Chapter 5

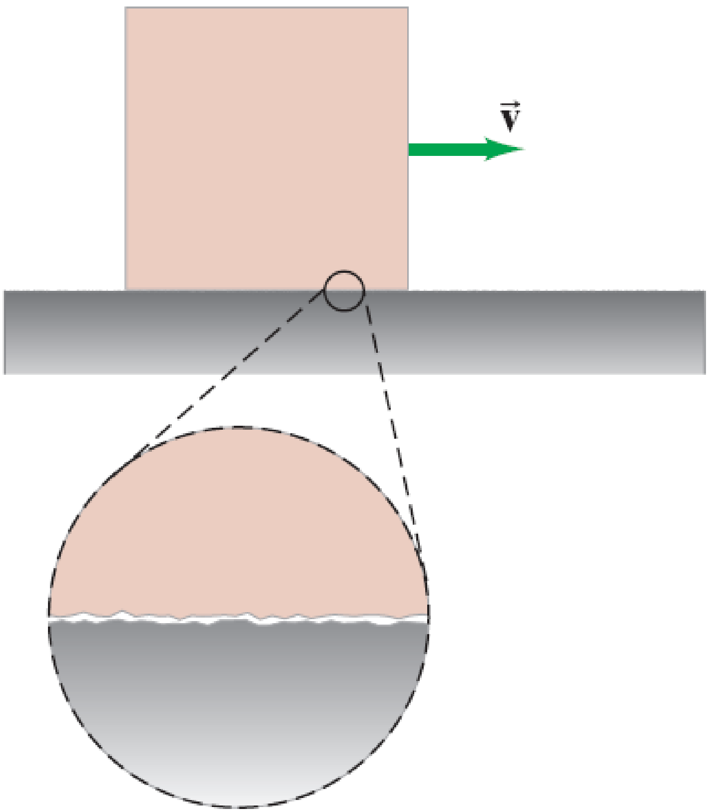
Using Newton's Laws: Friction, Circular Motion, Drag Forces

Units of Chapter 5

- **Applications of Newton's Laws Involving Friction**
- **Uniform Circular Motion—Kinematics**
- **Dynamics of Uniform Circular Motion**
- **Highway Curves: Banked and Unbanked**
- **Nonuniform Circular Motion**
- **Velocity-Dependent Forces: Drag and Terminal Velocity**

5-1 Applications of Newton's Laws Involving Friction

Friction is always present when two solid surfaces slide along each other.



The microscopic details are not yet fully understood.

5-1 Applications of Newton's Laws Involving Friction

Sliding friction is called **kinetic** friction.

Approximation of the frictional force:

$$F_{\mathrm{fr}} = \mu_{\mathrm{k}} F_{\mathrm{N}} .$$

Here, F_{N} is the **normal** force, and μ_{k} is the **coefficient of kinetic friction**, which is different for each pair of surfaces.

5-1 Applications of Newton's Laws Involving Friction

Static friction applies when two surfaces are at rest with respect to each other (such as a book sitting on a table).

The static frictional force is as big as it needs to be to prevent slipping, up to a maximum value.

$$F_{\mathrm{fr}} \leq \mu_s F_{\mathrm{N}} \,.$$

Usually it is easier to keep an object sliding than it is to get it started.

5-1 Applications of Newton's Laws Involving Friction

Note that, in general, $\mu_s > \mu_k$.

TABLE 5–1 Coefficients of Friction†

Surfaces	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Wood on wood	0.4	0.2
Ice on ice	0.1	0.03
Metal on metal (lubricated)	0.15	0.07
Steel on steel (unlubricated)	0.7	0.6
Rubber on dry concrete	1.0	0.8
Rubber on wet concrete	0.7	0.5
Rubber on other solid surfaces	1–4	1
Teflon® on Teflon in air	0.04	0.04
Teflon on steel in air	0.04	0.04
Lubricated ball bearings	<0.01	<0.01
Synovial joints (in human limbs)	0.01	0.01

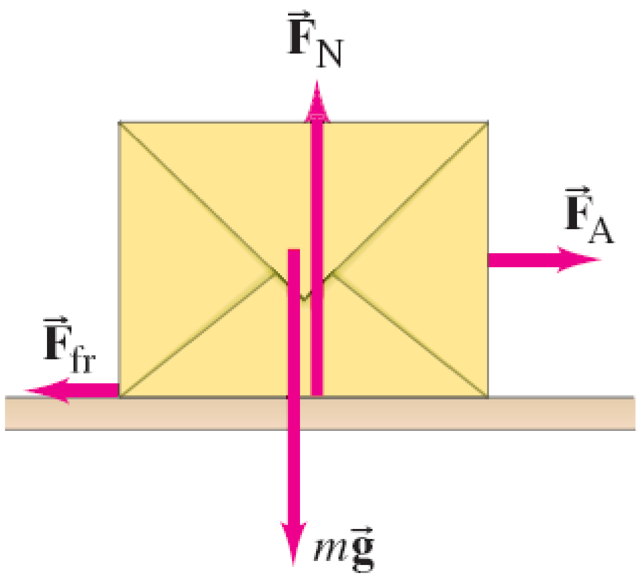
†Values are approximate and intended only as a guide.

