Jacopo Parravicini

The Foundations of Experimental Physics

Unraveling the Premises of Physical and Scientific Knowledge

Springer

The Foundations of Experimental Physics

Jacopo Parravicini

The Foundations of Experimental Physics

Unraveling the Premises of Physical and Scientific Knowledge

Springer

Jacopo Parravicini
Department of Physics and Astronomy
University of Florence
Sesto Fiorentino (Firenze), Italy

ISBN 978-3-031-55451-3 ISBN 978-3-031-55452-0 (eBook)
https://doi.org/10.1007/978-3-031-55452-0

The translation of the original texts was done by the author. Where available, some English translations were consulted, but the exposed text is an own translation unless explicitly stated otherwise. Professor V. Sanvito's consultancy was also used, in particular for German and Russian texts.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Πολλὰ τὰ δεινὰ κοὐδὲν ἀνθρώπου
δεινότερον πέλει.

Sophocles, Antigone

*Visibilia regenda, invisibiles regentes:
interroga ista.
Respondent tibi omnia: Ecce vide, pulchra
sumus.*

Saint Augustine, Sermones

To my wife Viola and my children Tecla, Martino, Clara

To my mother Mirella and my father Giambattista

Foreword

What is the scientific method today, roughly 400 years after Galileo and 100 years after the quantum physics revolution? What are the logical, philosophical, mathematical, and physical patterns and ingredients underlying the experimental physics of our time? Jacopo Parravicini answers these important questions with a beautiful journey along the Foundations of Experimental Physics, a book that crosses all the founding aspects of today's scientific method in an original and stimulating way. The book was born as the text of a very successful university course with the same title, started 3 years ago by Jacopo Parravicini for Ph.D. students in Physics and Astronomy at the University of Florence. However, the text does not assume a deep knowledge about experimental physics, rather it guides readers in an in-depth but also exciting and often amusing way to discover the many involved conceptual aspects, which go far beyond the typical preparation of physics students.

This book addresses the important relationship between physics and mathematics in the research and verification of physical laws, and it shows that the scientific method has gradually evolved with the introduction of new scientific methodologies, new physical laws, and in general with the evolution of culture and knowledge at a global level. The text discusses important epistemological aspects, making them understandable with practical examples of scientific approaches drawn from the past and the present. Aspects of scientific research that we all certainly know, such as the difference between theoretical and experimental research, the units of measurement, the uncertainties of measurement, are for the first time explained and connected to each other in a way that makes us grasp their relationships and importance. The book also addresses much less known aspects, such as that of scientific frauds, describing them in a fascinating way and discussing the role of the scientific community, both in the past and in the present, with all its related open issues.

The journey along the Foundations of Experimental Physics by Jacopo Parravicini—an Experimental Matter Physicist at the Department of Physics and Astronomy of the University of Florence—is certainly aimed at a much wider audience than the Ph.D. students in physics for whom it was born. I am sure that many researchers and teachers, and more generally all the public with a passion for scientific research, will find this book instructive and stimulating as I did.

Florence, Italy
September 2023

Giovanni Modugno

Preface

A discussion of the nature of any intellectual effort is difficult per se—at any rate, more difficult than the mere exercise of that particular intellectual effort.

Johan von Neumann

Those who have a passion for Physics and scientific research usually focus their energies towards the specific content of the discipline, i.e. the study of natural phenomena. Whether this research is carried out as a job or that it is a simple curiosity, it is very rare to spend time to think about the methods and meaning of this intellectual enterprise. Looking at university courses in scientific branches, we notice how it is very difficult for a student to face, during his training course, a specific study regarding the foundations of sciences, what we see when experiments are carried out, what is the meaning of the claim that natural sciences are based on experiments. In short, in the curricula of the scientific faculties there is no a Method Course, where one learns how to "do science". What the scientific method is and how it is applied can only be learned through practice, there is no systematic treatment about it, not even broadly speaking. The text here presented aims at addressing this lack, proposing a reflection path on the general principles of Physics, as the discipline at the basis of all natural sciences.

There are many textbooks having, in their respective languages, titles such as "Fundamentals of Physics" or "Principles of Physics" or similar ones. Almost all of these deal with the main, or elementary, specific contents of the physical sciences, such as, for example, classical mechanics, thermodynamics, electromagnetism. Similarly, the addition of the "experimental" adjective ("Principles of Experimental Physics", etc.) makes the content a reasoned exposition of the main techniques and of the most important experimental methods. Allow me a metaphor, which I will recall throughout the text. Let physical science be a great building. The "foundations" or "principles" referred to by the titles of the aforementioned books are the structural elements of the building (mechanics, electromagnetism, etc.), those general concepts on which it is possible to build a peculiar and detailed explanation of a large number of natural phenomena. However, those same pillars and architraves, which support the weight of the building and give it shape, require solid foundations, the deeper and wider the bigger the building. These foundations are made not to be seen and not to be directly exploited by the users of the building. However, it is clear that they are the prerequisite for the whole construction. Well, the subject of this text is the foundations of the Physics building, not the pillars and lintels. The subject will be that which is not immediately before the eyes.

