Preface

This is the first in a series of four volumes, all written at an elementary calculus level. The complete course covers the most important areas of classical physics such as mechanics, thermodynamics, statistical mechanics, electromagnetism, waves, and optics. The volumes result from a translation, an in depth revision and update of the Italian version published by Decibel-Zanichelli. This first volume deals with classical mechanics, including an introduction to relativity.

The laws of Physics, and more in general of Nature, are written in the language of mathematics. The reader is assumed to know already the basic concepts of calculus: functions, limits, and the differentiation and integration operations. We shall however, without mathematical rigor, give the necessary information on vectors and matrices.

Physics is an experimental science, meaning that it is based on the experimental method, which was developed by Galileo Galilei in the seventeenth century. He taught us, in particular, that to try to understand a phenomenon one must simplify as much as possible the relevant working conditions, understanding which of the aspects are secondary and eliminating them as far as possible. The understanding process is not immediate, but rather it proceeds by trial and error, in a series of experiments, which might lead, with a bit of fortune and a lot of thinking, to discover the governing laws. Induction of the physics laws process goes back from the observed effects to their causes, and, as such, cannot be purely logic. Once a physical law is found, it is necessary to consider all its possible consequences. This is now a deductive process, which is logical and similar to the mathematical one. Each of the consequences, the predictions, of the law must then be experimentally verified. If only one prediction is found to be false by the experiment, even if thousands of them had been found true, it is enough to prove that the law is false. This implies that we can never be completely sure that a law is true; indeed the number of its possible predictions does not have limits, and in any historical moment not all of them have been controlled. However, this is the price we must pay in choosing the experimental method, which has allowed humankind to advance in the past four centuries much more than in all the preceding millennia.

Classical Mechanics is one of the big intellectual constructions of Physics. Its laws are well established as well as their limits of validity. Consequently, it can be exposed in an axiomatic way, as a chapter of mathematics. We can start from a set of propositions whose axioms are assumed to be true by definition, and deduce from them a number of theorems using only logics, as from the Euclid postulates the Euclidean geometry theorems are deduced.

We shall not follow this path. The reason is that, while it allows a shorter and quicker treatment and is also logically more satisfactory for somebody, it also hides the inductive trial-and-error historical process through which the postulates and the general laws have been discovered. These are arrival, rather than starting points. This path has been complex, laborious, and highly nonlinear. Errors have been made, hypotheses have been advanced that turned out to be false, but finally the laws were discovered. The knowledge of at least a few of the most important aspects of this process is indispensable to develop the mental capabilities that are necessary to anybody contributing to the progress of natural sciences, whether they pursue applications or teach them. This is one of the reasons for which we shall read and discuss several pages of the two scientists that built the foundations of physics, Galileo Galilei and Isaac Newton. A second reason is that reading the geniuses is always an enlightening experience.

The Galilei and Newton mechanics that we shall discuss in this book is a coherent set of laws able to describe a great number of physical phenomena. These laws, however, have a limited validity. One type of limitations does not have a fundamental nature. Some of the laws, as for example the laws of friction or the elastic force are, consciously we can say, approximate. In other words, they provide a description that we know to be valid only in a first approximation and provided that the values of certain quantities are within some definite intervals (for example, for the elastic force, for not too large strains). We shall always clearly state those limits.

The limits of the second type are of a fundamental nature. A first limit of the Galilei-Newton laws is met when the velocities are very high, high enough to get close to the speed of light.

The latter is so high, 300,000 km/s, that the speeds of all objects of a common experience, planets included, are extremely small in comparison. However, we can reach velocities close to that of light in experiments with microscopic particles, like atomic nuclei and electrons. In the universe there are double stars and double black-holes, which are extremely dense and rotate about each other at very high speeds, close to the speed of light. We observe that in these conditions the predictions of Newtonian mechanics are in contradiction with experience. Newtonian mechanics is an approximation valid at velocities substantially smaller than the speed of light. The theory that generalizes Newtonian mechanics, including high-speed phenomena, is relativistic mechanics, which was developed between the end of the nineteenth and the beginning of the twentieth centuries by, principally, Hendrik Lorentz, Henry Poincaré, and Albert Einstein. We discuss the basic elements of relativistic mechanics in Chap. 6. They are not necessary for understanding of the following ones.

Newton or relativistic mechanics, depending on the velocities of the problem, is called classical mechanics. However, not even this is true in every circumstance; the laws of classical mechanics do not describe correctly the very small-scale phenomena, like vibrations and rotations of molecules, those of the electrons inside atoms, the nuclear, and subnuclear phenomena. As a matter of fact, the bodies at these microscopic scales behave in a completely different way than those of everyday experience. The theory able to describe all the known phenomena both at small and large scale is quantum physics. Its limit for large scales is classical mechanics. The study of quantum physics not only requires mathematical instruments more advanced than classical physics, but, even more importantly, cannot be profitably studied without an in-depth knowledge of classical physics. Consequently, this course is limited to classical physics. We shall however warn the reader of the limit of validity, whenever necessary.

In this book we deal with the mechanics of a material point and of extended bodies, in particular of the rigid ones. The mechanics of fluids will be one of the objects of study in the second volume, together with their thermal properties. Mechanical oscillations are treated here only in their most elementary aspects. A deeper discussion will be given, together with electric oscillations in the fourth volume.