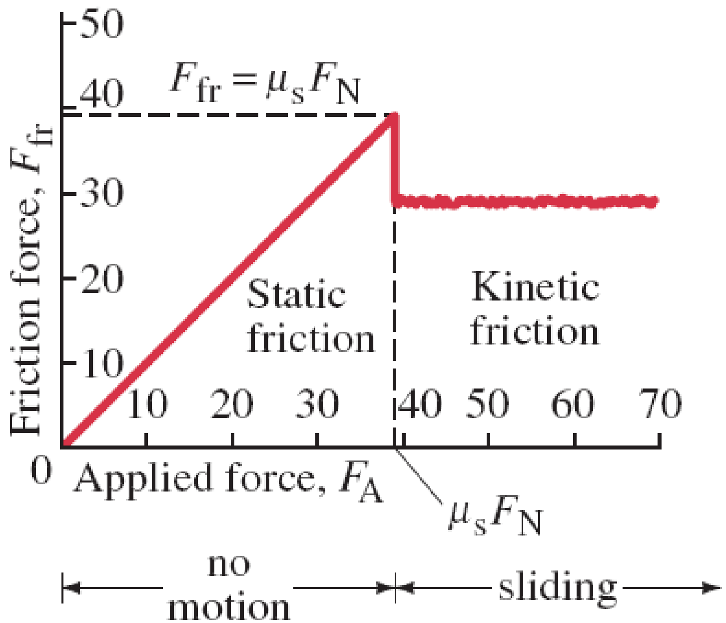
5-1 Applications of Newton's Laws Involving Friction

Example 5-1: Friction: static and kinetic.

Our 10.0-kg mystery box rests on a horizontal floor. The coefficient of static friction is 0.40 and the coefficient of kinetic friction is 0.30. Determine the force of friction acting on the box if a horizontal external applied force is exerted on it of magnitude:

(a) 0, (b) 10 N, (c) 20 N, (d) 38 N, and (e) 40 N.

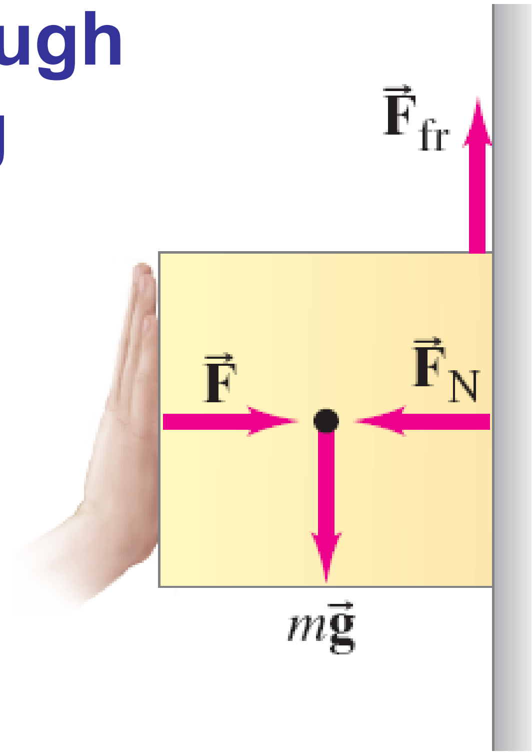




5-1 Applications of Newton's Laws Involving Friction

Conceptual Example 5-2: A box against a wall.