It is therefore clear that, although the present text has a very similar title to the aforementioned ones, it will deal with quite different subjects. The proposed path will address the study of what lies at the basis of science, in general, and of Physics in particular. Therefore, we will treat those elements which, in the practice of this discipline, are generally "taken for granted". We will address elements such as the relationship between the natural phenomena that Physics studies and the mathematical language it uses. I will highlight the main hubs of the conceptual development of science, also outlining the conceptual and practical instruments gradually conceived for the purpose of investigating nature. The life of every human being takes place between a concrete dimension, made up of body and matter, and an abstract one, made up of mind and thought. Similarly, Physics insists between a material world of experiments, highly concrete, and an ideal one made by mathematical entities and models, often highly abstract. In the middle there is "scientific practice", i.e. that set of proven, more or less empirical, more or less codified customs and methods, stabilized by successive approximations, which today determine the life of what is called the "scientific community", which determines the advancement of knowledge with its own work.

These and other highly heterogeneous elements contribute to the construction of knowledge in Physics. It is with all these elements that both those who practice research and those who benefit from its results deal, often unconsciously. If the small group of scientists, especially physicists, belongs to the first category, everyone belongs to the second one. Everyone, in the modern era, has known or used the fruit of scientific knowledge. Never as in our times we have been confronted with that powerful method of investigating reality which is called "science", a word, a principle, a concept, alas, often more abused than used. For this reason, in general, I don't like to talk about "science", but about "scientific research". During the text, however, I will be forced to use the word "science" several times, but I will always take care that the specific meaning attributed to it in that specific context is clear. As my personal contribution to clarity and truth based on facts, in this text I intend to describe the functioning and the main mechanisms of that sort of "machine", or rather, of *organism*, whose result is scientific knowledge in the discipline of Physics.

The here proposed path comes from a class for the Ph.D. course in Physics and Astronomy that I held at the University of Firenze. Therefore, it gives as notes the main notions of Physics and Mathematics that are learned in the first years of the technical-scientific faculties and, with them, the fundamental concepts of so-called modern physics. However, I believe that this text is within the reach of any university student or professor who, despite not having studied Physics in detail, intends to know the question of its foundations. Concepts that I take for granted non-physicists will easily find in suitable introductory textbooks.

As a general method criterion, in my text I will "make the great scientists speak", reporting as much as possible the quotations of those who were the builders of the discipline, Physics in particular, but not only. Similarly, to illustrate the concepts of the scientific method, I will propose the cases of some important paradigmatic discoveries, analysing their circumstances and procedures. I chose this approach not because of a historicist inclination, but because I don't consider myself entitled to explain "what Physics is" or, worse, "what science is". I will therefore ask the great ones to take me on their shoulders and I will lend them my voice so that whoever reads me can hear theirs.

Of course, I make no claim to exhaustiveness. On the one hand, anyone will certainly find works on the subject by great scientists that have escaped me and have not found a place here. In the text I have necessarily made a choice, but, in case, I ask my reader to report me further pertinent quotations. The intrinsic non-exhaustiveness of this book also derives from the fact that each of the individual considered topics would alone deserve a much more extensive treatment. For each of the topics that will be here treated, it is possible to find various texts that go into it in much larger detail than here. There are several books that deal in detail with subjects such as the planning of an experiment, or the features of measurement units, or the structure and principles of Mathematics, or scientific revolutions, or the features of the scientific community. This text, on the other hand, aims at highlighting a common thread between all these elements, showing how they all come together to support the adventure of scientific research in the field of Physics. Therefore, each element will necessarily be exposed in broad terms, favouring its role in the general framework of science rather than its particular articulations. With this I prevent possible criticisms for excessive conciseness and simplification or, worse, superficiality: my aim is not to provide an analysis, but a synthesis. I intend to propose an itinerary where the correlation of each element with respect to the others is highlighted, in the belief that in the "science phenomenon" we can find a great plurality and, in it, a unity.

