1 *The method of physics*

1.1. Introduction

In this book I shall describe the principles of physics. Physics is a science that has developed enormously during the last four centuries, apparently at an increasingly rapid rate. In recent years physicists have at times felt that they had reached a dead end. However, this may be a result of having too close a perspective – "He who is at the foot of a mountain sometimes cannot see the summit." Perhaps in some areas we are following a dried stream, whereas at a short distance there may be a new and rich stream of knowledge, which we are about to discover. Or maybe it is simply a matter of having to stop occasionally and to *digest* the enormous quantity of knowledge we have acquired before proceeding to obtain more. In any case, one cannot deny that new and important discoveries are being made even today, so that the prophecies of doom that have sometimes been heard appear to be at least imprudent. Only history will decide to what extent our period has been fruitful or barren.

What we can say for certain is that the quantitative effort expended by each generation so far in the field of physics research has greatly exceeded that of the previous generation. Apart from some fluctuations, the number of physicists, as well as the number of institutions devoted to physics, and the number of countries concerned with physics, have steadily increased. Most of all, the number of printed pages giving information on physics research has grown amazingly, year after year.

If all this could be based solely on the growth of and spread of interest in scientific knowledge, then there would be cause for gratification. Unfortunately, this is not so. The main stimuli that have progressed scientific research in the last century have been the desire for military power and the needs of industrial competition.

Wars have become extremely scientific. The military have realized for a long time now that the most powerful armed force is the one having the greatest amount of scientific knowledge and the capacity to use it. Scientists willingly or unwillingly, directly or indirectly, have been enlisted en masse and incorporated in the war machines of the great powers.

At the same time, and not independently, industry has also become scientific. In order to withstand competition and to capture more of the industrial market, industry must keep products up-to-date by making them more functional, or simply more attractive. By applying scientific and technical knowledge, a company can hope to secure the market over its competitors that do not yet have the know-how. Another value of scientific knowledge is that it enables the worker's productivity to be increased to the maximum.

This commercialization of science, along with its reduction to a mere tool, has had an important effect on the behavior of the research worker. The *competitive* aspect of what once was disinterested and independent intellectual activity has lately undergone considerable development. This does not only apply to the military forces or industrial laboratories of the developed countries. Even institutions such as universities or scientific organizations of the less industrialized countries have been unable to resist the influence of the general climate in which science is developing.

No doubt, there are still researchers who work (or *believe* they are working) for the pure love of knowledge. However, they have much less of a decisive role in establishing custom and can avoid the competitive system to even a smaller extent.

The young person beginning a scientific career today, particularly in physics, believes he is taking part in a race. His goal must be to get there before the others, at whatever cost – to learn his job and to accumulate a certain number of papers as soon as possible. But does the "runner" in the race notice the scenery around him? No; by being so intent on winning he sees and thinks of nothing. Sometimes the young scientist even forgets the motives for entering the race. Unfortunately, this is the sad fate awaiting many researchers: lack of culture and alienation.

Many, of course, are able to react and somehow preserve their humanity. But it is a hard-earned victory against the environment, one that cannot be achieved without character and determination.

The situation just described has been reflected in the way that physics is taught and presented in textbooks. Students must acquire a large amount of precise technical information as quickly as possible. There is no time to reflect and examine critically what is being done. A standard and aseptic method of teaching has been set up that, in the hands of the best authors, can yield excellent results in terms of the purpose for which it is intended. But this method fails to satisfy some deep cultural needs of students and surely does not stimulate them to examine what they are doing more closely. In a sense, then, they are encouraged to choose the easiest way. For as C. Weizsäcker (1971, p. 110) rightly observes: "Science is easier to practice than to understand. It is easier to be a physicist and acquire correct knowledge of physics than to explain what exactly one does when doing physics."

