York the next month. As a consequence of the butterfly effect, models of nonlinear systems will never be able to predict future behavior exactly. In addition, the farther in the future that a model predicts, the less likely it is to be accurate. For example, weather forecasts will never be much better than they are today. We will never be able to predict successfully the exact time or place a thunderstorm will occur on the next day, nor predict with certainty whether it will rain a few days in the future. Similarly, we will never be able to forecast or predict the exact future status of any complex nonlinear system, including **plate tectonic** movements, **ecosystem** dynamics, or fish and wildlife population variations.

Fortunately, although many complex nonlinear systems never reach an equilibrium, they do tend to oscillate chaotically within a range of conditions (values of the component parameters) that is predictable. For example, weather is chaotic and unpredictable, but **climate** (the average and range of temperature, rainfall, etc., at a specific location and time of year) can be predicted with some confidence because it changes little from year to year. Hence, models of complex systems (**CC10**), if they adequately resemble the real world, can be used with reasonable success to predict the average conditions and range of variations that will occur in the future.

Unfortunately, although complex nonlinear systems do tend to oscillate chaotically within a range of conditions that is predictable, this dynamic "equilibrium" can be disturbed by small changes in the component characteristics. In some instances, if a critical value of one or more components is changed, the system can "jump" from one set of average conditions to a completely different set of average conditions around which it oscillates chaotically. Thus, a system may appear to suddenly change drastically, even though none of the components of the system changed substantially before the "jump" occurred. For example, a very small increase in a parameter, such as the average temperature of the oceans and atmosphere, could have little effect on climate until a critical point was reached. At that point, the Earth's climate could suddenly become much warmer or colder.

We now know that this type of sudden climate change has occurred in the past (Chaps. 9, 10, **Fig. 9.21**). Similarly, sudden changes in ecosystems, such as drastic declines or **blooms** of some species, may be a natural consequence of the nonlinearity of nature. Sudden changes in other complex systems, such as ocean circulation and the motions of tectonic plates, may have occurred in the past for this same reason. It is important to realize that sudden changes in natural systems have occurred in the past and will occur again in the future. Furthermore, no matter how well we are able to model such systems, it will be very difficult to reproduce such changes faithfully, and virtually impossible to develop an accurate predictive capability that will alert us to such changes before they occur.

CRITICAL CONCEPT 12

The Coriolis Effect

ESSENTIAL TO KNOW

- When set in motion, freely moving objects, including air and water masses, move in straight paths while the Earth continues to rotate independently.
- Because freely moving objects are not carried with the Earth as it rotates, they are subject to an apparent deflection called the "Coriolis effect." To an observer rotating with the Earth, freely moving objects that travel in a straight line appear to travel in a curved path on the Earth.
- The Coriolis effect causes an apparent deflection of freely moving objects to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The deflection is said to be *cum sole*, or "with the sun."
- The Coriolis deflection is greatest at the poles and decreases at lower latitudes. There is no Coriolis effect for objects that move directly east to west or west to east at the equator.
- Regardless of their speed, freely moving objects at the same latitude appear to complete a circle and return to their original location in the same period of time. This period, called the "inertial period," is 12 h at the poles and increases progressively at lower latitudes. The inertial period is 24 h at 30°N or 30°S, and it approaches infinity near the equator.
- For objects moving within 5° on either side of the equator, the Coriolis effect often can be ignored because the deflection is small and the inertial period is very long.
- Freely moving objects moving at the same speed appear to follow circular paths with smaller radii at higher latitudes.

- Freely moving objects at the same latitude appear to follow paths with larger radii if they are moving at higher speeds.
- The magnitude of the Coriolis deflection (the rate of increase of distance from a straight-line path) increases with increasing speed.

UNDERSTANDING THE CONCEPT

From common experience we know that freely moving objects, such as bullets, move in a straight line unless acted on by an external force. However, all is not what it seems. If we very carefully examine the bullet's flight, we find that its path is deflected very slightly to one side (in addition to the downward deflection due to **gravity**). Curiously, this deflection is always to the right in the Northern Hemisphere and the left in the Southern Hemisphere. This apparent deflection, called the **Coriolis effect**, occurs because we live on a rotating Earth, and it occurs for all objects that move freely without connection to the solid Earth surface, including bullets, thrown footballs, and moving air and **water masses**.

Some simplified examples help to explain how the Coriolis deflection works.

Merry-Go-Round without Gravity

Consider a merry-go-round rotating counterclockwise when viewed from above (**Fig. CC12.1a**). This is equivalent to the Earth seen from above the North Pole (**Fig. CC12.1c**). Imagine that you are an observer sitting on the merry-go-round and that someone at the center of the merry-go-round throws a ball outward. As the ball travels *through* the air in a straight line, the merry-go-round continues to turn, carrying you around with it (**Fig. CC12.1a**). You do not see the ball travel in a straight line. Instead, the ball appears to travel in a curve deflected to the right (**Fig. CC12.1b**). If the merry-go-round spins clockwise (equivalent to viewing the Southern Hemisphere from above the South Pole; **Fig. CC12.1d**), the apparent deflection of the ball is to the left (**Fig. CC12.1e**).

If you sit on the merry-go-round away from its center of rotation and throw a ball from here at a target, the ball again appears to be deflected to the right. However, it misses the target, even though it flies in a straight line. The reason is that the ball was moving with the merry-go-round when it was thrown. While in the observer's hand, the ball is constrained to move in a circle with the merry-go-round, but when released, it is no longer constrained. In fact, if the ball were simply released on the merry-go-round instead of thrown, it would roll off in the direction it was moving at the instant it was released. The same thing occurs when we twirl an object on the end of a piece of string and then let go. The object flies off in a straight line whose direction is determined by where it was in its circle of rotation when it was released (**Fig. CC12.2a**).

If a ball is thrown from a rotating merry-go-round, it is given straight-line motion by the throw. However, because of the rotation of the merry-go-round, it is already in motion in a direction tangential to the ball's circle of rotation at the point it was released. These two straight-line motions (components) are combined, so the ball's actual direction is a straight line between the directions of the two components (**Fig. CC12.2b**). The ball's direction and speed are easily calculated from the two components, which are called "vectors" (**Fig. CC12.2c**).

Centripetal Force

Spinning objects, like the object on the end of a twirled string, fly off if released. This tendency is often called "centrifugal" force. However, centrifugal force does not exist. Circling objects tend to fly off when released because the force restraining them in their circular path is no longer present. A force that acts toward the center of rotation, called **centripetal force,** must be applied to maintain any orbiting object in its circular path. This force may be exerted in several ways. For example, **friction** between the observer and merry-go-round keeps the observer from flying off, whereas tension in the string prevents a twirled object from leaving its circular path. Gravity is the centripetal force that prevents us from flying off the Earth.

Centripetal force must increase as the rate of rotation increases. For example, the amount of friction needed to keep an observer on the merry-go-round becomes greater as the merry-go-round speeds up. The rate of rotation is measured by the angular velocity (the rate of rotation measured in degrees of angle per unit time; **Fig. CC12.3a**). For a constant angular velocity, **orbital velocity** increases at points more distant from the center of rotation (**Fig. CC12.3a**). At a fixed distance from the center of rotation, angular velocity increases if orbital velocity increases, and decreases if orbital velocity decreases (**Fig. CC12.3b**).

Merry-Go-Round with Gravity

Now imagine a merry-go-round with gravity that acts toward a point located below its center of rotation (**Fig. CC12.4a**). This merry-go-round is equivalent to a small circular area of the Earth's surface centered at the North Pole with gravity acting toward the Earth's center (**Fig. CC12.4b**).

