

*Francis Weston Sears*

# Mechanics, Wave Motion and Heat



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# MECHANICS, WAVE MOTION, AND HEAT

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*by*

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## PREFACE

This book is designed as a text for the first year of a two-year course in General Physics, or for an intermediate course in Mechanics and Heat following a briefer introduction to these subjects. In order that the book can be used by a student who is concurrently taking his first course in Calculus, the use of that subject is postponed until Chapter 4.

The book follows the same general plan as the author's earlier text, *Mechanics, Heat, and Sound*. More extended treatment has been given to a number of topics, including angular momentum, elasticity, damped and forced harmonic motion, and wave motion. Vector quantities are consistently represented by bold-face type. The vector product is introduced in Chapter 3 in connection with the moment of a force, and the scalar product in Chapter 7 in connection with work.

Most of the problems are new. Answers are given immediately following odd-numbered problems.

The author wishes to express his gratitude to all those students and teachers whose criticisms and suggestions have helped to guide him in writing this book. He will appreciate having any errors called to his attention.

FRANCIS W. SEARS

April, 1958  
Hanover, N. H.

## FOREWORD TO THE THIRD PRINTING

It is hoped that as a result of the invitation extended in the last sentence of the *Preface*, most of the author's mistakes have been found and corrected. Thanks are due in particular to E. H. Clark, L. M. Clendenning, Ronald Flegel, John L. Gergen, David R. Goosman, Franklin A. Ruehl, Jr., and Edwin F. Taylor. And the invitation still holds.

F. W. S.

## CONTENTS

CHAPTER 1. COMPOSITION AND RESOLUTION OF VECTORS . . . . .	1
1-1 Units and standards . . . . .	1
1-2 Force . . . . .	3
1-3 Graphical representation of forces. Vectors . . . . .	5
1-4 Vector addition. Resultant of a set of forces . . . . .	6
1-5 Resultant of parallel and antiparallel forces . . . . .	10
1-6 Components of a vector . . . . .	11
1-7 Resultant by rectangular resolution . . . . .	13
1-8 Vector difference . . . . .	15
CHAPTER 2. EQUILIBRIUM . . . . .	19
2-1 Introduction . . . . .	19
2-2 Equilibrium. Newton's first law . . . . .	19
2-3 Discussion of Newton's first law of motion . . . . .	22
2-4 Stable, unstable, and neutral equilibrium . . . . .	24
2-5 Newton's third law of motion . . . . .	24
2-6 Examples of equilibrium . . . . .	26
2-7 Friction . . . . .	34
CHAPTER 3. MOMENT OF A FORCE. TORQUE. . . . .	45
3-1 Moment of a force . . . . .	45
3-2 Vector product. Vector moment . . . . .	48
3-3 The second condition of equilibrium . . . . .	50
3-4 Resultant of parallel forces . . . . .	55
3-5 Center of gravity . . . . .	57
3-6 Couples . . . . .	62
CHAPTER 4. RECTILINEAR MOTION . . . . .	69
4-1 Motion . . . . .	69
4-2 Average velocity . . . . .	69
4-3 Instantaneous velocity . . . . .	70
4-4 Average and instantaneous acceleration . . . . .	73
4-5 Velocity and coordinate by integration . . . . .	76
4-6 Rectilinear motion with constant acceleration . . . . .	78
4-7 Freely falling bodies . . . . .	82
4-8 Relative velocity and acceleration . . . . .	87

