Given the above discussion, I think we can say that for a hypothesis to be a genuinely scientific statement it must be testable, and that it will be easier to test if the following are true:

1 It is clearly stated and makes precise rather than vague predictions.
2 It does not keep making *ad hoc* exceptions when it comes across counter-examples.

1 Which of the following statements make scientifically testable claims?
  a In 2010 you may or may not win the lottery.
  b It always rains on Tuesdays.
  c We have all lived past lives, but most of us are too unenlightened to remember them.
  d Real men don't cry.
  e Unlike magnetic poles attract each other.
  f Everyone is selfish.
  g Acids turn litmus paper red.
  h Something surprising will happen to you next week.

2 To what extent do you think astrology consists of genuinely testable propositions?

The scientific method

In trying to distinguish science from non-science, you might list all the subjects that count as science – such as physics, chemistry and biology – and then say that everything else is non-science. However, this does not seem very helpful because it does not explain *why* some things count as science and other things do not. A better approach might be to say that what distinguishes science from non-science is a distinctive *method*. On this view, science is not so much a fixed body of knowledge as a way of thinking about the world.

1 Each of the elements below is relevant to the scientific method. Try to put them into sequential order and write a short description of how a scientist typically works.
  a Experiment
  b Induction
  c Hypothesis
  d Law
  e Measurement
  f Observation
  g Repeatability
  h Theory

2 How is each of the following similar to scientific activity and how is it different?
  a Baking a cake by following a recipe.
  b 'Experimenting' with ingredients and making your own recipe.
  c Collecting and organising stamps from around the world.
  d Repairing a car that has broken down.

e Heating a fixed volume of gas to see what happens to the pressure.
f Speculating on the origins of the universe.
g Studying human anatomy before making a sculpture.
h Doing detective work to solve a murder.
i Inventing the light bulb.
j Predicting rain because the clouds look threatening.
k Solving a crossword puzzle.
l Noticing that you always need something just after you have thrown it away.

Inductivism

According to the traditional picture of the scientific method, which is known as **inductivism**, science consists of five key steps:

1. observation
2. hypothesis
3. experiment
4. law
5. theory

You begin by observing and classifying the relevant data. You then look for a pattern in the data and formulate a hypothesis. You then make a prediction, which you test by an experiment. A good experiment should have the following features:

- *Controllability* You vary only one factor at a time so that you can determine its effect. For example, you might vary the temperature of a gas while keeping its volume constant. This helps you to isolate the cause of the phenomenon that you are investigating.
- *Measurability* You can measure the relevant variables. This adds precision and objectivity to your experiment.
- *Repeatability* Your experiment can be repeated by other people who will be able to confirm your results. This ensures that your results have some kind of objectivity.

If your experimental results confirm your hypothesis, then you may have discovered a *scientific law*. If your results disconfirm your hypothesis, then you will need to go back and think again.

Finally, you may develop a theory which explains and unifies various laws in terms of some underlying principles. A good theory explains why the laws are the way they are and provides a focus for further research.

An example: the Copernican revolution

To illustrate the scientific method, consider the way our views have changed about the place of the earth in the universe. Since it does not look or feel as if we are moving, it is natural to think that the earth is stationary. So it is not surprising that the Greek astronomer Claudius Ptolemy (85–165) developed a model of the universe with the earth at the centre of things and the sun and the planets going round it. Ptolemy's model not only reflected common sense, but also enabled people to make accurate predictions about the movements of the planets. The steps that led to the breakdown and eventual replacement of this model could be traced in the following simplified story:

Observation As people made new and better observations, Ptolemy's model became increasingly complicated in order to accommodate them, so that, by the sixteenth century, it had become a 'disorderly monster'.

Hypothesis This led Nicolaus Copernicus (1473–1543) to suggest a simpler and more elegant approach which put the sun at the centre of the solar system and had the planets revolve around it.