If a ball is placed at any point on the merry-go-round other than the center, a small component of the gravitational force pulls it toward the center of rotation (**Fig. CC12.4c**). If the merry-go-round and ball are rotating and the ball is released to roll freely, the ball will move outward, away from the center of rotation, just as the object on the end of a twirled string flies outward if released. However, except at the center, the component of gravity that acts toward the center of rotation (**Fig. CC12.4c**) pulls the ball toward this center. If the ball is at

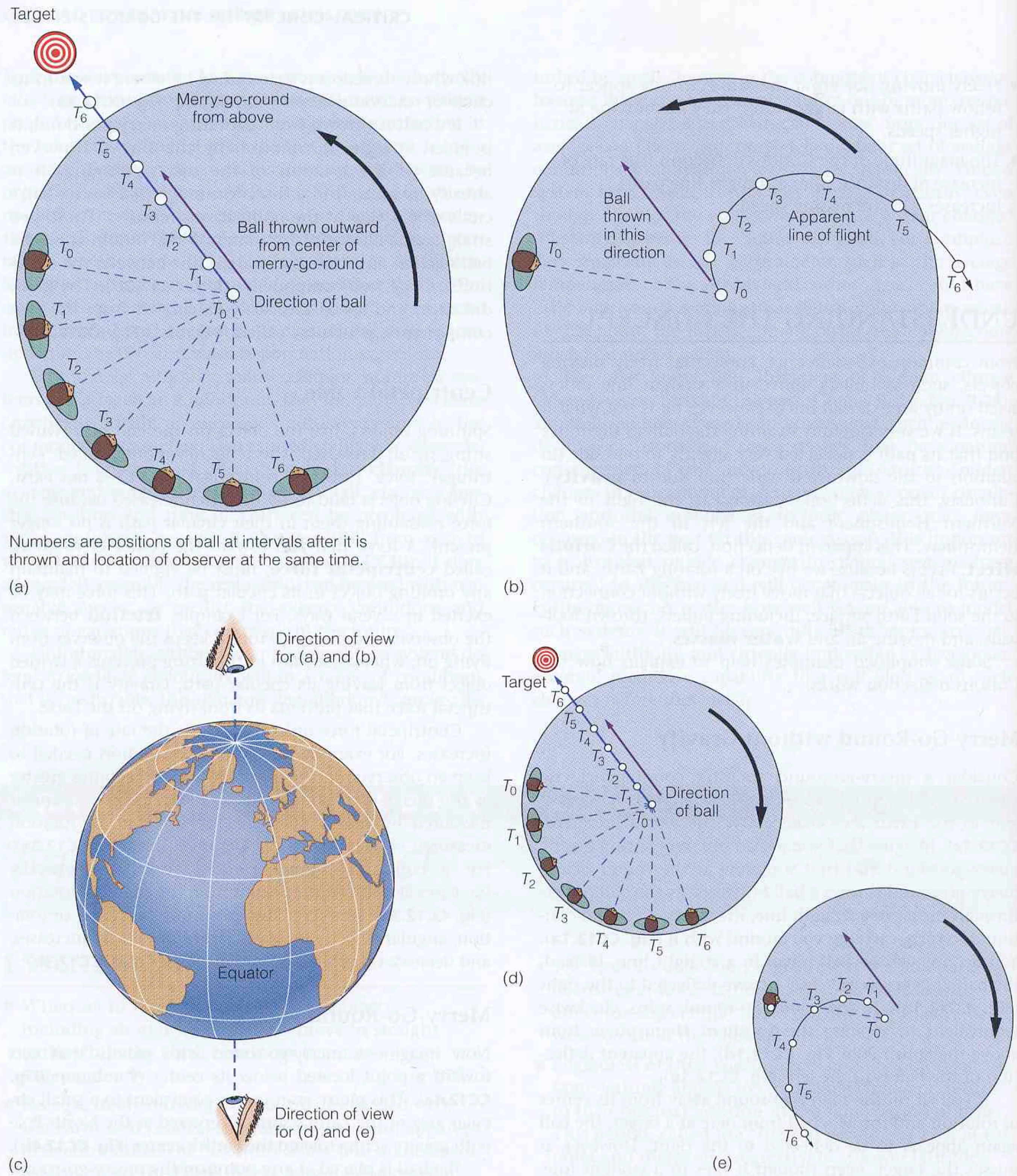


FIGURE CC12.1 (a) A ball thrown outward toward a target from the center of rotation of a merry-go-round has zero orbital velocity due to the merry-go-round rotation, and will travel outward in a straight line to hit the target. However, an observer sitting away from the axis of rotation moves around with the merry-go-round such that the observer's angle of vision to the ball and target change. (b) If the observer is not aware of the merry-go-round rotation (just as we are not aware of the Earth's rotation), the observer will see the ball appear to move in a circular path, curving to the right. To observe this phenomenon, rotate part (a) to place the observer at the observing location in part (b) for each of the time intervals T_1, T_2, and so on. (c) Looking down on the merry-go-round depicted in parts (a) and (b) is equivalent to looking down on the Earth from above the North Pole. If we were to look down from above the South Pole, the merry-go-round would appear to rotate clockwise instead of counterclockwise. (d) If the merry-go-round rotates clockwise (the equivalent of the Southern Hemisphere), the ball still moves in a straight line. However, (e) the apparent deflection is in the opposite direction, and the observer sees the ball curve to the left.

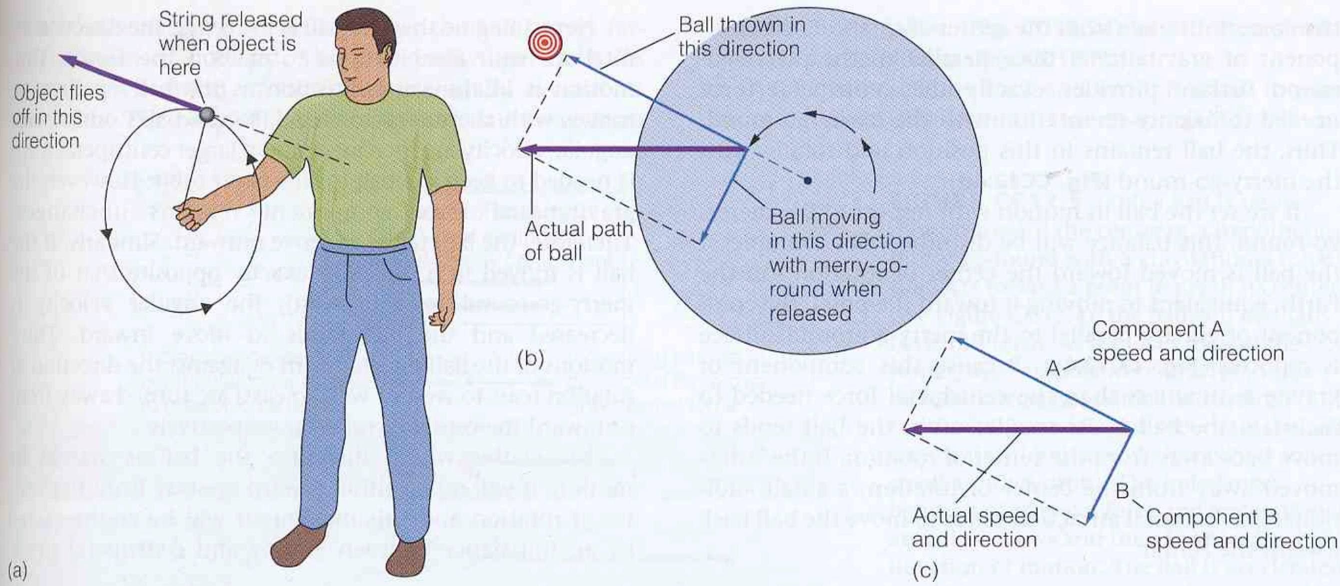


FIGURE CC12.2 (a) A centripetal force is needed to keep an orbiting object in its orbit. When an object is twirled on the end of a string, we supply this force with our muscles through tension in the string. If we release this tension by letting go of the string, the object will fly outward. (b) When a ball is thrown outward from a rotating merry-go-round, it flies off in a straight line (just as the object twirled on the end of a string does), but it also has an additional velocity (speed and direction) imparted to it by the throw. The actual velocity with which the ball moves is a combination of the two velocities. (c) We can easily determine the actual velocity of the ball by geometrically combining the two component velocities. The lines A and B are drawn in the respective directions of the two velocities. The length of each line is proportional to the speed imparted in that direction. The actual direction of the ball's motion can be determined by drawing lines (the dotted lines) parallel and equal to each arrow from the head of the other to form a parallelogram (in this case it is a rectangle). The diagonal of this parallelogram shows the actual direction of motion, and its length shows the speed.