CHAPTER 5. NEWTON'S SECOND LAW . . . . .	96
5-1 Introduction . . . . .	96
5-2 Newton's second law of motion. Mass . . . . .	96
5-3 Force . . . . .	100
5-4 Systems of units . . . . .	102
5-5 Units and dimensions . . . . .	106
5-6 Mass and weight . . . . .	108
5-7 Methods of measuring mass . . . . .	109
5-8 Center of mass . . . . .	110
5-9 Applications of Newton's second law . . . . .	113
5-10 D'Alembert forces . . . . .	121
CHAPTER 6. MOTION IN A PLANE . . . . .	130
6-1 Motion in a plane . . . . .	130
6-2 Average and instantaneous velocity . . . . .	130
6-3 Average and instantaneous acceleration . . . . .	132
6-4 Components of acceleration . . . . .	133
6-5 Motion of a projectile . . . . .	136
6-6 Circular motion . . . . .	143
6-7 Centripetal force . . . . .	146
6-8 Motion in a vertical circle . . . . .	149
CHAPTER 7. WORK AND ENERGY . . . . .	157
7-1 Work-energy theorem for a particle . . . . .	157
7-2 Work . . . . .	159
7-3 Scalar product . . . . .	163
7-4 Kinetic energy . . . . .	164
7-5 Gravitational potential energy of a particle . . . . .	165
7-6 Elastic potential energy of a particle . . . . .	169
7-7 The principle of conservation of mechanical energy of a particle . . . . .	171
7-8 Work-energy theorem for a system of particles . . . . .	174
7-9 Kinetic energy of a system of particles . . . . .	178
7-10 Power . . . . .	181
7-11 Power and velocity . . . . .	183
CHAPTER 8. IMPULSE AND MOMENTUM . . . . .	187
8-1 Impulse . . . . .	187
8-2 Impulse and momentum . . . . .	188
8-3 Momentum of a system of particles . . . . .	189
8-4 Conservation of linear momentum . . . . .	191
8-5 Elastic and inelastic collisions . . . . .	193
8-6 Recoil . . . . .	200
8-7 Principles of rocket propulsion . . . . .	202
8-8 Newton's second law . . . . .	204
8-9 Mass and energy . . . . .	205

CHAPTER 9. ROTATION OF A RIGID BODY ABOUT A FIXED AXIS . . .	213
9-1 Introduction . . . . .	213
9-2 Angular velocity . . . . .	213
9-3 Angular acceleration . . . . .	215
9-4 Rotation with constant angular acceleration . . . . .	216
9-5 Relation between angular and linear velocity and acceleration . . . . .	217
9-6 Coriolis acceleration . . . . .	219
9-7 Torque and angular acceleration. Moment of inertia . . . . .	222
9-8 Calculation of moments of inertia . . . . .	225
9-9 Kinetic energy, work, and power . . . . .	231
CHAPTER 10. ANGULAR MOMENTUM . . . . .	238
10-1 Introduction . . . . .	238
10-2 Axial angular momentum . . . . .	238
10-3 Rotation of a rigid body about a fixed axis . . . . .	241
10-4 Plane motion of a rigid body . . . . .	243
10-5 Center of percussion . . . . .	252
10-6 Angular momentum with respect to a fixed point . . . . .	254
10-7 The top and the gyroscope . . . . .	259
CHAPTER 11. ELASTICITY . . . . .	270
11-1 Introduction . . . . .	270
11-2 Stress . . . . .	270
11-3 Plane stress . . . . .	272
11-4 Examples of plane stress . . . . .	275
11-5 Hydrostatic pressure . . . . .	280
11-6 Strain . . . . .	281
11-7 Elastic modulus . . . . .	284
11-8 Internal elastic potential energy . . . . .	287
11-9 Relations between elastic constants . . . . .	288
11-10 Torsion . . . . .	290
11-11 The coil spring . . . . .	291
CHAPTER 12. HARMONIC MOTION . . . . .	297
12-1 Introduction . . . . .	297
12-2 Elastic restoring forces . . . . .	297
12-3 Definitions . . . . .	298
12-4 Equations of simple harmonic motion . . . . .	299
12-5 Motion of a body suspended from a coil spring . . . . .	307
12-6 The simple pendulum . . . . .	310
12-7 Lissajous' figures . . . . .	311
12-8 Damped harmonic motion . . . . .	314
12-9 Forced harmonic motion. Resonance . . . . .	318
12-10 Angular harmonic motion . . . . .	322
12-11 The physical pendulum . . . . .	323



