University Fundamental Physics (Vol 1)

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A BRIEF INTRODUCTION TO THE CONTENT

The content of thi^s volume includes two parts: mechanics and theory of heat. In the part of mechanics, the fundamental concepts and principles, as Newton's laws of motion, Momentum and angular momentum, work and energy, rotation and relativity. In the part of theory of heat, temperature, the kinetic theory of gases, the two laws of thermodynamics are introduced.

This Volume 1 together with Volume 2 cover all the pedagogic requirements of physics course in colleges and universities and hence can be used as textbooks of physics there. They can also be used as pedagogic references by high school teachers or as self-learning materials by other readers.

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FOREWORD

This English edition of the University Fundamental physics is written for Bilingual pedagogy of physics. The physics contents include mechanics, heat, electromagnetism, optics and fundamental quantum physics. All these contents satisfy the kernel fundamental requirements declared by the physics pedagogic directing committee of Ministry of Education. So this book can be used as a reference book for the physics course given to non-physics specialized students in science and engineering universities. The writer thinks that there are surely many detects and errors in this book both in language and explanations of physical principles. He waits and welcomes your comments and corrections.

Zhang Sanhui
In Tsinghua Yuan
May 2009

CONTENTS

PART 1 MECHANICS

PART 1 MECHANICS

Mechanics is a branch of ancient knowledge which in the West might be traced to 4th century B. C. when the ancient Greek scholar Plato considered that the circular motion of the heavenly bodies was the most perfect motion and Aristotle taught that force motivated motion. In China it may be traced to the explanation of the principle of level in "Mo Jing" written in 5th century B. C.. However, it ought to be said that only from the description of inertial motion given by Galileo in 17th century mechanics (and the whole physics) began to be a scientific theory. Then Newton advanced his three laws of motion. Now the theory of mechanics based on Newton's laws is called Newtonian mechanics or classical mechanics. It had been considered honorably as a perfect and general theory and dominated for about 300 years. Although at the beginning of 20th century its limitation was found, and then in high-speed realm it was replaced by the theory of relativity and in microscopic realm it was replaced by quantum mechanics, in common technical realm, including machine manufacture, civil construction, and even aviation and spaceflight techniques, the classical mechanics still works as the fundamental theory and keeps its full power. Such practicality is one reason for us to study classical mechanics.

Since classical mechanics is a physical theory formed first in history, many theories later, including the theories of relativity and quantum mechanics, are affected by it. Many of the ideas and thoughts in the theory of relativity and quantum mechanics are the developments and reformations of that in classical mechanics. In a certain sense, the classical mechanics is the foundation of the whole physics. This is another reason for us to study classical mechanics.

In this Part, we study mainly the fundamentals of particle mechanics and rigid body mechanics. We shall emphatically explain the concepts of momentum, angular momentum, energy and the corresponding conservation laws. The relativistic spacetime view has been the fundamental idea of modern physics and is closely related to Newtonian mechanics. It can be included in the realm of classical mechanics. In Chapter 6 we introduce the fundamental concepts and principles of the theory of special relativity.

The quantum mechanics is a completely new theory which can not be included in classical mechanics and hence not introduced in this Part. Even as this, we shall, at appropriate places, insert some concepts of quantum mechanics to compare them with the corresponding classical ones.

Classical mechanics has long been considered as deterministic. However, in the sixties of 20 century, due to the application of computers, it was found that although most of the subjects of classical mechanics are deterministic, but they are also unpredictable. To help the readers to realize this new development of calssical mechanics, some fundamental knowledge about it is introduced in Section 2. 6 under the title “Chaos”.

KINEMATICS OF A PARTICLE

Classical mechanics, or Newtonian mechanics, studies the mechanical motions of bodies. To study, first describe. The part in mechanics to describe motion is called *kinematics*. As the structure of moving bodies may be very complicated and their shape and size may be quite different from each other, we shall begin with the most simple and basic case, the motion of a particle. A **particle** is an ideal model of real bodies which is a point with certain mass. In this chapter we consider every body involved as a particle and discuss its kinematics. Most concepts here you have met in the high-school physics course. We shall repeat them in a more rigorous and systematic way. The concept of reference systems is emphasized. Vectors are used generally. Velocity and acceleration are defined with derivatives in calculus. The two components, tangential and normal, of circular motion are introduced. At last, the transformation of velocities between different reference systems, the Galilean velocity transformation is given.