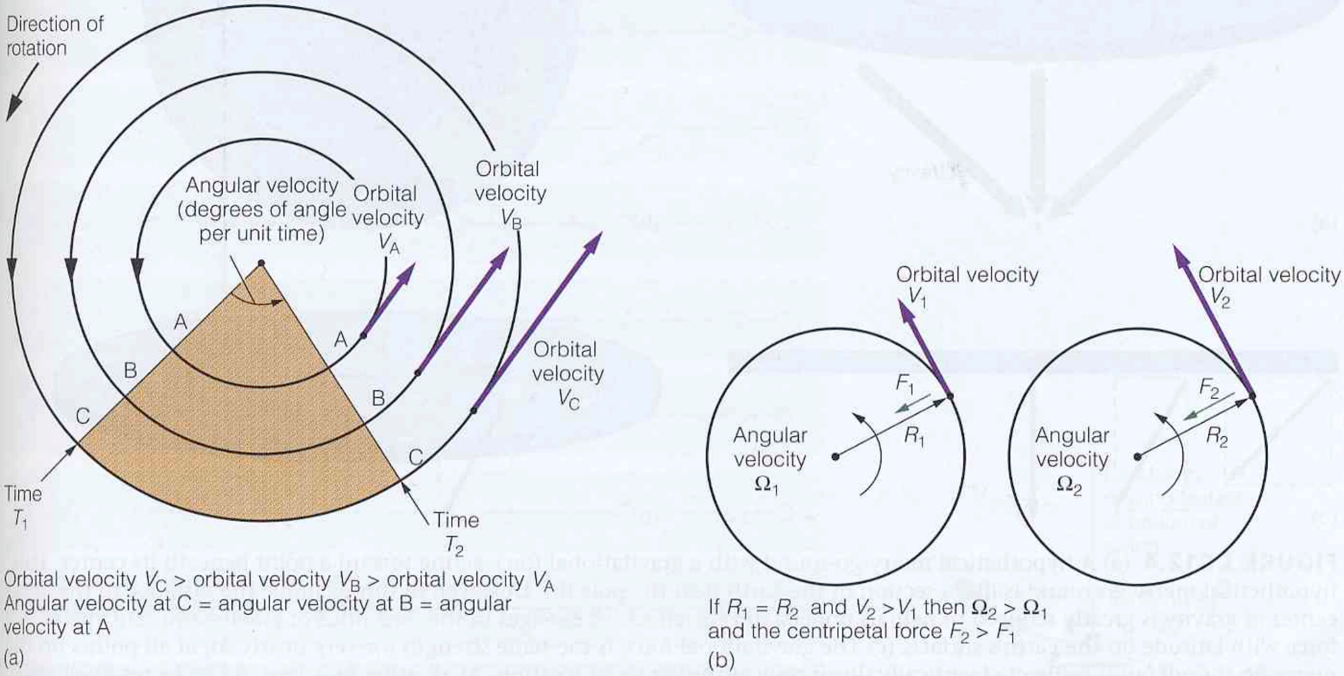


FIGURE CC12.3 The velocity of an orbiting object can be expressed as either angular velocity or orbital velocity. (a) The angular velocity is the number of degrees of angle moved through in unit time. The orbital velocity is the distance the object moves along its orbital path per unit time. On a rotating solid object (like a merry-go-round or the Earth), the orbital velocity of a point increases with distance from the center of rotation, and the angular velocity is the same for all points regardless of location. (b) Angular velocity, orbital velocity and centripetal force are related. For two objects at the same distance from the center of rotation, if the angular velocity (rate of rotation) is increased, the orbital velocity is also increased and a larger centripetal force is needed to maintain the object in orbit. For example, the tension in a string becomes greater as we twirl it and its attached object faster.

the correct distance from the center of rotation, the component of gravitational force parallel to the merry-go-round surface provides exactly the centripetal force needed to balance its rotation with the merry-go-round. Thus, the ball remains in this position and rotates with the merry-go-round (**Fig. CC12.4d**).

If we set the ball in motion with respect to the merry-go-round, this balance will be disturbed. For example, if the ball is moved toward the center of rotation (on the Earth, equivalent to moving it toward the pole), the component of gravity parallel to the merry-go-round surface is reduced (**Fig. CC12.4c**). Because this component of gravity is now less than the centripetal force needed to maintain the ball in its smaller orbit, the ball tends to move back away from the center of rotation. If the ball is moved away from the center of rotation, a small additional gravitational attraction tends to move the ball back toward the center.

Next, imagine that the ball is moved in the direction of rotation (equivalent to west to east on the Earth). This motion is in the same direction as the ball's path as it rotates with the merry-go-round, so the ball's orbital and angular velocity are increased, and a larger centripetal force is needed to keep the ball in this faster orbit. However, the gravitational force component remains unchanged. Therefore, the ball tends to move outward. Similarly, if the ball is moved in a direction exactly opposite that of the merry-go-round (east to west), the angular velocity is decreased and the ball tends to move inward. Thus, motions of the ball directed with or against the direction of rotation (east to west or west to east) are turned away from or toward the center of rotation, respectively.

No matter which direction the ball is started in motion, it will move either toward or away from the center of rotation and this movement will be counteracted by an imbalance between gravity and centripetal force.