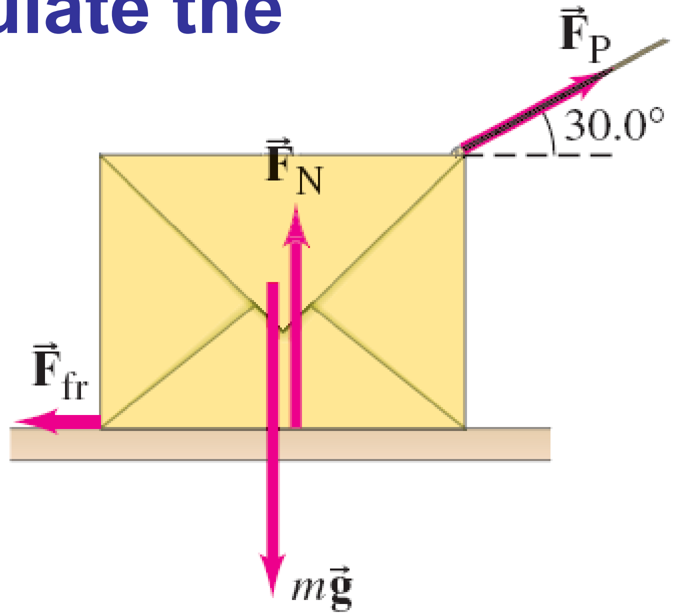
You can hold a box against a rough wall and prevent it from slipping down by pressing hard horizontally. How does the application of a horizontal force keep an object from moving vertically?



5-1 Applications of Newton's Laws Involving Friction

Example 5-3: Pulling against friction.

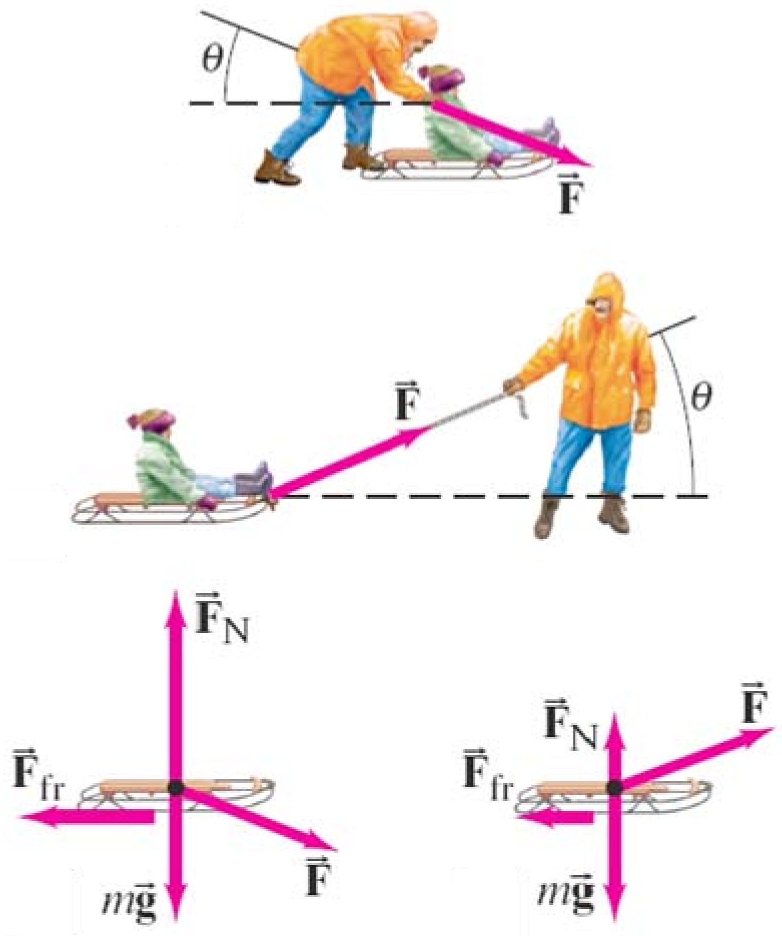
A 10.0-kg box is pulled along a horizontal surface by a force of 40.0 N applied at a 30.0° angle above horizontal. The coefficient of kinetic friction is 0.30. Calculate the acceleration.



5-1 Applications of Newton's Laws Involving Friction

Conceptual Example 5-4: To push or to pull a sled?

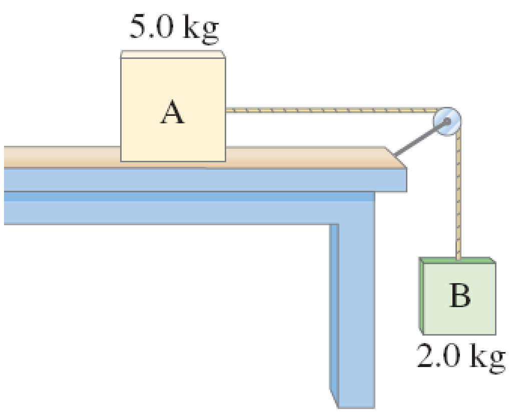
Your little sister wants a ride on her sled. If you are on flat ground, will you exert less force if you push her or pull her? Assume the same angle θ in each case.

