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# Basics of Engineering Mechanics

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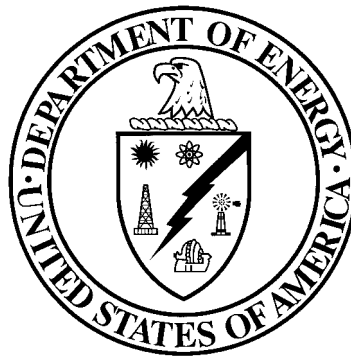
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# DOE FUNDAMENTALS HANDBOOK

## CLASSICAL PHYSICS



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**Department of Energy  
Fundamentals Handbook**

**CLASSICAL PHYSICS  
Module 3  
Force and Motion**

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## **TERMINAL OBJECTIVE**

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- 1.0 **APPLY** Newton's laws of motion to a body.

## **ENABLING OBJECTIVES**

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- 1.1 **STATE** Newton's first law of motion.
- 1.2 **STATE** Newton's second law of motion.
- 1.3 **STATE** Newton's third law of motion.
- 1.4 **STATE** Newton's law of universal gravitation.
- 1.5 **DEFINE** momentum.
- 1.6 **EXPLAIN** the conservation of momentum.
- 1.7 Using the conservation of momentum, **CALCULATE** the velocity for an object (or objects) following a collision of two objects.



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## NEWTON'S LAWS OF MOTION

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*The study of Newton's laws of motion allows us to understand and accurately describe the motion of objects and the forces that act on those objects.*

**EO 1.1      STATE Newton's first law of motion.**

**EO 1.2      STATE Newton's second law of motion.**

**EO 1.3      STATE Newton's third law of motion.**

**EO 1.4      STATE Newton's law of universal gravitation.**

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The basis for modern mechanics was developed in the seventeenth century by Sir Isaac Newton. From his studies of objects in motion, he formulated three fundamental laws.

Newton's first law of motion states "an object remains at rest (if originally at rest) or moves in a straight line with constant velocity if the net force on it is zero."

Newton's second law states "the acceleration of a body is proportional to the net (i.e., sum or resultant) force acting on it and in the direction of that net force." This law establishes the relationship between force, mass, and acceleration and can be written mathematically as shown in Equation 3-1.

$$F = ma \qquad (3-1)$$

where:

F = force (Newton = 1 Kg-m/sec<sup>2</sup>, or lbf)

m = mass (Kg or lbm)

a = acceleration (m/sec<sup>2</sup> or ft/sec<sup>2</sup>)

This law is used to define force units and is one of the most important laws in physics. Also, Newton's first law is actually a consequence of this second law, since there is no acceleration when the force is zero, and the object is either at rest or moving with a constant velocity. Equation 3-1 can be used to calculate an objects weight at the surface of the earth. In this special case, F is the force, or weight, caused by the gravitational acceleration of the earth acting on the mass, m, of the object. When dealing with this type of problem, we designate the acceleration, g, which equals 9.8m/sec<sup>2</sup> or 32.17 ft/sec<sup>2</sup> (g is called gravitational acceleration constant). Thus, equation 3-1 becomes F = mg for this case.

Newton's third law of motion states "if a body exerts a force on a second body, the second body exerts an equal and opposite force on the first." This law has also been stated as, "for every action there is an equal and opposite reaction."

The third law is basic to the understanding of force. It states that forces always occur in pairs of equal and opposite forces. Thus, the downward force exerted on a desk by a pencil is accompanied by an upward force of equal magnitude exerted on the pencil by the desk. This principle holds for all forces, variable or constant, regardless of their source.

One additional law attributed to Newton concerns mutual attractive forces between two bodies. It is known as the universal law of gravitation and is stated as follows.

"Each and every mass in the universe exerts a mutual, attractive gravitational force on every other mass in the universe. For any two masses, the force is directly proportional to the product of the two masses and is inversely proportional to the square of the distance between them."

Newton expressed the universal law of gravitation using Equation 3-2.

$$F = G \frac{m_1 m_2}{r^2} \tag{3-2}$$

where:

- F = force of attraction (Newton = 1Kg-m/sec<sup>2</sup> or lbf)
- G = universal constant of gravitation (6.673 x 10<sup>-11</sup> m<sup>3</sup>/kg-sec<sup>2</sup> or 3.44 x 10<sup>-8</sup>  $\frac{\text{lbm} \cdot \text{ft}^2}{\text{slug}^2}$ )
- m<sub>1</sub> = mass of the first object (Kg or lbm)
- m<sub>2</sub> = mass of the second object (Kg or lbm)
- r = distance between the centers of the two objects (m or ft)

Using this universal law of gravitation, we can determine the value of g (gravitational acceleration constant), at the surface of the earth. We already know this value to be 9.8 m/sec<sup>2</sup> (or 32.17 ft/sec<sup>2</sup>), but it can be calculated using Equation 3-2.

Calculation:

First, we will assume that the earth is much larger than the object and that the object resides on the surface of the earth; therefore, the value of r will be equal to the radius of the earth. Second, we must understand that the force of attraction (F) in Equation 3-2 for the object is equal to the object's weight (F) as described in Equation 3.1. Setting these two equations equal to each other yields the following.

$$F = G \frac{M_e m_1}{r^2} = m_1 a$$

where:

$$\begin{aligned} M_e &= \text{mass of the earth } (5.95 \times 10^{24} \text{ kg}) \\ m_1 &= \text{mass of the object} \\ r &= \text{radius of the earth } (6.367 \times 10^6 \text{ m}) \end{aligned}$$

The mass ( $m_1$ ) of the object cancels, and the value of ( $g$ ) can be determined as follows since  $a=g$  by substituting ( $g$ ) for ( $a$ ) in the previous equation.

$$\begin{aligned} g &= G \frac{M_e}{r^2} \\ g &= \left( 6.673 \times 10^{-11} \frac{\text{m}^3}{\text{kg sec}^2} \right) \left( \frac{5.95 \times 10^{24} \text{ kg}}{(6.367 \times 10^6 \text{ m})^2} \right) \\ g &= 9.8 \frac{\text{m}}{\text{sec}^2} \end{aligned}$$

If the object is a significant distance from the earth, we can demonstrate that ( $g$ ) is not a constant value but varies with the distance (altitude) from the earth. If the object is at an altitude of 30 km (18.63 mi), then the value of ( $g$ ) is as follows:

$$\begin{aligned} r &= 30000 \text{ m} + 6.367 \times 10^6 \text{ m} = 6.397 \times 10^6 \text{ m} \\ g &= \left( 6.673 \times 10^{-11} \frac{\text{m}^3}{\text{kg sec}^2} \right) \left( \frac{5.95 \times 10^{24} \text{ kg}}{(6.397 \times 10^6 \text{ m})^2} \right) \\ g &= 9.7 \frac{\text{m}}{\text{sec}^2} \end{aligned}$$

As you can see, a height of 30 km only changes ( $g$ ) from  $9.8 \text{ m/sec}^2$  to  $9.7 \text{ m/sec}^2$ . There will be an even smaller change for objects closer to the earth. Therefore, ( $g$ ) is normally considered a constant value since most calculations involve objects close to the surface of the earth.

## **Summary**

Newton's laws of motion are summarized below.

### **Newton's Laws of Motion Summary**

#### Newton's First Law of Motion

An object remains at rest (if originally at rest) or moves in a straight line with constant velocity if the net force on it is zero.

#### Newton's Second Law of Motion

A particle with a force acting on it has an acceleration proportional to the magnitude of the force and in the direction of that force.

#### Newton's Third Law of Motion

The forces of action and reaction between interacting bodies are equal in magnitude and opposite in direction.

- or -

For every action there is an equal and opposite reaction.

#### Newton's Universal Law of Gravitation

Each and every mass in the universe exerts a mutual, attractive gravitational force on every other mass in the universe. For any two masses, the force is directly proportional to the product of the two masses and is inversely proportional to the square of the distance between them.

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## MOMENTUM PRINCIPLES

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*Momentum is a measure of the motion of a moving body. An understanding of momentum and the conservation of momentum provides essential tools in solving physics problems.*

**EO 1.5      DEFINE momentum.**

**EO 1.6      EXPLAIN the conservation of momentum.**

**EO 1.7      Using the conservation of momentum, CALCULATE the velocity for an object (or objects) following a collision of two objects.**

---

### Momentum

*Momentum* is a basic and widely applicable concept of physics. It is, in a sense, the measure of the motion of a moving body. It is the result of the product of the body's mass and the velocity at which it is moving. Therefore, momentum can be defined using Equation 3-3.

$$P = mv \qquad (3-3)$$

where:

P = momentum of the object (Kg-m/sec or ft-lbm/sec)

m = mass of the object (Kg or lbm)

v = velocity of the object (m/sec or ft/sec)

Momentum is a vector quantity since it results from the velocity of the object. If different momentum quantities are to be added vectorially, the direction of each momentum must be taken into account. However, to simplify the understanding of momentum, only straight line motions will be considered.

Example:

Calculate the momentum for a 16 lbm bowling ball rolling down a lane at 22 ft/sec.

Solution:

$$P = mv$$

$$P = (16 \text{ lbm}) \left( 22 \frac{\text{ft}}{\text{sec}} \right)$$

$$P = 352 \frac{\text{ft-lbm}}{\text{sec}}$$

### **Force and Momentum**

There is a direct relationship between force and momentum. The rate at which momentum changes with time is equal to the net force applied to an object. This relationship comes directly from Newton's second law of motion,  $F = ma$ . This is a special case of Newton's second law for a constant force which gives rise to a constant acceleration. The linking fact is that acceleration is the rate at which velocity changes with time. Therefore, we can determine the following:

We know that,  $F = ma$

$$\text{and since, } a = \frac{(v - v_0)}{(t - t_0)}$$

$$\text{then, } F = m \left( \frac{v - v_0}{t - t_0} \right) \quad (3-4)$$

$$\text{which can also be written, } F = \frac{mv - mv_0}{t - t_0} \quad (3-5)$$

$$\text{Substituting } P \text{ for } mv \text{ and } P_0 \text{ for } mv_0, F = \frac{P - P_0}{t - t_0}$$

$$\text{or } F = \frac{\Delta P}{\Delta t} \quad (3-6)$$

From Equation 3-6, we can determine that force (F) is equal to the change in momentum per time.

