behind the covering law model is straightforward. Hempel noted that scientific explanations are usually given in response to what he called ‘explanation-seeking why questions’. These are questions such as ‘why is the earth not perfectly spherical?’, ‘why do women live longer than men?’, and the like – they are demands for explanation. To give a scientific explanation is thus to provide a satisfactory answer to an explanation-seeking why question. If we could determine the essential features that such an answer must have, we would know what scientific explanation is.

Hempel suggested that scientific explanations typically have the logical structure of an argument, i.e. a set of premises followed by a conclusion. The conclusion states that the phenomenon that needs explaining actually occurs, and the premises tell us why the conclusion is true. Thus suppose someone asks why sugar dissolves in water. This is an explanation-seeking why question. To answer it, says Hempel, we must construct an argument whose conclusion is ‘sugar dissolves in water’ and whose premises tell us why this conclusion is true. The task of providing an account of scientific explanation then becomes the task of characterizing precisely the relation that must hold between a set of premises and a conclusion, in order for the former to count as an explanation of the latter. That was the problem Hempel set himself.

Hempel’s answer to the problem was three-fold. Firstly, the premises should entail the conclusion, i.e. the argument should be a deductive one. Secondly, the premises should all be true. Thirdly, the premises should consist of at least one general law. General laws are things such as ‘all metals conduct electricity’, ‘a body’s acceleration varies inversely with its mass’, ‘all plants contain chlorophyll’, and so on; they contrast with particular facts such as
‘this piece of metal conducts electricity’, ‘the plant on my desk contains chlorophyll’ and so on. General laws are sometimes called ‘laws of nature’. Hempel allowed that a scientific explanation could appeal to particular facts as well as general laws, but he held that at least one general law was always essential. So to explain a phenomenon, on Hempel’s conception, is to show that its occurrence follows deductively from a general law, perhaps supplemented by other laws and/or particular facts, all of which must be true.

To illustrate, suppose I am trying to explain why the plant on my desk has died. I might offer the following explanation. Owing to the poor light in my study, no sunlight has been reaching the plant; but sunlight is necessary for a plant to photosynthesize; and without photosynthesis a plant cannot make the carbohydrates it needs to survive, and so will die; therefore my plant died. This explanation fits Hempel’s model exactly. It explains the death of the plant by deducing it from two true laws – that sunlight is necessary for photosynthesis, and that photosynthesis is necessary for survival – and one particular fact – that the plant was not getting any sunlight. Given the truth of the two laws and the particular fact, the death of the plant had to occur; that is why the former constitute a good explanation of the latter.

Schematically, Hempel’s model of explanation can be written as follows:

General laws
Particular facts
⇒
Phenomenon to be explained

The phenomenon to be explained is called the *explanandum*, and the general laws and particular facts that do the explaining are called the *explanans*. The explanandum itself may be either a particular fact or a general law. In the example above, it was a particular fact – the death of my plant. But sometimes the things we want to explain are general. For example, we might wish to explain why exposure to the sun leads to skin cancer. This is a general law, not a particular fact. To explain it, we would need to deduce it from still more fundamental laws – presumably, laws about the impact of radiation on skin cells, combined with particular facts about the amount of radiation in sunlight. So the structure of a scientific explanation is essentially the same, whether the *explanandum*, i.e. the thing we are trying to explain, is particular or general.

It is easy to see why Hempel’s model is called the covering law model of explanation. For according to the model, the essence of explanation is to show that the phenomenon to be explained is ‘covered’ by some general law of nature. There is certainly something appealing about this idea. For showing that a phenomenon is a consequence of a general law does in a sense take the mystery out of it – it renders it more intelligible. And in fact, scientific explanations do often fit the pattern Hempel describes. For example, Newton explained why the planets move in ellipses around the sun by showing that this can be deduced from his law of universal gravitation, along with some minor additional assumptions. Newton’s explanation fits Hempel’s model exactly: a phenomenon is explained by showing that it had to be so, given the laws of nature plus some additional facts. After Newton, there was no longer any mystery about why planetary orbits are elliptical.