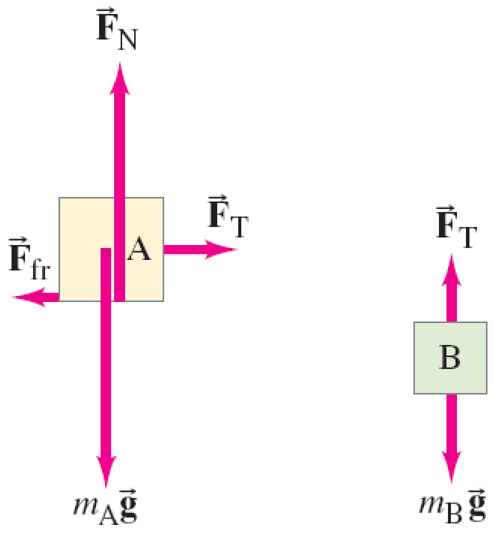


5-1 Applications of Newton's Laws Involving Friction

Example 5-5: Two boxes and a pulley.

Two boxes are connected by a cord running over a pulley. The coefficient of kinetic friction between box A and the table is 0.20. We ignore the mass of the cord and pulley and any friction in the pulley, which means we can assume that a force applied to one end of the cord will have the same magnitude at the other end. We wish to find the acceleration, *a*, of the system, which will have the same magnitude for both boxes assuming the cord doesn't stretch. As box B moves down, box A moves to the right.

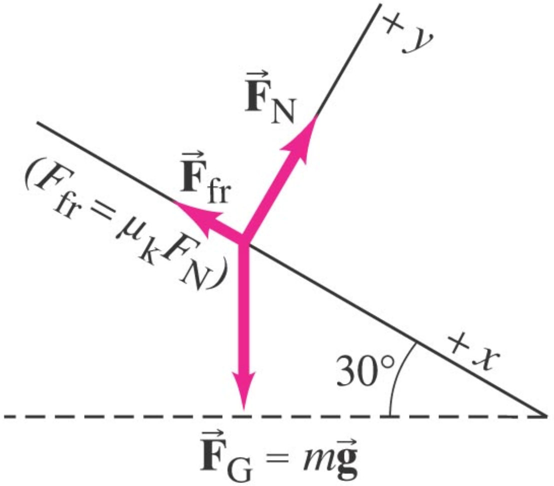


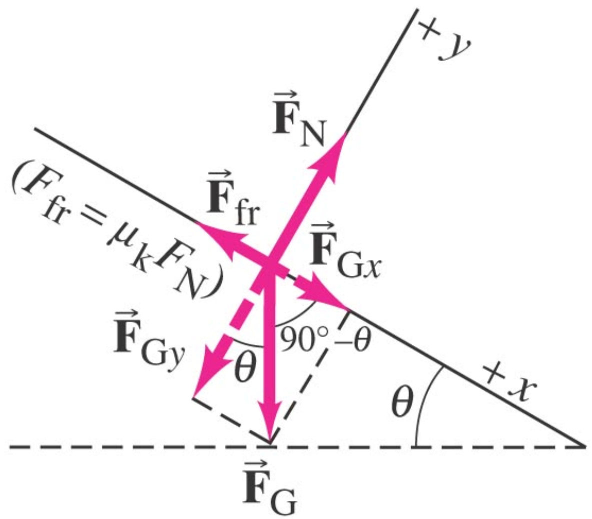


5-1 Applications of Newton's Laws Involving Friction

Example 5-6: The skier.

This skier is descending a 30° slope, at constant speed. What can you say about the coefficient of kinetic friction?

