

Chapter 2

Science

2.1 A Very Brief, Incomplete and Highly Selective History of Science

My experience indicates that Ph.D. students, and therefore, presumably, younger scientists in general, implicitly consider science to be a systematic, rational, time honoured and stable approach to generating knowledge, and that there is little need to consider its historical development. The lack of awareness among younger researchers of the major developments that have taken place in science is quite understandable. After all, the research fields they work in may be undergoing such rapid change that it appears that almost all of the results that are directly relevant for their research have been achieved and published in recent years. Furthermore, there may be little or no emphasis placed on the history of science in their curricula and their advisors may not raise questions that stimulate them to delve into historical matters.

Thus, although they clearly recognize that major changes have taken place as regards the tools of science as well as its results (theories, technologies, publications), there is but limited realization among younger scientists of the fact that the role of science in society and its fundamental perspectives on reality have undergone significant changes over time—and that in recent years some of its most fundamental characteristics have been seriously challenged.¹

¹A highly cited example of such challenges is the book *Against Method* (Feyerabend 1975). Based on his studies of the history of science, the noted and controversial Austrian-American philosopher of science Paul Feyerabend (1924–1994) argues that there are no general norms or rules of the game for science—that we cannot distinguish between science and non-science and that the special status of science today is not due to its methodology, but rather to its results. Instead he argues for an extreme form of methodological pluralism—that advocating a particular methodology for science will stifle scientific practice—and that “The only principle that does not inhibit progress is: *anything goes*.” (Ibid.; 23).

In the sequel, I will at various times discuss some of these challenges as they deal directly with several of the most important concepts in science, including how science progresses and the role of verification in science. Here however I will simply provide a very brief overview of the development of science as an introduction to the next section that deals with the fundamental question: “What is science?” I emphasize that these introductory perspectives on the history of science are *extremely* selective and are limited to reflections as to two epochs of great significance for the development of science as it is practiced in the world today: Ancient Greece and the period in Europe in the 16th and 17th centuries that later became known as the Scientific Revolution. Such a selective and capsulated view most certainly does injustice to the major developments in other parts of the world. I ignore for example the early and significant contributions to the development of science in the ancient Near East (Babylonia, Egypt), India, China and the Islamic world. And I also ignore the developments in science and in the philosophy of science since the Scientific Revolution. The reason is simply that, given the restrictions on time and space here, as well as my own cultural biases and limitations, I consider these two periods as the most important in order to develop an (albeit highly superficial) appreciation of the developments that have lead up to modern science, no matter where it is practiced.

Ancient Greece, where the corner stones were laid for what was later to be modern science, did not distinguish between science and philosophy, between objective and subjective, or between factual descriptive accounts of the world (e.g. in terms of structural properties of things and laws governing them) and an evaluative or even a moral interpretation of the world as embodying an order, pattern, beauty, purpose and even goodness. In the *Republic*, Plato (ca. 428–348 Before the Common Era, BCE) characterized what modern scientists tend to refer to as objective reality in terms of an idea or eternal form of “the good” as the ultimate basis of a unified, ordered whole. Therefore, according to Plato, in order to understand experience we must have knowledge of the purpose which pervades all experience and which unifies it in a coherent and meaningful fashion. From this perspective, empirical observation can at best provide only limited insights into reality. To obtain a fuller understanding of our experiences, the methods of “science” (the concept as we know it today did not exist then) must be complemented by insight into the more basic principles and patterns which govern everything. Therefore the emphasis was not on observation and experimentation but on deduction from first principles that were assumed to be true and were not questioned. In fact geometry with its clarity and proofs based on deduction was a model for Plato’s and many other ancient Greek thinkers’ vision of methodology. “The old rationalist Plato admired geometry and thought less well of the high quality metallurgy, medicine or astronomy of his day.” (Hacking 1983; 4)

In contrast, Hippocrates (somewhere between ca. 450–370 BCE), commonly referred to as “the father of medicine” as a profession, is known for advocating the systematic study of clinical medicine whereby it became separated from superstition. He is perhaps most widely known for the so-called “Hippocratic oath” he established and which to this day serves as the basis for oaths taken by new doctors

throughout the world as to their duties and ethical responsibilities. In particular, two of his statements regarding science in contrast to opinion and belief are still often cited to this day: “Science is the father of knowledge, but opinion breeds ignorance.” (Warrell et al. 2005; 7) and “There are in effect two things: to know and to believe one knows. To know is science. To believe one knows is ignorance.”²

Aristotle (384–322 BCE), who was the most famous pupil of Plato at his Academy in Athens, integrated Plato’s respect for deduction in his own view of science. However, in contrast to his teacher, he also accepted the reality of the world as it appears to us.³ He argued that we live in a physical, biological and social world and it is the job of “natural philosophy”, what we today would call science, to study that world—to find causes and laws for the changes that take place in nature and society. While Plato focused on ideal ideas, Aristotle focused on classifying the multitude of individual objects and argued that nature is simply the combination of form and matter that gives reality to things. Taken together, he argued, classifications, causal explanations and laws can be said to constitute the principles that determine nature and society—and that knowledge is belief that is justified as being true on the basis of proper reasoning, empirical evidence and a rational method of inquiry. In this manner, he developed an inductive-deductive approach to pursue truth as to physical reality. It is interesting to note that in spite of his approach to determining truth based on observation and reasoning (corresponding to what is today referred to as a “correspondence concept of truth”), he also left a negative mark on the development of science by his lack of interest in experimentation. His view of science concerned nature as it is, not in learning from its manipulation, and his mark on science was so profound that this impeded the development of experimental science for more than 1500 years.

While there was a contrast between Plato’s idealistic and rational approach to science and Aristotle’s more empirical and common sense approach whereby ideas are general terms that result from induction, they both considered science to be based on first principles that form the basis for all of physical reality, independent of time and place: According to their thinking, the world is an ordered cosmos where the same structures, causes and laws characterize and determine the physical world and society at all times. It is thus the aim of science to find, behind the appearances of phenomena, laws that could provide certain knowledge.

This view of science and reality, in particular the thinking of Aristotle, dominated philosophical and scientific thinking (at least in the West) until the end of the European Renaissance in the 1600s and the development of an empirically and experimentally based natural science. With the advent of classical mechanics with

²See <http://www.goodreads.com/author/quotes/248774.Hippocrates>; accessed 27.03.2015.

³The school that Aristotle established in 335 BCE. (Lyceum; in Greek, Lykeion) lasted for over 860 years which is longer than any other university. It had its own library and the world’s first museum of natural history.

its emphasis on the use of a mathematical language (e.g. formulas, deduction) and quantitative concepts (e.g. mass, force, acceleration), science took a giant step forward.

However, this “giant step” did not take place all at once. Many years went by before most members of the “scientific community” no longer regarded such fields as e.g. alchemy and astrology as worthy of the qualification “science”. According to (Thagard 1998; 72) “...a theory can be scientific at one time but pseudo-scientific at another. ... Astrology was not simply a perverse side line of Ptolemy and Kepler, but part of their scientific activity, even if a physicist involved with astrology today should be looked at askance. ... Rationality is not a property of ideas eternally: ideas, like actions, can be rational at one time but irrational at others.”

The following example illustrates the immensity of this huge step forward that occurred when, perhaps for the first time in 2000 years, knowledge in the West was *systematically* sought not by referring to first principles or to authority, especially that of Aristotle or of the Bible, but by referring to experimentation, observation and measurement—to what we today refer to as empirical-based research. Based on his observations of falling bodies, Galileo Galilei (1564–1642) challenged the axiom of Aristotle (that had not been challenged—believe it or not—for almost 2000 years) that the speed with which an objects falls is proportional to its weight. According to this axiom, if two objects having the same weight are released at the same height at the same time, they will hit the ground at the same time. Therefore he reasoned that if they are tied together, they will have double the weight and the combined object should therefore fall twice as fast as when its parts were separate. He was convinced by this thought experiment that such reasoning was counter-intuitive and this led him to theorize that it is necessary to remove weight as the determining factor for the speed of fall.

Although it is not documented, there is a widely accepted story that after he had formed his hypothesis, Galileo performed a “test of hypothesis” by simultaneously dropping two balls, one weighing one pound and one weighing 100 pounds, both of which had been placed on the edge of the parapet of the leaning tower of Pisa in northern Italy. This was witnessed by those university professors that had attacked his hypothesis—they all saw that the two balls fell evenly and hit the ground at the same time.⁴

⁴Although this gave considerable support to Galileo’s hypothesis, a more exact test could not take place until roughly 50 years later when the discovery in 1658 of the air pump permitted the creation of a vacuum. This permitted controlled experiments where the influence of air resistance was removed and, so to speak, a feather and a cannon ball could be shown to follow the same “law of gravity” as expressed by the mathematical formula that relates the distance an object falls to the surface of the earth in a vacuum directly to the square of the time it has fallen: $s = \frac{1}{2}at^2$, where ‘s’ is distance, ‘a’ is the constant of acceleration, and ‘t’ is time.

Galileo's teachings and writings paved the way for Newton (1642–1727) to develop what we now call the inverse square law of gravity (the force between any two masses is proportional to the product of the masses divided by the square of the distance separating them).⁵ Newton's theories as to mechanics emphasized that legitimate knowledge could be obtained via induction based on observation and experimentation.

Since we will focus on the relationship between deductive and inductive reasoning later on, I briefly note here that this was in contrast to the approach of another great thinker, René Descartes (1596–1650), who preceded Newton. Descartes had emphasized reasoning as the surest source of truth (an example is his famous deductive statement: “Cogito ergo sum”—“I think, therefore I am”), rather than what he referred to as uncertain observations and risky induction. According to (Salmon 1967; 2), “... Descartes shows a complete lack of appreciation of the empirical approach. For Descartes, science is not an experimental enterprise in which one attempts to investigate clearly defined phenomena by observation of highly controlled situations. For him the order is reversed. One understands the broadest aspects of nature by deduction from indubitable first principles, the details come at the end rather than the beginning. The first principles are grounded in pure reason.”

Newton described his own method as empirical and inductive and he strongly criticized Descartes for his emphasis on preconceived rational principles that should not be based on observations and experiments. I note too that even to this day the relative degree to which emphasis is placed on deduction and induction characterizes debates about research methodology. We will treat this matter far more thoroughly later on, particularly in connection with reflection on the justification of theory via verification and falsification.

Thus a mechanical picture of the world developed that challenged the focus on deduction from first principles (and the authority of Aristotle and the Bible) that had dominated science in the West for so long. First principles, faith and reason were no longer sufficient—ideas had to be tested in the real world. Nature was looked upon as a vast machine (characterized by its matter and motion) that is governed by quantitative laws, by relationships that are, so to speak, written in the language of

⁵In his main scientific publication, *Philosophiæ Naturalis Principia Mathematica* from 1687 (better known today as *Principia*), Newton presented the principles of theoretical mechanics (commonly referred to today as classical or Newtonian mechanics). These included not only the movement of physical bodies on or near the surface of the Earth, but the movement of any physical body *anywhere* in the universe, including the movement of the moon around the earth and the movement of the Earth and the other planets around the sun. Classical mechanics formed *the* basis for physics and astronomy up until the time that Einstein developed his theory of relativity. And of course classical mechanics is still highly accurate for most calculations, including e.g. those concerning the trajectory of rockets, where the velocities of interest are much smaller than the speed of light. Einstein's relativistic equations reduce to the classical equations when $v/c \ll 1$, where v is the velocity of an object and c is the speed of light.

mathematics.⁶ Rational methods of inquiry via observation, experiment, and measurement of the world around us became the royal road to meaningful knowledge.⁷

This development took place to a great extent outside of the universities. It reflected the political and ideological conflict between the Roman Catholic Church, that to a great extent dominated the universities, and the new empirically oriented natural sciences that were developing in private academies, often under the protection of kings and noblemen, and that challenged much religious dogma. However, towards the end of the 1700s, when major political, economic and religious changes were taking place in European countries, scientific research began to be based in universities that were now becoming more independent of both church and state. Science could now develop as an area of rational intellectual pursuit that was independent of philosophy, theology and the powers of vested interests. Thus, university teaching began to be based on knowledge obtained via observation and experiment—and this knowledge was now open for criticism! This led in turn to science being accepted as setting new standards for what could count as genuine knowledge. The practitioners of science were referred to then as “natural philosophers”; in fact, the term “*scientist*” was first coined in 1834 by members of British Association for the Advancement of Science to describe students of nature, by analogy with the existing term “*artist*”.

From about 1800 more specialized and application-oriented institutions of higher learning developed (dealing with engineering, agriculture, pharmacy, commerce, etc.). For example, today we find the word science connected to many fields of study that are far removed from the natural sciences, including not only those well-established fields within the social sciences (economics, sociology, anthropology, political science, etc.), but also such fields as library science, management science, dairy science, computer science ...

These developments, characterized by the independence of science and by disciplinary differentiation, were also characterized by a number of basic beliefs and attitudes regarding science that still dominate our views of science today. These include:

⁶This perspective on science and nature was stated as early as 1623 by Galileo Galilei in his scientific-philosophical publication, *The Assayer* (*Il Saggiatore* in Italian). Here he described a research methodology that built on measurable data, mathematically formulated hypotheses as to law-like relationships between phenomena, and experimental testing of hypotheses. The book contained Galileo’s famous statement that mathematics is the language of science. His method also included the use of thought experiments, something he himself used with considerable success in his actual experiments (Lübcke 1995; 150).

⁷According to (Hacking 1983; chap. 9) times have once again changed, at least as regards the way that historians of science treat their domain. The history of the natural sciences is today almost always written as a history of theory, and not of experiment. This perspective is supported by (Gooding et al. 1989; xiii): “Experiment is a respected but neglected activity. ...it is all the more surprising that students of science have paid so little attention to how and why this particular activity has become so significant.”

- science is, and *should* be (a moral perspective), autonomous, that is, responsible solely to its own norms,
- science leads to the highest form of knowledge as compared to e.g. common sense or belief,
- there are meaningful distinctions between pure/basic science and applied science, and
- science is neutral and value-free in its investigation of an objective, material reality.

I will return to these (more or less tacit) assumptions later on. Here I can simply note that this institutionalization of science, together with its emphasis on providing a privileged access to “truth” via a particular “scientific method”, has also resulted in a growing divide between science and other fields of intellectual inquiry (Snow 1993). In any case, today it is considered completely natural that teaching at universities and other institutions of higher learning is scientifically based—with the authority and responsibility this leads to.

This development with increased disciplinary differentiation and specialization can also be said to lead to a growing divide *within* science. We have continually spoken here of “science”—but are there different sciences or is there just one science? And are there different methodologies for each of these different sciences—is it reasonable to speak of one general “scientific method”? This last query is particularly relevant as branches of science have become more specialized and yet have also joined together in investigating increasingly complex systems. Such questions are treated in greater detail in Chap. 7 (Scientific Method and the Design of Research) as well as in Chap. 9, Sect. 9.2 (Multidisciplinary and Interdisciplinary Research).

The “authority” referred to above is said to be provided by the so-called “scientific community”. I have already referred a number of times to this term, and I have, for example, spoken of “the demands of the scientific community”. What is this community and what characterizes it? In fact, not that much is known about the way that scientists organise themselves and how they determine the norms that they apply to characterize good science and good scientific behaviour. Thomas Kuhn in his provoking and challenging book on the history and sociology of science provides some tentative generalizations as to what is required for membership in such a community (Kuhn 1970; 169). These include:

1. a concern to solve problems about the behaviour of nature
2. the solutions that satisfy the scientist cannot be merely personal but must be accepted by many in the community
3. the group that shares them must be a well-defined group of the scientist’s peers
4. the group is recognized for its unique professional competence and as the exclusive arbiter of professional achievement, and therefore
5. by virtue of its members’ training and experience, the community is seen as the sole possessor of the norms, standards and rules of the game for passing unequivocal judgements. Kuhn notes (Ibid.; 164): “there are no other

professional communities in which individual creative work is so exclusively addressed to and evaluated by other members of the profession”.

We will return to Kuhn’s analysis of the history and sociology of science in Sect. 2.2.5 of this chapter where traditional and more commonly accepted perspectives on the history and development of science are challenged.

Before ending this brief overview of the history of science, it is necessary to introduce the theme “positivism” that has for many years exerted a dominating influence on science and its methodology, and, in spite of severe criticisms, to this day is the implicit starting point for most researchers in the natural sciences, at least for those who do not investigate the micro-world of quantum reality.

From the 1920s and until what its critics celebrate as its philosophical death around 1960 (although it still is alive and kicking in the mind-set of most scientists) this school of thought, referred to at times as logical empiricism or logical positivism or just positivism, dominated scientific rationality.⁸ The central idea of positivism is that true scientific statements can only be based upon sensory-experience (empirical observations) and logical inferences based on these observations. This perspective on the establishment of true scientific statements had no place for metaphysics and denies that there are presuppositions for science; what is real is measurable. I note that in the literature one will meet various synonyms for what I often refer to as metaphysical assumptions; these include the terms: pre-suppositions, a priori assumptions, first principles and axioms.

Although there are many different interpretations of the concept of positivism and no single, widely accepted definition, the following underlying assumptions, based on an in-depth study by Lincoln and Guba (1985), appear to characterize most understandings of positivism:

- There is a single, knowable, measurable physical reality that can be reduced to elements that can be studied independently of each other.
- This external reality can in principle be exhaustively described in scientific language, where true propositions are in a one-to-one relation to facts about reality, including facts that are not observable.
- Independent observers can study reality since the knower and the known are independent.
- Observations can be made independent of existing theory and of an observer’s values.
- There are real causes that temporally precede or are simultaneous with their effects.
- It is possible to make time- and context-free generalizations.

⁸This perspective on science and truth owes much to the philosopher David Hume (1711–1766), whose scepticism led him to argue that science should only aim at describing observations and to avoid philosophical speculation about an external physical reality and about the ability of science to obtain objective truth. See in particular (Hume 1748/1955).

Summing up, the underlying goal of a positivist perspective on scientific investigation was and is the creation of a clear, well-defined version of science based on firm data and free of philosophical speculation.

Yet problems emerged and led to the erosion of positivism's credibility amongst many philosophers of science (but not most scientists!) by 1960. These problems, many of which we will return to later on in the discussions dealing with the justification of theories, included, amongst others, the following:

- (a) Theories cannot be tested individually by means of their observational consequences. For example, theories about planetary motion implicitly imply the acceptance of other theories about space and time—and the observations they are based on imply theories about optics, perception and the like. A result is that if a theory's predictions fail when confronted with observational data it can be unclear whether the theory itself is at fault or whether one of its auxiliary theories is wrong (or whether an instrument of observation was faulty). Thus, empirical data can neither falsify nor confirm a theory—truth is elusive.
- (b) Positivism did not include considerations of the fact that humans (as observers, analysers, mediators) are fallible. For example, our observations are determined to some extent by the theories we as scientists implicitly accept as well as by our values; inquiry is not and cannot be value-free. In addition, we may implicitly use a multiple of criteria when choosing between alternative theories, each of which can be supported by the same data. Nature does not necessarily constrain theory choice.
- (c) A great deal of scientific investigation is not based on direct sensory experience but on our own mental activities. Interaction with the external world is mediated via the use of technologically advanced instruments that have been constructed on the basis of theories which are products of our cognition and not of direct sensation. And the questions that we ask most often arise not from data obtained via the senses but from already existing knowledge. In this connection, the role of an intuitional leap from experience must be noted. According to Einstein, "For the creation of a theory, the mere collection of recorded phenomena never suffices—there must always be added a free invention of the human mind that attacks the heart of the matter"; quoted in (Pagels 1982; 58).

Thus, our modern period is characterized by a diversity of views on science. In a nutshell, a rationalist tradition has emphasized reason and logic, while an empiricist tradition has emphasized sensory experience and empirical evidence. My own experience, including my discussions with many other scientists, leads me to conclude that to be a reflective practitioner of science today means that one must appreciate and balance the roles played by evidence, logic and the presuppositions that underlie science. This implies that there is a need for you as a researcher to master both your field of specialization and the basics of research methodology, as

well as to appreciate your field's dependence on and interplay with other fields of science. Perhaps doing this in a manner similar to that of a musician who aspires to become respected for her talent and virtuosity—and perhaps as well for her creativity; s/he must learn how to master her musical instrument (often more than one), must learn to work together with other musicians in a band or orchestra, and must have an understanding and appreciation of music as a field, including its relevant theories and the cultural traditions and expectations of music lovers.

For those interested in easily accessed information on the history of science, there are a number of online resources, including the following:

<http://www.ebscohost.com/academic/history-of-science-technology-and-medicine>

Website of the History of Science Society that describes its database as “The Definitive International Database for the History of Science, Technology and Medicine” and that “reflects the influences of these fields on society and culture from prehistory to the present.”

