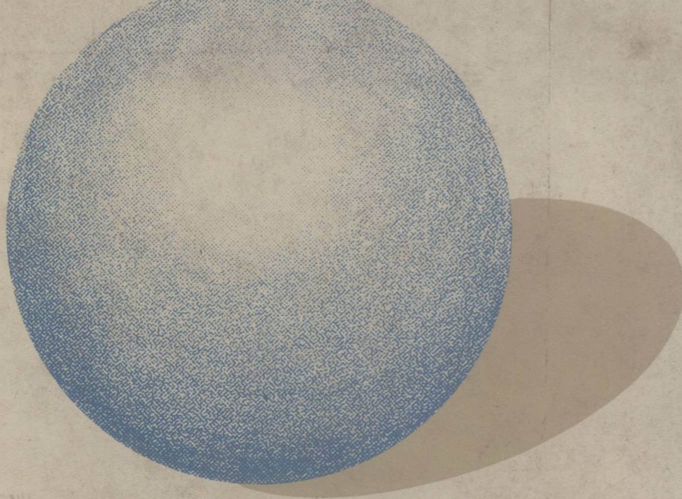

CONCEPTS OF MODERN PHYSICS

ARTHUR BEISER

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Third Edition

Arthur Beiser

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PREFACE

This book is intended for use with one-semester courses in modern physics that have elementary classical physics and calculus as prerequisites. Relativity and quantum theory are considered first to provide a framework for understanding the physics of atoms and nuclei. The theory of the atom is then developed with emphasis on quantum-mechanical notions, and is followed by a discussion of the properties of aggregates of atoms. Finally atomic nuclei and elementary particles are examined.

The balance here deliberately leans more toward ideas than toward experimental methods and practical applications, because I believe that the beginning student is better served in an introduction to modern physics by a conceptual framework than by a mass of individual details. However, all physical theories live or die by the sword of experiment, and a number of derivations are included in order to demonstrate exactly how an abstract concept can be related to actual measurements. Many instructors will prefer not to hold their students responsible for some of the more complicated (though not necessarily mathematically difficult) discussions, and I have indicated with asterisks sections that can be passed over lightly without loss of continuity; problems based on the contents of these sections are also marked with asterisks. Other omissions are also possible, of course. Relativity, for example, may well have been covered elsewhere, and Chapters 8, 9, and 10 may be skipped entirely when their contents will be the subject of later work. Thus there is scope for an instructor to fashion the type of course desired, whether a general survey or a deeper inquiry into selected subjects, and to choose the level of treatment appropriate to a given audience.

Those familiar with the previous edition of *Concepts of Modern Physics* will notice many changes. Entirely new are sections on the doppler effect in light, how relativity connects electricity and magnetism, specific heats of solids, crystal defects, the origin of Ohm's law, semiconductor devices, radiometric dating, nuclear reactors, how various radiations interact with matter, and particle and track detectors. Topics whose treatment has been expanded include the twin paradox, the wave-particle duality, x-ray spectra, the laser, blackbody radiation, nuclear models, thermonuclear energy, and, of course, elementary particles and the fundamental interactions. Much of the remainder of the text has been revised and some of it reorganized; for instance, quantum-mechanical barrier penetration and the nature of stationary states are introduced earlier than before because of their bearing on a variety of phenomena. The material on statistical mechanics was completely redone to be more accessible on first acquaintance, with the derivations of the three distribution laws shifted to an appendix. Other appendixes cover how operators, eigenfunctions, and eigenvalues are related and the details of the quantum theory of the harmonic oscillator. To make room for the new material, some discussions have had to be abbreviated or omitted, notably those of the Michelson-Morley experiment, molecular orbitals, and the theory of the deuteron.

Whenever possible, important subjects are introduced on an elementary level, which enables even relatively unprepared students to gain an insight into what is going on and also encourages the development of physical intuition in readers in whom the mathematics inspires no terror. The problems, too, are on all levels, from the quite easy (for practice and reassurance) on up to those for which real thought is needed (to provide the joy of discovery). The number of problems has been increased, and nearly half of them are new. Several dozen illustrative problems are now incorporated in the text.

