2 What is Science?

The key to the approach is to keep firmly in mind that the classic position of a researcher is not that of one who knows the right answers but of one who is struggling to find out what the right questions might be!

—E.M. Phillips and D.S. Pugh

The purpose of this chapter is to discuss what science is, and what it is not. This is more of a tall order than it first seems, since science spans so many disciplines. Still, if we are going to learn how to develop science, it is important that we at least reflect on what that means.

Scientists at the beginning of their careers are introduced to the methods of science in different ways. Most learn the tools of the trade from experienced researchers but some complement this training with a course in the philosophy of natural science. Philosophy and science are different subject areas, so philosophers tend to see science from a different perspective than scientists do. You could say that they are more interested in the nature of knowledge than in knowledge of nature. Both perspectives are important but it can sometimes be difficult for science students to merge them in a constructive way. This chapter, along with other sections of this book, is an attempt to bridge the gap between some basic ideas in the philosophy of science and everyday scientific praxis.

Since philosophers and scientists approach science differently, I find it necessary to discuss the methods of science from different standpoints. To avoid confusion, therefore, I will try to indicate when I am speaking from the point of view of a philosopher and when from that of a scientist. I will start by introducing and discussing some basic concepts in the philosophy of natural science. It is important to point out that I neither aim to, nor can, give a deeper account of this subject. This is best left to real philosophers; further reading is suggested at the end of the chapter for those who wish to plunge deeper into it. Later in this chapter I will criticize some of these ideas from the more practical standpoint of a scientist. Although the philosophy of science is important for understanding the nature of scientific knowledge it can be perceived to be detached from the diverse reality of research. I hope that this approach will provide a balanced view in the end.

2.1 Characteristics of the Scientific Approach

Imagine that you are driving a rental car in a foreign country. You have never driven the model of car before and, despite the car being brand new, you find that it does not seem to work properly. Sometimes when you turn the ignition key the engine just will not start. Although you are not a specialist you do have a basic understanding of how an engine works and, starting from there, you begin to investigate the problem.
Based on your limited knowledge of engines you make a list of potential causes of the problem. Comparing the symptoms you would expect from these causes with your experience of the problem, you find yourself forced to discard one point after another on the list until there are no potential causes left. The next time the engine fails to start you are faced with the fact that you are completely clueless about what to do. In an act of desperation you decide to walk around the car before turning the ignition key again and, to your immense surprise, the engine now starts without a problem. Encouraged, you begin to experiment with this new method and find that walking in a clockwise direction around the car does not work. After a walk in a counter-clockwise direction, however, the engine always starts perfectly. So, in the course of your systematic investigation of the problem you have made a discovery, and a highly unexpected discovery at that!

Later, when returning the car to the rental car office, you complain about the problem. The woman behind the desk asks you if you remembered to push down the brake pedal when turning the key. She explains that this is a safety feature in some cars with automatic gearboxes. To decrease the risk of the car moving during starting, the brake must be pushed down. Thinking back you realize that you must unconsciously have put your foot on the brake pedal when entering the car after the counter-clockwise walk but not after the clockwise walk. That could explain why your method worked.

This may sound like a contrived example but I assure you that it is a true story from life, once told to me by a friend. (Being an engineer he was not particularly proud of trying to walk counter-clockwise around the car, but he admitted to being desperate when doing it.) We will return to this example later. It is useful here because the two methods presented in it could be said to represent two types of knowledge of a problem. Surely, many of us would agree that walking counter-clockwise around the car seems like a less “scientific” method than pushing on the brake. A possible justification is that the latter method is based on a deeper understanding of how cars work. On the other hand, the former method was discovered through a more or less structured investigation of the problem. Isn’t that how scientists work? At any rate, we have seen that the fact that a method seems unscientific does not necessarily mean that it does not work.

Scientific research is about obtaining new knowledge, but what kind of knowledge becomes science and how is it obtained? In school, many of us have completed tasks that were called research. They generally involved a visit to the school library to collect information on a topic and summarizing this information in writing. Being able to find information is an important skill for researchers, and scientists do spend considerable time studying their literature, but simply collecting information from books is not research. Since the aim is to acquire new knowledge, it requires something beyond moving facts from one place to another, structuring them neatly and referencing the sources.

Science is often connected with measurements. Are measurements the crucial difference between science and non-science? Measurements are made in different parts of society, from laboratories to the fruit market. In applied research fields, academic researchers and development engineers in industry often make the same kind of measurements. How can it be that a Ph.D. student gets a fancy academic title after using a measurement technique for a few years at a university, while a young engineer making the same type of measurements in industry would be lucky to get a pat on the back for a job well done? If we are not to blame this difference on old tradition, and thereby deprive the Ph.D. degree of its value as an academic merit, there must be a central difference between what the engineer and the scientist do. Something beyond the everyday activities (like calibrating instruments, meticulously following procedures to assure good data quality and taking measurements)
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in the laboratory. To begin to cast some light over this difference I am going to borrow the following example from Molander [1]:

The main character of the example, Mr. Green, is a keen gardener who one day decides to count the apples in his garden. He goes about the task systematically and methodically and finds out that there are 1493 apples. This is definitely new knowledge, previously unknown to humanity, but is it science? Most people that I ask agree that it is not, even though they may have difficulties explaining why they think so. Those who have published their results in scientific journals and know how results are scrutinized in peer review processes may say that Mr. Green’s chances of getting his results published are very slim. But why? It is not because Mr. Green does not have the proper scientific training – even with a Ph.D. in plant physiology he would not get these results published. For his results to become scientifically interesting they need to be incorporated into a greater context, a theoretical framework that gives them generality and helps us better understand some aspect of the world. If Mr. Green had counted his apples every year while also recording information about temperature, precipitation and hours of sun per day he could have searched for relationships in the data. That would approach a scientific way of obtaining new knowledge. When we judge scientific quality it also involves appraising the value of the new knowledge. What is it worth to know something about the number of apples in Mr. Green’s garden? Is the garden unique in some sense, for example regarding microclimate, soil, or the type of apples grown there?

Collecting data is an important aspect of research, but it is also important in technical development, politics and other activities that are not considered to be science. There is a wealth of things that we do not yet know and that we could find out, like the oxygen content of the water in a particular bay, or the number of flowers in a particular field. Finding these things out requires planning, meticulous data collection and possibly statistical analysis to provide an unbiased picture of reality. Still, when finding them out we are only describing what we see, we are answering “what” questions. Science goes beyond pure description. It aspires to explain what happens in the world and to predict what will happen under certain circumstances. In other words, it aspires to answer what Phillips and Pugh [2] call “why” questions. Why is the oxygen level low in the bay? Why are there fewer flowers in the field some years? Answering such questions requires something more than careful collection of information. It requires a scientific approach. If you are an engineer working towards a strict deadline in a product development project, or a politician dealing with a problem that suddenly attracts media attention, your need to act can often be more pressing than your need to understand. For the scientist it is always the other way around. In research, trying to find a solution before you understand the nature of the problem is a bit like tying your shoelaces before you put your shoes on.