Hempel was aware that not all scientific explanations fit his model exactly. For example, if you ask someone why Athens is always immersed in smog, they will probably say ‘because of car exhaust pollution’. This is a perfectly acceptable scientific explanation, though it involves no mention of any laws. But Hempel would say that if the explanation were spelled out in full detail, laws would enter the picture. Presumably there is a law that says something like ‘if carbon monoxide is released into the earth’s atmosphere in sufficient concentration, smog clouds will form’. The full explanation of why Athens is bathed in smog would cite this law, along with the fact that car exhaust contains carbon monoxide and
Athens has lots of cars. In practice, we wouldn’t spell out the explanation in this much detail unless we were being very pedantic. But if we were to spell it out, it would correspond quite well to the covering law pattern.

Hempel drew an interesting philosophical consequence from his model about the relation between explanation and prediction. He argued that these are two sides of the same coin. Whenever we give a covering law explanation of a phenomenon, the laws and particular facts we cite would have enabled us to predict the occurrence of the phenomenon, if we hadn’t already known about it. To illustrate, consider again Newton’s explanation of why planetary orbits are elliptical. This fact was known long before Newton explained it using his theory of gravity – it was discovered by Kepler. But if it had not been known, Newton would have been able to predict it from his theory of gravity, for his theory entails that planetary orbits are elliptical, given minor additional assumptions. Hempel expressed this by saying that every scientific explanation is potentially a prediction – it would have served to predict the phenomenon in question, had it not already been known. The converse was also true, Hempel thought: every reliable prediction is potentially an explanation. To illustrate, suppose scientists predict that mountain gorillas will be extinct by 2010, based on information about the destruction of their habitat. Suppose they turn out to be right. According to Hempel, the information they used to predict the gorillas’ extinction before it happened will serve to explain that same fact after it has happened. Explanation and prediction are structurally symmetric.

Though the covering law model captures the structure of many actual scientific explanations quite well, it also faces a number of awkward counter-examples. These counter-examples fall into two classes. On the one hand, there are cases of genuine scientific explanations that do not fit the covering law model, even approximately. These cases suggest that Hempel’s model is too strict – it excludes some bona fide scientific explanations. On the other hand, there are cases of things that do fit the covering law model, but intuitively do not count as genuine scientific explanations. These cases suggest that Hempel’s model is too liberal – it allows in things that should be excluded. We will focus on counter-examples of the second sort.

**The problem of symmetry**

Suppose you are lying on the beach on a sunny day, and you notice that a flagpole is casting a shadow of 20 metres across the sand (Figure 8).

8. A 15-metre flagpole casts a shadow of 20 metres on the beach when the sun is $37^\circ$ overhead.

Someone asks you to explain why the shadow is 20 metres long. This is an explanation-seeking why question. A plausible answer might go as follows: "light rays from the sun are hitting the flagpole, which is exactly 15 metres high. The angle of elevation of the sun is $37^\circ$. Since light travels in straight lines, a simple trigonometric calculation (\(\tan 37^\circ = 15/20\)) shows that the flagpole will cast a shadow 20 metres long.'

This looks like a perfectly good scientific explanation. And by rewriting it in accordance with Hempel’s schema, we can see that it fits the covering law model:
The general moral of the flagpole example is that the concept of explanation exhibits an important asymmetry. The height of the flagpole explains the length of the shadow, given the relevant laws and additional facts, but not vice-versa. In general, if \( x \) explains \( y \), given the relevant laws and additional facts, then it will not be true that \( y \) explains \( x \), given the same laws and facts. This is sometimes expressed by saying that explanation is an asymmetric relation. Hempel's covering law model does not respect this asymmetry. For just as we can deduce the length of the shadow from the height of the flagpole, given the laws and additional facts, so we can deduce the height of the flagpole from the length of the shadow. In other words, the covering law model implies that explanation should be a symmetric relation, but in fact it is asymmetric. So Hempel's model fails to capture fully what it is to be a scientific explanation.

