5.1

Forces and the Law of Combination

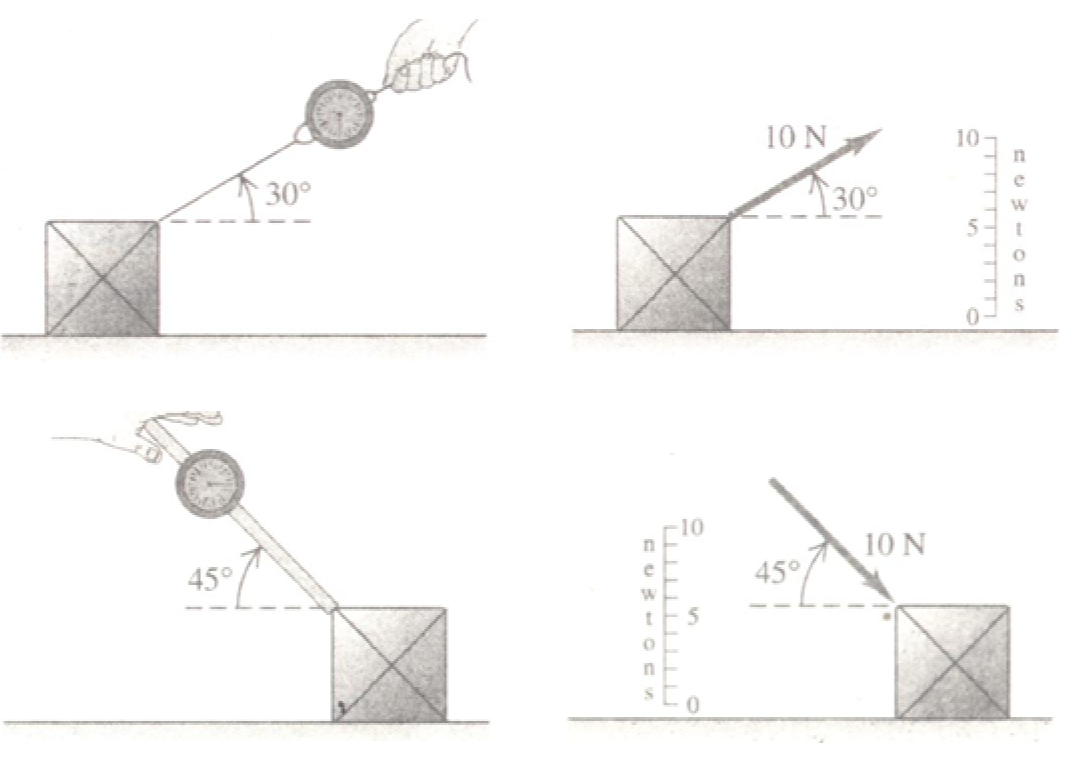
A ***force*** is a push or pull. The concept of a force gives a quantitative description of the interaction between two bodies or between a body and its environment. When you push a car, you exert a force on it. A steel cable exerts a force on the beam it is hoisting at a construction site.

When a force involves direct contact between two bodies, it is called a ***contact force***. Examples of contact forces are the pushes and pulls exerted by the hand, the force of a rope pulling on a block, and the friction force that the ground exerts on a sliding block.

There are also forces, called ***long-range forces*** or ***field forces***, which act even when the bodies are separated by empty space. Gravity is a field force; the sun exerts a gravitational pull on the earth that keeps the earth in orbit. The force of gravitational attraction that the earth exerts on objects is called the weight of objects.

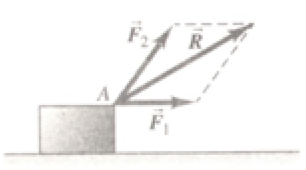
Force is a vector quantity; you can push or pull a body in different directions. Thus, to describe a force, we need to describe the *direction* in which it acts as well as its *magnitude*. The SI unit of the magnitude of the force is *newton*, N.

Suppose we slide a box along the floor, applying a force to it by pulling it with a string or pushing it with a stick. In each case we draw a vector to represent the force applied.



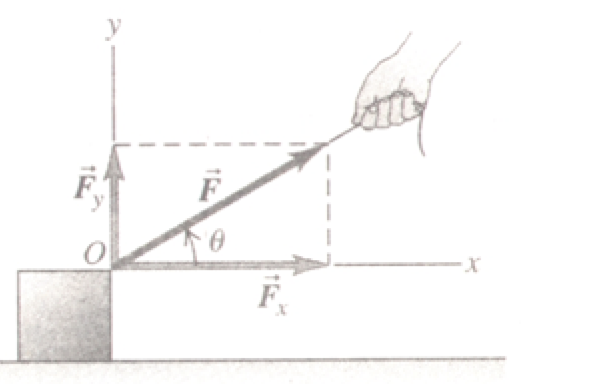
The labels indicate the magnitude and direction of the force, and the length of the arrow (drawn to some scale, such as 1 cm = 10 N) also shows the magnitude.

When two forces $\mathbf{F}_1$ and $\mathbf{F}_2$ act at the same time at a point A of a body, experiment shows that the effect on the body's motion is the same as the effect of a single force **R** equal to the vector sum of the original forces: $\mathbf{R} = \mathbf{F}_1 + \mathbf{F}_2$.