Example:

The velocity of a rocket must be increased by 110 ft/sec to achieve proper orbit around the earth. If the rocket has a mass of 5 tons and it takes 9 sec. to reach orbit, calculate the required thrust (force) to achieve this orbit.

Solution:

Even though the initial velocity ( $v_o$ ) and final velocity ( $v$ ) are unknown, we do know the change in velocity ( $v-v_o$ ), which is 110 ft/sec. Therefore, using Equation 3-4 we can find the solution.

$$F = m \left( \frac{v - v_o}{t - t_o} \right)$$

$$F = 10000 \text{ lbm} \left( \frac{110 \text{ ft/sec}}{9 \text{ sec}} \right)$$

$$F = 1.2 \times 10^5 \frac{\text{ft-lbm}}{\text{sec}^2}$$

### **Conservation of Momentum**

One of the most useful properties of momentum is that it is conserved. This means that if no net external force acts upon an object, the momentum of the object remains constant. Using Equation 3-6, we can see that if force ( $F$ ) is equal to zero, then  $\Delta P = 0$ . It is most important for collisions, explosions, etc., where the external force is negligible, and states that the momentum before the event (collision, explosion) equals the momentum following the event.

The conservation of momentum applies when a bullet is fired from a gun. Prior to firing the gun, both the gun and the bullet are at rest (i.e.,  $V_G$  and  $V_B$  are zero), and therefore the total momentum is zero. This can be written as follows:

$$m_G v_G + m_B v_B = 0$$

or

$$m_G v_G = -m_B v_B$$

When the gun is fired, the momentum of the recoiling gun is equal and opposite to the momentum of the bullet. That is, the momentum of the bullet ( $m_B v_B$ ) is equal to the momentum of the gun ( $m_G v_G$ ), but of opposite direction.

The development of the law of conservation of momentum does not consider whether the collision is elastic or inelastic. In an elastic collision, both momentum and kinetic energy (i.e., energy due to an object's velocity) are conserved. A common example of an elastic collision is the head-on collision of two billiard balls of equal mass. In an inelastic collision, momentum is conserved, but system kinetic energy is not conserved. An example of an inelastic collision is the head-on collision of two automobiles where part of the initial kinetic energy is lost as the metal crumples during the impact. The concept of kinetic energy will be discussed further in Module 5 of this course.

The law of conservation of momentum can be mathematically expressed in several different ways. In general, it can be stated that the sum of a system's initial momentum is equal to the sum of a system's final momentum.

$$\sum P_{\text{initial}} = \sum P_{\text{final}} \quad (3-7)$$

In the case where a collision of two objects occurs, the conservation of momentum can be stated as follows.

$$P_{1 \text{ initial}} + P_{2 \text{ initial}} = P_{1 \text{ final}} + P_{2 \text{ final}} \quad (3-8)$$

or

$$(m_1 v_1)_{\text{initial}} + (m_2 v_2)_{\text{initial}} = (m_1 v_1)_{\text{final}} + (m_2 v_2)_{\text{final}} \quad (3-9)$$

In the case where two bodies collide and have identical final velocities, equation 3-10 applies.

$$m_1 v_1 + m_2 v_2 = (m_1 + m_2) v_f \quad (3-10)$$

For example, consider two railroad cars rolling on a level, frictionless track (see Figure 1). The cars collide, become coupled, and roll together at a final velocity ( $v_f$ ). The momentum before and after the collision is expressed with Equation 3-10.

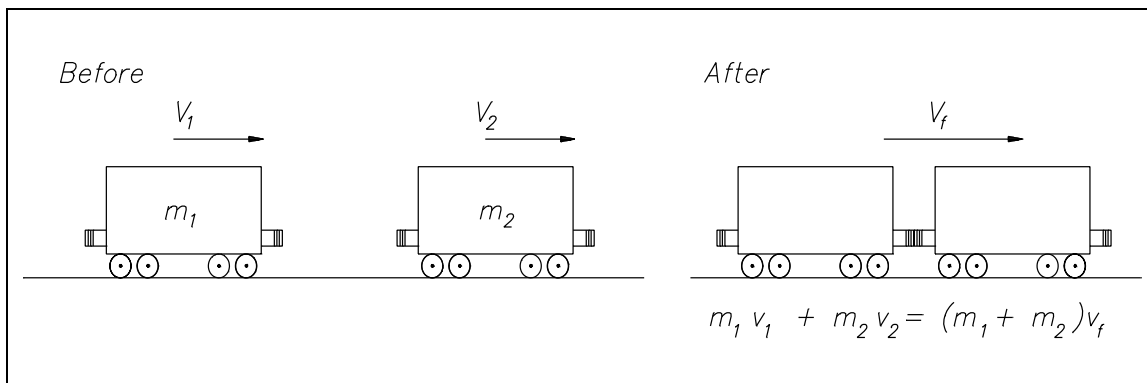


Figure 1 Momentum



If the initial velocities of the two objects ( $v_1$  and  $v_2$ ) are known, then the final velocity ( $v_f$ ) can be calculated by rearranging Equation 3-10 into Equation 3-11.

$$v_f = \frac{m_1 v_1 + m_2 v_2}{m_1 + m_2} \quad (3-11)$$

Example:

Consider that the railroad cars in Figure 1 have masses of  $m_1 = 2300$  lbm and  $m_2 = 2800$  lbm. The first car ( $m_1$ ) is moving at a velocity of 29 ft/sec and the second car ( $m_2$ ) is moving at a velocity of 11 ft/sec. The first car overtakes the second car and couples with it. Calculate the final velocity of the two cars.

Solution:

The final velocity ( $v_f$ ) can be easily calculated using Equation 3-8.

$$v_f = \frac{m_1 v_1 + m_2 v_2}{m_1 + m_2}$$

$$v_f = \frac{(2300 \text{ lbm})(29 \text{ ft/sec}) + (2800 \text{ lbm})(11 \text{ ft/sec})}{2300 \text{ lbm} + 2800 \text{ lbm}}$$

$$v_f = 19.1 \text{ ft/sec}$$

## **Summary**

The concepts of momentum and the conservation of momentum are summarized below.

### **Momentum Summary**

Momentum is the measure of the motion of a moving body. It is the result of the product of the body's mass and the velocity at which it is moving. Therefore, momentum can be defined as:

$$P = mv.$$

The conservation of momentum states that if no net external force acts upon a system, the momentum of the system remains constant. If force ( $F$ ) is equal to zero, then  $\Delta P = 0$ .

The momentum before and after a collision can be calculated using the following equation.

$$(m_1v_1)_{\text{initial}} + (m_2v_2)_{\text{initial}} = (m_1v_1)_{\text{final}} + (m_2v_2)_{\text{final}}$$

**Department of Energy  
Fundamentals Handbook**

**CLASSICAL PHYSICS  
Module 4  
Application of Newton's Laws**

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## **TERMINAL OBJECTIVE**

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- 1.0 From memory, **APPLY** the principles of force to stationary or moving bodies.

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## **ENABLING OBJECTIVES**

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- 1.1 **DEFINE** the following:
- a. Force
  - b. Weight
- 1.2 **STATE** the purpose of a free-body diagram.
- 1.3 Given all necessary information, **CONSTRUCT** a free-body diagram.
- 1.4 **STATE** the conditions necessary for a body to be in force equilibrium.
- 1.5 **DEFINE** the following:
- a. Net force
  - b. Equilibrant
- 1.6 **DEFINE** the following:
- a. Tensile force
  - b. Compressive force
  - c. Frictional force
- 1.7 **EXPLAIN** the difference between a static-friction force and a kinetic-friction force.
- 1.8 **STATE** two factors that affect the magnitude of the friction force.
- 1.9 **EXPLAIN** the difference between centripetal force and centrifugal force.



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## **FORCE AND WEIGHT**

---

*Force can be thought of simply as a push or pull, but is more clearly defined as any action on a body that tends to change the velocity of the body. Weight is a force exerted on an object due to the object's position in a gravitational field.*

- EO 1.1      DEFINE the following:**
- a.      Force**
  - b.      Weight**
- 

### **Introduction**

In the study of forces, the student must make valid assumptions called for in the formulation of real problems. The ability to understand and make use of the correct assumptions in the formulation and solution of engineering problems is certainly one of the most important abilities of a successful operator. One of the objectives of this manual is to provide an opportunity to develop this ability through the study of the fundamentals and the analysis of practical problems.

An effective method of attack on all engineering problems is essential. The development of good habits in formulating problems and in representing their solutions will prove to be a valuable asset. Each solution should proceed with a logical sequence of steps from hypothesis to conclusion, and its representation should include a clear statement of the following parts, each clearly defined: a) given data, b) results desired, c) necessary diagrams, d) calculations, and e) answers and conclusions. Many problems become clear and straightforward once they are begun with a logical and disciplined method of attack.

In addition, it is important to incorporate a series of checks on the calculations at intermediate points in the solution. Also, all work must be neat and orderly.

The subject of classical physics is based on surprisingly few fundamental concepts and involves mainly the application of these basic relations to a variety of situations. Newton's laws of motion are some of the fundamental concepts used in the study of force and weight.

## **Force**

*Force* is defined as a vector quantity that tends to produce an acceleration of a body in the direction of its application. Changing the body's velocity causes the body to accelerate. Therefore, force can be mathematically defined as given by Newton's second law of motion (Equation 4-1).

$$F = ma \quad (4-1)$$

where:

- F = force on object (Newton or lbf)
- m = mass of object (Kg or lbm)
- a = acceleration of object (m/sec<sup>2</sup> or ft/sec<sup>2</sup>)

Force is characterized by its point of application, its magnitude, and its direction. A force that is actually distributed over a small area of the body upon which it acts may be considered a concentrated force if the dimensions of the area involved are small compared with other pertinent dimensions.

Two or more forces may act upon an object without affecting its state of motion. For example, a book resting upon a table has a downward force acting on it caused by gravity and an upward force exerted on it from the table top. These two forces cancel and the net force of the book is zero. This fact can be verified by observing that no change in the state of motion has occurred.