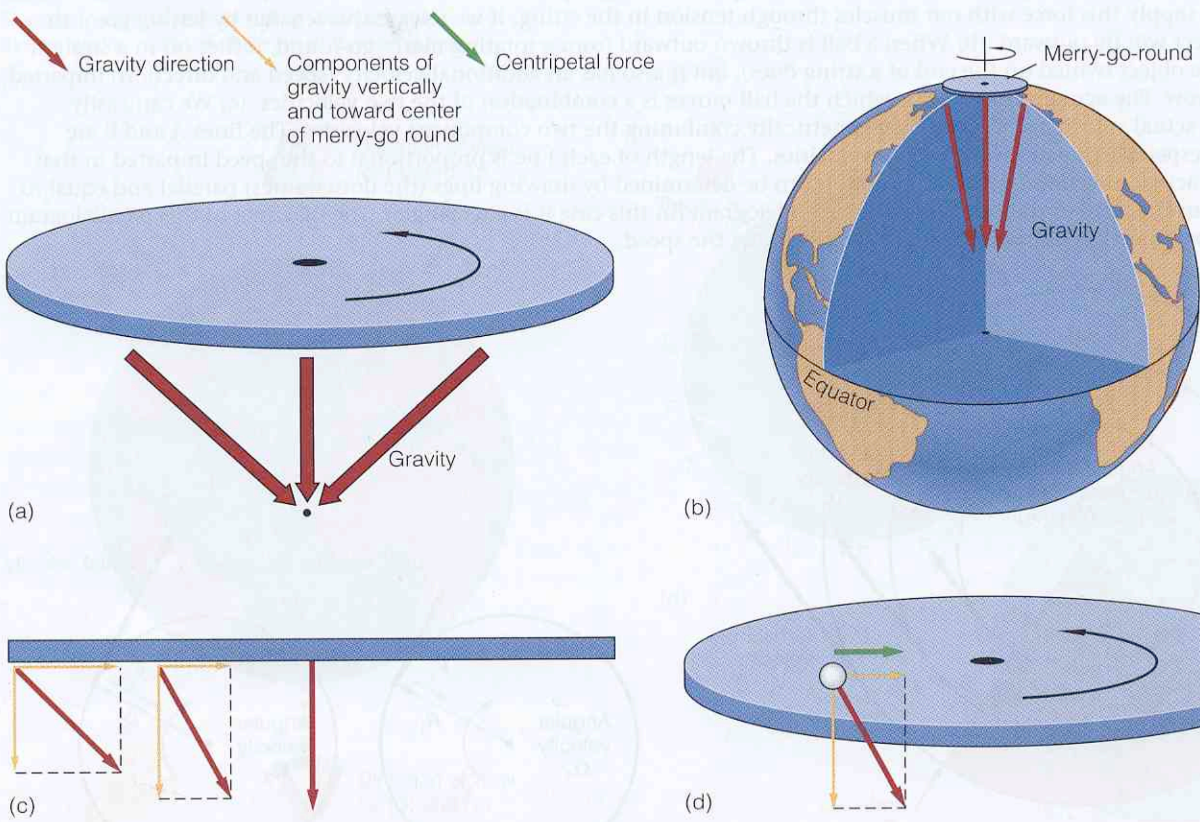
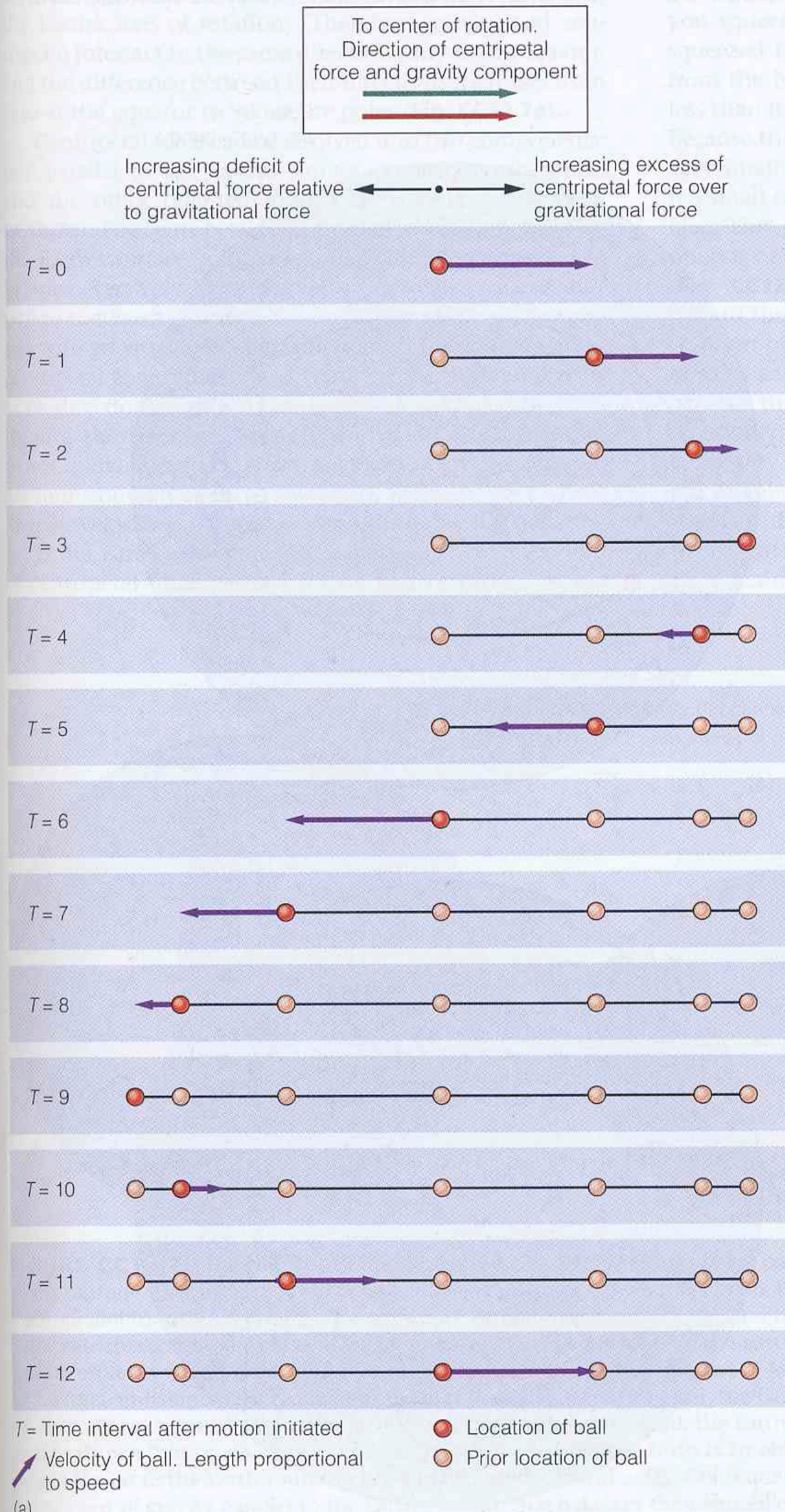


FIGURE CC12.4 (a) A hypothetical merry-go-round with a gravitational force acting toward a point beneath its center. This hypothetical merry-go-round is like a section of the Earth near the pole (b). However, in this example the distance to the center of gravity is greatly reduced to help us understand the effects of changes in the directions of gravity and centripetal force with latitude on the Earth's surface. (c) The gravitational force is the same strength (or very nearly so) at all points on the merry-go-round, but it is directed vertically down only at the center of rotation. At all other locations, it can be resolved into two components (the yellow lines), one parallel to the merry-go-round surface and another vertically downward. The component parallel to the surface increases in strength with increasing distance from the center of rotation. (d) If we place a ball on the surface of the merry-go-round, hold it in place so that it rotates with the merry-go-round, and then release it, it will tend to fly outward like an object twirled on a string. However, there is a component of gravity that acts toward the merry-go-round center. This component provides a centripetal force that, if exactly balanced with the rotation rate of the ball on the merry-go-round (its orbital velocity), will prevent the ball from flying outward.

The counteracting force will grow as the ball moves farther inward or outward. This force will slow the ball's inward or outward motion and eventually reverse its direction. The ball will oscillate toward and away from the center of rotation (**Fig. CC12.5a**) in a motion similar to that of a pendulum (**Fig. CC12.5b**).

As the ball oscillates back and forth, it is still moving in its circular orbit with the merry-go-round. We can



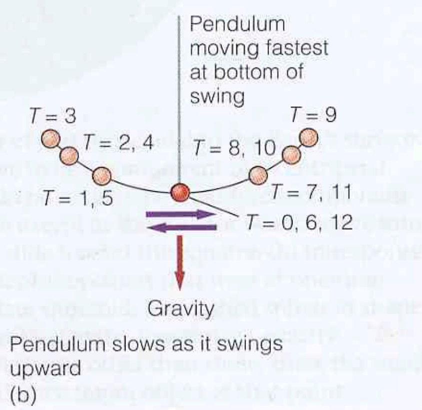


FIGURE CC12.5 (a) If a ball is set in motion toward the center of a hypothetical merry-go-round with a gravitational force that acts toward a point beneath its center (see Figure CC12.4), the ball will oscillate back and forth. As it moves toward the center, the component of gravity in this direction decreases while the required centripetal force increases (because the ball retains its orbital velocity but is now in a smaller-radius orbit). The imbalance between centripetal force and gravitational attraction slows and then reverses the ball's direction of motion. The ball is accelerated until it passes through its original location relative to the center of rotation, but it has enough momentum to continue outward. As the ball moves farther away from the center, the component of gravity increases while the required centripetal force decreases. As a result, there is an excess of gravitational force over centripetal force, and the ball is slowed and its motion eventually reversed back toward the center of rotation. (b) These oscillating motions are very similar to the movements of a pendulum.

show mathematically that the ball would always go through one complete oscillation from its extreme innermost point outward and back to this innermost point in exactly the time it takes for the merry-go-round to complete one revolution. You need not be concerned with this calculation, but the result is important because we can now see what the path of the ball set in motion would be (**Fig. CC12.6**). To an observer anywhere on the rotating merry-go-round, the ball would appear to travel in clockwise circles. It would complete a circle twice for each time the merry-go-round completed one revolution (the equivalent of two circles every 24 h on the Earth).