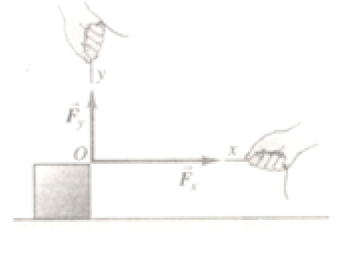
More generally, the effect of any number of forces applied at a point on a body is the same as the effect of a single force equal to the vector sum of the forces. This principle is known as ***superposition of forces***.

The experimental discovery that forces combine according to vector addition allows us to replace a force by its component vectors. For example, in the figure below, force **F** acts on a body at point O. The component vectors of **F** in the direction of Ox and Oy are $\mathbf{F}_x$ and $\mathbf{F}_y$.



Component vectors: $\vec{F}_x$ and $\vec{F}_y$
Components: $F_x = F\cos\theta$ and $F_y = F\sin\theta$

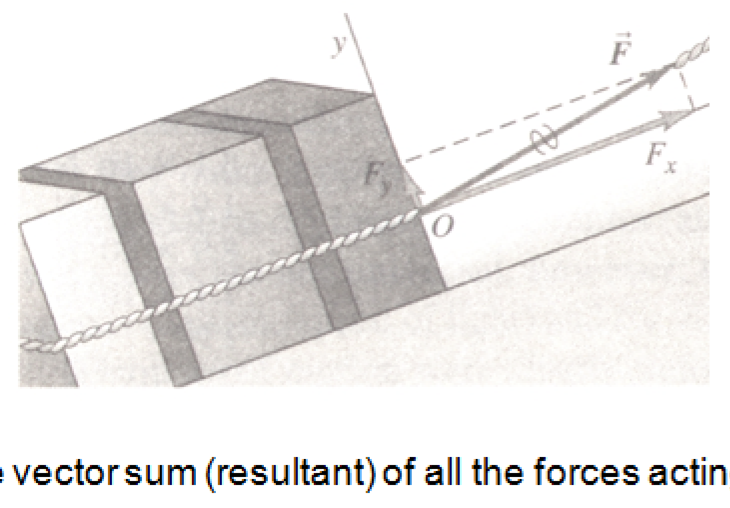
When $\mathbf{F}_x$ and $\mathbf{F}_y$ are applied simultaneously, as shown in the figure below, the effect is exactly the same as the effect of the original force **F**.



Component vectors $\vec{F}_x$ and $\vec{F}_y$ together have the same effect as original force $\vec{F}$.

Any force can be replaced by its component vectors, acting at the same point. It is convenient to describe a force **F** in terms of its *x*- and *y*-components F_x and F_y rather than by its component vectors. For the case shown in the figure above, both F_x and F_y are positive; for other orientations of the force **F**, either F_x or F_y can be negative or zero.

The coordinate axes need not be horizontal and vertical. Figure below shows a crate being pulled up a ramp by a force **F**, represented by the components F_x and F_y parallel and perpendicular to the sloping surface of the ramp.



The vector sum (resultant) of all the forces acting on a body is called the ***net force*** acting on the body. If the forces are labeled $\mathbf{F}_1$, $\mathbf{F}_2$, $\mathbf{F}_3$, and so on, we abbreviate the sum as

$$\mathbf{R} = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 + \ldots = \Sigma\,\mathbf{F}$$

where $\Sigma\,\mathbf{F}$ is read as "the vector sum of the forces" or "the net force." The component version of this equation is the pair of component equations

$$R_x = \sum F_x \qquad R_y = \sum F_y$$

where $\sum F_x$ is the sum of the *x*-components, and so on. Each component may be positive or negative. Once we have R_x and R_y, we can find the magnitude and direction of the net force $\mathbf{R} = \Sigma\,\mathbf{F}$ acting on the body. The magnitude is

$$R = \sqrt{R_x^2 + R_y^2}$$

and the angle θ between **R** and the +*x*-axis can be found from the relation $\tan\theta = \frac{R_y}{R_x}$. The components R_x and R_y may be positive, negative, or zero, and the angle θ may be in any of the four quadrants.

In three-dimensional problems, forces may also have *z*-components; then we have the equations

$$R_x = \sum F_x \qquad R_y = \sum F_y \qquad R_z = \sum F_z$$

The magnitude of the net force is then

$$R = \sqrt{R_x^2 + R_y^2 + R_z^2}$$

5.2

Newton's First Lawa

In the previous module, we have learnt how several forces are combined to yield a net force, or the resultant force, that has the same effect as the combination of the individual forces. In this and the next module, we learn how forces affect motion. First, we consider the case when the net force on a body is zero. If a body is at rest, and if no net force acts on it (that is, no net push or pull), we might agree that the body will remain at rest. On the other hand, if the body is in motion, we wish to inquire what happens if there is a zero net force acting on it.

Suppose you slide a disk along a horizontal table top, applying a horizontal force to it with your hand. After you withdraw your hand, the disk slows down and stops. Now imagine pushing the disk across the smooth surface of a freshly waxed floor. After you quit pushing, the disk will slide a lot farther before it stops. In both cases, what slows the disk down is *friction*, an interaction between the lower surface of the disk and the surface on which it slides; the magnitude of the friction is different. The slippery waxed floor exerts less friction than the table top, so the disk travels farther. If we could eliminate friction completely, the disk would never slow down, and we need no force at all to keep the disk moving once it had been started.

