Chapter 2
The Scientific Method

Ruben Fossion and Leonardo Zapata-Fonseca

Abstract It is surprisingly difficult to define what makes something scientific. It is not what is being studied, i.e. the topic, but rather how the study is carried out, i.e. whether a correct methodology – or the so-called scientific method – is being used. The scientific method is not very different from the common sense with which we interpret events in our daily life, but with the important difference that the successive steps of observation, hypothesis and empirical verification are well articulated and controlled. Two different views exist on the scientific method. On the one hand, there are the philosophers who try to define a universal method that is valid for all scientific disciplines and for all times. From the philosophical point of view, scientific research is not 100 % objective, and it turns out impossible to confirm or refute any theory in an absolute way, which seems to be in paradoxal contradiction with the profound success of scientific research in all domains of human achievement. On the other hand, there are the working scientists who are interested in a pragmatic method that in the first place must be applicable to their daily research activities. According to the latter view, a theory does not need to be absolutely certain but instead has a certain level of probability based upon how well it fits into the coherent network of all scientific knowledge; an individual scientific investigation might be subjective up to a certain degree, but science as a whole converges to objectivity.

Keywords Scientific method • Common sense • Iterative process • Idealistic vs. pragmatic view • Paradigm • Complexity

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R. Fossion (✉)
National Institute of Geriatrics, Mexico City, Mexico

Centre for Complexity Science (C3), National Autonomous University of Mexico, Mexico City, Mexico
e-mail: ruben.fossion@gmail.com; fossion@nucleares.unam.mx

L. Zapata-Fonseca
Plan of Combined Studies in Medicine MD/PhD (PECEM), Faculty of Medicine, National Autonomous University of Mexico, Mexico City, Mexico
e-mail: lizf_3@hotmail.com; leonardo3zapata@gmail.com

C. García-Peña et al. (eds.), *Aging Research - Methodological Issues*,
DOI 10.1007/978-3-319-18323-7_2

2.1 Philosophy of Science and Common Sense

The most direct contact between society and science is probably through technology-based products derived from a specific scientific specialty: the computer, the mobile telephone, satellite television, or medical applications such as tomography and organ transplantations, among others. A less tangible but no less transcendent contact is the way in which different scientific disciplines have changed our perception of Nature, the cosmos and our place in it –e.g., Darwin's theory of evolution, which demonstrated that we are not the owners of the flora and fauna as taught in the Bible, but rather part of it; or the Big Bang theory, according to which we are not the center of the universe, but rather the insignificant inhabitants of just another planet circling a mediocre star in a far-away corner of the Milky Way. Although science is sometimes plagued with a negative connotation because of abuses and degradations such as the atomic bomb, pollution and global warming, society esteems science for its presumed quality of being based on objective facts, so that scientific research has more weight and authority than a personal opinion [1]. But what makes something scientific? It is not the object or the topic under study but rather the methodology with which a study is carried out and the standards that are used to judge the obtained results [2]. The methodology that is used in science, or the so-called *scientific method*, is not very different from the way in which we use common sense to interpret events in our daily lives. *Common sense* analyzes the information we receive through our senses (sight, hearing, touch, smell, taste, proprioception and vestibular orientation) as being real and independent from the observer. Without thinking consciously about the steps taken, our common sense is based on a sequence of observation, evidence and verification; scientific thinking follows the same logic, but the scientific train of thought is slowed down for the purpose of increasing transparency and control during the various steps. Transparency is important because it enables both peers and colleagues to repeat experiments, verify results and construct more advanced theories based upon them [2]. Science is a collaborative activity, and recent examples of this are the peer review process and open access journals.

The study of the scientific method is a science of science, also called *meta-science*, and therefore belongs to the field of *philosophy of science* (Fig. 2.1). Philosophy is a forum to question and clarify concepts that other disciplines believe to be obvious without having investigated them explicitly [2]. Philosophy of science analyzes the various steps of a scientific investigation. The experts who have written on the scientific method are the philosophers [1–3] and less frequently the scientists themselves [4–6], resulting in two completely different approaches to the topic. On the one hand, scientists learn and apply the scientific method implicitly in their daily activities, usually without noticing the abstract pattern that underlies every scientific investigation. On the other hand, instead of concentrating on the object or topic under study, philosophers are more interested in the research method that is employed and they investigate the logical structure of the sequence of scientific activities carried out [3]. Consequently, the philosophical approach tends to be abstract and idealistic, and the goal is to define an absolute and universal scientific method that is valid for all disciplines and for all times; in contrast, the scientific