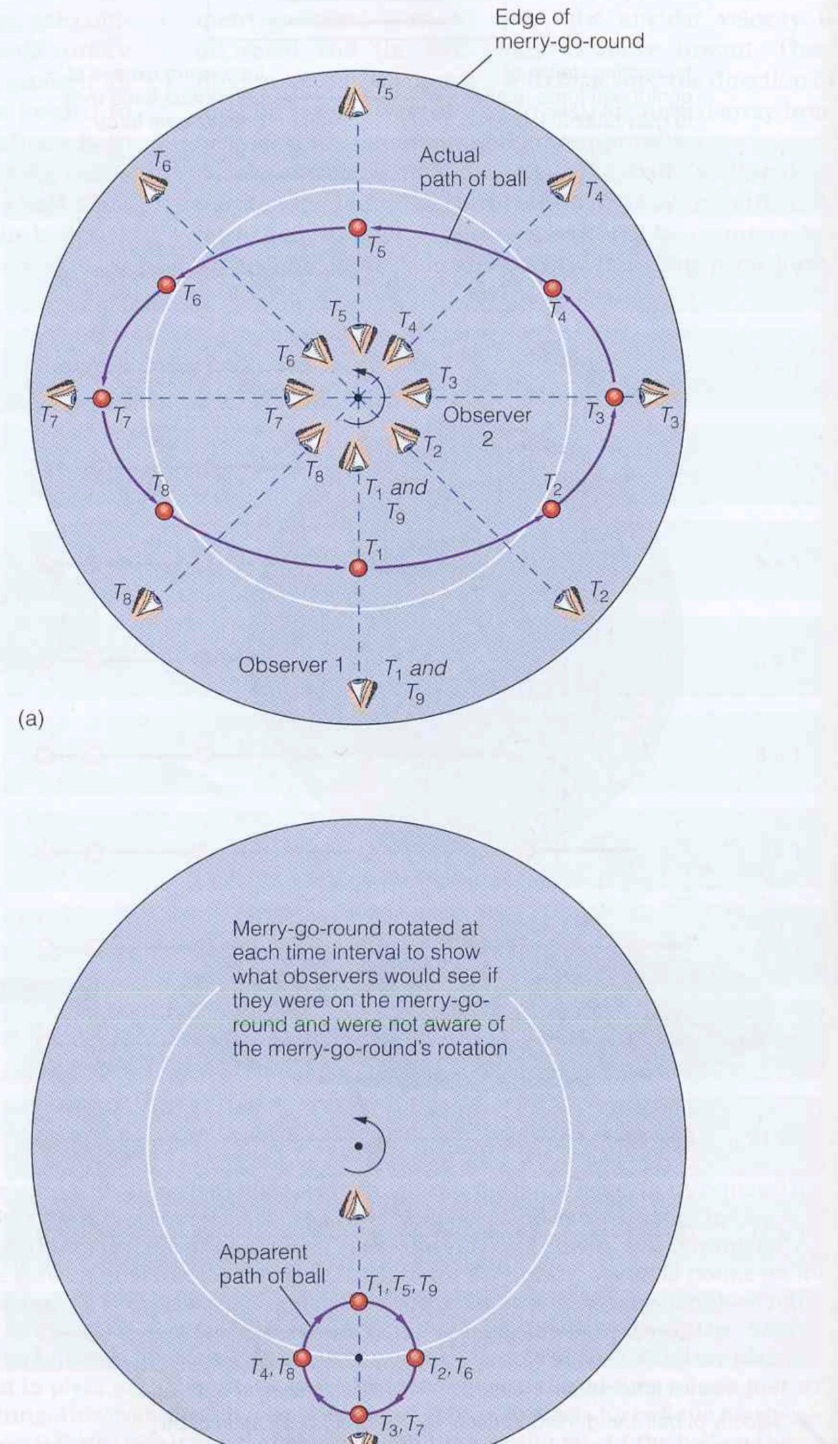


FIGURE CC12.6 (a) If a ball is set in motion toward the center of a hypothetical merry-go-round with a gravitational force that acts toward a point beneath its center (see Figure CC11.4), this motion is added to the orbital motion that the ball already has due to the rotation of the merry-go-round. The added motion and the interaction of centripetal force and gravity cause the ball to oscillate back and forth toward and away from the center as shown in Figure CC11.5. When the rotational motion is added, the actual path of the ball on the merry-go-round is an ellipse, and it returns to its original position after exactly one revolution. (b) To an observer at any location on the rotating merry-go-round, the ball appears to move in a circle. Follow the ball's direction and distance from each observer's eye in part (a) of this figure and see how they plot in a circle in part (b).

The Earth, Centripetal Force, and Gravity

The Earth is more complicated than a merry-go-round because it is a sphere, although not quite an exact sphere. Gravity acts toward the Earth's center, whereas centripetal force acts toward the center of rotation (perpendicular to the Earth's axis of rotation). Therefore, gravity and centripetal force act in the same direction only at the equator, and the difference between their directions increases from zero at the equator to 90° at the poles (**Fig. CC12.7a**).

Centripetal force can be resolved into two components: one parallel to the Earth's surface oriented north–south, and the other oriented toward the Earth's center (**Fig. CC12.7a**). The centripetal force needed to keep an object on the Earth's surface, and variations in this force needed to balance even very large changes in an object's speed relative to the Earth's surface, are extremely small in comparison with gravity. Therefore, variations in the component of centripetal force that acts toward the Earth's center (the same direction as gravity) are easily compensated by gravity and the **pressure gradient** (**Fig. CC12.8**). In other words, moving objects whose angular velocity is increased are immeasurably reduced in weight, whereas those whose angular velocity is reduced are immeasurably heavier.

If the Earth were perfectly spherical, the component of centripetal force parallel to the Earth's surface would not be compensated by gravity, because gravity would act perpendicular to the Earth's surface at all locations. Consequently, freely moving objects would "slide" across the surface toward the equator (**Fig. CC12.7a**). This explains why the Earth is not a perfect sphere, but is instead an oblate spheroid (the shape you would get if you squeezed the Earth at its poles to deform it like a squeezed basketball). The Earth's diameter as measured from the North to the South Pole is 12,714 km, slightly less than its 12,756-km diameter measured at the equator. Because the Earth is not a perfect sphere, gravity acts at a very small angle to the surface (**Fig. CC12.7b**), and there is a small component of gravity parallel to the Earth's surface. This gravity component compensates for the component of centripetal force parallel to the Earth's surface (**Fig. CC12.7b**), so freely moving objects do not slide toward the equator.

