



PRINCIPLES OF PHYSICS SERIES

MECHANICS, HEAT, AND SOUND

by

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PREFACE

This book is the first volume of a series of texts written for a two-year course in general physics. It is assumed that students using the book have completed a course in calculus or that they are studying calculus concurrently.

The title of the series, *Principles of Physics*, has been chosen deliberately to indicate that its emphasis is on physical principles. Historical background and practical applications have been given a place of secondary importance.

This volume opens with several chapters on statics in order that kinematics may be postponed until the student has acquired some familiarity with the concepts and notation of calculus. Beginning with Chapter 4, simple differentiation and integration are introduced to supplement and extend the algebraic development of the equations of linear motion with constant acceleration. From that point on, the calculus is used freely wherever its inclusion is warranted.

Three systems of units are used: the English gravitational because it is the one used in engineering work throughout this country, the cgs system because some familiarity with it is essential for any intelligent reading of the literature of physics, and the mks system because of its increasing use in electricity and magnetism as well as because it seems destined eventually to supplant the cgs system.

The author is particularly indebted to Professor M. Stanley Livingston for many stimulating and informative discussions and for his encouragement in the task of developing a set of lecture notes into this book.

The multiframe photographs were taken with the advice and assistance of Professor Harold E. Edgerton, to whom the author is duly grateful. Collective acknowledgment is made to numerous contributors to the *American Journal of Physics* (formerly the *American Physics Teacher*) since its inception.

F.W.S.

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March 1944.

PRINCIPLES OF PHYSICS I
MECHANICS, HEAT, and SOUND

PRINCIPLES OF PHYSICS II
ELECTRICITY and MAGNETISM

PRINCIPLES OF PHYSICS III
OPTICS

MECHANICS

CONTENTS

MECHANICS

CHAPTER 1. COMPOSITION AND RESOLUTION OF VECTORS	1
1-1 Force	1
1-2 Units and standards	1
1-3 The pound	2
1-4 Graphical representation of forces. Vectors	3
1-5 Components of a vector	4
1-6 Composition of forces	7
1-7 Composition of forces by rectangular resolution	10
1-8 Resultant of a set of nonconcurrent forces	11
1-9 Vector difference	12
CHAPTER 2. STATICS	14
2-1 Introduction	14
2-2 Newton's first law	14
2-3 Newton's third law	16
2-4 Simple structures	17
2-5 Other examples of equilibrium	19
2-6 Friction	22
2-7 Coefficient of friction	23
CHAPTER 3. MOMENTS—CENTER OF GRAVITY	30
3-1 Introduction. Units of standards of length	30
3-2 Moment of force. Torque	31
3-3 Rotational equilibrium.	33
3-4 Stable and unstable equilibrium	34
3-5 The resultant of a set of parallel forces	35
3-6 Center of gravity	37
3-7 Couples	45
CHAPTER 4. LINEAR MOTION	52
4-1 Motion	52
4-2 Average velocity and average speed	52
4-3 Instantaneous velocity	54
4-4 Average acceleration	56
4-5 Instantaneous acceleration	57
4-6 Linear motion with constant acceleration	58
4-7 Uniform motion	61
4-8 Freely falling bodies	61
4-9 Motion with variable acceleration	65
4-10 Graphical representation	66
4-11 Velocity components. Relative velocity.	68
CHAPTER 5. NEWTON'S SECOND LAW	74
5-1 Introduction	74
5-2 Mass	74

5-3	Newton's second law	76
5-4	Systems of units	79
5-5	Weight and mass	80
5-6	D'Alembert's principle	87
5-7	Density	88
5-8	The equal-arm analytical balance	89
✓ CHAPTER 6.	MOTION OF A PROJECTILE	97
6-1	Projectiles	97
6-2	Motion of a body projected horizontally	98
6-3	Body projected at an angle	100
CHAPTER 7.	CENTER OF MASS	107
7-1	Center of mass	107
7-2	Coordinates of the center of mass	108
7-3	Acceleration of the center of mass	112
7-4	Pure translational acceleration	117
CHAPTER 8.	WORK AND ENERGY	124
8-1	Conservation of energy	124
8-2	Work	126
8-3	Energy and work	128
8-4	Units of energy. Dimensions	131
8-5	Absolute values of potential and kinetic energy	132
8-6	Potential energy of a stretched spring	133
8-7	Work against friction	135
8-8	Conservative and dissipative forces	136
8-9	The principle of virtual work	141
8-10	Power	141
8-11	Power and velocity	143
CHAPTER 9.	IMPULSE AND MOMENTUM	149
9-1	Impulse and momentum	149
9-2	Conservation of momentum	151
9-3	Newton's third law	153
9-4	Elastic and inelastic collisions. Coefficient of restitution	154
9-5	The ballistic pendulum	156
9-6	Newton's second law	158
9-7	Mass and energy	159
9-8	The principles of jet propulsion	162
✓ CHAPTER 10.	CIRCULAR MOTION	168
10-1	Introduction	168
10-2	Angular velocity	169
10-3	Angular acceleration	171
10-4	Constant angular acceleration	172
10-5	Angular velocity and acceleration as vectors	174
10-6	Tangential velocity.	175
10-7	Acceleration of a point in circular motion	177
10-8	Centripetal and centrifugal forces	185

