Preface

This is the fourth 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 are the result of a translation, an in-depth revision and an update of the Italian version published by Decibel-Zanichelli. This fourth volume deals with oscillations, waves, and light.

It is assumed that the reader knows differential calculus and the simplest properties of the vector fields (the same as in Volume 3), such as the gradient of a scalar field, the divergence and curl of a vector field, and the basic theorems on the line integral of a gradient, the Gauss divergence theorem and the Stokes curl theorem. We shall also assume that the reader has already learned the basic concepts of mechanics and electromagnetism up to Maxwell's equations, as developed in the first volumes of this course, to which we shall make explicit reference when needed, or equivalent ones.

Oscillations about a stable state of equilibrium are a very common natural phenomenon, present in all sectors of physics ranging from mechanics to electromagnetism and from astrophysics to atomic and nuclear physics. A spider hanging from its gossamer thread, if displaced from the equilibrium position, oscillates back and forth as long as passive resistances do not stop it. A blade of grass pushed by the wind moves periodically up and down. A boat on the surface of a lake oscillates under the action of the waves. Large systems vibrate as well. The earth's atmosphere does so under the periodic action of the moon over a period of about 12 h. The earth itself vibrates for a while when hit by an intense seismic shock, as do extremely small objects. Light itself is produced by the vibrations of atoms, namely the oscillations of the electrons they contain, which, as all accelerating charges do, produce an electromagnetic wave. An electric circuit containing an inductance and a capacitance performs harmonic, electric oscillations that are completely similar to the mechanical oscillations of a pendulum. Electric and the magnetic fields also oscillate in a vacuum, when they are the fields of an electromagnetic wave. And space-time itself vibrates when a gravitational wave crosses it.

Hence, many physical systems exist that can perform oscillations. Each system may obey a different law, the Newtonian law if it is mechanical, the Maxwell's equation if it is electromagnetic, or the quantum equation if it is an atom, but their motions have similar characteristics. In particular, they are very often harmonic motions, in a first, but usually very good, approximation. This is a consequence of the fact that the oscillation takes place in the proximity of a stable equilibrium configuration and the system is attracted to that by a restoring force (or, more generally, by an action) proportional to the displacement from that configuration. As a consequence, the differential equation governing their motions is the same for all of these systems. The first part of this book deals with such small oscillation phenomena.

In the remaining parts, we shall discuss waves. The word immediately brings to mind the motion of the sea. Suppose, then, that we are on a beach and observing the motion of the waves approaching us from the open sea, moving with a defined speed, and crashing on the rocks under our observation point. Each wave is different from the previous one, but some features are always evidently equal for all of them: their speed, the distance between two crests (namely the wavelength), and the period during which a given point of the surface rises and lowers. The show is fascinating and could hold our attention for a long time, but, we may ponder, are there other waves around us? They are not as evident, but knowing a bit about physics, we know that there are indeed. The sound that reaches our ears was caused by the impact of the water on the rocks and the cries of seagulls, both are waves. And so is the sunlight that enlightens and heats us. It is waves that allow us to perceive the image of the sea and of the person standing close to us. Waves run along our nerves from the retina and the eardrum to the brain, and then, there are those that intersect in our brain while we think and feel, although we do not know how.

Wave phenomena, therefore, are present in different physical systems, ranging from mechanical to electrical and from biological to quantum. Like oscillations, the different types of waves have common characteristics. Again, this is due to the fact that the equation governing the different systems is, under many circumstances, exactly the same. Our study will therefore be initially addressed to the general properties of waves, common to their different types. To be concrete, we shall exemplify this phenomenon through two of the most important cases, namely sound and electromagnetic waves. Subsequently, we will focus on the visible electromagnetic waves, which are light. That is to say, we will study optics.

Quantum physics describes the phenomena on the atomic and subatomic levels by associating each particle, atom, electron, nucleus, etc., with a "wave function." This is a complex function of the coordinates and of time, whose amplitude squared gives the probability of finding the particle at a given point in a given instant. This function behaves exactly like a wave. All of this is outside the scope of these lectures. However, we observe that several surprising aspects of quantum mechanics are entirely similar to completely classical aspects of the physics of oscillations and waves. For example, inverse proportionality relationships, which we shall look at in Chap. 2, between the duration of a signal in time and the width of its frequency spectrum and that between the extension of a wave front and the width of the angular distribution of the wave vector, strictly correspond in quantum physics to the Heisenberg uncertainty relations. In other words, the uncertainty relations are characteristic of *all wave phenomena*, not only of the quantum examples but of the classical ones as well. Another example is the wave phenomenon of the "frustrated vanishing wave," which we will look at in Chap. 4. It corresponds to the "tunnel effect" in quantum mechanics. Consequently, a deep enough understanding of classical wave phenomena will substantially help the student when he/she tackles quantum physics.