<http://web.clas.ufl.edu/users/rhatch/pages/03-Sci-Rev/SCI-REV-Home/05-RSW-Sci-Rev.htm>

Website dealing with the Scientific Revolution and the role of historians of science.

<http://plato.stanford.edu/contents.html> Website of the comprehensive *The Stanford Encyclopaedia of Philosophy*. Although primarily oriented towards philosophy, it also includes a large number of brief articles on subjects and individuals that are particularly relevant for the history of science.

<http://web.clas.ufl.edu/users/rhatch/pages/10-HisSci/links/index.htm> Website providing informative links on the history of science.

2.2 What Is Science?

We have now used the word “science” a number of times without defining it, relying on the reader’s familiarity with the word. Such lack of attention to definition is not uncommon, even amongst authors who write about science; an often-cited book (Chalmers 1999) with the title *What is this thing called science?* never really tells us what the author himself means by “science”.

Presumably, this lack of definition did not cause you any difficulties up until now. “Science” is an everyday word, used by practicing scientists, the so-called “man-on-the-street”, journalists, and university teachers—all of whom assume they know what is meant by “science”, at least in a manner that is sufficient for them to communicate meaningfully with others. It is my experience that a scientist will say that he knows from experience and common sense what he is doing, that he does not need a definition to guide him in his work—that a conventional learned wisdom in his field will guide him. While this could appear to be a strange reaction by just those people who are engaged in the demanding, abstract, intellectual, competitive activity we call science, scientists appear to simply carry on the tradition they were brought up in. When they defended their Ph.D. dissertations they were not challenged with more reflective and philosophical questions dealing with methodology.

They might have been asked why they used a particular instrument, or about the reliability of some measurement, or about what other scientists have written on the subject, or about their use of statistics. But they did not face questions dealing with more fundamental topics such as whether, when they describe objects that cannot be seen (e.g. electrons or black holes) they are describing physical reality or whether their descriptions simply provide meaningful models of an unobserved/unobservable reality—or in what sense a theory can be said to be verified by the observation of some favourable instances (or falsified by an anomalous observation). Scientific investigation appears to be considered as a practical, although highly skilled, art by most scientists—who tend to ignore the potential benefit of reflecting on the meaning of such central concepts as science, truth, validity, proof, etc. According to (Ziman 1968 in Klemke et al. 1998; 50) “No scientist really doubts that theories are verified by observation, any more than a common law judge hesitates to rule that hearsay evidence is admissible.”

However, the definition of science, or rather the attempt to understand the concept “science”, can play an important role in our ability to understand and appreciate what science aims at, what its limits are—and what it tacitly presumes.

An experience I had a number of years ago illuminates the importance of focusing on the concept of science as such, and not just on its specific procedures and contents. An internationally known and highly respected physicist who was also the Vice-Chancellor/Rector/President of the University of Copenhagen had written an essay (in Danish) on science and spirituality.⁹ It started as follows (my translation): “At a social gathering I was asked by the person sitting beside me what I thought about such phenomena as reincarnation, aura, healing and the like. ‘Badly’ I replied, ‘it’s pure nonsense.’” In his rejection of these phenomena as “nonsense”, he implied that they did not exist and were not worthy of scientific investigation. I wrote a letter to this highly esteemed person, whom I knew professionally, and asked him the very simple question: “How can science show that something does not exist?” I argued that science—and common sense for that matter—can demonstrate that something does exist. For example, if one wanted to demonstrate that cockroaches exist in the well-known five-star hotel in Copenhagen, Hotel D’Angleterre, it suffices to find just one such insect anywhere in the hotel. But can a scientific investigation, no matter how thorough, demonstrate that they do not exist?¹⁰

⁹The essay by Professor Dr. Scient. Ove Nathan was the first in a series on ‘Science and Spirituality’ in the major Danish morning newspaper *Berlingske Tidende* in 1993; it appeared on January 1, 1993.

¹⁰This question is most tricky—see if you can answer it. The same applies to its ‘opposite’: Can scientific investigation prove universal claims—such as “all ravens are black”? One might note that this claim corresponds to the statement that there are no ravens that are not black—and we are back to the original question of whether, based on evidence, one can prove that something does not exist (here, non-black ravens)! I note that the famous Michelson-Morley experiment (1887), which was designed to demonstrate the existence of the so-called “aether wind” as a medium for the movement of light waves, can be said to have provided the first strong evidence that such an all-pervading aether does *not* exist. The experiment with great accuracy demonstrated the absence

Perhaps I should have presented this anecdote later on when we discuss the limits of science—but I chose to bring it here as it clearly demonstrates that even experienced scientists, no matter how knowledgeable they may be in their field of specialization and how significant a role they play in the development of science, can have a rather limited concept of what science is (and what it is not).

2.2.1 *Science as Facts*

So let's start by looking at the way my former M.Phil. and Ph.D. students understood the meaning of "science". In 2004, when I first developed and taught the course on research methodology at Sri Sathya Sai Institute of Higher Learning in the state of Andhra Pradesh in India, after some discussion the students arrived at a consensus as to a definition of science:

Science is the observation, collection, and analysis of facts.

This definition is in line with the thinking of many of my students during the decade I taught the course as well as of many observers and practitioners of science. The underlying thought is that so-called "facts" provide the basis for theory development and verification and for knowledge about the natural world in general. Scientific knowledge is said to have a special status due to its being based on facts, that is, on claims about the physical world that can be established by careful, systematic, unbiased use of our senses and reasoning, rather than by common sense, personal opinion, hearsay, belief, or imagination. In other words, a "fact" is generally understood as something that has actually happened or is "true". If in addition, "the reasoning that takes us from this factual basis to the laws and theories that constitute scientific knowledge is sound, then the resulting knowledge can itself be taken to be securely established and objective." (Chalmers 1999; 1)

Therefore let us temporarily use this definition as a starting point for reflections as to the nature of science.

The very simple definition provided by the students raises a number of questions. For example, consider the question: what are facts in a scientific context?¹¹ We have mentioned that they can be considered to be observations/statements based on the careful, systematic and unbiased use of our senses and reasoning. In the

(Footnote 10 continued)

of an anticipated drift of the aether as the earth moved through it without obstruction. In 1905, Einstein abolished the existence of the medium (Pais 1982; 20–21).

¹¹Of course we could also raise other questions regarding the idea that "Science is the observation, collection, and analysis of facts." For example: Are there criteria as to the quality of one's observation, collection and analyses of facts? What do we mean by facts if, at least at the quantum level, the nature of reality is probabilistic? Doesn't science also deal with more than facts—what about "understanding" and "meaning"? Doesn't science also deal with the establishment of verifiable theories/laws? And so on! We will return to such important questions later on.

natural sciences in particular, such facts are considered to be: (a) data that are obtained by careful and well-documented investigation (observation/experiment), and b) that are so accepted by one's peers that it becomes difficult to consider other interpretations of the data. In other words, facts could be measurements that have been carefully performed and recorded, where we know details about the precision of the equipment employed, and where the observation/experiment has been performed accurately and in accordance with generally accepted standards as well as ideals as to objectivity.

But things are not all that simple. For example, according to (Chalmers 1999; xxi): "...the idea that the distinctive feature of scientific knowledge is that it is derived from the facts of experience can only be sanctioned in a carefully and highly qualified form, if it is to be sanctioned at all. ... (There are) reasons for doubting that facts acquired by observation and experiment are as straightforward and secure as has traditionally been assumed. ... a strong case can be made for the claim that scientific knowledge can neither be conclusively proved nor conclusively disproved by reference to the facts, even if the availability of these facts is assumed."

The arguments that Chalmers provides to support such scepticism are primarily based on analyses of the nature of observation and of the history of science, as well as on the nature and limitations of logical reasoning. He argues that there are three implicit, and challengeable, assumptions that underlie a definition of science based on facts. These are:

1. Facts are directly available to careful, unprejudiced observers via the senses
2. Facts are prior to and independent of theory
3. Facts constitute a firm and reliable formulation of scientific knowledge.

Let us briefly consider these assumptions; in particular, we will go into more detail as to the second assumption when we consider what is meant by a "scientific theory". Let us start by considering the role of human perception and focus on eyesight. Consider the following drawings of a "staircase" from (Chalmers 1999; 6) and of a "cube" from (Hanson 1958 in Klemke et al. 1998; 343) (Fig. 2.1).

Start by looking at the drawing of the "cube". Look at it for some time and you may find that what you see changes spontaneously. At one moment it appears to be a cube that you look at from above, only to become a cube that you view from

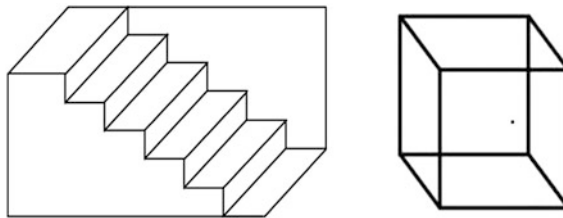


Fig. 2.1 A "staircase" and a "cube"

below—and vice versa. Or perhaps you simply see it as a wire frame for a kite, or perhaps simply as some criss-crossed lines in a plane. If we all see the same thing (the same drawing), why do we see different things? According to (Hanson 1958 in Klemke et al. 1998; 343) a traditional perspective on seeing leads scientists to (mistakenly) argue that the explanation is that we interpret things differently. The traditional argument is that since there does not appear to be a place in the seeing for these differences, the disparities in accounts of the observations must be due to ex-post interpretations. But Hanson argues that this is not so; “one does not first soak up an optical pattern and then clamp an interpretation on it.” His argument is that although normal retinas are impressed by the lines on the paper in the same way, some observers will see the cube viewed from above, others from below—and the same observer may see it, at one moment, as viewed from above, and at another moment as viewed from below. No interpretation or thinking is involved.

Let us continue this line of thought. Look now at the drawing of what appears to be a staircase. Once again, if you look at the picture for some time, you may find that what you see changes spontaneously, involuntarily, and without any conscious thought involved. At one moment it appears to be a staircase that you look at from above, only to become a staircase that you view from below—and vice versa. Yet it must be the same object that you view since no one has changed the picture and the retinal images do not change. Whether you see the picture as a staircase view from above seems to depend on something other than the image on your retina.

If what you see changes, even though the object itself does not change what are the “facts” here? Is what you see “firm and reliable”? The answer is neither a clear “no” nor a clear “yes”. The above arguments tend to evoke an answer of “no”. On the other hand, there is an ambiguity that results from representing three dimensional objects on a two dimensional space like a sheet of paper. However this ambiguity can be overcome, for example by employing a stereoscopic representation by using stereo cameras. This would certainly be done in situations where the depth perspective is crucial to an observation. So since it is possible to overcome the ambiguity mentioned, there are good reasons for answering “yes”—we are able in science to obtain firm and reliable representations of the objects to be studied. One might say that scientific observation is not limited but that ordinary human perception is. The problem remains of course that so much of the way science develops is affected by human perception.

Let us continue with this matter of perception. According to (Chalmers 1999; 6), “the results of experiments on members of African tribes, whose culture does not include the custom of depicting three-dimensional objects by two-dimensional perspective drawings, nor staircases for that matter, indicate that the members of those tribes would not see the drawing as a staircase at all”. They could not see the drawing as you do. Since, if we assume that you and the members of an African tribe have reasonably good eyesight and you are both seeing the same thing (with your eyes, neural connections, brain), why do you see different things? It seems that perceptual experiences in the act of seeing are not uniquely determined by the images on one’s retina but depend on the experiences and expectations of the

observer. So “facts” may not be independent of who you are and what you know in advance.

To elaborate on the question of whether facts are independent of the observer, consider now the situation where a medical student who has not yet had training in working with X-ray photos and an experienced radiologist both look at the X-ray images of a patient being examined for lung cancer. The perceptual experiences of the senior, skilled observer are not identical to those of the untrained novice; he sees things that the student does not see and is able to make a diagnosis that the student cannot. To be a competent observer requires training and experience. Perception is influenced by our background, knowledge, worldviews, and expectations. An infant looking at a book would only see marks and lines where you see letters, words and sentences. Humans do not have direct perceptual contact (like film in an X-ray camera) with the physical world, and this is not the same as saying that different people who see the same object or phenomenon interpret it differently; they simply *see* different things!

According to physicist Amit Goswami who has studied the relationship between human consciousness and physical reality, “...the picture is not the object. The map is not the territory. Is there even a picture out there? All we know for sure is that there is some sort of picture in our brains, a truly theoretical image. In any event of perception it is this theoretical, very private image that we actually see. We assume that the objects we see around us are empirical objects of a common reality—quite objective and public, quite open to empirical scrutiny. Yet in fact, our knowledge about them is always gathered by subjective and private means.” (Goswami 1993; 142)

Thus arises the old philosophical question: What is real—the theoretical image that I (whether I am a scientist or a member of an African tribe) actually see but only privately, or the empirical object that I do not seem to see directly but about which I form a consensus (with other scientists or tribe members)? As we shall see later on in Sect. 2.7 of this chapter, this question as to the authenticity of empirical objects that we never experience without the intermediary of a theoretical image, is at the heart of “realism”, one of the metaphysical foundations of the natural sciences.

So it appears that facts as observable states of affairs in the physical world can be fallible; different scientists may not see the same thing even though they have good eyesight, are using the same equipment, and are looking at the same object of study. On the other hand, it may also be argued that: (a) use of proper equipment (e.g. stereo cameras to photograph what would otherwise be two dimensional representations), (b) proper education and shared experiences (e.g. whereby African tribesmen who are familiar with staircases can see staircases as we do), and (c) experience (e.g. where a young medical student eventually develops into an experienced radiologist), together with critical application of the methods of science, can provide science with reliable data—with “facts”.

Since we have just considered X-rays, we may extend this line of reasoning to ask what the objects of the physical universe would look like if we had X-ray eyes, that is, if we were not able to see in the frequency range that we do as humans ($4 - 8 \times 10^{14}$ Hz), but in the frequency range corresponding to X-rays ($3 \times 10^{16} - 3 \times 10^{19}$ Hz). Clearly our aesthetics would be totally changed—for

example, our concept of a “handsome” person would not be based on the person’s exterior, but on the person’s skeleton. But more important here, all our data as to the physical universe would be different. We would not be able to “see” many things we now see, and we would be able to “see” many things that we cannot see now with our human eyesight. It is reasonable to assume that the same scientific laws would exist, at least potentially, since what we have come to accept as scientific laws are assumed to have universal legitimacy, independent of how they are arrived at. I write “potentially” to indicate that they might not be discovered/developed in a world where vision was limited to the X-ray range, and that the formulation of such laws would of necessity be transformed to fit a world perceived by people with such X-ray vision. In addition, they might discover other laws that we have not yet been able to uncover, since they would have access to different data/facts than we do. It is also most likely that the history of science, and of the world, would be immensely different than we have known them to be.

Consider now the following closely related reflection from (Hawking and Mlodinow 2010; 91) as to how we gather knowledge of the world via our ability to see: “It’s probably no accident that the wavelengths we are able to see with the naked eye are those in which the sun radiates most strongly; it’s likely that our eyes evolved with the ability to detect electromagnetic radiation in that range precisely because that is the range of radiation most available to them. If we ever run into beings from other planets, they will probably have the ability to ‘see’ radiation at whatever wavelengths their own sun emits most strongly”. It follows that such beings would have had access to different data than we do and would most likely have developed different sciences than we have been able to! And it follows too that ‘scientific truth’ can be said to be relative; what is a fact/true for humans may not be a fact/true for such beings and vice versa.

Note that in science, the word “fact” does not only refer to an observable state of nature, it also refers to a *statement* that expresses the observable state of nature. Science is based on such statements, and these, unlike the observable states of nature, do not enter the brain by way of the senses. Rather, facts as statements are products of human cognition—and this too is notoriously fallible.

(Chalmers 1999; 15–16) provides a good example. He notes that prior to the realization that the earth spins on its axis and orbits the sun the statement that “the earth is stationary” was a fact, confirmed by observation. We cannot see or feel it move; if we jump in the air, it does not move away from under us. But we now know that what was earlier a “fact”—the observation statement that “the earth is stationary”—is false.

Let us briefly reflect on this historical development. We know that even though we at the surface of the earth are moving in a horizontal direction at more than 100 m per second, there is no reason why our relative position should change when we jump in the air; there are no horizontal forces acting on us that change our speed. So we retain the speed we share with the earth’s surface when we jump and land again. To appreciate why this is so requires understanding the great 17th century discovery of inertia by Galileo (which also is the first of Newton’s three laws of motion that laid the foundation for classical mechanics). This discovery/law was not

available earlier since the “fact” of the earth’s stationarity appeared to be obvious to earlier scientists. This demonstrates how judgment as to the truth of an observation statement (“fact”) depends on the knowledge one has prior to making the judgment. The Scientific Revolution involved not just a transformation of theory, but also of what were considered to be empirical facts.

The above reflections as to “facts” imply that the definition: “science is the observation, collection, and analysis of facts” is subject to challenge. As is the statement that facts can be firmly established by observation. We have shown that one challenge concerns the extent to which our perceptions are influenced by our background, our culture, and our expectations—so that what appears to be an observable fact for one observer may not be so for another. Another challenge concerns the extent to which what we already know or assume affects our judgments about the truth of observation statements. And yet another challenge arises from the dependence of our observations on the limitations of our senses. This is not to say that we should simply give up trying to establish a factual basis for our theories as to phenomena, relationships etc., but that we must be aware of the fact that facts are fallible—they may change as we and our knowledge of the world change!

So what appeared to be a straightforward, common sense definition of science based on “facts” is not so straightforward indeed. We may therefore ask whether there exist other, more reliable—and less challengeable—ways of defining science. Let us briefly consider another rather common definition.

2.2.2 *Science as Generalization—and as Establishing Verifiable and True Theories*

Many see generalization as the hallmark of the natural sciences. For the present purposes, we can loosely consider generalization to be the act of inferring from that which has been observed to that which is unobserved. Indeed, the “science” of our ancient forefathers that served as a basis for more modern science resulted from making quite a few generalizations of a comprehensive nature—for example that the laws of astronomy determine the progress of time and that laws of geometry, as developed in particular by Euclid in Greece roughly 300 BCE, hold for all space without exception. It is interesting to note in this connection that, as often has happened in the history of science, the assumption as to the universality of Euclidean geometry was shown to be false in 1764 when Thomas Reid developed the first non-Euclidean geometry; since then other types of geometries, each based on its own set of axioms, have been developed.¹²

Just as was the case with defining science as facts, defining science as a means of establishing reliable generalizations certainly contains important elements of what

¹²Euclidian and non-Euclidian geometries are equally consistent; if one of them contains a contradiction, so does the other (Salmon 1967; 36).

most members of the scientific community would consider to be science. But it too raises a number of questions, such as:

- How do/should scientists establish reliable generalizations/theories? Is verification the only way to determine the “goodness” of a theory?
- Does science have a special way of establishing true statements about the physical world—and does it have a special way of distinguishing between true statements about the physical world and statements which are not true?
- Can science “prove” that something is true, and if so, how?
- To what extent does e.g. usefulness in solving problems or developing technology influence the development of theory?

Once again we find that an attempt at providing a simple, straightforward definition of science leads to a number of fundamental questions. Instead of attempting to answer the above questions here, I suggest that no matter how we attempt to provide definitions of “science” we will encounter a series of questions that compel us to reflect a bit deeper as to what we are doing when we perform “science” and what distinguishes science from non-science.

This should not surprise us. We meet the same challenges when we try to define similar fundamental concepts such as e.g. “ethics” (which we will consider in relation to science in Chap. 10). There are a large number of publications that provide different perspectives on what the term ethics means, perspectives that are far more important, nuanced and meaningful for a philosopher than for the so-called man-on-the-street who is satisfied with an intuitive understanding of the term—in particular as to what is *unethical*! What is surprising is that although students of philosophy cannot avoid considering what they, and in particular what noted philosophers throughout history mean by “ethics”, students of science have not usually been motivated or compelled to ask themselves what they mean by “science”. Nor have most practitioners of science.

To conclude this digression on “what is science” on a more constructive note, I suggest that science is more than just the organised collection of facts, concepts, and knowledge about the structure, characteristics and behaviour of the physical universe; that it is more than the systematic investigation of reality; and that it is more than the rational establishment of verifiable theories—each of these being common definitions. It is all of these and more, and I therefore propose the following very broad definition:

Natural science is a special way of looking at the universe – a rational approach to discovering, generating, testing, and sharing true and reliable knowledge about physical reality.¹³

¹³ Although the concepts of “truth” and “reality” have not been dealt with in any depth so far, I feel they should nevertheless be included in the definition of science. I note at this early point that most scientists tend, consciously or unconsciously, to adhere to what has been called the “correspondence theory of truth” within a framework of “realism”, both of which will be presented shortly in Sect. 2.4 where we discuss the Aims and Claims of Science.