In preparing this edition of *Concepts of Modern Physics* I have had the benefit of comments by W. Anderson, Y. Beers, R. G. Fowler, A. L. Harvey, G. Q. Hassoun, C. A. Moyer, and T. Satoh. Their help was of great value and is much appreciated.

Arthur Beiser

CONCEPTS OF MODERN PHYSICS

CONTENTS

1

Special Relativity

The theory of relativity examines how measurements of physical quantities depend upon the observer as well as upon what is observed. From relativity emerges a new mechanics in which there are intimate relationships between space and time, mass and energy. Without these relationships it would be impossible to understand the microscopic world within the atom whose elucidation is the central problem of modern physics.

1.1 POSTULATES OF SPECIAL RELATIVITY

When such quantities as length, time interval, and mass are considered in elementary physics, no special point is made about how they are measured. Since a standard unit exists for each quantity, it would not seem to matter who makes a particular determination: everybody ought to get the same result. If we are on board an airplane, for instance, we could stretch a tape measure from its nose to its tail to find its length. If we are some distance away, we would need a more elaborate procedure involving a tape measure to establish a base line, a surveyor's transit to find angles, and trigonometry to make some calculations, but we would obtain the same length for the airplane. However, if we are on the ground and the airplane is in flight, things become more complicated—and more interesting. What we would find is that the moving airplane appears shorter to us than it does to somebody in the airplane itself, that time intervals on the moving airplane appear longer to us than they do to somebody on the airplane, and that the mass of the airplane appears greater to us than it does to somebody on the airplane. To understand the origins of these differences, we must analyze the process of measurement in a detailed way.

The first step is to clarify what we mean by motion. When we say that something is moving, what we mean is that its position relative to something else is changing. A passenger moves relative to an airplane, the airplane moves relative to the earth, the earth moves relative to the sun, the sun moves relative to the galaxy of stars (the Milky Way) of which it is a member, and so on. In each case a *frame of reference* is part of the description of the motion. To say that something is moving always implies a specific frame of reference. All frames of reference are equally valid, although one or another may be more convenient to use in a given case.

If we are in a closed laboratory, we cannot establish if the laboratory is moving at constant velocity or not since without an external frame of reference the concept of motion has no meaning. There is no universal frame of reference pervading all of space, so there is no such thing as "absolute motion."

The theory of relativity resulted from an analysis of the physical consequences implied by the absence of a universal frame of reference. The special theory of relativity, developed by Albert Einstein in 1905, treats problems involving *inertial frames of reference*, which are frames of reference moving at constant velocity with respect to one another. The general theory of relativity, proposed by Einstein a decade later, treats problems involving frames of reference accelerated with respect to one another. An observer in an isolated laboratory *can* detect accelerations. Anybody who has been in an elevator or on a merry-go-round can verify this statement from his or her own experience. The special theory has had a profound influence on all of physics, and we shall concentrate on it in this chapter with a brief glance at the general theory in Chap. 2.

The special theory of relativity is based upon two postulates. The first, the *principle of relativity*, states that **the laws of physics may be expressed in equations having the same form in all frames of reference moving at constant velocity with respect to one another.** This postulate expresses the absence of a universal frame of reference. If the laws of physics were different for different observers in relative motion, it could be determined from these differences which objects are "stationary" in space and which are "moving." But because there is no universal frame of reference, this distinction does not exist in nature; hence the above postulate.

The second postulate states that **the speed of light in free space has the same value for all observers, regardless of their state of motion.** This postulate follows directly from the results of many experiments.