## **Weight**

*Weight* is a special application of the concept of force. It is defined as the force exerted on an object by the gravitational field of the earth, or more specifically the pull of the earth on the body.

$$W = \frac{mg}{g_c} \quad (4-2)$$

where:

- W = weight (lbf)
- m = mass (lbm) of the object
- g = the local acceleration of gravity (32.17 ft/sec<sup>2</sup>)
- g<sub>c</sub> = a conversion constant employed to facilitate the use of Newton's second law of motion with the English system of units and is equal to 32.17 ft-lbm/lbf-sec<sup>2</sup>

Note that g<sub>c</sub> has the same numerical value as the acceleration of gravity at sea level.

The mass of a body is the same wherever the body is, whether on the moon or on the earth. The weight of a body, however, depends upon the local acceleration of gravity. Thus, the weight of an object is less on the moon than on the earth because the local acceleration of gravity is less on the moon than on the earth.

Example:

Calculate the weight of a person with a mass of 185 lbm.

$$\begin{aligned}W &= \frac{mg}{g_c} \\&= \frac{(185 \text{ lbm}) \left( 32.17 \frac{\text{ft}}{\text{sec}^2} \right)}{32.17 \frac{\text{ft-lbm}}{\text{lbf-sec}^2}} \\&= 185 \text{ lbf}\end{aligned}$$

Example:

Calculate the weight of a person with a mass of 185 lbm on the moon. Gravity on the moon is 5.36 ft/sec<sup>2</sup>.

$$\begin{aligned}W &= \frac{mg}{g_c} \\&= \frac{(185 \text{ lbm}) \left( 5.36 \frac{\text{ft}}{\text{sec}^2} \right)}{32.17 \frac{\text{ft-lbm}}{\text{lbf-sec}^2}} \\&= 28.19 \text{ lbf}\end{aligned}$$

With the idea of mass and weight understood, especially their differences, the concept of gravitational force is more easily explained. Any object that is dropped will accelerate as it falls, even though it is not in physical contact with any other body. To explain this, the idea of gravitational force was developed, resulting in the concept that one body, such as the earth, exerts a force on another body, even though they are far apart. The gravitational attraction of two objects depends upon the mass of each and the distance between them. This concept is known as Newton's law of gravitation, which was introduced in an earlier chapter.

### **Summary**

The important concepts of force and weight are summarized below.

#### **Force and Weight Summary**

- Force is a vector quantity that tends to produce an acceleration of a body in the direction of its application.

or

$$F = ma$$

- Weight is the force exerted on an object due to gravity. (On the earth it is the gravitational pull of the earth on the body.)

$$W = mg/g_c$$

---

## FREE-BODY DIAGRAMS

---

*In studying the effect of forces on a body it is necessary to isolate the body and determine all forces acting upon it. This method of using a free-body diagram is essential in understanding basic and complex force problems.*

**EO 1.2      STATE the purpose of a free-body diagram.**

**EO 1.3      Given all necessary information, CONSTRUCT a free-body diagram.**

---

In solving a problem involving forces it is essential that Newton's laws are carefully fixed in mind and that these principles are applied literally and exactly. In applying these principles it is essential that the body be isolated from all other bodies so that a complete and accurate account of all forces which act on this body may be considered. The diagram of such an isolated body with the representation of all external forces acting on it is called a *Free-Body Diagram*. It has long been established that the free-body-diagram method is the key to the understanding of engineering problems. This is because the isolation of a body is the tool that clearly separates cause and effect and focuses our attention to the literal application of a principle.

Example:

Consider the book resting on the table in Figure 1. Although the book is stationary, two forces are acting on the book to keep it stationary. One is the weight ( $W$ ) of the book exerting a force down on the table. The other is the force exerted up by the table to hold the book in place. This force is known as the normal force ( $N$ ) and is equal to the weight of the book. A normal force is defined as any perpendicular force with which any two surfaces are pressed against each other. The free-body diagram for this situation, illustrated on the right side in Figure 1, isolates the book and presents the forces acting on the object.

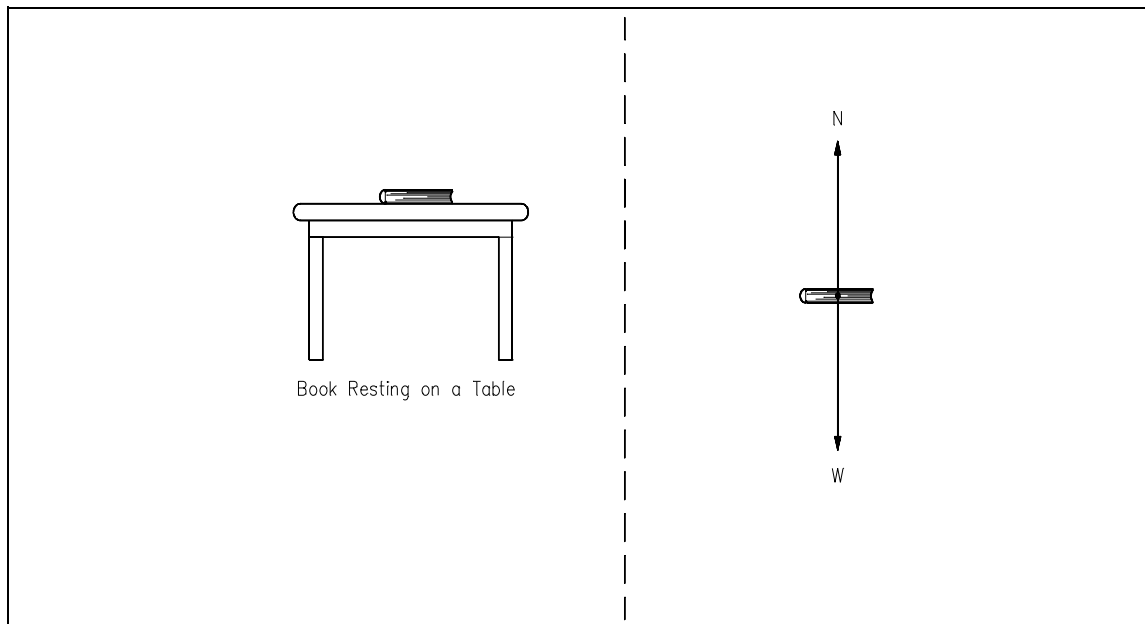


Figure 1 Book on a Table

### **Constructing a Free-Body Diagram**

In constructing a free-body diagram the following steps are usually followed.

- Step 1. Determine which body or combination of bodies is to be isolated. The body chosen will usually involve one or more of the desired unknown quantities.
- Step 2. Next, isolate the body or combination of bodies chosen with a diagram that represents its complete external boundaries.
- Step 3. Represent all forces that act on the isolated body as applied by the removed contacting and attracting bodies in their proper positions in the diagram of the isolated body. Do not show the forces that the object exerts on anything else, since these forces do not affect the object itself.
- Step 4. Indicate the choice of coordinate axes directly on the diagram. Pertinent dimensions may also be represented for convenience. Note, however, that the free-body diagram serves the purpose of focusing accurate attention on the action of the external forces; therefore, the diagram should not be cluttered with excessive information. Force arrows should be clearly distinguished from other arrows to avoid confusion. For this purpose colored pencils may be used.

When these steps are completed a correct free-body diagram will result, and the student can apply the appropriate equations to the diagram to find the proper solution.

Example:

The car in Figure 2 is being towed by a force of some magnitude. Construct a free-body diagram showing all the forces acting on the car.

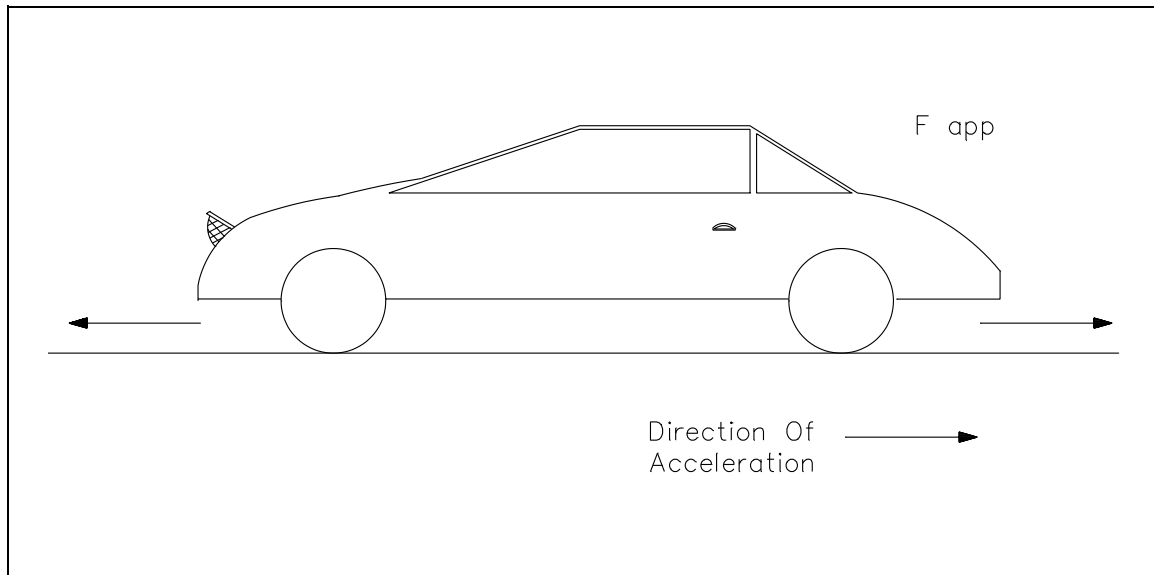


Figure 2 Car

Solution:

Following the steps to construct a free-body diagram (shown in Figure 3), the object (the car) is chosen and isolated. All the forces acting on the car are represented with proper coordinate axes. Those forces are:

- $F_{app}$  - The force applied to tow the car
- $F_K$  - The frictional force that opposes the applied force due to the weight of the car and the nature of the surfaces (the car's tires and the road)
- $W$  - The weight of the car
- $N$  - The normal force exerted by the road on the car