The shadow and flagpole case also provides a counter-example to Hempel's thesis that explanation and prediction are two sides of the same coin. The reason is obvious. Suppose you didn't know how high the flagpole was. If someone told you that it was casting a shadow of 20 metres and that the sun was 37° overhead, you would be able to predict the flagpole's height, given that you knew the relevant optical and trigonometrical laws. But as we have just seen, this information clearly doesn't explain why the flagpole has the height it does. So in this example prediction and explanation part ways. Information that serves to predict a fact before we know it does not serve to explain that same fact after we know it, which contradicts Hempel's thesis.

The problem of irrelevance

Suppose a young child is in a hospital in a room full of pregnant women. The child notices that one person in the room -- who is a man called John -- is not pregnant, and asks the doctor why not. The doctor replies: 'John has been taking birth-control pills regularly for the last few years. People who take birth-control pills regularly never become pregnant. Therefore, John has not become pregnant.'
Let us suppose for the sake of argument that what the doctor says is true – John is mentally ill and does indeed take birth-control pills, which he believes help him. Even so, the doctor’s reply to the child is clearly not very helpful. The correct explanation of why John has not become pregnant, obviously, is that he is male and males cannot become pregnant.

However, the explanation the doctor has given the child fits the covering law model perfectly. The doctor deduces the phenomenon to be explained – that John is not pregnant – from the general law that people who take birth-control pills do not become pregnant and the particular fact that John has been taking birth-control pills. Since both the general law and the particular fact are true, and since they do indeed entail the *explanandum*, according to the covering law model the doctor has given a perfectly adequate explanation of why John is not pregnant. But of course he hasn’t. Hence the covering law model is again too permissive: it allows things to count as scientific explanations that intuitively are not.

The general moral is that a good explanation of a phenomenon should contain information that is relevant to the phenomenon’s occurrence. This is where the doctor’s reply to the child goes wrong. Although what the doctor tells the child is perfectly true, the fact that John has been taking birth-control pills is irrelevant to his not being pregnant, because he wouldn’t have been pregnant even if he hadn’t been taking the pills. This is why the doctor’s reply does not constitute a good answer to the child’s question. Hempel’s model does not respect this crucial feature of our concept of explanation.

**Explanation and causality**

Since the covering law model encounters so many problems, it is natural to look for an alternative way of understanding scientific explanation. Some philosophers believe that the key lies in the concept of causality. This is quite an attractive suggestion. For in many cases to explain a phenomenon is indeed to say what caused it. For example, if an accident investigator is trying to explain an aeroplane crash, he is obviously looking for the cause of the crash. Indeed, the questions ‘why did the plane crash?’ and ‘what was the cause of the plane crash?’ are practically synonymous. Similarly, if an ecologist is trying to explain why there is less biodiversity in the tropical rainforests than there used to be, he is clearly looking for the cause of the reduction in biodiversity. The link between the concepts of explanation and causality is quite intimate.

Impressed by this link, a number of philosophers have abandoned the covering law account of explanation in favour of causality-based accounts. The details vary, but the basic idea behind these accounts is that to explain a phenomenon is simply to say what caused it. In some cases, the difference between the covering law and causal accounts is not actually very great, for to deduce the occurrence of a phenomenon from a general law often just is to give its cause. For example, recall again Newton’s explanation of why planetary orbits are elliptical. We saw that this explanation fits the covering law model – for Newton deduced the shape of the planetary orbits from his law of gravity, plus some additional facts. But Newton’s explanation was also a causal one, since elliptical planetary orbits are caused by the gravitational attraction between planets and the sun.

However, the covering law and causal accounts are not fully equivalent – in some cases they diverge. Indeed, many philosophers favour a causal account of explanation precisely because they think it can avoid some of the problems facing the covering law model. Recall the flagpole problem. Why do our intuitions tell us that the height of the flagpole explains the length of the shadow, given the laws, but not vice-versa? Plausibly, because the height of the flagpole is the cause of the shadow being 20 metres long, but the shadow being 20 metres long is not the cause of the flagpole being 15 metres high. So unlike the covering law model, a causal account of explanation gives the ‘right’ answer in the flagpole case – it respects our intuition that we cannot
explain the height of the flagpole by pointing to the length of the shadow it casts.