The text consists of three parts. A *first part* (I), *Concepts and Instruments*, deals with the intrinsically phenomenological nature of Physics and its most evident peculiarities (Chap. 1), highlighting the relationship between mathematical concepts and experimental data (Chap. 2), then discussing the two pillars on which physical quantities are defined, the mathematical one in requesting models, and the experimental one in requesting operating procedures and units of measurement (Chap. 3); the section concludes by briefly reviewing the development of scientific thought in relation to the language of Mathematics (Chap. 4). The *second part* (II), *Structure of Scientific Knowledge*, deals with the status of the knowledge obtained from Physics: a purely epistemological chapter (Chap. 5) is followed by the discussion of the hierarchy and the bases of knowledge, with the great issues of reductionism (Chap. 6) and the foundations of Mathematics (Chap. 7); finally, it will deal with the solidity of physical models and theories, related to measurement processes and the meaning of the notions of truth in scientific practice (Chap. 8). The *third part* (III), *Practice of Knowledge*, intends to expose the effective modalities of scientific inquiry, as a product of men who, with their behaviour towards research, teach how to carry out (Chap. 9) or not (Chap. 10) scientific investigation, and facing the problem of the features of the so-called scientific community. At the end of the discussion, I want it to emerge that the practice of experimental sciences is a *profoundly human activity* (Chap. 11). By this I mean that it is not given once and for all to be practiced with immutable rules; on the contrary, it has been and is the subject of continuous study and rethinking.

We can find two opposite attitudes (with all intermediate gradations) towards science. On the one hand, there is a *radical positivist* attitude, according to which the only real knowledge would be scientific knowledge, the one that goes under the horrendous name of *hard sciences*, and all the other disciplines would not be real, objective knowledge. On the opposite side there is the approach that we could call *radical humanist*, according to which the natural sciences can perhaps be considered knowledge, since they have an objective utility, but they cannot be defined as *culture*, their learning would not be considered necessary for spiritual maturation and cultural background of an individual with a deep education. It seems to me that both attitudes are highly reductive, if not completely incorrect. This text aims at overcoming the first attitude by showing that experimental science is an activity in which everything of man is involved, that is, in which history, philosophy, genius, creativity, morality are involved, categories generally considered external to the field of mathematical, physical, natural ("hard") sciences. On the other hand, the intention is to overcome the second attitude by highlighting the *cultural dignity* of humanity's scientific experience.

The great mathematician Ennio De Giorgi spoke of the *sapiential value* of the "mathematical, physical and natural sciences", which he compared to that of the "human sciences". Science is not only technique, it is not a sort of well-thought-out instruction manual, it is instead a building of conquests of human thought whose essential features should become part of all those who educate themselves, who should learn the foundations of experimental sciences (and of mathematics which is its language) just as they learn the rudiments of history, geography, grammar, literature.

I hope that the reader, at the end of this itinerary, has built a sufficiently clear picture of what lies at the foundation of physics and its experimental method. I wish for succeeding in proposing an agile path, which may be able to provide the essential coordinates of this great activity, whose instruments humanity has developed over centuries and whose results are among the greatest achievements of mankind.

Florence/Milan, Italy Jacopo Parravicini
July 2023

Acknowledgements

The reader has certainly already understood that there have been many cues that contributed to this book. At the origin of these suggestions, teachings, and reflections, there are many masters that here I intend to briefly recognize.

My first and most important thanks go to my two teachers in physics and science: *Giambattista Parravicini* and *Eugenio Del Re*. They taught me curiosity, method, ability to judge and reflect, articulated thought, a method for evaluating scientific texts and communities, passion, and the human and the cultural value of the discipline.

Among the physicists working at "Sapienza" University of Rome, and at the University of L'Aquila, I thank Profs. *Paolo Di Porto*, *Bruno Crosignani*, as well as Prof. *Claudio Conti* for their stimulating scientific discussions and for the experimental works carried out together.

In the Mathematics and Physics Departments of the State University of Milan, I thank first of all Profs. *Luigi Galgani* and *Andrea Carati*, for arousing my interest in the foundations of physics, for their attention to the original sources, and for teaching me intellectual nonconformism in scientific research; I also thank Prof. *Marcel Di Vece* for discussions and suggestions regarding the modern scientific community.

Moreover, I thank and remember *Alessandra Tomaselli* for her great teaching on carrying out laboratory activities and for her professional and human support she gave me in important moments of my career: she was an experimental physicist and engineer, teacher, researcher, and scientist with a humble personality but of great value, but unfortunately she prematurely died.

For their attention to a multidisciplinary approach, I would like to mention in particular Prof. *Elio Sindoni* from the University of Milano-Bicocca and the Rev. Prof. *Alberto Strumia* from the "F. Severi" High Mathematics Institute: they are the ones who taught me to range between the various branches of culture without worrying about the artificial subdivision between humanistic and scientific disciplines.