Prediction In the Ptolemaic model, Venus orbits the earth and so always appears the same size; but Copernicus said that if Venus orbits the sun its apparent size should vary as its distance from the earth changes. To the naked eye Venus appears to be a constant size as predicted by the Ptolemaic model. But when Galileo (1564–1642) looked at it through a telescope in 1609, he discovered that its size does indeed vary as had been predicted by Copernicus.

Law On the basis of the above observations and discoveries, Johannes Kepler (1571–1630), developed laws of planetary motion.

Theory Finally, Isaac Newton (1642–1727) came up with the theory of gravity, which says that there is a force of attraction between objects whose strength is directly proportional to their masses and inversely proportional to the square of the distance between them. (Thus if you double the distance between two objects, the gravitational attraction between them will be 1/4 of its original strength.) This was part of a more general theory that enabled Newton to explain a wide variety of phenomena such as why an apple falls from a tree, why people have weight, the movement of the tides, and the orbit of the planets. Newtonian physics also enabled later astronomers to make accurate predictions that led to the discovery of new planets such as Uranus in 1781 and Neptune in 1846.

The following points are worth drawing out of this brief account:

- Scientific progress needs a background of careful observation. Kepler was able to develop his laws of planetary motion because another astronomer called Tycho Brahe (1546–1601) had made meticulous observations and discovered various **anomalies** in the orbits of the planets. (An anomaly is an observation that seems to contradict a generally accepted theory.)
- Technology can extend our powers of observation, thereby making it easier to test new ideas. Galileo was only able to detect the change in the apparent size of Venus by using the newly invented telescope.
- Imagination plays an important role in the development of new scientific ideas. Part of Copernicus' genius was that while he saw what everyone else saw when he looked up at the night sky, he came up with a different way of looking at it. (In fact, a Greek astronomer called Aristarchus had suggested that the earth goes round the sun as early as the third century BCE, but the idea didn't catch on.)
- Mathematics also plays a central role in the development of scientific ideas. Newton's law of gravity not only fitted the observational data, but could also be expressed in precise mathematical terms.

- Many scientific discoveries are *counter-intuitive* and go against untutored common sense. We now take it as obvious that the earth rotates on its axis and orbits the sun but, when you think about it, it is difficult to believe that the earth is spinning at 1,000 miles an hour and travelling round the sun at about 67,000 miles an hour.

Try explaining the following to someone who doesn't know much physics.

a If the earth is round, why don't people fall off the bottom?
b If the earth is moving round the sun and rotating on its axis, how come it doesn't feel like we are moving?
c Since birds fly far slower than the earth rotates, how come they don't get left behind when they fly in the direction of the rotation (west to east)?

Our discussion so far might suggest that there is a straightforward procedure for generating scientific truth from raw observations. All you have to do is follow the scientific method. But things are not that simple. If we go over the various stages of the scientific method again, we will see that each step is more complicated than it first appears.

Problems with observation

Science is based on observation but, as we saw in Chapter 4, observation is not as straightforward as it first seems. In what follows, we shall briefly consider problems of relevance, expectations, expert seeing and the observer effect.

Relevance

Imagine that you are interested in finding out why some students catch a cold in the winter term and other students do not. Which of the following factors might you look at in comparing the two groups, and which would you consider irrelevant?

a Diet
b Colour of underwear
c Exercise
d Middle name
e Domestic heating
f Movies watched
g Warmth of clothing

Quite reasonably, you probably said that (a), (c), (e) and (g) are relevant, and (b), (d) and (f) are irrelevant. How, after all, could the colour of your underwear, or your middle name, or the movies you have watched, affect whether or not you catch a cold?

The important point that comes out of this example is that we always begin with some idea of what is and what is not relevant to the problem. If we did not, we would drown in a flood of observations. However, the selective nature of perception means that it is always possible that we have overlooked a factor that later turns out to be relevant. For example, when you do an experiment in chemistry, you do not normally count how many people are in the room. However, this will affect the temperature of the room, and in a sensitive experiment that might affect the speed of the chemical reaction.