This means that there are two central and intimately interconnected aspects of science: one that has to do with investigating the world and one that is about interpreting what we see. By investigation we hope to acquire hard facts about reality, and we hope to obtain understanding by interpreting these facts. Interpretation is done within a theoretical framework that allows us to explain the facts. Philosophy books about scientific method often use the words observation and theory instead of investigation and interpretation. Observation sounds more passive than investigation and certainly has a narrower meaning. This is perhaps significant of the fact that such books often focus on how theories are developed. Both aspects are, however, two sides of a coin.

The next few sections are about two basic approaches to research that are described in the philosophy of science. They are written from a philosophical point of view. Even when
I criticize the ideas I speak with the voice of a philosopher. In the remaining parts of this chapter I will again take a scientist’s point of view by being a little bit more practically oriented, recognizing the fundamental role of observation in science. I hope to show that the philosophical concepts are useful for understanding the nature of scientific knowledge, although they do not cover all aspects of practical research. We can learn important things from these ideas but should not be too worried if some research does not fit perfectly into their framework.

2.2 The Inductive Method

It is a popular notion that scientists begin by collecting facts through organized observation and then, somehow, derive theories from them. In logic, going from a large set of specific observations to a general, theoretical conclusion in this manner is called *induction* and the approach is, therefore, often called the inductive method. Logic is a branch of philosophy that dates back to Aristotle. It deals with how arguments are made and how to determine if they are true or false. This brief description of the inductive approach follows closely to Chalmers [3], whose book is one of the most widely read introductory books about the philosophy of science. It is useful to describe his rather extreme form of “naive inductivism” in order to highlight some characteristics of the approach, especially those that are generally considered to be its weaknesses.

The inductivist version of science begins with observations, carefully recorded in the form of observation statements. These are always singular statements, meaning that they refer to something that was observed at a particular place and time and in a particular situation. For example, an astronomer might state that the planet Mars was observed at a certain position in the sky at a certain time. The rental car customer from the beginning of this chapter might state that, on a particular day, the engine started only after walking counter-clockwise around the car. To be able to explain some aspect of the world researchers must make generalizations from such singular statements to obtain universal ones, for example that all planets move in elliptic orbits around the sun, or that cars with automatic transmissions require the brake pedal to be pushed down in order to start. The inductivist maintains that it is legitimate to make generalizations from singular observations granted a few conditions are met. Firstly, the number of observations must be large. Secondly, they must be made under a wide variety of conditions. Finally, no observation can be in conflict with the conclusion drawn.

As mentioned above, inductive reasoning moves from a set of specific observations to a general conclusion. You may, for example, note that you become wet when you jump into the water. From a large set of such observations, made under varying conditions, you may infer the general conclusion that water always makes you wet. Going the opposite way, from general statements to specific conclusions, is called *deduction*. Consider the following example of deductive logic:

**Premise 1:** All scientists are mad.
**Premise 2:** I am a scientist.
**Conclusion:** I am mad.

Here, the conclusion is a necessary logical consequence of the two premises. Premise 1 may be held to be a general law, derived from a large set of observations by induction. The problem is that the truth of the conclusion depends on the premises being true, which they
The Inductive Method

induction

Expectations and circumstances, so whereas people that case? Is it necessary to vary the ambient pressure, or the purity of the water?

Determination of boiling sufficient observation on different weekdays and under varying weather conditions but not what they can false inference to conclude, “I am always fed at 9 to his list. Finally, his inductivist conscience was satisfied and he carried out an cold days, on rainy days and dry days. Each number good inductivist, he did not jump to conclusions. He waited until he had collected a number

So, the inductivist’s first condition is problematic: however large the number observations they can never ensure the truth of the conclusion. Let’s look at the next condition and ask what counts as significant variation in circumstances. The turkey in the example made his observations on different weekdays and under varying weather conditions but not under sufficient variation of holiday seasons to find out what happens to turkeys on Christmas Eve. Determining the boiling point of water is perhaps an example more relevant to science. What should be changed to fulfill the criterion of sufficiently varying circumstances in that case? Is it necessary to vary the ambient pressure, or the purity of the water? Should we try different methods of heating, or different weekdays for the measurements? Most people would agree that the first two variables, pressure and purity, are sensible candidates, whereas the latter two make less sense. The point is that there are infinite ways to vary the circumstances, so how do we know which ones to choose? Well, we probably have some expectations of what will affect the boiling point of water and these expectations are based on some level of theoretical knowledge about the world. Theory could thereby be claimed to play a role prior to observation. In that case the inductivist assumption that science starts with observation does not hold true.

Figure 2.1
Induction moves from a set of specific observations to a general conclusion. Deduction moves from general statements to a set of expected, specific observations.
In addition to this, the observation statements we make to describe our observations
could be said to rely on theory. Statements are always made in some language that contains
definitions and they are thereby theoretically colored. As Chalmers puts it, even a simple
statement such as “the gas will not light” is based on a theory that divides substances
into classes, of which gases is one. It also presupposes that some gases are combustible.
These theoretical notions have not always been available. In modern science the theoretical
concepts are less commonplace and the observation statements may be more obviously
theory-colored. Critics of the inductivist approach argue that observation statements are no
more precise than the theory they rely on. If the theory turns out to be false, they say, the
observation statements will no longer be valid.

We could summarize the criticism raised against the inductive method so far in two
points. Firstly, observation is not a secure basis for knowledge. This is because induction
in itself cannot be logically justified. We may make as many observations of something as
we like, we still cannot use them to prove the truth of our conclusion. There is always the
possibility that one day we will make an observation that contradicts the conclusion, as our
inductivist turkey did on Christmas Eve. Secondly, it has been argued that observations and
observation statements involve theory and, therefore, are just as fallible as theories are.