There are many good books on the philosophy of science, epistemology, and the foundations of physics.[1] To some readers these might seem to refer to an activity separate and different from that of the physicist, to a kind of reflection from the outside on the science of the past rather than on science *in the making*. Sometimes scientists seeing physics from the inside cannot easily recognize in these writings the features of that science with which they are most familiar. They remain particularly perplexed when the validity of current methodologies, which they and their colleagues hold to be indispensable, are criticized or "refuted" without the author offering a valid alternative to be applied in the laboratory or on the theorist's desk. Common sense, then, prevents scientists from reading further when they come across an extreme case in which the philosopher implies that physicists, in spite of their successes, have "racked up" a lot of mistakes!

On the other hand, there are a number of historical and scientific works of great interest, in which some of the most eminent modern physicists have discussed the procedure, value, and results of science. But here, apart from a few worthy exceptions,[2] one gets the opposite impression. The philosophical thought often appears to be out of focus, bound to rather simple and outdated schemes, expressed in vague terminology. In extreme cases one may witness the efforts made by a great mind in order to discover and describe (badly) what Kant discovered and described (well) almost two hundred years before. This is not to mention those final chapters where the author without the least embarrassment draws conclusions on morals or on free will!

In my opinion, the epistemology of a given science is inseparable from that science; conceptually, even if not always chronologically, the birth of epistemology is simultaneous with the birth of science. Every advance in science is an advance in its epistemology.[3] Starting with this conviction, I have applied a somewhat unusual formula. I have tried to introduce the principles of physics, keeping in mind at all times their epistemological aspects and the critique of their foundations.

Discussions are never carried out in the abstract, but are always made in light of concrete subjects that suggest the analysis. Apart from Chapter 1 which covers general and preliminary concepts on the method of physics, the epistemological discussions are usually found interspersed with scientific expositions, and the two are developed together. As specific knowledge broadens and allows more profitable analysis, fundamental problems are raised and examined; some are taken up several times but at different levels.

Philosophy of science and history of science are closely related. One cannot develop a philosophy of science without reference to history nor can one write a history of science without consciously or unconsciously considering a philosophical view.[4] For this reason, historical references, wherever relevant, will be provided. But I wish to emphasize that this is not an historical work and that I am a physicist and not an historian of physics.[5] The most important historical concern of this book is to present physics *as it is*. The philosopher of science (or even the physicist) cannot always resist the temptation to criticize a physics that never existed or which, in any case, does not exist today. Having performed this operation, one is also tempted to go on to give his opinion on how physics *should be*. This method is not very profitable; it is much better to accept the nature of physics as an historically defined object and to proceed from there to a critical assessment. Of course, one can object and say that I cannot portray physics *as it is* but only *as it seems to me*. This is true, but at least I will not attempt to present physics as I *want* it to be.

The awareness of the important relationship between scientific thought and the social and political context in which it develops is very much alive for some scholars today.[6] This is a very positive fact, which regrettably many scientists have not yet learned. Although this theme is relevant, it will not be dealt with at length in this book, because it might extend the field of coverage too far. On the other hand, I think that even with the object of an in-depth study of the relationship between science and society, one should be aware of what science really is.

Given the object of this book, one should not be surprised that it does not contain *all* of physics. There are enormous gaps, even at the elementary level, that have been left intentionally. In support of this, I would like to say that I consider my readers sufficiently intelligent not to have to drink all the water in the sea in order to realize that it is salty! *Completeness* of information on the contents of physics can be found elsewhere, in excellent treatises written at all levels. Of more significance, however, is the fact that although physics is an empirical or, rather, an *experimental* science, the reader will find almost no description of apparatus or experiments here. One might think that this is a fine limitation for someone who wants to present physics *as it is*! So far I have failed to build up an *epistemology of the laboratory*. To explain what a laboratory is would be like trying to explain what music is to a person who has never listened to music. One learns in a laboratory; one learns how to make experiments only by experimenting; and one learns how to work with his hands only by using them. The first and fundamental form of experimentation in physics is to teach young people to work with their hands. Then they should be taken into the laboratory and taught to work with measuring instruments – each student carrying out real experiments in physics. This form of teaching is indispensable and cannot be read in a book. For this reason, I shall assume that the reader is familiar with some experimental physics learned in high school. But on the other hand, do not be misled into believing that physics as described here is a purely theoretical science developed a priori!

