PHYSICS
ONCE OVER-LIGHTLY

KENNETH R. ATKINS

PHYSICS—*Once Over—Lightly*

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The Interabang used as the basis of the computerized graphics of the frontispiece and the cover was introduced in 1967 by the American Type Founders Co. as the first new punctuation mark to be devised for print since the adoption of quotation marks in the late 17th Century. It is intended to express a simultaneous quality of exclamation and questioning. To the author it seems to symbolize perfectly his own personal philosophy and the attitude to physics embodied in this book. Exclamation is the appropriate reaction to physical theory, with its beauty, elegance, strangeness, and depth of revelation. Nevertheless, since physics is a science, this must always be accompanied by a questioning—questioning about meaning—questioning about significance—questioning about further consequences—and, perhaps the most important of all, a continuous critical questioning of its truth.

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Preface

This is a modified version of my book *Physics* shortened and simplified to make it more suitable for a one-semester or one-quarter course. It is much more than just the earlier book operated on with scissors and paste. Many sections have been rewritten. Some new sections have been introduced. The mathematical demands on the reader are even less than they were in the longer version. Trigonometry has been completely eliminated and only the most elementary aspects of algebra and geometry are required. Examples of problem solving have been removed from the main text, although simple problems are still included at the end of each chapter to be used or ignored by the instructor at his own discretion.

Anyone who has taught a short, self-contained course covering the basic concepts of physics knows that it presents an especially difficult challenge. This book meets that challenge in the following way. I have attempted to include no more material than can reasonably be covered in the time available. I have achieved this basically by eliminating the less essential topics. For example, Maxwell's equations are still included, but the electric generator has been omitted. The abbreviation has not been carried to the point of eliminating the essense of the essential. To illustrate what I mean by this, a reader pursuing the claim that Maxwell's equations are included will not find in the text merely an isolated sentence such as "*In 1865 the British physicist James Clark Maxwell summarized electromagnetic theory in a set of elegant mathematical equations.*" This is history with little physical content. Instead, turning to Section 7-7, the reader will find a descriptive nonmathematical discussion of Maxwell's equations and an attempt to explain their physical significance. In Section 8-3, he will find a discussion of the relationship between these equations and the phenomenon of electromagnetic waves.

Certain characteristic features of the longer version of the text have been retained. CGS units are used for reasons that the author is prepared to advocate vehemently at great length, but not here. In the diagrams, vectors representing different physical quantities have been distinguished from one another by the use of several different kinds of arrows, and throughout the book a particular vector quantity is always represented by the same kind of arrow. It is not necessary for the student to memorize this vector code, but it may improve the clarity of the diagrams as he subconsciously comes to realize that, for example, a certain kind of broken arrow always represents a velocity. The student is encouraged to use powers of ten instead of special units or prefixes. If the wavelength of an x-ray is expressed as 5×10^{-8} cm and the wavelength of visible light as 5×10^{-5} cm, their relative magnitudes are immediately obvious to a student who has expended the small amount of effort needed to understand the procedure. The alternative practice of expressing the x-ray wavelength as 5 Å and the light wavelength as 500 mμ is much more confusing, particularly for nonscientists whose experience of physics may be almost entirely confined to this one course.

The most obvious application of this book is to a short, terminal course for nonscientists, but it may find other uses in these days of educational innovation. I have used it myself for the first semester of a two-semester course given to business students. It provided an appropriate background for the second semester, when the basic physical concepts were applied to some exciting aspects of astronomy such as cosmology, stellar evolution, quasars, pulsars, and black holes.