The general moral of the flagpole problem was that the covering law model cannot accommodate the fact that explanation is an asymmetric relation. Now causality is obviously an asymmetric relation too: if x is the cause of y, then y is not the cause of x. For example, if the short-circuit caused the fire, then the fire clearly did not cause the short-circuit. It is therefore quite plausible to suggest that the asymmetry of explanation derives from the asymmetry of causality. If to explain a phenomenon is to say what caused it, then since causality is asymmetric we should expect explanation to be asymmetric too — as it is. The covering law model runs up against the flagpole problem precisely because it tries to analyse the concept of scientific explanation without reference to causality.

The same is true of the birth-control pill case. That John takes birth-control pills does not explain why he isn’t pregnant, because the birth-control pills are not the cause of his not being pregnant. Rather, John’s gender is the cause of his not being pregnant. That is why we think that the correct answer to the question ‘why is John not pregnant?’ is ‘because he is a man, and men can’t become pregnant’, rather than the doctor’s answer. The doctor’s answer satisfies the covering law model, but since it does not correctly identify the cause of the phenomenon we wish to explain, it does not constitute a genuine explanation. The general moral we drew from the birth-control pill example was that a genuine scientific explanation must contain information that is relevant to the explanandum. In effect, this is another way of saying that the explanation should tell us the explanandum’s cause. Causality-based accounts of scientific explanation do not run up against the problem of irrelevance.

It is easy to criticize Hempel for failing to respect the close link between causality and explanation, and many people have done so.

In some ways, this criticism is a bit unfair. For Hempel subscribed to a philosophical doctrine known as empiricism, and empiricists are traditionally very suspicious of the concept of causality. Empiricism says that all our knowledge comes from experience. David Hume, whom we met in the last chapter, was a leading empiricist, and he argued that it is impossible to experience causal relations. So he concluded that they don’t exist — causality is a figment of our imagination! This is a very hard conclusion to accept. Surely it is an objective fact that dropping glass vases causes them to break? Hume denied this. He allowed that it is an objective fact that most glass vases that have been dropped have in fact broken. But our idea of causality includes more than this. It includes the idea of a causal link between the dropping and the breaking, i.e. that the former brings about the latter. No such links are to be found in the world, according to Hume: all we see is a vase being dropped, and then it breaking a moment later. We experience no causal connection between the first event and the second. Causality is therefore a fiction.

Most empiricists have not accepted this startling conclusion outright. But as a result of Hume’s work, they have tended to regard causality as a concept to be treated with great caution. So to an empiricist, the idea of analysing the concept of explanation in terms of the concept of causality would seem perverse. If one’s goal is to clarify the concept of scientific explanation, as Hempel’s was, there is little point in using notions that are equally in need of clarification themselves. And for empiricists, causality is definitely in need of philosophical clarification. So the fact that the covering law model makes no mention of causality was not a mere oversight on Hempel’s part. In recent years, empiricism has declined somewhat in popularity. Furthermore, many philosophers have come to the conclusion that the concept of causality, although philosophically problematic, is indispensable to how we understand the world. So the idea of a causality-based account of scientific explanation seems more acceptable than it would have done in Hempel’s day.
Causality-based accounts of explanation certainly capture the structure of many actual scientific explanations quite well, but are they the whole story? Many philosophers say no, on the grounds that certain scientific explanations do not seem to be causal. One type of example stems from what are called ‘theoretical identifications’ in science. Theoretical identifications involve identifying one concept with another, usually drawn from a different branch of science. ‘Water is H\textsubscript{2}O’ is an example, as is ‘temperature is average molecular kinetic energy’. In both of these cases, a familiar everyday concept is equated or identified with a more esoteric scientific concept. Often, theoretical identifications furnish us with what seem to be scientific explanations. When chemists discovered that water is H\textsubscript{2}O, they thereby explained what water is. Similarly, when physicists discovered that an object’s temperature is the average kinetic energy of its molecules, they thereby explained what temperature is. But neither of these explanations is causal. Being made of H\textsubscript{2}O doesn’t cause a substance to be water – it just is being water. Having a particular average molecular kinetic energy doesn’t cause a liquid to have the temperature it does – it just is having that temperature. If these examples are accepted as legitimate scientific explanations, they suggest that causality-based accounts of explanation cannot be the whole story.

Can science explain everything?