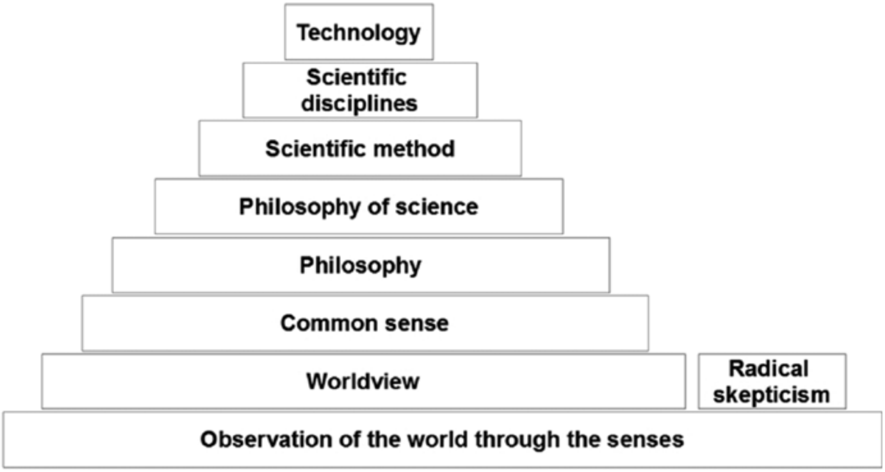

Fig. 2.1 The scientific method is founded on philosophy of science, which in turn depends on philosophy, common sense, and a worldview (for example, atheism, humanism, materialism, Christianity, Buddhism, etc.). The scientific method gives support to scientific specialties and technology. Radical skepticism treats the physical world that we observe through the senses as being non-existent, unknowable or illusive, and is not compatible with common sense or with the scientific method (modified from [5] with kind permission from Cambridge University Press)

approach is more realistic and conformist, and scientists are satisfied with an approximated scientific method that in the first place must be applicable to their daily research activities. Not surprisingly, scientists who are active both in research and in teaching tend to be the most pragmatic in their understanding of the scientific method [5, 7].

2.2 Foundations of the Scientific Method: From the Ancient Greeks to the Scientific Revolution

History of science is another discipline that belongs to the field of philosophy of science. The history of science illustrates how the scientific method developed gradually through time [6].

The ancient Greeks were pioneers in establishing a science independent of religious dogmas. Plato (427–47 BC) and his mentor Socrates (469–399 BC) developed a contemplative science based on some abstract axioms to which they applied *deductive logic*[1] to obtain new statements. Aristotle (384–322 BC), although he studied in Plato's Academy in Athens, preferred to combine abstract thought with passive

[1] Deduction is a tool of logic that allows obtaining conclusions from accepted premises. If the initial premises are correct, the conclusions are necessarily also correct; in other words, the truth of the premises ensures the truth of the conclusions.

observations of Nature and used *induction*[2] to obtain new hypotheses. Today, in retrospect, Aristotle is criticized for his exaggerated generalizations not verified with experimental data. The teachings of Aristotle continued to influence the development of science –though sometimes to their detriment– for the two following millennia.

In the dark ages of Europe's Medieval Period (500–1000 or 500–1300, depending on the source), much of the scientific knowledge of the Greeks was lost. Fortunately, a lot of that knowledge could be recovered thanks to the Arabs (700–1500), who had adopted the science of the ancient Greeks. The contribution of the Arabs to the scientific method was to include active *experimentation*, which proved to be an important step forward, because since then it became customary to check theoretical predictions with experimental results.

The next important period is the *scientific revolution* (1500–1800), whose development was due to the contribution of many factors, some of which will be mentioned in the following. The first universities in Italy, France and England, founded starting from the tenth and eleventh centuries, resulted in a gradual "liberalization" of the sciences leading to a more pluralistic vision not dictated by a few authorities, such as Aristotle in the centuries before. Humanism was a new philosophical and ethical current having as one of its purposes to explain all natural phenomena without any reference to the supernatural. During the scientific revolution, active experimentation was responsible for important advances. One example is the dissection of human cadavers, through which Andreas Vesalius (1514–1564) could gain a better understanding of human anatomy and which culminated in his main work *De Humani Corporis Fabrica*. In particular, Vesalius described the interconnected system of veins and arteries, refuting the scientific dogma of the ancient Greek physician Galen (130–200 AD), who had postulated two independent systems, a theory that was well accepted from the second century of our era till after the Middle Ages. Technological inventions further accelerated the advance of science: the telescope enabled Copernicus (1473–1543) and Kepler (1571–1630) to refute the theory of the geocentric system of the ancient Greek astronomer Ptolemy (90–180 AD) and to propose a new heliocentric system to describe the movement of the planets in our solar system; the microscope made it possible for Robert Hooke (1635–1703) and Antonie van Leeuwenhoek (1632–1723) to study the life of microorganisms for the first time. Another important factor driving science forward in many fields of knowledge was *mathematical modeling*, which allowed researchers to make not only *qualitative* predictions (e.g., the temperature will rise) but also *quantitative* predictions (e.g., the temperature will rise with exactly 2°C). The ability to make quantitative predictions increased dramatically the power of verification of the scientific method, because in this way it became possible to distinguish between two or more competing theories if one explained the numerical results of an experiment more satisfactorily.

[2] Induction is a tool of logic that simplifies and generalizes patterns observed in a limited amount of data into a theoretical principle (hypothesis, law, model, conjecture). Induction is a creative and imaginative step associated with the inspiration and genius of the researcher. The conclusion does not have absolute certainty, but rather a certain level of probability, which depends on the quality of the evidence. A classic example of induction is observing that all European swans are white and generalizing that all swans must be white. This conclusion was shown to be false when black swans were discovered in Australia.