Still within the context of the University of Milano-Bicocca, I would like to remember Prof. *Francesca Della Volta* from the Department of Mathematics, who helped my reflections to take a first coherent path, as well as Profs. *Leonardo Colzani*; *Matteo Luciani*, *Matteo Pavan*, and *Daniele Zanotti* for our fruitful intellectual exchanges about the problems of the foundations of physics and mathematics; Profs.

Maurizio Acciarri and *Simona Binetti* from the Department of Materials Science, with whom I shared a deep and formative experimental work; and Prof. *Marco Fanciulli* for our stimulating discussions.

Among colleagues from the Physics and Astronomy Department of Florence, I would like to thank the director Prof. *Duccio Fanelli*, the Ph.D. coordinator Prof. *Giovanni Modugno* and his predecessor Prof. *Raffaello D'Alessandro*, the President of the Degree Course Council Prof. Vitaliano Ciulli, who showed great appreciation for my work and put me in the best conditions to carry out. Moreover, for being valuable and stimulating, both intellectually and scientifically, colleagues, I want to remember Profs. *Francesco Biccari*, *Giuseppe Luca Celardo*, *Alessandro Cuccoli*, *Leonardo Fallani*, *Massimo Gurioli*, *Gabriele Pasquali*, and *Anna Vinattieri*.

Other important intellectual contributions came to me from teachers and scholars external to the specific physical-mathematical studies: I thank the Rev. Profs. *Gabriele Mangiarotti*, H.M.R.E. *Luigi Negri*, and Prof. *Stefano Tasselli* for the stimuli on philosophical, historical, logical topics, and Prof. *Giraldi* for introducing me to Aristotelian and symbolic logic. To them are added friends and colleagues from very different disciplines, who stimulated me to an in-depth investigation of scientific knowledge: Prof. *David Conversi* for psychology, Profs. *Nicola Schiavone* and *Mariano Bizzarri* for biomedical sciences, and Profs. *Dario Altobelli* and *Barbara Osimani* for sociology and philosophy of scientific research.

In conclusion, I thank Prof. *Marta Benedetti* for the English translation revision and Prof. *Viola Sanvito* for her help in analysing and translating the original texts.

Jacopo Parravicini

L. D.

Contents

Part I
Concepts and Instruments

This part provides some answers to the question of what the scientific method is in general, and in particular what is physics. The discussion starts with the following issues:

What is scientific knowledge?
What is physics?
What is the relationship between physics and mathematics?
What is a measure?
What is an experiment?
What are the conceptual instruments that make it possible to carry out
an objective measurement?
What are the assumptions that make it possible to carry out an experiment?
How have we arrived at the current discipline of physical science?

Chapter 1
The Bases of Scientific Knowledge

Δῆλον ὅτι καὶ τῆς περὶ φύσεως
ἐπιστήμης πειρατέον διορίσασθαι
πρῶτον τὰ περὶ τὰς αρχάς.
Aristotle

1.1 Phenomena

There is no instruction manual that describes how that intellectual challenge called "science" is done. Science intended as a subset of the larger enterprise of human knowledge. However, the great men who made the greatest contributions to the construction of this building have often provided insights into the structure of scientific research. In this text I rely on these men to explain what science is and what physics is.

It is a fact that the essential traits on which scientific research is based have gradually been revealed, coming from the work and reflection of so many men, of various inclinations, heterogeneous formations and different epochs. Therefore, it is all the more remarkable that, looking at the edifice of science as a whole, one can notice a surprising unity whereby each element, although of different origin and importance, relates to the others in a balanced way. Thus, we are facing a building similar to the ancient cathedrals, whose construction has often lasted for centuries, but whose result is equally harmonious and unitary, even in the variety of individual elements. This unity in plurality shows an aspect: at the base of scientific research there is a common factor, identical for all scholars and scientists. All the cultists of the discipline must confront themselves with it identically as it transcends the diverse and heterogeneous contexts. This makes it possible to reach that unity that has produced the great achievements of knowledge of recent centuries. A principle always identical to itself. What is the name of this item?