The methodologies of the various sciences have many common features; but they also present some specific differences that cannot be ignored. Very often people have used means of criticizing the methodological peculiarities of physics by taking examples from sciences completely different from physics. As such a procedure can confuse the issues, the reader should know that we will be dealing *only* with the methodology of physics in this book. However little I believe in the truth of rhetorical expressions such as "the unity of science,"[7]: I do believe that the unity of science should not be turned into the "confusion of science."

For the same reasons, one should not disregard the fact that the methodology of physics has evolved over the centuries. Some writers seem to believe that the twentiety-century physicist behaves exactly like his colleagues of the nineteenth or even of the eighteenth century. This is absolutely wrong! The modern physicist also has naïve beliefs and prejudices, but they are different. Physics today is *modern physics* and to discuss its procedures by continually calling up venerable ghosts such as epicycles, phlogiston, caloric, and so on is not very illuminating, except possibly from a purely historical point of view.

1.2. What is physics?

As the object of our study is physics, it seems appropriate to *try* to define first what is meant by physics. However, physics, like all other sciences, is not easily definable. Perhaps we should not pay much attention to definitions because of the risk of accepting deep meanings and concepts where there is a convention. The convention being made only to be sure that we are all discussing the same thing. But, as already emphasized, because we shall be dealing solely with physics, its methods and contents, a definition is needed.

I believe there are two possible ways to define physics. The first is to consider it as simply made up of those topics with which physics has been concerned during various historical periods.[8] Thus we have Aristotle's physics, Galileo's physics, Newton's physics, Maxwell's physics, and so on; each being different in part from the others. Without doubt, this purely historical method is acceptable, but it can lead to some difficulties, for not all these authors called their science physics (in the course of history different names such as world system, natural philosophy, etc. have been used). It may be more interesting to ask why physics has shown certain peculiarities, tackled certain problems, and had certain contents during different historical periods, and also, why the stress has shifted elsewhere today.

The term *physics* comes from Greek and means "everything that is concerned with nature." Therefore physics should cover all the problems of nature, but, in fact, it does not. Although it might have been true in the time of the Greek or medieval civilizations, a break called the *scientific revolution* took place between the sixteenth and seventeenth centuries. Since that time, in a rather approximate way, physics has dealt only with those parts of the natural world where biological processes are not considered. However, one can be much more precise.

Even if it were not clearly stated at first, people started to term physics as *all that could be profitably studied by using a certain method*. This method we attribute today mainly to Galileo. Naturally, this has a certain degree of convention, so we say, once and for all, that Galileo's contribution was neither the only one nor the first.[9] However, no one before him had formed and expressed such clear and precise ideas on science. Galileo discovered a method that when applied to a given class of problems, gave excellent results. Since then, all that could be studied with this method has constituted the unified and well-defined science that we currently call physics.[10]

This therefore is the second way in which to define physics: It is defined according to the *method* rather than to the *contents*.

As a result, physics did not include, especially at the beginning, some important parts of the study of nature. In particular, a large number of problems concerning living organisms were excluded. Also, other branches of research such as chemistry, mineralogy, and geology did not seem to fit quite well within the limits of application of the method.

One should notice an important point. Although there has been a period in which some sciences have gradually separated from physics, today we are witnessing a sort of reflux. There is a tendency to bring some branches of science, which previously were far removed, back again into the sphere of physics. The main reason is that whereas in the past the method could be applied fairly easily to only a certain class of problems, today it is possible to extend its application to an ever increasing number of disciplines. Because physics has interpreted all the fundamental laws of chemistry, chemistry, in a sense, has become a chapter of physics. Solid-state physics, a relatively recent science, has brought the specific methods of physics into mineralogy, even if descriptive mineralogy still exists as an historical inheritance.

Traditional geology exists, too, but *geophysics* is becoming more and more important.