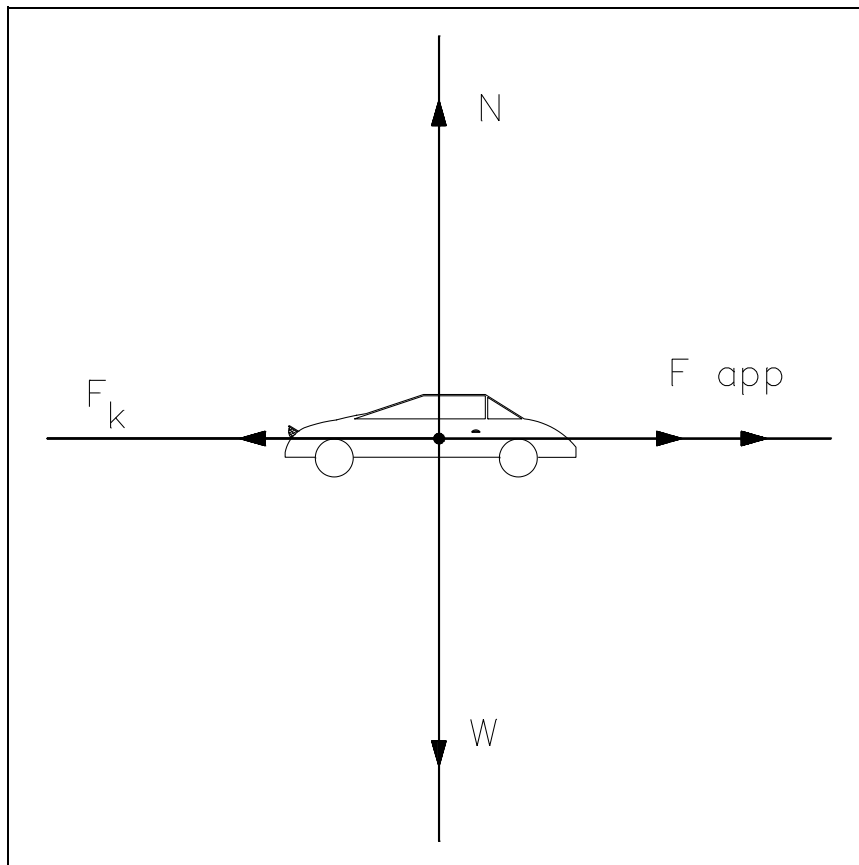


Figure 3 Free-Body Diagram

The frictional force ( $F_k$ ) is a force that opposes the direction of motion. This force is explained in more detail in the chapter on types of forces.

To solve this practical problem, the student would assign values for each force as determined by data given in the problem. After assigning a sign convention (e.g., + for forces upward and to the right, - for forces downward and to the left), the student would sum all forces to find the net force acting on the body. Using this net force information and appropriate equations, the student could solve for the requested unknowns. A variation would be to have the student find an unknown force acting on the body given sufficient information about the other forces acting on the body. The student will learn to solve specific examples using free-body diagrams in a later chapter.

Some advanced free-body diagrams for various types of systems are shown in Figure 4.



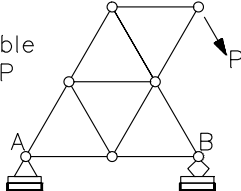
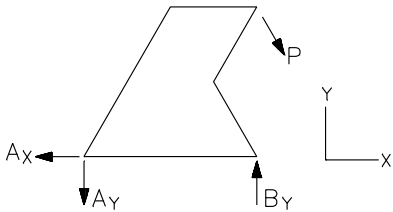
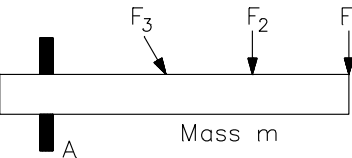
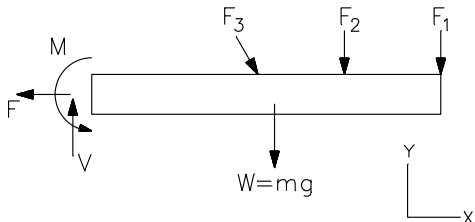
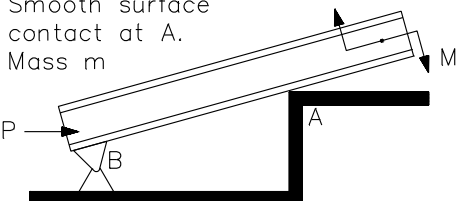
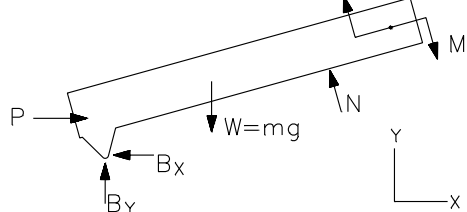
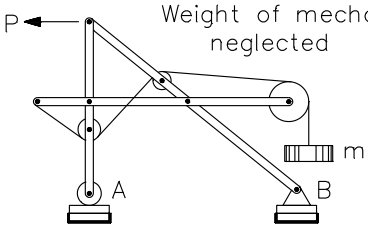
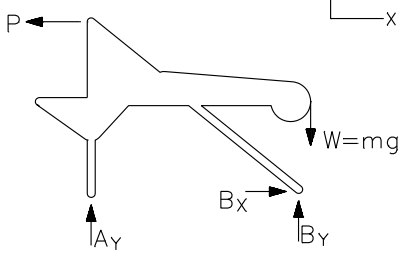
SAMPLE FREE-BODY DIAGRAMS	
Mechanical System	Free-Body Diagram of Isolated Body
<p>1. Plane truss</p> <p>Weight of truss assumed negligible compared with <math>P</math></p> 	
<p>2. Cantilever beam</p> 	
<p>3. Beam</p> <p>Smooth surface contact at A.</p> <p>Mass <math>m</math></p> 	
<p>4. Rigid system of interconnected bodies analyzed as a single unit</p> <p>Weight of mechanical neglected</p> 	

Figure 4 Various Free-Body Diagrams

## **Summary**

The concept of the free-body diagram is summarized below.

### **Free-Body Diagram Summary**

- A free-body diagram isolates a body and illustrates all the forces that act on the body so that a complete and accurate account of all of those forces may be considered.
- Four steps must be performed to construct a free-body diagram:
  - Determine the body or combination of bodies to be isolated.
  - Isolate the body or combination of bodies with a diagram that represents the complete external boundaries.
  - Represent all forces that act on the isolated body in their proper positions within the diagram.
  - Indicate the choice of coordinate axes directly on the diagram.

---

## **FORCE EQUILIBRIUM**

---

*Knowledge of the forces required to maintain an object in equilibrium is essential in understanding the nature of bodies at rest and in motion.*

**EO 1.4      STATE the conditions necessary for a body to be in force equilibrium.**

**EO 1.5      DEFINE the following:**  
**a.      Net force**  
**b.      Equilibrant**

---

### **Net Force**

When forces act on an object, the result may be a change in the object's state of motion. If certain conditions are satisfied, however, the forces may combine to maintain a state of equilibrium or balance.

To determine if a body is in equilibrium, the overall effect of all the forces acting on it must be assessed. All the forces that act on an object result in essentially one force that influences the object's motion. The force which results from all the forces acting on a body is defined as the *net force*. It is important to remember that forces are vector quantities. When analyzing various forces you must account for both the magnitude (displacement) of the force as well as the direction in which the force is applied. As described in the previous chapter, this is best done using a free-body diagram.

To understand this more clearly, consider the book resting on the table in section A of Figure 5.

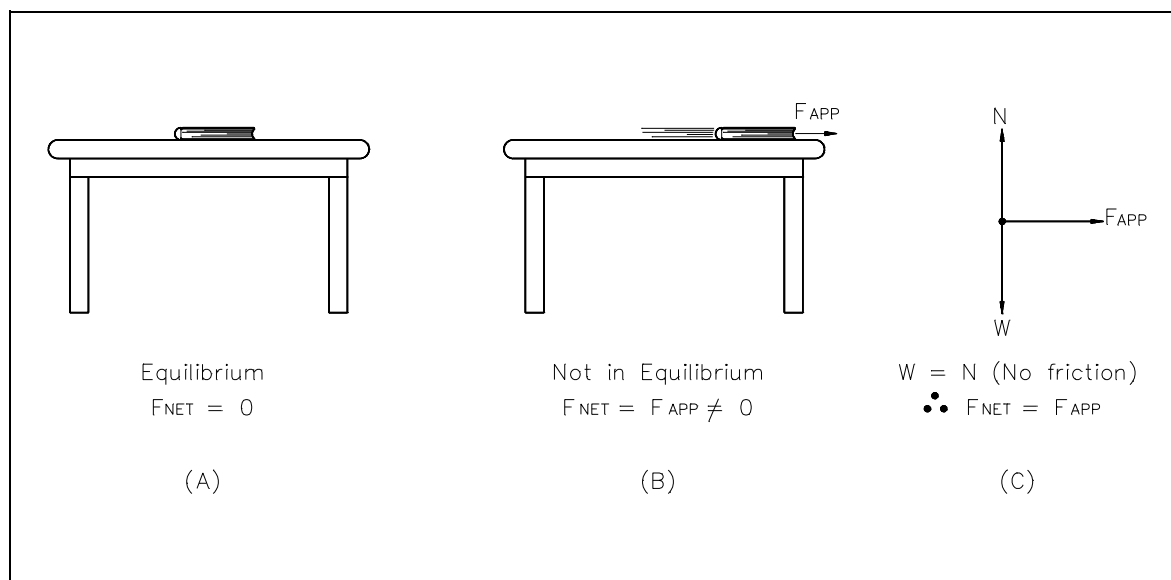


Figure 5 Net Force

The book remains stationary resting on the table because the table exerts a normal force upward equal to the weight of the book. Therefore, the net force on the book is zero. If a force is applied to the book (section B of Figure 5), and the effect of friction is neglected, the net force will be equal to the applied force, and the book will move in the direction of the applied force. The free-body diagram in section C of Figure 5 shows that the weight ( $W$ ) of the book is canceled by the normal force ( $N$ ) of the table since they are equal in magnitude but opposite in direction. The resultant (net) force is therefore equal to the applied force ( $F_{APP}$ ).