Besides these points there is another important weakness of a purely inductive approach
that has to do with the type of knowledge that it produces. The problem is how singular
observation statements can be generalized into theories that are scientifically useful. Science
aims to explain and predict. Theories without explanatory power are thereby of limited use
in science. If we note that we become wet every time we jump in the water we may infer that
water makes people wet, but we cannot obtain theories about the underlying properties of
water and people that explain why we get wet. The astronomer who observes the position of
the planet Mars in the sky is perhaps a more illuminating example – how does the inductivist
generalize from such observations to obtain Kepler’s first law, that planets move in elliptic
orbits with the sun as a focus? At the beginning of this chapter I said that the two solutions
to the problem with the rental car represented different types of knowledge. The customer
knew that walking around the car worked, at least if it was done in the counter-clockwise
direction, but was not able to explain why. This is the type of knowledge that an inductive
approach can provide us with. The woman at the rental car office knew that pushing down
the brake pedal worked but she could also explain that this was a result of a certain safety
feature of the particular car model. Can you think of any way to obtain this knowledge by
a purely inductive approach?

Humankind has long noticed that there are regularities in Nature. Things tend to happen
in certain ways and not in others, as if they were guided by machinery hidden from our
eyes. The ultimate aim of science is to explain, rather than just describe, what happens in
the world. As researchers we must therefore aspire to understand something of that hidden
machinery. Since it is hidden from our eyes this task requires a more imaginative approach
than just watching what goes on in the world and making notes of it.

2.3 The Hypothetico-Deductive Method

When the young Isaac Newton was toying with prisms in 1666 he noticed that they dispersed
a white beam of sunlight into all the colors of the rainbow. If the colored light from a part
of this rainbow was passed through a second prism it did not result in a new rainbow, only
in further dispersion of the colored beam. The experiment is described schematically in
Figure 2.2
Schematic representation of Newton’s experimentum crucis. The second prism does not produce rainbow colors, as the first one does. Newton concluded that prisms do not add color to white light, but the colors are constituents of white light.

Figure 2.2. Newton concluded that the prism did not add the rainbow colors to the light. Maybe the white light of a sunbeam already contained all the colors and all the prism did was to spread them out over the wall opposite his window? As a consequence, he thought, re-combining the colors should produce white light [4]. He set up an experiment to do just this and, as most readers are probably aware, his thought was confirmed.

This is an example of working out the consequence of an hypothesis by logical deduction and testing it by an experiment (although Newton himself would not agree that this is the full story of what he did [4]). An hypothesis can be seen as a preliminary attempt to explain something – a theoretical statement without much observational support. We shall now discuss a method based on this procedure, where scientific inquiry begins with theory instead of observation. According to it, a scientist faced with a seemingly inexplicable phenomenon should begin by proposing speculative theories, or hypotheses, about its cause. These can then be tested rigorously against observation, for example by controlled experiments, to see if the consequences that follow from them correspond with reality. Working out consequences from premises is called deduction, speculative theories are called hypotheses and, accordingly, the method is called hypothetico-deductive. My description of the method closely follows how Chalmers describes falsificationism [3], which is a variant of the method proposed by Karl Popper. Most working scientists seem to apply some of the method’s central elements, not least since they often discuss hypotheses and generally agree that hypotheses must be testable in order to be scientifically useful. In the words of Popper, hypotheses must be falsifiable.

If an hypothesis is formulated in a way that makes it theoretically impossible to disprove, it is not falsifiable. For example, a recruitment firm that throws half of the applications for a job into the wastebasket with the motivation “we don’t want to recruit unlucky people” bases its decision on a non-falsifiable hypothesis. It is non-falsifiable because people whose applications end up in the wastebasket are, by definition, unlucky. Why would their applications otherwise be thrown away? It is a bit like saying that all sides of an equilateral triangle have equal length. If they did not it would not be an equilateral triangle – the statement is logically impossible to contradict. Non-falsifiable hypotheses are statements that are true whatever properties the world may have. Such hypotheses tell us nothing about the world and are, therefore, of no use in science.

According to the hypothetico-deductivist, research begins with an hypothesis and proceeds by testing it against observation. If our observations contradict the hypothesis we discard it and look for a new one. If the hypothesis is supported by our observations we
keep it, but continue testing it under various conditions. The following classical example from Hempel [5] gives a flavor of how it could work.

**Example 2.1: Semmelweis and the solution to childbed fever** Ignaz Semmelweis was a Hungarian physician who worked at Vienna General Hospital in the mid-1800s. He noted that a relatively large portion of the women who delivered their babies at the first maternity division contracted a serious disease called childbed fever. About 7–11% died from it. The second maternity division at the same hospital accommodated about as many women as the first, but only 2–3% of them died from childbed fever. The theory that diseases are caused by microorganisms would not be widely accepted until the late 1800s, so Semmelweis considered various other explanations. He quickly dismissed some of them as they were contradicted by what he already knew. One of these was the then common idea that diseases were caused by “epidemic influences”, attributed to “atmospheric-cosmic-telluric changes”, affecting whole districts. If this were so, how could the first division be plagued by the disease while the second was relatively spared? He also noted that women who gave birth in the street had a much lower risk of contracting childbed fever, although they were later admitted to the first division. These were often women who lived far from the hospital and were not able to arrive in time after going into labor. A street birth just outside the hospital should not decrease the risk for epidemic influences.

Could the problem be due to overcrowding? Semmelweis saw that it was not. The second division tended to be more crowded, partly because the patients desperately wanted to avoid the notorious first division. Instead, he turned to psychological factors: The priest, bearing the last sacrament to dying women, had to pass five wards to reach the sick-room of the first division. He was accompanied by an assistant ringing a bell. Presumably, this display would be terrifying to the other patients. Fear could explain the fever, because in the second division the priest could access the sick-room directly, without passing other patients. To test his idea Semmelweis persuaded the priest to take a roundabout route and enter the sick-room unobserved and silently, without ringing the bell. Unfortunately, this had no effect on the mortality in the first division.

Semmelweis also noticed another difference. In the first division the women were delivered lying on their backs, while in the second division they lay on their sides during birth. He decided to try the lateral position in the first division but, again, without result.