1.1 Reference System

The mechanical motion of a body refers to the change of its position with time. The position of a body has meaning only when it is specified with respect to some other body. The other body is called the *reference body*. For example, to describe the motion of a car, some body fixed on the ground, such as a house or a road sign, is used as the reference body. Relative to different reference bodies, the motion of a body appears in different manners. This fact is called the *relativity of motion*. Just due to this relativity, to describe the motion of a body, the reference body must be specified first.

With the reference body given, to specify the spatial position of a particle *quantitatively*, it is needed to establish a *coordinate system* fixed on the reference body. The coordinate system often used is the *cartesian coordinate system*, or the *rectangular coordinate system*. This system takes some point fixed on the reference body as the **origin** O. Three mutually perpendicular straight lines drawn from O, with appropriate scale, are taken as **axes**, labeled with x, y, and z respectively, as shown in Fig. 1.1. In this coordinate system, the position of a particle at any instant, as P in Fig. 1.1, can be specified numerically with three coordinate values (x, y, z).

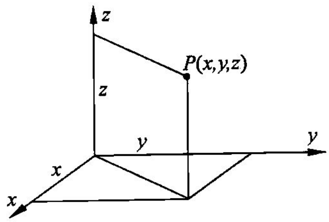

Fig. 1.1 Cartesian coordinate system

To describe the motion of a particle completely, it is necessary to point out the time instant t of the arrival of the particle at each point along its path. This time instant t is indicated by a set of *synchronized* clocks (all give the same reading at any instant) installed everywhere. When a particle arrives at any point on its path, the clock by its side there indicates the instant t of its arrival (Fig. 1.2). The motion of the particle is thus described completely.

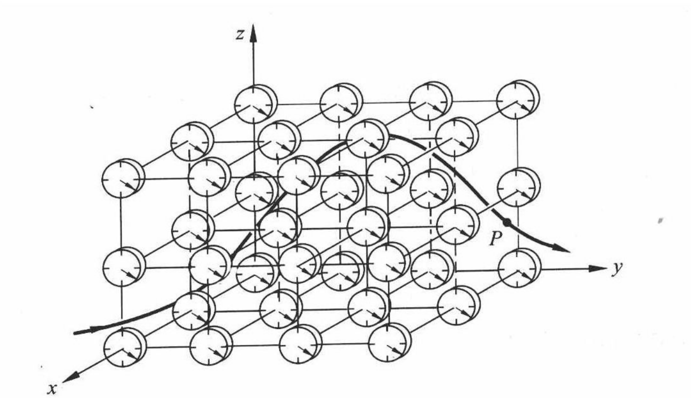

Fig. 1.2 A frame of reference

A coordinate system together with a set of synchronized clocks constitutes a system or a **frame of reference**. A system of reference is always named by the reference body. For example, a reference system fixed on the ground (usually with an axis upwards) is called the *ground* system of reference (coordinate $O''x''y''z''$ in Fig. 1.3). The reference system with its origin fixed at the center of the Earth and axes pointing to definite stars is called *geocentric* system of reference (coordinate $O'x'y'z'$ in Fig. 1.3). The reference system with its origin fixed at the center of the Sun and axes pointing to definite stars is called *heliocentric* system of reference (coordinate $Oxyz$ in Fig. 1.3).

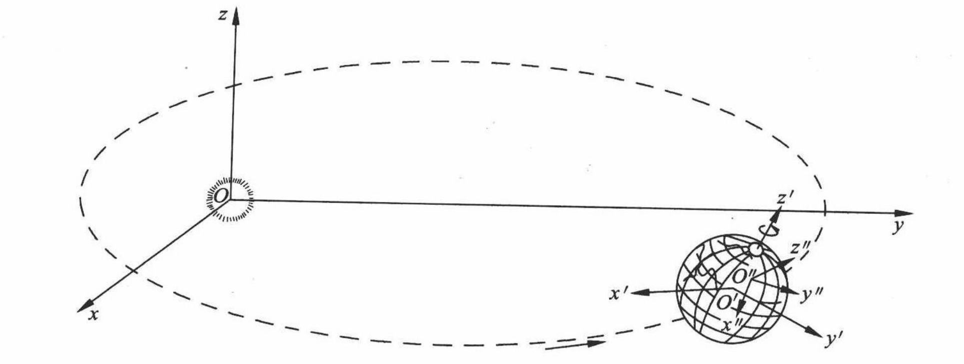

Fig. 1.3 Three practical frames of reference

The coordinate values defining the position of a particle are given by the distances from the origin along the axes. The basic SI units of length is *meter* (m) which is defined as 1m is the distance traveled by light in vacuum in (1/299 792 458) s. This definition is based on the precise technique of laser and the theory of relativity.