CHAPTER 13. GRAVITATION . . . . .	330
13-1 Introduction . . . . .	330
13-2 Kepler's laws . . . . .	330
13-3 Newton's law of gravitation . . . . .	331
13-4 Gravitational attraction of a sphere . . . . .	335
13-5 The Cavendish balance . . . . .	338
13-6 The mass of the earth . . . . .	340
13-7 Gravitational and inertial mass . . . . .	340
13-8 Variations in " $g$ " . . . . .	341
13-9 Gravitational potential energy . . . . .	343
13-10 Energy and orbits . . . . .	346
13-11 The gravitational field . . . . .	348
CHAPTER 14. HYDROSTATICS AND SURFACE TENSION . . . . .	356
14-1 Introduction . . . . .	356
14-2 Change of pressure with elevation . . . . .	356
14-3 The hydrostatic paradox . . . . .	359
14-4 Pressure gauges . . . . .	360
14-5 Archimedes' principle . . . . .	363
14-6 Forces against a dam . . . . .	367
14-7 Surface tension . . . . .	368
14-8 Surface tension and surface energy . . . . .	370
14-9 Pressure difference across a surface film . . . . .	371
14-10 Minimal surfaces . . . . .	374
14-11 Contact angle . . . . .	377
14-12 Capillarity . . . . .	379
CHAPTER 15. HYDRODYNAMICS AND VISCOSITY . . . . .	387
15-1 Introduction . . . . .	387
15-2 The equation of continuity . . . . .	389
15-3 Bernoulli's equation . . . . .	389
15-4 Applications of Bernoulli's equation . . . . .	392
15-5 Flow in a curved duct . . . . .	397
15-6 Viscosity . . . . .	398
15-7 Poiseuille's law . . . . .	401
15-8 Stokes' law . . . . .	404
15-9 Dynamic lift . . . . .	406
15-10 Reynolds number . . . . .	410
CHAPTER 16. TRAVELING WAVES . . . . .	414
16-1 Introduction . . . . .	414
16-2 Equation of a traveling wave . . . . .	414
16-3 Speed of propagation of waves in a stretched string . . . . .	419
16-4 Longitudinal waves in a bar . . . . .	423
16-5 Plane waves in a fluid . . . . .	425

16-6	Transmission of energy by a traveling wave . . . . .	431
16-7	Waves in a canal . . . . .	434
16-8	Fourier series . . . . .	437
16-9	Group speed and phase speed . . . . .	439
CHAPTER 17. REFLECTION. STATIONARY WAVES . . . . .		447
17-1	Introduction . . . . .	447
17-2	Reflection and transmission at a junction . . . . .	447
17-3	Reflection at a fixed end of a stretched string . . . . .	452
17-4	Reflection at a free end of a stretched string . . . . .	455
17-5	Boundary conditions for no reflection . . . . .	457
17-6	Normal modes and proper frequencies of a stretched string . . . . .	459
17-7	Damped and forced vibrations of a string. Resonance . . . . .	463
17-8	Reflection of compressional waves in a tube . . . . .	465
17-9	Vibrations of rods and plates . . . . .	468
CHAPTER 18. SOUND WAVES . . . . .		473
18-1	Introduction . . . . .	473
18-2	Intensity and intensity level . . . . .	473
18-3	Loudness and pitch . . . . .	475
18-4	Waves in three dimensions . . . . .	476
18-5	Interference of spherical waves . . . . .	480
18-6	Radiation from a piston. Diffraction . . . . .	482
18-7	Radiation efficiency of a sound source . . . . .	486
18-8	Beats . . . . .	487
18-9	Combination tones . . . . .	489
18-10	The Doppler effect . . . . .	490
CHAPTER 19. TEMPERATURE AND HEAT . . . . .		497
19-1	Introduction . . . . .	497
19-2	Temperature . . . . .	497
19-3	The celsius and fahrenheit temperature scales . . . . .	499
19-4	The absolute gas-thermometer temperature scale . . . . .	502
19-5	Coefficient of expansion . . . . .	505
19-6	Thermal stresses . . . . .	509
19-7	Heat, a form of energy . . . . .	510
19-8	Units of heat. The mechanical equivalent of heat . . . . .	511
19-9	Specific heat capacity . . . . .	512
19-10	The method of mixtures . . . . .	516
CHAPTER 20. TRANSFER OF HEAT . . . . .		521
20-1	Conduction . . . . .	521
20-2	Heat flow through a compound wall . . . . .	527
20-3	Radial heat flow in a sphere or cylinder . . . . .	528