Expectations

Another problem with observation is that *our expectations can influence what we see.* When the planet Mercury was found to be deviating from the orbit predicted by Newton's laws, some nineteenth-century astronomers suggested that the anomaly was caused by an undiscovered planet called Vulcan. So confident were they in their belief that several astronomers then claimed that they had observed Vulcan. But it turned out that Vulcan does not exist. The correct explanation for the deviation of Mercury had to wait for Einstein's theory of relativity.

Expert seeing

The use of *scientific equipment* such as microscopes and telescopes to make observations further complicates things. We may laugh when we hear that some of Galileo's contemporaries refused to look through his telescope preferring to rely on the authority of the Church rather than the evidence of their senses. But it is worth pointing out that the telescope Galileo used to discover the phases of Venus and the moons of Jupiter was a fairly crude instrument. Some of Galileo's drawings of the moon are quite inaccurate and include some craters and mountains that do not in fact exist. From your own experience in the science lab, you are probably aware that it takes quite a lot of practice to learn how to see through a microscope.

The observer effect

A final problem with observation is that *the act of observation can sometimes affect what we observe.* To take a simple example, imagine that you want to know exactly how hot a cup of tea is. You put a thermometer in the tea and read off the temperature. The problem is that, instead of measuring the temperature of the tea, you are now measuring the temperature of the tea-with-the-thermometer-in-it. The very act of putting the thermometer in the tea has changed its temperature. Of course, for most practical purposes this does not make a significant difference. If you are in bed with a fever and the doctor comes and tells you that you have a temperature of 102 °F, it would be pedantic to point out that she has in fact taken the temperature of you *plus* the thermometer. However, the effect of the observer on the observed plays an important role in a branch of physics known as quantum physics. We shall also have more to say about the observer effect when we discuss the human sciences in the next chapter.

While our discussion has focused on the fallibility of perception, it is important not to exaggerate the problem. The great strength of science is that it is a communal and self-correcting enterprise. Sooner or later the errors of one individual are likely to be corrected by someone else.

'An uneducated child and a trained astronomer, both relying on the naked eye and twenty-twenty vision, will literally see a different sky.' What do you understand by this quotation?

Testing hypotheses

Testing hypotheses is also less straightforward than the naive account of the scientific method implies. Among the complications are: confirmation bias, background assumptions and the fact that many different hypotheses are consistent with a given set of data.

Confirmation bias

Confirmation bias refers to the fact that people tend to look for evidence that confirms their beliefs and overlook evidence that goes against them. If, for example, you believe that Virgos are particularly shy individuals, you will notice every time you come across a shy Virgo. But if you only observe confirming instances of your hypothesis this does not show that it is true. You also need to look for evidence that might falsify it.

In the above example, as well as looking at Virgos who are shy, what else might you look at that could falsify your hypothesis?

The two other key things you should look out for are: (a) Virgos who are not shy; and (b) people of other star signs who are also shy. When all the evidence is in, it may turn out that, despite your initial belief, there is no relationship between a person's star sign and whether or not they are shy.

A good scientist will be aware of the danger of confirmation bias and actively seek to combat it. In one of his notebooks Charles Darwin (1809–82) stated that 'I followed a golden rule, namely that whenever a new observation or thought came across me, which was opposed to my general results, I make a memorandum of it without fail and at once; for I had found by experience that such facts and thoughts were far more apt to escape from the memory than favourable ones.' This is a tribute to Darwin's intellectual integrity.

One common form of confirmation bias is for a scientist to dismiss results they don't expect as 'experimental error'. Imagine, for example, that you do an experiment and get the following results. You would probably be tempted to ignore observation X_4.