Philadelphia
May, 1971

Kenneth R. Atkins

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1 The Way Ahead

1-1 Describing the World Around Us

Physics is an attempt to describe, in as fundamental and penetrating a way as possible, the nature and behavior of the world around us. Before dismissing this sentence as an abstract and profitless philosophical statement of the type that authors must use to get their books smoothly under way, the reader should accept the challenge, lift his, or her, eyes from the page, and look at the world around. As I do this myself, I am first conscious of a multitude of shapes and colors; a subtle interplay of patches of color on the wallpaper; an expanse of bright red carpet; through the window, the intricate shape of a green tree against a flat expanse of blue sky. On the wall is a reproduction of Picasso's "Boy with a Horse." On the bookshelf the most conspicuous item is a bulky *Complete Works of Shakespeare*. From the record player I hear the sounds of Schubert's Octet in F Major. Whatever the circumstances surrounding the reader, he will probably not have to look far to find things equally complicated and marvellous, and certainly the mind

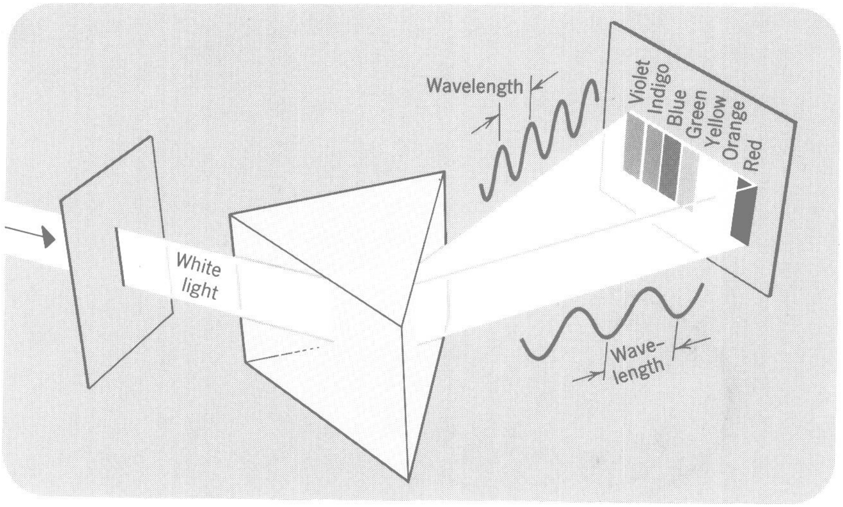

Figure 1-1 A glass prism resolves white light into a spectrum of basic colors. The different colors correspond to different wavelengths.

that he is using to consider these matters is an example of one of the most complicated and marvellous structures that can be contemplated.

Obviously, a complete description of the world around us must include the tree, the mind of man, the art of Picasso, the plays of Shakespeare, and the music of Schubert. Even more obviously, these things are not the primary concern of physics. However, if I lift my Picasso off its hook and then let it go, it falls to the ground. The same thing happens with the *Complete Works of Shakespeare* and the record of Schubert's Octet. Moreover, if all three objects are held at the same height and released at the same time, they all strike the ground at the same time (ignoring small, almost imperceptible differences in falling time mainly due to the resistance of the air). This is the sort of thing that is the concern of physics. Whatever is relevant to the aesthetic appeal of the Picasso is clearly irrelevant to the rate at which it falls to the ground, and we are led to make a very general, fundamental statement that: "*All unsupported bodies fall toward the center of the earth at the same rate.*" Of course we shall have to be more precise about the meaning of the phrase "at the same rate," and also we might be well advised to specify that the bodies are to fall through an evacuated space, in order to eliminate the effect of the air which, in an extreme case, makes a balloon rise. But when, following in the steps of Newton, we have refined the idea to the point where the statement becomes: "*Any two bodies attract one another with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them,*" then we have arrived at one of the most important and basic laws of physics, Newton's law of universal gravitation.

The patches of color that are an essential part of our immediate experience can be analyzed by means of an instrument known as a spectroscope, which is essentially a prism of glass. If white light, such as the sunlight now streaming in through my windows, falls upon this glass prism, it is spread out into a spectrum of the colors of the rainbow, as shown in figure 1-1. All the rays of light are bent by the prism, but the red light is bent least and