20-4	Convection . . . . .	529
20-5	Radiation . . . . .	532
20-6	The complete radiator or blackbody . . . . .	532
20-7	Planck's law . . . . .	537
20-8	Wien's displacement law and Stefan's law . . . . .	538
20-9	Heat transfer by radiation . . . . .	541
20-10	Newton's law of cooling . . . . .	544
CHAPTER 21. GASES, LIQUIDS, AND SOLIDS . . . . .		548
21-1	Equations of state . . . . .	548
21-2	The ideal gas . . . . .	548
21-3	$P$ - $V$ - $T$ surface for an ideal gas . . . . .	553
21-4	$P$ - $V$ - $T$ surface for a real substance . . . . .	555
21-5	Heats of transformation . . . . .	563
21-6	Humidity . . . . .	565
21-7	The Wilson cloud chamber and the bubble chamber . . . . .	567
CHAPTER 22. THERMODYNAMICS . . . . .		571
22-1	Introduction . . . . .	571
22-2	The first law of thermodynamics . . . . .	573
22-3	Work done in a volume change . . . . .	576
22-4	Internal energy of a gas . . . . .	580
22-5	Specific heat capacities of an ideal gas . . . . .	582
22-6	Adiabatic processes . . . . .	585
22-7	Isothermal and adiabatic bulk modulus . . . . .	588
22-8	Heat engines and refrigerators . . . . .	589
22-9	Refrigeration cycles . . . . .	594
22-10	The second law of thermodynamics . . . . .	595
22-11	The Carnot cycle . . . . .	596
22-12	The kelvin absolute temperature scale . . . . .	600
22-13	The Clausius-Clapeyron equation . . . . .	602
22-14	Entropy . . . . .	604
22-15	The principle of the increase of entropy . . . . .	608
CHAPTER 23. THE KINETIC THEORY OF GASES . . . . .		614
23-1	Introduction . . . . .	614
23-2	Avogadro's number . . . . .	614
23-3	Equation of state of an ideal gas . . . . .	617
23-4	Specific heat capacity of a gas . . . . .	623
23-5	The principle of equipartition of energy . . . . .	625
23-6	Distribution of molecular speeds . . . . .	628
23-7	Experimental measurement of molecular speeds . . . . .	630
23-8	Mean free path . . . . .	632
23-9	Viscosity of a gas . . . . .	634
23-10	The Clausius and van der Waals equations of state . . . . .	637

COMMON LOGARITHMS . . . . .	644
NATURAL LOGARITHMS OF NUMBERS . . . . .	646
NATURAL TRIGONOMETRIC FUNCTIONS . . . . .	647
EXPONENTIAL FUNCTIONS . . . . .	648
CORRESPONDING FORMULAS FOR DIFFERENTIATION AND INTEGRATION .	649
ASTRONOMICAL DATA . . . . .	649
PERIODIC TABLE OF THE ELEMENTS . . . . .	650
CONVERSION FACTORS . . . . .	651
INDEX . . . . .	653

## CHAPTER 1

### COMPOSITION AND RESOLUTION OF VECTORS

**1-1 Units and standards.** Physics has been called the science of measurement. To quote from Lord Kelvin (1824-1907), "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 process of measuring a physical quantity consists of finding the ratio of its magnitude to that of some unit of the quantity. Thus when we say that the length of a rod is 10 centimeters, we mean that its length is 10 times as great as the unit of length called the centimeter. As a result of international collaboration over a long period, practically all of the units used in physics are now the same throughout the world.

It would be possible to define an arbitrary unit of any quantity of interest in physics. As we shall see later, however, units of three properly chosen quantities are sufficient, at least in the field of mechanics. The unit of any other quantity can then be expressed as some combination of these three (in some cases, only two are required). The choice of the three quantities is to some extent arbitrary, and in this book we shall consider them to be *length*, *mass*, and *time*.

A material object which embodies a unit is called a *standard*. The international standard of length is a bar of platinum-iridium alloy of X-shaped cross section (see Fig. 1-1) called the *standard meter*, which is kept at the International Bureau of Weights and Measures at Sevres, near Paris. The distance between two lines engraved on gold plugs near the ends of the bar, when the bar is at the temperature of melting ice, is called *one meter*, and one one-hundredth of this distance is *one centimeter*. Copies of the Paris meter have been distributed to the standardizing agencies of various nations, such as the National Bureau of Standards at Washington, D. C. The meter was originally intended to represent one ten-millionth of the earth's quadrant through Paris, but later, more accurate measurements have shown that it differs from its intended value by a small amount. The standard meter has been carefully compared with the wavelength of one particular color of light emitted by cadmium vapor in an electrical discharge, and if it were ever destroyed it could be replaced with an accuracy better than one part in a million.