One might inquire why I have delimited the above definition to “physical reality”. The reason is twofold. First of all, to distinguish “natural science” from other branches of science, such as e.g. the social sciences, that do not share all of these aims and that are characterized by subject matters (e.g. human and social activity) that may be investigated with other aims than those listed above regarding “true and reliable knowledge” (for example, how to make better decisions). Secondly, to exclude phenomena that *may* have non-physical characteristics and causes—for example consciousness, a theme we will reflect on several times later in the present chapter on the essence, aims and limitations of science, as well as in the final chapter on science and ethics.

This “special way of looking at the universe” has led to activities we call science, to a profession we call science, and to an institution we call science. In the remainder of this book, we will continually reflect on the nature of science and on how you can develop a worldview and the research methodology that will enable you to become a respected, reflective practitioner of science.

2.2.3 *Some Distinctions When Describing Science*

In order to further characterize science, briefly consider the following distinctions that are commonly employed when describing science (as an activity, a profession, or an institution):

First, there is an often stated distinction between science as creating knowledge (what is generally referred to as *pure/basic science*) and science as applications of knowledge (*applied science*). As was seen in the discussion of the history of science, this distinction was made very early in the development of science when special institutions of higher learning were established to promote the applied aspects of science (such as schools of engineering, agriculture, medicine) leaving so-called pure science to the disciplines that were developing in the universities of Europe.

Within pure science we find another distinction: between the *formal sciences* such as logic, computer science and mathematics and the *empirical sciences*, such as physics, chemistry, biology, botany, psychology, sociology and economics.

And digging even deeper we find in the empirical sciences (and these are the sciences we are primarily concerned with in this book) a number of commonly applied distinctions between major domains of science: the *natural sciences* (concerned with the nature of matter and energy and that study the physical and natural world, nature’s phenomena—physics, chemistry, biology, astronomy, the earth sciences ...), the *life sciences* (concerned with living things, their components and interactions—biology, zoology, pharmacology, botany....), the *behavioural sciences* (concerned with human behaviour—psychology, anthropology, social neuroscience ...), and the *social sciences* (sociology, economics, management, political science ...).

There are several scientific disciplines that cross the boundaries of such categories of science (natural, life, behavioural ...). For example, one often sees biology classified as both a natural and a life science, and anthropology may be considered both a life, behavioural and social science. In particular, in an age characterized by huge developments in specialization as well as in multidisciplinary and interdisciplinary research, an increasing number of new “hybrid” scientific disciplines are emerging (e.g. social neuroscience, evolutionary psychology, genetic engineering) that are difficult to classify as belonging to any one category. Of course any such categorization can be considered artificial and arbitrary; “Knowledge ... is one. Its division into subjects is a concession to human weakness.” (Lee 2000; 3)

This development whereby disciplines differentiate and specialize is a result of and a characteristic of a traditional reductionist and materialist perspective on science that provides focus and amazingly detailed information about both micro (DNA, quarks) and macro phenomena (animals, black holes, an expanding universe). From such a perspective, matter is the fundamental substance in nature such that all that exists is material, and all physical reality is built up of individual units of matter that obey the laws of nature.

At the same time, this perspective on reality also makes it increasingly difficult for a scientist to appreciate a perspective whereby everything that appears to exist does so in relation to everything else—that all of reality is interconnected. Another way of saying this is that the way science is developing increases our tendency to look upon reality, at whatever level, as being ontologically separate, although perhaps functionally interrelated.¹⁴

Keeping to the empirical sciences, one also meets distinctions between the *observational/non-experimental sciences* (typically associated with the more descriptive approaches to science as in astronomy, zoology, meteorology or geology) and *experimental sciences* (typically associated with a more analytical approach, as in much of physics or medical research). I note that since all natural sciences observe and describe, it is difficult to speak of a non-observational or a non-descriptive science, but that some branches of science are primarily oriented towards describing and answering questions while others are more oriented towards active experimentation and testing hypotheses. For example, scientists may be interested in answering questions such as: What is the surface of Venus like? What species of plants live in the Himalaya Mountains? What patterns of nucleotides make up human genes? Such questions are more representative of a descriptive rather than an analytic/causal approach to scientific inquiry.

To answer such descriptively-oriented questions a study might rely primarily on library research, photos, extracting physical samples and the like, and not on

¹⁴An alternative to such a reductionist perspective is provided by a holistic/systemic perspective whereby all of nature, including all its living and non-living components, is self-regulating and can only be understood via systemic thinking. This later perspective is commonly referred to as the “Gaia Hypothesis”, originally developed by the chemist and environmental scientist Dr. James Lovelock in the 1960s and 1970s (Lovelock 1979) in connection with his work at the Jet Propulsion Laboratory in California on methods of detecting life on Mars.

experiments. For example, in some branches of life sciences, like botany or zoology, pictorial descriptions of a species based on photos of members of the species might be sufficient to establish that something new has been found. Some researchers may carry out such work all their lives and add more flora and fauna to their list. The work may remain primarily non-experimental and descriptive and still provide a background for theory development and make a valuable addition to scientific knowledge.

Yet another distinction, closely related to the distinction above between observational and experimental sciences, is the distinction between *law finding sciences* (physics, chemistry ...) that attempt to discover universal laws that apply to nature (always and everywhere), and *fact-finding sciences* (geography, history....) that are primarily descriptive. Note that even the fundamental concept of a 'scientific law' has been challenged by the renowned mathematician and philosopher of science, Alfred North Whitehead (1861–1947): "People make the mistake of talking about 'natural laws'. There are no natural laws. There are only temporary habits of nature." (Whitehead (1954), *Dialogues of Alfred North Whitehead*, Boston, USA: Little Brown; quoted in (Sheldrake 2012; 99).

Finally here, we can refer to a distinction between *historical science* (a longer time-scale characterizes the process involved—e.g. as in geological processes such the formation of the Himalaya Mountains) and *non-historical science* (where a far shorter time-scale is involved—e.g. as in chemical reactions). Even slow chemical reactions are extremely fast when compared to geological processes (Siever 1968).

2.2.4 Science as a Social Activity

A further characterization of science deals with its social aspects. Essentially all modern approaches to science assume that the facts and theories of science must survive critical study and testing. From this perspective, science also deals with obtaining consensus of rational opinion in the scientific community. According to (Ziman 1968 in Klemke et al. 1998; 51–2): "Technology, art and religion are perhaps possible for Robinson Crusoe, but law and science are not ... The young scientist ... learns by imitation and experiences a number of conventions that embody strong social relationships ... He learns to play his *role* in a system by which knowledge is acquired, sifted, and eventually made public property."

The ability to play such a role is developed, slowly but surely, via a process of socialization. The young, budding scientist observes how others at his laboratory/university behave and speak, and he or she receives guidance as to dissertation research, attends conferences at other institutions, reads articles and perhaps interacts with the editor of a journal in connection with a paper submitted for publication, receives feedback on grant proposals, and so on.

These social aspects of science are manifested in its institutionalization via more or less universally accepted norms as to what is "good" scientific behaviour, including:

- lack of bias
- maintaining data and records of one's research
- giving due credit to others who have contributed to one's research
- making the results of one's research available to the scientific community
- judging the scientific work of others solely on its merits.

We will directly or indirectly return to the concept of scientific norms when we consider such topics as: acceptance, peer review and the scientific community (in Chap. 3); the scientific method (Chap. 7); and the role of values and ethics in research (Chap. 10).

As we shall soon see, the next section on scientific revolutions concludes with a rather special and controversial perspective on the social aspects of science, one that turns ordinary more traditional approaches to science on their head. While by far the most common perspective on science is that it is a higher standard for what is true (as compared to e.g. common sense), the position to be considered is that science is not a higher standard which determines both the scientific community's as well as the layman's assent to truth—but vice versa: What makes a statement scientific is that scientists make the statement. Sociology replaces method in this rather radical account of what is scientific.

2.2.5 *Scientific Revolutions and Paradigms*

Based on the brief presentations earlier of the history of science and of the characteristics of science, it is tempting to accept the traditional assumption that science develops gradually over time and that it provides a continually improving standard for what is true knowledge. This section presents a contentious challenge regarding this traditional understanding of progress in science.

The challenge is to a great extent due to the path-breaking research on the history and sociology of science performed by Thomas Kuhn (1922–1996). In his book *The Structure of Scientific Revolutions* (1962, 1970),¹⁵ Kuhn introduced the now widely referred to concepts of “paradigm” (from the Greek word *paradigma* meaning “pattern”) and “paradigm shift” or its synonym, “scientific revolution”. The term paradigm is widely used by scientists today to refer to more-or-less universally accepted scientific positions or frameworks that, for a time, provide a community of scientific practitioners with a model for formulating and solving problems. It is not simply a current theory or set of theories, but rather a shared cultural lens—the whole worldview in which theories exist within a field, including the broadly accepted pre-suppositions, theories, practices, terminologies, schools of thought, and even values. A more concise and more popular phrasing would be: a scientific

¹⁵Originally published in 1962, the second and enlarged edition in 1970 includes a postscript where Kuhn replies to criticisms and where he provides sketches of revisions based on the criticisms.

worldview that shapes our perceptions of reality within a discipline. Examples of paradigms include Newtonian mechanics, Darwinian evolution, Maxwellian electromagnetics, Einsteinian relativity, quantum mechanics, and the psychoanalytic model of the unconscious mind. The term paradigm is now a very popular term that is (mis)used in many other realms of human experience than science.

In order to reflect on Kuhn's challenge to the traditional assumption that science develops gradually, continually and cumulatively, we must consider the following concepts he developed: "paradigms", "normal science", "anomalies", "crises" and "revolutions".¹⁶ I introduce these terms by considering the so-called Copernican revolution (Russell 2003; 20–25). For roughly 1500 years, astronomers had interpreted their observations based on the geocentric (earth-centred) model developed by the first century Greek philosopher Claudius Ptolemy (100–178). According to this model, the sun, moon, planets, and stars all revolve around the earth. This was a most reasonable assumption for these astronomers, even though there were problems with the model. For example, although the stars appeared to move along circular orbits, the planets appeared to wander among the stars; their orbits appeared to wobble, their speeds varied, and at times they appeared to reverse direction. These were examples of *anomalies* that the geocentric model could not explain. To get around such problems and to maintain the fundamental geocentric model, astronomers developed the concept of epicycles whereby the planets follow circular paths around larger circular paths (this enabled the paths to reverse directions as seen from the earth). When more accurate data showed that even this model had irregularities, more complex epicycles were developed, with circles rolling around circles rolling around circles, all to maintain the belief in circular motion of the celestial objects around an earth that was not moving and at the centre of the universe.

In the 16th century, Nicolaus Copernicus (1473–1543) showed that the existing geocentric model was incompatible with the radically different heliocentric model he had developed whereby the planets revolve around the sun. According to Copernicus, the apparent motion of the celestial bodies was an illusion (e.g. the rising and setting of the sun) caused by the motion of observers on earth—which was not stationary and was not even at the centre of the universe; it was just another planet revolving about its axis as well as around the sun. This challenged what everyone, including the scientists of his time, believed and that common sense supported; that the earth stands still and the planets, sun and stars all move around it. So radical, so heretical was this model that the clergyman Copernicus dared not publicize it for roughly 30 years, and only did so on his deathbed; the first copy of

¹⁶In his richly documented historical study of creativity Arthur Koestler presents similar reflections on the "jerky, unpredictable" development of science and relates the phases in the evolution of ideas in the individual scientist to that of the branch of science he works in: "The Eureka act proper, the moment of truth experienced by the creative individual, is paralleled on the collective level ...The collective advance of science as a whole, and of each of its specialized branches, shows the same alternation between relatively brief eruptions which lead to the conquest of new frontiers, and long periods of consolidation." (Koestler 1989; 225–26)

his little book *On the Revolutions of Celestial Spheres* was placed in his hands on the day he died.

The shift in the direction of a new *paradigm* was given a big shove in 1609 by Galileo Galilei whose observations in his newly invented telescope¹⁷ supported Copernicus's ideas. Amongst other things he had observed that Venus moved through phases, like the moon, indicating it circled the sun, and that moons orbited Jupiter, both of which went against the accepted paradigm which included the supposition that all heavenly bodies circled the earth.¹⁸ It should be noted here that when Galileo published his findings the Pope (the leader of the worldwide Roman Catholic Church) demanded that he retract his heretical ideas, which he did to save his life. Later, in 1632 he once again published his observations and defended Copernican theory—and once again he was forced to retract his statements and was then condemned to house arrest for the remainder of his life. According to Cardinal Bellarmine who participated in the trial of Galileo, "To assert that the earth revolves around the sun is as erroneous as to claim that Jesus was not born of a virgin." (Russell 2003; 24)

The *paradigm shift* received another shove when the German mathematician Johannes Kepler, using data provided by the Danish astronomer Tycho Brahe, showed that even if the planets were orbiting the sun, they were not following circular orbits. Kepler was able to explain all the apparent irregularities in the orbits of the planets if they were assumed to follow elliptical orbits. The reason for such orbits was first provided 70 years later when Newton showed that all heavenly bodies are governed by exactly the same laws as earthly objects and that *any* orbiting body would move in an ellipse. This completed the paradigm shift or *scientific revolution*. It took 150 years and significant breakthroughs by scientists from five countries before the key idea developed by Copernicus—that the sun is at the centre of our solar system—became accepted. However, it was not until 1992

¹⁷Although another person had already developed a similar tool (he was denied a patent), and although "Galileo astonished the world when he turned the telescopic toys, invented by Dutch opticians, to astronomic use." (Koestler 1989; 102), Galileo Galilei's refraction telescope from 1609 was the first well-functioning and patented telescope. Already in March, 1610 he published his book *Sidereus Nuncius* (translated into English as *The Sidereal Messenger* by Albert van Halden in 1989, but often referred to as *The Starry Messenger*) where he described his telescope and his observations of the moon, stars and the moons of Jupiter.

¹⁸In addition to demonstrating that these heavenly bodies did not orbit the Earth, Galileo also provided a bold conjecture about motion and friction that lent support to the "Copernican Revolution". Since Aristotle, philosophers/scientists had believed that in order for an object to sustain its motion, an external source of energy is required. Therefore, if the earth is revolving about its axis as it orbits the sun, a force must be pushing the Earth, which would result in a huge wind from the East. Galileo Galilei conjectured that without friction to slow it, an object will sustain its speed without any force "pushing" it, whereby it made sense that the Earth (together with the air around it) turns on its axis. It can be added that Newton (1642–1727) built upon Galileo's analyses of motion and inertia; his famous first law of motion essentially states that a force is not needed to keep an object in motion; in fact a force such as friction is required to bring a moving object to rest.

that the Vatican, the central governing body of the Catholic Church, formally apologized for its treatment of Galileo!

Another, more “modern” example of a “scientific revolution”, and one that took place in a far shorter period of time, is when Newtonian mechanics gave way to Einstein’s relativity. This paradigm shift occurred when experiments piled up data that falsified Newtonian mechanics for velocities approaching that of light, but fitted the theory of relativity.

Based on the study of these, and many other developments in science, particularly in physics, Kuhn developed his thesis that the development of knowledge does not take place in a purely cumulative manner, as commonly assumed, but in a far more discontinuous and revolutionary manner, such that the transition from one paradigm to the next is not smooth. Thus, according to Kuhn, the history of science has alternating episodes of *normal science*, during which scientists refine and apply an accepted paradigm, and episodes of *revolutionary science*, during which scientists switch to a new paradigm, and thereby to new norms for the practice and understanding of normal science.

In a nutshell, according to Kuhn, such a switch occurs when a stable period of *normal science*, characterized by *puzzle solving*, is replaced by a *crisis*, arising from observed and persistent *anomalies*—failures of the current paradigm to take into account observed phenomena. Such crises can lead to periods where bold scientists embark on *revolutionary science*. They explore alternatives to the long held, and what have seemed to be obvious, assumptions characterizing the existing paradigm.

During periods with anomalies, most practicing scientists do not lose faith in the established paradigm and in the normal science they practice, since no credible alternative is available. Were they to lose faith, they would face huge challenges to their role and identity as scientists and as members of the scientific community. Occasionally the explorations lead to the identification of one or more new candidates that challenge the established frame of thought. These will of course be severely countered by the practitioners of normal science—and often such practitioners’ confidence in the established frame of reference has been vindicated. But if the challenges due to the anomalies persist, and if credible alternatives become available, according to Kuhn a phase develops where more-or-less incompatible and incomplete theoretical frameworks coexist. If, over time, the challenging paradigm demonstrates its ability not only to solve the problems solved by normal science, but to convincingly deal with the anomalies that have persisted and resisted solution using normal science, a transition period obtains that leads eventually to a scientific revolution—a paradigm shift.

Kuhn speaks of revolutions because he argues that different paradigms, before and after a shift, are incommensurable—not only do scientific beliefs about nature change, but also the standards and criteria of scientific judgement change. Textbooks are rewritten—often the history of science is rewritten. Therefore scientific revolutions are like religious conversions. There is a transfer of allegiance that is not simply brought about by solid logic and objective evidence. The process of such paradigmatic change is a most complex social process, where many beliefs,

standards and explanations are replaced—and where the status, self-conceptions, language, and practices of scientists are modified.

This leads to the position that science is not a higher standard which determines the scientific community's assent to truth—but vice versa. Sociological phenomena replace scientific method in this rather radical account of what is scientific, where what makes a belief scientific is not the underlying methodology of investigation, but what scientists say about the belief. Science, according to this perspective, is simply what scientists say it is.

For most scientists, these are radical and upsetting ideas. They share adherence to more-or-less traditional and stable worldviews as to science and its methods. They reply that science certainly does progress in a continual manner and that paradigm shifts, if they occur at all, are not characterized by incompatible worldviews. Certainly at the level of practical day-to-day scientific research, our ability to develop technology based on scientific findings demonstrates that the methods of science find much that we can call truth and that we are able to confirm. From this more traditional perspective, progress and truth are intertwined and science is far more than what scientists simply say it is; the strength of its statements lies in its methods and the vigilance of the scientific community in controlling its results.

Having reflected for some time now on what “science” is we should now be prepared to consider now what it is not.

2.3 Science and Non-science/Pseudo-science

Science (as an activity, profession and institution) is highly regarded by most people, even though there have been serious criticisms of science and of scientists for contributing, directly or indirectly, to the development of debatable technologies. These include weapons of mass destruction, products and production processes that pollute the environment, techniques for controlling our movements and invading our privacy, and for engineering our genes. But on the whole, “science” is considered by the great majority of people to be a positive buzzword—it is widely regarded as providing not only advanced technologies that can contribute to our wealth, well-being and health, but also to knowledge that enriches our lives and make them meaningful.

But what distinguishes science from non-science? I note that many philosophers of science prefer to use the derogatory but perhaps more precise term “pseudo-science” when the promoters of say astrology or faith-based theories such as creationism present their methods and results as though they are in accord with traditional scientific standards.

In the seminal work “Science: Conjectures and Refutations”, Karl Popper (Popper 1957 in Klemke et al. 1998) attempted to distinguish science from non-science. He referred to:

... the autumn of 1919 when I first began to grapple with the problem, ‘*When should a theory be ranked as scientific?*’ or ‘*Is there a criterion for the scientific character or status of a theory?*’ The problem which troubled me at the time was neither, ‘When is a theory true?’ nor, ‘When is a theory acceptable?’ My problem was different. I *wished to distinguish between science and pseudo-science*; knowing very well that science often errs, and that pseudo-science may happen to stumble on the truth.” (Ibid.; 38)

His interest for these matters developed in Austria after the First World War based on his readings of Einstein’s theory of relativity, Marx’s theory of history, Freud’s psychoanalysis and Adler’s so-called “individual psychology”.¹⁹ He became increasingly dissatisfied with the last three theories and their claims to scientific status: “... these other three theories, though posing as sciences, had in fact more in common with primitive myths than with science; they resembled astrology rather than astronomy.” (Ibid.; 39) The underlying reason was that these theories appeared to be compatible with the most divergent human behaviour; they could be interpreted so they appeared to always lead to correct predictions. What in the eyes of their admirers appeared to be strong arguments supporting the theories, for Popper began to resemble weaknesses.