At first sight these postulates hardly seem radical. Actually they subvert almost all the intuitive concepts of time and space we form on the basis of our daily experience. A simple example will illustrate this statement. In Fig. 1-1 we have two boats, *A* and *B*, with boat *A* at rest in the water while boat *B* drifts at the constant velocity **v**. There is a low-lying fog present, and so on neither boat does the observer have any idea which is the moving one. At the instant that *B* is abreast of *A*, a flare is fired. The light from the flare travels uniformly in all directions, according to the second postulate of special relativity. An observer on either boat must find a sphere of light expanding with *himself* at its center, according to the principle of relativity, even though one of them is changing his position with respect to the point where the flare went off. The observers cannot detect which of them is undergoing such a change in position since the fog eliminates any frame of reference other than each boat itself, and so, since the speed of light is the same for both of them, they must both see the identical phenomenon.

Why is the situation of Fig. 1-1 unusual? Let us consider a more familiar analog. The boats are at sea on a clear day and somebody on one of them drops a stone into the water when they are abreast of each other. A circular pattern of ripples spreads out, as at the bottom of Fig. 1-1, *which appears different* to observers on each boat. Merely by observing whether or not he is at the center of the pattern of ripples, each observer can tell whether he is moving relative to the water or not. Water is in itself

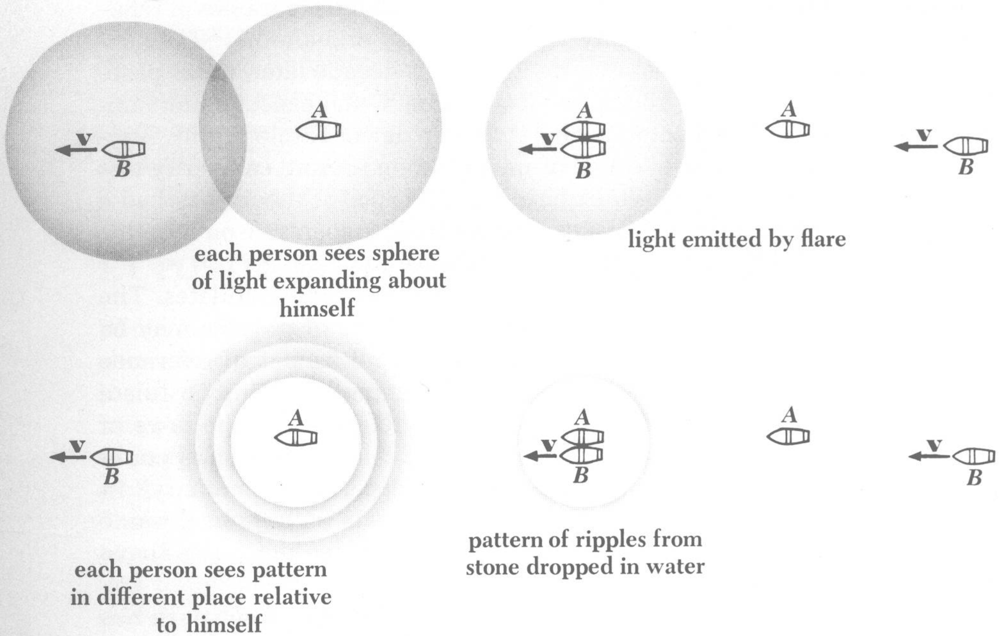


FIGURE 1-1 Relativistic phenomena differ from everyday experience.

a frame of reference, and an observer on a boat moving through it measures ripple speeds with respect to himself that are different in different directions, in contrast to the uniform ripple speed measured by an observer on a stationary boat. It is important to recognize that motion and waves *in water* are entirely different from motion and waves *in space;* water is in itself a frame of reference while space is not, and wave speeds in water vary with the observer's motion while the wave speed of light in space does not.

The only way to interpret the perception of identical expanding spheres of light by the observers in the two boats is to regard the coordinate system of each observer, from the point of view of the other, as being affected by their relative motion. When this idea is developed with the help of Einstein's postulates, we shall find that many unexpected effects are predicted, all of which have been confirmed by experiment. Special relativity is today considered one of the most securely established scientific theories. Prior to the development of relativity, a conflict had existed between newtonian mechanics and the electromagnetic theory of Maxwell in regard to the relationship between measurements of a phenomenon made in one frame of reference and those made in another frame in relative motion. Einstein showed that Maxwell's theory is consistent with special relativity whereas newtonian mechanics is not, and his modification of mechanics brought these branches of physics into accord.