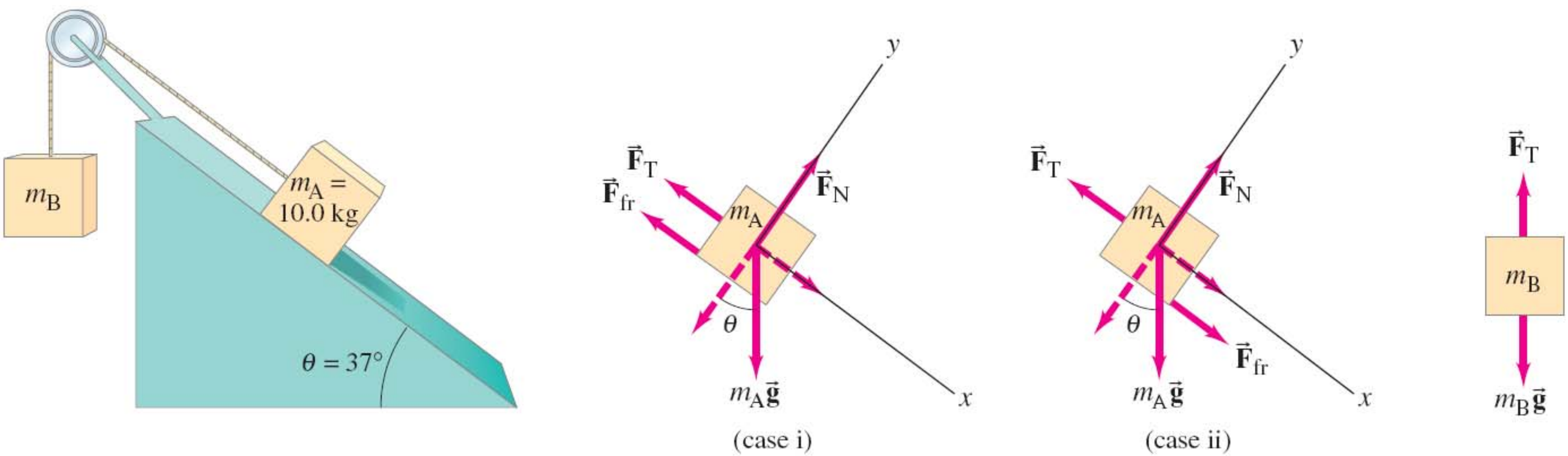




5-1 Applications of Newton's Laws Involving Friction

Example 5-7: A ramp, a pulley, and two boxes.

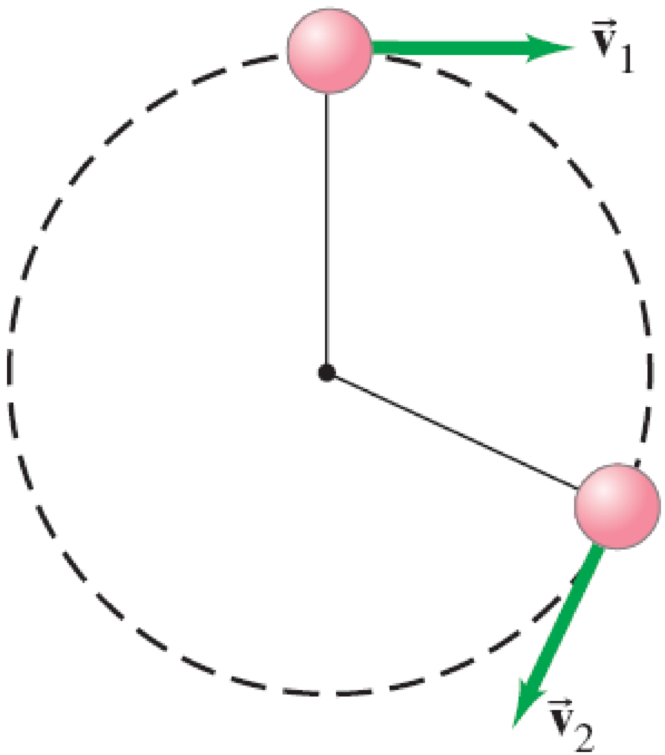
Box A, of mass 10.0 kg, rests on a surface inclined at 37° to the horizontal. It is connected by a lightweight cord, which passes over a massless and frictionless pulley, to a second box B, which hangs freely as shown. (a) If the coefficient of static friction is 0.40, determine what range of values for mass B will keep the system at rest. (b) If the coefficient of kinetic friction is 0.30, and m_B = 10.0 kg, determine the acceleration of the system.



5-2 Uniform Circular Motion—Kinematics

Uniform circular motion: motion in a **circle** of constant **radius** at constant **speed**