Things were quite different with Einstein’s theory. The British astronomer, mathematician and physicist Arthur Eddington (1882–1944) had just performed observations that confirmed Einstein’s gravitational theory which implied that light must be attracted by heavy bodies (such as the sun). He had subjected Einstein’s theory to a strong test: If observation had shown that the predicted bending of the light was absent, strong arguments would exist for refuting the theory. Such considerations led Popper to the following conclusions (Ibid.; 40; my synthesis):

1. It is easy to obtain confirmations/verifications for nearly every theory—if we look for them.
2. Confirmations should count only if they are the result of risky predictions.
3. Every good scientific theory is a prohibition—it forbids certain things to happen. The more it forbids, the better the theory.
4. Theory that is not refutable by any conceivable event is non-science.
5. Every genuine test of a theory is an attempt to falsify it, to refute it.
6. Some theories are more testable than others in that they forbid more outcomes, take so to speak a greater risk.
7. Evidence should not count as a confirmation unless it is the result of a genuine test—a serious but unsuccessful attempt to falsify it.
8. Some genuinely testable theories, when found to be false, are still upheld by their admirers—for example by introducing some auxiliary assumptions or reinterpreting the theory—this is at the price of lowering their scientific status.

¹⁹Alfred Adler (1870–1937) was an Austrian medical doctor and psychologist, founder of the school of individual psychology and especially known for introducing the concept of “inferiority complex”. Adler had a major effect on the development of psychotherapy in the course of the 20th century.

Summing up the above, Popper concluded (Ibid.; 40): “*The criterion of the scientific status of a theory is its falsifiability, or refutability, or testability.*”

I underscore here that Popper was not concerned with the meaningfulness, significance, utility, truth or acceptability of a theory, but only with the problem of drawing a line between statements founded in empirical science and all other statements. This has since been referred to as “the problem of demarcation”. We will return to the concept of falsification in more detail later on in Chap. 4 as it is one of the major ingredients in consideration of how theories can be justified. Although many scientists today disagree with some of Popper’s conclusions, they are all worthy of serious contemplation and discussion by reflective practitioners of science.

Let us now reflect on this issue of the demarcation of science from non-science/pseudo-science by considering specific several examples provided by (Lee 2000; Chap. 7), who argues that it is better to reject a few correct ideas than to accept many incorrect ones and that well-established theories should not be discarded easily. Therefore pseudo-scientists must provide strong evidence in order to overthrow conventional scientific knowledge; the more outrageous the claim, the stronger the evidence must be (Ibid.; 134).

Astrology: This is the classic case in almost all writings on non-science/pseudo-science. According to Lee, the assessments made are typically vague and this leaves much room for interpretation which makes people believe its predictions were specifically made for them, when in fact they apply to many people. He also provides evidence that when astrology is subjected to careful experiments, it fails.

Note however that (Thagard 1978 in Klemke et al. 1998; 67–69) provides strong arguments that challenge such experimental approaches to declaiming the scientific nature of astrology. In addition, Thagard argues that astrology cannot be condemned as pseudo-scientific on the grounds typically proposed, such as those dealing with its origin, its lack of a physical foundation, or its lack of verifiability. Rather, he argues that astrology is pseudo-science for the following two principle reasons that are said to provide a basis for distinguishing between science and pseudo-science:

1. It has been less progressive than alternative theories over a long period of time, and faces many unsolved problems (progressive here refers to the success of a theory in adding to the set of facts it explains and the problems it solves; my comments);
2. In spite of this, the community of practitioners has made little attempt to develop the theory towards solutions of the problems, shows no concern for attempts to evaluate the theory in relation to others, and is selective in considering confirmations and disconfirmations.

I note in this connection that Thagard also provides strong arguments *against* a statement from 1975 and signed by 192 leading scientists, including 19 Nobel Prize laureates, attacking astrology as pseudo-scientific. He does so not because he disagrees with their conclusion, but because of their arguments, each of which he argues could be applied to what are now firmly established domains of science. (Ibid.; 70–71) There is much food for thought here for reflective scientists!

Lysenkoism: The theories of Lysenko (that rejected much of what was at the time accepted by most biologists, especially Mendelian genetics) strongly affected the agricultural and biological sciences in the Soviet Union from the 1930s to the 1960s—with disastrous consequences. Lysenko's theories concerned, amongst others, the transformation of species. He argued that young plants do not compete with others of the same species in a given environment and that if they are planted in clusters, most will sacrifice themselves for the good of the species and let one or a few survive. This was in line with the collectivist-ideology of the Communist regime and led Stalin to order the planting of vast belts of forests in the grasslands of the southern Soviet Union so as to alter the climate and make the region better for agriculture. The results were disastrous for the grasslands and the farmers. Lysenko also claimed that a species can be transformed into other species quickly (in opposition to most Darwinian-based theories of evolution), and that if a plant lives in an environment where it is poorly suited to survive, within that plant, seeds or buds of a better adapted species will develop. Many scientists supported his work, claiming that they had experimental observations that supported his theories; this is believed to have been a result of the great pressures on them by the government as well as of the chance of improved working conditions if they supported Lysenko's theories. Those scientists who opposed his thinking were removed from their positions, or suffered a much worse fate. There was no real peer review; no open and honest criticism was permitted.

Creation "Science": This "science" is based on the belief that the book of Genesis in the Old Testament of the Bible provides an accurate description of Earth history. According to the interpretations made by the supporters of "Creationist Science" (often also referred to as "Intelligent Design", although this term implies a less strict or fundamentalist interpretation of the Bible and emphasizes instead a rejection of Darwinian evolution), the Earth is 6–10,000 years old. According to this "science", fossils are remnants of the Great Flood from the time of Noah. In particular, the theory of evolution is said to be invalid because according to the Bible all plant and animal species were created in their present form.

Creationism is promoted in particular by certain fundamentalist Christian groups in the USA and is supported by a number of scientists as well as politicians who share its religious foundation.²⁰ Its method is to start with "theory" (the interpretations of the book of Genesis) rather than with existing evidence and to seek evidence that supports the creationist perspectives and that goes against other theories which are a result of established science. For example, Creationists challenge the technique of radioactive dating that shows the Earth to be roughly 4.55

²⁰Not only fundamentalist Christians support creationist perspectives. For example, the spiritual organisation, the Brahma Kumaris, based in Mount Abu in Rajasthan, India, which emphasizes social and environmental action, also supports similar perspectives. They do so within a framework of a cyclical cosmology, whereby history repeats itself every roughly 5000 years when a new phase of creation occurs. It is interesting to note that in spite of the fact that the organization ascribes to a cosmology that is rejected by modern science, since 1983 it achieved consultative status with the Economic and Social Council at the United Nations.

billion years old. They use fossil records to argue that the theory of evolution is false because fossils showing transition from one species to another are not found—while biologists say they have such evidence. Likewise, Creationists argue there is no widely supported theory for the origin of life on Earth, and therefore argue that this must have been divinely accomplished.

In a nutshell, while the theory of evolution as well as the theory that the Earth is billions of years old is well supported by evidence, Creation Science is poorly supported by empirical evidence.

With the provocative title: “Believing Where We Cannot Prove,” (Kitcher 1982/1998) provides an in-depth treatment of the perspective by Creationists that the theory of evolution is wrong and that it is not part of science because, according to them, science demands proof and evolution cannot be proved. Kitcher’s point is that “...science is not a body of demonstrated truths. Virtually all of science is an exercise in believing where we cannot prove. Yet scientific conclusions are not embraced by faith alone”. In his concluding remarks, he notes: “Like Newton’s physics in 1800, evolutionary theory today rests on a huge record of successes. In both cases we find a unified theory whose problem-solving strategies are applied to illuminate a host of diverse phenomena. Both theories offer problem solutions that can be subjected to rigorous independent checks. Both open up new lines of inquiry and have a history of surmounting apparent obstacles. The virtues of successful science are clearly displayed in both.” (Ibid.; 32/78)

UFOs (Unidentified Flying Objects): The evidence provided by believers in UFOs is challenged by many scientists who claim that human perception and memory are not reliable under conditions like those where UFOs are reported to have been spotted. Nevertheless, there are many respected people that have given detailed descriptions of UFOs; see e.g. the website <http://www.ufoevidence.org/researchers/index.asp> and the website of the international organisation promoting research on UFOs: <http://www.ufoevidence.org/>.

Among the other domains that Lee (2000; Chap. 7) categorises as pseudo-science are *paranormal/extrasensory phenomena and perception* and *health related pseudo-science* (including essentially the whole field of so-called alternative medicine).

In contrast to Lee’s position, which is mainly in the form of common sense and scientific reasoning rather than empirical investigation, in *The Conscious Universe: The Scientific Truth of Psychic Phenomena*, (Radin 1997) provides extensive empirical evidence based on controlled experiments of the existence and effectiveness of the very paranormal/extrasensory phenomena that Lee categorises as pseudo-science. Included in Radin’s investigations are mind-to-mind connections (telepathy), perception of future events (precognition), perception of distant objects and events (clairvoyance) and mind-matter interaction (psychokinesis).

In this connection I note that the history of science clearly demonstrates that what at one time was considered to be non-science by the scientific community later on became accepted as powerful pillars of existing science; “Newton’s notions of a field of force and of action at a distance and Maxwell’s concept of electromagnetic

waves were at first decried as ‘unthinkable’ and ‘contrary to intuition.’” (Feller 1968; 2)

According to Kuhn: “Closely examined, whether historically or in the contemporary laboratory, that enterprise (normal science; my comment) seems an attempt to force nature into the pre-formed and relatively inflexible box that the paradigm supplies. No part of the aim of normal science is to call forth new sorts of phenomena; indeed those that will not fit the box are often not seen at all. Nor do scientists aim to invent new theories, and they are often intolerant of those invented by others.” (Kuhn 1970; 24)

So it appears that demarcating science and pseudo-science is not all that simple and straightforward. Although a number of positions have been presented here regarding the distinction between what is science and what is non-science or pseudo-science, what Popper referred to as the problem of demarcation is not solved once and for all. While you may have an intuitive feeling regarding such a distinction, the following exercise indicates that the intuition of even highly educated people, including those with backgrounds in science, can lead to conclusions and behaviour that are at odds with scientific thinking.

2.3.1 An Exercise as to Science and Pseudo-Science

The following is a “case study” that concludes the section of (Klemke et al. 1998) dealing with “Science and Pseudo-science” (pp. 99–100):

“The following is a letter which was received by the editor of a science journal.

‘Dear Sir:

I am taking the liberty of calling upon you to be the judge in a dispute between me and an acquaintance who is no longer a friend. The question at issue is this: Is my creation, umbrellalogy, a science? Allow me to explain...For the past 18 years assisted by a few faithful disciples, I have been collecting materials on a subject hitherto almost wholly neglected by scientists, the umbrella. The results of my investigations to date are embodied in the nine volumes which I am sending to you under separate cover. Pending their receipt, let me describe to you briefly the nature of their contents and the method I pursued in compiling them. I began on the Island of Manhattan. Proceeding block by block, house by house, family by family, and individual by individual, I ascertained (1) the number of umbrellas possessed, (2) their size, (3) their weight, (4) their colour. Having covered Manhattan for many years, I eventually extended the survey to other boroughs of the city of New York, and at length completed the entire city. Thus I was ready to carry forward the work to the rest of the state and indeed the rest of the United States and the whole known world.

It was at this point that I approached my erstwhile friend. I am a modest man, but I felt I had the right to be recognized as the creator of a new science. He, on the other hand, claimed that umbrellalogy was not a science at all. First, he said, it was silly to investigate umbrellas. Now this argument is false, because science scorns not to deal with any object, however humble and lowly, even to the ‘hind leg of a flea.’ Then why not umbrellas? Next, he said that umbrellalogy could not be recognized as a science because it was of no use or benefit to mankind. But is not truth the most precious thing in life? Are not my nine volumes filled with the truth about my subject? Every word in them is true. Every sentence

contains a hard, cold fact. When he asked me what was the object of umbrellaology I was proud to say. “To seek and discover the truth is object enough for me.” I am a pure scientist; I have no ulterior motives. Hence it follows that I am satisfied with truth alone. Next, he said my truths were dated and that any one of my findings might cease to be true tomorrow. But this, I pointed out, is not an argument against umbrellaology, but rather an argument for keeping it up to date, which exactly is what I propose. Let us have surveys monthly, weekly, or even daily, to keep our knowledge abreast of the changing facts. His next contention was that umbrellaology had entertained no hypotheses and had developed no theories or laws. This is a great error. In the course of my investigations, I employed innumerable hypotheses. Before entering each new block and each new section of the city, I entertained a hypothesis as regards the number and characteristics of the umbrellas that would be found there, which hypotheses were either verified or nullified by my subsequent observations, in accordance with proper scientific procedure, as explained in authoritative texts. (In fact, it is of interest to note that I can substantiate and document every one of my replies to these objections by numerous quotations from standard works, leading journals, public speeches of eminent scientists, and the like.) As for theories and laws, my work represents an abundance of them. I will here mention only a few, by way of illustration. There is the Law of Colour Variation Relative to Ownership by Sex. (Umbrellas owned by women tend to a great variety of colour, whereas those owned by men are almost all black.) To this law I have given exact statistical formulation (See vol. 6, Appendix 1, Table 3, p. 582.) There are curiously interrelated Laws of Individual Ownership of Plurality of Umbrellas and Plurality of Ownership of Individual Umbrellas. The interrelationship assumes the form, in the first law, of almost direct ratio to annual income, and in the second, in almost inverse relationship to annual income. (For an exact statement of the modifying circumstances, see vol. 8, p. 350.) There is also the Law of Tendency Toward Acquisition of Umbrellas in Rainy Weather. To this law I have given experimental verification in Chap. 3 of Volume 3. In the same way I have performed numerous other experiments in connection with my generalizations.

Thus I feel that my creation is in all respects a general science, and I appeal to you for substantiation of my opinion”

Dear reader, please compose a reply to this letter based on the chapter you have just read.

Based on considerable experience with my former students in science I predict that it will not be easy for you to develop a strong, rational argument for categorizing “umbrellaology” as science or as non-science.

2.4 The Aims and Claims of Science

Earlier I referred to the often stated distinction between science as *creating* knowledge (what is generally referred to as “pure science”) and science as *applying* knowledge (“applied science”). Clearly, these have different ends.

The aims associated with pure science can be said to deal primarily with the aims of the individual scientist and with that of science as an institution, rather than with its utility in the form of contributions to technologies and products.

If we consider first the aims of the *individual scientist*, we can say that these most likely include at least the following: a) the pursuit of knowledge—to become a more knowledgeable, more competent scientist, b) the satisfaction that is derived

from using one's intellectual powers—to grow as a person and to receive recognition from one's colleagues, and, hopefully, c) to contribute to the well-being of society and of the world.

When we consider the aims of *science as an institution*—and here I emphasize the natural sciences—we tend to focus on establishing true and generalizable statements about the world, i.e. on improving the existing descriptions, explanations and predictions as to physical reality. For example, according to (Kitcher 1982 in Klemke et al. 1998; 79): “Scientific investigation aims to disclose the general principles that govern the workings of the universe. These principles are not intended merely to summarize what some select groups of humans have witnessed ... Science offers us laws that are supposed to hold universally, and it advances claims that are beyond our power to observe. The nuclear physicist who sets down the law governing a particular type of radioactive decay is attempting to state a truth that holds throughout the entire cosmos and also to describe the behaviour of things that we cannot even see.”

But this apparently straight-forward and clear aim “to disclose the general principles that govern the workings of the universe” is perhaps not as clear, or at least not as generally applicable, as we tend to think it is. According to the internationally recognized founder of “the Copenhagen School” in atomic physics, Nobel Prize laureate Niels Bohr (1885–1962), it is “wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can *say* about nature.” (Pais 1991; 427) In other words, according to Bohr, at least at the micro-level of the atom and sub-atomic particles, science does not aim at presenting a true picture of nature, but only of improving our ability to *speak about* nature.²¹

This was in line with Bohr's philosophical reflections on our ability as language-users to describe events in a quantum reality that is so far removed from our experience as humans. We will return to this subtle distinction in Sect. 2.7 of this chapter when we discuss the concepts of realism and anti-realism.

Over and above aims as to disclosing or speaking about the principles that govern the workings of the universe, science can also be considered as having the aim of improving its *own ability* to describe, explain and predict. We generally think of applied science as having the aim of improving our ability to control, plan and utilize resources (physical and social) for practical purposes, in contrast to pure or basic science's more fundamental aims of generating knowledge for the sake of

²¹From this perspective, at the quantum level, the laws of nature no longer deal with the elementary particles but with our knowledge of them such that, for example, an electron does not have properties such as its position or momentum unless it is observed via measurement. According to (Morrison 1990; 41), “... the central question of wave-particle duality is not ‘can a thing be both a wave and a particle?’ Rather, the question is, ‘can a thing be *observed* behaving like a wave and a particle in the same measurement?’ Bohr's answer is no: in a given observation, quantum particles exhibit *either* wave-like behaviour (if we observe their propagation) *or* particle-like behaviour (if we observe their interaction with matter). ... Note that by restricting ourselves to observed phenomena, we are dodging the question: ‘what is the nature of reality behind the phenomena?’ Many quantum physicists answer, ‘there is no reality behind the phenomena.’”

knowledge. But since science also aims at improving its own capabilities to generate valid knowledge, it aims not only to improve our knowledge of the world but also *to improve our ability to improve our knowledge*. In this way, the borderline between pure and applied science becomes amorphous. The development of electron microscopes, laser technology, cloud chambers, nanotechnology and radio telescopes are examples of how scientific theories indirectly extend our perceptual capabilities, just as the development of computer models, for example as to development in climatic conditions, indirectly extend our cognitive abilities.

Furthermore, if a primary aim of science is to develop general laws from specific observations, a number of branches of science have difficulty in living up to this aim. Physics is the domain where generalizations based on empirical investigation are relatively easy to make (not that performing research in physics is an easy matter!). This is due to the fact that, with many exceptions of course, the data that physicists work with has relatively small variances compared to analyses in other fields. In addition, physics has a foundation in first principles dealing with the fundamental nature of matter and energy. This ability to build upon first principles is reduced as one moves further away from the well-structured domain of physics, with its apparent isomorphic relationship with mathematics (whereby the physical universe appears to be subject to precise description using the language and logic of mathematics), to that of chemistry and other natural sciences, to the life sciences such as biology and botany, to the behavioural sciences such as psychology and anthropology, and to the social sciences such as sociology and economics. In each case, as we move further away, so to speak, from physics, the data tend to have larger and increasing variances, such that when we reach the behavioural and social sciences, generalizations in the form of precise and widely accepted theories/laws do not exist—even though these branches of science with living organisms, organisations, and cultures as their objects of study, have their own norms and methodologies.

I note as well that there is also a very large variance in the data in some areas of scientific investigation where controlled experimentation is not possible, and where perhaps only one or a very limited number of observations is possible, and perhaps only very indirectly. Consider for example the investigation of such historic processes and phenomena as the origin of life on Earth, organic macroevolution, and the development of mountain ranges—and more modern processes and phenomena such as the effects on people and the environment of global warming and of massive catastrophes such as melt-downs at nuclear power stations (e.g. Chernobyl in Ukraine, 1986), the emission of dioxin into the air (Bhopal, India 1984), or the tsunami that devastated parts of southeast Asia in 2004. Since the relevant data generated by such phenomena are not obtained via experimentation they tend to have relatively large variances, whereby generalization becomes extremely difficult in these fields of study. Which is not the same as saying that scientists cannot and should not study such phenomena; in fact, just the opposite is true, and the catastrophes referred to have provided scientists with a wealth of data that enable research into their causes and effects.

Returning now briefly to applied science in general, the closer the scientific endeavour is focused on application the greater is the focus on empirical investigation rather than on first principles. According to (Siever 1968; 38): "... we have fields, such as engineering, where empiricism is the order of the day simply because there is no generally valid group of first principles from which to operate."

Thus, although the overall aims of science as an institution may be the same, no matter which branch of science we focus on, there are major differences in the ability of the various domains of science to provide accurate descriptions, explanations and predictions of physical reality.

Let us now delve a bit deeper into the claims of science and follow the arguments of (Gauch 2003; 28–41, 72), who argues that all natural scientists implicitly make four principle claims and that it is the simultaneous assertion of all four of these interconnected claims that fully expresses science's boldness.

Rationality: Rationality is good reasoning that regulates belief and guides action. Rational persons base their beliefs on evidence and reasoning. Scientists are rational and they use such beliefs to guide their actions so they are in accord with the goal of science of developing true statements (theories and laws) regarding the universe. I note however that stories told by creative scientists throughout the ages indicate that scientific discovery is often kick-started by *a*-rational processes (Koestler 1989; 208). We will consider the limits of rationality in science in greater detail in Sect. 2.5.3.