J. Parravicini, *The Foundations of Experimental Physics*,
https://doi.org/10.1007/978-3-031-55452-0_1

Since, with good approximation, the problem of the foundations of physics is largely overlappable with that of the foundations of science, we can begin by asking ourselves what is modernly called science. Albert Einstein writes

> (1.1) Science is the attempt to make the chaotic diversity of our sense-experience correspond to a logically uniform system of thought. In this system single experiences must be correlated with the theoretic structure in such a way that the resulting coordination is unique and convincing.[1]

A feature of many of Einstein's texts is the large conceptual density exhibited in a clear and seemingly simple form. The items which he finds here in the scientific enterprise are

1. sensible experience;
2. the apparent chaos of such experience;
3. thought;
4. logical coherence;
5. the mental construction of a system;
6. the internal uniformity of such a system;
7. the necessity of a correlation between mental construction and experience;
8. the necessity of a sufficiently robust ("convincing") resulting balance;
9. the nature of attempt of the scientific investigation, for which it is inherently incomplete.

It is clear that the elements listed above are many and each of them deserves a discussion on its own. For the sake of our argument, we begin talking about the first element: sensible experience. The starting point is therefore the sensitive experience of each one. Einstein continues

> (1.2) The sense-experiences are the given subject-matter.[2]

What is given, which is the subject of science, is what reaches our senses, i.e. what is shown to us. This is "the data", this is the subject of scientific investigation. What is shown to us is told *phenomenon*. Phenomena are the bases of all science.

The word phenomenon comes from the Greek verb φαίνειν, which means "to show", "make evident", "make clear". "Phenomenon", in particular, is the substantiated neuter gender of the middle-passive participle:

τὸ φαινόμενον

It has got a simultaneously passive and reflexive meaning. Therefore, it means at the same time "that which is showing itself" and "that which is shown"; it can also be translated as "that which is evident", "that which is made evident", or "that which becomes evident". Summarizing, we can state that:

Definition 1.1 (*General object*) The object and starting point of all scientific research is what reaches our senses from the world around us.

[1] Albert Einstein in Einstein (1940).

[2] A. Einstein in Einstein (1940).

Approaching the specific topic of this discussion, we refer to the natural world. Thus, we reformulate the above statement as

Definition 1.2 (*Specific object*) The object and starting point of all scientific research are NATURAL PHENOMENA.

The sciences that have got the phenomena of nature as their object are therefore called *natural sciences*. Consequently, we may set a first fixed point of our reasoning: scientific research (particularly physics) *does not* arise from reasoning, but from OBSERVATION. We find this concept in the thought of Alexis Carrel[3]:

> (1.3) *Observer est moins facile que raisonner. Comme on le sait peu d'observation et beaucoup de raisonnement conduisent à l'erreur; beaucoup d'observations est peu de raisonnements, à la vérité. Mais il y a un plus grand nombre d'esprits capables de faire des syllogismes que de saisir exactement le concret. [...] Pour ne pas se tromper dans la poursuite du réel, il importe de se baser non sur les vues de l'esprit mais sur les résultats de l'observation et de l'expérience.*[4]
>
> Observing is less easy than reasoning. It is known that little observation and much reasoning lead to error; much observation and little reasoning to truth. But there are many more souls capable of doing syllogisms rather than grasping exactly the concrete [...] In order not to be mistaken in pursuing the real, one must rely not on the visions of the soul but on the results of observation and experience.

The above statements are obviously not an invitation to deny the use of reason. On the contrary, they are a reminder of a correct use of reason, as an instrument that has got a precise purpose, namely, the knowledge of reality, and not an end in itself. Somehow this can be interpreted as a modern version of the principle "adequatio rei et intellectus"[5] enunciated by St. Thomas Aquinas centuries earlier. Carrel's affirmation also invites us to always prefer the observation, which in scientific research is condensed into what are called *data* (which are discussed later), to any mental construction. In the research process, the practice of the natural sciences must constantly be guided by observation, and must constantly return to observation.

Given the phenomenological basis of the natural sciences, we may now take a closer look at how the scientific approach to phenomena is specifically structured. According to Richard P. Feynman , three actions can be identified that form the basis of the scientific approach:

1. OBSERVATION,
2. REASONING,
3. EXPERIMENT.

To develop scientific knowledge these actions in themselves are not sufficient: they must be carried out in a peculiar way. Specifically, in order to develop a scientific discourse, it is necessary:

[3] 1912 Nobel Prize in Medicine.

[4] A. Carrel in Carrel (1950).

[5] "Correspondence between reality and intellect".

1. to observe the *right things* in the *right way*;
2. to ask the *right* questions;
3. to consider the experiment as a true *judge*.

At this point our discussion focuses on the features of these two groups: the first contains a list of actions, the second the peculiarities that these actions must present.

The starting point of scientific knowledge is, precisely, a given phenomenon, which is *observed* and recorded. After such a process, our mind employs *reason* in order to construct a logical-rational scheme of what has been observed. Such scheme determines logical implications with the features that they can, at least in part, be proven through an *experiment* in the real world. It is worth noting that in the first action (observation) nature (which produces the phenomenon) is active and man (that records the phenomenon), in some way, is passive: what is observed is a given.