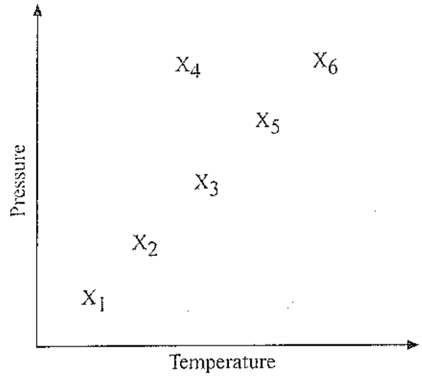


Figure 8.3 Pressure–temperature graph

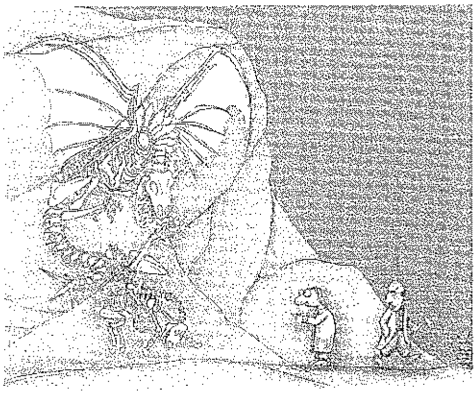
To what extent do you think you would be justified in dismissing observation X_4 in this example as experimental error?

In the above case, it might seem reasonable to assume that X_4 is a result of human error, but it would be wise to take more observations to be on the safe side. In practice, however, it is difficult to say where 'trimming' one's results to exclude experimental error ends and 'cooking the books' begins. Scientists naturally want to show their results in the best possible light, and they often have strong expectations about the way an experiment should turn out. When the notebooks of one famous physicist were examined, the following comments were found alongside his experimental observations:

> 'Very low. Something wrong.'
> 'This is almost exactly *right* and the best one I have ever had!!!'
> 'Agreement poor.'

To take another example, Gregor Mendel's (1822–84) work on the hereditary traits of peas laid the foundations for modern genetics. But according to some modern geneticists, his results are just too good to be believable, and he has been accused of only reporting results that favoured his case. The following is an amusing account of Mendel's method:

> IN THE BEGINNING, there was Mendel, thinking his lonely thoughts alone. And he said: 'Let there be peas,' and there were peas, and it was good. And he put the peas in the garden, saying unto them, 'Increase and multiply, segregate and assort yourselves independently,' and they did, and it was good. And now it came to pass that when Mendel gathered up his peas, he divided them into round and wrinkled and called the round dominant and the wrinkled recessive, and it was good. But now Mendel saw that there were 450 round peas and 102 wrinkled ones; this was not good. For the law stateth that there should be only three round for every wrinkled. And Mendel said unto himself, 'Gott in Himmel, an enemy has done this; he has sown bad peas in my garden under the cover of night.' And Mendel smote the table in righteous wrath, saying, 'Depart from me, you cursed and evil peas, into the outer darkness where Thou shalt be devoured by the rats and mice,' and lo, it was done, and there remained 300 round peas and 100 wrinkled peas, and it was good. It was very, very good. And Mendel published.



"No, ignore that one Davies. It's unscientific."

Figure 8.4

Background assumptions

Whenever we test a hypothesis, we make various background assumptions, any one of which could turn out to be false. For example, at the time of Copernicus, it was generally agreed that the fixed stars are relatively close to the earth. Given this, it follows that if the earth is orbiting the sun the position of nearby stars relative to more distant stars ought to change as the earth moves round the sun. Such a change of relative position is known as a *parallax*. (An analogy may help you to get the point here. Hold a pencil out in front of you so that it exactly covers a distant object, such as a tree. If you now close each of your eyes in turn, the position of the pencil relative to the tree will appear to change. In a similar way, the relative position of the stars should change if the earth is moving.) The problem was that no one was able to observe the required parallax; and neither Copernicus nor Galileo had an answer to this criticism. Finally it turned out that the assumption that the fixed stars are relatively close to the earth was wrong, and in the nineteenth century the stellar parallax was finally observed.

Many different hypotheses are consistent with a given set of data

Since it is possible to come up with many different hypotheses that are consistent with a given set of observations, it is in practice impossible to *prove* that any particular hypothesis is true. For example, in our discussion of astronomy above, I said that Galileo saw that the relative size of Venus changes as predicted by Copernicus' heliocentric theory. While this observation is inconsistent with Ptolemy's model, it is in fact consistent with another model according to which the sun orbits the earth and the other planets orbit the sun.