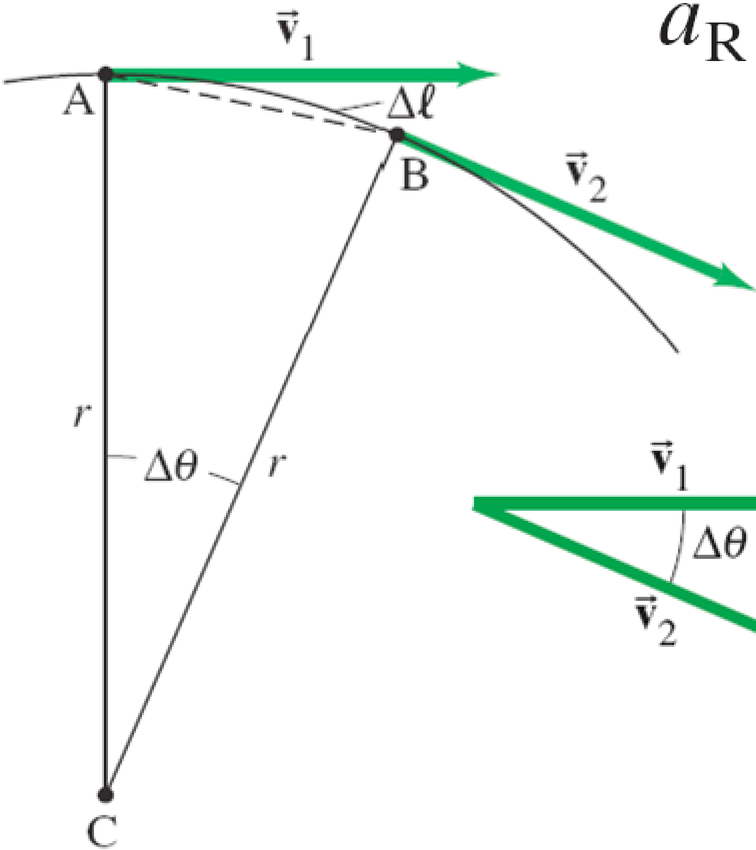
Instantaneous velocity is always **tangent** to the circle.

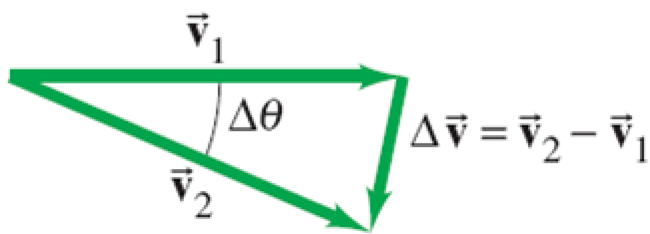


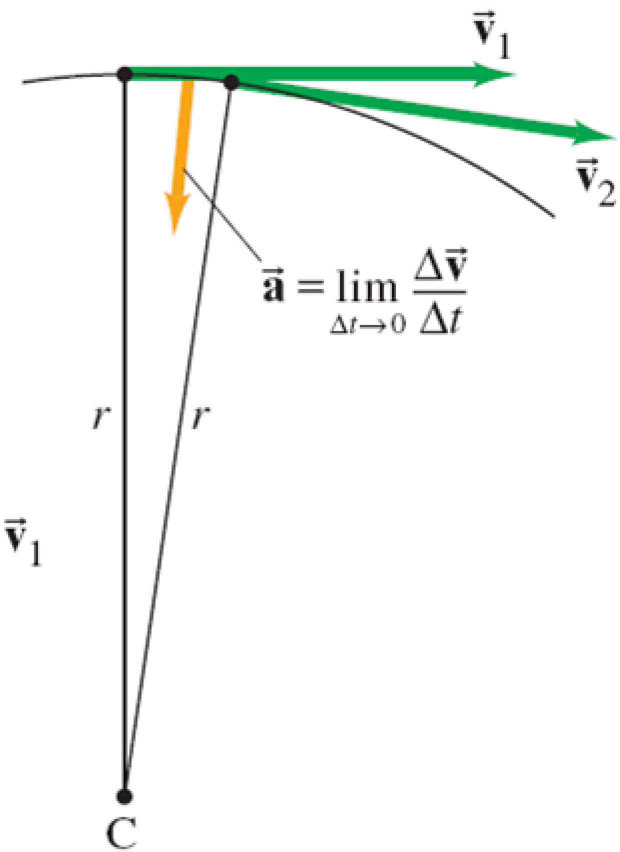
5-2 Uniform Circular Motion—Kinematics

Looking at the change in velocity in the limit that the time interval becomes infinitesimally small, we see that