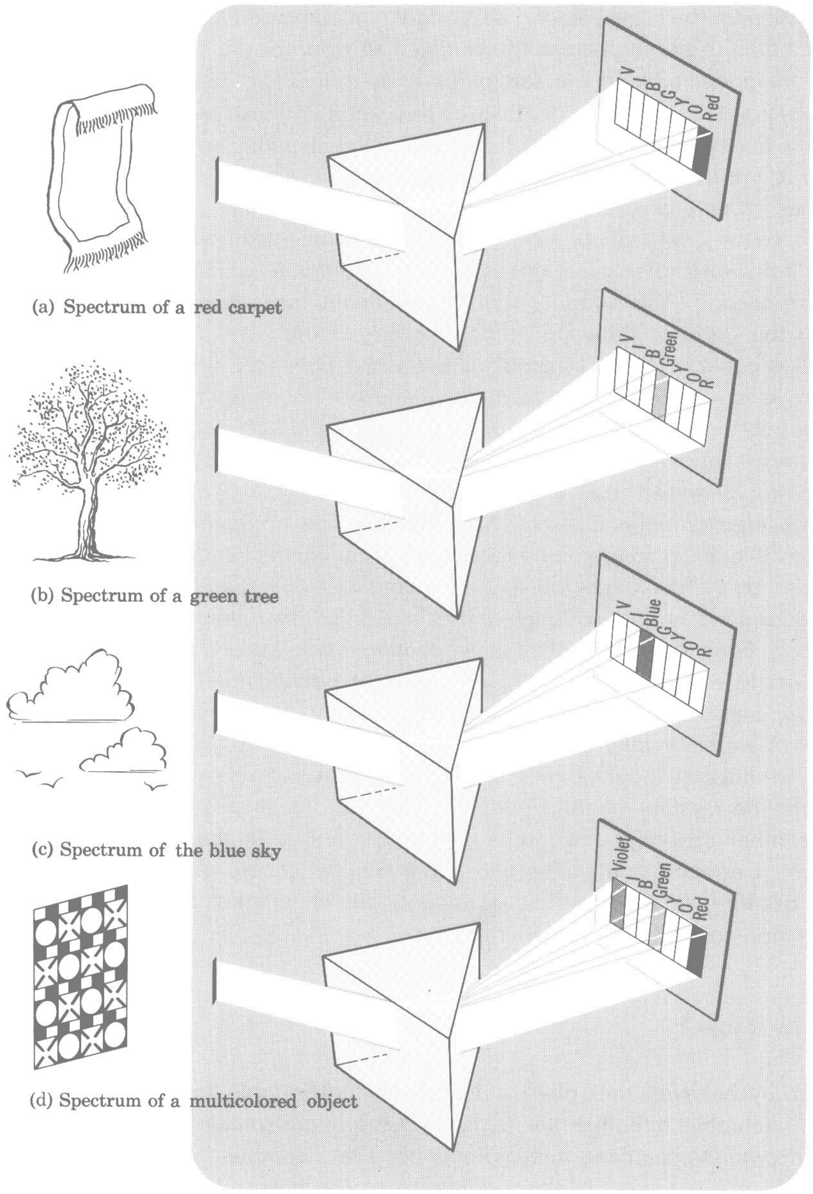

Figure 1-2 The glass prism analyzes various samples of light into basic color components.

the violet light most, the other colors coming in between, as shown in the diagram. The colors of this spectrum are the basic components of all visible light. If the spectroscope were arranged to accept only light from my red carpet, then only the red region of the spectrum would be illuminated; if the light came from the green tree, the spectrum would be illuminated mainly in the green region; and if the light came from the blue sky it would be the blue region that would be illuminated (see figure 1-2). However, if the spectroscope were made to accept light from my multicolored wallpaper, then several regions of the spectrum would be illuminated, as shown in figure

1-2*d*. In this way, any sample of visible light can be analyzed into some or all of the basic colors of the spectrum mixed in appropriate proportions.

We are again making the sort of analysis that is the concern of physics, but physics is not satisfied to stop at this stage. It must penetrate more deeply into the heart of the matter and ask, "What is the nature of light, and what is the difference between various basic colors?" This particular question led to several centuries of speculation, culminating in the early nineteenth century with a burst of ingenious experimental activity that provided the following answer: *"Light is a wave, similar to a wave on the surface of the ocean."* The quantity that characterizes the color is the **wavelength,** or the distance between adjacent crests of the wave. For red light this distance is about twice as great as for violet light (see figure 1-1).