In fact, there are an endless number of different hypotheses consistent with a given set of observations. This can be easily shown by considering the graphs below. Imagine you are investigating the relationship between the temperature and pressure of a gas. You make some observations, X_1, X_2 and X_3. On the basis of your observations, you formulate a hypothesis H1, and make a prediction P. Your prediction is confirmed. Does this conclusively confirm hypothesis H1? No! For your observations are also consistent with another hypothesis H2.

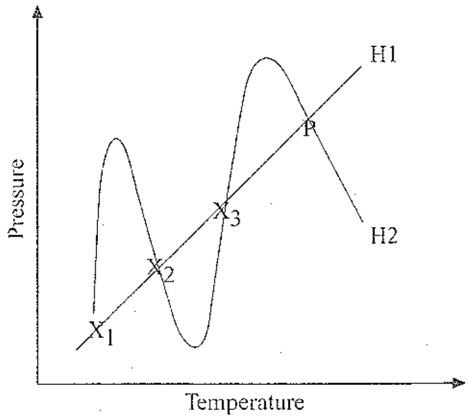


Figure 8.5 Temperature–pressure graph showing hypotheses H1 and H2

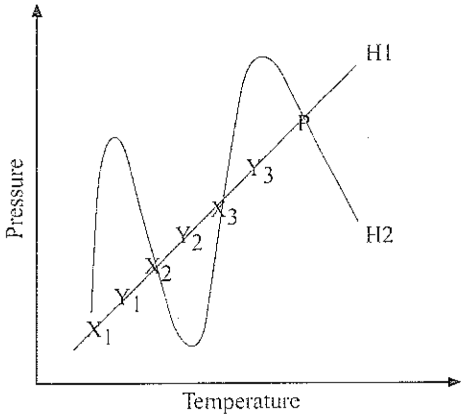


Figure 8.6 Temperature–pressure graph, with extra observations

To decide between hypotheses H1 and H2 you might make some further observations, Y_1, Y_2 and Y_3 as in Figure 8.6. These new observations would seem to confirm H1 and eliminate H2.

But once again H1 is not conclusively confirmed. For we might now make another hypothesis H3 which is also consistent with our observations (Figure 8.7). Further observations might eliminate H3 and confirm H1, but you could then make another hypothesis H4 and so on. Extrapolating from this, you can see that, no matter how many observations you make confirming H1, there will always be other hypotheses that are also consistent with the data.

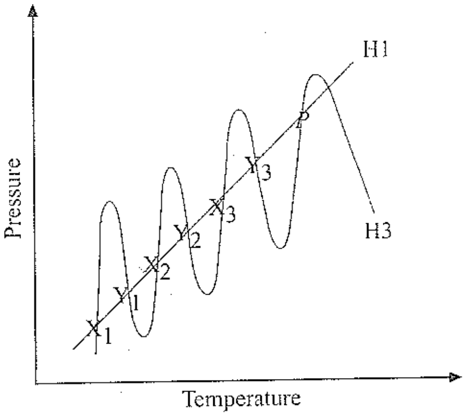


Figure 8.7 Temperature–pressure graph with new hypothesis H3

The principle of simplicity

Having said that, hypotheses such as H3 do seem absurd, and it is hard to avoid thinking that H1 is the more natural hypothesis. In fact, scientists usually appeal to a **principle of simplicity** which says that given two competing theories which make exactly the same predictions the simpler theory is to be preferred. This justifies our preference for H1 over H2 or H3. However, if you asked a scientist to justify their belief in the principle of simplicity, they would probably shrug their shoulders and say that's just what they believe. The principle reflects a deep belief in the orderliness and comprehensibility of nature, but no further justification can be given for it. Since simplicity is also related to concepts such as 'beauty' and 'elegance', we can say that in practice aesthetic considerations are likely to play a role in a scientist's choice of hypothesis.

But we must be careful. For our aesthetic prejudices can sometimes lead us astray. Copernicus was convinced that the planets must orbit the sun in circles because he thought that a circle is a perfect figure. However, it turned out that planetary orbits are elliptical rather than circular. The moral of the tale is that nature's aesthetic may not be the same as our own, and beautiful theories are sometimes slain by ugly facts!