We start the first chapter with introductory elements: the measurement of physical quantities, the measurement units and their internationally adopted system, the International System, reference frames, and basic concepts on vectors and matrices. The second part of the first chapter deals with kinematics, which is the mathematical description of motion, without reference to its causes. The second chapter contains the fundamental laws of the material point (the simplest body) and the basic concepts of mass (both the inertial and the gravitational masses), of force, of momentum, of moment of a force, and of angular momentum. We introduce also the concepts of work of a force, of energy, of power, and the energy conservation principle. We work on these arguments mainly considering the two most usual examples of force, weight and friction. At this point we have acquired the basic laws of mechanics. Historically, these are the result of the work of G. Galilei and I. Newton. It is important to have some knowledge of how these great authors came to establish the laws of mechanics. For this purpose a few of their fundamental pages, describing experiments and mathematical arguments, are reproduced and discussed. The reader will see also how both authors expose the concepts in a scientific superb language.

The third chapter describes the different forces, gives their mathematical expressions, and discusses their limits of validity. We discuss important examples of motion, in particular the circular and the oscillatory ones. We know now that the different forces that we see in nature and that look at first sight very different can be reduced to a very limited number of fundamental forces. The forces present at macroscopic level, the level of classical mechanics, are different manifestations of two basic ones: the gravitational and the electromagnetic forces. The latter will be studied in the third volume of this course, the former in the fourth chapter of this first book. As a matter of fact the study of gravitation has enormous historic and cultural importance. It underlines our comprehension of the universe in which we live. For this reason we recall the most important steps in the historical development of the universal gravitation theory.

The description of any motion depends on the frame to which it is referred. In particular it is different in two frames moving one relative to the other. The study of this issue is the object of the fifth chapter, in the limit of velocities much smaller than that of light. We shall meet with the extremely important principle of relativity, a universally valid principle established already by Galilei. The relations between reference frames at speed comparable to that of light and the critical analysis of the concepts of time and space intervals leading to the relativistic mechanics are dealt with in Chap. 6.

In the last two chapters we study the mechanics of extended bodies. We start Chap. 7 with systems made of only two different material points. We show that in any case in which a force acts on a body, this is due to another body, which in turn is acted upon by a force due to the first one. In other words the forces are always due to the interaction between bodies. Having studied the issue on two-body systems, we proceed in the second part of the chapter with the study of material systems in full generality, finding the fundamental laws of their motion. In the last chapter we study the principal aspects of the motion of particular, and importantly, material systems, namely rigid bodies. Their motion is described by well-defined differential equations. Their solution is an important mathematical problem, which is however outside the scope of this course.

Each chapter of the book starts with a brief introduction to a scope that will give to the reader a preliminary idea of the arguments he/she will find. There is no need to fully understand these introductions, at the first reading, as all the arguments are fully developed in the following pages.

At the end of each chapter the reader will find a number of queries on which to check his/her level of understanding of the arguments of the chapter. The difficulty of the queries is variable; some of them are very simple, some more complex, a few are true numerical exercises. On the other hand, the book does not contain a sequence of full exercises, considering the existence of very good textbooks dedicated specifically to that.

The answers to a large majority of the queries are included. However, the solution of numerical exercises (without looking at the answers) is mental gymnastics that is absolutely necessary for understanding the subject. Only the effort to apply what has been learned to specific cases allows us to master them completely. The reader should be conscious of the fact that the solution of numerical exercises requires mental mechanisms different from those engaged in understanding a text. The latter, indeed, has been already organized by the author; solving a problem requires much more active initiative from the student. This is just the type of initiative, a creative activity that is needed, for advancing scientific knowledge and its technical applications as well. Consequently, the student should work on exercises alone, without looking at the solutions in the book. Even failed attempts to autonomously reach the solution, provided they are undertaken with sufficient persistence, give important returns, because they develop processing skills. If after several failed attempts the solution has not yet been reached, it is a better practice to momentarily abandon the exercise, rather than looking at the solution, going to another one, and coming back later.

The following working scheme is methodologically advisable:

1. Examine at depth the conditions posed by the problem. If it is possible, make a drawing containing the essential elements.
2. Solve the problem using letters, not numbers, in the formulas, then develop them until the requested quantities are expressed in terms of the known ones. Only then should you put numbers in the formulas.
3. Confirm the correctness of the physical dimensions (see Sect. 1.3).
4. When necessary transform all the data into the same system of units (preferably SI, see Sect. 1.2). Use scientific notation, for example 2.5×10^3 rather than 2500, 2.5×10^{-3} rather than 0.0025. In general two or three significant figures are enough.
5. Once you have the final result, always verify if it is reasonable. For example the mass of a molecule cannot turn out to be 30 mg, the speed of a bullet cannot be 10^6 m/s, the distance between two towns cannot be 25 mm, etc.

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The pages from Isaac Newton's, *Phylosophyae Naturalis Principia* are from the English translation from Latin by Andrew Motte (1729) modernized by the author.

The pages from G. Galilei's *Dialogue concerning two chief world systems* are a translation into English by the author from the Edizione Nazionale delle Opere, edited by Antonio Favaro; Florence, tip. Barbèra, 1890–1909.

The pages from G. Galilei's *Dialogues and mathematical demonstrations concerning two new sciences* are adapted from the English translation from Italian and Latin by Henry Crew and Alfonso de Salvio; McMillan 1914.

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