The *yard*, originally embodied by a physical standard like the meter, is now defined as

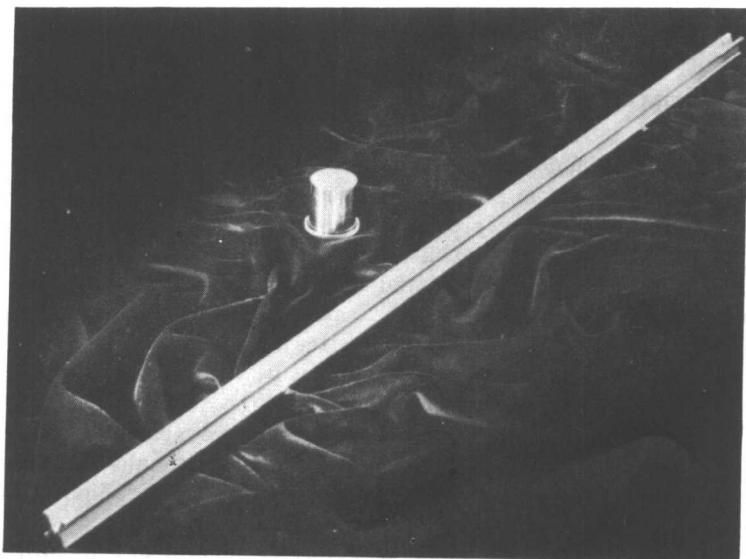


FIG. 1-1. The standard meter and the standard kilogram.

$$1 \text{ yard} = \frac{3600}{3937} \text{ meter (exactly),}$$

so that the same physical standard serves for both the yard and the meter. The *foot* is defined as one-third of a yard.

The international standard of mass\* is a cylinder of platinum-iridium (see Fig. 1-1) called the *standard kilogram*. It was originally intended to have a mass equal to that of  $1000 \text{ cm}^3$  of pure water at  $4^\circ\text{C}$  but, as with the standard meter, more precise measurements have shown that this is not exactly true.

The pound mass, like the yard, was formerly embodied by a physical standard of its own, but the *standard avoirdupois pound* is now defined in the U. S. as a body of mass  $0.4535924277 \text{ kgm}$ .

The standard of time is our rotating earth, and the fundamental unit of time is the *mean solar day*, the average time for the earth to make one revolution on its axis with respect to the sun. The length of a solar day increases and decreases gradually in the course of a year because of the orbital motion of the earth. The length of a solar day averaged over a year is the mean solar day.

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\* The concept of mass is discussed more fully in Chapter 5.

The unit of time used in scientific work is the *second*, defined as  $1/86,400$  of a mean solar day.

We shall adopt the convention that an algebraic symbol representing a physical quantity stands for both a *numerical value* and a *unit*. Thus the symbol  $l$  might represent a length of 10 ft, the symbol  $m$  a mass of 15 kgm, and the symbol  $t$  a time of 20 sec. The numerical value and the unit together constitute the *magnitude* of the quantity. The numerical value is the ratio of the magnitude of the quantity to that of the unit.

An algebraic symbol occurring in a physical equation can be replaced by the magnitude it represents but not by the numerical value alone. For example, the density  $\rho$  of a homogeneous body is defined as the quotient of its mass  $m$  and its volume  $V$ :

$$\rho = m/V.$$

Then if  $m = 150$  gm and  $V = 20.0$  cm<sup>3</sup>,

$$\rho = \frac{m}{V} = \frac{150 \text{ gm}}{20.0 \text{ cm}^3} = 7.50 \frac{\text{gm}}{\text{cm}^3}.$$

The numerical value of the density is 7.50 and the unit is 1 gm/cm<sup>3</sup>.

**1-2 Force.** Mechanics is the branch of physics which deals with the motion of material bodies and with the forces that bring about the motion. Since motion is best described by the methods of calculus and many readers of this book are just beginning their study of this subject, we shall postpone a discussion of motion until Chapter 4, and start with a study of forces.