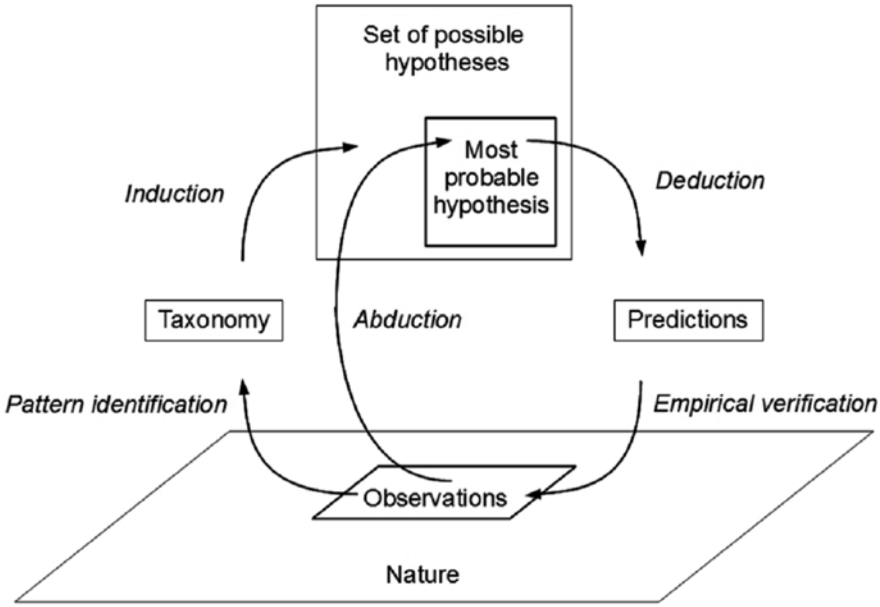

Fig. 2.2 The process of scientific reasoning is iterative and alternates between deduction, induction and abduction. Induction generalizes observed patterns in nature in theoretical models. Abduction selects the most probable working hypothesis from a set of possible hypotheses to explain an observed phenomenon. Using deduction, predictions are made from the hypothesis to be verified with data from controlled experiments, so that the hypothesis can be checked and corrected if necessary

The structure of the scientific method, in its most basic form, can be summarized as successive repetitions of the following sequence (Fig. 2.2):

$$\textit{Observation} \rightarrow \textit{Taxonomy} \rightarrow \textit{Hypothesis} \rightarrow \textit{Prediction} \rightarrow \textit{Empirical Verification}$$

In the *observation* phase, relevant data about a natural phenomenon of interest are recognized. The *taxonomy* stage detects and classifies regular patterns in the data. The induction phase enables the researcher to generalize and simplify these patterns in one or more *theoretical hypotheses* to explain the phenomenon. *Abduction*[3] is a type of logical inference that is used to select the most probable hypothesis from a set of possible hypothesis to explain a given phenomenon (see also Sect. 2.3.2). Applying deductive logic to the working hypothesis allows deriving predictions, which can be *verified* with the results of carefully controlled experiments. A *controlled experiment* is one where a certain (independent) variable is varied to study the consequent changes in another (dependent) variable. It is preferable that all the other variables remain constant to avoid confusion factors. When new observations are

[3]Abduction is a tool of logic that infers a premise from a conclusion. For example, since grass becomes wet when it rains, observing wet grass in the morning, a good working hypothesis might be that it must have rained during the night. Abductive reasoning is prone to the fallacy of affirming the consequent.

made, and new experimental data are obtained, the working hypothesis may be retained, modified or refuted. It is assumed that the repetition of the sequence Observation → Taxonomy → New Hypothesis → Prediction → Experimental Verification → … will converge to an accurate description of the true state of Nature [4–7].

2.3 An Idealistic Interpretation of the Scientific Method According to Philosophers

In day-to-day scientific practice, the following properties are often taken for granted:

- The data are previous to and independent from theory;
- The data constitute a firm and reliable base for scientific knowledge;
- The experimental data are obtained by impartial observation through the senses.

However, philosophers have identified some problems with these assertions, such as theory-ladeness and subjectivity, confirmation and rejection of the theories, and how to evaluate scientific progress [1].

2.3.1 Theory-Ladeness and Subjectivity

The American philosopher of science Norwood Russell Hanson (1924–1967) argued that all observations are *theory-laden* [8]. The most intuitive way to illustrate the concept of theory-ladeness is with an optical illusion, where what is perceived depends on previous knowledge and assumptions (or prejudices) of the observer [1] (Fig. 2.3). The concept of theory-ladeness gives rise to several philosophical problems because it introduces *relativism* to the choice of theories, which means that empirical evidence does not always distinguish among different hypotheses. The question then would be: what is it that limits the choice of theories? If the theory-laden observations cannot limit those choices, the restrictions that operate are the subjective preferences of the scientists or the rules of conduct of groups of scientists. The logic of confirmation appears to be intrinsically contaminated by idiosyncratic and social factors, threatening the very idea of scientific rationality [9].