Modern science can explain a great deal about the world we live in. But there are also numerous facts that have not been explained by science, or at least not explained fully. The origin of life is one such example. We know that about 4 billion years ago, molecules with the ability to make copies of themselves appeared in the primeval soup, and life evolved from there. But we do not understand how these self-replicating molecules got there in the first place. Another example is the fact that autistic children tend to have very good memories. Numerous studies of autistic children have confirmed this fact, but as yet nobody has succeeded in explaining it.

Many people believe that in the end, science will be able to explain facts of this sort. This is quite a plausible view. Molecular biologists are working hard on the problem of the origin of life, and only a pessimist would say they will never solve it. Admittedly, the problem is not easy, not least because it is very hard to know what conditions on earth 4 billion years ago were like. But nonetheless, there is no reason to think that the origin of life will never be explained. Similarly for the exceptional memories of autistic children. The science of memory is still in its infancy, and much remains to be discovered about the neurological basis of autism. Obviously we cannot guarantee that the explanation will eventually be found. But given the number of explanatory successes that modern science has already notched up, the smart money must be on many of today’s unexplained facts eventually being explained too.

But does this mean that science can in principle explain everything? Or are there some phenomena that must forever elude scientific explanation? This is not an easy question to answer. On the one hand, it seems arrogant to assert that science can explain everything. On the other hand, it seems short-sighted to assert that any particular phenomenon can never be explained scientifically. For science changes and develops very fast, and a phenomenon that looks completely inexplicable from the vantage-point of today’s science may be easily explained tomorrow.

According to some philosophers, there is a purely logical reason why science will never be able to explain everything. For in order to explain something, whatever it is, we need to invoke something else. But what explains the second thing? To illustrate, recall that Newton explained a diverse range of phenomena using his law of gravity. But what explains the law of gravity itself? If someone asks why all bodies exert a gravitational force on each other, what should we tell them? Newton had no answer to this question. In Newtonian science the law of gravity was a fundamental principle: it explained other things, but could not itself be explained. The
moral is generalizable. However much the science of the future can explain, the explanations it gives will have to make use of certain fundamental laws and principles. Since nothing can explain itself, it follows that at least some of these laws and principles will themselves remain unexplained.

Whatever one makes of this argument, it is undeniably very abstract. It purports to show that some things will never be explained, but does not tell us what they are. However, some philosophers have made concrete suggestions about phenomena that they think science can never explain. An example is consciousness – the distinguishing feature of thinking, feeling creatures such as ourselves and other higher animals. Much research into the nature of consciousness has been and continues to be done, by brain scientists, psychologists, and others. But a number of recent philosophers claim that whatever this research throws up, it will never fully explain the nature of consciousness. There is something intrinsically mysterious about the phenomenon of consciousness, they maintain, that no amount of scientific investigation can eliminate.

What are the grounds for this view? The basic argument is that conscious experiences are fundamentally unlike anything else in the world, in that they have a 'subjective aspect'. Consider, for example, the experience of watching a terrifying horror movie. This is an experience with a very distinctive 'feel' to it; in the current jargon, there is 'something that it is like' to have the experience. Neuroscientists may one day be able to give a detailed account of the complex goings-on in the brain that produce our feeling of terror. But will this explain why watching a horror movie feels the way it does, rather than feeling some other way? Many people believe that it will not. On this view, the scientific study of the brain can at most tell us which brain processes are correlated with which conscious experiences. This is certainly interesting and valuable information. However, it doesn't tell us why experiences with distinctive subjective 'feels' should result from the purely physical goings-on in the brain. Hence consciousness, or at least one important aspect of it, is scientifically inexplicable.

Though quite compelling, this argument is very controversial and not endorsed by all philosophers, let alone all neuroscientists. Indeed, a well-known book published in 1991 by the philosopher Daniel Dennett is defiantly entitled Consciousness Explained. Supporters of the view that consciousness is scientifically inexplicable are sometimes accused of having a lack of imagination. Even if it is true that brain science as currently practised cannot explain the subjective aspect of conscious experience, can we not imagine the emergence of a radically different type of brain science, with radically different explanatory techniques, that does explain why our experiences feel the way they do? There is a long tradition of philosophers trying to tell scientists what is and isn't possible, and later scientific developments have often proved the philosophers wrong. Only time will tell whether the same fate awaits those who argue that consciousness must always elude scientific explanation.