There is much more to be said about the nature of light. An ocean wave requires the presence of the ocean, but a light wave can travel through empty space, as it does between the sun and the earth. The explanation of this, provided later in the nineteenth century, was that *"Light is a wave in an electromagnetic field."* Now the analysis has penetrated so deeply that it can no longer be expressed in familiar terms and the uninitiated reader cannot be expected to understand even vaguely what is meant. The explanation is in fact so lengthy that it will not be attempted until later in this book. Even so, it is a nineteenth century explanation, and today a physicist would rather say that *"Light consists of particles (or quanta or photons) whose behavior is governed by a wave in an electromagnetic field,"* all of which we shall attempt to explain later on. Having thus overreached ourselves to illustrate how physics is always penetrating more and more deeply into the mystery of the behavior of things, let us also emphasize again the other aspect of the matter. Whatever is true in these statements about light is equally true of the light from the red carpet and the light from the painting by Picasso. The statements are an attempt to find something common to all visual experiences.

1-2 Is It True?

It is generally believed that physics deals with indisputable facts and absolute truth. Actually, although the facts are usually indisputable, they are frequently incomplete, and the interpretation of the incomplete facts leads to theories that are only rough approximations to the truth. The situation can be fully appreciated only when one has an understanding of the whole of physics, but we shall attempt to illustrate it by reference to the atomic theory with which, it is safe to assume, the reader already has some familiarity.

In the nineteenth century, when this theory was progressing from triumph to triumph in its clarification of chemistry and the behavior of gases, its proponents might have expounded it in the form of the following postulates.

Postulate A

Matter cannot be divided indefinitely into smaller and smaller pieces: at a certain stage it will be found to consist of very small, submicroscopic entities called atoms, which cannot be divided any further.

Postulate B

Atoms cannot be created or destroyed.

Postulate C

All the atoms of a particular chemical element have identical properties; for example, they all have the same mass.

Postulate D

Atoms of different chemical elements have different properties; for example, they have different masses.

Postulate E

An atom of one chemical element cannot be changed into an atom of a different chemical element.

Now let us examine these postulates in the light of modern knowledge, pointing out the extent to which they are false, but also (to avoid generating too sceptical an attitude) pointing out the extent to which they are good, useful approximations to the true situation.

Postulate A

Atoms can be further subdivided into small fundamental particles known as electrons, protons, and neutrons. It is an open question whether these fundamental particles themselves can be subdivided still further. However, an atom is a stable, compact entity that can remain unchanged for long periods of time, and exceptional measures have to be taken to break it up into its constituent parts.

Postulate B

Modern physicists are aware of processes during which atoms are created out of energy, and reverse processes during which atoms are destroyed and changed into energy. However, these processes are very rare in everyday experience.

Postulate C

The atoms of a particular chemical element can occur in different forms, known as isotopes, with different masses. The element is determined by the number of electrons in the atom (which is the same as the number of protons), but the number of neutrons can then vary to give various isotopes. However, each element has only a small number of stable isotopes and the naturally occurring form of the element usually contains these stable isotopes in fixed proportions.

Postulate D

It is possible for an isotope of one element to have almost the same mass as an isotope of another element. The two atoms are then called isobars. However, isobars do have slightly different masses, and so this postulate is strictly true.

Postulate E

It is well known that nuclear physicists can readily convert an atom of one element into an atom of another element. This process is basic to the performance of a nuclear reactor and an atomic, or hydrogen, bomb. However, the process is not very common in everyday life and is certainly not relevant to ordinary chemical reactions.