10-9	The banking of curves	186
10-10	The conical pendulum	188
10-11	Motion in a vertical circle	190
10-12	Effect of the earth's rotation on weight	193
10-13	The centrifuge	195
10-14	Work and power in circular motion	195
CHAPTER 11.	MOMENT OF INERTIA	202
11-1	Moment of inertia	202
11-2	Moment of inertia. General case.	205
11-3	Radius of gyration	209
11-4	The parallel-axis theorem	210
11-5	Forces at the axis	211
✓ CHAPTER 12.	ROTATION AND TRANSLATION	218
12-1	The general equations of motion	218
12-2	Rolling	222
12-3	Instantaneous axis	225
12-4	Angular momentum and angular impulse	228
12-5	Vector representation of angular quantities	231
12-6	Precession	232
12-7	The gyroscope	235
CHAPTER 13.	ELASTICITY	244
13-1	Introduction	244
13-2	Stress	244
13-3	Strain	247
13-4	Elastic modulus.	248
13-5	Poisson's ratio	252
13-6	Relations between elastic constants	254
13-7	Torsion	255
13-8	Bending of a beam	257
13-9	The force constant	258
✓ CHAPTER 14.	HARMONIC MOTION	263
14-1	Introduction	263
14-2	Elastic restoring forces.	263
14-3	Definitions	264
14-4	Equations of simple harmonic motion	265
14-5	Energy relations in harmonic motion	273
14-6	The simple pendulum	274
14-7	Lissajous' figures	276
14-8	Damped harmonic motion.	277
14-9	Forced harmonic motion. Resonance	280
14-10	Angular harmonic motion	281
14-11	The physical pendulum	282

14-12	Center of oscillation	283
14-13	Center of percussion	285
CHAPTER 15. GRAVITATION		291
15-1	Newton's law of universal gravitation	291
15-2	The mass of the earth	292
15-3	Variations in " g "	293
15-4	The gravitational field	295
15-5	Gravitational potential energy	301
15-6	Gravitational potential	303
15-7	Planetary motion	306
CHAPTER 16. Hydrostatics and Surface Tension		310
16-1	Introduction	310
16-2	Pressure in a fluid	310
16-3	Pressure gauges	313
16-4	Archimedes' principle	315
16-5	Stability of a ship	317
16-6	The hydrostatic paradox	317
16-7	Forces against a dam	318
16-8	The physics of surfaces	319
16-9	Coefficient of surface tension	322
16-10	Angle of contact	325
16-11	Capillary rise in tubes	326
16-12	Alternate treatment of surface tension	328
16-13	Excess pressure in bubbles	329
16-14	Formation of drops	330
16-15	Surface tension and surface energy	332
CHAPTER 17. HYDRODYNAMICS AND VISCOSITY		337
17-1	Streamline flow	337
17-2	Bernoulli's equation	338
17-3	Discharge rate of a pipe	340
17-4	Applications of Bernoulli's equation	340
17-5	Viscosity	345
17-6	Stokes' law	349
17-7	Flow of viscous fluids through tubes	351
17-8	Derivation of Poiseuille's law	352

HEAT

CHAPTER 18. TEMPERATURE—EXPANSION		361
18-1	Temperature	361
18-2	Thermometers	361
18-3	Temperature scales	362
18-4	Other methods of thermometry	364
18-5	Linear expansion	367
18-6	Surface and volume expansion	370
18-7	Thermal stresses	372