The time instant specifying the arriving of a particle at some point is expressed with the basic SI unit *second* (s), which is now defined as 9 192 631 770 times the period of the light with a characteristic frequency emitted by isotope ^{133}Cs.

In practice, for convenience, appropriate multiples or fractions of the basic units, such as kilometer (km, 1km=1000m), nanosecond (ns, 1ns $= 10^{-9}$s) are often used. The prefixes used for this purpose are listed in Table 1.1.

Table 1.1 Prefixes used in SI

Factor	Prefix	Symbol
10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M

Continued

Factor	Prefix	Symbol
10^3	kilo	k
10^2	hecto	h
10^1	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

1.2 Position Vector, Displacement, and Velocity

After a reference frame chosen, the motion of a particle, i. e., the change of its position with time can be expressed by a mathematical function. The functions of time for the three coordinates are expressed generally as

$$x = x(t), \quad y = y(t), \quad z = z(t). \tag{1.1}$$

These functions are called the **functions of motion** of the particle.

The position of the particle can be expressed more simply and clearly with a vector. To do this, draw a directional segment OP from the origin O to the position of the particle at instant t and denote it by $\boldsymbol{r}$ (Fig. 1. 4). The direction of $\boldsymbol{r}$ indicates the orientation of P relative to the axes and the length of $\boldsymbol{r}$ gives the distance from O to P. As the orientation and the distance relative to the origin are given, the position of the particle is specified completely. Vector $\boldsymbol{r}$ is then called the **position vector** or the radius vector of the particle at instant t. As the particle moves, its position vector changes with time. This change with time can be expressed generally as

$$\boldsymbol{r} = \boldsymbol{r}(t) \tag{1.2}$$

This is the vector form of the function of motion of the particle.

Geometrically, the position vector can be expressed by three *components* along the

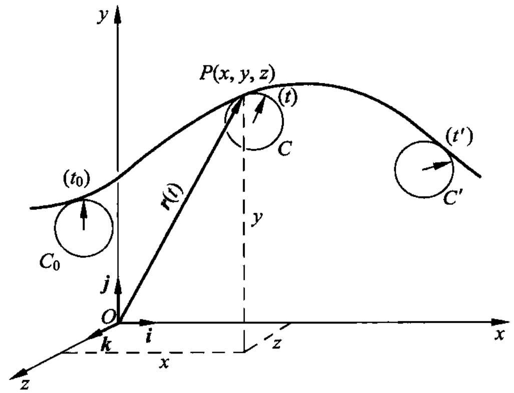

Fig. 1.4 Position vector

three axes x,y,z. Let $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$ be the unit vectors (with magnitude 1) along the positive direction of x,y,z axis respectively. Then the position vector can be expressed as

$$\boldsymbol{r} = x\boldsymbol{i} + y\boldsymbol{j} + z\boldsymbol{k} \tag{1.3}$$

Here $x\boldsymbol{i}$ is the *vector component* of $\boldsymbol{r}$ along the x axis, which is parallel or antiparallel to the positive x direction according to x being positive or negative. Likewise, $y\boldsymbol{j}$ and $z\boldsymbol{k}$ are the vector components along the y and z axis respectively. x, y, z are called *scalar components* of $\boldsymbol{r}$.

Combined with Eqs. (1.1) and (1.2), Eq. (1.3)can be written as

$$\boldsymbol{r}(t) = x(t)\boldsymbol{i} + y(t)\boldsymbol{j} + z(t)\boldsymbol{k} \tag{1.4}$$

this equation means that the motion of a particle in space is the resultant of three component motions, $x(t)\boldsymbol{i}$, $y(t)\boldsymbol{j}$, and $z(t)\boldsymbol{k}$, along the three axes.