$$a_R = \frac{v^2}{r}.$$

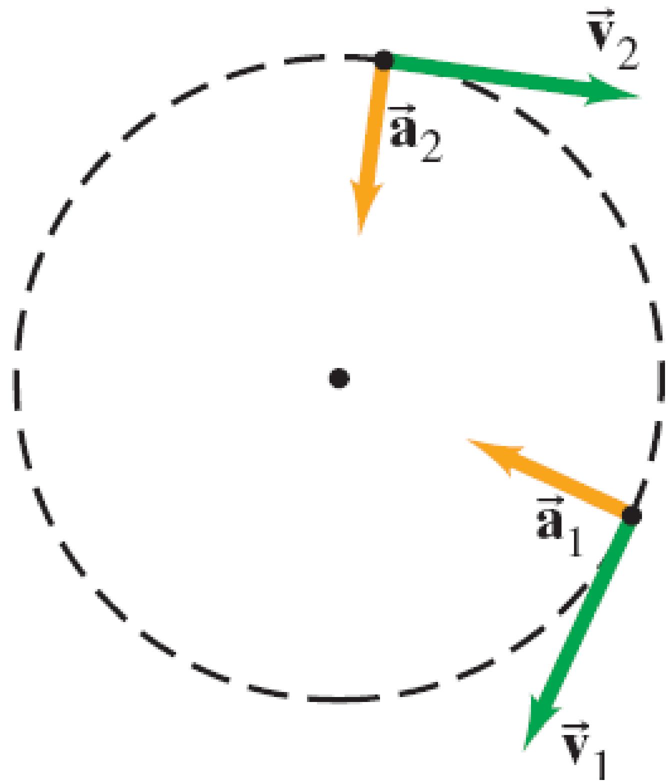






5-2 Uniform Circular Motion—Kinematics

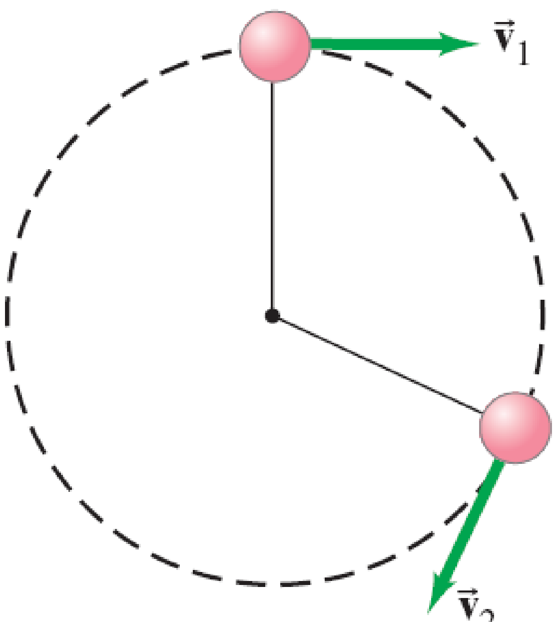
This acceleration is called the centripetal, or radial, acceleration, and it points toward the center of the circle.



5-2 Uniform Circular Motion—Kinematics

Example 5-8: Acceleration of a revolving ball.

A 150-g ball at the end of a string is revolving uniformly in a horizontal circle of radius 0.600 m. The ball makes 2.00 revolutions in a second. What is its centripetal acceleration?

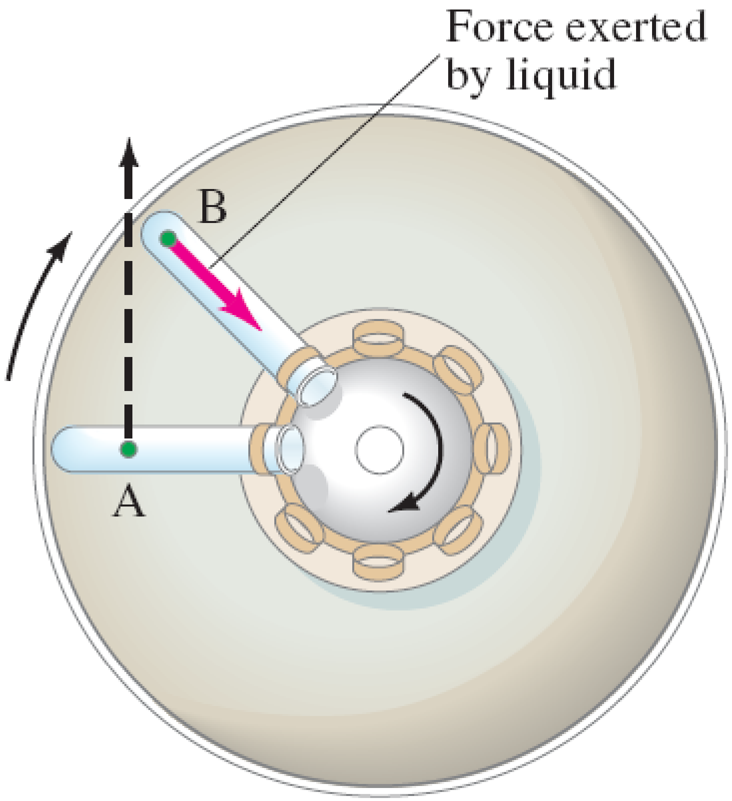


5-2 Uniform Circular Motion—Kinematics

Example 5-9: Moon's centripetal acceleration.