Experiments show that when no net force acts on a body, the body either remains at rest or moves with constant velocity in a straight line. In other words:

> *A body acted on by no net force moves with constant velocity (which may be zero) and zero acceleration.*

This is ***Newton's first law of motion***.

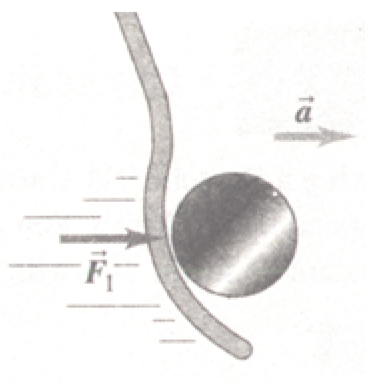
The tendency of a body to keep moving once it is set in motion results from a property called ***inertia***. The tendency of a body at rest to remain at rest is also due to inertia.

It is important to note that the *net* force is what matters in Newton's first law. For example, a book at rest on a horizontal table top has two forces acting on it: the downward force of the earth's gravitational attraction (a field force) and an upward supporting force exerted by the table top (a contact force). The upward push of the table surface is just as great as the downward pull of gravity, so the net force acting on the book (that is, the vector sum of the two forces) is zero. In agreement with Newton's first law, if the book is at rest on the table top, it remains at rest.

The same principle applies to a block sliding on a horizontal, frictionless surface: The vector sum of the upward push of the surface and the downward pull of gravity is zero. Once the block is in motion, it continues to move with constant velocity because the net force acting on it is zero.

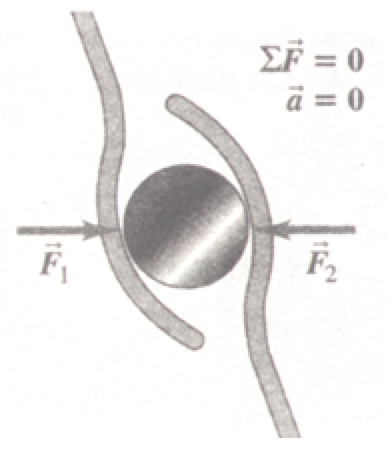
The upward supporting force of the surface is called a ***normal force*** because it is normal, or perpendicular, to the surface of contact.

We consider another example of a disk resting on a horizontal surface with negligible friction, such as a slab of wet ice. If the disk is initially at rest and a single horizontal force $\mathbf{F}_1$ acts on it, the disk starts to move.



If the disk is in motion to begin with, the force changes its speed, its direction, or both, depending on the direction of the force. In this case the net force is equal to $\mathbf{F}_1$, which is *not* zero. (There are also two vertical forces: the earth's gravitational attraction and the upward contact force exerted by the surface. But these two forces cancel.)

Now suppose we apply a second force $\mathbf{F}_2$, equal in magnitude to $\mathbf{F}_1$ but opposite in direction.



The two forces are negatives of each other, $\mathbf{F}_2 = -\mathbf{F}_1$, and their vector sum is zero:

$$\Sigma \mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2 = \mathbf{F}_1 + (-\mathbf{F}_1) = 0$$

Again, we find that if the body is at rest at the start, it remains at rest: if it is initially moving, it continues to move in the same direction with constant speed. These results show that in Newton's first law, *zero net force is equivalent to no forces at all.*

When a body is acted on by no forces, or by several forces such that their vector sum (resultant) is zero, we say that the body is in ***equilibrium***. In equilibrium, a body is either at rest or moving in a straight line with constant velocity. For a body in equilibrium, the net force is zero:

$$\Sigma \mathbf{F} = 0$$

For this to be true, each component of the net force must be zero, so

$$\sum F_x = 0 \qquad \sum F_y = 0$$

When these equations are satisfied, the body is in equilibrium.

We are assuming that the body can be represented adequately as a point particle. When the body has finite size, we also have to consider where on the body the forces are applied. This aspect will be considered in a later unit.

5.3

Newton's Second Law

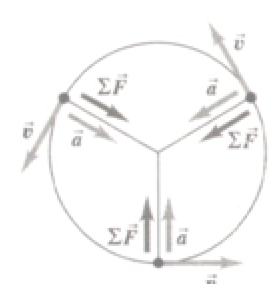
Suppose a disk is sliding to the right on wet ice (so there is negligible friction). There are no horizontal forces acting on the disk; the downward force of gravity and the upward contact force exerted by the ice surface sum to zero. So, the net force **ΣF** acting on the disk is zero, the disk has zero acceleration, and its velocity is constant.

We, now, apply a constant horizontal force to the sliding disk in the same direction that the disk is moving. Then **ΣF** is constant and in the same horizontal direction as **v**. We find that during the time the force is acting, the velocity of the disk changes at a constant rate; that is, the disk moves with constant acceleration. The speed of the disk increases, so the acceleration **a** is in the same direction as **v** and **ΣF**.

We consider another experiment, in which we reverse the direction of the force on the disk so that **ΣF** acts in the direction opposite to **v**. In this case, the disk moves more and more slowly to the right. If the leftward force continues to act, the disk eventually stops and begins to move more and more rapidly to the left. The acceleration **a** in this experiment is to the left, in the same direction as **ΣF**. As in the previous case, experiment shows that the acceleration is constant if **ΣF** is constant.