Truth: From a scientific perspective, truth is a property of a statement; true statements correspond with reality and truth is determined by the objective state of nature. In other words, according to this so-called "correspondence theory of truth" there is a correspondence between the external physical world of objects and events and the internal mental world of perceptions and beliefs—and where reality has priority over belief. Such truth claims can be made with various levels of confidence but not with absolute certainty. As we have reflected on earlier, as observers, analysers, and mediators we are fallible; scientific knowledge is tentative and subject to revision.

Objectivity: The dominating idea of objectivity in science, what we might refer to as classical objectivity, concerns observer-independent knowledge, i.e. knowledge about physical objects that exist independently of our observations. Such knowledge can be tested and verified so that consensus will emerge among knowledgeable persons. Thus there is a strong link between objectivity and inter-subjective agreement. It is this link that characterizes the consensual activity in what we earlier referred to as the "scientific community" where objective knowledge is considered to transcend political, religious and cultural divisions.

I note however that, as we recently touched on, at the micro-level of atoms and quarks, the indeterminacy of the quantum world implies that the classical idea/ideal of an objective reality must be replaced by the concept of an observer-dependent reality where what one measures depends on the apparatus used and on what has been chosen to observe. As strange as this may sound to observers who do not investigate quantum weirdness, one cannot speak of events in the micro-world without observing them.

I note too that the focus in the natural sciences on observer-independent truths about external physical objects is perhaps the major characteristic that differentiates the natural from the social sciences. In the social sciences understanding and decision

making are often more in focus than truth, and the “external objects” are humans or collectivities of humans (groups, organisations) that may be affected by, and affect, the researcher’s behaviour, rather than observer-independent physical entities.

Realism: Realism is the contention—the metaphysical presupposition—that physical objects exist independent of human thought and that our minds and senses enable access to the physical world so that it can be reliably known—that there is a correspondence between human thought and an external, independent reality. This is clearly closely related to the concept of objectivity considered above. We will return to the notions of realism and its counterpart, anti-realism, in Sect. 2.7 of this chapter.

2.4.1 *Science and Democratic Development*

Finally, over and above such aims of science, there are also aims that are far more general and involve society as a whole. In order for a democracy to function well, citizens have an obligation to be informed on issues that face the government. Since many such issues have a scientific component, for example, those dealing with environmental and educational policy, it follows that an aim of science is/should be to help citizens to develop a scientific literacy so as to be better able not only to make their own decisions, but also to contribute to the decisions made by their political representatives (Lee 2000; 7).

This aim with regard to democratic development is far from being achieved and the ability to achieve it is perhaps decreasing, rather than increasing, due to the accelerating increase in scientific knowledge. On the one hand, increased specialization within the sciences makes it increasingly difficult for ordinary citizens, even those who are “scientifically literate”, as well as for professional scientists too for that matter, to understand the results and implications of highly specialized scientific investigations. On the other hand, when we face more complex, interdisciplinary investigation, even greater demands may be placed on us if we are to be able somehow, directly or indirectly, to contribute to the decision making processes of our political representatives.

In order to obtain the level of scientific insight that can empower a citizen to contribute to democratic development may require both a reasonably strong background in one or more fields of science as well as considerable investments of time and energy. Consider e.g. the demands on our understanding if we are to be able to meaningfully contribute to societal debate on such issues as global warming, the long term implications of using nuclear power for the generation of electricity, the effects of permitting patents to be taken out on genetic structures and computer software, the effects of building dams on local and regional economies as well as on the environment, the effect on our morals and belief systems of genetic engineering (e.g. cloning, stem cell research), etc. In each case, the ability of citizens to decide for themselves and to contribute to democratic/parliamentary decision making presumes an ability to deal with complex issues that far exceed the talents and knowledge of most ordinary human beings, including politicians and scientists, as such issues often involve not only scientific but also social, economic, ecological and ethical aspects!

An article in the major Indian daily newspaper, *The Hindu* (January 28, 2007), “Taking science out of the labs”, presents a more optimistic perspective on democracy and science. Rather than focusing on an obligation of science to inform the citizenry, it deals with the participation of ordinary people in the conduct of experiments. The article commences as follows: “Radical biologist Rupert Sheldrake is working to change the way people think about science.” It continues by citing Sheldrake, who is Perrick-Warwick Scholar at Trinity College, Cambridge University:

I think we need to change not only the content of science and what it is about but also the way science is done. Western science was shaped by the needs of the industrial revolution, the needs to produce machines, so the image of scientists was of an elite priesthood. This spread across Europe and to India too. Science excludes ordinary people. A democratic society like ours, where computing power is available to everybody, creates a condition for a new way of doing science. ... Participatory research will become very big, very fast, as this transformation will happen through the internet.” The article notes that Sheldrake’s research “involves ordinary people conducting experiments at home and through his website: www.Sheldrake.org. His highly successful participatory online experiments have led Microsoft, Google and, recently, AOL, to show interest in his work.

These thoughts as to the difficulties—and possibilities—involved in living up to major aims of science pave the way to the next issue to be considered in these reflections on science: its limitations.

2.5 The Limitations of Science

When we use a tool or technology in our daily lives we are usually interested not only in its capabilities, but also in its limits. A lack of such knowledge can lead to an ineffective use of the tool (the battery on my laptop will only supply me with power for a limited period of time), to its destruction (cameras may be sensitive to heat; frozen food can only maintain its freshness for a limited period of time)—or even to the user’s own destruction (too much of a pain-killer can kill you). Certainly therefore reflections on research methodology should also include consideration of the limitations of science.

According to the American Association for the Advancement of Science (AAAS), which is the world’s largest scientific society and the umbrella organisation for roughly 300 societies and academies, “Being liberally educated requires an awareness not only of the power of scientific knowledge but also its limitations.” Furthermore, according to the AAAS, learning the limits of science “should be a goal in all science courses”. (AAAS 1990; 20–21)

We have already briefly considered limitations that are a result of our limited abilities to objectively observe physical reality. These limitations arise due to our physical characteristics (the limits of the senses in perceiving), our limited experiences and our varying expectations. We will now consider some other principle limitations of science—limitations in its “special way of looking at the world” and its “method of discovering, generating, testing, and sharing true and reliable knowledge about physical reality.”

2.5.1 *Presuppositions—and Science as Faith*

Let us start by considering the proposition that just as geometry is based on a number of axioms (statements that are not proven or demonstrated to be valid but whose truth is taken for granted), so is science based on a set of presuppositions or beliefs that cannot be proved by logic or firmly established by evidence. *IF* this proposition is correct, then it would be reasonable to conclude that since science rests on a foundation of statements that are assumed to be true but that cannot be proved/firmly established, *science fundamentally is a matter of faith!* A statement that many scientists would find shocking due to their lack of serious reflection on the foundations of their fields of endeavour and their strong faith (!) in science as providing true and objectively testable knowledge of physical reality.

But is the proposition true? This appears to be the case. There are certainly a number of what we might be tempted to call common sense propositions underlying science. For example that the physical world exists, that it is orderly, that our sense perceptions are generally reliable, and that rational thought can synthesize the ordered reality of the physical world and the observations of our senses into true and reliable knowledge—in other words, that the physical world is comprehensible. Later on, we will reflect in some depth on these most fundamental presuppositions of science in connection with the treatment of “realism”.

Here, let us instead start by reflecting on another of the major presuppositions, part of the metaphysics one might say, of science: that we are (or at some time will be) able, either directly or indirectly, with the aid of technology that extend our perceptual and cognitive abilities, to observe or measure every physical object/phenomenon that exists. In other words, that our intellect and senses enable us to access all of objective reality.²² By this we do not require that we have access to these objects and phenomena here and now, since some may at present be outside of the direct reach of our measuring instruments, for example sub-atomic entities or some objects/phenomena in outer space or at the middle of the Earth or that occurred earlier in time. What we are talking about here is the implicit assumption

²²As we have briefly considered earlier, quantum physics in particular presents us with the following dilemmas as to what we even mean when we speak of “objective reality”: (1) the properties of microscopic entities are not, in general, well defined *until* they are measured, and (2) since interaction between an observer and the observed is unavoidable, and since a microscopic system cannot be observed without the process of observation altering some its properties, it is meaningless, at least at the level of the microscopic world, to speak of an objective world that exists external to and independently of our perceptions and therefore to speak of physics as studying objective reality (Morrison 1990; 7–8).

of the natural sciences that whatever exists is *potentially* subject to our observation, experimentation and measurement.²³

To commence reflection on this implicit assumption, suppose that there are in fact phenomena that we do not and cannot have access to via our senses and intellect, such as e.g. the generation of thoughts or so-called psychic/paranormal phenomena.

Let us consider first the generation of thoughts. Most scientists would agree that at present we are limited in our ability to observe and measure such processes, even though they could point to the increased focus by neuroscience on analyses of the brain via scanning technologies. They might very well contend that since (and here comes another major presupposition) everything that exists has a physical cause, thought generation, self-awareness and all of conscious activity will at some time be observable/measurable.²⁴ They might also argue that all conscious activity will eventually be reducible (here comes yet another major presupposition!) to chemical, electrical and biological activity in the brain and central nervous system. Therefore, according to this materialist and reductionist line of thought, at some time, when our understanding of the brain and our measuring instruments are sufficiently improved, consciousness and the generation of thoughts will be observable, measurable, and explainable.

However, these assumptions can be seriously challenged. For example, extensive analyses in *Irreducible Mind* (Kelly et al. 2007) challenge what the authors consider to be the apparent consensus among scientists that “Mind and consciousness are entirely generated by—or perhaps in some mysterious way identical with—neurophysiological events and process in the brain.” Their analyses provide theoretical arguments and empirical evidence that the mind cannot be understood as the product of simple physiological sensations or processes and that it is itself a “fundamental elementary and causal principle in nature” (Ibid.; 56). In *Beyond Physicalism* (Kelley et al. 2015), the theory-oriented sequel to the huge 2007 book, these analyses are further developed and synthesized within an overarching framework of the relationship between science and spirituality.

Let us now also consider psychic/paranormal phenomena, for example so-called “near-death experiences”, typically occurring to individuals close to death (e.g. cardiac arrest, near-drowning, or a motor vehicle accident) or in situations of

²³In some domains of natural science, such as e.g. astronomy and geology, this potential is extremely limited due to limitations on the ability to experiment. Here scientists must primarily rely on simple observation to generate their data. So this can limit their ability to focus on a limited number of independent variables and thus to generate data with low variances. I note however that the distinction between simple observation and experiments is not that clear. For example, in 2005 a rocket was sent into the middle of a comet in order to obtain better observations of its contents. This was neither passive observation, nor a controlled experiment.

²⁴Buddhists, for example, would contest this, arguing that there is a continuum of consciousness but no physical basis in that continuum for an individual, solid, permanent and autonomous self. From this perspective, we are only aware of consciousness inasmuch as it is qualified by an object, and only contemplative practice—not scientific investigation—enables us to see the nature of the mind (Revel and Ricard 1998; 29–35).

intense physical or emotional danger. They are often characterized by overwhelming feelings of peacefulness and well-being, out-of-body experience (the impression of being located outside one's physical body), a flash-back of one's life, and meeting and communicating with deceased relatives (Moody 1975), (Charland-Verville et al. 2014). A scientist unfamiliar with the considerable literature on such experiences²⁵ and who met someone who said that she had such an experience might very well reply that the person most likely suffered from a hallucination or that any number of such scenarios can be created by the imagination—although strongly felt, the experiences could not be “real” and the person's statement cannot be considered to be a true/valid/reliable observation statement (a “fact”) from a scientific perspective. Suppose then that the scientist was presented with similar statements by a large number of otherwise reliable, trustworthy and respected people, including other scientists, all of whom told of their own near-death experiences? Once again the scientist would most likely reply that such experiences cannot be considered to be objective observations and that no controlled experiment can be devised that could confirm or falsify their statements. And since the scientist herself did not have such experiences, she would reject such reports since they would challenge a number of the implicit presuppositions underlying the profession of science.

This illustrates a methodological challenge: whether “scientific method” (see Chap. 7) which emphasizes objectivity and replicability of observations can be supplemented with subjective and non-replicable observations of individuals—and if so, how this could/should be done. A striking example of the challenge is provided by (Alexander 2012). While clearly subjective and personal, this experienced neurosurgeon's story of his near-death experience appears to provide evidence as to the existence of consciousness independent of the brain and that the brain essentially performs a filtering function that enables us to limit the amount of information to be processed, which would otherwise be overwhelming, thereby facilitating a normal, conscious daily existence.

However, his non-replicable experience would not be accepted as valid evidence in a traditional scientific investigation, in spite of the details provided by a scientist who has considerable knowledge of the brain, having performed thousands of brain operations in the course of his career. We have earlier (in Sect. 2.3 in our discussions of non-science/pseudo-science) reflected on such limitations on our ability to expand our knowledge base by including information based on personal experiences due to the demands from scientific method as to objectivity and replicability as well as well-grounded theoretical explanations; personal experiences cannot provide objective, replicable data.

Therefore, the assertions of people who have had near-death experiences do not in general threaten scientists' convictions as to the “truth” of the implicit metaphysical assumption that whatever exists is potentially subject to observation and

²⁵See e.g. the website of IANDS, The International Association for Near-Death Studies: <http://iands.org/nde-stories.html>.

measurement; most scientists would simply deny the relevancy/truth of the testimony. Since the personal experiences of individuals cannot be observed by others (their “observations” cannot be replicated by carrying out experiments whereby “neutral” and “objective” scientists can experience the same observations or carry out tests), a reverse logic is employed: The experiences do not exist as other than figments of the imagination. As mentioned in Sect. 2.2 (“What is science?”) of this chapter, empirical science has a far more difficult task when it tries to demonstrate that something does not exist, than that it exists.

However, there are an increasing number of respected scientists who are trying to amass and analyse data that support what otherwise have been considered anecdotal evidence as to e.g. parapsychological phenomena, including telepathy, perception at a distance, mind-matter interaction and mental interactions with living organisms. Radin (1997) refers to research at highly recognized institutions as to the existence of such phenomena, and relies in particular on the use of meta-analyses.²⁶ Not only may this development potentially contribute to a deeper understanding as to such phenomena, but also contribute to an expansion of research methodology!

So if we assume, in contrast to the traditional presuppositions of the natural sciences, that reality is more inclusive than we can observe and measure with our senses, intellect and technologies, then we must conclude that the natural sciences as we know them are limited in their ability to describe, explain and predict. It would also mean that the sciences unknowingly have erected barriers that limit our ability to meaningfully deal with phenomena that are outside of the reach of our senses (even when these are “extended” via technology). One might even say that if the scientific community denies that humans can have reliable access to phenomena by other than the methods of science, science would be totalitarian.²⁷

Thus, although traditional science has for centuries distanced itself from metaphysics, one can nevertheless argue that it is a metaphysical choice—let us call it an act of faith!—of the natural sciences that humans, with the help of their cognition and senses (and language) are or will be able to observe, describe and measure all of the phenomenal universe, which is said to exist independent of our cognition and senses.

Note that I do not imply that even though science cannot justify its presuppositions by referring to its own methodology, that its metaphysical choices—its acts

²⁶These are analyses of analyses where the units of observation are, so to speak, the independent studies rather than the individual observations of an individual study. Such analyses are becoming increasingly important as there may be individual studies that provide conflicting results or that may be based on too small a sample size. Ideally, the meta-analysis is equivalent to a single study with the combined size of all the original studies.

²⁷It is perhaps appropriate here to recall the condemnation of the great Galileo Galilei, who was twice put on trial by the so-called “Inquisition” of the Roman Catholic Church for his support of the Copernican heliocentric view of the universe. In 1632, under threat of death, he was compelled to retract his views and to spend the remainder of his life under house arrest. The point being made here is that whoever appears to have a “patent” on the truth and the power to determine what is true and false, must use this power with great discretion and humility. We will return to this theme in Chap. 10, Ethics and Responsibility in Scientific Research.

of faith—are arbitrary or unstable. Rather, the point is that reflective scientists should be aware of the presuppositions that underlie their research and, when appropriate, they should raise them from the level of implicit to explicit assumptions, for example when they perform their analyses and publish their results.

2.5.2 Fundamental Questions as to Physical Reality

Another limitation of the natural sciences is their inability to provide strong answers to a number of fundamental questions regarding physical reality. Although scientists recognize the challenges involved, most tend to shy away from confronting them, both as subjects to be professionally researched and as questions to be dealt with at a personal, existential level. This is due most likely to the holistic nature of the questions that can be far more inclusive and methodologically demanding than one traditionally faces in one's own field of specialization. Included here are such questions as:

How did life evolve from non-life?

Has everything (including life and consciousness) existed somehow in a “seed state” or been programmed since Planck time (said to be the smallest measurable unit of time, roughly 10^{-43} s after the presumed “Big Bang”)?

Is the universe a random event?

And perhaps the biggest question of all: Why is there anything rather than nothing?

Commenting on such questions, the American physicist Heinz Pagels (1939–1988), former executive director of the New York Academy of Sciences, wrote: “What is the universe? Is it a great 3-D movie in which we are all unwilling actors? Is it a cosmic joke, a giant computer, a work of art by a Supreme Being, or simply an experiment? ... I think the universe is a message written in code, a cosmic code, and that the scientist's job is to decipher that code.” (Pagels 1982; 343)

Closely related to the above questions regarding physical reality are fundamental questions dealing with our experiences as human beings. We have already briefly referred to the question as to where thoughts come from. We can extend this to other areas such as: where do morals come from? preferences? love? aesthetics? conscience? loyalty? faith? awareness and self-awareness? Can these all aspects of consciousness be observed and explained by science—perhaps reduced to molecular/genetic/chemical/quantum-mechanical explanations? According to Erwin Schrödinger (1887–1961), Nobel Prize laureate in Physics in 1937: “The image of the world around us that science provides is highly deficient. It supplies a lot of factual information, and puts all our experience in magnificently coherent order, but keeps terribly silent about everything close to our hearts, everything that really counts for us.” (Schrödinger 1954 as quoted by Revel and Ricard 1998; 185)

The noted Zen Buddhist rishi (sage) Steve Hagen (2003; 229) notes that the way that the natural sciences look upon the relationship between consciousness and matter may be 180° out of phase and that we may have put the cart (matter) before

the horse (consciousness): "... unlike consciousness, which is directly experienced, matter is always secondary—that is experienced indirectly via mind. This is our actual, immediate, direct experience—it's purely mental, not physical. In short, physical reality cannot be fully accounted for apart from consciousness. Yet it's not at all clear that matter is necessary to account for consciousness."

It has not been my purpose here to pursue this issue of whether consciousness has a material basis, a question we will also meet several times in the sequel. Rather, it has been to underline that just as there exist fundamental questions as to the nature of physical reality, e.g. "why is there anything rather than nothing?" so too are there fundamental questions that deal with such a basic phenomenon as consciousness—something we are all aware of and mean that we possess, yet do not know why we have it or what its source is. It is the inability of the natural sciences (at least at present) to provide strong answers to such fundamental questions that constitutes a limitation of science.

Closely related to the above is the fundamental question of the relationship between a physical reality "out there" and our perceptions of that reality. The sciences dealing with cognition make it clear that we do not and cannot experience the world directly. Our knowledge of the world emerges in the mind. And as we briefly have touched on earlier and will shortly consider in more depth, scientific investigation often has to deal with phenomena that cannot even be perceived by our senses, even with the aid of the most advanced technologies, e.g. quarks and black holes. So it is perhaps not too strong an ontological statement that the world that is investigated by the natural sciences is *not* just an external physical world, rather it is also a product of our senses and consciousness; we cannot perceive the world in any other way.

2.5.3 *Rationality*

Another limitation characterizing science deals with the relationship between means and ends. Just as natural science, with its emphasis on rational investigation and analysis, cannot justify its own presuppositions, neither can it help us to decide whether a goal ought to be pursued or not; that is a matter of choice, where values, not truth, determine the outcome. Science can, at best, only help to determine which means are well suited to fulfilling pre-established goals. Thus, the natural sciences have contributed to the development of knowledge and technologies that can be used to serve ends that can be considered both beneficial and destructive. An example is knowledge regarding nuclear fission that can be used both to create weapons of mass destruction and to generate electricity. Another example is from the medical sciences. Medical science has established the veracity of the conditional statement that if we wish to deliver an incurably ill person from prolonged physical suffering, then a large dose of morphine affords an effective means of so doing; it reduces pain but, depending on the dose, can also lead to the patient's peaceful death. However medical science may also indicate ways of prolonging the patient's

life—and thereby his or her suffering as well. This leaves open the question of whether it is right to give the one goal (relief of suffering) precedence over the other (preserving life). Such value judgments are not amenable to scientific analysis; they are simply outside the realm of science. I myself was once compelled to make such a value judgment towards the very end of my mother's terminal illness; the information I received from the doctors attending my mother had a scientific foundation—but the decision as to what was the “best” or “right” thing to do could not, morally or scientifically (!) be made by practitioners of science.