## **Equilibrium**

Since an object in equilibrium is considered to be in a state of balance, it can be surmised that the net force on the object is equal to zero. That is, if the vector sum of all the forces acting on an object is equal to zero, then the object is in equilibrium.

Newton's first law of motion describes equilibrium and the effect of force on a body that is in equilibrium. That law states "An object remains at rest (if originally at rest) or moves in a straight line with a constant velocity if the net force on it is zero." Newton's first law of motion is also called the law of inertia. *Inertia* is the tendency of a body to resist a change in its state of motion.

The first condition of equilibrium, a consequence of Newton's first law, may be written in vector form, "A body will be in translational equilibrium if and only if the vector sum of forces exerted on a body by the environment equals zero."

For example, if three forces act on a body it is necessary for the following to be true for the body to be in equilibrium.

$$F_1 + F_2 + F_3 = 0 \quad (4-3)$$

This equation may also be written as follows.

$$\Sigma F = 0 \quad (4-4)$$

This sum includes all forces exerted on the body by its environment. The vanishing of this vector sum is a necessary condition, called the first condition of equilibrium, that must be satisfied in order to ensure translational equilibrium. In three dimensions ( $x, y, z$ ), the component equations of the first condition of equilibrium are:

$$\Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \Sigma F_z = 0 \quad (4-5)$$

This condition applies to objects in motion with constant velocity and to bodies at rest or in static equilibrium (referred to as STATICS).

Applying the knowledge that an object in equilibrium has a net force equal to zero, the following example can be solved:

Example:

The object in Figure 6 has a weight of 125 lbf. The object is suspended by cables as shown. Calculate the tension ( $T_1$ ) in the cable at  $30^\circ$  with the horizontal.

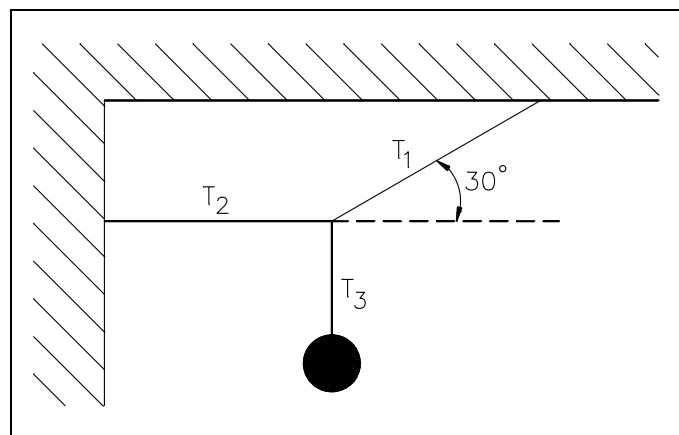


Figure 6 Hanging Object

The tension in a cable is the force transmitted by the cable. The tension at any point in the cable can be measured by cutting a suitable length from it and inserting a spring scale.

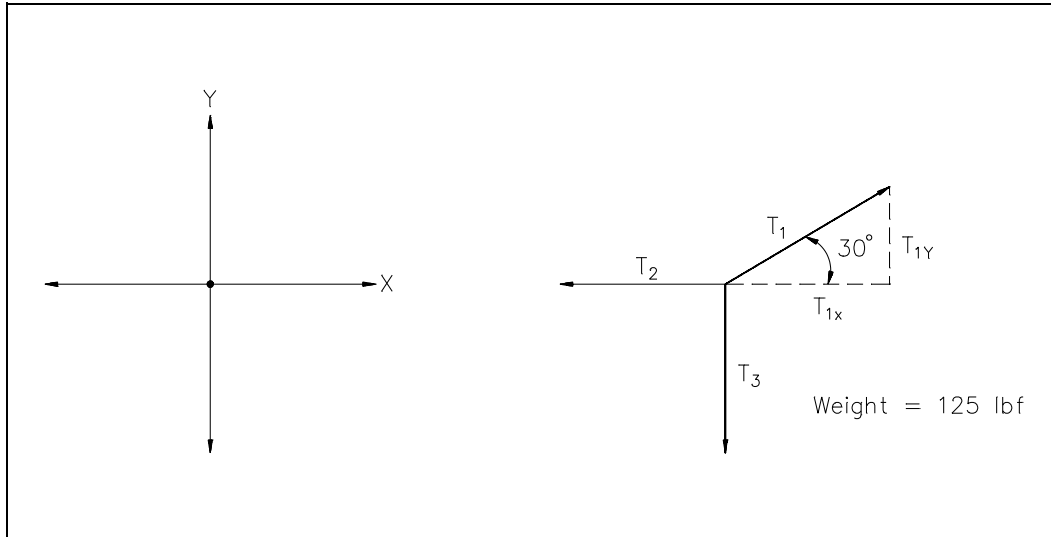


Figure 7 Free-Body Diagram

Solution:

Since the object and its supporting cables are motionless (i.e., in equilibrium), we know that the net force acting on the intersection of the cables is zero. The fact that the net force is zero tells us that the sum of the x-components of  $T_1$ ,  $T_2$ , and  $T_3$  is zero, and the sum of the y-components of  $T_1$ ,  $T_2$ , and  $T_3$  is zero.

$$\begin{aligned} \Sigma F_x &= T_{1x} + T_{2x} + T_{3x} = 0 \\ \Sigma F_y &= T_{1y} + T_{2y} + T_{3y} = 0 \end{aligned}$$

The tension  $T_3$  is equal to the weight of the object, 125 lbf. The  $x$  and  $y$  components of the tensions can be found using trigonometry (e.g., sine function). Substituting known values into the second equation above yields the following.

$$\begin{aligned} \Sigma F_y &= (T_1 \sin 30^\circ) + (T_2 \sin 180^\circ) + (T_3 \sin 270^\circ) = 0 \\ &= (T_1)(0.5) + (T_2)(0) + (125 \text{ lbf})(-1) = 0 \\ &0.5T_1 - 125 \text{ lbf} = 0 \\ &0.5T_1 = 125 \text{ lbf} \\ &T_1 = 250 \text{ lbf} \end{aligned}$$

A simpler method to solve this problem involves assigning a sign convention to the free-body diagram and examining the direction of the forces.

By choosing (+) as the upward direction and (-) as the downward direction, the student can determine by examination that 1) the upward component of  $T_1$  is  $+ T_1 \sin 30^\circ$ , 2) the tension  $T_3$  is -125 lbf, and 3)  $T_2$  has no  $y$ - component. Therefore, using the same equation as before, we obtain the following.

$$\begin{aligned}\sum F_y &= (T_1 \sin 30^\circ) - 125 \text{ lbf} = 0 \\ 0.5 T_1 &= 125 \text{ lbf} \\ T_1 &= 250 \text{ lbf}\end{aligned}$$

If the sum of all forces acting upon a body is equal to zero, that body is said to be in force equilibrium. If the sum of all the forces is not equal to zero, any force or system of forces capable of balancing the system is defined as an *equilibrant*.

Example:

A 2000 lbf car is accelerating (on a frictionless surface) at a rate of 2 ft-sec. What force must be applied to the car to act as an equilibrant for this system?

Solution: a. Draw a free-body diagram.

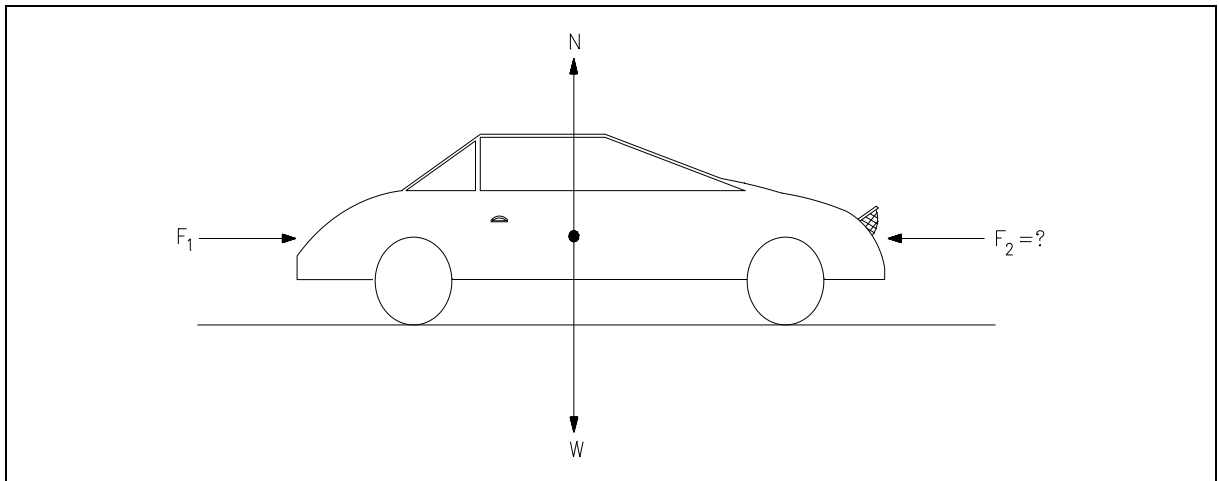


Figure 8 Free-Body Diagram

b. A Force,  $F_2$ , MUST be applied in the opposite direction to  $F_1$  such that the sum of all forces acting on the car is zero.

$$\sum \text{ Forces} = F_1 + F_2 + N + W = 0$$

- c. Since the car remains on the surface, forces N and W are in equal and opposite directions. Force  $F_2$  must be applied in an equal and opposite direction to  $F_1$  in order for the forces to be in equilibrium.

$$F_2 = F_1 = \frac{ma}{g_c} = (2000 \text{ lbm} \times 2 \text{ ft-sec}^2) \div 32.17 \frac{\text{ft-lbm}}{\text{lbf-sec}^2} \\ = 124 \text{ lbf}$$

## **Summary**

The concepts presented in this chapter are summarized below.