The line along which a particle travels is called its **orbit**. The length of the orbit traveled by the particle in a certain time interval is called the **distance**, denoted by the letter s. The change in position of the particle in that interval is called the **displacement**. Assume that the particle passes points P and P_1 at instants t and $t+\Delta t$, with position vectors $\boldsymbol{r}(t)$ and $\boldsymbol{r}(t+\Delta t)$, respectively. Then the vector from P to P_1, which is the increment of the position vector, is

$$\Delta\boldsymbol{r}=\boldsymbol{r}(t+\Delta t)-\boldsymbol{r}(t)$$

This is the displacement of the particle in the time interval $\Delta t=(t+\Delta t)-t$(Fig. 1.5).

It should be noted that, the displacement $\Delta\boldsymbol{r}$ is a vector, having both magnitude and direction. Its magnitude is denoted by $|\Delta\boldsymbol{r}|$ which is not the same as Δr. $\Delta r=r(t+\Delta t)-r(t)$ is the increment of the magnitude of the position vector. In general, $|\Delta\boldsymbol{r}|\neq\Delta r$.

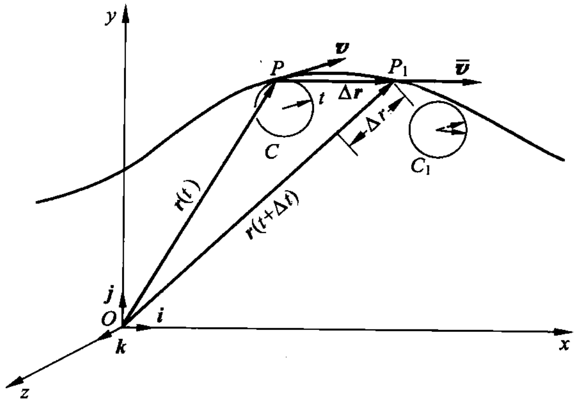

Fig. 1.5 Displacement and velocity

The average velocity $\bar{\boldsymbol{v}}$ in the time interval $\Delta t=(t+\Delta t)-t$ is defined as

$$\bar{\boldsymbol{v}}=\frac{\Delta \boldsymbol{r}}{\Delta t} \tag{1.5}$$

which is also a vector with the same direction as $\Delta \boldsymbol{r}$.

As $\Delta t \to 0$, $\bar{\boldsymbol{v}}$ in Eq. (1.5) tends to a limit which is the time rate of the change of the position vector at instant t. This limit is defined as the **instantaneous velocity**, or simply **velocity**, of the particle at instant t. Expressing velocity with $\boldsymbol{v}$, we have

$$\boldsymbol{v}=\lim_{\Delta t \to 0}\frac{\Delta \boldsymbol{r}}{\Delta t}=\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} \tag{1.6}$$

The direction of $\boldsymbol{v}$ is the direction of $\Delta \boldsymbol{r}$ as $\Delta t \to 0$. As shown in Fig. 1.5, this direction is tangent to the orbit at the position of the particle at instant t and pointing forwards.

The magnitude of the velocity is called the **speed**. Denoted by v, the speed is

$$v=|\boldsymbol{v}|=\left|\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t}\right|=\lim_{\Delta t \to 0}\left|\frac{\Delta \boldsymbol{r}}{\Delta t}\right| \tag{1.7}$$

Since as $t \to 0$, $|\Delta \boldsymbol{r}| \to |\Delta s|$, we have also

$$v=\lim_{\Delta t \to 0}\left|\frac{\Delta \boldsymbol{r}}{\Delta t}\right|=\lim_{\Delta t \to 0}\left|\frac{\Delta s}{\Delta t}\right|=\frac{|\mathrm{d}s|}{\mathrm{d}t} \tag{1.8}$$

This means that the speed is the time rate of the change of the distance.

Substituting Eq. (1.4) into Eq. (1.6), since the unit vectors do not change with time, we have

$$\boldsymbol{v}=\frac{\mathrm{d}x}{\mathrm{d}t}\boldsymbol{i}+\frac{\mathrm{d}y}{\mathrm{d}t}\boldsymbol{j}+\frac{\mathrm{d}z}{\mathrm{d}t}\boldsymbol{k}=v_x\boldsymbol{i}+v_y\boldsymbol{j}+v_z\boldsymbol{k} \tag{1.9}$$

The three vectors on the right side of Eq. (1.9) are the **component velocities** along