According to the Nobel laureate in Economics in 1978 Herbert A. Simon (1916–2001) who wrote extensively on the limits of reason: “Reason, then, goes to work only after it has been supplied with a suitable set of inputs, or premises. If reason is to be applied to discovering and choosing courses of action, then these inputs include, at the least, a set of *should's*, or values to be achieved, and a set of *is's*, or facts about the world in which the action is to be taken. Any attempt to justify these *should's* and *is's* by logic will simply lead to a regress to new *should's* and *is's* that are similarly postulated. ... We see that reason is wholly instrumental. It cannot tell us where to go; at best it can tell us how to get there.” (Simon 1983; 7)

In other words, rationality cannot rationally justify itself. Thus, the aim of rational justification that not only underlies science, as was demonstrated earlier in this chapter in Sect. 2.4, but also much of human behaviour, is itself a choice that cannot be rationally justified. On the other hand, such a choice is clearly not arbitrary. Science, at least as it developed since the time of the so-called Scientific Revolution, has been built on a foundation of rationality. And this has enabled it to provide descriptions, predictions and explanations that are consistent with observations—and as a result, knowledge and technologies that could not possibly have been developed in the absence of such rationally-based descriptive, predictive and explanatory power. This, in turn, suggests that a choice of rationality is consonant with the structure of the world; further reflections on this fundamental assumption are provided in Sect. 2.8 of this chapter dealing with mathematics and science.

Continuing this line of thought, consider next a controversy that has been framed under the provocative name of “Science Wars” and that deals with the traditional perspective on science that it is a rational method of inquiry that provides objective truth about physical reality. Perhaps the origin of this “war” can be traced back to some of the past century's most influential reflections on the meaning and limits of science by the British philosopher of science Sir Karl Popper. As we saw earlier, Popper (1957 in Klemke et al. 1998) offered his demarcation criterion of “falsifiability” to separate science from non-science—but at the cost of separating science from truth. In a nut-shell, Popper argued that those meanings we can justifiably call knowledge are not verified or proved meanings—have not been *shown* to be true. Rather they are meanings that have been *challenged* by critical examination and have not yet been falsified—that is shown to be false—when confronted with facts, with reality. From this perspective, science does not provide us with rationally established truth. Rather, it offers an effective way for us to interpret events of nature and to cope with the world.

Later on, such noted scientists/philosophers of science as Thomas Kuhn (1922–1996), Imre Lakatos (1922–1974) and Paul K. Feyerabend (1924–1994) emphasized concerns such as:

- Empirical data can neither confirm nor falsify a theory. In other words, science cannot prove that a theory is either true or that it is false.
- Observations are theory-laden (the way we see the world is to some extent determined by the theories we accept) and theory choices are underdetermined (there are always rival theories that can also be supported by the empirical evidence).
- Different scientific worldviews or paradigms are incompatible. (Earlier we discussed how Newtonian mechanics gave way to Einstein's relativity when experiments went against the former and supported the latter theory for velocities approaching that of light.) So science cannot be said to progress towards truth, in the ordinary understanding of progress as a more or less "smooth" process.
- What makes a belief scientific is not the underlying methodology of investigation, but what scientists say about the belief. Science is simply what scientists say it is.

They concluded essentially that science is *a*-rational (not based on or governed by logical reasoning)—and that nature does not significantly constrain the choice of theory!

If they were presented with such radical perspectives and conclusions, the vast majority of scientists would most likely reply that our ability to develop technology based on scientific findings clearly demonstrates that (a) the methods of science find much that we consider to be true, (b) data help confirm or falsify theories, and (c) progress and truth are intertwined. In addition, they would argue that although science certainly rests on many beliefs and presuppositions, the strength of its statements lies in its methods and the vigilance of the scientific community in controlling its results. Therefore, most authors who write about science do not subscribe to a conclusion that science is *a*-rational. This is certainly the case with most of the literature I have referred to in this book. In particular, I can refer to the strong positions taken in some of the publications often referred to here, in particular the books (Chalmers 1999; Hacking 1983; Gauch 2003; Gooding et al. 1989).

Like those authors just referred to, Arthur Koestler (1903–1983), renowned as a keen observer of science and Fellow of the Royal Astronomical Society, does not observe that science as such is *a*-rational. However, his empirical investigation indicates the limits of rationality with respect to the development, one might even say the emancipation of creativity in science. In his opus work *The Act of Creation* (Koestler 1989) he presents results of his studies of the behaviour of a number of highly renowned scientists known for their creativity and observes: "... true creativity often starts where language ends. ... the evidence indicates that verbal thinking, and conscious thinking in general, plays only a subordinate part in the decisive phase of the creative act. ... On the testimony of those original thinkers

who have taken the trouble to record their methods of work, this seems to be the rule in other (than mathematics; my comment) branches of science. Their virtually unanimous emphasis on spontaneous intuitions, unconscious guidance, and sudden leaps of imagination which they are at a loss to explain, suggests that the role of strictly rational thought processes has been vastly overestimated since the Age of Enlightenment.” (Ibid.; 177, 208)

2.5.4 *Innate Limitations*

Without going into any great depth here, let us conclude this section on the limitations of science by briefly considering three fundamental discoveries that demonstrate certain inherent limitations on scientific reasoning and observations: Heisenberg’s uncertainty principle (quantum physics), Gödel’s theorem (mathematics) and more recently, chaos theory (non-linear dynamics). Each of these demonstrate that there are limits on our ability to describe reality and that these limits cannot be removed, or even reduced, by developing better technologies; in other words, they are intrinsic and due to the essential nature of reality.

Werner Heisenberg (1901–76) was a founder of quantum physics and is particularly known for his formulation of the so-called “uncertainty principle”. In a paper written in German from 1927, (English translation: “On the Perceptual Content of Quantum Theoretical Kinematics and Mechanics”), he pointed out that the more precisely the position of a subatomic particle is determined, the less precisely the momentum is known at that instant, and vice versa.²⁸ So no matter how precise the measuring instruments used, there is an inherent limit to the precision of the measurements when these two properties are measured simultaneously. In other words, the outcomes of physical processes cannot be predicted with certainty simply because nature determines its future states through a process that is fundamentally uncertain! This has had profound implications, not only for the ability of physicists to describe/predict the future behaviour of subatomic particles, but also for fundamental concepts of causality.

(Bohm and Peat 1989; 79–87) provide a fascinating discussion of the effect of this principle on the informal language of physics whereby terms which had well defined meanings within Newtonian physics became ambiguous within quantum physics. This makes it difficult to discuss quantum theory using our ordinary language. In addition, it led to the separation of Einstein and Bohr whose use of the informal language of physics made it impossible for them to continue their dialogues. “This separation has had particularly serious consequences for the development of relativity and quantum theory, for there is now no common, informal

²⁸It should be noted that the uncertainty relation does not apply to a single measurement on a single particle; it is a statement about a statistical average over many measurements of position and momenta (Pagels 1982; 90). A result of the relation is that the laws of classical physics are valid only at distances much larger than atomic scales—i.e., involving distances $\gg 10^{-8}$ m.

language that covers them both. As a result, although both theories are regarded as fundamental, they exist in an uneasy union with no real way of unifying them” (Ibid.; 85–86).

In 1931 Kurt Gödel (1906–78) at the age of 25 published his now famous paper in German: (English translation: “On Formally Undecidable Propositions of Principia Mathematica and Related Systems”). In it he developed two theorems of great significance for our understanding of the limitations of formal or logical systems of axioms and rules of procedure. Very briefly, Gödel demonstrated in his first theorem that *any* formal system of axioms and rules capable of containing/supporting certain axioms for the natural numbers, such as ordinary arithmetic, and that is consistent (the property of a logical system whereby there are not statements which the system regards as both true and false), is necessarily incomplete or “undecidable”—it contains statements that are neither provably true nor provably false by the approved procedures. A perhaps simpler way of stating this is that “he proved that in any sufficiently complex formal system, such as arithmetic, there must exist statements that make sense but can neither be proved nor disproved within the system”. (Davies 2010; 88)

In his second theorem he showed that such an axiomatic system cannot prove itself to be consistent and complete from within without also proving itself inconsistent. He did this by showing that the statement of the consistency of the system, when coded into the form of a mathematical proposition, must be “undecidable”. Although we may be able to prove any conceivable statement about numbers within the system by going outside the system (in order to come up with new rules and axioms), in so doing we create a larger system with its own undecidable statements. This implies that all such systems are incomplete; they contain more true statements than can possibly be proved according to the system’s own defining set of rules.²⁹

According to the renowned mathematical physicist Roger Penrose (Penrose 1989; 111–12): “...it seems to me that it is a clear consequence of the Gödel argument that the concept of mathematical truth cannot be encapsulated in any formalistic scheme. Mathematical truth is something that goes beyond mere formalism. This is perhaps clear even without Gödel’s theorem. For how are we to decide what axioms or rules of procedure to adopt in any case when trying to set up a formal system? ... Any particular formal system has a provisional and ‘man-made’ quality about it. Such systems indeed have a very valuable role to play in mathematical discussions, but they can supply only a partial (or approximate) guide to truth. Real mathematical truth goes beyond mere man-made constructions.”

In his lecture, “Gödel and the End of Physics”, (Hawking 2002), Stephen Hawking builds upon this concept of mathematical truth by asking “how far we can

²⁹Although the details of the proof are very difficult to follow for those without considerable mathematical training, (Nagel and Newman 1958) enables readers with limited, but basic, mathematical and logical training to understand the basic structure of Gödel’s demonstrations and the core of his conclusions.

go in our search for understanding and knowledge” and considers the relationship between Gödel’s theorem and whether we can formulate the theory of the universe in terms of a finite number of principles. Towards the end, he argues that “One connection is obvious. According to the positivist philosophy of science, a physical theory is a mathematical model. So if there are mathematical results that cannot be proved, there are physical problems that cannot be predicted. ... Some people will be very disappointed if there is not an ultimate theory that can be formulated as a finite number of principles. I used to belong to that camp, but I have changed my mind, I’m now glad that our search for understanding will never come to an end, and that we will always have the challenge of new discovery.”

Together, Gödel’s two theorems demonstrated the existence of limitations on what one can seek from a logical system—that any attempt to produce a paradox free mathematical system is bound to fail if the system is reasonably complex. His theorems indicate as well that what many consider to be an ideal of science—that we can devise a set of basic assumptions from which all phenomena in the external world can be deduced—cannot possibly be achieved.

Finally, in this brief discourse on innate limitations on scientific reasoning and observations, let us turn now to chaos theory. This theory had its origins not in logical deductions, systematic observations or experiments, but in a chance observation in 1961 by a meteorologist working with a system of equations that he hoped could contribute to weather forecasting. In brief, what is now referred to as chaos theory can, more correctly, be said to be a set of ideas that attempts to reveal structures in what are apparently disordered, aperiodic, unpredictable systems—i.e., to reveal an underlying order behind what appear to be random data. In a nut shell, such so-called “chaotic systems” are deterministic, non-linear models (systems of equations) that demonstrate unpredictable behaviour.

What is particularly significant for our reflections here is that chaos theory demonstrates the sensitivity of certain phenomena (more correctly: of the system of non-linear equations that have been chosen to describe the phenomena) to their initial conditions. Even minute changes in the initial conditions characterizing such a system (for example due to experimental errors, background noise, the lack of precision of measuring equipment or inaccuracy with which the measurement is made) can lead to significant changes in the long term behaviour of a chaotic system. Examples of such systems are the (models describing) the turbulent flow of liquids such as white water in a river, cloud formation, and plate tectonics. At a more down-to-earth level, our ability to give accurate descriptions of an apparently simple everyday occurrence as mixing milk in tea is amazingly limited. Although we may have excellent theories as to fluids, molecular motion and the like, the ability to describe what actually takes place when a particular portion of milk is poured into a particular cup of tea is extremely limited and no reliable prediction can be made as to the dynamics of the system! Reference is made to the “classic” exposition (Gleick 1987).

What is truly fascinating is that scientists have been able to discover or uncover such inherent limitations on scientific reasoning and observations as have been referred to above. It may be argued that the limitations are not inherent in science as

such, but are a result of the way the “real world” is—that the limitations are of ontological rather than epistemological origin. In any case, we may regard it to be a triumph of science that its methods not only are effective in describing, predicting and explaining natural phenomena and relationships, but also in uncovering its own limitations.

Finally, on a more personal note, rather than considering such limitations as something negative, I strongly suggest that we consider them to reflect the magnificent complexity of what we refer to and experience as reality.

2.6 Description, Causality, Prediction, and Explanation

These four terms, description, causality, prediction, and explanation, are fundamental concepts in science. They are also, more or less, parts of our everyday vocabularies, so we tend not to really think much about their meaning. Having, so to speak, two sets of vocabularies, where many of the words are used by both the proverbial “man-on-the-street” and an academic working in a field of scientific investigation, is not unusual. For example, in everyday language people speak of their “philosophy”, while the term has a far deeper meaning for students of philosophy (its actual etymological meaning is “love of wisdom”). Similarly, we speak of traffic systems, and computer systems, and the communist system, and simply “the system” (“you can’t beat the system”, here referring to a bureaucracy of some sort)—while a student of systems science attaches a more general and abstract meaning to the word “system” (e.g.: interacting elements that manifest as a whole). And as we saw earlier, even the strange word “paradigm” that Kuhn developed in his now-classic work on *The Structure of Scientific Revolutions* soon became used in common every-day language and in a far broader sense than originally intended.

Since the natural sciences aim at establishing statements (facts, hypotheses, theories and laws) with a higher degree of precision than our ordinary common sense and language enable us to do, as students and practitioners of science we have an obligation to dig a bit deeper and consider the meaning of fundamental terms we use in science. In so doing, we hopefully develop a greater appreciation of what science is really about, and what it is not about.

2.6.1 Description

Let us start with “description”, which is in many ways the most fundamental of these terms. To begin with, I refer to our earlier reflections on observation, since description, at least in the natural sciences, presupposes observation. We saw that e.g. visual observation is not simply a mechanical process whereby e.g. light waves from an illuminated object causes retinal changes and these cause changes in the optic nerve which in turn lead to changes in brain cells. Observation is also a

process involving memory, comparison, recognition and selection. There are many things we do not “see” when we look say at a room with its windows, doors, furniture, lamps, books, etc. What we see is a product of choice, of a filtering process whereby we are aware of certain images, and unaware of a great number of other potential images that have been recorded/observed. For example, although we may have seen the books in a bookcase, we cannot recall their titles, placements in the bookcase etc., nor can we recall whatever was on the desk, whether there was a bit of dust on the floor, the motif of the paintings on the wall, and so on, even though we in fact saw all these things. In general, even before we describe what we see/hear/feel/smell/taste, a filtering process takes place. And when we translate what we observe into a form that is available to others via a verbal statement or other form of description, additional filtering processes take place. Therefore, no matter how “objective” we may try to be, description is always selective, incomplete and can be fallible.

All branches of the natural sciences employ and are based on description, while they do not all focus on the other topics to be considered in this section: causality, prediction and explanation. For example, due to a lack of suitable theory, geologists may tend to place greater emphasis on describing the historical developments of the crust of the earth in a particular region, than on predicting its future development. Furthermore, particularly in the early stages of a field of study, there may be a tendency to emphasize description for its own sake, such that the collection, structuring and presentation of data are far more in focus than analysis and attempts at causal explanations.

Yet most scientists do not consider it to be “science” when investigations are simply aimed at observing everything that can be said to characterize an object, activity, or phenomenon, and then recording, categorizing the data, and mediating it—recall our exercise about umbrellaology! There appears to be a tacit agreement in science that the goal of data collection is analysis (leading hopefully to understanding, explaining, and predicting), and not just straightforward description. For example astronomy, which has extremely limited opportunities for direct experimentation and is primarily characterized by more passive forms of observation rather than experimentation, nevertheless aims at going beyond description to make cosmological predictions and to explain and theorize as to the development of say a particular galaxy or nebula or the existence and properties of planets beyond our solar system.

I emphasize too, that even rather straightforward description requires some analysis and reflection as to the purpose of the description. Otherwise it would not be possible to rationally determine the desired accuracy of one’s measurements, how to categorize the data, and how to present it in some well-organised manner.

In other words, in general, scientific investigations, even when performed in “pure science” without explicit motivation regarding some future application, must be based on ideas as to how the knowledge gathered will be used, why, and by whom. Astronomers studying sun storms, physicists studying quarks, chemists studying the properties of U_{238} and biologists studying the migration patterns of barn swallows, may say that they are studying these objects for no other reason than

to add to our knowledge of the world. Nevertheless, in all such investigations, decisions are being made as to how to perform the observations and experiments, how to make measurements, how to allocate the available time and other resources to the various activities involved, how to determine which observations are of interest to one's peers and which are not, how best to communicate one's findings to others, and so on. Description in science automatically implies reflection, no matter how implicit, as to the aims and limitations of one's investigations.

In addition, what we actually observe under an investigation depends on our understandings of the phenomena we want to describe. And as considered earlier, our culture, our previous training, and the theories we have learned all influence what we perceive and what we deem to be worthy of our consideration.

Therefore description for the sole sake of description is a misleading concept, as is objectivity in observation. This is not to say that one description cannot be evaluated as better than another description in a given context, or that we should not emphasize objectivity in our observations, but rather that we must be aware of what it is that affects our judgment as to what a good description is—and what good science is. It is postulated that the more we are aware of the aims and limitations of our research and of our (implicit) biases and “cultural baggage”, the better we will be able to carry out our investigations, make our observations, descriptions and explanations, and contribute to the development of science.

2.6.2 *Causality*

Causality is a tricky word. We are so used to saying things like: “my lack of sleep last night is the cause of my headache today,” or “the drought caused the crops to wither,” or simply, “every effect has a cause”. But things are not that simple. My headache may be seen as related to or caused by a lack of sleep last night—but may also, perhaps, be related to or caused by how well I slept the last few days, as well, perhaps, by the food I ate before going to bed, the number of hours I sat looking at my computer screen before going to bed, the stress I felt due to a forthcoming examination, the humidity in the air, and so on. And maybe one can even argue that the relationship between a headache and poor sleep is 180° reversed—that a headache I had yesterday led to my having poor sleep—which may in turn have led to my again having a headache today. So it is not always clear as to what is cause and what is effect in a given situation.

So if we are to more meaningfully speak of *A* as a cause of the effect *B*, we see that the relationship may be characterized by:

- *A* being one of many possible causes of *B* (one possible cause of the headache is stress felt about an examination, another possible cause is overeating, a third possible cause is lack of sleep).

- A being a single step along a causal chain (stress due to being worried about an examination can lead to overeating which can lead to a lack of sleep which can lead to a headache).
- A being one of a number of factors which together lead to *B* (overeating in a very unpleasant and noisy restaurant and worrying about one's work all act together to lead to a headache).

Continuing with this train of thought, crop failure—however we may define this—may certainly be affected by draught. But the amount and quality of what is harvested may also be a function of the quality of the seeds that were sown, the characteristics of the soil, the weather conditions that prevailed when the seeds were sown, the timing and amount of fertilizers and pesticides used, the pattern of temperature and humidity during the growth season, the weather conditions on the day the crop was harvested, how the harvesting was performed, how the harvest was stored, and so on. So once again there are three possibilities: (a) draught may be one of many possible causes of the poor harvest; (b) the poor harvest may be due to several factors working in a sequence: poor seeds followed by poor weather at the time of planting, followed by ...; and (c) the poor harvest may be due to a combination of several factors.

The above reflections look upon *A* as being *a* the cause of *B*. But as we have touched on earlier, sometimes it is difficult to determine what is cause and what is effect. Scientists working in the field of ecology tend to work with a concept of “systemic causality” rather than simple (or linear) cause and effect. By this they mean that all the phenomena they study are interrelated, and therefore there is in some sense a cyclical causality at work, rather than a linear—“*A* is the cause of *B*”—causality.

Before proceeding, let us summarize the implications of the above reflections in a more precise terminology:

- If *A* is said to be **a** cause of *B*, then *A* must always be followed by *B* and *B* cannot precede *A*; $A \Rightarrow B$. In other words, *A* is a sufficient condition for *B*.
- If *A* is said to be **the** cause of *B*, then *A* is both a necessary and sufficient condition for *B*; $A \Leftrightarrow B$; *B* occurs if and only if *A* occurs.

It follows, for example, that it is incorrect to say that smoking cigarettes causes lung cancer. Even though there may be a strong statistical correlation between smoking and the occurrence of lung cancer, many smokers do not get lung cancer, and many who have lung cancer have not smoked; smoking alone is neither *a* cause nor *the* cause of cancer (although we cannot ignore the possibility that smoking, together with some other phenomena, e.g. a particular DNA pattern, can be **a** cause of cancer—and that given the strong statistical correlation it would be foolish to smoke).