If an object is set in motion relative to the Earth, the object's angular velocity will change just as it did for the ball on the merry-go-round. On the Earth, the vertical component of the altered centripetal force is compensated by gravity and the Earth's pressure gradient. However, if the angular velocity of an object is altered, the balance between the small component of gravity acting parallel to the Earth's surface and the component of centripetal force acting parallel to the Earth's surface is upset. The

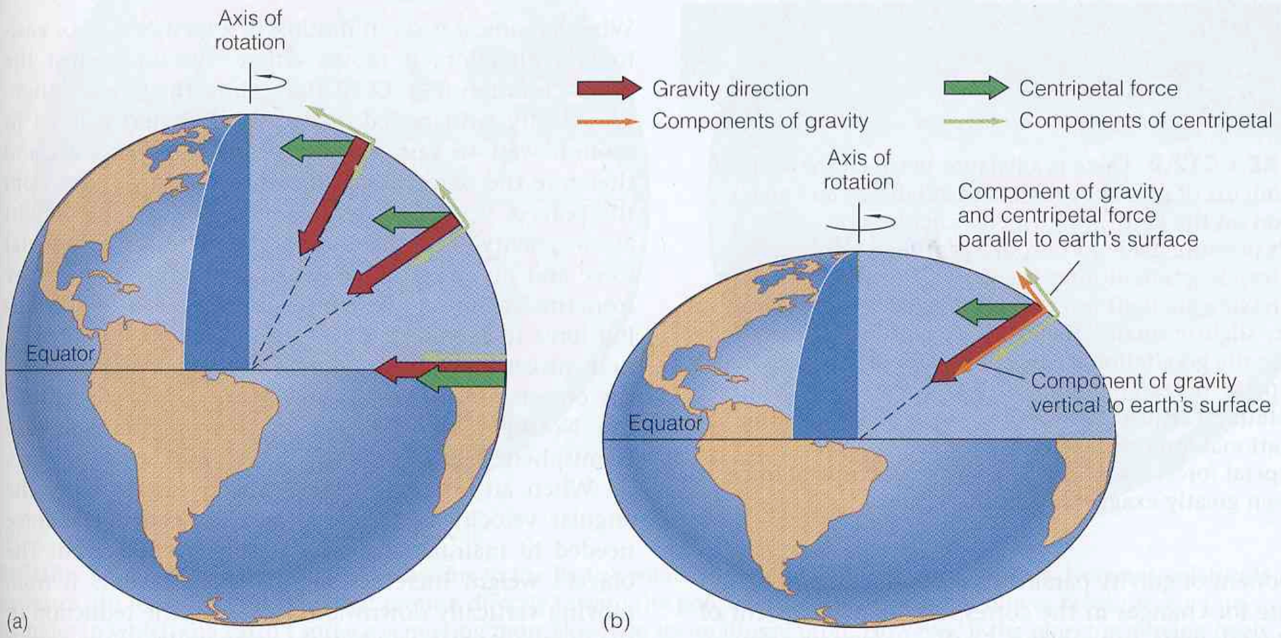


FIGURE CC12.7 (a) If the Earth were exactly spherical, there would be no component of gravity parallel to the Earth's surface at any latitude. However, to keep an object in orbit at the Earth's surface there would have to be a component of a centripetal force parallel to the Earth's surface, everywhere except at the equator. Because there would be no gravitational force component to provide this component of centripetal force, an object anywhere on the Earth's surface except at the equator would move into a wider orbit (in which the required centripetal force was lower). Thus, the object would slide toward the equator. (b) In response to the force imbalance that would be created if the Earth were spherical, the Earth and all other planets that were at one time totally molten or gaseous were not formed as perfect spheres. Instead, the Earth is an oblate spheroid, a squashed spheroid shape such as shown (but much exaggerated) in the figure. Because the Earth is an oblate spheroid, gravity does not act exactly perpendicular to the Earth's surface, except at the equator and poles. Consequently, at all points other than these, there is a small component of gravity parallel to the Earth's surface that balances the required centripetal force for an object at that point.

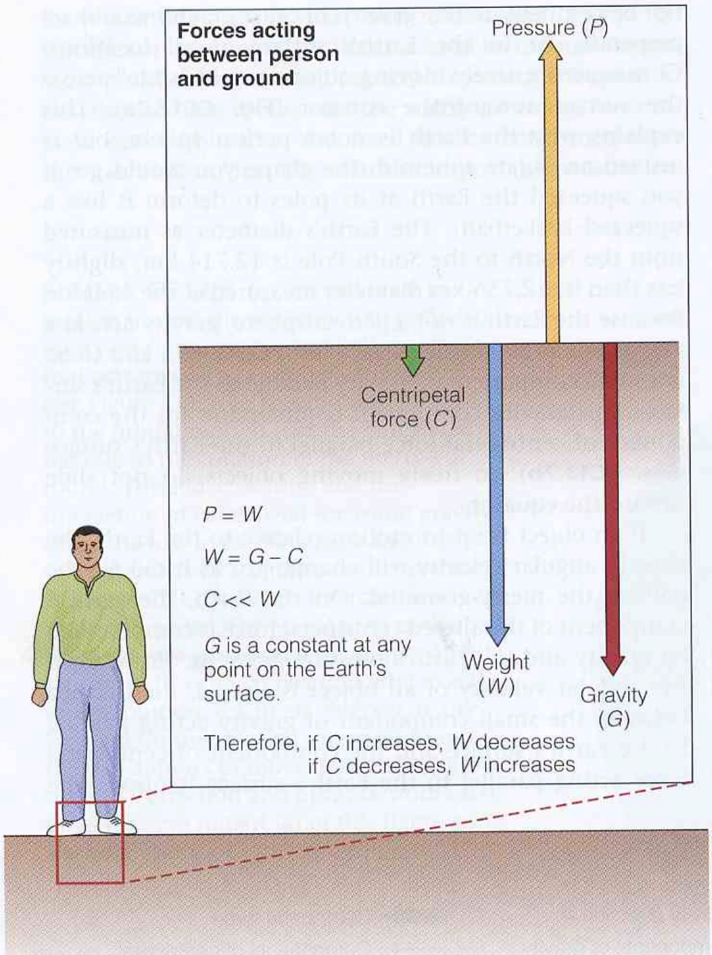


FIGURE CC12.8 There is a balance between the vertical components of gravity (which is invariable at any given location on the Earth), centripetal force, and the Earth's pressure gradient for objects at the Earth's surface. The pressure gradient force is equal to the object's weight. The pressure gradient force and the object's weight must be very slightly smaller than the gravitational force because the gravitational force must provide the required centripetal force to maintain the object in its orbit with the rotating Earth. Thus, the object's weight equals the gravitational force minus the very much smaller centripetal force. The magnitude of the centripetal force has been greatly exaggerated in this figure.

component of gravity parallel to the surface cannot compensate for changes in the corresponding component of centripetal force (unless the Earth changes its shape). Consequently, altering the angular velocity of a freely moving object on the Earth's surface causes it to move across the surface, toward or away from the pole.

Motion on the Earth: North and South

Now let's look at motions on the Earth's surface. First, consider a projectile fired toward the north in the Northern Hemisphere. This projectile has a component of motion from west to east imparted to it by the Earth's rotation. The projectile retains this west-to-east velocity, but the velocity of the Earth rotating underneath it decreases as the projectile moves north (**Fig. CC12.9a**). The projectile continues eastward while the Earth below it moves eastward progressively more slowly. Thus, the projectile "leads" the Earth's rotation at an increasing rate and follows a path that appears to an observer to be a curve deflected to the right (**Fig. CC12.9b**). In addition, because gravity prevents the projectile from maintaining its original distance from the Earth's axis of rotation, the projectile's angular velocity increases as it moves north. This requires increased centripetal force and creates a force imbalance that "pushes" the projectile back to the south away from the Earth's axis of rotation.

Similarly, a projectile fired southward in the Northern Hemisphere passes over an Earth that moves eastward progressively faster under the projectile, and it "lags" the Earth's rotation (**Fig. CC12.9c**). It also appears to be deflected to the right and is "pushed" back north because it has a lower angular velocity. In the Southern Hemisphere, the situation is similar, but the deflection is to the left (**Fig. CC12.9b,c**).