Concerning biology, there are already a considerable number of problems such as those dealt with by *molecular biology*, which can be approached with methods very close to those of physics. An interdisciplinary science has been born called *biophysics*. We are still very far from referring to biology as "physics," but it is not inconceivable that one day, perhaps not too far in the future, all of biology will become a chapter of physics.[11]

Apart from the historical and methodological characterizations of physics, there is a fairly important question regarding its *contents*, the answer to which can shed some light on why physics is approaching other sciences that were completely separated in the past. Is physics concerned with single *objects* and contingent *facts* or, rather, with general *laws*?

Galileo was definitely interested in both single objects and facts (e.g., the physical nature of the moon) and general laws (e.g., the fall of material bodies). But after Galileo there has been an increasing tendency to think that physics should be concerned only with general laws; to ascertain or to describe factual situations was thought to belong in the province of other sciences, such as astronomy, geology, and natural history. However, in modern times it has become very difficult to stick precisely to this distinction (see §5.1). Increasingly, one has the impression that the general laws of the universe are inseparable from its apparently contingent structure. As we shall see, strong doubts in this sense can arise even from the second law of thermodynamics (see §3.16), not to speak, of course, of cosmology.

We shall deal first with that aspect of physics that is concerned with general laws, calling this the *nomological* aspect. Later, we shall show that the *factual* aspect is sometimes closely connected with or even inseparable from it.

1.3. A first approach to the method

Having explained what physics means, and having shifted the accent from content to method, let us stop now to examine this method.

A scientific method cannot adequately be discussed if it is divided from the science to which it applies. To understand fully the significance of the brief survey of the method of physics that we present here, one should see it at work on concrete examples, which will be given in later chapters.

To put the following discussion in the proper perspective, we reiterate that this is not a *history* of physics. The historian dealing with Galileo's method must refer to that author's writings[12] and determine from them what Galileo himself intended his method to be. We, instead shall take the philosophical viewpoint of one who comes three and a half centuries later,[13] by analyzing what Galileo's methodological lesson means to us. As a result, we shall feel authorized to say, with some caution, even things that Galileo never explicitly said nor stated in that form.[14]

Because our interest for the time being is purely methodological, we shall consider only one aspect of Galileo's work. But do not forget that there is much more than method in Galileo. The battle and the victory against the Aristotelian and theological conception of science implies much larger problems than those that can be faced by using the method of physics. However, having discovered this method, and having shown that it works well, Galileo had a powerful weapon for following up the victory on an even larger scale.

Galileo's method is an *experimental* method. What does this mean? At an elementary level, the explanation is very easy, but it becomes much more complicated when a deeper insight is sought.

In a first and simplified version, one can say that the method consists in relying on facts or, rather, in taking experience as a guide and not in proceeding with abstract and a priori theories that are not based on experimental evidence. By saying only this, however, we do not clarify Galileo's great discovery, and do him an injustice.

To approach the center of the problem, one must first notice the distinction between *observation* and *experiment*. We can use a generalization that, although not always true, is useful as a reference. Before Galileo's time the scholar observing a phenomenon had, as it were, the role of a spectator, or of a witness; after Galileo, the scholar not only listens to what nature spontaneously says, but interrogates it. This changes observation into experiment and provides the main key that opens the door to the modern conception of physics: Nature is interrogated and humans formulate the questions.

What is the importance of all this? Today, a posteriori, we can describe Galileo's approach by saying that he worded his questions in a biased way. This is not to say that he required prefabricated answers from nature; but that his questions fitted at least partly with the answer, which he managed to guess. Galileo's questions were certainly not haphazard, which is why he referred to ''sensible experiments'' rather than to just "experiments."[15] What distinguishes a sensible experiment from just an experiment?

A physical phenomenon generally depends on a number of different factors or *parameters*, as we call them today. Some of them are essential, whereas others are secondary, and may disturb the phenomenon one wishes to study. When formulating a question, Galileo first simplified the problem by stripping the phenomenon of all those secondary parameters that would otherwise complicate the answer, rendering it incomprehensible. The problem was then formed in such a way as to make it depend on only a few parameters; therefore one could study nature's behavior as a function of only these parameters.