The problem of induction

A final problem with the naive picture of the scientific method concerns induction. As we saw in Chapter 5, inductive reasoning goes from the particular to the general, and it plays a central role in the way that scientists think. Take, for example, our belief that all metals expand when heated. How did we come by this belief? Not by reason, or intuition, or divine revelation, but by observation. As far as we know, every time a piece of metal has been heated, it has expanded, and there are no recorded cases of metals not expanding when heated. So it seems reasonable to conclude that this is a law of nature. What's the problem?

Although it is unlikely to keep you awake at night, the problem is that when we reason inductively we are moving from the observed to the unobserved. For example, when we reason that since metal A and metal B and metal C etc. expand when heated, then *all* metals expand when heated, we are making a generalisation from things we have observed to things we have not observed.

Practical problems

At a practical level, the problem of induction raises the question of how many observations we should make before we are entitled to make a generalisation. We saw in Chapter 6 that we have a tendency to jump to conclusions on the basis of insufficient evidence, and we looked at various criteria for distinguishing reasonable generalisations from unreasonable ones. But there is no hard and fast rule about how many observations you should make before you are entitled to generalise. All we can say is the more observations you make that support your hypothesis the more confident you will feel about it.

The trouble is that even well-confirmed generalisations sometimes let us down. Up until the eighteenth century, it was commonly believed by Europeans that all swans are white. There were innumerable confirming instances of this belief and no disconfirming instances. Then some black swans were discovered in Australia. More dramatically, for two and a half centuries experiment after experiment seemed to confirm the truth of Newtonian physics. Nevertheless, Einstein showed that there is a deep sense in which Newton's laws are not the best description of physical reality. What this appears to show is that even very well-confirmed hypotheses can sometimes turn out to be wrong.

When you start to think about it, our confidence in scientific knowledge is quite breathtaking. On the basis of a few observations that we have made on planet Earth, we claim to have discovered laws of physics that apply to *all* times and *all* places – billions of years ago and billions of light-years away. Yet we have observed only a minute fraction of the universe. (As we mentioned in Chapter 1, astronomers estimate that there are ten times more stars in the night sky than grains of sand in the world's deserts and beaches!)

Given the above, you might argue that scientists should show greater humility and make less ambitious claims. For example, instead of saying 'all metals expand when heated', perhaps we should restrict ourselves to the more modest assertion that 'all *observed* metals expand when heated'. This may show admirable humility, but the fact is that deep down most physicists believe that they really are discovering the fundamental laws in accordance with which the universe operates.

Theoretical problems

The problem of induction bites not only at the practical level, but also at the theoretical level. For science is supposed to be an *empirical* discipline which makes no claims beyond what has been observed. Indeed, the claim that it is grounded in observation is supposed to be what distinguishes genuine science from pseudo-science. So we seem to be faced with a dilemma. On the one hand, we could take the alleged empiricism of science seriously, and refuse to make any claims that go beyond what has actually been observed. There would, however, be a very high price to pay for this. For it would mean that we would have to abandon any talk of discovering laws of nature that apply in all times and all places. On the other hand, we could defend the right of scientists to reason from the particular to the general, and abandon the claim that science is a strictly empirical discipline. Again, this seems to be a high price to pay. Another approach is to simply not worry about the problem too much and just get on with the business of doing science!

The scientific method: summary of problems	
Observation	1. Selectivity 2. Expectations 3. Expert seeing 4. The observer effect
Hypothesis	5. Confirmation bias 6. Background assumptions 7. Under-determination
Law	8. Problem of induction

? Write short paragraphs explaining each of the above problems in your own words.

Falsification

One person who took the problem of induction seriously and tried to resolve the dilemma was a philosopher called Karl Popper (1902–94). Popper's interest in the problem grew out of his concern to distinguish genuine science, such as Einstein's theory of relativity, from what he saw as pseudo-science, such as Marxism and psychoanalysis.