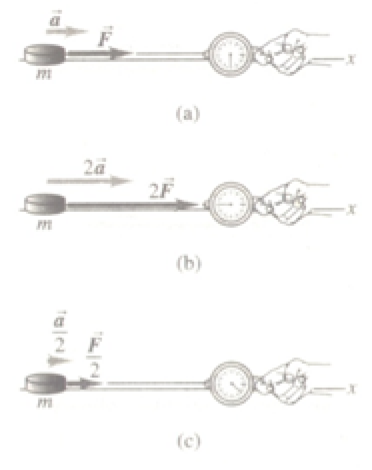
We conclude that the presence of a net force acting on a body causes the body to accelerate. The direction of the acceleration is the same as that of the net force. If the magnitude of the net force is constant, then so is the magnitude of the acceleration.

These conclusions about the net force and acceleration also apply to a body moving along a curved path. For example, the figure below shows a disk moving in a horizontal circle on an ice surface of negligible friction.



A string attached to the disk exerts a force of constant magnitude towards the center of the circle. This force causes acceleration that is constant in magnitude and directed toward the center of the circle. The speed of the disk is constant, so this is uniform circular motion. At any point in the motion, the acceleration **a** and the net force **Σ F** are in the same direction, toward the center of the circle.

Figure below shows another experiment to explore the relationship between the acceleration of a body and the net force acting on that body.



We apply a constant horizontal force to a disk on a frictionless horizontal surface, using a spring balance. This horizontal force is the net force on the disk. If we change the magnitude of the net force, the acceleration changes in the same proportion. Doubling the net force doubles the acceleration, halving the force halves the acceleration, and so on. Many such experiments show that for any given body the magnitude of the acceleration is directly proportional to the magnitude of the net force acting on the body.

For a given body the ratio of the magnitude $|\Sigma \mathbf{F}|$ of the net force to the magnitude $a = |\mathbf{a}|$ of the acceleration is constant, regardless of the magnitude of the net force. We call this ratio the ***mass*** of the body, and denote it by *m*. That is, $m = |\sum \mathbf{F}|/a$, or

$$\left|\sum \mathbf{F}\right| = ma$$

Mass is a quantitative measure of inertia. The greater its mass, the more a body "resists" being accelerated. If you hit a table-tennis ball and then a basket-ball with the same force, the basket-ball has much smaller acceleration because it has much greater mass.

The SI unit of mass is the ***kilogram***. The kilogram is officially defined to be the mass of a chunk of platinum-iridium alloy kept in a vault near Paris. We can use this standard kilogram to define the newton:

One ***newton*** is the amount of net force that gives an acceleration of one meter per second squared to a body with a mass of one kilogram. It is related to the units of mass, length, and time:

1 newton = (1 kilogram) (1 meter per second squared)

1 N = 1 kg . m/s^2

Experiment shows that if a combination of forces $\mathbf{F}_1$, $\mathbf{F}_2$, $\mathbf{F}_3$, ... is applied to a body, the body will have the same acceleration (magnitude and direction) as when only a single force is applied, if that single force is equal to the vector sum $\mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 + ...$ In other words, the principle of superposition holds true when the net force is not zero and the body is accelerating.

Equation $\left|\sum \mathbf{F}\right| = ma$ relates the magnitude of the net force on a body to the magnitude of the acceleration that it produces. We have also seen that the direction of the net force is the same as the direction of the acceleration, whether the body's path is straight or curved. Newton wrapped up all these relationships and experimental results in a single concise statement that is called ***Newton's second law of motion***:

If a net external force acts on a body, the body accelerates. The direction of acceleration is the same as the direction of the net force. The net force vector is equal to the mass of the body times the acceleration of the body.

In symbols,

$$\sum \mathbf{F} = m\mathbf{a}$$

Newton's second law is a fundamental law of nature, the basic relation between force and motion.

The above equation is a vector equation. Usually, we will use it in component form, with separate equation for each component of force and the corresponding acceleration:

$$\sum F_x = ma_x \qquad \sum F_y = ma_y \qquad \sum F_z = ma_z$$

This set of component equations is equivalent to the single vector equation. Each component of total force equals the mass times the corresponding component of acceleration.

The statement of Newton's second law refers to *external* forces. External forces are forces exerted on the body by other bodies in its environment.

The vector equation, or its equivalent the three component equations, are valid only when the mass *m* is constant. Examples of systems, whose masses change, are a leaking tank, a rocket ship, or a moving railroad car being loaded with coal. Such systems will be handled by using a different concept.

Newton's second law is valid only in inertial frames of reference, just like the first law. Thus it is not valid in the reference frame of an accelerating vehicle. We will assume that the earth is an adequate approximation to an inertial frame, although because of its rotation and orbital motion it is not precisely inertial.

5.4
Mass and Weight

The weight of a body is the force of the earth's gravitational attraction for the body. Mass characterizes the inertial properties of a body. The greater the mass, the greater the force needed to cause a given acceleration; this is reflected in Newton's second law, $\sum \mathbf{F} = m\mathbf{a}$. Weight, on the other hand, is a force exerted on a body by the pull of the earth. Everyday experience shows us that bodies having large mass also have large weight. A large stone is hard to throw because of its large mass, and hard to lift off the ground because of its large weight. On the moon the stone would be just as hard to throw horizontally, but it would be easier to lift.