CHAPTER 19. QUANTITY OF HEAT	376
19-1 Heat, a form of energy	376
19-2 Quantity of heat	377
19-3 The mechanical equivalent of heat	378
19-4 Heat capacity. Specific heat	379
19-5 Calorimetry	381
19-6 Heat of combustion	383
19-7 Internal energy	384
CHAPTER 20. TRANSFER OF HEAT	388
20-1 Conduction	388
20-2 Heat flow through a compound wall	390
20-3 Heat flow through a cylindrical pipe cover	392
20-4 Convection	392
20-5 Radiation	393
20-6 Stefan's law	395
20-7 The ideal radiator	396
CHAPTER 21. CHANGE OF PHASE	400
21-1 Change of phase	400
21-2 Work done in a volume change	403
21-3 Effect of dissolved substances on freezing and boiling points	406
21-4 Measurement of heats of fusion and vaporization	407
CHAPTER 22. PROPERTIES OF GASES—THE IDEAL GAS	410
22-1 Boyle's law	410
22-2 Gay-Lussac's law	412
22-3 The equation of state of an ideal gas	413
22-4 Internal energy of a gas	417
22-5 Specific heats of a gas	419
22-6 Internal energy and heat	423
22-7 Adiabatic processes	424
22-8 Compressibilities of a gas	427
CHAPTER 23. REAL GASES	432
23-1 Liquefaction of gases	432
23-2 Effect of pressure on boiling and freezing points	435
23-3 The Clausius-Clapeyron equation	438
23-4 Humidity	441
23-5 The Wilson cloud chamber	443
23-6 Thermodynamic surfaces	444
23-7 The Van der Waals equation of state	445
CHAPTER 24. THE SECOND LAW OF THERMODYNAMICS	448
24-1 The second law of thermodynamics	448
24-2 The internal-combustion engine	451
24-3 The Diesel engine	452
24-4 The steam engine	453

24-5	The Carnot engine	454
24-6	The refrigerator	456
24-7	Entropy	459
24-8	The principle of the increase of entropy	461
24-9	The Kelvin absolute-temperature scale	464
CHAPTER 25. KINETIC THEORY OF GASES		468
25-1	Derivation of ideal gas law	468
25-2	Specific heats	472
25-3	Brownian motion	475
25-4	Mean free path	476
25-5	Viscosity of a gas	477
25-6	The Maxwell-Boltzmann distribution of molecular speeds	479
SOUND		
CHAPTER 26. WAVE MOTION		485
26-1	Introduction	485
26-2	Transverse waves in a string	485
26-3	Fourier series	491
26-4	The wave equation	492
26-5	Sound waves in a gas	494
26-6	Pressure variations in a sound wave	499
CHAPTER 27. VIBRATION OF STRINGS AND AIR COLUMNS		504
27-1	Boundary conditions	504
27-2	Standing waves	506
27-3	String fixed at both ends	509
27-4	Vibration of membranes and plates	511
27-5	Standing waves in an air column	512
27-6	Beats	514
27-7	Combination tones	516
CHAPTER 28. SOUND WAVES. THE EAR AND HEARING.		521
28-1	Intensity.	521
28-2	Intensity level. The decibel	524
28-3	The ear and hearing	526
28-4	The Doppler effect	532
28-5	Reflection of sound waves	534
28-6	Acoustics of rooms. Reverberation time	536
28-7	Refraction of sound	539
28-8	Interference of sound waves	539
28-9	Diffraction of sound	540
COMMON LOGARITHMS		544
NATURAL TRIGONOMETRIC FUNCTIONS		546
ANSWERS TO ODD-NUMBERED PROBLEMS		547
INDEX		558

CHAPTER 1

COMPOSITION AND RESOLUTION OF VECTORS

1-1 Force. Mechanics is the branch of physics and engineering which deals with the interrelations of force, matter, and motion. We shall begin with a study of forces. The term force, as used in mechanics, refers to what is known in everyday language as a *push* or a *pull*. We can exert a force on a body by muscular effort; a stretched spring exerts forces on the bodies to which its ends are attached; compressed air exerts a force on the walls of its container; a locomotive exerts a force on the train which it is drawing. In all of these instances the body exerting the force is in contact with the body on which the force is exerted, and forces of this sort are known as *contact* forces. There are also forces which act through empty space without contact, and are called *action-at-a-distance* forces. The force of gravitational attraction exerted on a body by the earth, and known as the *weight* of the body, is the most important of these for our present study. Electrical and magnetic forces are also action-at-a-distance forces, but we shall not be concerned with them for the present.

All forces fall into one or the other of these two classes, a fact that will be found useful later when deciding just what forces are acting on a given body. It is only necessary to observe what bodies are in contact with the one under consideration. The only forces on the body are then those exerted by the bodies in contact with it, together with the gravitational force or the weight of the body.

Those forces acting on a given body which are exerted by other bodies are referred to as *external* forces. Forces exerted on one part of a body by other parts of the same body are called *internal* forces.