2.3.2 The Problem of the Confirmation of Theories

Many theories make statements about things that are not directly observable (as were germs before the era of the microscope, or quarks in today's subatomic physics), which makes *direct empirical verification* impossible in these theories. It is possible to carry out *indirect empirical verification* by means of observable implications from the theory using the *hypothetical-deductive method* [2], which deduces a prediction

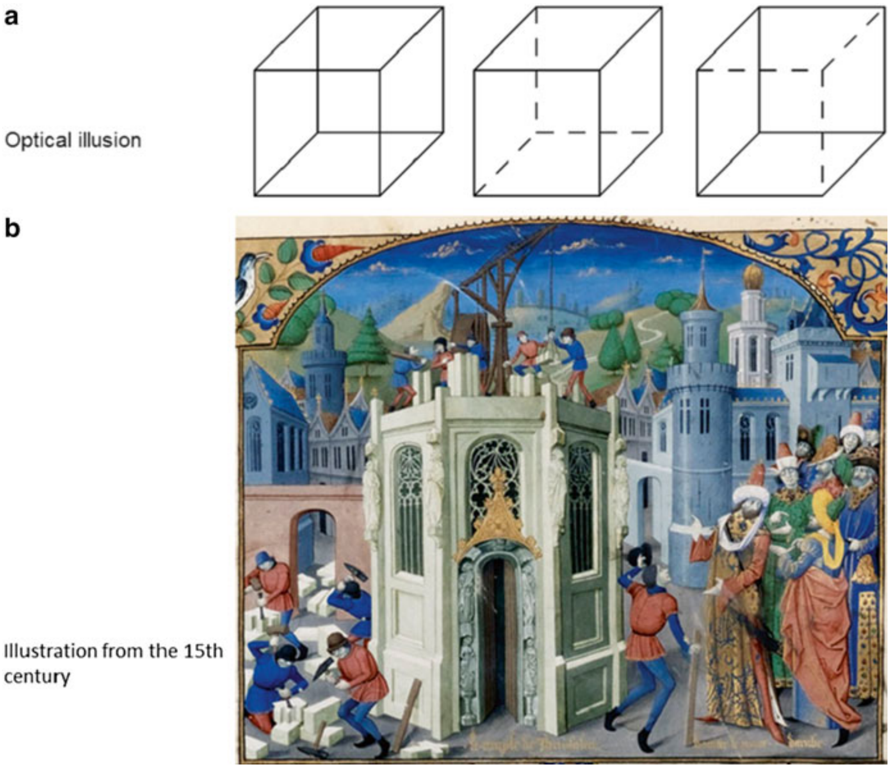

Fig. 2.3 Illustration of the concept of theory-ladeness. (**a**) The two-dimensional representation of a three-dimensional cube constitutes an optical illusion where, depending on the perspective, the front face can be the bottom one, and the upper face the rear one. The interpretation of graphical perspective depends on a previous knowledge of geometry; as a convention, continuous lines are interpreted to be visible whereas discontinuous lines represent invisible features. (**b**) Paintings from before the Renaissance do not present the graphical perspective correctly because knowledge of geometry was insufficient at that time. As an example, shown is an illustration of the reconstruction of the temple of Jerusalem from the fifteenth century in the manuscript “Histoire d’Outremer” by William of Tyre (National Library of France, Paris). The figure is from the public domain taken from Wikipedia, from the article “Perspective (graphical)”

(p) given a certain hypothesis (H). Checking the data, if prediction p is true, one can conclude that hypothesis H is also true, or symbolically,

If H, then p
p

H

For the American philosopher, logician, mathematician and scientist Charles Sanders Peirce (1839–1914) this way of reasoning is the basis of the third type of logical inference, namely abduction. One has to be careful because it is possible to commit the *fallacy of affirming the consequent* [2]. This can be seen more clearly with the following example: let us suppose that malaria causes fever (hypothesis H), so everyone who has malaria will also have fever (prediction p); if we diagnose fever in a patient (so that p is true), we cannot confirm that the patient in question has malaria (hypothesis H), because there are many other illnesses that could cause fever in addition to malaria. However, Peirce argued that abductive reasoning has evolved in humankind and that humans have become experts in choosing the best hypothesis to explain a given phenomenon. In the case of a patient with fever, as in the example mentioned, a treating physician would make a mental list of several possible causes and then would select the most probable cause (perhaps the flu?) as a working hypothesis to be further examined by comparison with additional data.

2.3.3 The Problem of Refuting Theories

The Austrian-British philosopher of science Sir Karl Raimund Popper (1902–1994) is best known for his *falsifiability* approach to the scientific method [10]. Falsificationism is an attempt to avoid induction (the creative and thus subjective step) in the scientific method. Popper suggested that, in order to explain a given phenomenon, it is possible to generate a very large number of hypotheses and try to reject them; a theory that survives several attempts to be falsified is not necessarily true, but is interpreted as a relative improvement to competing but falsifiable theories. From this perspective, scientific progress may be described as the replacement of falsified theories with new theories that up to that moment have withstood every attempt of falsification [10, 1]. However, the falsification of a theory turns out to be just as difficult as its confirmation, which can be understood considering again the *hypothetical-deductive method* [2] with a working hypothesis (H) and a deduced prediction (p). The negation of the prediction ($\neg p$) implies the rejection of the hypothesis ($\neg H$). However, a hypothesis usually does not stand alone but is supported by *auxiliary theories* and/or assumptions (A_1, A_2, …). For example, any use of a microscope is supported with auxiliary theories of optics that explain how and under what circumstances a correct magnification is obtained for the object being studied. In such a case, the negation of the system of a hypothesis *and* auxiliary theories results in the negation of the hypothesis *or* in the negation of one of the auxiliary theories. In symbolic form,

Case of a single hypothesis:
If H, then p
$\neg p$

$\neg H$

Case of a hypothesis with auxiliary theories:
If (H and A_1 and A_2 and…), then p
$\neg p$

$\neg$ (H and A_1 and A_2 and …)
Which is equivalent to $\neg H$ or $\neg A_1$ or $\neg A_2$ or …

The *Duhem-Quine thesis*, after the French physicist Pierre Maurice Duhem (1861–1916) and the American philosopher Willard Van Orman Quine (1908–2000), establishes that a theory can never be definitively falsified because it is impossible to rule out that an erroneous prediction is caused by an untrue assumption or a false auxiliary theory [1]. The Hungarian philosopher of science Imre Lakatos (1922–1974) nicknames the system of auxiliary theories a *protective belt* that prohibits the definitive falsification of a hypothesis [11].