A freely falling body has an acceleration equal to g, and a force must act to produce this acceleration. If a 1-kg body falls with an acceleration of 9.8 m/s^2, the required force has magnitude

$$F = ma = (1\,\text{kg})\,(9.8\,\text{m/s}^2) = 9.8\,\text{kg}\cdot\text{m/s}^2 = 9.8\,\text{N}$$

The force that makes the body accelerate downward is the gravitational pull of the earth, that is, the weight of the body. Any body near the surface of the earth that has a mass of 1 kg must have a weight of 9.8 N to give it the acceleration we observe when it is in free fall. More generally, a body with mass m must have weight with magnitude w given by

$$w = mg$$

The weight of the body is a force, a vector quantity, and we can write the previous equation as a vector equation:

$$\mathbf{w} = m\mathbf{g}$$

The weight of the body is a force, a vector quantity, and we can write the previous equation as a vector equation:

$$\mathbf{w} = m\mathbf{g}$$

We remember that g is the *magnitude* of **g**, the acceleration due to gravity, so g is always a positive number, by definition. Thus w, given by the equation $w = mg$, is the *magnitude* of the weight and is also always positive.

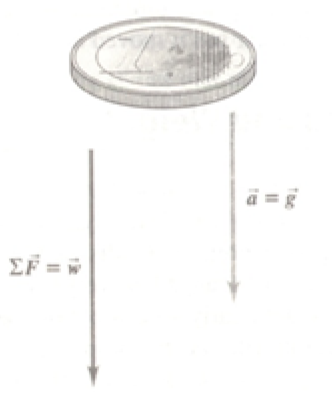
It is important to understand that the weight of a body acts on the body all the time, whether it is in free fall or not. When a 10-kg flowerpot hangs suspended from a chain, it is in equilibrium, and its acceleration is zero. But its weight, given by $\mathbf{w} = m\mathbf{g}$, is still pulling down on it. In this case the chain pulls up on the pot, applying an upward force. The vector sum of the forces is zero, and the pot is in equilibrium.

Example

A coin is dropped from rest from the top of a tower. If the coin falls freely, so that the effects of the air are negligible, how does the net force on the coin vary as it falls?

Solution

In free fall, the acceleration **a** of the coin is constant and equal to **g**. Hence by Newton's second law the net force $\sum \mathbf{F} = m\mathbf{a}$ is also constant and equal to $m\mathbf{g}$, which is the weight **w** of the coin.



The velocity of the coin changes as it falls, but the net force acting on it remains constant. The "common sense" idea that greater speed implies greater force is not correct.

The net force on a freely falling coin is constant even if you initially toss it upward. The force that your hand exerts on the coin is a contact force, and it disappears the instant that the coin loses contact with your hand. From then on, the only force acting on the coin is its weight **w**.

Variation of g with Location

The value of g varies from point to point on the earth's surface, from about 9.78 to 9.82 m/s^2, because the earth is not perfectly spherical and because of effects due to its rotation and orbital motion. At a point where $g = 9.80\,\text{m/s}^2$, the weight of a standard kilogram is $w = 9.80\,\text{N}$. At a different point, where $g = 9.78\,\text{m/s}^2$, the weight is $w = 9.78\,\text{N}$ but the mass is still 1 kg.

The weight of the body varies from one location to another; the mass does not. If we take a standard kilogram to the surface of the moon, where the acceleration of free fall is 1.62 m/s^2, its weight is 1.62 N, but its mass is still 1 kg. An 80.0-kg astronaut has a weight on earth of (80.0 kg) (9.80 m/s^2) = 784 N, but on the moon the astronaut's weight would be only (80.0 kg) (1.62 m/s^2) = 130 N.

Example

A $1.96\times10^4\,\text{N}$ car traveling in the +x-direction makes a fast stop; the x-component of the net force acting on it is $-1.50\times10^4\,\text{N}$. What is its acceleration?

Solution

The mass m of the car is

$$m = \frac{w}{g} = \frac{1.96\times10^4\,\text{N}}{9.80\,\text{m/s}^2} = \frac{1.96\,\text{kg}\cdot\text{m/s}^2}{9.80\,\text{m/s}^2} = 2000\,\text{kg}$$

$$a_x = \frac{\sum F_x}{m} = \frac{-1.50\times10^4\,\text{N}}{2000\,\text{kg}} = \frac{-1.50\times10^4\,\text{kg}\cdot\text{m/s}^2}{2000\,\text{kg}} = -7.5\,\text{m/s}^2$$

Example

Suppose an astronaut landed on a planet where $g = 19.6\,\text{m/s}^2$. Compared to earth, would it be easier, harder, or just as easy for him to walk around? Would it be easier, harder, or just as easy for him to catch a ball that is moving horizontally at 12 m/s?

Solution: It would take twice the effort for the astronaut to walk around because his weight on the planet would be twice as much as on the earth. But it would be just as easy to catch the ball. The ball's mass remains the same, so the horizontal force the astronaut would have to exert to bring it to a stop (i.e., to give it the same acceleration) would be the same as on earth.

Example

Superman throws a 2400-N boulder at an adversary. What horizontal force must Superman apply to the boulder to give it a horizontal acceleration of 12.0 m/s^2?

Solution: The mass of the boulder is

$$m = \frac{w}{g} = \frac{2400}{9.80} = 244.9\,\text{kg}$$

Then

$$F = ma = 244.9 \times 12.0 = 2940\,\text{N}$$

Example

At the surface of Jupiter's moon Io, the acceleration due to gravity is $g = 1.81\,\text{m/s}^2$. A watermelon weighs 44.0 N at the surface of the earth.