Man has only to be open and listen to reality. In the other two steps the man plays a markedly active part. Reasoning must be properly carried out in such a way that it can be tested by experience. The *experiment* is as decisive as it is conceptually delicate. On the one hand, it is a pure construction of the scientist, where he can exercise his imagination as well as his expertise and technical ability in properly interrogating nature. On the other hand, it is nature itself that responds to the experiment, with its own answers, which can confirm or refute, totally or partially, the reasoning previously conducted by the researcher.

With regard to the features that the aforementioned actions must have, first of all it is necessary to understand what is meant by "right". If our aim is to build knowledge of natural phenomena, the meaning of the adjective "right" must be practical and utilitarian: it is what makes the knowledge of natural phenomena develop to be considered right. Outside this criterion, it is not possible to establish a mechanical procedure to understand what are actually the *right things* to observe and what is the *right way* to do it. This is in the realm of experience and intuition. Some examples can be provided. If I wanted to study the motion of a macroscopic object by neglecting its mass and concentrating on its colour, evidently I would not observe the *right thing* about it. If I wanted to describe a tree by trying to give instantaneously the number of atoms of which it is composed, it would *not* be equally *right*. Similarly, if you pretended to measure the size of an atom, or the distance between the earth and the sun, with an ordinary ruler, this would obviously be *not the right way*. The *reasoning* step requires asking *the right questions*. Again, *right* according to the criterion of advancing knowledge. Among the right questions we can include that about the predictions and the measurable implications of the model that is being developed.[6] Finally, the experiment is said to be the *judge*. It is constructed by the researcher and the researcher submits himself to it. Thus, the experiment is the judge chosen by the defendant himself. Consequently it is noteworthy how the honest researcher builds with his own hands that tribunal which is potentially able to prove him wrong

[6] On this topic, it is worth making a distinction: it is not necessary that every single part of the developed model is measurable, but it is necessary that there are sufficient measurable elements, verifiable through experiments, so that the degree of correctness of the model can be resolved. This issue is discussed in more detail in Sects. 8.2.1 and 8.2.2.

and, nevertheless, submits himself to it.[7]. The distinguishing factor of what is called *science* has been seen in this:

> (1.4) The principle of science, the definition, almost, is the following: *The test of all knowledge is experiment*. Experiment is the *sole judge* of scientific "truth."[8,9]

It is worth noting that the need to accept the real data, even taken to the extreme—even when they do not confirm the research's reasoning and thus constitute a judge to the work—represents a strong ethical teaching. The scientific method is a test bench on which whoever wants to progress in knowledge must humbly accept being judged, sacrificing, if necessary, the mental schemes he has built to accept real data. As mentioned above (quote 1.3), in many cases it is not easy to abandon one's mental schemes in favour of reality: in the daily practice of scientific research various obstacles are introduced, which we explore in Chap. 10.

> (1.5) *Certes, [ce qu'on étudie l'expérimentation] c'est une nature simplifiée, préparée, parfois mutilée en fonction de l'hypothèse préalable, que l'expérimentation interroge; il n'empêche qu'elle garde en général les moyens de démentir la plupart des hypothèse. Einstein faisait remarquer que la nature, aux questions qu'on lui pose, répond le plus souvent* non*, et, parfois,* peut-être.[10]
>
> Certainly, [what experimentation considers] is a simplified nature, it is prepared, sometimes mutilated according to prior hypothesis, which experimentation investigates. However, nature generally maintains the ability to refute most hypotheses. Einstein pointed out that nature most often answers *no* and sometimes *perhaps* to the questions we ask.

To explain in more detail how scientific investigation is carried out and the conceptual strategies that are normally employed, Feynman uses the metaphor of a chess game[11], which is a vivid example. Let us suppose that the set of natural phenomena is a chess game that is taking place before our eyes, and also suppose that we know nothing about chess except that it is a game. In these conditions, our goal is to deduce the rules, but we cannot do anything else but attend the game. The investigation of nature is very similar to this condition: an attempt to reconstruct the rules of the great chess game in which we are present exclusively by observing it, without anyone from outside explaining the rules to us. You can make the first hypotheses on how the game works by watching the match. Typically the verification of such hypotheses takes place using different strategies.

1. SIMPLIFYING the situation, the phenomenon, the problem. For example, we can neglect the colour of the pieces and concentrate on the different shapes.

---

[7] These concepts on the conduct of scientific research are developed more extensively in Chap. 8 and in Part III.

[8] R. Feynman Sect. 1–1 in Feynman et al. (2005a).