2.3.4 Paradigm Shift and Scientific Progress

The American physicist and philosopher of science Thomas Kuhn (1922–1996) revolutionized the way in which *scientific progress* is perceived. Before Kuhn, scientific progress was interpreted as a gradual process; it has been suggested that our textbooks are to blame for reinforcing this view of a continuous accumulation of ideas up to the current state of science, whereas Kuhn argues that scientific achievements of the past need to be interpreted within the context of sociological factors and scientific perspectives of the time in which they were developed [6]. It appears that within each scientific specialty, prolonged periods of stability and consolidation precede short bursts of major conceptual revision, which Kuhn called *paradigm shifts* [12] (Fig. 2.4a).

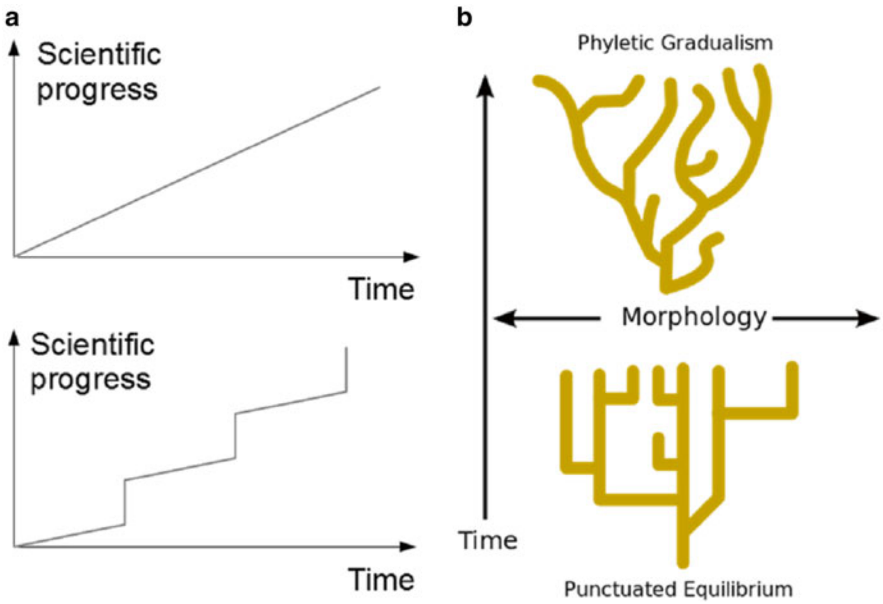

Fig. 2.4 Similarities between (**a**) scientific progress and (**b**) biological evolution. Traditionally, advances and changes were thought to be gradual, whereas more recent interpretations suggest an intermittent equilibrium. The figures from panel (b) are from the public domain, taken from Wikipedia, from the article "Punctuated equilibrium"

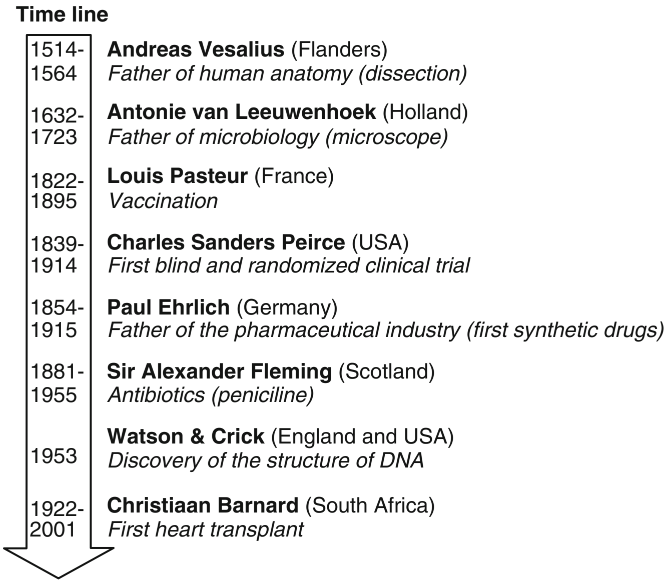

Fig. 2.5 Some key moments in the history of medicine that possibly constituted a paradigm shift

A *paradigm* is a coherent set of theories and concepts that guides interpretations, the choice of relevant experiments, and the development of additional theories in a field of study. Examples of contrasting paradigms in physics are: Newtonian dynamics as opposed to Einstein's theory of general relativity, and classical physics versus quantum mechanics. In medicine, possible examples of paradigm shifts are the dissection of human cadavers as introduced by Vesalius, the use of the microscope and the development of synthetic drugs (Fig. 2.5).