(a) What is its mass on the earth's surface?
(b) What are its mass and weight on the surface of Io?

Solution: The mass of the watermelon is constant, independent of its location.

(a) $m = \frac{w}{g} = \frac{44.0}{9.80} = 4.49\,\text{kg}$

(b) On Io, Jupier's moon, $m = 4.49\,\text{kg}$ the same on earth. The weight on Io is

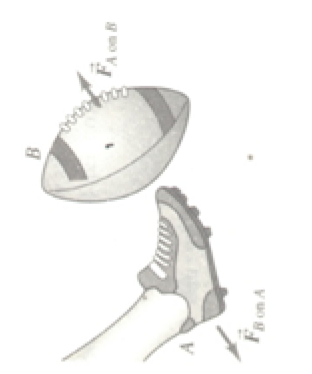
$$w = mg = 4.49 \times 1.81 = 8.13\,\text{N}$$

5.5
Newton's Third Law

A force acting on a body is always the result of its interaction with another body, so forces always come in pairs. You can't pull on a doorknob without the doorknob pulling back on you. When you kick a football, the forward force that your foot exerts on the ball launches it into its trajectory, but you also feel the force the ball exerts back on your foot. If you kick a boulder, the pain you feel is due to the force that the boulder exerts on your foot.

In each of these cases, the force that you exert on the other is in the opposite direction to the force that body exerts on you. Experiments show that whenever two bodies interact, the two forces that they exert on each other are always *equal in magnitude* and *opposite in direction*. This fact is called ***Newton's third law of motion***.

In the figure below, $\mathbf{F}_{A\,on\,B}$ is the force applied *by* body A (first subscript) *on* body B (second subscript), and $\mathbf{F}_{B\,on\,A}$ is the force applied *by* body B (first subscript) *on* body A (second subscript).



The mathematical statement of Newton's third law is

$$\mathbf{F}_{A\,on\,B} = -\mathbf{F}_{B\,on\,A}$$

Expressed in words:

If body A exerts a force on body B (an "action"), then the body B exerts a force on body A (a "reaction"). These two forces have the same magnitude but are opposite in direction. These two forces act on different bodies.

The two opposite forces "action" and "reaction" are referred to as an ***action-reaction pair***. There is no cause-and-effect relationship; we can consider either force as the "action" and the other as the "reaction."

We stress that the two forces described in Newton's third law act on *different* bodies. The net force acting on the football is the vector sum of the weight of the football and the force $\mathbf{F}_{A\,on\,B}$ exerted by the kicker. You would not include the force $\mathbf{F}_{B\,on\,A}$ because this force acts on the *kicker*, not on the football.

In the figure above, the action and reaction forces are *contact* forces that are present only when the two bodies are touching. Newton's third law also applies to *long-range* forces that do not require physical contact, such as the force of gravitational attraction. A table-tennis ball exerts an upward gravitational force on the earth that's equal in magnitude to the downward gravitational force the earth exerts on the ball. When you drop the ball, both the ball and the earth accelerate toward each other. The net force on each body has the same magnitude, but the earth's acceleration is microscopically small because its mass is so great.

Example

After your car breaks down, you start to push it to the nearest repair shop. While the car is starting to move, how does the force you exert on the car compare to the force the car exerts on you? How do these forces compare when you are pushing the car along at a constant speed?

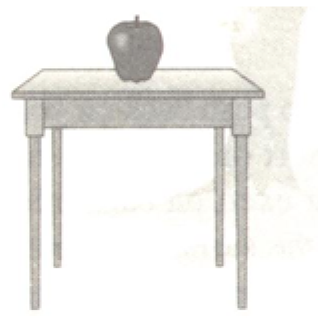
Solution

In both cases, the force you exert on the car is equal in magnitude and opposite in direction to the force the car exerts on you. It's true that you have to push harder to get the car going than to keep it going. But no matter how hard you push on the car, the car pushes just as hard back on you. Newton's third law gives the same result whether the two bodies are at rest, moving with constant velocity, or accelerating.

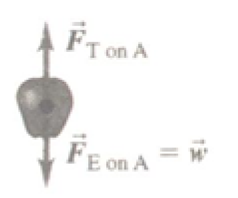
Example

An apple sits on a table in equilibrium. What forces act on it? What is the reaction force to each of the forces acting on the apple? What are the action-reaction pairs?

Figure below shows the apple on the table.

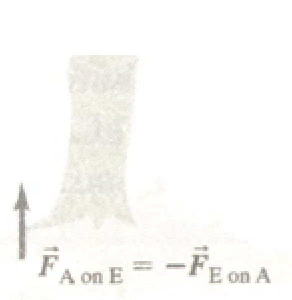


The figure below shows the forces acting on the apple. The apple is A, the table T, and the earth E.



In the diagram, $\mathbf{F}_{E\,on\,A}$ is the weight of the apple; that is, the downward gravitational force exerted *by* the earth E (first subscript) *on* the apple A (second subscript). Similarly, $\mathbf{F}_{T\,on\,A}$ is the upward force exerted *by* the table T (first subscript) *on* the apple A (second subscript).