Motion on the Earth: East and West

When an object is set in motion in a west-to-east or east-to-west direction, it moves either with or against the Earth's rotation (**Fig. CC12.10a**). Thus, the object's angular velocity is increased or decreased. When it is set in motion west to east, angular velocity is increased and therefore the object tends to move outward away from the pole. A very small reduction in the object's weight allows gravity to compensate for the increased centripetal force and prevents the object from flying upward away from the Earth's surface. However, there is no compensating force to provide the needed increase in the component of centripetal force across the Earth's surface, and the object moves toward the equator, or to the right in the Northern Hemisphere and left in the Southern Hemisphere (**Fig. CC12.10b**).

When an object is set in motion east to west, the angular velocity is decreased and the centripetal force needed to maintain its orbit is slightly decreased. The object's weight increases slightly and prevents it from moving vertically downward. However, the reduction in the component of centripetal force parallel to the Earth's surface remains unbalanced and the object is moved across the Earth's surface toward the pole. Again, the deflection is to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (**Fig. CC12.10b**).

If the object is moving either west to east or east to west exactly at the equator, there is no component of centripetal force parallel to the Earth's surface, a small adjustment in weight can totally compensate the changes in centripetal force, and there is no deflection (**Fig. CC12.10b**).

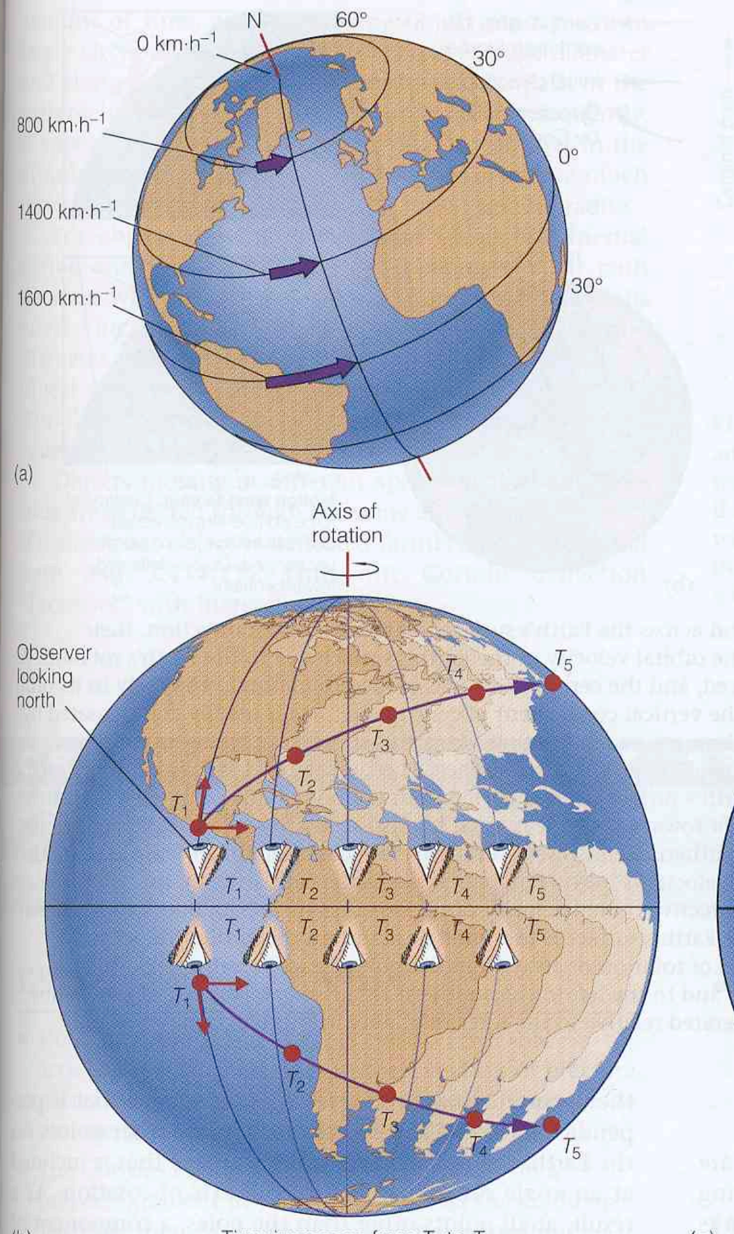


FIGURE CC12.9 (a) The orbital velocity due to the Earth's rotation of points on the Earth's surface decreases as latitude increases. (b) If an object is started in motion directly toward the pole in either hemisphere, it moves progressively into latitudes in which the Earth's surface is moving more slowly in its rotational orbit. However, if the object is moving freely (that is, if it is not attached by strong frictional forces to the solid Earth), it retains the orbital velocity that it had when it was started in motion. Thus, in addition to its motion to the north (or south in the Southern Hemisphere), the object continues to move to the east at its original orbital velocity and progressively moves ahead of the latitude from which it was set in motion. To an observer moving with the Earth's surface, the result is an apparent deflection in the path of the object, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. (c) If an object is started in motion directly toward the equator in either hemisphere, it moves progressively into latitudes in which the Earth's surface is moving more quickly in its rotational orbit. Thus, in addition to its motion to the south (or north in the Southern Hemisphere), it continues to move to the east at its original orbital velocity and progressively falls behind the latitude from which it was set in motion. The apparent deflection of the path of the object is, once again, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