I also note that while most scientists subscribe to the so-called scientific method (the subject of Chap. 7) and consider experiments as a means of determining causality in the physical world, some scientists tend to downplay causality. They argue that there is no causality in nature; what we tend to regard as cause and effect

is simply a high degree of consistency with which events of one kind are followed by events of another kind.³⁰ From this perspective, all that we can observe are correlations, not causations, and based on these we tend to make inductive inferences.

Such scientists assert, for example, that when people speak of the moon's gravitational pull being the cause of tidal movement, this is not a correct statement, not a fact. By this they mean that gravity is simply an expression of a constant observable relationship among masses, and the movement of the tides is an example of that relationship. From this perspective, the moon does not exert a pull that precedes and causes the tide to rise; the relationship between the masses involved is completely symmetrical. According to (Stace 1967 in Klemke et al. 1998; 354): "Gravitation is not a 'thing', but a mathematical formula ... as a mathematical formula cannot cause a body to fall, so gravitation cannot cause a body to fall. Ordinary language misleads us here. We speak of the law 'of' gravitation, and suppose that this law 'applies to' the heavenly bodies. We are thereby misled into supposing that there are *two* things, namely the gravitation and the heavenly bodies, and that one of these things, the gravitation, causes changes in the other. In reality nothing exists except the moving bodies. And neither Newton's law nor Einstein's law is, strictly speaking, a law of gravitation. They are both laws of moving bodies, that is to say, formulae which tell us how these bodies will move."

An example of how, depending on our aims and focus, one can draw misleading inductive inferences as to cause and effect, deals with lightning and thunder. Ordinary people (without a scientific background) tend to speak of lightning as causing thunder since we observe a constant relationship between them, whereby lightning is always followed, with a time delay dependent on the distance of the lightning from us, by thunder. It may be more correct to see both lightning and thunder as being caused by—or simply two results/perceptions of—the same physical event, an electric discharge that we perceive first with the aid of our eyes as light, then with the aid of our ears as sound, since the speed of light is far greater than that of sound.

Since the notion of causality is closely related to that of "determinism", it can be fruitful now to briefly consider the relationship between these two concepts in order to demonstrate the potentially wide-reaching consequences of causality. According to determinism, since there is a cause underlying every effect, everything is necessarily predetermined—therefore everything has a primal cause. From a religious or spiritual perspective, such a cause is typically considered to be the "Creator";

³⁰This is not a newer reflection. The reflections of David Hume (1711–76), referred to earlier, when we considered the concept of positivism, formed the basis for future empirical analyses of cause and effect. In his "regularity theory" he argued that no amount of experience in observing that *A* precedes *B* permits us to say that *A* is a cause of *B* (in our terminology: induction cannot provide us with proof). When we think in this way it is simply a reflection of the habits of our mind; we appear to have a need to make sense of our observations that *A* always appears (at least up to now) to occur before *B*; (Hume 1748/1955; 26–41, 64–67).

from a scientific perspective, such a primal cause is typically considered to be the “laws of nature”.³¹

Continuing with these reflections, let us very briefly consider the arguments of Popper (1983; 1–2), in which he sets forth his reasons for being an indeterminist and where he discusses the relationship between the concepts of determinism and causality. “My central problem is to examine the validity of the arguments in favour of what I call ‘*scientific*’ determinism; that is to say, the doctrine that the structure of the world is such that *any event can be rationally predicted with any desired degree of precision, if we are given sufficiently precise descriptions of past events, together with all the laws of nature*”.

Popper argues that examining the validity of arguments in favour of scientific determinism is relevant mainly because exponents of quantum physics tend to argue that classical physics entails determinism, while quantum physics compels us to reject both classical physics and determinism. Popper argues that this position is not correct and that even the validity of classical physics would not impose a deterministic doctrine about the world. It can also be argued that quantum physics does not undermine determinism as such, only that it leads to a new form of determinism where the laws of nature determine the probabilities of future and past states rather than determining the future and past with certainty (Hawking and Mlodinow 2010; 72).

In the arguments he develops against determinism Popper presents an intuitive idea of determinism by using a metaphor of a motion picture film. He likens the World to such a film, where the picture being shown at any given time is the present, where those parts of the film already shown constitute the past, and where those parts not yet shown constitute the future. Building on this metaphor, he argues that the future coexists with the past, and that it is known to the producer of the film/the Creator of the World. This is a religious, not a scientific, perspective of determinism, connected as it is with the idea of omnipotence (the Creator created the film/physical reality) and omniscience (the Creator as film producer knows what has not yet been shown on the screen). What Popper refers to as *scientific* determinism is the above, but with the idea of the Creator (God) replaced by the idea of nature, and with divine law replaced by the so-called laws of nature. He essentially argues that while God may be known by revelation, determinism assumes that the laws of nature may be discovered by human reason and experience—and that one can use these laws to predict the future state of a physical system based on the present data (or past data) that characterize it and by using rational methods. In other words, if only we know the laws of nature and the state of the system at any time, we can rationally calculate any future event in advance of its occurrence. It follows as well according to Popper that if only one future event could not in principle be predicted using the natural laws and data as to the present or past state of the world, then scientific determinism must be rejected.

³¹However, an argument can also be made that if these laws first ‘emerged’ after the Big Bang, then they cannot be a primal cause.

I will not continue with further reflections on Popper's analyses, which are based on a physical interpretation of probability theory. The purpose of the presentation was simply to indicate that working with a concept of causality can compel us to consider far more inclusive questions, e.g. prediction and determinism.

2.6.3 *Prediction*

Prediction in everyday language is a statement that a particular event will occur in the future. In a scientific context, prediction is a precise statement, given specific starting or initial conditions, about the future state of a system. Prediction is a key concept in scientific method, where it is a precondition for testing hypotheses. It is by applying deductive reasoning to our hypotheses that we generate predictions, and it is by analysing the results of our observations/experiments that we evaluate whether our predictions are confirmed or contradicted, and thus whether our hypotheses are supported or not by our observations/experiments.

Note that an extended concept of prediction would permit inferences not just regarding future events, but as to past events as well; the physical system is characterized by reversibility. We might, for example, be interested in 'predicting' earlier astronomical events (eclipses, the trajectory of comets) in just the same way as we make inferences as to future eclipses, trajectories of comets, etc. In this sense, prediction is the application of logical/mathematical reasoning to the dynamics of a physical system, and the mathematical system that describes the dynamics of the physical system is totally indifferent as to future and past. Clearly this understanding of prediction is closely related to the concepts of causality and determinism that we have just treated.

Note too that predictions do not need to be evaluated by the use of experiment in order to be "scientific". For example, consider the prediction in 1705 by Edmund Halley (1656–1742) that a bright comet would return some time in December, 1758. His prediction was the result of his applications of Kepler's theory of elliptical orbit and Newton's laws of planetary motion, together with his own studies of existing reports of comets that appeared in 1456, 1531, 1607 and 1682. His analyses led him to hypothesize that the earlier comets were in fact the same comet since they appeared to follow similar paths. His prediction was shown to be true on Christmas day, 1758, 16 years after his death. Since then the comet has been named after him.

Another example of predictions not being evaluated via experiment is the many experiences I had while being on the board of an international consulting company in the late 1960s and early 1970s. The primary resource of this company was the talent of its employees in building mathematical models that could be used to predict the outcomes of an organization's decisions. In particular, simulation techniques were used with considerable success to enable the leaders of private, public and governmental organisations to consider in advance the potential results of alternative actions. There was no ability to run controlled experiments, so the

models became a kind of “management’s laboratory”.³² Although there was no capability of comparing the actual outcome to what might have occurred had other decisions been made, the leaders were able to evaluate the “goodness” of the models and thereby, indirectly, of the predictions, by simulating the outcomes of earlier decisions and comparing the results to what actually occurred, as well as by evaluating the logic (as expressed via the mathematical relationships) of the models employed.

Tying together the concepts of causality and prediction, as well as placing them in a historical context, consider the ideas of the French astronomer and mathematician Pierre-Simon Laplace (1749–1827). Based on his work with Newton’s mechanics, Laplace was convinced that everything in the universe is predetermined by the laws of motion and that the universe could simply be considered to be a big machine—a deterministic mechanical system. The following quote from (Truscott and Emory 1951; 4), the translation of Laplace’s publication *Essai philosophique sur les probabilités* (*Philosophical Essay on Probabilities*) sums up his argument: “We may regard the present state of the universe as the effect of its past and as the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect, nothing would be uncertain and the future just like the past would be present before its eyes.”

In other words, according to the Danish physicist Niels Bohr (1957; 118, my translation): “The idea was that all interactions between the machine’s parts were subject to the laws of mechanics and that therefore an intelligence with knowledge of all these parts’ relative positions and velocities at any given time would be able to predict any future event in the world, including the behaviour of animals and humans.”

To round off these reflections that link prediction, causality and determinism, the following are six concise arguments, primarily based on our reflections so far, as to why deterministic prediction is not, neither in principle nor in practice, achievable:

1. First of all, at a more philosophical level, there is the logical problem of recursion: If the “intelligence” (say something like a huge super-computer) is assumed to be inside the universe, it has a physical structure (particles) that affects and is affected by everything else, and therefore must include itself in its description which can lead to an unlimited recursion. It also means that the “super-computer” is subject to the laws of nature and these may limit its ability to find the laws; for example, its ability to transfer information would be limited by the finite speed of light. On the other hand, if the “intelligence” is not part of the universe, the universe is not complete and therefore the calculations cannot take into account the influence of the intelligence on the universe.

³²The title of my very first publication, written together with several classmates at Harvard Business School in 1959 was: *Simulation: Management’s Laboratory*.

2. Determinism is based on the underlying assumption that the universe is a mechanical system characterized by its elementary particles and the forces that act upon them/their movements. This assumption is not supported by quantum physics where, at the microscopic level of atoms, quarks, bosons etc., it is not even meaningful to speak of the universe as composed of particles.
3. It is also presumed that classical mechanics applies; yet as we know from Heisenberg's uncertainty principle, in quantum systems one cannot specify precisely the required data as to position and momentum. According to (Hawking and Mlodinow 2010; 72) "... the outcomes of physical processes cannot be predicted with certainty because they are not *determined* with certainty. Instead, given the initial state of a system, nature determines its future state through a process that is fundamentally uncertain."
4. The reductionist assumption as to a universe being built up of individual units of matter that obey the laws of nature is also challenged when we consider the nature of consciousness. It can be argued that human consciousness (and that of other sentient beings) cannot be reduced to a physical system, and therefore consciousness itself can lead to behaviour that is not predictable—this will also be considered in this book's concluding chapter.³³
5. As we referred to earlier, if in fact physical reality can be represented, at least to some extent, by systems of nonlinear equations, then it may demonstrate chaotic behaviour which would not permit precise prediction.
6. Finally, on a very practical level: The number of particles in the universe is amazingly large (there are on the order of 10^{23} molecules in just one cubic centimetre of gas), and even to be able to calculate their future states would require precise data on their present positions and momenta, a task which no computer can achieve. So even if we assume that Laplace's assumptions and reasoning are correct, since we as humans are not the "intelligence" referred to and have a limited ability to know everything about the material structure of the universe as well as a limited ability to make all the computations that would be required, we are only able to predict events with a certain probability.

³³A differing opinion is held by the distinguished scientist Stephen Hawking who, based on the implicit assumption that consciousness is a biological system, argues that since "... biological processes are governed by the laws of physics and chemistry and therefore are as determined as the orbits of planets. ... we are no more than biological machines and that free will is just an illusion." But "... since we cannot solve the equations that determine our behaviour, we use the effective theory that people have free will." (Hawking and Mlodinow 2010; 32, 33)

2.6.4 Explanation

We conclude this section by reflecting briefly on the concept of explanation, which will be seen to be closely related to that of causality as well as to that of reductionism.

In science, to explain the events or phenomena we observe is to answer the question “why” rather than simply the question “what”, that we met in connection with our reflections on the concept of description. Answering such “why-questions” is generally considered to be one of the primary aims of scientific inquiry. For example, although a person without scientific training may be able to observe and to provide reasonably accurate descriptions of the phenomenon of natural materials reflecting light in one direction—when you place a straw in a glass of water, it appears to bend toward the surface—a scientific explanation will be required in order to provide an answer to the question *why* the straw appears to bend.

While a typical dictionary definition of the verb “explain” is: “to make understandable ... to give the meaning or interpretation of ... to account and state reasons for”, the philosophy of science provides us with a far more nuanced approach to explanation. I will frame the major part of our reflections on “explanation” by referring to the seminal work of Carl. G. Hempel (1902–1997), in particular to (Hempel 1948). Since Hempel’s model of explanation assumes a process whereby the event or phenomenon to be explained is subsumed under a general law, it is often referred to as a “covering law” model of explanation.

To illustrate the model, consider an example from (Hempel 1948 in Klemke et al.; 206–7, 210):

A mercury thermometer is rapidly immersed in hot water; there occurs a temporary drop of the mercury column, which is then followed by a swift rise. How is this phenomenon to be explained? The increase in temperature affects at first only the glass tube of the thermometer; it expands and thus provides a larger space for the mercury inside, whose surface therefore drops. As soon as due to heat conduction the rise in temperature reaches the mercury, however, the latter expands, and as its coefficient of expansion is considerably larger than that of glass, a rise of the mercury level results. ... This account consists of statements of two kinds. Those of the first kind indicate certain conditions which are realized prior to, or at the same time as, the phenomena to be explained; we shall refer to them briefly as antecedent conditions. In our illustration, the antecedent conditions include, among others, the fact that the thermometer consists of a glass tube which is partly filled with mercury, and that it is immersed into hot water. The statements of the second kind express certain general laws; in our case, these include the laws of the thermic expansion of mercury and of glass, and a statement about the small thermic conductivity of glass. The two sets of statements, if adequately and completely formulated, explain the phenomenon under consideration; they entail the consequence that the mercury will first drop, then rise. Thus, the event under discussion is explained by subsuming it under general laws ...

Hempel then adds that so far “... we have only considered the explanation of particular events occurring at a certain time and place. But the question ‘Why’ may be raised also in regard to general laws. ... the explanation of a general regularity consists in subsuming it under another, more comprehensive regularity, under a more general law ... the validity of Galileo’s law for the fall of free bodies near the

earth’s surface can be explained by deducing it from a more comprehensive set of laws, namely Newton’s laws of motion and his law of gravitation, together with some statements about particular facts, namely, about the mass and radius of the earth.”

Thus, according to Hempel’s model, explanations are arguments offered to establish that the event or phenomenon to be explained had to occur given the prevailing initial conditions and one or more laws of nature (which he also refers to as regularities). In brief, his model, which is in essence deterministic but which can be extended to treat probabilistic events, can be represented as follows:

There are statements of initial conditions:	$C_1, C_2, \dots C_k$
And scientific laws:	$L_1, L_2, \dots L_r$
Logical deduction based on these leads to:	E

which is an explanation—a statement describing the event/phenomenon to be explained.

Hempel notes that the same formal analysis applies as well to scientific prediction, where the difference between the two is that if E is given (the event/phenomenon has occurred) and a suitable set of statements $C_1, C_2, \dots C_k$ and $L_1, L_2, \dots L_r$ is provided afterwards, we speak of an explanation—while if the statements are given and E is derived prior to the occurrence of the actual event/phenomenon, we speak of a prediction.

The type of explanation considered here is often referred to as a “causal explanation” (reference is made to our previous discussion of causality), since the regularities expressed by the laws $L_1, L_2, \dots L_r$ imply that whenever conditions of the kind indicated by $C_1, C_2, \dots C_k$ occur, an event of the kind described in E will occur.

Since Hempel’s seminal work, a number of relevant criticisms have been offered of his equating the logical characteristics of explanation and prediction. For example, there may be good predictors of events that we would not regard as explanatory when provided after the event occurred; for example, barometers serve as reliable predictors of storms yet we would not explain a storm’s occurrence by referring to the readings of a barometer. And a good explanation may not be accepted as a good predictor of an event should it be known prior to the occurrence of the event; theoretical knowledge as to why a roulette wheel stops on a particular number doesn’t serve as a basis for predicting the number the wheel will stop at prior to spinning the wheel (Ibid.; 202).

It should be noted as well that there are other characterizations of explanation in the natural sciences than those provided by causal models. For example the concept of motivation has been used in the biosciences, as well as in the behavioural and social sciences. In models that employ this concept, a person’s actions (or perhaps the actions of less complex forms of life, even those of a cell) are explained based on the living creature’s motives, purposes or intentions.

Before concluding this section on explanation it should also be noted that not all scientists agree that explanation is a reasonable aim of science. In spite of the observation that it appears to be a characteristic of human nature to seek explanations, that is, to come up with answers to “why” questions, arguments can be made that challenge the ability of science to provide explanations. It can be argued that science simply provides us with generalized statements as to *what* happens, but not as to *why* it happens. For example, as we briefly touched on earlier, we tend to explain the movement of the planets by referring to “gravitation” or “forces”. But “gravitation” and “forces”, although apparently providing answers to such questions, can be said to be human constructions—not things out there in the so-called real world that can be studied by using the methods of science. Similarly, one can argue that although the mathematical formulae which comprise atomic theory are simply formulae for calculating what effects/sensations will occur under certain conditions, we tend to demand that something corresponding to these formulae exists and we refer to that something as atoms. According to (Stace 1967 in Klemke et al. 1998; 356), who takes a strong anti-realist stance: “The ‘existence’ of atoms is but the expiring ghost of the pellet and billiard-ball atoms of our forefathers. They of course had size, shape, weight, hardness. These have gone. But thinkers still cling to their existence, just as their fathers clung to the existence of forces, and for the same reason. The reason is not in the slightest that science has any use for the existent atom. But the imagination does. It seems somehow to explain things, to make them homely and familiar. ... strictly speaking, *nothing exists except sensations* (and the minds which perceive them). The rest is a mental construction or fiction. ... Their truth and value consist in their capacity for helping us to organise our experience and predict our sensations.”

This so-called “instrumentalist” or “anti-realist” perspective is in direct opposition to a “realist” position as to the existence of phenomena that we regularly speak of in science but that are not perceivable by our senses. It is to the differences between such fundamental perspectives regarding the nature of reality that we now turn.

2.7 Realism and Anti-realism

We have previously introduced the term “realism” when we considered the aims and limitations of science. Realism was presented as the contention—the metaphysical presupposition—that physical objects exist independent of human thought and that our minds and senses enable access to the physical world so that it can be reliably known—that there is a correspondence between human thought and an external, independent reality. In other words, realism is the position that the physical world has objectivity that transcends subjective experience such that science can present an objective, true picture of nature, including those parts of nature

that are not available to our senses, and that the universe really is as described and explained by our scientific statements.³⁴ (Husted and Lübcke 2001; 108)

Before continuing, a brief clarification is called for about the statement “those parts of nature that are not available to our senses”. Consider for example the concept in astronomy of a black hole. Such an object cannot be directly observed since its gravitational pull is so powerful that light cannot escape it. An “objective, true picture” of such a black hole can however be deduced from the fact that we can observe an acceleration of stars in their orbit and this indicates the presence of a powerful gravitational force. In fact, such observations permit astronomers to both infer its position and mass.

The perspective of realism is not that straightforward as it might appear. As touched on earlier, according to Bohr, at least at the level of the atom, science does not aim at presenting a true picture of nature, but only of improving our ability to *speak* about nature. Similarly, one of the most celebrated scientists of our more recent times, Stephen Hawking clearly takes the position that one need not worry too much about whether or not it is meaningful to assume an isomorphic relationship between theory and reality, since the term “reality” has little meaning for him: “I don’t demand that a theory corresponds to reality because I don’t know what it is. Reality is not a quality you can test with litmus paper. All I’m concerned with is that the theory should predict the results of measurements.” (Hawking and Penrose 1996; 121) He elaborates on this in a more recent book: “...it is pointless to ask whether a model is real, only whether it agrees with observations. If there are two models that both agree with the observation ... then one cannot say that one is more real than the other. One can use whichever model is more convenient in the situation under consideration” (Hawking and Mlodinow 2010; 46). From this perspective, the Copernican heliocentric model that replaced the geocentric model of the nature of the universe cannot be said to be a more “real” model, but certainly a more useful model; the earlier model can in principle be developed to provide accurate descriptions of the heavens, but the equations of motion would be far more complex and the resultant model extremely difficult to apply. We return to such ideas in Sect. 3.2 when we consider the concept of parsimony in connection with the choice of criteria for determining “good” theories.