**Explanation and reduction**

The different scientific disciplines are designed for explaining different types of phenomena. To explain why rubber doesn't conduct electricity is a task for physics. To explain why turtles have such long lives is a task for biology. To explain why higher interest rates reduce inflation is a task for economics, and so on. In short, there is a division of labour between the different sciences: each specializes in explaining its own particular set of phenomena. This explains why the sciences are not usually in competition with one another – why biologists, for example, do not worry that physicists and economists might encroach on their turf.

Nonetheless, it is widely held that the different branches of science are not all on a par: some are more fundamental than others. Physics is usually regarded as the most fundamental science of all.
Why? Because the objects studied by the other sciences are ultimately composed of physical particles. Consider living organisms, for example. Living organisms are made up of cells, which are themselves made up of water, nucleic acids (such as DNA), proteins, sugars, and lipids (fats), all of which consist of molecules or long chains of molecules joined together. But molecules are made up of atoms, which are physical particles. So the objects biologists study are ultimately just very complex physical entities. The same applies to the other sciences, even the social sciences. Take economics, for example. Economics studies the behaviour of corporations and consumers in the market place, and the consequences of this behaviour. But consumers are human beings and corporations are made up of human beings; and human beings are living organisms, hence physical entities.

Does this mean that, in principle, physics can subsume all the higher-level sciences? Since everything is made up of physical particles, surely if we had a complete physics, which allowed us to predict perfectly the behaviour of every physical particle in the universe, all the other sciences would become superfluous? Most philosophers resist this line of thought. After all, it seems crazy to suggest that physics might one day be able to explain the things that biology and economics explain. The prospect of deducing the laws of biology and economics straight from the laws of physics looks very remote. Whatever the physics of the future looks like, it is most unlikely to be capable of predicting economic downturns. Far from being reducible to physics, sciences such as biology and economics seem largely autonomous of it.

This leads to a philosophical puzzle. How can a science that studies entities that are ultimately physical not be reducible to physics? Granted that the higher-level sciences are in fact autonomous of physics, how is this possible? According to some philosophers, the answer lies in the fact that the objects studied by the higher-level sciences are ‘multiply realized’ at the physical level. To illustrate the idea of multiple realization, imagine a collection of ashtrays. Each individual ashtray is obviously a physical entity, like everything else in the universe. But the physical composition of the ashtrays could be very different – some might be made of glass, others of aluminium, others of plastic, and so on. And they will probably differ in size, shape, and weight. There is virtually no limit on the range of different physical properties that an ashtray can have. So it is impossible to define the concept ‘ashtray’ in purely physical terms. We cannot find a true statement of the form ‘$x$ is an ashtray if and only if $x$ is . . . ’ where the blank is filled by an expression taken from the language of physics. This means that ashtrays are multiply realized at the physical level.

Philosophers have often invoked multiple realization to explain why psychology cannot be reduced to physics or chemistry, but in principle the explanation works for any higher-level science. Consider, for example, the biological fact that nerve cells live longer than skin cells. Cells are physical entities, so one might think that this fact will one day be explained by physics. However, cells are almost certainly multiply realized at the microphysical level. Cells are ultimately made up of atoms, but the precise arrangement of atoms will be very different in different cells. So the concept ‘cell’ cannot be defined in terms drawn from fundamental physics. There is no true statement of the form ‘$x$ is a cell if and only if $x$ is . . . ’ where the blank is filled by an expression taken from the language of microphysics. If this is correct, it means that fundamental physics will never be able to explain why nerve cells live longer than skin cells, or indeed any other facts about cells. The vocabulary of cell biology and the vocabulary of physics do not map onto each other in the required way. Thus we have an explanation of why it is that cell biology cannot be reduced to physics, despite the fact that cells are physical entities. Not all philosophers are happy with the doctrine of multiple realization, but it does promise to provide a neat explanation of the autonomy of the higher-level sciences, both from physics and from each other.