As a young man, Popper had been impressed by the ability of theories put forward by people such as Karl Marx (1818–83), Sigmund Freud (1856–1939) and Alfred Adler (1870–1937) to explain *everything*. Adler, for example, believed that human beings are dominated by feelings of inferiority. 'To be human', he said, 'means to feel inferior.' He then used this insight to explain more or less the entire range of human behaviour. As impressive as this seems, Popper came to the conclusion that what looked like a strength of the theory – its ability to explain everything – was in fact a weakness.

Imagine, for example, that a man is walking along the bank of a fast-flowing river when he sees a child fall in. He has two choices: either he jumps in and tries to rescue the child or he does not. Suppose that he jumps in and tries to rescue the child. 'Ah', says Adler, 'this is exactly what my theory predicted. The man was clearly trying to overcome his feeling of inferiority by demonstrating his bravery.' Now suppose that the man does not jump in to the river. 'Just as I thought', says Adler. 'This man is clearly suffering from an inferiority complex which he is unable to overcome.'

The above may be a caricature of Adler's beliefs, but the point I want to emphasise is that from a scientific point of view *a theory that explains everything explains nothing.* According to Popper, a genuinely scientific theory differs from the one considered above in that it puts itself at risk. For example, Einstein's general theory of relativity led to certain predictions being made which were famously tested and confirmed in 1919. Had the relevant observations not confirmed Einstein's theory, scientists would have rejected it.

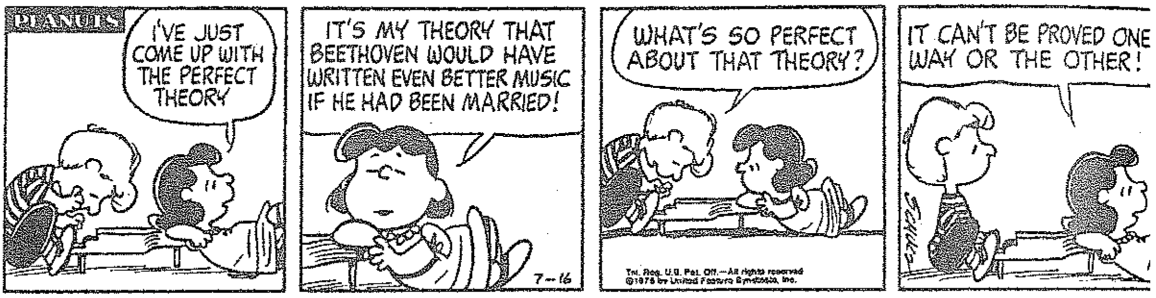


Figure 8.8

Conjectures and refutations

The scientific method advocated by Popper is based on **conjectures and refutations**. A conjecture is basically an imaginative hypothesis and, in his discussion of conjectures, Popper emphasises the fact that there is no mechanical way of coming up with good hypotheses on the basis of the observational data. What is frequently required is a leap of imagination that enables you to look at the data in a different way. This is essentially what Copernicus did when he first put forward the idea that the earth goes round the sun rather than vice versa. As we saw when discussing intuition in Chapter 6, scientists often have their best ideas in a flash of intuition. For example, Newton is said to have come up with the idea of universal gravity when he saw an apple fall from a tree, and Mendeleyev's idea for the periodic table came to him in a dream. However, you are only likely to have such intuitions if you have the right background knowledge and have put in the necessary work. When Newton was asked how he had discovered the law of gravity, he replied 'By thinking on it continually'. And Mendeleyev made a set of cards with the names of the elements written on them, and played around with them endlessly before he finally made his great breakthrough.

The most important thing about genuinely *scientific* conjectures is that they are *testable*. This brings us to the concept of 'refutations' and Popper's attempt to solve the problem of induction. In thinking about this problem, Popper was struck by the asymmetry between confirmation and falsification. Consider again our standard example, 'All metals expand when heated.' We cannot be sure that the law is true no matter how many confirming observations we have made; for it is always possible that the next metal we test will *not* expand when heated. But we only need to find one metal which does *not* expand when heated to be sure that it is *false* that all metals expand when heated. In other words, while confirmation is tentative and