[9] A precise enunciation of the experiment is provided in Chap. 4, especially in the definition 4.2, distinguishing between a more generic concept of *Observational investigation* of natural phenomena, defined in 4.1 (editor's note).

[10] I. Prigogine et al., Chap. 1 of Prigogine and Stengers (1986).

[11] Section 2–1 in Feynman et al. (2005a).

2. In LIMITING the situation one evaluates a single phenomenon in simpler circumstances, trying to sketch partial rules. For example, we can evaluate only the movement of the pieces and not the act of capturing them.
3. If we APPROXIMATE, only a part of the involved elements can be considered. In the example of chess, we can limit ourselves to what happens around a single piece.

Simplifying, limiting, and approximating are the typical strategies that are employed in scientific research. They are the result of the experience, and *trying and trying again*[12] has proved they are fruitful strategies: they are *right* in the aforementioned sense.

All the above considerations concern the phenomenological foundations of scientific research and of the scientific method and are valid for all the natural sciences. So what distinguishes physics from the other natural sciences?

1.2 Peculiarity of Physics

At this point the question arises as to what is physics. To start with, the etymology of the word "physics" is provided:

φύσις

which comes from ancient Greek and literally means "nature". The correlated adjective, which literally means "natural" is φυσικός, but the word "physics" comes from the noun plural neutral, i.e.

τὰ φυσικά

which literally means "natural things" or rather "what is related to nature": the concept is rendered with a plural neuter. Physics is therefore by etymology everything that is found in nature and the term already has in itself the concept of plurality. Recalling Einstein's quotation 1.1, we underline the fact that what pertains to physics is only and exclusively what is perceived by our senses. Therefore, physics has nothing to do with reality outside our senses[13] such as, for example, abstract mathematical or logical systems. In short, being based on the experience of our senses, by definition physics does not deal with everything that is μετὰ τὰ φυσικά, that is, "beyond what is related to nature".

[12] "*Provando e riprovando*", motto of the Accademia del Cimento (1657–1667), the first scientific association in the modern sense, founded by the disciples of Galileo Galilei. This Italian syntagm is taken from Dante Alighieri's *Divine Comedy*, the III Canto of Paradise; in that context the words mean "demonstrating and refuting". Therefore, the motto assumed by the Academy has a double meaning: a more modern and literal one, stating the need for experimentation—"*trying and trying again*"—and an original and ideal one—"*demonstrating and demonstrating again*"—stating the need for demonstration, including counterfactual reasoning.

[13] Chapter 1 of Lindsay and Margenau (1957), Part I Chap. 1 of Duhem (2016).

> (1.6) Physics is the most fundamental and all-inclusive of the sciences, and has had a profound effect on all scientific development. In fact, physics is the present-day equivalent of what used to be called *natural philosophy*, from which most of our modern sciences arose.[14]

What we call physics, understood as a discipline at the foundation of all studies concerning the investigation of natural phenomena, has sprung from what for centuries has been called

philosophia naturalis,

that is, "natural philosophy" or, better, "philosophy of nature". *Philosophia*, of course, should also be understood in an etymological sense as "love for" -and therefore "practice of"- knowledge. We here see that at the beginning there was no dichotomy between that knowledge which today we would call humanistic, the tout-court philosophy, and scientific knowledge, physics. The former is the philosophy today called theoretical (including what are classically called ontology and "metaphysics"), the second one is the philosophy of nature. Both of them were and are parts of a single discipline, *philosophia*, the background of the one who loves knowledge and wants to devote himself to it[15].

The aforesaid considerations have anticipated some concepts that we now need to systematize. To say that physics deals with phenomena, and natural phenomena specifically, does not allow us to fully identify physics as a discipline. In fact, it is necessary to specify further details within a scheme that is more systematic.

To precisely identify the specific features of this branch of knowledge, we may refer to the most classic and tested system of classification of disciplines, which provides us with a precise and relatively simple scheme.[16] The purpose of any discipline is to increase knowledge through a specific investigation of reality. On the basis of which criteria, therefore, is it possible to clearly specify the discipline here considered? Referring to the aforementioned scheme, we assume the *subiectum* ("subject") of the investigation as the starting point; moreover, we identify four specific features that describe the conceptual content of the discipline considered. We could make an analogy with an origin and a four-dimensional Cartesian axis system. Through these coordinates, which are defined starting from subject and object, the discipline is uniquely determined[17]:

0. *subiectum*, i.e. the *subject* of the investigation;
1. *obiectum materiale*, i.e. the *material object*, the actual matter that the discipline deals with;

---

[14] R.P. Feynman Sect. 3–1 in Feynman et al. (2005a).