At this point, we should ask, "How did Galileo know that by carrying out the experiment in a certain way the phenomenon was stripped of those secondary parameters that he called 'external and accidental impediments'?" This question leads us to a consideration that probably did occur to Galileo, although he did not make it explicit.[16]

The following example may clarify this point. How can we be sure that the fall of a strangely shaped body, part stone and part wood, half red and half blue, part cold and part hot, through a dense atmosphere, crossed by irregular air currents, has less right to represent the natural world than the fall of a simple ball in empty space without any of the previous complications?

In other words, it would appear that nature should not "like" the latter phenomenon better than the former and that both should have exactly the same native rights.

Where is the difference? The difference lies in the intervention of the researcher, who does not simply ask for an answer from nature, but asks for an *intelligible* answer.

One need not necessarily be ready to accept the whole Kantian approach to appreciate, at least in general terms, the truth stated here from the preface to the second edition of *Critique of Pure Reason*:

> When Galileo caused balls, the weights of which he had himself previously determined, to roll down an inclined plane; when Torricelli made the air carry a weight which he had calculated beforehand to be equal to that of a definite volume of water; or in more recent times, when Stahl changed metals into oxides, and oxides back into metal, by withdrawing something and then restoring it, a light broke upon all students of nature. They learned that reason has insight only into that which it produces after a plan of its own, and that it must not allow itself to be kept, as it were, in nature's leading-strings, but must itself show the way with principles of judgment based upon fixed laws, constraining nature to give answer to questions of reason's own determining. Accidental observations, made in obedience to no previously thought-out plan, can never be made to yield a necessary law, which alone reason is concerned

to discover. Reason, holding in one hand its principles, according to which alone concordant appearances can be admitted as equivalent to law, and in the other hand the experiment which it has devised in conformity with these principles, must approach nature in order to be taught by it. It must not, however, do so in the character of a pupil who listens to everything that the teacher chooses to say, but of an appointed judge who compels the witnesses to answer questions which he has himself formulated. Even physics, therefore, owes the beneficent revolution in its point of view entirely to the happy thought, that while reason must seek in nature, not fictitiously ascribe to it, whatever as not being knowable through reason's own resources has to be learnt, if learnt at all, only from nature, it must adopt as its guide, in so seeking, that which it has itself put into nature. It is thus that the study of nature has entered on the secure path of a science, after having for so many centuries been nothing but a process of merely random groping (translated by N. K. Smith).

Some students reject with horror all that allegedly leads to idealistic attitudes and the negation of objective reality. However, asking an interlocutor to answer our question and to speak our own language (instead of an unknown one), is not the same as believing that the interlocutor does not exist and that we are concocting an answer of our own.

Thus we become acquainted with a procedure that modern physics has worked out in a very stimulating way. An experiment represents a question that is not independent of the nature of the questioner. It is formulated by that observer and leads to an answer suited to the observer. One must think of an encounter between subject and object, the scientist on one side and nature on the other. The researcher can manage to insert some subjective elements to describe phenomena that are seen to take place objectively in the outside world, but as far as nature is concerned, it would be nonsense to introduce preferential elements. Out of this complicated babel of words, the observer begins to select those nearest to his own language. In order to be understood, nature must speak the language of the observer.

To be honest, Galileo has expressed himself in apparently antithetic terms. There is a famous passage in the *Assayer* in which he says:

Philosophy is written in that great book which ever lies before our eyes, I mean the universe, but we cannot understand it if we do not first learn the language and grasp the symbols in which it is written. This book is written in the mathematical language, and the symbols are triangles, circles and other geometrical figures, without whose help it is humanly impossible to comprehend a single word of it, and without which one wanders in vain through a dark labyrinth.

Literally, therefore, it is nature that forces its own language on the observer, and not the other way around. Often when speaking of this, Galileo's Platonism is mentioned (see e.g., A. Crombie, 1950; W. Shea,