The first two chapters are devoted to the study of oscillations of physical systems whose state is determined by a single coordinate (Chap. 1) and more than one coordinate (Chap. 2). Chapter 1 studies the oscillatory motion of a simple pendulum and similar physical systems, in as much as they are described by the same differential equation. We shall study oscillations in both the presence and absence of damping and the presence and absence of an external periodic solicitation. In the second chapter, we shall study more complicated systems, such as two pendulums connected by a spring. We shall see that while the generic motion of these systems is complicated, there are special motions, called normal modes, which are very simple; namely, they are harmonic oscillations of all parts of the system in phase with one another. We shall then see that even a continuous system like a guitar string has particular motions that are its normal modes. The discussion will lead us to discover an important mathematical tool, namely the harmonic analysis (Fourier transform). This is an instrument that we shall use often in what follows.

In Chap. 3, we define the concept of the wave. We shall then study how a wave can be produced, how it is reflected, and how it can be destroyed (absorbed). We shall deal with electromagnetic waves and sound waves, as particularly important examples. In Chap. 4, we learn that there are different concepts of wave velocity and their relations with energy propagation, in particular the velocity of the phase for a wave of definite wavelength and the group velocity for all types of wave. We shall see that under several physical circumstances, the phase velocity is a function of the wavelength. This is especially true for light waves in material media. We shall examine the consequences and study the physical reason for the phenomenon.

In the subsequent chapters, we will focus solely on light waves, which are electromagnetic waves in the range of wavelength in which they can be perceived by the human eye. These wavelengths are very small, a few tenths of a micrometer, and the frequencies are very high, on the order of hundreds of THz. In Chap. 5, we shall study the phenomena of interference and diffraction of light, which are the characteristics of the wave nature of light. In the sixth chapter, we shall deal with the consequences of the fact that the electric field of light waves can vibrate in different directions, all perpendicular to the propagation direction. These are the polarization phenomena. We shall study the different polarization states of light, how polarization can be produced from non-polarized light, and how the polarization state can be experimentally analyzed.

In the last two chapters, we study the imaging processes. These are the processes that take place in our own eye, as well as in optical instruments, providing us with much of the information we have on the outside world. In Chap. 7, we shall learn, step-by-step, the process for the formation of images of point-like objects, of objects of two and then of three dimensions. The processes of image formation may be different, depending on whether one uses mirrors, lenses, or interference patterns. Topics covered in the first part of the chapter normally fall under the name of geometrical optics. However, the physics of these phenomena is dealt here with constant attention to the wave nature of light. In the last chapter, we shall see that the image formation process through a lens amounts to a succession of a Fourier transform (from the image to the back focal plane) followed by a Fourier anti-transform (from the back focal plane to the image plane). Finally, using the coherent light of the laser, we shall see how we can produce those actual three-dimensional images known as holograms.

Physics is an experimental science, meaning that it is based on the experimental method, which was developed by Galileo Galilei in the seventeenth century. The process of understanding physical phenomena is not immediate, but rather, it advances through trial and error, in a series of experiments, which might lead, with a bit of fortune and a lot of thought, to the discovery of the governing laws. Induction of the process of physical laws goes back from the observed effects to their causes, and, as such, cannot be purely logical. Once a physical law is found, it is necessary to consider all its possible consequences. This then becomes a deductive process, which is logical and similar to that of mathematics. Each of the consequences of the law, in other words, its predictions, must then be experimentally verified. If only one prediction is found to be false through the experiment, even if thousands of them had been found true, it is enough to prove that the law is false. As R. Feynman wrote on the blackboard at the very beginning of his famous lecture course, "We are not concerned with where a new idea comes from—the sole test of its validity is experiment."

This implies that we can never be completely sure that a law is true; indeed, the number of its possible predictions is limitless, and at 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 much further in the last four centuries than in all the preceding millennia.

The path of science is complex, laborious, and highly nonlinear. In its development, errors have been made and hypotheses have been advanced that turned out to be false, but ultimately, laws were discovered. The knowledge of at least a few of the most important aspects of this process is indispensable for developing the mental capabilities necessary for anybody who wishes to contribute to the progress of the natural sciences, whether they pursue applications or teach them. For this reason, we have included brief historical inserts recalling the principal authors and quoting their words describing their discoveries.

Quite often, aspects of oscillation and wave phenomena described in this book can be observed in the nature around us. Some of these observations are mentioned, including pictures when relevant. More photographs and movies can be found on the Web.

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

At the end of each chapter, the reader will find a summary and a number of queries with which to check his/her level of understanding of the chapter's arguments. The difficulty of the queries is variable: Some of them are very simple, some is more complex, and a few are true numerical exercises. However, the book does not contain any sequence of full exercises, owing to the existence of very good textbooks dedicated specifically to that.

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