In 1847 he got a decisive clue to the solution. During an autopsy, a colleague of his received a puncture wound in the finger from a scalpel. Later, the colleague showed the same symptoms as the women that had contracted childbed fever and, eventually, he died. As previously mentioned, the role of microorganisms was not yet recognized but Semmelweis started to suspect that some kind of “cadavic matter” caused the disease. In that case, the physicians and their students would carry infectious material to the wards directly from dissections in the autopsy room. The difference in mortality between the divisions could then be explained by the patients in the second division being attended by to midwives, whose training did not include dissections. To test his hypothesis he required all medical students to wash their hands in a solution of chlorinated lime, which he assumed would destroy the infectious material chemically, before examining the patients. As a result, in 1848 the mortality in childbed fever decreased to 1.27% in the first division. This was fully comparable with the 1.33% in the second division that year. The hypothesis was further supported by the lower mortality among women giving street birth: mothers who arrived with babies in their arms were rarely examined after admission and, thereby, escaped infection.
Consequences of Falsification

We see how Semmelweis proceeded by first trying to understand the cause of the disease and then comparing his ideas to the information at hand, or to information obtained by specific experiments. Unsuccessful ideas were discarded and new ones proposed until the problem was solved. We may also note that, although his idea about “cadavic matter” improved the understanding of the disease, it was still far from the more modern, microbiological theory. Although it may be tempting for modern readers to exchange the term with “bacteria”, Semmelweis did not understand that living organisms caused the disease. It is again clear that observational support does not prove an hypothesis to be true. The hypothetico-deductivist must abandon the claim that theories can be proved by observation, at least in a strictly logical sense. Still, hypotheses that resist falsification in a wide variety of tests tend to become established theories with time, as the support for them grows ever stronger. Even though they are not proven true, we may still acknowledge that they are the best theories available, since they are supported by the most evidence.

Finally, hypotheses should not only be falsifiable, they should even be as falsifiable as possible. It is difficult to contradict a vague statement. For science to progress there cannot be any doubt whether an observation supports an hypothesis or not. A good hypothesis is falsifiable just because it makes precise assertions about the world. It becomes more falsifiable the more wide-ranging the claims it makes, since the number of observations that could potentially contradict it increases. For instance, Newton’s theory for the movement of the planets around the sun is more falsifiable than Kepler’s older theory. Newton’s theory consists of his three laws of motion and the law of gravity, stating that all pairs of objects in the universe attract each other with a force that varies inversely with the square of their separation. Whereas Kepler’s laws of planetary motion only apply to the planets, Newton’s theory is more general: it describes planetary motion as well as a large number of phenomena, including falling bodies, the motion of pendulums, and the relationship of the tides to the positions of the sun and moon. This means that there are more opportunities to make observations that contradict Newton’s theory. In other words, the set of potential falsifiers of Kepler’s theory is a subset of the potential falsifiers of Newton’s theory, which then becomes more falsifiable.

2.4 Consequences of Falsification

When the scientific knowledge grows within a field, the theories of that field are sometimes affected. New insights are not always compatible with current theory. There are, in principle, three possible scenarios in such cases. The theory may be modified to explain more aspects of the world, it may be completely replaced, or, sometimes, it is not affected at all. We will continue to use the laws of planetary motion as examples to illustrate these scenarios.

Today, few physics undergraduates learn about Ptolemy’s theory for planetary motion. This is because it has been proven wrong and has been successively replaced with better theories. Ptolemy lived in the second century of the Common Era (CE) and his theory was based on Aristotle’s cosmology, stating that the earth was situated at the center of the universe with the sun and planets revolving around it. The planets moved in perfect circles with uniform motion, since nothing in heaven could deviate from perfection.

Readers who have studied the motions of the planets in the night sky may have noticed a curious effect called retrograde motion. Looking night after night at the planet Mars, for example, it seems to move westward relative to the backdrop of the stars. At some pointit
suddenly makes a halt and starts to move backwards. Later, the backwards motion ceases and the planet continues in the westward direction. This motion makes perfect sense in a heliocentric system, where the earth revolves with the other planets around the sun. From our point of view it looks as if Mars moves backwards, because the earth “overtakes” it in its inner orbit. In the Ptolemaic system this motion was, of course, more difficult to explain. Ptolemy attempted to do so by letting the planets move in smaller circular orbits, called epicycles. These, in turn, revolved in larger, circular orbits around the earth. This solved the problem at the cost of immense complexity. Instead of one circular orbit for each planet the Ptolemaic universe consisted of several dozens of cycles and epicycles rotating upon and about each other. There were equants, eccentrics, deferents, but still this system could only approximately match the observations. By the sixteenth century the calendar and the seasons diverged by weeks, and predictions of eclipses and conjunctions could miss their mark by a month [6]. In the hypothetico-deductive account of science the Ptolemaic system had been falsified since the observations did not match its predictions.

Copernicus realized that a heliocentric system was a more accurate model of the universe. He placed the planets and the earth in orbit around the sun and the moon in orbit around the earth, but held on to the assumption of circular orbits. His system was both more accurate and mathematically simpler than the Ptolemaic one, though it still made use of epicycles to better match astronomical observations. Although modern astronomers do not accept the details of the Copernican system, the heliocentric theory of the solar system has certainly replaced the geocentric one. This is an example of how a theory that fails to describe reality may eventually be replaced.

In the hypothetico-deductive approach, a falsified theory should be discarded and replaced with a new and better theory. The new theory should account for more phenomena than old theory did. Besides explaining the phenomena that falsified the old theory, it should also account for everything that the old theory explained. Then, how can it be that some theories survive falsification? Consider, for instance, Newton’s laws of motion. At the beginning of the last century physicists found that these laws, which had been believed to be universal laws of motion, did not apply to the motion of the tiny constituents of atoms. On the scale of the very small, the established theories describing our everyday world broke down completely. This became the starting point of a new theory called quantum mechanics, developed to describe the microscopic world of atoms and elementary particles. Newton’s theory had been falsified since it had been shown not to be as general as previously believed. An area had been found in which it did not apply, but should it be discarded?

Completely replacing an established theory is a formidable task. At the beginning of the twentieth century Newton’s theory had been supported by a plethora of various observational tests for more than two centuries. It had predicted new phenomena and had even been used to predict the existence of the previously unknown planet Neptune. With such merits it would be preposterous to suggest that the theory was completely false. It had obviously been brought to its limit when it was confronted with the mysteries of the quantum world, but it still applied to the macroscopic world.

The new theory of quantum mechanics is indeed more falsifiable, since it includes Newton’s mechanics as a special case, and this is an important aspect of the growth of science. But although quantum mechanics may be a more general theory, there is no doubt that Newtonian mechanics are still used extensively by scientists and engineers to solve problems on the macroscopic scale. It is an example of a theory that has been falsified without being replaced. It is still valid and useful but we are more conscious of its limitations.
As previously mentioned, there is another alternative to replacing a whole theory that is in trouble. A smaller modification might save it from being falsified. Newton’s laws have previously been described as an improvement over Kepler’s laws. These, in turn, were an improvement on Copernicus’ heliocentric theory. Johannes Kepler had access to the best astronomical data available before the invention of the telescope and struggled to find a mathematical representation that fitted with them. After years of calculations he overthrew the last two fundamental assumptions of the Aristotelian cosmology – that planets move in circles and that the motion is uniform. His system can be described as an addition to the heliocentric theory. The planets were ordered around the sun as in the Copernican system but they moved in elliptic orbits with the sun in one focus and they moved faster when they were closer to the sun. Since this addition removed the discrepancy between the data and the heliocentric theory, the theory was saved from falsification. Most readers will probably agree that his addition was a legitimate one but the following example illustrates that not all modifications of theories are.