Standard science works within the framework of an existing paradigm that guides a field of research. In this case, almost all of the research relates to the paradigm: research is carried out according to a fixed scheme, and it is the paradigm that indicates which topics for research are appropriate and worthwhile; theoretical and experimental studies imply the collection of data to verify predictions of the paradigm, and consider also efforts to extend the paradigm in order to include apparent problems or ambiguities. Research within an existing paradigm is sometimes described in a pejorative way as "cleaning up." In a new field, that is, a field in a *pre-paradigm* state, no fixed scheme exists that indicates how experiments should be done or how data should be interpreted. To draw an analogy: data collection within the framework of an existing paradigm is like a hunter pursuing a prey, whereas without the guidance of a paradigm it rather resembles going for fishing in a lake to see what comes out [6]. In the absence of a paradigm, lots of data may be available but they are extremely complicated to interpret, and the general pattern and the main principles are vague; several currents of reasoning compete without agreement on which phenomena are worth studying, and no single current of reasoning is capable of providing a more general view of the field (see also Sect. 2.5).

The progress of science has been interpreted as a *punctuated illumination*, very similar to the theory of *punctuated equilibrium*, also known as interrupted equilibrium or intermittent equilibrium [6] (Fig. 2.4b). Punctuated equilibrium is a theory of evolutionary biology that proposes *stasis*, i.e., stability or only minor changes during most of the time of existence of a species; in contrast, evolutionary changes accumulate during the process of *speciation*, i.e., the formation of a new species which is sudden and of brief duration in comparison with the geological time scale [13]. Whereas neo-Darwinists defend the idea that evolution develops over time according to a linear or phylogenetic pattern, the punctuationists support the idea of evolution as a mosaic, in other words, branched. The idea of the former is a linear succession from one species to another; for the latter, an ancestral species gives place to multiple descendent species that in turn either become extinct or continue to branch out.

2.4 A Pragmatic Interpretation of the Scientific Method According to Scientists

2.4.1 From the Myth of Objectivity to Pragmatism

Scientists are interested in general concepts and principles, not in personal subjective perspectives. However, from the philosophical point of view (Sect. 2.3), it is possible that scientists cling to a *myth of objectivity*, in other words, scientists believe that objective knowledge of the true state of Nature is accessible, whereas in reality this might not be the case [6]. This does not imply that objectivity is a fallacy or an illusion, but that it could be an unattainable ideal. According to the great German quantum physicist Werner Heisenberg (1901–1976) science does not provide an objective explanation of Nature; rather, it describes what is exposed of Nature through the specific method of questioning being used [6]. This results in the following paradox: how is it possible to reconcile the apparent and profound success of science with the problem that scientific objectivity might be an elusive ideal because of the inherent subjectivity in perception? Apparently, science depends less on absolute objectivity than is thought traditionally. It can be argued that scientists are in the first place *pragmatists*: the challenge is to use methods and assumptions, bearing in mind that they are subjective and imperfect, and at the same time try to obtain an as objective as possible understanding of the patterns and principles of Nature [6, 14]. Certainly, any scientific investigation must necessarily use a biased scale to weigh and evaluate data because all scales are biased; but if we are fully conscious of the bias in the scale, it can be used effectively. To increase the precision of the scale, we need to know the sources of error. In order to achieve this, we need to understand the limits of our methods and it is important to understand, too, how the process of perception affects our observations and thus be able to recognize our own biases.

2.4.2 Full Disclosure

A first step toward the recognition of possible biases in research is complete transparency, or *full disclosure*, to reveal all the elements and steps taken to arrive at a scientific conclusion. Already Aristotle was interested in the transparency of scientific reasoning: "What is it that goes in so that scientific conclusions come out?" he asked. A modern model of transparency is the PEL model [5] (Fig. 2.6). The first element of the PEL model is the list of *presuppositions* (*P*), which offers a basic and indispensable image of the system being studied. The presuppositions are important because they enable one to restrict the set of all possible hypotheses, which are infinite, to a limited set. Without constraint, the set of possible hypotheses would be infinite and it would be impossible to reject all the absurd hypotheses and keep the realistic ones, based on the finite quantity of empirical evidence accessible to us. Evidently, presuppositions do not differentiate between the credibility of each of the realistic hypotheses because the presuppositions are what all hypotheses have in common. On the other hand, *evidence* (*E*) is data that can distinguish among the different hypotheses. Finally, l*ogic* (*L*) combines the premises of presuppositions and evidence with logical reasoning (deduction, induction and abduction) in order to arrive at a conclusion.

It is possible to incorporate the PEL model of full disclosure into the iterative process of *Observation* → *Taxonomy* → *Hypothesis* → *Experimental Verification* (Fig. 2.7). Full disclosure enables the scientific community to evaluate the possible biases in a research project (e.g., are all the presuppositions reasonable?); one important aspect of science as a joint activity is the peer review process of scientific articles before they are accepted for publication [15].