### **Force Equilibrium Summary**

- The force that is the resultant force of all forces acting on a body is defined as the net force.
- If the vector sum of all the forces acting on an object is equal to zero, then the object is in equilibrium.
- The first condition of equilibrium is stated as follows: "A body will be in translational equilibrium if and only if the vector sum of forces exerted on a body by the environment equals zero."

$$F_1 + F_2 + F_3 = 0 \\ \text{or} \\ \Sigma F = 0$$

- Any force or system of forces capable of balancing a system so that the net force is zero is defined as an equilibrant.



---

## TYPES OF FORCE

---

*When determining how an object reacts to a force or forces, it is important to understand the different types of forces that may act on the object.*

- EO 1.6**      **DEFINE** the following:
- a.**      **Tensile force**
  - b.**      **Compressive force**
  - c.**      **Frictional force**
- EO 1.7**      **EXPLAIN** the difference between a static-friction force and a kinetic-friction force.
- EO 1.8**      **STATE** two factors that affect the magnitude of the friction force.
- EO 1.9**      **EXPLAIN** the difference between centripetal force and centrifugal force.
- 

The previous section discussed the equilibrium of forces as they act on bodies. Recalling that a force is defined as a vector quantity that tends to produce an acceleration of a body in the direction of its application, it is apparent that the student must be acquainted with the various types of forces that exist in order to construct a correct free-body diagram and apply the appropriate equation. A force is applied either by direct mechanical contact or by remote action.

### **Tensile and Compressive Forces**

In discussing the types of forces, a simple rule is used to determine if the force is a tensile or a compressive force. If an applied force on a member tends to pull the member apart, it is said to be in *tension*. If a force tends to compress the member, it is in *compression*. It should also be mentioned that ropes, cables, etc., that are attached to bodies can only support tensile loads, and therefore such objects are in tension when placed on the free-body diagram. In addition, when a fluid is involved, it should be understood that fluid forces are almost always compressive forces.

### **Friction**

Another type of force often used in classical physics is the force resulting from two surfaces in contact, where one of the surfaces is attempting to move parallel to or over the other surface. Such forces are referred to as *friction forces*. There are two types of friction forces: those due to dry friction, sometimes called Coulomb friction, and those resulting from fluid friction.

Fluid friction develops between layers of fluid moving at different velocities. This type of frictional force is used in considering problems involving the flow of fluids through pipes. Such problems are covered in the Fundamentals Manual on fluid flow. In this section, problems involving rigid bodies which are in contact along dry surfaces are considered.

The laws of dry friction are best understood by the following experiment. A block of weight  $W$  is placed on a horizontal plane surface (see Figure 9). The forces acting on the block are its weight  $W$  and the normal force  $N$  of the surface. Since the weight has no horizontal component, the normal force of the surface also has no horizontal component; the reaction is therefore normal to the surface and is represented by  $N$  in part (a) of the figure. Suppose now, that a horizontal force  $P$  is applied to the block (see part (b)). If  $P$  is small, the block will not move. Some other horizontal force must therefore exist which balances  $P$ . This other force is the static-friction force  $F$ , which is actually the resultant of a great number of forces acting over the entire surface of contact between the block and the plane. The nature of these forces is not known exactly, but it is generally assumed that these forces are due to the irregularities of the surfaces in contact and also to molecular action.

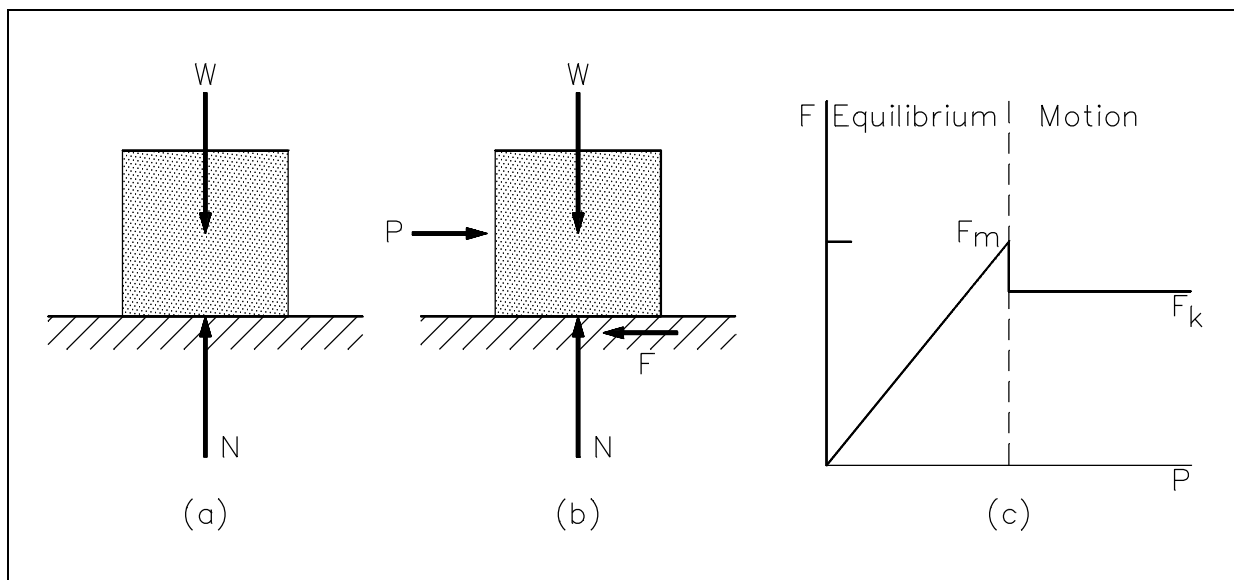


Figure 9 Frictional Forces

If the force  $P$  is increased, the friction force  $F$  also increases, continuing to oppose  $P$ , until its magnitude reaches a certain maximum value  $F_M$  (see part (c) of Figure 9). If  $P$  is further increased, the friction force cannot balance it any more, and the block starts sliding. As soon as the block has been set in motion, the magnitude of  $F$  drops from  $F_M$  to a lower value  $F_K$ . This is because there is less interpenetration between the irregularities of the surfaces in contact when these surfaces move with respect to one another. From then on, the block keeps sliding with increasing velocity (i.e., it accelerates) while the friction force, denoted by  $F_K$  and called the kinetic-friction force, remains approximately constant.

Experimental evidence shows that the maximum value  $F_M$  of the static-friction force is proportional to the normal component  $N$  of the reaction of the surface, as shown in Equation 4-5.

$$F_M = \mu_s N \quad (4-5)$$

The term  $\mu_s$  is a constant called the coefficient of static friction. Similarly, the magnitude  $F_K$  of the kinetic-friction force may be expressed in the following form.

$$F_K = \mu_K N \quad (4-6)$$

The term  $\mu_K$  is a constant called the coefficient of kinetic friction. The coefficients of friction,  $\mu_s$  and  $\mu_K$ , do not depend upon the area of the surfaces in contact. Both coefficients, however, depend strongly on the nature of the surfaces in contact. Since they also depend upon the exact condition of the surfaces, their value is seldom known with an accuracy greater than 5 percent. It should be noted that frictional forces are always opposite in direction to the motion (or impending motion) of the object.

## **Centripetal Force**

An object moving at constant speed in a circle is not in equilibrium. Although the magnitude of the linear velocity is not changing, the direction of velocity is continually changing. Since a change in direction requires acceleration, an object moving in a circular path has a constant acceleration towards the center of the circular path.

Recalling Newton's second law of motion,  $F = ma$ , a force is required to cause acceleration. Therefore, to have constant acceleration towards the center of the circular path, there must be a net force acting towards the center. This force is known as centripetal force. Without this force, an object will move in a straight line. Figure 10 illustrates the centripetal force.

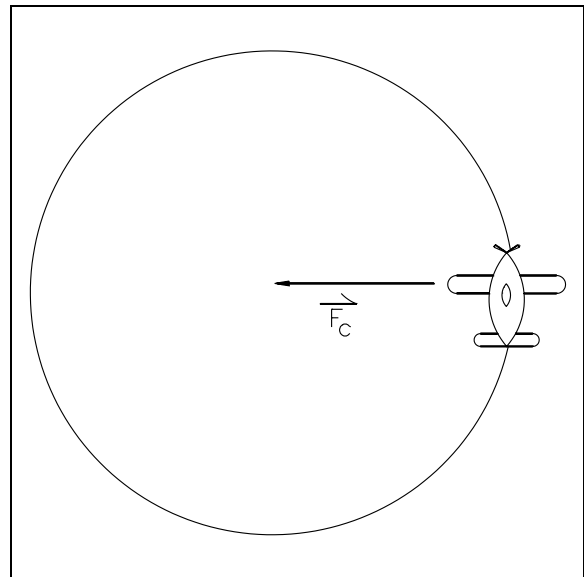


Figure 10 Centripetal Force

**Centrifugal Force**

Another force, which appears to be opposite the direction of motion, is the centrifugal force acting on an object that follows a curved path. This force appears to be a force directed away from the center of the circular path. This is actually a fictitious force, but is an apparent force that is used to describe the forces present due to an object's rotation.

To better understand centripetal and centrifugal forces, consider that a string is attached to the plane in Figure 10. As the plane rotates about the center, the string places a centripetal force on the plane. This

causes the plane's velocity to change in direction, thus causing it to travel in a circle.

The apparent outward force, centrifugal force, seems to pull the plane away from the center shown in Figure 11. This is the same apparent outward force one feels when riding in a car when the car travels in a circle. It can be proven that centrifugal force is not an actual force by cutting the string. In doing so, the plane will fly off in a straight line that is tangent to the circle at the velocity it had the moment the string was cut. If there were an actual centrifugal force present, the plane would not fly away in a line tangent to the circle, but would fly directly away from the circle (see Figure 12).