A central assumption in Aristotle’s cosmology was that nothing in the heavens could deviate from perfection. As a result, it was long believed that all celestial objects were perfect spheres. When Galileo Galilei pointed his telescope towards the moon in 1609 he was intrigued to find that it was far from a perfect sphere. It was scattered with mountains, some of which he estimated were more than 6000 meters high [7]. One of his Aristotelian adversaries agreed that it looked that way in the telescope but cunningly suggested that there was an invisible substance filling the valleys and covering the mountains in such a way that the moon was still a perfect sphere. When Galileo asked how this invisible substance could be detected, the answer was that it couldn’t. The only purpose of this additional theory was to save the original one. It was an ad hoc modification. The moon was still spherical, it just did not look that way. Any modification of a theory must of course be testable. It must also be testable independently of the theory that is saved from falsification. Galileo went right to the core of this problem in his brilliant response to his adversary. He agreed that there was an invisible and undetectable substance on the moon but instead of filling out the valleys he suggested that it was piled on top of the mountains, so that the surface was even less smooth than it appeared in his telescope [3].

2.5 The Role of Confirmation

From now on I am going to switch perspectives. So far I have described science from the point of view of philosophy, which is an outside perspective. Researchers, who apply the scientific method every day, tend to look at it differently. Many scientists think that the hypothetico-deductive method, and falsificationism in particular, gets a negative taint by stating that science progresses by disproving theories. With a little bit of travesty, falsificationists would remain unmoved if their observations were to support their hypotheses. Instead of cheering at the confirmation of their ideas they would begin to think about new ways to kill them. This is counter-intuitive to most working scientists. People are seldom awarded Nobel prizes for having disproved a theory but rather for discovering and explaining new phenomena. In all fairness, confirmation does play a role in the hypothetico-deductive approach [3]. If a bold hypothesis is confirmed it corresponds to the discovery of something unlikely. Similarly, if a cautious hypothesis is falsified it means that something that seems self-evident is, in fact, incorrect. Both of these scenarios represent significant advances in science. Conversely, little is learnt from the falsification of a bold
theory (something unlikely is false) or confirmation of a cautious theory (something likely is true). For the hypothetico-deductivist, confirmation is important so long as it is of novel predictions resulting from bold hypotheses [3].

Problems do arise with the hypothetico-deductive method when we realize that observations that are contrary to a theory do not necessarily render it false. This was arguably the case with Newton’s mechanics. I think that the following (imaginary) example shows that scientists do not necessarily think like falsificationists. Imagine that we discover that a certain type of mold kills bacteria. We may then hypothesize that it can be used as an antidote to bacterial infection. To test the hypothesis we set up a program of double blind tests on a group and a control group of patients. The results of the study turn out to be encouraging and, after follow-up studies, we start using the drug and successfully treat patients on a large scale. We may now ask ourselves if we have proven our hypothesis. The falsificationist would firmly say no; it is not logically possible to prove an hypothesis by observation. But many scientists would consider the statement of the hypothesis to be true, at least until proven otherwise. Most scientists are more pragmatic than many philosophers of science and tend to consider theories to be “innocent until proven guilty”.

Now, to add some excitement to this research program, suppose that some bacteria develop a resistance to the drug. As a result, some patients do not recover when treated with it. Does this new state of affairs disprove the theory? The falsificationist would probably vote yes, although I think it is evident from the example that it is difficult to make a clear-cut decision. Large-scale treatment of patients with a new drug changes the environment in which the bacteria live. This exerts an evolutionary pressure on the bacteria to adapt to the new situation. If a mutation in a bacterium improves its ability to survive in the new environment, its genes will gradually become more common in the gene pool and a resistant strain will develop. The state of Nature has thus changed after the study was made. Figure 2.3 illustrates these events and how a falsificationist would react to them.

As scientists, we may prefer to make an addition to our theory instead of discarding it altogether. We may say that the drug works as an antidote to bacterial infection, except when the bacteria have developed resistance to the drug. Does it sound like an ad hoc modification? Well, if we can think of a way to identify the resistant bacteria without using the drug the modification is independently testable. Otherwise it is not. So, if the addition is to be considered to be ad hoc or not depends on if we have enough knowledge to test it independently of the original theory. If that knowledge is not in place, the falsificationist would want us to discard the theory. In reality, scientists would probably know better than that. After all, the drug used to be completely effective. The fact that it has become less effective will certainly inspire us to look deeper into the problem but not to discard a theory that has been confirmed in rigorous tests. The trustworthiness of theories is not quite so black and white as the falsificationist describes it to be. There is often a gradual transition from the suspicion that there is a problem to the realization that the theory no longer fills its purpose; practically minded people will probably realize when it is time to abandon the theory without consulting the philosophy books.

I ended the section about inductivism by saying that scientists must strive to understand the hidden machinery of Nature to be able to explain, rather than just describe, what they see. Since the hypothetico-deductive method begins by formulating hypotheses, the striving to understand this machinery is built into the method. As opposed to pure inductivism, it has the ability to produce theories with explanatory power. Although the example above illustrates some of the risks of following it too slavishly, the basic principle of the hypothetico-deductive method is highly useful. This is why the remaining parts of this book tend to
An imaginary example of testing an hypothesis. In the first trials the drug kills the bacteria and the patients are cured. The hypothesis is kept and subjected to further tests. At a later time, a resistant strain has developed. The drug is suddenly less effective and the hypothesis should be discarded. But has it been disproved?

favor it over the inductive method. Before we discard inductivism completely, however, let us discuss if the criticism against it really holds together from a scientist’s perspective.

### 2.6 Perception is Personal

According to the inductive method, scientists seek – and find – the truth without being guided by personal opinions or preferences. Inductive science begins with objective observation. The resulting theories always enter the picture at a later stage.