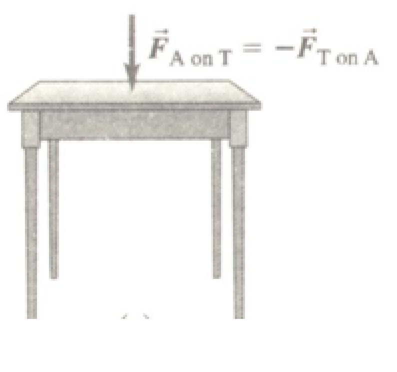
As the earth pulls down on the apple, the apple exerts an equally strong upward pull $\mathbf{F}_{A\,on\,E}$ on the earth as shown below.



$\mathbf{F}_{A\,on\,E}$ and $\mathbf{F}_{E\,on\,A}$ are an action-reaction pair, representing the mutual interaction of the apple and the earth, so

$$\mathbf{F}_{A\,on\,E} = -\mathbf{F}_{E\,on\,A}$$

Also, as the table pushes up on the apple with force $\mathbf{F}_{T\,on\,A}$, the corresponding reaction is the downward force $\mathbf{F}_{A\,on\,T}$ exerted by the apple on the table.



So, we have

$$\mathbf{F}_{A\,on\,T} = -\mathbf{F}_{T\,on\,A}$$

The two forces acting on the apple, $\mathbf{F}_{T\,on\,A}$ and $\mathbf{F}_{E\,on\,A}$, are not an action-reaction pair, despite being equal and opposite. They do not represent the mutual interaction of two bodies; they are two different forces acting on the *same* body. *The two forces in an action-reaction pair **never** act on the same body.*

5.6

Coordinates and Reference Frames and Inertial Reference Frames

Any phenomenon is fully described by stating what happened at diverse points of space at sucessive instants of time. Measurements of positions and times require the use of coordinate grids and reference frames.

A macroscopic body, such as a ball, is made of atoms. Since the size of an atom is extremely small, we can regard an atom as almost a point like mass for most practical purposes. In several problems, even a macroscopic body, like a rocket, can be treated as a point like mass if we are interested in its mass and its position at each instant of time.

A point like mass of no discernible size or internal structure is called an **ideal particle**. At any given instant of time, the ideal particle occupies a single point of space. The particle has a mass. Position, time, and mass give a complete description of the behavior and the attributes of an ideal particle.

The ideal particle is a model. In physics, a **model** is a simplified version of a physical system.

We assume that every macroscopic body consists of particles. We can describe the behavior and the attributes of such a body by describing the particles within the body.

Thus, measurements of position, time, and mass are of fundamental significance in physics. We learn the units for these measurements in this unit.

To achieve a precise, quantitative description of the position of a particle, we take some convenient point of space as **origin** and then specify the position of the particle relative to this origin. For this purpose, we place a grid of lines around the origin and give the location of the particle within this grid. A rectangular grid is most common, and we specify the position of the particle by means of coordinates read off from the grid. The coordinates are called **rectangular coordinates**.

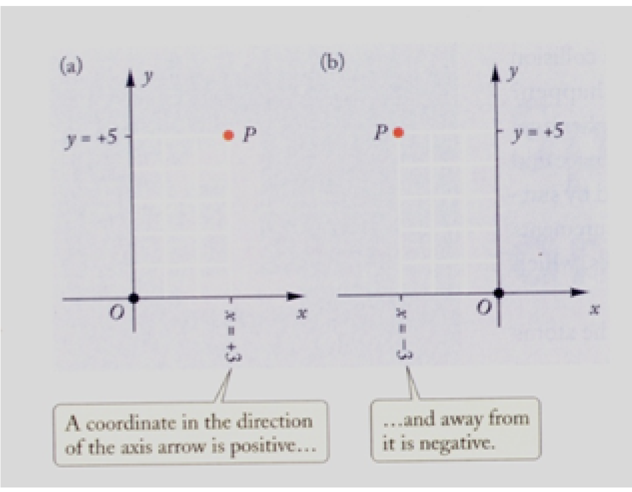


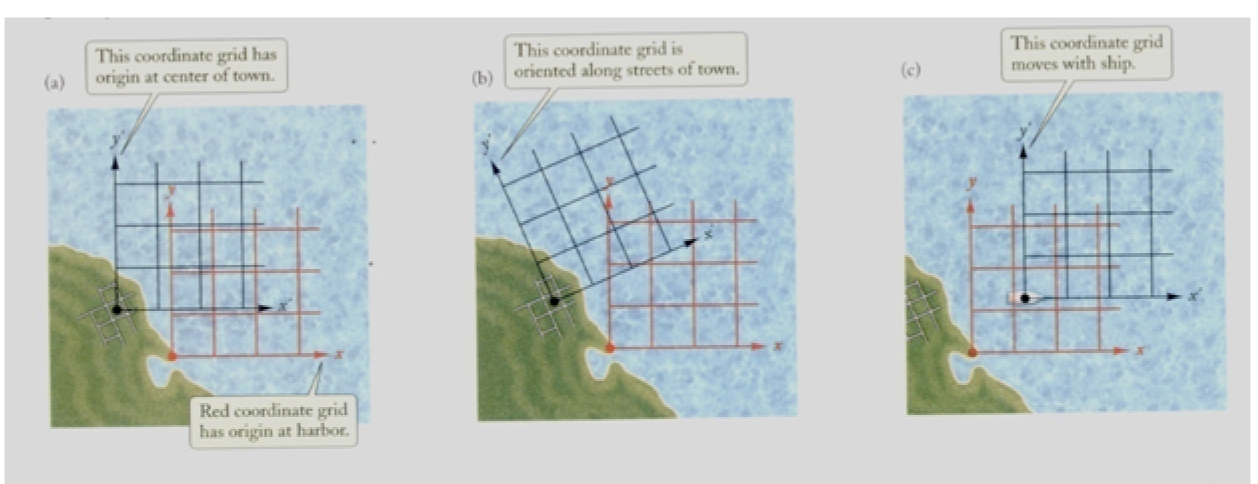
Figure above shows a rectangular grid. The mutually perpendicular lines through the origin O are called the x and y axes. The coordinates of the grid point P, where the particle is located, simply tell us how far we must move parallel to the corresponding axis in order to go from the origin O to the point P. For example, the point P shown in figure (a) has coordinates $x = 3$ units and $y = 5$ units. If we move from the origin in a direction opposite to that indicated by the arrow on the axis, then the coordinate is negative; thus, the point P shown in figure (b) has a negative x coordinate, $x = -3$ units.