In the course of this book we shall discuss several cases of well-established theories that have been found to be not quite true and have had to be modified to bring them a little closer to the truth. An outstanding example is Newtonian mechanics, which is quite adequate to describe the motion of bodies that are not moving extremely fast, and is therefore all that is needed to predict the path of a guided missile, but which breaks down when the bodies begin to move with velocities comparable with the velocity of light and has to be replaced by Einstein's special theory of relativity. It follows inescapably that our best modern physical theories are probably only rough approximations to the truth and will eventually have to be replaced by something better. For example, the special theory of relativity does not cope adequately with the subject of gravitation, and so Einstein was led to formulate the general theory of relativity. However, there are very few experimental tests of the general theory and it has not been accepted with the same degree of confidence as the special theory. Many physicists believe that in this particular field there will be some surprising developments during the next few decades.

Physics must therefore be regarded as an evolving subject approaching closer and closer to the truth but never quite attaining it.

1-3 Classical Physics and Modern Physics

During its evolution, physics has passed through two major phases, which are commonly referred to as classical physics and modern physics. Because these two phases differ so radically, in their attitude toward the nature of the universe and in their philosophical implications, their separation is a profitable one that we shall continually emphasize. In order to give the reader some perspective on the detailed explanations of the succeeding chapters, we shall now present a very brief summary of the evolution of physics.

Classical physics started in earnest in the seventeenth century when Galileo and Newton discovered the laws governing the motion of bodies. It came to regard the universe as a collection of isolated bodies separated by regions of empty, featureless space. The bodies exerted forces on one another in spite of the lack of any obvious direct connection through the intervening space. At first, the bodies discussed were the sun, the planets, the earth's moon, the moons of the other planets, bodies falling to the earth, cannonballs shot from cannons, and so on. The forces were initially gravitational forces, electric and magnetic forces, and certain incompletely understood forces such as the upward force that the top of a table exerts on a plate to prevent it from falling under gravity.

In the nineteenth century the idea that all matter is composed of **atoms** was fully accepted, and the universe then came to be regarded as a collection of isolated atoms moving through empty space and exerting forces on one another. This point of view seemed capable of providing a complete explanation of all the phenomena associated with heat, sound, electricity, magnetism, and the various properties of matter, such as elasticity, viscosity, and surface tension. However, the nature of electricity and the origin of the interatomic forces remained obscure until early in the twentieth century when it was discovered that atoms are themselves complicated structures built up out of **fundamental particles.** The most abundant and most important of these fundamental particles are the **electron,** which is a very light particle and the unit of negative electricity; the **proton,** which is a more massive particle than the electron and the unit of positive electricity; and the **neutron,** which has about the same mass as the proton, but no electric charge. With the discovery of these particles it became necessary to modify the picture of the universe and to think in terms of electrons, protons, and neutrons moving through empty space. This promised to give an even more complete and fundamental description of physical phenomena.

An important feature of this view of the universe was the implication that once the fundamental laws of physics had been formulated, it would be possible to describe completely the motion of the particles and therefore to predict the state of the universe at all future times. This view therefore encouraged the belief that everything that will happen in the future is determined by what has happened in the past and that our lives are governed by Inescapable Destiny. The two capital letters are used to give the phrase an ominous ring and the rest is left to the imagination of the reader.

This brief summary of the situation is an oversimplification, and not all classical physicists would have subscribed to all the above views, particularly the philosophical implications. Moreover, there is an alternative view of the universe that has received considerable attention. This view refuses to regard space as empty and featureless, and prefers to endow all points in space with physical properties. It is sometimes expressed in the extreme form that all of space is filled with a continuous, indivisible fluid frequently called the **ether.** This point of view received considerable support at the beginning of the nineteenth century when Young and Fresnel performed a series of decisive experiments to demonstrate that light is a wave, a wave that can travel through "empty space." At the same time Faraday performed some crucial experiments on the nature of electricity and magnetism. He came to the conclusion that all the space surrounding an electric charge must be visualized as a field of electric force somewhat similar to a continuous all-pervading liquid (the ether) in a state of strain and that, similarly, the region surrounding a bar magnet must be regarded as a field of magnetic force. This implied that every point in space, whether it is occupied by matter or not, is associated with two quantities that specify the nature of the electric and magnetic fields at that point.