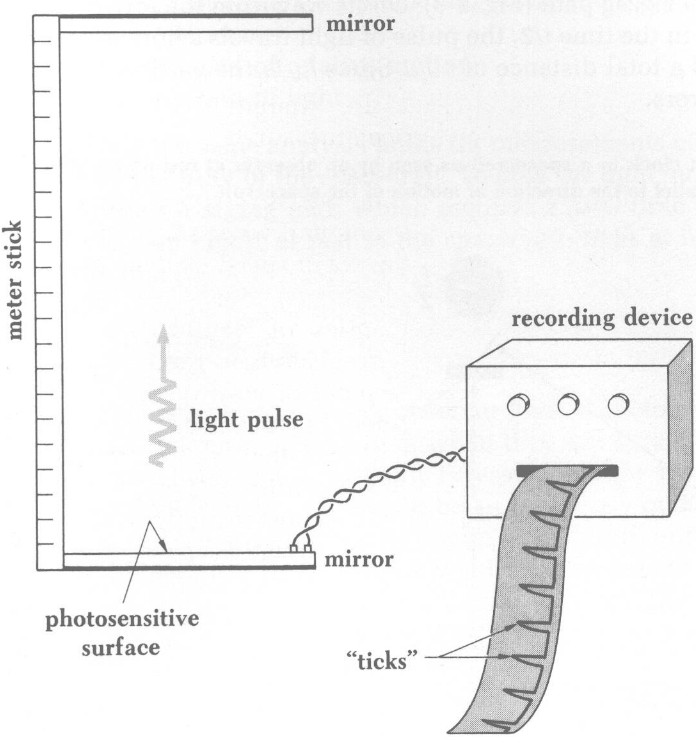
1.2 TIME DILATION

We shall first use the postulates of special relativity to investigate how relative motion affects measurements of time intervals.

A clock moving with respect to an observer appears to tick less rapidly than it does when at rest with respect to him. That is, if someone in a spacecraft finds that the time interval between two events in the spacecraft is t_0, we on the ground would find that the same interval has the longer duration t. The quantity t_0, which is determined by events that occur *at the same place* in an observer's frame of reference, is called the *proper time* of the interval between the events. When witnessed from the ground, the events that mark the beginning and end of the time interval occur at different places, and in consequence the duration of the interval appears longer than the proper time. This effect is called *time dilation.*

To see how time dilation comes about, let us examine the operation of the particularly simple clock shown in Fig. 1-2 and inquire how relative motion affects what we measure. This clock consists of a stick L_0 long with a mirror at each end. A pulse of light is reflected up and down

FIGURE 1-2 A simple clock. Each "tick" corresponds to a round trip of the light pulse from the lower mirror to the upper one and back.



between the mirrors, and an appropriate device is attached to one of the mirrors to give a "tick" of some kind each time the pulse of light strikes it. (Such a device might be a photosensitive surface on the mirror which can be arranged to give an electric signal when the light pulse arrives.) The proper time t_0 between ticks is