The two-dimensional grid shown in the previous figure is adequate when we want to describe the two-dimensional (east—west and north—south) motion of an automobile traveling on flat ground or the motion of a ship on the (nearly) flat surface of the water of a harbor. However, if we want to describe the three-dimensional (east—west, north—south, and up—down) motion of an aircraft flying through the air or a submarine diving through the ocean, then we need a three-dimensional grid, with x, y, and z axes.

If we want to describe the motion of an automobile along a straight road, then we need only a one-dimensional grid; that is, we need only the x axis, which we imagine placed along the road.

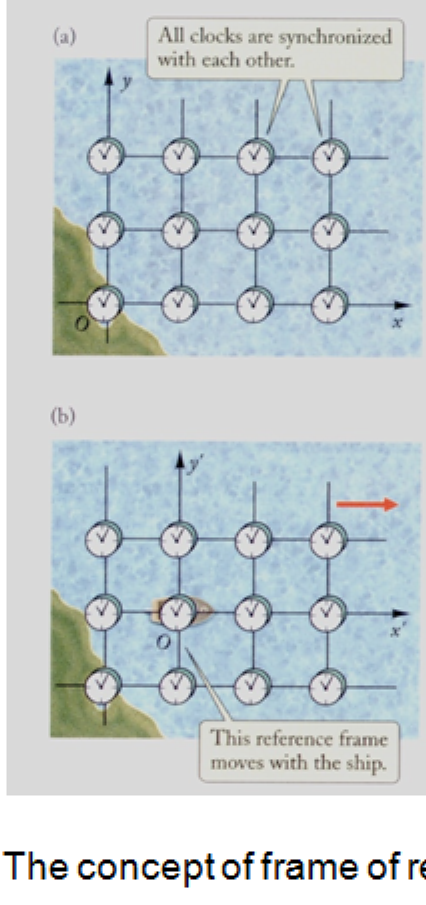
When we determine the position of a particle by means of a coordinate grid erected around some origin, we perform a relative measurement—the coordinates of the point at which the particle is located depend on the choice of origin and on the choice of coordinate grid. The choice of origin of coordinates and the choice of coordinate grid are matters of convenience.

For instance, a harbormaster might use a coordinate grid with the origin at the harbor; but a municipal engineer might prefer a displaced coordinate grid with its origin at the center of town (figure (a) below) or a rotated coordinate grid oriented along the streets of the town (figure (b)). The navigator of a ship might find it convenient to place the origin at the midpoint of his ship and to use a coordinate grid erected around this origin; the grid then moves with the ship (figure (c)). If the navigator plots the track of a second ship on this grid, he can tell at a glance what the distance of closest approach will be, and whether the other ship is on a collison course (whether it will cross the origin).



For the description of the motion of a particle, we must specify both its position and the time at which it has this position. To determine the time, we use a set of synchronized clocks which we imagine arranged at regular intervals along the coordinate grid. When a particle passes through a grid point P, the coordinate gives us the position of the particle in space, and the time registered by the nearby clock gives us the time t. Such a coordinate grid with an array of synchronized clocks is called a **reference frame**.

Like the choice of origin and the choice of coordinate grid, the choice of reference frame is a matter of convenience. For instance, figure (a) below shows a reference frame erected around the harbor, and figure (b) shows a reference frame erected around the ship. Reference frames are usually named after the body or point around which they are erected. Thus, we speak of the reference frame of the harbor, the reference frame of the ship, the reference frame of the laboratory, the reference frame of the Earth, etc.



The concept of frame of reference, introduced in the relative velocity module, is central to Newton's laws of motion.

Suppose that you are in an airplane that is accelerating down the runway during takeoff. If you stand in the aisle on roller skates, you would start moving *backward* relative to the plane as the pilot opens throttle. If instead the airplane was landing, you would start moving forward down the aisle as the airplane slowed to a stop. In either case, it looks as though Newton's first law is not obeyed; there is no net force acting on you, yet your velocity changes. This needs an explanation.

The point is that the airplane is accelerating with respect to the earth and is *not* a suitable frame of reference for Newton's first law. This law is valid in some frames of reference, and is not valid in others. A frame of reference in which Newton's first law is valid is called an ***inertial frame of reference***. The earth is at least approximately an inertial frame of reference, but the airplane is not. (The earth is not a completely inertial frame, owing to the acceleration associated with its rotation and its motion around the sun. These effects are quite small, however.) Because Newton's first law is used to define an inertial frame of reference, it is sometimes called the *law of inertia*.