One of the criticisms against this method that we have mentioned is that theories cannot be proved on the basis of observations. This problem remains unresolved in the hypothetico-deductive method. If we define truth in strictly logical terms, we have to live with a certain degree of uncertainty about the truth of our theories, regardless of which method we use. To prove something logically, we need access to all the facts relevant to our problem. This is possible, for example, in mathematics, where theories are derived from axioms laid down by people. Axioms can be said to define the researcher’s private universe, because if we make the rules ourselves we have access to a complete set of facts. In the natural sciences, Mother Nature makes the rules and the researcher’s job is to find them. For this reason,
empirical scientists must play down the role of logical proofs and find ways to compensate for the naturally incomplete information they have to work with – and they have to do this whatever scientific approach they use. One way is to search for many independent types of support for a theory. Although we may not have information sufficient for valid logical proofs, the collected support for a theory may be convincing enough to reduce our doubts in it to a mere minimum. Electromagnetic field theory, for example, has been supported by countless experiments and observations since it was developed in the 1800s and has been employed in widespread technical applications like mobile phones and radar. You would need very compelling reasons to doubt that it is a valid theory.

Another criticism is raised against the inductivist claim that science is based on objective observations. According to the critics, observations cannot be objective as they are colored by theory. This non-objectivity is less problematic in the hypothetico-deductive approach, as it is based on investigating one hypothesis at a time. When testing an hypothesis it is of course natural to be temporarily biased towards one idea. But if we understand the talk of theory-dependent observations as meaning “observations can never be trusted as a source of information”, then science in general is in trouble. Without empirical data there can be no empirical science. The theory-dependence of observation is a main theme in many books about scientific method. Chalmers uses a whole chapter to discuss why it means that the inductive method must be rejected [3]. It is worthwhile to use a little space here to discuss this aspect of observation from a practical point of view. Firstly, I would like to discuss what a sensible definition of objectivity might be. Thereafter, I would like to ask in what sense all observations are theory-dependent.

Imagine that you are a detective arriving at the scene of a murder. A lifeless body lies on the floor of a Victorian library and you have been called there to investigate the crime. Where do you start looking? Presumably, you do not start by investigating the wood paneling on the walls to see if it is made from oak or teak. Nor do you try to determine the optical quality of the glass in the crystal chandelier. No, you probably start by looking at the body. How is it positioned? Are there any indications of violence? It is likely that you continue with particular aspects of the rest of the scene. Did the murderer leave any traces? Is something missing that could provide a clue about the motive? There is an immense wealth of facts that could be observed in the library and to solve the case you obviously have to choose what to observe. Strictly speaking, this means that you are not objective. Still, most people would not accuse you of being biased if you conducted your investigation this way, because they think that objectivity has to do with having an open mind and not jumping to conclusions before looking at the relevant facts. This is the common sense definition of objectivity. Figure 2.4 illustrates how it differs from the strict definition.

Since our knowledge is incomplete (otherwise we would not need to investigate the murder) it is difficult to determine beforehand which facts are the most relevant, but the examples above show that many facts can be discarded as irrelevant at an early stage. If later findings should suggest that the murderer was looking for diamonds and that these may have been hidden among the crystals of the chandelier, a closer look at the chandelier will be justified. But before we know anything about the motive it would be foolish to pay the chandelier special attention. If objectivity means giving the same weight to every single fact, an objective investigation is probably impossible and, at any rate, it could never solve the case. This strict definition of objectivity is impractical. Regardless of if we are solving a scientific problem or if we are making a cheese sandwich we must prioritize between observations, concentrate on the important ones and disregard the unimportant ones. It is
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Figure 2.4
The observer on the left is strictly objective and pays equal attention to all facts. The observer on the right selectively pays attention to facts relevant to the problem. The larger the number of facts, the less successful the left observer is at solving the problem.

not sensible to say that an observer who does not pay equal attention to all facts is not objective.

Before we leave our detective to go about his/her investigation at the scene of this hideous crime we may stop and ask how he/she knows what to observe and what to ignore. He/she probably has an idea about how murders happen and how such events leave traces on a crime scene. This knowledge comes from a mixture of training, experience and common sense. We can think of such knowledge as a filter placed between the facts of the scene and the mind of the investigator. It filters out irrelevant information and transmits the aspects that should be prioritized. A good filter clearly distinguishes between the relevant and irrelevant facts, while a poor one is less reliable. The quality of the filter could be called the investigator’s power of observation and it can be improved with training, experience and reflection. This means that not all observers observe the same things. Even a single observer may observe different things on different occasions if the filter should change over time. Acknowledging that observation is a skill does not necessarily imply that skilled observers are less objective than others – at least not if we use the common sense definition of objectivity. It could simply mean that skilled observers are more efficient at getting an objective view of the problem under study. We should not empty our heads of all knowledge every time we try to solve a problem. At least not if we want to solve it.

Let’s turn to the other question. In what sense are all observations theory-dependent? What observers see depends on their knowledge, skill and personality. Perception, in other words, is personal. Chalmers uses several examples to underline this [3]. One of them is how a student and an expert radiologist perceive X-ray images. Where the student may only see shadows of the heart and ribs, with a few spidery blotches between them, the expert sees a wealth of significant features. With training, the student may gradually forget about the ribs and begin to see the lungs as well as a rich panorama of details on them. Another example from Chalmers is an amusing entry from Johannes Kepler’s notebook, made after observation through a Galilean telescope. It reads, “Mars is square and intensely coloured”. This statement can be said to have relied on the theory that the telescope gave a true picture of reality, which it clearly did not. Chalmers proceeds to say that this means that “observation statements do not constitute a firm basis on which scientific knowledge can be founded, because they are fallible”.

The point I wish to make is that the fact that observations, and observation statements, are fallible does not undermine their role as fundamental information carriers in science. I
think Chalmers would agree with this but I still want to make the point because it is easy to be overwhelmed by the alleged problems with observation when reading statements like this. It is worth mentioning again that if observations could not be trusted there could be no science. We know from a vast body of experience that science is, in fact, a highly successful endeavor. Of course, observers can make mistakes when observing or when explaining what they see, just as philosophers can make mistakes while thinking or expressing their thoughts. That does not undermine the fundamental role of thoughts in philosophy. When discussing the theory-dependence of observation it is easy to indulge in pessimistic statements about how unreliable observations are and forget that the proof of the pudding is, in fact, in the eating. If faulty observations lead to a theory that is incorrect, this will not go unnoticed. Observations must be repeated and elaborated independently by several researchers to have an impact. Scientists do not necessarily make fewer mistakes than other people, neither are they less prone to be led astray by their pet ideas, but the methods of science have elements built into them that make it more difficult for scientists to fool themselves. For observations to have scientific impact we demand a high degree of inter-observer correlation. This means that many observers must be able to see the same thing and that it must be possible for other researchers to successfully repeat our experiments. Before publication, scientific results are examined and criticized by other researchers in anonymous peer review processes. These systems are in place because we are aware of the risk of mistakes, and to increase the degree of objectivity in the results.