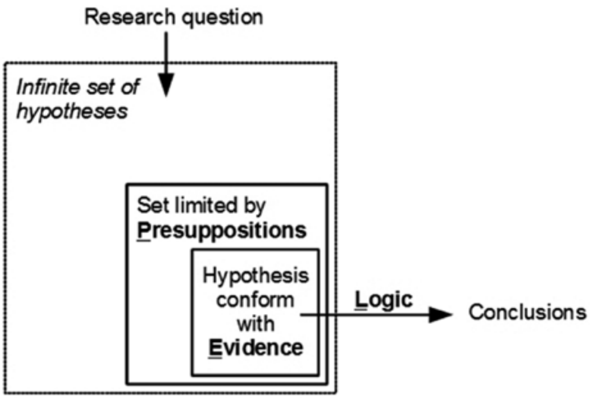

Fig. 2.6 Complete transparency, or *full disclosure*, of a research project according to the PEL model. The set of all possible hypotheses is infinite. The presuppositions (*P*) enable to discard unrealistic hypotheses. The evidence (*E*) allows to choose an appropriate working hypothesis. Logic (*L*) combines the presuppositions and the evidence to arrive at a conclusion

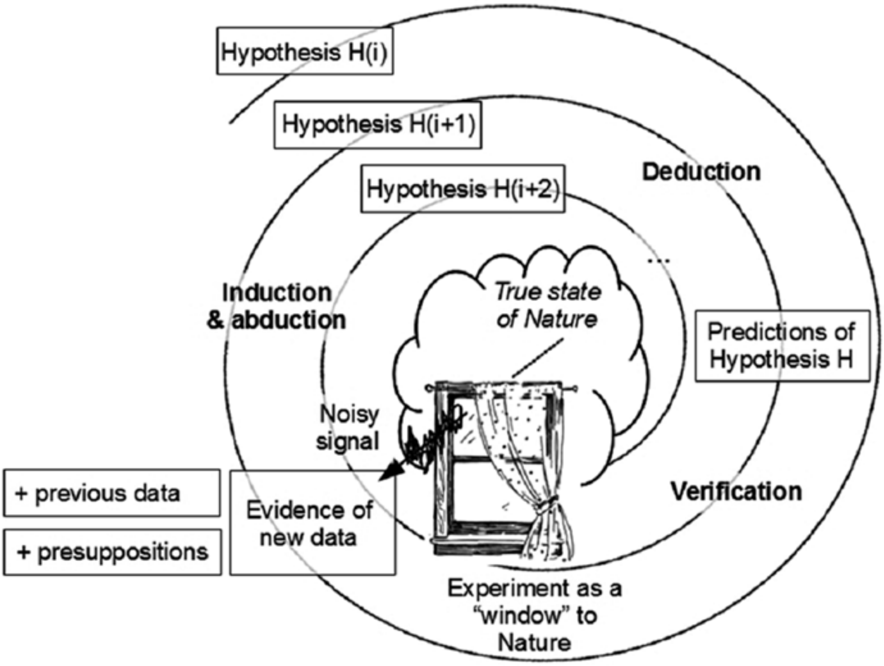

Fig. 2.7 Diagram of the scientific method that combines the iterative process of scientific reasoning (Fig. 2.2) with the PEL model of full disclosure (Fig. 2.6). The purpose is to make the working hypothesis converge towards an accurate description of the true state of the Nature (Modified from Ref. [4] with kind permission of John Wiley & Sons, licence number 3602580414728)

2.4.3 Certainty Spectrum and Knowledge Network

The scientific method is based on evidence and logic, but the details of empirical verification show that evidence and logic by themselves do not solve the problem of which hypotheses are absolutely true and which are absolutely false. As was mentioned in previous sections of this chapter, no isolated proof can definitively confirm or refute a hypothesis. In general terms, empirical proofs are never decisive: a false hypothesis can result in a true prediction and a true hypothesis could give a false prediction. Despite this, empirical verification is not useless because, from a pragmatic point of view, a true prediction provides some probability that the working hypothesis could be true, while a false prediction obliges us to rethink some aspects of the combined system of hypothesis, presuppositions and auxiliary theories [2]. The scientific method and its companion from daily life, common sense, have the important limitation that they never result in perfect or *absolute certainty*. In science as in life, we are always confronted with uncertainty and we are sensitive to *levels of certainty*: everything exists on a spectrum between mere conjecture and absolute certainty. The objective of the scientific method is to localize a particular theory within this spectrum; when evidence accumulates, the position of the theory on the spectrum can change. To increase our confidence in a hypothesis large numbers and varieties of different tests are necessary. One good way to gain confidence in a hypothesis is to verify how it fits within a coherent network of other theoretical statements and experimental claims. The concept of a *coherent network of ideas* plays an important role within the scientific method. The most important requirement for coherency is *logical consistency* because a network of knowledge does not tolerate contradiction. This does not mean that inconsistencies that persist in diverse scientific specialties cannot exist, but when such inconsistencies are identified they need to be studied and in the end usually give way to new scientific discoveries; that is why contradictions in science cannot be ignored. In addition to being consistent, scientific claims have to be *cooperative*, which means that they need to generate connections between different ideas, such that a new claim in one field of science can play the role of an auxiliary theory in the same or in other scientific disciplines. There is a variety of links between different theories, resulting in an interrelated and coherent network of scientific claims. When evidence accumulates and a new theory becomes better interconnected with other theories, the classification of this theory as uncertain slowly disappears and the theory converges toward the side of certainty on the spectrum. When a hypothesis arrives at equilibrium within a network of scientific knowledge, confidence in its certainty is established; this is also part of the scientific method [2].