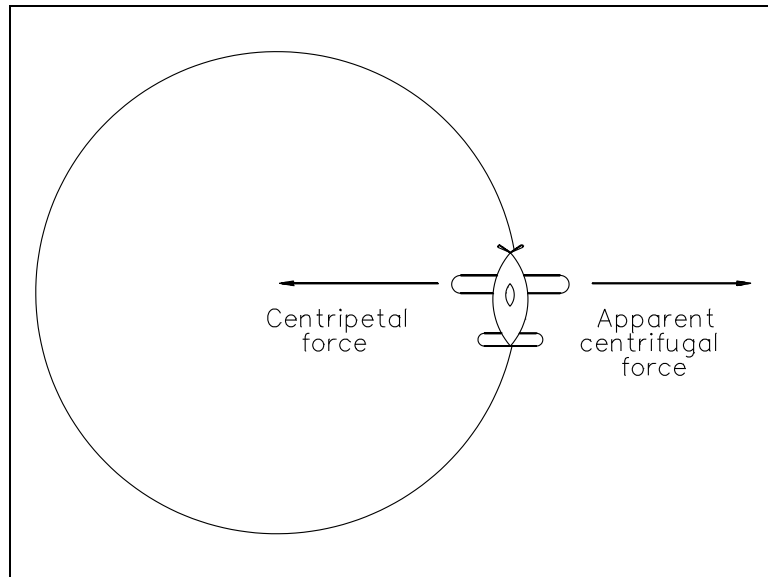


Figure 11 Centrifugal Force

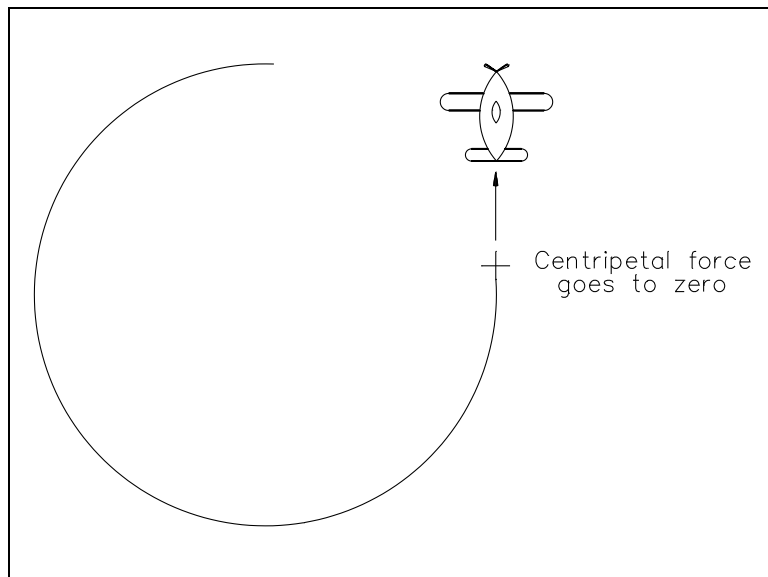


Figure 12 Loss of Centripetal Force

## **Summary**

The concepts of this chapter are summarized below.

### **Types of Force Summary**

- A tensile force is an applied force that tends to pull an object apart.
- A compressive force is an applied force that tends to compress an object.
- Frictional force is the force resulting from two surfaces in contact, where one of the surfaces is attempting to move with respect to the other surface.
- Static-frictional forces are those frictional forces present when an object is stationary, whereas kinetic-frictional forces are those frictional forces present between two objects that are moving.
- The magnitude of the frictional force is affected by the following:
  - Weight of the object being moved
  - Type of surface on the object being moved
  - Type of surface on which the object is moving.
- Centripetal force is the force on an object moving in a circular path that is directed towards the center of the path, whereas the centrifugal force is the fictitious force that appears to be directed away from the center of the circular path.

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**Department of Energy  
Fundamentals Handbook**

**CLASSICAL PHYSICS  
Module 5  
Energy, Work, and Power**

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## **TERMINAL OBJECTIVE**

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- 1.0 Given necessary information about a system, **CALCULATE** the work performed and/or power produced or used by that system.

---

## **ENABLING OBJECTIVES**

---

- 1.1 **DEFINE** the following terms:
- a. Energy
  - b. Potential energy
  - c. Kinetic energy
  - d. Work
  - e. Power
- 1.2 **STATE** the mathematical expression for:
- a. Potential energy
  - b. Kinetic energy
  - c. Work
  - d. Power
- 1.3 For a mechanical system, **CALCULATE** energy, work, and power.
- 1.4 **STATE** the First Law of Thermodynamics, "Conservation of Energy."

---

## ENERGY AND WORK

---

*Energy is the measure of the ability to do work or cause a change. Work is a measure of the amount of energy required to move an object.*

- EO 1.1**      **DEFINE** the following terms:
- a.      **Energy**
  - b.      **Potential energy**
  - c.      **Kinetic energy**
  - d.      **Work**
- EO 1.2**      **STATE** the mathematical expression for:
- a.      **Potential energy**
  - b.      **Kinetic energy**
  - c.      **Work**
- EO 1.3**      **For a mechanical system, CALCULATE** energy, work, and power.
- 

### Energy

*Energy* is defined as the measure of the ability to do work. Energy determines the capacity of a system to perform work and may be stored in various forms. Some of the more basic mechanical systems involve the concepts of potential and kinetic energy. Both of these terms will be explained more fully later in this chapter. More advanced systems may include other types of energy such as chemical, electromagnetic, thermal, acoustic, and nuclear. A piledriver hammer performs work by virtue of its falling motion. Coal burned in a fossil-fueled power plant is undergoing energy release by a chemical reaction. Fuel elements in a nuclear power reactor produce energy by a nuclear reaction. For the purposes of this course, our discussions will be limited to mechanical and thermal forms of energy (e.g., heat). It should be noted, however, that the principles involved with energy calculations are similar for all types of energy.

Both thermal and mechanical energy can be separated into two categories, transient and stored. Transient energy is energy in motion, that is, energy being transferred from one place to another. Stored energy is the energy contained within a substance or object. Both of these categories of energy will be discussed in this module.

### Potential Energy

*Potential energy* is defined as the energy stored in an object because of its position. An example is the potential energy of an object above the surface of the earth in the earth's gravitational field. Potential energy also applies to energy due to separation of electrical charge and to energy stored in a spring, in other words, energy due to position of any force field.

As an example, consider the energy stored in hydrogen and oxygen as potential energy to be released on burning. Burning changes their relative separation distance from the elemental form to the compound form as water releases the potential energy.

When discussing mechanical potential energy, we look at the position of an object. The measure of an object's position is its vertical distance above a reference point. The reference point is normally the earth's surface, but can it be any point. The potential energy of the object represents the work required to elevate the object to that position from the reference point. Potential energy is mathematically represented by Equation 5-1.

$$PE = \text{work to elevate} = \text{weight} \times \text{height} = \frac{mgz}{g_c} \quad (5-1)$$

where:

$$\begin{aligned} PE &= \text{potential energy in ft-lbf} \\ m &= \text{mass in lbm} \\ g &= 32.17 \text{ ft/sec}^2 \\ g_c &= 32.17 \text{ (lbm-ft)/(lbf-sec}^2\text{)} \\ z &= \text{height above a reference in ft} \end{aligned}$$

It should be noted the  $g_c$  is used only when using the English system of measurement.

Example: What is the potential energy of a 50 lbm object suspended 10 feet above the ground?

$$PE = \frac{mgz}{g_c} = \left( \frac{50 \text{ lbm}}{1} \right) \left( \frac{32.17 \text{ ft}}{\text{sec}^2} \right) \left( \frac{10 \text{ ft}}{1} \right) \left( \frac{\text{lbf-sec}^2}{32.17 \text{ lbm-ft}} \right)$$

Answer: PE = 500 ft-lbf

## **Kinetic Energy**

Kinetic energy is defined as the energy stored in an object because of its motion. If you have a baseball in your hand, it has no kinetic energy because it is not moving. But if you throw the ball, your hand has provided energy to give the ball motion. When you release the ball, it leaves your hand at some velocity. The energy you have given the ball will determine the velocity of the ball. Because the kinetic energy is due to the motion of the object, and motion is measured by velocity, kinetic energy can be calculated in terms of its velocity, as shown below.

$$KE = \frac{mv^2}{2g_c} \quad (5-2)$$

where:

$$\begin{aligned} \text{KE} &= \text{kinetic energy in ft-lbf} \\ m &= \text{mass in lbm} \\ v &= \text{velocity in ft/sec} \\ g_c &= (32.17 \text{ lbm-ft})/(\text{lbf-sec}^2) \end{aligned}$$

Example: What is the kinetic energy of a 10 lbm object that has a velocity of 8 ft/sec?

$$\begin{aligned} \text{KE} &= \frac{mv^2}{2g_c} = \left( \frac{10 \text{ lbm}}{2} \right) \left( \frac{8 \text{ ft}}{\text{sec}} \right)^2 \left( \frac{\text{lbf-sec}^2}{32.17 \text{ lbm-ft}} \right) \\ \text{KE} &= (5 \text{ lbm}) \left( \frac{64 \text{ ft}^2}{\text{sec}^2} \right) \left( \frac{\text{lbf-sec}^2}{32.17 \text{ lbm-ft}} \right) \end{aligned}$$

Answer: KE = 9.95 ft-lbf

The kinetic energy of an object represents the amount of energy required to increase the velocity of the object from rest ( $v = 0$ ) to its final velocity, or the work it can do as it pushes against something in slowing down (waterwheel or turbine, for example.)

## **Thermal Energy**

*Thermal energy* is that energy related to temperature (the higher the temperature, the greater the molecular movement, and the greater the energy). If one object has more thermal energy than an adjacent substance, the substance at the higher temperature will transfer thermal energy (at a molecular level) to the other substance. Note that the energy is moving from one place to another (it is in motion) and is referred to as transient energy or, more commonly in the case of thermal energy, heat.

The only stored energy in a solid material is internal energy. Internal energy is the energy stored in a substance because of the motion and position of the particles of the substance. Heat and internal energy will be covered in the Fundamentals Manual on Heat Transfer, Fluid Flow, and Thermodynamics.

## **Mechanical Energy**

*Mechanical energy* is energy related to motion or position. Transient mechanical energy is commonly referred to as work. Stored mechanical energy exists in one of two forms: kinetic or potential. Kinetic and potential energy can be found in both fluids and solid objects.