To say that all observations are theory-dependent is, in practice, misleading. Some observations are indeed heavily theory-dependent, while others are not. For instance, if our detective remarks that the victim lies face-down on the floor, this statement does not presuppose any theoretical knowledge at all. Stating that the victim was beaten with a blunt instrument only presupposes that such instruments leave other types of traces on a body than sharp ones. To call this knowledge a theory empties the word of any meaning relevant in science. If, on the other hand, scientists say that they have been observing a single electron oscillating in the electric field of a laser beam, this observation statement clearly relies on involved, high-level theory. If this theory turns out to be false it could render the observation statement invalid but, as we soon shall see, this is not necessarily so.

For those who think that observation statements are always interpretations in the light of theories, Hacking provides ample examples of the opposite [8]. I am going to mention a few of them briefly here. One of them is the discovery of double refraction in Iceland Spar (calcite) by Erasmus Bartholin in 1689. If you put a piece of this material over a printed page you see the text double. Iceland Spar was the first known producer of polarized light. This phenomenon had to wait well over a century for Fresnel’s theoretical explanation, so it is clear that the discovery did not rely on theory. Another optical phenomenon that was discovered long before any theoretical explanation is diffraction. Grimaldi, and later Hooke, discovered that there was illumination in the shadow of an opaque body. Careful observation revealed regularly spaced bands at the edge of the shadow, which come from diffraction. These are examples of phenomena discovered by alert observers. What about deliberate experiments then, do not they always involve theoretical assumptions? If we return for a second to the frustrated rental car customer from the beginning of this chapter, we may recall that walking counter-clockwise around the car clearly was an experiment without theoretical motivation. Similar examples are not uncommon in science. One of Hacking’s examples is David Brewster, who experimentally determined the laws of reflection and refraction of polarized light, and also managed to induce birefringence (polarizing properties) in materials under stress. These things were later theoretically explained within Fresnel’s
wave theory but Brewster himself was advocating the Newtonian view that light consisted of rays of corpuscles. As Hacking puts it, “Brewster was not testing or comparing theories at all. He was trying to find out how light behaves.” This summarizes the important point that our understanding of Nature’s machinery often begins with the discovery of an interesting phenomenon, and not necessarily with theoretical considerations. I could go on quoting Hacking, whose book is full of convincing examples like these. To establish that there are plenty of examples also outside it, and thereby strengthen the point, I would like to add a couple of examples of my own choosing. I will first briefly mention Gregor Mendel, who is known to many as a brilliant experimental biologist. The experiments leading to his discovery of the laws of inheritance are described in a separate example in Chapter 6. Here, I will restrict myself to pointing out that this discovery had to wait half a century to be acknowledged by the scientific community, because there was no theory available that gave them meaning. My other example comes from the history of chemistry. In this connection I cannot resist referring back to the observation statement “the gas will not light”, used in the section on inductivism to exemplify a theoretically colored statement. The following example involves similar statements but made in a scientifically more relevant context.

Example 2.2: Joseph Priestley and the discovery of oxygen Before Antoine Lavoisier introduced the oxygen theory, the phlogiston theory was the prevailing theory of combustion. Phlogiston was believed to be a material that escaped from substances during combustion. It can be thought of as a slightly modernized version of Aristotle’s fire element, with the difference that its existence had found some support in experiments. Besides combustion, phlogiston was also believed to be involved in calcination of metals. When metals were heated in air they were believed to change because they lost phlogiston. The resulting calxes (oxides) changed back into metals when heated with charcoal, as they regained phlogiston from it. Since the charcoal only left a small amount of ash after the process it was presumed to be rich in phlogiston. Furthermore, combustion could not be sustained in vacuum since air was needed to absorb phlogiston. Correspondingly, combustion in a sealed container ceased when the air inside it was saturated with phlogiston. The theory thus explained a range of phenomena, but it had a weak point: metal oxides lose weight when they are reduced to metals. How could that be the case when they gained phlogiston? [8]

The gas formed when reducing calxes with charcoal was called fixed air. We know it as carbon dioxide. It had been found that fixed air was produced also during fermentation and respiration and it was known not to support life. In August 1774 the English chemist Joseph Priestley collected a gas that had been formed when heating Mercurius Calcinitus (mercury oxide) without charcoal. His investigations showed that the gas had properties opposite to those of fixed air: “what surprised me more than I can well express, was that a candle burned in this air with a remarkably vigorous flame” [9]. Later, he noticed that a mouse survived twice as long in the gas as in ordinary air. Encouraged by this result he decided to breathe the gas himself: “I fancied that my breast felt peculiarly light and easy for some time afterwards. Who can tell that but in time, this pure air may become a fashionable article in luxury. Hitherto only two mice and myself have had the privilege of breathing it” [9]. He was breathing pure oxygen but he called it dephlogisticated air because, in the phlogiston system, a gas was thought to promote combustion if it was deficient in phlogiston. This gave the phlogiston in the burning material somewhere to go [9].

Antoine Lavoisier, who made more quantitative studies, later discarded the phlogiston theory. He realized that the gas that Priestley had collected was not a variety of air, but a
There are many examples of scientists who have said that they work from observations to build theories. Charles Darwin, the father of modern biology and one of the most astute intellects in the history of natural science, described himself as “a kind of machine for grinding theories out of huge assemblages of facts” [11]. This sounds like a rather inductivist approach, even though it is probably not a complete description of his way of working. The point is that theories do not pop up from nowhere. They are developed because there is a phenomenon that needs explanation, and the phenomenon must be discovered before a theory can be considered. Once Darwin’s great idea had been born, he developed it by testing it against facts collected by him and the many people he corresponded with. His approach probably contained elements from both the inductive and hypothetico-deductive method, and he was not alone in this mode of working. Newton himself said that the best and safest method of research is, “first to inquire diligently into the properties of things, and establishing those properties by experiments and then to proceed more slowly to hypotheses for explanations of them” [4]. I am sure that many with me have experienced, when reviewing data from an experiment, that an unexpected aspect of the data suddenly appears, spurring new ideas that may completely change the course of the investigation. Science does not have to start with a theoretical assumption. Noticing something unexpected that tickles one’s curiosity is quite sufficient. There is much wisdom in the famous words attributed to Isaac Asimov, “The most exciting phrase to hear in science, the one that heralds new discoveries, is not Eureka! (I found it!) but rather, ‘hmm … that’s funny …’.”