$$t_0 = \frac{2L_0}{c} \tag{1.1}$$

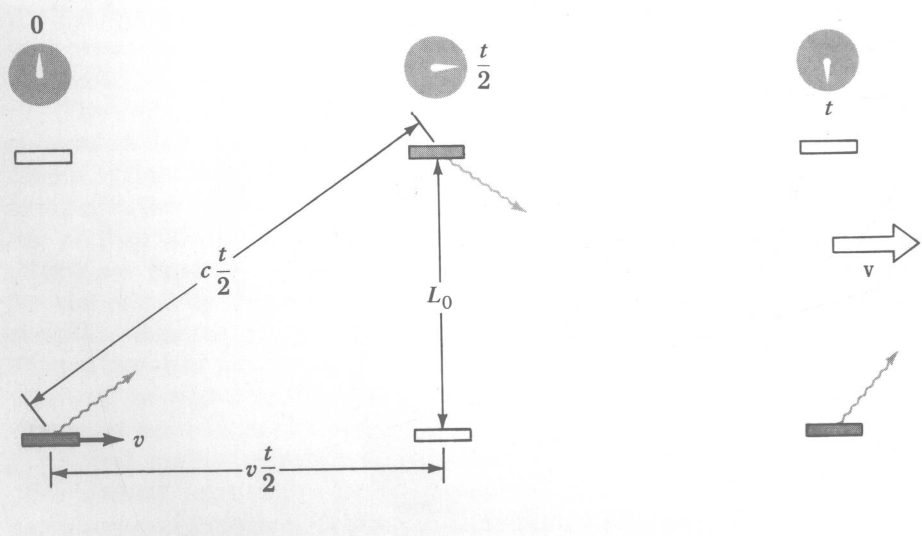
If the stick is 1 m long.

$$t_0 = \frac{2 \text{ m}}{3 \times 10^8 \text{ m/s}} = 0.67 \times 10^{-8} \text{ s}$$

and there are 1.5×10^8 ticks/s. Two identical clocks of this kind are built, and one is mounted in a spacecraft perpendicular to its direction of motion while the other remains at rest on the earth's surface.

Now we ask how much time t elapses between ticks in the moving clock as measured by an observer on the ground with an identical clock that is stationary with respect to him. Each tick involves the passage of a pulse of light at the speed c from the lower mirror to the upper one and back. During this round-trip passage, the entire clock in the spacecraft is in motion, which means that the pulse of light, as seen from the ground, actually follows a zigzag path (Fig. 1-3). On its way from the lower mirror to the upper one in the time $t/2$, the pulse of light travels a horizontal distance of $vt/2$ and a total distance of $ct/2$. Since L_0 is the vertical distance between the mirrors,

FIGURE 1-3 A light clock in a spacecraft as seen by an observer at rest on the ground. The mirrors are parallel to the direction of motion of the spacecraft.



$$\left(\frac{ct}{2}\right)^2 = L_0^2 + \left(\frac{vt}{2}\right)^2$$

$$\frac{t^2}{4}(c^2 - v^2) = L_0^2$$

and $$t^2 = \frac{4L_0^2}{c^2 - v^2} = \frac{(2L_0)^2}{c^2(1 - v^2/c^2)}$$

1.2 $$t = \frac{2L_0/c}{\sqrt{1 - v^2/c^2}}$$

But $2L_0/c$ is the time interval t_0 between ticks on the clock on the ground, as in Eq. 1.1, and so

1.3 $$t = \frac{t_0}{\sqrt{1 - v^2/c^2}}$$ **Time dilation**

Because the quantity $\sqrt{1 - v^2/c^2}$ is always smaller than 1 for a moving object, t is always greater than t_0: the moving clock in the spacecraft appears to tick at a slower rate than the stationary one on the ground, as seen by an observer on the ground.

Here is a reminder of what the symbols in Eq. 1.3 represent:

t_0 = time interval on clock at rest relative to an observer
t = time interval on clock in motion relative to the same observer
v = speed of relative motion
c = speed of light

Exactly the same analysis holds for measurements of the clock on the ground by the pilot of the spacecraft. To him, the light pulse of the ground clock follows a zigzag path which requires a total time t per round trip, while his own clock, at rest in the spacecraft, ticks at intervals of t_0. He too finds that

$$t = \frac{t_0}{\sqrt{1 - v^2/c^2}}$$

so the effect is reciprocal: *every* observer finds that clocks in motion relative to him tick more slowly than when they are at rest.

We have been assuming that v is less than c. If v were greater than c, the denominator of Eq. 1.3 would be an imaginary quantity, which suggests that our clock would not be operating properly under these circumstances. Indeed, if $v > c$ the clock would not operate at all: a light pulse leaving one mirror would never reach the other one. But in fact this situation cannot arise because, as we shall see later, no material object can move faster than light, or even as fast.