The distinction between a true picture of nature and our ability to practically describe nature is the distinction between realism and anti-realism. This latter, more pragmatic, perspective does not aim at “truth”—at developing a truer description/understanding of reality, including its unobservable parts—but only at

³⁴Other observers of science have a narrower definition of realism whereby only the ontological aspects are included—that the world exists independently of our representations of it. For example, (Searle 1995; Chaps. 7–9) considers in depth: “Does the real world exist?” and “Truth and Correspondence”. Searle’s conclusions are very much in line with this narrower definition of realism; “... if we had never existed, if there had never been any representations—and statements, beliefs, perceptions, thoughts, etc.—most of the world would have remained unaffected. Except for the little corner of the world that is constituted or affected by our representations, the world would still have existed and would have been exactly the same as it is now.” (Ibid.; 153).

developing theories and models that provide us with knowledge of reality that is sufficient for the purposes of explaining, predicting, and controlling events and phenomena. Thus, for a realist, electrons and gravitational forces exist, while for an instrumentalist they are practical concepts that may or may not exist. According to (Hawking and Mlodinow 2010; 44) “Anti-realists suppose a distinction between empirical knowledge and theoretical knowledge ... theories are no more than useful instruments that do not embody any deeper truths underlying the observed phenomena.”

The natural sciences, at least as they are taught and understood by most scientists, are tied to realism. In general, the natural sciences claim to have rational methods that provide humans with objective truth about an independent physical reality. Another way of saying this is that the realist view of the natural sciences is that their *epistemological* methods (epistemology deals with what is, or should be, regarded as acceptable knowledge) aim at *ontological* knowledge (knowledge of the nature of reality).

Note that this aim is not characteristic for the social sciences, where many adhere to the idea that the (social) world is a projection of the mind and that we create rather than discover reality. This social constructivist or social constructionist perspective (I will use the two terms interchangeably, although some distinctions can be made between them) is anti-realist. Although its perspective on reality is therefore far removed from the traditional realist perspective of the natural sciences, with their emphasis on an objective, independent external reality that it is the task of science to develop true knowledge about, the constructivist approach to reality offers all scientists thought-provoking challenges. Let us therefore briefly consider this perspective from the social sciences, which also has supporters in the natural sciences.

Social constructionism was first introduced into the field of sociology in the book: *The Social Construction of Reality* (Berger and Luckmann 1966). Its underlying idea is that social reality—social phenomena and objects of consciousness—does not exist independently of our attempts to know and describe it. Our theories therefore are a product of the social aspects of scientific processes. Some of social constructivism’s major perspectives are:

- We (both scientists and the participants in the social processes they observe) make sense of our realities based on our historical and social perspectives.
- We are born into a world of meaning bestowed on us by our culture.
- Knowledge is constructed by humans (both the observers and those being observed) as they engage with the world they interpret.
- Knowledge is not only personally constructed—it is also socially mediated and therefore is shaped by our political and social contexts.
- Social reality is a constantly shifting emergent property of individual and collective creation.

A radical expression of this perspective, a so-called “strong social constructionist” view on the nature of science, is provided in (Gross and Levitt 1994; Chap. 3): “Science is a highly elaborated set of conventions brought forth by one

particular culture (our own) in the circumstances of one particular historical period; thus it is not, as the standard view would have it, a body of knowledge and testable conjecture concerning the real world. It is a discourse, devised by and for one specialized interpretive community, under terms created by the complex net of social circumstance, political opinion, economic incentive and ideological climate that constitutes the ineluctable human environment of the scientist. Thus, orthodox science is but one discursive community among the many that now exist and that have existed historically. Consequently its truth claims are irreducibly self-referential, in that they can be upheld only by appeal to the standards that define the scientific community and distinguish it from other social formations.”

It should be noted that this quote does not represent the opinion of the book’s authors, who are opposed to this strong constructionist concept of science.

The social constructivist perspective on truth, whereby knowledge is tentative and a result of not only objective and rational processes but also of social processes, is rather challenging for most natural scientists. The traditional realism perspective whereby science can present an objective, true picture of nature, including those parts of nature that are not available to our senses, is far more in line with common sense. But, as we have already noted earlier, common sense has severe limitations as regards scientific investigation and rationality. I note in this connection that the debates about realism are primarily based on those objects and phenomena that are *not* observable—and therefore not amenable to our common sense.

Perhaps then the main question to face when considering the perspective provided by scientific realism is whether the entities and relationships that are postulated to exist by the natural sciences, and in particular by physics, are real, or whether they are simply our perceptions of reality, constructs of the human mind that enable us to order, classify, experiment and develop meaningful knowledge. Realism contends that the entities, phenomena, and processes described by correct theories really exist, no matter whether they are the smallest of the small or in the most distant reaches of the universe. According to (Hacking 1983; 21): “Protons, photons, fields of force, and black holes are as real as toe-nails, turbines, eddies in a stream and volcanoes. The weak interactions of small particle physics are as real as falling in love. Theories about the structure of molecules that carry genetic codes are either true or false, and a genuinely correct theory would be a true one.”

The anti-realist/instrumentalist takes the opposite position. According to Hacking, the position here is that there are no such things as photons, DNA, gravitation, dinosaurs, and viral infections—light bulbs emit light, but not photons; inheritance takes place, but there are no genes; heavenly bodies move together, but there are no gravitational forces; fossilised bones exist; but not dinosaurs; colds exist, but not viruses.

But anti-realism is not only based on objects and phenomena, observable or not. It also deals with our theories and explanations. The anti-realist accepts that the theories we develop may certainly be useful tools for our thinking and may help us to develop technologies. But the theories cannot be said to be true or false; we cannot obtain true knowledge of the physical world; theories are logical constructions, instruments, for reasoning about reality. They can be useful and adequate

for their purposes, but we have no compelling reasons to believe that they are *true*. And the entities/phenomena they deal with may or may not exist, but there is no need to assume their existence in order to develop a meaningful understanding of the physical world.

I conclude this section on realism and instrumentalism/anti-realism by suggesting that there cannot be any final, conclusive argument for or against realism in the natural sciences. However, there is ample evidence that no matter whether one takes a realist or an anti-realist/instrumental position (or for that matter a constructivist or a positivist position), as a basis for investigating and understanding the world, science works! From this pragmatic epistemological vantage point, scientists develop theories and technologies that describe the world reasonably precisely—including its unobservable parts. Just how these theories and descriptions are developed in the natural sciences is considered in the next section on the relationship between mathematics and the natural sciences.

2.8 Mathematics and Science

Mathematics, which is deductive in nature, is not a natural science, at least given the perspectives on the natural sciences provided here with their emphasis on empirical investigation. Nevertheless, mathematics plays a vital role in the natural sciences. Its significance for the natural sciences is that it is essentially their language. The so-called laws of nature are in general expressed in, that is reduced to, a mathematical form.

The following brief series of reflections on mathematics and science is structured around four basic questions that I consider to be of great significance for the natural sciences. The first of these questions serves as the leitmotif of this section:

2.8.1 *Is Mathematics Created by Humans, or Is It Immanent in Nature and Discovered?*

Neither practitioners of the natural sciences, nor mathematicians, can provide a definitive answer to the above question. In spite of the fundamental nature of this question, it is surprising to note that educational programs in science do not attempt to answer it—or even to raise it. The main reason for the question's significance is that if mathematics, like ordinary language, is an artefact, a creation of human endeavour, and not something inherent in physical reality, then we are compelled to reflect on the extent to which it is sufficient for describing relationships between objects and phenomena in the physical world. After all, the natural sciences rely greatly on mathematics for describing physical reality and essentially all the “laws” of nature are expressed in, that is reduced to, a mathematical form. So if there are

structures, processes and relationships in the physical world that cannot be precisely translated/described via the language of mathematics, scientists face the question as to how they can gain access to and communicate the “secrets” of physical reality that are *not* reducible to mathematics.³⁵

Let us continue with this line of thought as to what we are able to “say about nature”. It is not possible to have a one-to-one direct translation between languages that have different syntaxes, say from Sanskrit to English. In the same manner, if mathematics is not “embodied in nature”—and by this I mean isomorphic with structures in nature—it may not be possible to “translate” directly, even from observable physical reality, to mathematics—and translation may be even more out of the question if we consider those aspects of reality that are not directly observable. If this is the case, we must rethink fundamental concepts in science such as truth, objectivity and scientific laws!

Thus, it may be very optimistic and unrealistic to assume, as most scientists do without further reflection, that mathematics is sufficient to provide truthful/isomorphic depictions of nature’s elements, processes and relationships.

If, on the other hand, mathematics is embodied in nature, i.e. if all of physical reality has a mathematical structure, then we can perhaps feel secure in assuming that all of nature can be reduced to, expressed in, mathematical statements—that mathematics is the language, so to speak, *of* physical reality, observable or not.³⁶ Another way of expressing this is to say that if physical reality has a mathematical structure, then humans in their scientific investigations will discover (not invent, as is the case with artefacts) mathematical realities.

2.8.2 *What Is the Ontological Status of Mathematics?*

Closely related to the question of the relationship between mathematics and reality therefore is the question of the ontological status of mathematics: whether the elements of mathematics have an existence of their own, whether they are not only

³⁵When I refer to ‘mathematics’ here, I refer to the study and the methods of study of deductive relationships dealing with quantities (arithmetic), structures (algebra), space (geometry), and change (analysis). A humanistic perspective is provided by emeritus professor of mathematics E. Brian Davies (2010; 101) who refers to mathematics as an aspect of human culture, just like ordinary language, music and architecture. According to Davies, it is because its vocabulary is so highly specialized that its domain of applicability excludes much of importance in our daily lives.

³⁶Professor Claus Emmeche, Niels Bohr Institute, Denmark, sent me the following example that illustrates the complex nature of the question as to whether there an isomorphic relationship between mathematical and physical structures. If one looks at a head of cauliflower it appears to have a fractal structure—but is fractal geometry imbedded in the cauliflower? It appears that the answer can be both yes and no. Yes, since we may be able to describe its form using fractals. No, since fractals are limitless (are self-similar at arbitrarily small scales) while the number of times that a form on a cauliflower head can recursively repeat itself is limited since its basic building blocks are cells, which themselves are not fractal in nature.

useful in describing reality, but in fact are part of the reality they describe? This is a question that was central to the reflections of the schools of thought that developed around Pythagoras (roughly 570–495 BCE) and Plato (429–347 BCE) in ancient Greece.

After presenting the famous so-called Mandelbrot set,³⁷ (Penrose 1991; 94–5) poses the question: “How ‘real’ are the objects of the mathematician’s world? From one point of view it seems that there can be nothing real about them at all. Mathematical objects are just concepts; they are the mental idealizations that mathematicians make, often stimulated by the appearance and seeming order of aspects of the world about us, but mental idealizations nevertheless. Can they be other than mere arbitrary constructions of the human mind? At the same time there often does appear to be some profound reality about these mathematical concepts, going quite beyond the mental deliberations of any particular mathematician. It is as though human thought is, instead, being guided towards some external truth—a truth which has a reality of its own, and which is revealed only partially to any one of us. ... The Mandelbrot set is not an invention of the human mind; it was a discovery, like Mount Everest, the Mandelbrot set is just *there*!”

Even though they lack spatiotemporal properties, Penrose attributes ontological existence to mathematical objects themselves: “... my sympathies lie strongly with the Platonistic view that mathematical truth is absolute, external and eternal, and not based on man-made criteria; and that mathematical objects have a timeless existence of their own, not dependent on human society or on particular physical objects.”³⁸ (Penrose 1991; 116) Penrose does *not* here say that all physical objects have a mathematical structure, only that there are mathematical objects, like the Mandelbrot set, that exist eternally, unchangingly and independently of anything else.

But if we take the position that mathematics exists, i.e. is part of reality (even though its objects may not have physical properties such as mass or location) and that, like physical reality, it is discovered and not created by us, then we face a series of significant metaphysical questions: Is there/was there an “Intelligence” that embodied mathematics in nature? If so, did this “Intelligence” have a plan—is it a predetermined part of evolution that the physical world should be amenable to human investigation such that humans should discover mathematics so as to be able to use it to crack the “cosmic code”? To pretend that one can answer such questions conclusively would be the height of audacity.

According to the Hungarian American physicist and mathematician, Nobel laureate in physics in 1963, Eugene Wigner (1902–1992): “...the enormous usefulness of mathematics in the natural sciences is something bordering on the mysterious and there is no rational explanation for it.” (1960; 2) ... “The miracle of

³⁷The Mandelbrot set is defined as the set of complex values of c for which the mapping of c under iteration of the complex quadratic polynomial $z_{n+1} = z_n^2 + c$ remains bounded.

³⁸In contrast to Penrose, the renowned mathematician E. Brian Davies (2010; 97–113) provides a critical assessment of Platonism.

the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research and that it will extend, for better or for worse, to our pleasure, even though perhaps also to our bafflement, to wide branches of learning.” (Ibid.; 14)

Finally, before leaving these reflections as to whether there is an isomorphic relationship between mathematics and physical reality I would briefly like to reflect on the following question: If mathematics is embodied in nature is it only in the nature of this Earth or is it embodied in the entire universe?

It is a basic presupposition of the natural sciences that the regularities we describe via the so-called “laws of nature” are invariant and universal. In other words, it is presumed that since the advent of the Big Bang the laws and the phenomena they describe are independent of time and space; gravitational or electromagnetic forces are not just regarded as phenomena that exist in this world of this solar system, but everywhere and at all times—that is, after “time” began. This basic presupposition as to the regularity of the universe appears to be well-founded and documented; e.g. investigations of stellar activity support the generalizability of the relevant laws of nature as they have been uncovered here on Earth.

While this last statement appears to be obvious, Wigner (1960; 6) raises the question as to whether what appear to be invariant, universal laws can be in conflict with each other:

We have seen that there are regularities in the events in the world around us which can be formulated in terms of mathematical concepts with an uncanny accuracy. ... The question which presents itself is whether the different regularities, that is, the various laws of nature which will be discovered, will fuse into a single consistent unit, or at least asymptotically approach such a fusion. Alternatively, it is possible that there always will be some laws of nature which have nothing in common with each other. At present, this is true, for instance, of the laws of heredity and of physics. It is even possible that some of the laws of nature will be in conflict with each other in their implications, but each convincing enough in its own domain so that we may not be willing to abandon any of them. ... We may lose interest in the “ultimate truth,” that is, in a picture which is a consistent fusion into a single unit of the little pictures, formed on the various aspects of nature.

I conclude this sub-section with the observation that the entire universe appears to be “designed and constructed” with an amazing precision—based on a few constants. If for example the gravitational constant (or the speed of light or absolute zero on the Kelvin scale or Planck’s constant or...) had been just slightly different, the universe would not have the conditions that could support the development of life on earth—and perhaps the universe might never have come about (Ward and Brownlee; Chaps. 2, 3, 12). So has *everything*, including life and consciousness, existed embodied as a seed—that has been “programmed”—since “Planck-time” (roughly 5.4×10^{-44} s after the Big Bang)? Or is the universe simply a random event? This leads to a third basic question regarding the relationship between mathematics and science.

2.8.3 If Mathematics Is Embodied in Nature, Is the Universe Deterministic?

In connection with reflection on whether the world is mathematical, I raised the question: “Is there/was there an ‘Intelligence’ that embodied mathematics in nature?” In connection with our earlier reflections on the concept of prediction in science, we considered the thought experiment of the French astronomer and mathematician Pierre-Simon Laplace that involved a hypothetical master-intelligence or intellect. Laplace reasoned that if the intellect somehow was able to know the precise location and momentum of every element in the universe then, since Newton’s laws of motion were assumed to hold universally, it would be possible, in theory at least, to calculate the position and momentum of every object in the universe at any time. In other words, he argued that the universe is a deterministic mechanical system.

When we considered this argument earlier, I strongly challenged it:

- (a) The findings of quantum physics challenge the underlying assumption that everything that exists consists of particles whose position and motion can be described by classical mechanics and therefore as well that all physical processes are reversible.
- (b) Human behaviour (as well as that of other sentient beings) is conscious behaviour, and since consciousness may not be a deterministic mechanical system—at least there is no compelling evidence that it is—and since humans consciously intervene in the system, the universe cannot be a deterministic system in the sense that its past, present and future can be completely and precisely described by mathematics.
- (c) Even if we assume that Laplace’s assumptions and reasoning as to the universe being a deterministic mechanical system are correct, this does not imply that scientists are able to completely describe this system where all there is are particles interacting in a completely deterministic manner. Scientists, even employing the most powerful computers, are not the “intelligence” referred to by Laplace. We have a limited ability to know at any given moment of time everything about the material structure of the universe, and have limited capacity to compute the evolution of the universe. Thus, at least in practice, scientists are only able to predict events with a certain probability.

I conclude these brief reflections on mathematics and determinism by referring to (Hofstadter 1989) who touches on this question in a similar manner in his section on Formal Systems and Reality: “... it is natural to wonder about what portion of reality can be imitated in its behaviour by a set of meaningless symbols governed by formal rules. Can all of reality be turned into a formal system? In a very broad sense, the answer might appear to be yes. One could suggest, for instance, that reality itself is nothing but one complicated formal system. Its symbols do not move around on paper, but rather in a three-dimensional vacuum (space); they are elementary particles of which everything is composed. (Tacit assumption: that there is

an end to the descending chain of matter so the expression ‘elementary particles’ makes sense) ... The ‘typographical rules’ are the laws of physics ... the theorems of this grand formal system are the possible configurations of particles at different times in the history of the universe. The sole axiom is (or perhaps *was*) the original configuration of all the particles at ‘the beginning of time’. This is so grandiose a concept, however, that it has only the most theoretical interest; and besides, quantum mechanics (and perhaps other parts of physics) casts at least some doubt on even the theoretical worth of this idea. Basically, we are asking if the universe operates deterministically, which is an open question.” (Ibid.; 53–54)

2.8.4 *Are We Able to Describe All Relationships in the Universe with Mathematics?*

It should be clear that if we do *not* assume that mathematics is embodied in nature, then we cannot a priori answer this question affirmatively.³⁹ But what if we assume that mathematics is embodied in nature—are we then able to describe all phenomena and relationships using mathematics?

It is argued that if we adhere to a presupposition that the *physical* universe *is* mathematical—that there is an isomorphic relationship between physical reality and mathematics—we risk being blind with respect to phenomena that cannot (reasonably) be reduced to physical elements and thus cannot be described using mathematics. For example, we risk a mathematization of areas of investigation such as economics, psychology, anthropology, consciousness, aesthetics and ethics whereby the resulting theories and models may be (most probably are) unable to accurately and operationally describe the phenomena being investigated. Even more threatening: we risk that such areas of investigation become so dominated by their mathematization that the phenomena and relationships they investigate are transformed to “fit” the models and theories that have been formulated mathematically—instead of the opposite.

The risk is real. Educational programs in science, including the cognitive-, bio-, behavioural- and social sciences, are becoming ever more enamoured with such mathematization and the supposed “order” it enables. However, and as was argued earlier in Sect. 2.5.4 of this chapter where we considered chaos theory, reality is not necessarily characterized by order, at least the kind of “order” we are accustomed to refer to. So-called chaotic systems are disordered, aperiodic and unpredictable even though their mathematical representation is deterministic, i.e. without any random elements.

³⁹We will many times, particularly in Chap. 8 dealing with uncertainty in science, refer to the concepts a priori and a posteriori: The truth or falsity of an a priori statement can be established without reference to observational evidence (e.g. as in determining the truth of a theorem in geometry or in a tautological statement such as “All bachelors are unmarried”) while such evidence is required to establish the truth or falsity of an a posteriori statement.

Another way to consider the question as to whether we are able to describe all relationships in the physical world with the aid of mathematics is to reflect on the role of probability theory in science. For over two thousand years following the development of mathematics as an axiomatic-deductive system, science was considered as dealing with causes, not with chance. Then, with the development of probability theory from the mid-17th century (and later on, the development of statistics as a related area of study), science and chance gradually became reconciled. In the 18th century probability theory expanded its focus from gambling problems to law, to the analysis of data, and insurance—and from there to sociology, to physics to biology, and to psychology in the 19th century, and to agronomy, polling, medical testing, sports and so on in the 20th century.⁴⁰ The theory developed as its applications developed. Today, the study of probability is not solely confined to quantitative matters; concepts of chance also are predominant in considerations of philosophical and scientific matters such as free-will, causality, explanation and inference.

⁴⁰For a fascinating exposition on what the authors refer to as “the probability revolution” that is said to have taken place between 1830 and 1920 “and began with a statistical revolution, that is with a mania for collecting and analysing quantifiable data about people and their doings and that got underway at the turn of the seventeenth century”, leading to a “shift in the conceptual and methodological underpinnings of many sciences”, see Chap. 8 in (Depew, D.J. and Weber, B.H. 1996), particularly pp. 202–208.

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