After this discussion of the alleged theory-dependence of observation it might be tempting to ask whether the hypothetico-deductive method really begins with theory? The attentive reader may have noticed that the method assumes that there are already observations to generate hypotheses from. When faced with a seemingly inexplicable phenomenon, we said the scientist should propose speculative theories about its cause. Observation of the phenomenon actually precedes the theories. In the example with the prisms, Newton saw that they disperse white light into several colors before he thought of recombining the colors. Semmelweis noticed the difference in mortality between the two maternity divisions before working out hypotheses. Theory does not necessarily precede observation. More importantly, there are no pure inductivists or falsificationists among working scientists. These are idealized concepts used by philosophers to make it easier to discuss various aspects of research. From a scientist’s point of view, the most important thing to keep in mind when comparing the two approaches is that they lead to different types of knowledge. There is nothing wrong with objective observation as a starting point for the advancement
of science, but if we want to explain what we see we must – at some point – formulate hypotheses and test them against reality.

2.7 The Scientific Community

It is very difficult to solve complex problems on your own. Luckily, science is a collective process. Even if you do work on your own you always build on foundations laid by others. Our knowledge would grow too slowly if every scientist were to invent the wheel every time they solved a problem. Therefore, science is also an open process. By sharing their results through publications scientists help each other make progress and all researchers within a field benefit from this. This open, collaborative aspect of research is called the scientific community. When starting out in research it is important to get to know it and to start interacting with it.

The scientific community has many subcommunities. The most obvious one consists of the people that you work with every day, such as your closest colleagues and your supervisor. Another fairly obvious subcommunity is the people working within your subdiscipline, whether it is behavioral ecology, laser spectroscopy, or any other research field. These are the people that your research group collaborates with, and the ones you meet at scientific conferences. Disciplines such as physics and chemistry are on an intermediate level, and the top level includes all people that have ever worked with, and ever will work with, scientific research. Some parts of the scientific community are very closely connected, sharing techniques, theories and problem areas with each other. Other parts are more distantly related. Since science both builds knowledge and transfers knowledge between people it can be seen as a web that interconnects all nations and all times. Every node of the web is a scientist, every thread is a transfer of knowledge. When you read scientific papers you can follow those threads by looking at the reference list at the end. Scientists who have made a great contribution to science have more threads connected to their node but each and every one who contributes to science is part of the web. I have never tried it, but I am positively sure that it is possible to follow the threads back in time through the web from any researcher today to the pioneering scientists during the renaissance.

When discussing scientific method, it is interesting to ask if research should be considered to be “unscientific” if it falls outside the inductive or hypothetico-deductive framework. Much research does. Some scientists get research grants and academic prizes for developing new measurement techniques, without ever explaining any natural phenomenon at all. Others use routine techniques to map out some aspect of nature. For instance, physicists who investigate the structure of atoms use established spectroscopic techniques to collect data. They proceed to interpret their spectra by established analysis techniques. The results are published in databases and are accepted as good quality research within their field, despite the fact that not a single bold hypothesis has been formulated or tested. Some philosophers of science maintain that such results become useless after a theoretical paradigm shift, since the information is incorporated in the definitions and concepts of the existing theory. As we have seen, this is not necessarily true. More importantly, we could equally well maintain that science becomes useless without such results. The quantum mechanical theory of the atomic world is obviously a great scientific breakthrough but if it were not used to analyze the structure of atoms in this way we would not be able to use atomic spectra to other scientific ends, such as analyzing the composition of distant stars. This would obviously be an impediment to our ability to develop theories about the evolution of stars. Without the
tedious everyday work with established theories, the theories become museum pieces, to be admired but never put to use. Science builds on itself, using established theories to develop new knowledge. New theories are not developed by individuals but by communities. Science is a much more complex, inhomogeneous, and multifaceted activity than inductivists and hypothetico-deductivists wish to let on. And even though not all science is conducted in the same manner, all science is nonetheless interconnected.

If scientists do not adhere strictly to the methods proposed by philosophers, where do they learn scientific method? In many places, a course in the philosophy of natural science is a healthy part of the Ph.D. curriculum, but the major part of the training to become a scientist takes place elsewhere. Scientific method is learnt where science is being made, under supervision by experienced researchers. It involves a wide variety of skills; the craft of operating experimental apparatus, sometimes also of designing and building this apparatus, knowing how to create experimental conditions that make it possible to obtain useful information, the craft of acquiring and interpreting data, and so forth. As a budding researcher you also learn a process of working in parallel with facts and ideas to solve research problems, generating ideas from facts, comparing ideas with facts. You learn a combination of craftsmanship and mindset that, in time, will enable you to contribute in peer review processes yourself. In practice, it is these reviews by fellow scientists, and not the philosophy books, that judge what good scientific praxis is.

In this chapter we have attempted to understand what science is. We have seen that this is no easy task. Quite possibly, we are now faced with more questions than we started with. This, on the other hand, is a natural consequence of reflection on any problem. The next chapter is about how it happens that we have science at all. This is by no means as self-evident as it may seem.

2.8 Summary

- The ultimate goal of science is to explain the world. Observations should, therefore, be related to theories to make a lasting contribution to science.
- In the inductive approach, science starts with unbiased observations from which general theories are developed. Such theories cannot be proven in a logical sense. Critics of the approach maintain that observations always are biased, since they rely on theory in some form. The theories obtained by induction have no explanatory power.
- In the hypothetico-deductive approach, science starts with an hypothesis, a tentative theory, which is to be tested against observations. Hypotheses that do not survive the tests are discarded. The others may become established theories with time. Neither these theories can be proved logically, but they have explanatory power. A disadvantage of this method is that it seems counter-intuitive to many scientists, who tend to think of the progress of science as governed by confirmation of theories, rather than falsification of them.
- Observation and experimentation have more central roles in practical science than in the inductive and hypothetico-deductive approaches, and may even exist independently of theories. Theory-independent observations often play an important role in the discovery of new phenomena but they must be related to theories to explain the phenomena.
- Observation is a skill. Our powers of observation can be improved by training and experience. This does not imply that skilled observers are biased. We are not required to give equal weight to all facts to be objective.
Science is an open, collective process. The participants in the scientific community contribute to and criticize each other’s work. Scientific method is complex, since different parts of the scientific community may employ different approaches to research, while all parts are still interconnected.

Further Reading

Chalmers [3] gives a lucid introduction to the major developments in the philosophy of natural science during the twentieth century. It is recommended as a first book on the topic and the interested reader will be guided to some influential books through it. It does not allow much space for observation and experimentation. For those interested in these topics, the second half of Hacking’s book [8] provides a coherent treatment of experimental science, including a large number of nice examples.

References