2.5 Complexity Sciences: Towards a New Paradigm?

Since the 1970s an epidemiological transition is being observed, from a predominance of acute infectious diseases to a higher prevalence of chronic-degenerative illnesses [16]. *Acute infectious diseases*, e.g., a bacterial infection or a bone fracture, are usually relatively simple to diagnose and treat because often it is possible to localize and delimit the affected part of the body, and although several risk factors can be in play, the causes of the symptoms are quite clear in general. In contrast, *chronic-degenerative illnesses* like cancer, diabetes, frailty associated with aging, chronic stress, fibromyalgia, etc. seem to be more complex. Those afflictions are usually *systemic*, whereby several organs or biological processes are affected simultaneously, and *multifactorial*, with a broad spectrum of risk factors ranging from the microscopic (e.g., genetic predisposition) and mesoscopic (e.g., lifestyle) to the macroscopic (e.g., health policies). Often it is impossible to identify a clear cause-effect relationship, possibly due to a complicated interaction among the multiple risk factors.

It is possible that the current paradigm of the scientific method as used in medicine is not the most suitable one to study those more "complex" illnesses. It is noteworthy that many fields of knowledge presently face problems that at a first glance might appear very different but that are similar in terms of their inherent complexity e.g., species in danger of extinction in ecology, financial crises in econ-

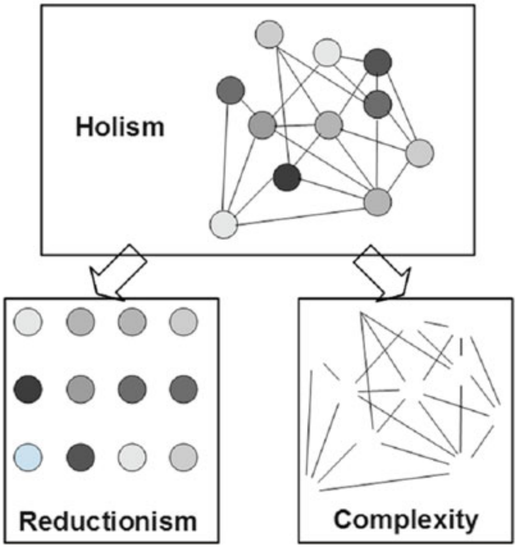

Fig. 2.8 Holism attempts to study systems in their totality, which is not always possible. Reductionism and complexity are different approximations of reality. *Reductionism* focuses on the components of a system and neglects information on time, space, interactions and context. *Complexity sciences*, or *systems biology*, focus on the interactions and the dynamics, giving less importance to the study of the individual components

omy, global warming in climatology, etc. [17]. The current scientific paradigm is characterized by *reductionism* and high specialization, which tend to focus on individual factors and lose sight of the context and interactions among factors that cross the borders of individual disciplines [18–20] (Fig. 2.8). There are many efforts to break free from the different limitations of the prevailing paradigm: *multi-, inter-* and *transdiscipline* try to integrate different scientific disciplines and make them interact [21]; *data mining* investigates patterns in huge quantities of crude data and translates the generated knowledge into predictive models that can be used in decision-making [22, 23]; *network theory* describes the interactions among elements or factors of a set [24]; *time series* statistics analyzes the temporal evolution of a specific observable [25], etc. Although all the techniques mentioned form part of the toolkit of the so-called *complexity sciences* or *systems biology*, each technique has its particular focus, and a general overview of the topics being studied is lacking. It would appear that the application of complexity sciences to economy, ecology and climatology and to the understanding of complex ailments in medicine, such as age-related frailty [26], are still in a *pre-paradigm state* (Sect. 2.3.4): the taxonomy of the phenomena observed has not yet been established clearly, and a general descriptive theory still needs to be constructed.

2.6 Conclusions

It is not the *topic* which determines whether something under study is scientific or not, but rather the *way* in which it is studied; in other words, whether the study follows the scientific method. The scientific method is similar to the common sense that we use in daily life but with the sequence of the different successive steps *Observation → Taxonomy → Hypothesis → Prediction → Verification* well articulated and well documented.

There are two different approaches to the scientific method. The philosophers, on the one hand, are idealists and try to define an absolute and universal method, with one of the unresolved questions being: "how can one obtain objective knowledge if some of the steps in the method are subjective?". Scientists, on the other hand, are realists and conformists, and are satisfied with an approximate description of the scientific method that can be applied in daily practice. Key aspects of this pragmatic approach to the scientific method are full disclosure of any investigation, interaction with the scientific community, and fitting the research into a coherent and cooperative knowledge network. In this pragmatic approach, individual research projects might be subjective, but science as a whole converges toward objectivity.

The current paradigm of the scientific method has been based on reductionism; on the other hand, many problems of the modern world are characterized by such a high level of complexity that they cannot be solved using the reductionist approach. Complexity science is an attempt to establish a new way of thinking and possibly represents a paradigm shift in the making.

Acknowledgments We acknowledge financial support from CONACyT (Grant No. CB-2011-01-167441) and the National Institute of Geriatrics (Project No. DI-PI-002/2012). RF acknowledges his Newton Advanced Fellowship from the British Academy of Medical Sciences. LZF is grateful to A. Flisser and the Plan of Combined Studies in Medicine M.D./Ph.D. (PECEM) for the research opportunities offered during the undergraduate career of Medicine.

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