Our discussion has been based on a somewhat unusual clock that employs a light pulse bouncing back and forth between two mirrors. Do the same conclusions apply to more conventional clocks that use machinery—spring-controlled escapements, tuning forks, vibrating quartz crystals, or whatever—to produce ticks at constant time intervals? The answer must be yes, since if a mirror clock and a conventional clock in the spacecraft agree with each other on the ground but not when in flight, the disagreement between them could be used to determine the speed of the spacecraft without reference to any other object—which contradicts the principle that all motion is relative.

Problem What is the speed of a spacecraft whose clock runs 1 s slow per hour relative to a clock on the earth?

Solution Here $t_0 = 3{,}600$ s is the proper time interval on the earth and $t = 3{,}601$ s is the time interval in the moving frame. We proceed as follows:

$$t = \frac{t_0}{\sqrt{1 - v^2/c^2}}$$

$$\sqrt{1 - \frac{v^2}{c^2}} = \frac{t_0}{t}$$

$$\frac{v^2}{c^2} = 1 - \frac{t_0^2}{t^2}$$

$$v = c\sqrt{1 - \frac{t_0^2}{t^2}} = (3 \times 10^8 \text{ m/s}) \times \sqrt{1 - \left(\frac{3{,}600 \text{ s}}{3{,}601 \text{ s}}\right)^2}$$

$$= 7.1 \times 10^6 \text{ m/s}$$

Today's spacecraft are much slower than this. For instance, the highest speed of the Apollo 11 spacecraft that went to the moon was only 10,840 m/s, and its clocks differed from those on the earth by less than one part in 10^9. Most of the experiments that have confirmed time dilation made use of unstable nuclei and elementary particles which readily attain speeds not far from that of light.

Although time is a relative quantity, not all the notions of time formed by everyday experience are incorrect. Time does not run backward to *any* observer, for instance: a sequence of events that occur somewhere at $t_1, t_2, t_3, \ldots$ will appear in the same order to all observers everywhere, though not necessarily with the same time intervals $t_2 - t_1, t_3 - t_2, \ldots$ between each pair of events. Similarly, no distant observer, regardless of his state of motion, can see an event before it happens—more precisely, before a nearby observer sees it—since the speed of light is finite and signals require the minimum period of time L/c to travel a distance L. There is no way to peer into the future, although temporal (and, as we shall see, spatial) perspectives of past events may appear different to different observers.

1.3 DOPPLER EFFECT

We are all familiar with the increase in pitch of a sound when its source approaches us (or we approach the source) and the decrease in pitch when the source recedes from us (or we recede from the source). These changes in frequency constitute the *doppler effect,* whose origin is straightforward. For instance, successive waves emitted by a source moving toward an observer are closer together than normal because of the advance of the source, and since their separation is the wavelength of the sound, the corresponding frequency is higher. The relationship between the source frequency ν_0 and the observed frequency ν is

$$\nu = \nu_0 \left(\frac{1 + v/c}{1 - V/c}\right) \tag{1.4}$$

Doppler effect in sound

where c is here the speed of sound, v is the speed of the observer (+ if he moves toward the source, − if he moves away from it), and V is the speed of the source (+ if it moves toward the observer, − if it moves away from him). If the observer is stationary, $v = 0$, and if the source is stationary, $V = 0$.

The doppler effect in sound evidently varies depending on whether the source, or the observer, or both are moving, which appears to violate the principle of relativity: all that should count is the relative motion of source and observer. But sound waves occur only in a material medium such as air or water, and this medium is itself a frame of reference with respect to which motions of source and observer are measurable. Hence there is no contradiction. In the case of light, however, no medium is involved and only relative motion of source and observer is meaningful. The doppler effect in light must therefore differ from that in sound.

We can analyze the doppler effect in light by considering a light source as a clock that ticks ν_0 times per second and emits a wave of light with each tick. We will examine the three situations shown in Fig. 1-4.

FIGURE 1-4 The frequency of the light seen by an observer depends upon the direction and velocity of his motion relative to its source.