## **Work**

Work is commonly thought of as any activity requiring exertion. However, the definition in physics is much more specific. *Work* is done by a force acting on a moving object if the object has some component of motion in the direction of the force. Work can be done **BY** a person, a machine, or an object by applying a force and causing something to move. More specifically, work is done by a force acting on a moving object if the object has some component of motion in the direction of the force. Work can be done **ON** an object by applying a force that causes it to move. For example, if you push on a box (apply a force) and it moves three feet, work has been performed **BY** you to the box, while work has been performed **ON** the box. If you push on the box and it does not move, then work, by our definition, has not been accomplished. Work can be defined mathematically by Equation 5-3.

$$W = F \times d \quad (5-3)$$

where:

- W = work done in ft-lbf
- F = force applied to the object in lbf
- d = distance the object is moved (in ft.) with the force applied

**Example:** You push a large box for three minutes. During that time, you exert a constant force of 200 lbf to the box, but it does not move. How much work has been accomplished?

$$\begin{aligned} W &= F \times d \\ W &= 200 \text{ lbf} \times 0 \text{ ft} \\ W &= 0 \text{ ft-lbf work done} \end{aligned}$$

Remember that if no movement is achieved, no work has been accomplished. Even if you feel fatigued, no work has been done. Work can be thought of as what has been accomplished. If nothing is accomplished, then no work has been done.

**Example:** You push the same box as mentioned above. You apply a horizontal force of 200 lbf to the box, and the box moves five feet horizontally. How much work have you done?

$$\begin{aligned} W &= F \times d \\ W &= 200 \text{ lbf} \times 5 \text{ ft} \\ W &= 1000 \text{ ft-lbf} \end{aligned}$$

In this case, work can be described as work done by the person pushing the box or work performed on the box. In either case, the amount of work is the same.



## **Summary**

The main points covered in this chapter are summarized below.

### **Energy and Work Summary**

- Energy is the ability to do work.
- The work done by a force on an object is the product of the force and the distance the object moves in the direction of the force.
- Kinetic energy is the energy an object has because of its motion.
- $KE = \frac{mv^2}{2g_c}$  or  $KE = \frac{1}{2} mv^2$
- Potential energy is the energy of an object due to its position.
- $PE = \frac{mgz}{g_c}$

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## LAW OF CONSERVATION OF ENERGY

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*Energy does not simply appear and disappear. Energy is transferred from one position to another or transformed from one type of energy to another.*

**EO 1.4 STATE the First Law of Thermodynamics, "Conservation of Energy."**

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### Conservation of Energy

The First Law of Thermodynamics is simply stated "energy cannot be created or destroyed, only altered in form." In the previous chapter, we discussed potential energy, where a force is applied to an object, raising it from some point of origin to some height. The energy expended in raising the object is equivalent to the potential energy gained by the object because of its height. This is an example of a transfer of energy as well as an alteration of the type of energy. Another example is throwing a baseball. While the ball is in your hand, it contains no kinetic energy. You apply a force to the ball by throwing it. The ball leaves your hand with a velocity, giving it kinetic energy equal to the work applied by your hand. Mathematically, this can be described by the following simplified equation.

$$\text{Energy}_{\text{initial}} + \text{Energy}_{\text{added}} - \text{Energy}_{\text{removed}} = \text{Energy}_{\text{final}} \quad (5-4)$$

where:

$\text{Energy}_{\text{initial}}$  is energy initially stored in an object/substance. This energy can exist in various combinations of kinetic energy and potential energy.

$\text{Energy}_{\text{added}}$  is energy added to the object/substance. Heat can be added. Energy can be added in the form of stored energy in any mass added, such as water to a fluid system. Work can be done on a system. Heat is energy gained or lost at a microscopic level. Work is the same at a macroscopic level.

$\text{Energy}_{\text{removed}}$  is energy removed from an object/substance. Heat can be rejected. Work can be done by the system. This energy can be in the form of energy stored in any mass removed.

$\text{Energy}_{\text{final}}$  is energy remaining within the object/substance after all energy transfers and transformations occur. This energy can exist in various combinations of kinetic, potential, flow, and internal energy.

To further describe each of the components of the above equation, each component can be broken down as follows:

$$\text{Energy}_{\text{initial}} = \text{KE}_1 + \text{PE}_1$$

$$\text{Energy}_{\text{added}} = \text{Work done on and heat added to the system}$$

$$\text{Energy}_{\text{removed}} = \text{Work done by and heat removed from the system}$$

$$\text{Energy}_{\text{final}} = \text{KE}_2 + \text{PE}_2$$

The resulting energy balance is provided in Equation 5-5.

$$\text{KE}_1 + \text{PE}_1 + E_{\text{added}} - E_{\text{removed}} = \text{KE}_2 + \text{PE}_2 \quad (5-5)$$

Neglecting any heat removed or added to a system, we can replace  $E_{\text{added}}$  and  $E_{\text{removed}}$  in Equation 5-5 with their associated work terms to obtain Equation 5-6.

$$\text{KE}_1 + \text{PE}_1 + W_{\text{on}} = \text{KE}_2 + \text{PE}_2 + W_{\text{by}} \quad (5-6)$$

The final energy balance is called a "simplified energy balance." Any energy balance is a statement of the Law of Conservation of Energy. In this simplified form, the balance applies only to mechanical problems, since we neglected heat. However, more specific energy balances that include heat will be discussed in other Fundamental Manuals. For example, specific energy balances for flow systems will be discussed in the Heat Transfer, Fluid Flow, and Thermodynamics modules.

## **Summary**

The law of conservation of energy is summarized below.

### **Conservation of Energy Summary**

- Energy cannot be created or destroyed, only altered in form.
- Simplified energy balance:

$$\text{KE}_1 + \text{PE}_1 + E_{\text{added}} = \text{KE}_2 + \text{PE}_2 + E_{\text{removed}}$$

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## POWER

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*Power is a measure of the rate at which energy is used. Thermal power is the term used to refer to the transfer of heat. Mechanical power is the term used to describe when work is being done.*

- EO 1.1**      **DEFINE** the following terms:  
e.      **Power**
- EO 1.2**      **STATE** the mathematical expression for:  
d.      **Power**
- EO 1.3**      **For a mechanical system, CALCULATE** energy, work, and power.
- 

### Power

*Power* is defined as the amount of energy used per unit time or rate of doing work. It has the units of watt, Btu/hr, horsepower, or ft-lbf/sec.

### Thermal Power

*Thermal power* is the measure of thermal energy used per unit time. It is the rate of heat transfer or heat flow rate. Examples of thermal power units are British Thermal Units (Btu) or kilowatts (Kw). Thermal power is calculated basically by the mathematical expression of:

$$\text{Thermal Power} = \frac{\text{heat used}}{\text{time required}}$$

Thermal energy and calculations of thermal power will be covered in more detail in the Fundamentals Manual for Heat Transfer, Fluid Flow, and Thermodynamics.

## **Mechanical Power**

Mechanical energy used per unit time is called *mechanical power*. Mechanical power is the rate at which work is done. Mechanical power is expressed in units of joules/sec (joules/s) or a watt (W) in the mks system, and feet - pounds force per second (ft-lbf/s) or horsepower (hp) in the English system. Mechanical power can be calculated using the following mathematical expression.

$$\text{Power} = \frac{\text{work done}}{\text{time required}}$$

Because work can be defined as force times distance, we can also use the following equation:

$$P = \frac{Fd}{t} \quad (5-6)$$

where:

$$\begin{aligned} P &= \text{Power (W or ft-lbf/s)} \\ F &= \text{Force (N or lbf)} \\ d &= \text{distance (m or ft)} \\ t &= \text{time (sec)} \end{aligned}$$

One horsepower is equivalent to 550 ft-lbf/s and 745.7 watts. Because in the equation above  $d$  divided by  $t$  is the same as velocity, an alternate description of power is as follows.

$$P = \frac{Fv}{550} \quad (5-7)$$

where:

$$\begin{aligned} P &= \text{power (hp)} \\ F &= \text{force (lbf)} \\ v &= \text{velocity (ft/s)} \end{aligned}$$

When using equations 5-6 or 5-7, you must either assume force and velocity are constant or that average values of the force and velocity are used.

Example 1: A pump provides a flow rate of 10,000 gpm. The pump does  $1.5 \times 10^8$  ft-lbf of work every 100 minutes. What is the power of the pump in hp?

$$\text{Power} = \frac{\text{work done}}{\text{time required}}$$

$$P = \left( \frac{1.5 \times 10^8 \text{ ft-lbf}}{100 \text{ min}} \right) \left( \frac{1 \text{ min}}{60 \text{ sec}} \right) \left( \frac{1 \text{ hp}}{550 \text{ ft-lbf/sec}} \right)$$

$$P = 45.5 \text{ hp}$$

Example 2: A boy rolls a ball with a steady force of 1 lbf, giving the ball a constant velocity of 5 ft/s. What is the power used by the boy in rolling the ball?

$$P = \frac{Fv}{550}$$

$$P = \frac{(1 \text{ lbf})(5 \text{ ft/sec})}{550}$$

$$P = 9 \times 10^{-3} \text{ hp}$$

Example 3: A race car traveling at constant velocity can go one quarter mile (1455 ft) in 5 seconds. If the motor is generating a force of 1890 lbf pushing the car, what is the power of the motor in hp? Assume the car is already at full speed at  $t=0$ .

$$P = \frac{Fd}{t}$$

$$P = \left[ \frac{(1890 \text{ lbf})(1455 \text{ ft})}{5 \text{ sec}} \right] \left[ \frac{1 \text{ hp}}{550 \text{ ft-lbf/sec}} \right]$$

$$P = 1000 \text{ hp}$$

or

$$P = \frac{Fv}{550}$$

$$P = \frac{(1890 \text{ lbf})(291 \text{ ft/sec})}{550}$$

$$P = 1000 \text{ hp}$$

## **Summary**

The main points of this chapter are summarized below.

### **Power Summary**

- Power is the amount of energy used per unit time.
- Power =  $\frac{\text{work done}}{\text{time required}}$

end of text.

CONCLUDING MATERIAL

Review activities:

DOE - ANL-W, BNL, EG&G Idaho,  
EG&G Mound, EG&G Rocky Flats,  
LLNL, LANL, MMES, ORAU, REEC<sub>o</sub>,  
WHC, WINCO, WEMCO, and WSRC.

Preparing activity:

DOE - NE-73  
Project Number 6910-0016