1-2 Units and standards. The early Greek philosophers confined their activities largely to speculations about Nature, and to attempts to reconcile the observed behavior of bodies with theological doctrines. What has been called the *scientific method* began to appear in the time of Galileo Galilei (1564-1642). Galileo's studies of the laws of freely falling bodies were made not in an attempt to explain *why* bodies fell toward the earth, but rather to determine *how far* they fell in a given time, and *how fast* they moved. Physics as it exists today has been called the science of measurement, and the importance of quantitative knowledge and reasoning has

been expressed by Lord Kelvin (1824–1907) as follows: “I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *Science*, whatever the matter may be.”

The first step in the measurement of a physical quantity consists in choosing a *unit* of that quantity. As the result of international collaboration over a long period, practically all of the units used in physics are now the same throughout the world. The second step is an experiment that determines the ratio of the magnitude of the quantity to the magnitude of the unit. Thus, when we say that the length of a rod is 10 centimeters, we state that its length is ten times as great as the unit of length, the centimeter.

It is possible to simplify many of the equations of physics by the proper choice of units of physical quantities. Any set of units which is chosen so that these simplified equations can be used is called a *system* of units. We shall use three such systems in this book. They are, first, the *English gravitational* system; second, the meter-kilogram-second or *mks* system; and third, the centimeter-gram-second or *cgs* system. The units of these systems will be defined as the need for them arises.

Most of the fundamental units of physics are embodied in a physical object called a *standard*. One of the functions of the National Bureau of Standards in Washington, D. C. is to maintain in its vaults standards of various quantities with which commercial and technical measuring instruments can be compared for accuracy.

1–3 The pound. The unit of force which we shall use for the present is the English gravitational unit, the *pound*. Other units will be discussed in Chapter 5. This unit is embodied in a cylinder of platinum-iridium called the *standard pound*. The unit of force is defined as the weight of the standard pound. That is, it is a force equal to the force of gravitational attraction which the earth exerts on the standard pound. Since the earth's gravitational attraction for a given body varies slightly from one point to another on the earth's surface it is further stipulated that the unit force shall equal the weight of the standard pound *at sea level and 45° latitude*.*

In order that an unknown force can be compared with the force unit (and thereby measured) some measurable effect produced by a force must be used. One common effect of a force is to alter the dimensions or shape of a body on which the force is exerted; another is to alter the state of motion of the body. Both of these effects are used in the measurement of

*See Section 15–3 for a more precise definition.

forces. In this chapter we shall consider only the former; the latter will be discussed in Chapter 5.

The instrument used to measure forces is the spring balance, which consists of a coil spring enclosed in a case for protection and carrying at one end a pointer that moves over a scale. A force exerted on the balance increases the length of the spring. The balance can be calibrated as follows. The standard pound is first suspended from the balance and the position of the pointer marked 1 lb. Any number of duplicates of the standard can then be prepared by suspending each of them in turn from the balance and removing or adding material until the index stands at 1 lb. Then, when two, three, or more of these are suspended simultaneously from the balance, the force stretching it is 2 lb, 3 lb, etc., and the corresponding positions of the pointer can be labeled 2 lb, 3 lb, etc. This procedure makes no assumptions about the elastic properties of the spring, except that the force exerted on it is always the same when its index stands at the same point. The calibrated balance can then be used to measure any unknown force.

1-4 Graphical representation of forces. Vectors. Suppose we are to slide a box along the floor by pulling it with a string or pushing it with a stick, as in Fig. 1-1. That is, we are to slide it by exerting a force on it.

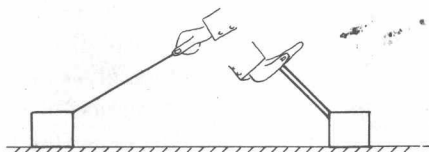


FIG. 1-1. The box is pulled by the string or pushed by the stick.

The point of view which we now adopt is that the motion of the box is caused not by the *objects* which push or pull on it, but by the *forces* which these exert. For concreteness assume the magnitude of the push or pull to be 10 lb. It is clear that simply to write "10 lb" on the diagram would not completely describe the force, since it would not indicate

the direction in which the force was acting. One might write "10 lb, 30° above horizontal to the right," or "10 lb, 45° below horizontal to the right," but all of the above information may be conveyed more briefly if we adopt the convention of representing a force by an arrow. The length of the arrow, to some chosen scale, indicates the size or magnitude of the force, and the direction in which the arrow points indicates the direction of the force. Thus Fig. 1-2 (in which a scale of $\frac{1}{8}$ in = 1 lb has been chosen) is the force diagram corresponding to Fig. 1-1. (There are other forces acting on the box, but these are not shown in the figure.)