[15] It is worth noting that in the same Aristotelian classification the investigation of nature, τά φυσικά, anticipates the theoretical investigation: nowadays the latter is considered a discipline belonging to philosophy alone as it is called *metaphysics*, from the expression μετὰ τὰ φυσικά, literally "after what is related to nature".

[16] We here refer to the classical epistemological classification (Strumia 2017; Basti 2002).

[17] (Strumia 2017).

2. *obiectum formale*, i.e. the *formal object*, the form that the aforementioned material assumes for investigation;
3. *obiectum formale quo*, i.e. the *formal object from which* [we investigate], the specific *point of view* of the discipline;
4. *obiectum formale quod*, i.e. the *formal object which* [is investigated], the aspects of the subject that are inspected by the investigation as determined by the aforementioned point of view.

The *first item*, the SUBJECT, is the origin of our reference system, it is what science studies. We have thus already identified the subject in "what is related to nature" (τὰ φυνικά), making physics part of the complex of natural sciences.

The other four items, the coordinates, are all theses, doctrines, specific concepts of the discipline. As far as physics is concerned, we have already introduced the first three coordinates. The MATERIAL OBJECT are the aforementioned phenomena. The FORMAL OBJECT is correlated with the methodology employed, i.e. the investigation of an experimental nature, and coincides with what can actually be grasped of the subject: these are the observations and the corresponding experiments. Specifically, the results of observations and experiments.

This first pair of coordinates, material and formal objects, are common to all natural sciences. Conversely, the last two coordinates allow us to identify physics with precision, grasping its specific features.

Definition 1.3 (*Einstein's definition of Physics*)

> (1.7) What we call physics comprises that group of natural sciences which base their concepts on measurements, and whose concepts and propositions lend themselves to mathematical formulation.[18]

Here, in addition to synthetically recalling the formal object ("measurements"), Einstein clearly defines the FORMAL OBJECT QUO and the FORMAL OBJECT QUOD.

The formal object *quo* is the point of view of the investigation. It is the key feature that distinguishes physics from other disciplines. Specifically, the formal object *quo* is mathematics.

The formal object *quo*, we said, determines the *quod*, i.e. what is actually studied and investigated of the subject. In the specific case of physics this coincides with those "concepts and propositions [that] lend themselves to mathematical formulation". Among these are the *physical quantities* (which are discussed in more detail in Chap. 3), i.e. all those measurable elements of reality that can be placed in a correspondence one-to-one with mathematical entities; however, there are also all the concepts related to the terms of relation and extension (studied for example by topology).

Thus, Table 1.1 summarizes the specific coordinates we have just discussed. In brief, we can reduce these coordinates to the two essential pillars of the discipline:

[18] A. Einstein in Einstein (1940).

Table 1.1 Coordinates of physics discipline

General feature	Specific feature
Subject	Nature
Material object	Natural phenomena
Formal object	Observations and experiments
Formal object *quo*	Mathematics
Formal object *quod*	Mathematizable quantities

natural phenomena and reality. Paraphrasing Einstein's Definition 1.3 (quotation 1.3), we can therefore state that

Definition 1.4 (*Field of investigation of physics*) Field of investigation of physical science coincides with the mathematizable characteristics of natural phenomena.

Proceeding along this line of thought, the next chapters of I part are written from a perspective aimed at specifically highlighting the features and the complex relationship between mathematics and physical science.

References

G. Basti. *Filosofia della Natura e della Scienza*, vol. 1, 1a edn. (Pontificia Università Lateranense, Roma, Città del Vaticano, 2002)

A. Carrel, *Réflexions sur la conduite de la vie* (Librairie Plon, Paris, France, 1950)

P. Duhem. *La théorie physique. Son objet, sa structure*, 2nd edn. (ENS Éditions, Lyon, France, 2016). http://books.openedition.org/enseditions/6077

A. Einstein, Considerations concerning the fundaments of theoretical physics. Science **91**, 487–492 (1940)

R.P. Feynman, R. Leighton, M. Sands, *The Feynman Lectures on Physics*, vol. 1, 2nd edn. (Addison-Wesley, Boston, USA, 2005)

R.B. Lindsay, H. Margenau, *Foundations of Physics*, 2nd edn. (Dover, New York, USA, 1957)

I. Prigogine, I. Stengers, *La nouvelle alliance-Metamorphose de la science*, 2nd edn. (Gallimard, Paris, France, 1986)

A. Strumia, *Dalla filosofia della scienza alla filosofia nella scienza*, 1a edn. (ESC-Edizioni Santa Croce, Roma, Italia, 2017)