When we push or pull on a body, we are said to exert a *force* on it. Forces can also be exerted by inanimate objects; 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 it is drawing. The force of which we are most aware in our daily lives is the force of gravitational attraction exerted on every body by the earth, and is called the *weight* of the body. Gravitational forces (and electrical and magnetic forces also) can act through empty space without contact. In this respect they differ from the forces mentioned above, where the body doing the pushing or pulling must make contact with the body being pushed or pulled.

The process of measuring a physical quantity consists of finding the ratio of its magnitude to the magnitude of some unit of the quantity. Thus to measure a force we must find the ratio of its magnitude to that of a unit of force. Two steps are therefore involved: (1) a definition of the ratio of the magnitudes of two forces, and (2) the selection of a unit force.

One effect of a force is to alter the dimensions or shape of a body on which the force acts; another is to alter the state of motion of the body. Either of these effects can be used to define the ratio of the magnitudes of two forces. In this Chapter we shall consider only the former; the latter will be discussed in Chapter 5.

The instrument most commonly used to measure forces is the *spring balance*, which consists of a coil spring mounted in a case for protection and carrying at one end a pointer that moves over a scale. The position of the pointer indicates the extension of the spring above its no-load length. When one end of the spring is kept fixed and a stretching force is exerted on the other end, the length of the spring increases and the pointer moves along the scale. *The ratio of the magnitudes of two forces  $F_1$  and  $F_2$  is defined as equal to the ratio of the extensions  $x_1$  and  $x_2$  which they produce in the same spring:*

$$\frac{F_1}{F_2} = \frac{x_1}{x_2}.$$

If the definition is to be meaningful, the same ratio must be obtained for two given forces whatever spring is used. This is found to be the case provided the spring is not stretched beyond its proportional limit of elasticity.

A unit of force *might* now be defined as the force necessary to stretch a standard spring by some specified amount. Such a definition is open to the objection that the elastic properties of the standard spring might change over a long period of time and the standard would not be permanent. To avoid this difficulty, we define a unit force as the force of the earth's gravitational attraction for some standard body at a specified point on the earth's surface. That is, the unit force is defined as the *weight* of the standard body. Three such units of force are in common use:

*One kilogram-force (1 kgf) is defined as the weight of a standard kilogram body.*

*One gram-force (1 gf) is defined as the weight of a standard gram body.*

*One pound-force (1 lbf) is defined as the weight of a standard pound body.\**

That is, each of these units is defined as *the force of the earth's gravitational attraction on a specified body*. Since the earth's attraction for a given body varies slightly from point to point on the earth's surface, some particular

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\* We use the abbreviations kgf, gf, and lbf for these units of force, rather than kg, g, and lb, because the names kilogram, gram, and pound are also given to units of *mass*. The latter units will be abbreviated kgm, gm, and lbm.



point must be specified. The effect of the earth's rotation must also be taken into account. A more complete discussion will be found in Chapter 13.

Now suppose we wish to calibrate a spring balance in, say, pounds-force. A standard pound body is first suspended from the balance. The force stretching the spring is then equal to the weight of the standard pound body, or is 1 lbf. The position of the pointer is noted and is marked 1 lbf. The position of the pointer at twice this extension can now be marked 2 lbf, and so on.

**1-3 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. 1-2. That is, we are to slide it by exerting a force on it.

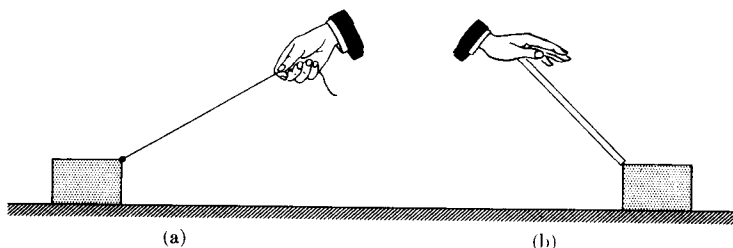


FIGURE 1-2

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 lbf. It is clear that simply to write "10 lbf" 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 lbf, 30° above horizontal to the right," or "10 lbf, 45° below horizontal to the right," but all 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. 1-3 is the force diagram corresponding to Fig. 1-2. (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 a direction in space as well as a magnitude. For example, the velocity of an aircraft is not completely specified by stating that it is 300 miles per hour; we need to know the direction also. The concept of volume, on the other hand, has no direction associated with it.

Quantities like volume, which involve a magnitude only, are called