Force is not the only physical quantity which requires the specification of direction as well as magnitude. For example, the velocity of a plane is not completely specified by stating that it is 300 miles per hour; we need

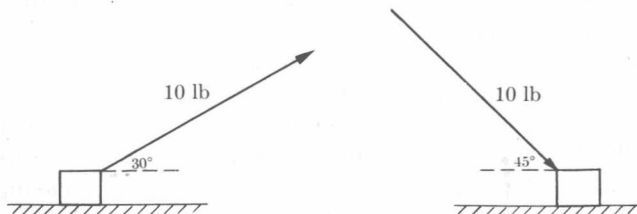


FIG. 1-2. The force diagram corresponding to Fig. 1-1.

to know the direction also. The concept of density, on the other hand, has no direction associated with it.

Quantities like force and velocity, which involve both magnitude and direction, are called *vector* quantities. Those like density, which involve magnitude only, are called *scalars*. Any vector quantity can be represented by an arrow, and this arrow is called a vector (or if a more specific statement is needed, a force vector or a velocity vector). We shall first consider force vectors only, but the ideas developed in dealing with them can be applied to any other vector quantity.

1-5 Components of a vector. When a box is pulled or pushed along the floor by an inclined force as in Fig. 1-1, it is clear that the effectiveness of the force in moving the box along the floor depends upon the direction in which the force acts. Everyone knows by experience that a given force is more effective for moving the box the more nearly the direction of the force approaches the horizontal. It is also clear that if the force is applied at an angle, as in Fig. 1-1, it is producing another effect in addition to moving the box ahead. That is, the pull of the string is in part tending to lift the box off the floor, and the push of the stick is in part forcing the box down against the floor. We are thus led to the idea of the *components* of a force, that is, the effective values of a force in directions other than that of the force itself.

The component of a force in any direction can be found by a simple graphical method. Suppose we wish to know how much force is available for sliding the box in Fig. 1-1 if the applied force is a pull of 10 lb directed 30° above the horizontal. Let the given force be represented by the vector OA in Fig. 1-3, in the proper direction and to some convenient scale. Line OX is the direction of the desired component. From point A drop a perpendicular to OX , intersecting it at B . The vector OB , to the same scale as that used for the given vector, represents the component of OA in the direction OX . Measurements of the diagram show that if OA represents a force of 10 lb, then OB is about 8.7 lb. That is, the 10-lb

force at an angle of 30° above the horizontal has an effective value of only about 8.7 lb in producing forward motion.

The component OB may also be computed as follows. Since OAB is a right triangle, it follows that

$$\cos 30^\circ = \frac{OB}{OA},$$

$$OB = OA \cos 30^\circ.$$

The lengths OB and OA , however, are proportional to the magnitudes of the forces they represent. Therefore the desired component OB , in pounds, equals the given force OA , in pounds, multiplied by the cosine of the angle between OA and OB . The magnitude of OB is therefore

$$\begin{aligned} OB \text{ (lb)} &= OA \text{ (lb)} \times \cos 30^\circ \\ &= 10 \text{ lb} \times 0.866 \\ &= 8.66 \text{ lb.} \end{aligned}$$

This result agrees as well as could be expected with that obtained from measurements of the diagram. The superiority of the trigonometric method is evident, however, since it does not depend for accuracy on the careful construction and measurement of a scale diagram.

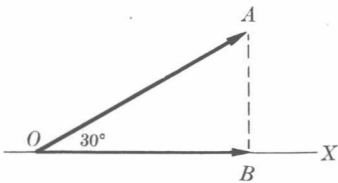


FIG. 1-3. Vector OB is the component of vector OA in the direction OX .

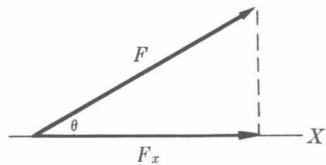


FIG. 1-4. $F_x = F \cos \theta$ is the X -component of F .

The line OX in Fig. 1-3 is called the X -axis, and the foregoing analysis may be generalized as follows. If a force F makes an angle θ with the X -axis (Fig. 1-4), its component F_x along the X -axis is

$$F_x = F \cos \theta. \quad (1-1)$$

It should be obvious that if the force F is at right angles to the X -axis, its component along that axis is zero (since $\cos 90^\circ = 0$), and if the force lies along the axis, its component is equal to the force itself (since $\cos 0^\circ = 1$).