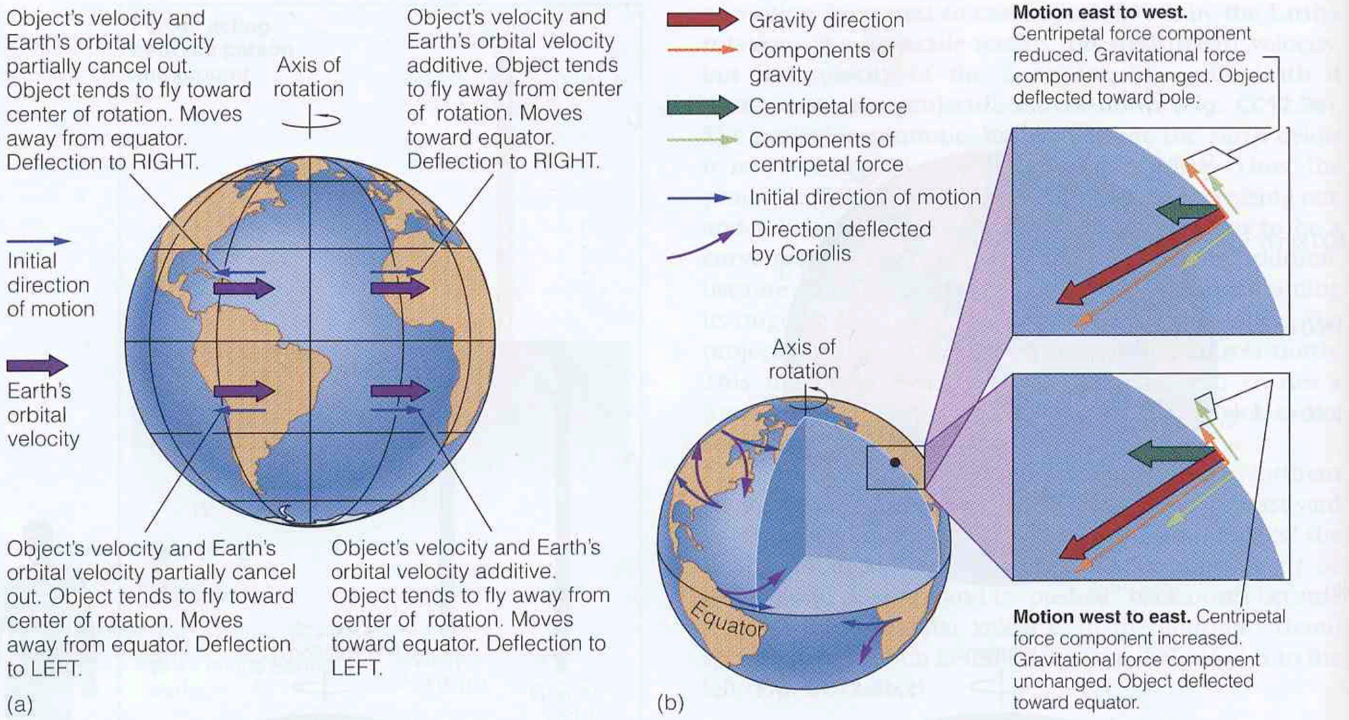


FIGURE CC12.10 (a) When objects are started in motion across the Earth's surface in an east-to-west direction, their velocity is in the opposite direction to that imparted by the orbital velocity of the Earth's surface due to the Earth's rotation. As a result, the effective orbital velocity of the object is reduced, and the centripetal force needed to maintain the body in its orbit with the Earth's spin is decreased. The slight decrease in the vertical component of centripetal force is readily compensated by a negligibly small increase in the object's weight (change in pressure gradient). (b) In contrast, no such compensation is possible for the component of centripetal force that acts parallel to the Earth's surface. The slight excess of gravitational force over the component of centripetal force parallel to the Earth's surface needed to maintain the body in its orbit with the Earth's spin deflects the object's path toward the axis of rotation or toward the pole in each hemisphere. Thus, the deflection is to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Similarly, (a) when objects are started in motion across the Earth's surface in a west-to-east direction, their velocity is in the same direction as that imparted by the orbital velocity of the Earth's surface due to its rotation. (b) The effective orbital velocity of the object is increased, but the centripetal force provided by the component of gravity parallel to the Earth's surface is too small to maintain this orbital velocity. Therefore, the object's path is deflected away from the axis of rotation or away from the pole in each hemisphere. This deflection is also to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. For ease of illustration, the magnitude of centripetal force has been greatly exaggerated relative to the force of gravity in this diagram.

Coriolis Effect Characteristics

All objects moving freely relative to the Earth are deflected by the Coriolis effect unless they are moving directly east or west along the equator. The deflection is always to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. However, it is easier to say that the direction of the deflection is ***cum sole,*** which means "with the sun." To an observer in the Northern Hemisphere looking toward the equator and thus toward the arc of the sun across the sky, the sun moves across the sky from left to right. In the Southern Hemisphere, the sun moves from right to left.

Freely moving objects appear to move in circular paths on the Earth's surface. These circular paths are distorted if objects move large distances across the Earth's surface. This is because the Earth is equivalent to a flat merry-go-round only at the North or South Pole, where the apparent rotation occurs across a surface that is perpendicular to the axis of rotation. At all other points on the Earth, the motion occurs on a surface that is inclined at an angle other than 90° to the axis of rotation. As a result, at all points other than the poles, a component of the Coriolis deflection is directed vertically downward and "blocked" by adjustments of the object's weight. Consequently, the rate of deflection is reduced.

The proportion of centripetal force directed vertically downward increases from zero at the poles to 100% at the equator (**Fig. CC12.7a**). Therefore, the Coriolis deflection is at a maximum at the poles, is reduced progressively with decreasing **latitude**, and reaches zero at the equator. In addition, the time necessary for a freely moving object to complete a circle increases with decreasing latitude. This time period, called the "inertial period," is 12 h at the poles, increases to 24 h at 30° latitude, and is infinity at the equator.

The diameter of the circle in which freely moving objects appear to move is determined by both the object's speed and its latitude. Because freely moving objects at the same latitude will complete a circle in the same amount of time, a faster moving object must move in larger circles. A bullet travels in a circle of huge diameter and along only a very tiny part of its circular path in the extremely short time it remains airborne. Consequently, it appears to travel in a "straight" line. Air masses in the atmosphere and water masses in the oceans move much more slowly and travel in paths of much smaller radius.

For objects moving at the same speed, the inertial period and the diameter of the apparent circular path decrease with increasing latitude. Therefore, the Coriolis effect "increases" with increasing latitude. Because the diameter of the circle in which even a slowly moving object appears to travel is very large near the equator, the Coriolis deflection is often considered negligible at latitudes within 5° of the equator.

Objects moving at different speeds at the same latitude are deflected through the same angle in equal times, but the faster object is deflected farther from its original path (**Fig. CC12.11**). Thus, the Coriolis deflection "increases" with increasing speed.

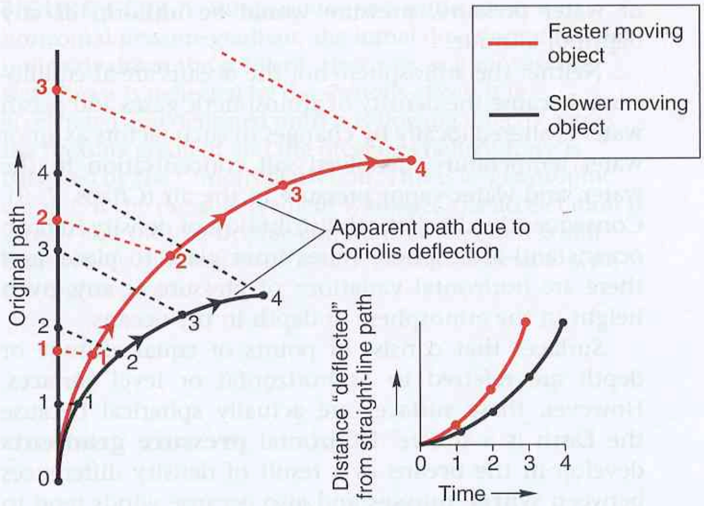


FIGURE CC12.11 The distance between the location of an object deflected by the Coriolis effect and the location it would be expected to occupy if it were not deflected (that is, if it followed a straight-line path) increases more quickly with time if the object's speed is greater. Thus, the magnitude of the Coriolis deflection is said to "increase" with increasing speed of the object.

CRITICAL CONCEPT 13

Geostrophic Flow

ESSENTIAL TO KNOW

- Horizontal pressure gradients exert a force that accelerates fluid molecules in the direction of pressure decrease on the gradient. The acceleration increases as the strength of the the pressure gradient increases.
- The Coriolis effect deflects fluids that flow on a pressure gradient until they flow across the gradient. The flow then continues along a line of constant pressure (isobar) as a geostrophic flow.
- Geostrophic flow conditions occur when the pressure gradient force is balanced by the Coriolis deflection.
- Geostrophic wind and current speeds are determined by the steepness of the pressure gradient. Wind or current speed increases as the steepness of the gradient increases.
- Geostrophic wind or current speed and direction can be determined from isobaric maps. The direction of flow is parallel to the isobars, and the speed is higher where the pressure gradient is steeper (isobars are closer together).
- Geostrophic winds and currents flow counterclockwise around low-pressure zones and clockwise around high-pressure zones in the Northern Hemisphere. In the Southern Hemisphere, they flow clockwise around low-pressure zones and counterclockwise around high-pressure zones.

UNDERSTANDING THE CONCEPT

The atmosphere and ocean waters are **stratified** fluids (**CC1**), in each of which **density** decreases with increasing distance from the Earth's center. The only exceptions are in limited areas where stratification is unstable. It is in these areas of unstable stratification that density-driven vertical motions of the fluid occur.

If the oceans or atmosphere were at equilibrium, density would be uniform at any one depth or altitude. The vertical density gradient would be the same everywhere, so the total weight of the overlying water and/or air column at a specific depth or altitude would be the same everywhere. Because this total weight determines atmospheric