The Moon's nearly circular orbit about the Earth has a radius of about 384,000 km and a period *T* of 27.3 days. Determine the acceleration of the Moon toward the Earth.

5-2 Uniform Circular Motion—Kinematics



A **centrifuge** works by spinning very fast. This means there must be a very large **centripetal** force. The object at A would go in a straight line but for this force; as it is, it winds up at B.

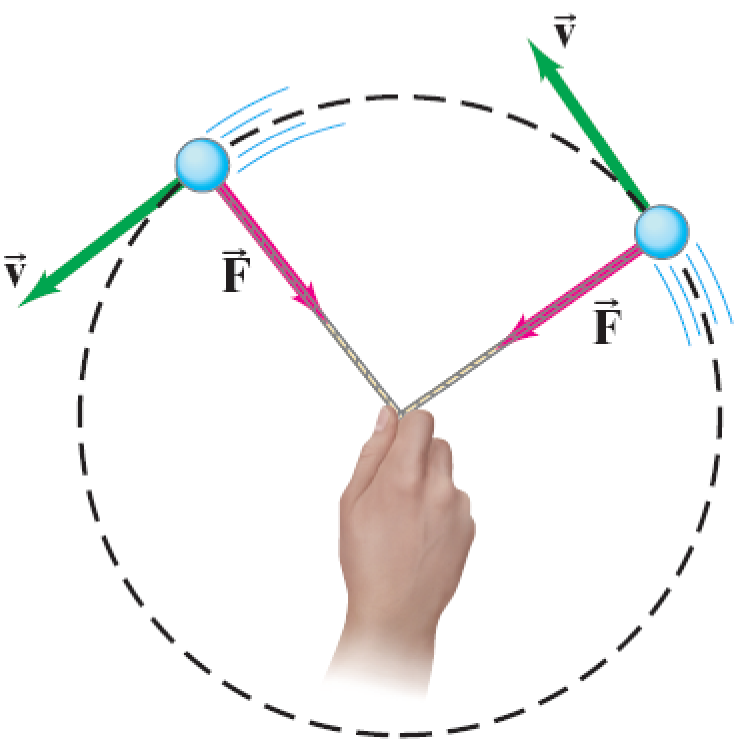
5-2 Uniform Circular Motion—Kinematics

Example 5-10: Ultracentrifuge.

The rotor of an ultracentrifuge rotates at 50,000 rpm (revolutions per minute). A particle at the top of a test tube is 6.00 cm from the rotation axis. Calculate its centripetal acceleration, in "*g*'s."

5-3 Dynamics of Uniform Circular Motion

For an object to be in uniform circular motion, there must be a **net force** acting on it.

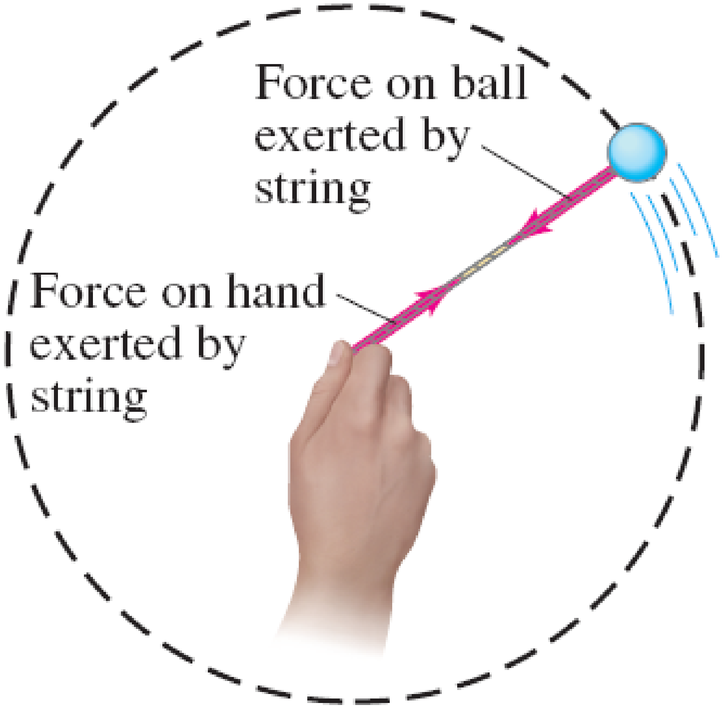


We already know the acceleration, so can immediately write the force:

$$\Sigma F_{\mathrm{R}} = ma_{\mathrm{R}} = m\frac{v^2}{r}.$$

5-3 Dynamics of Uniform Circular Motion

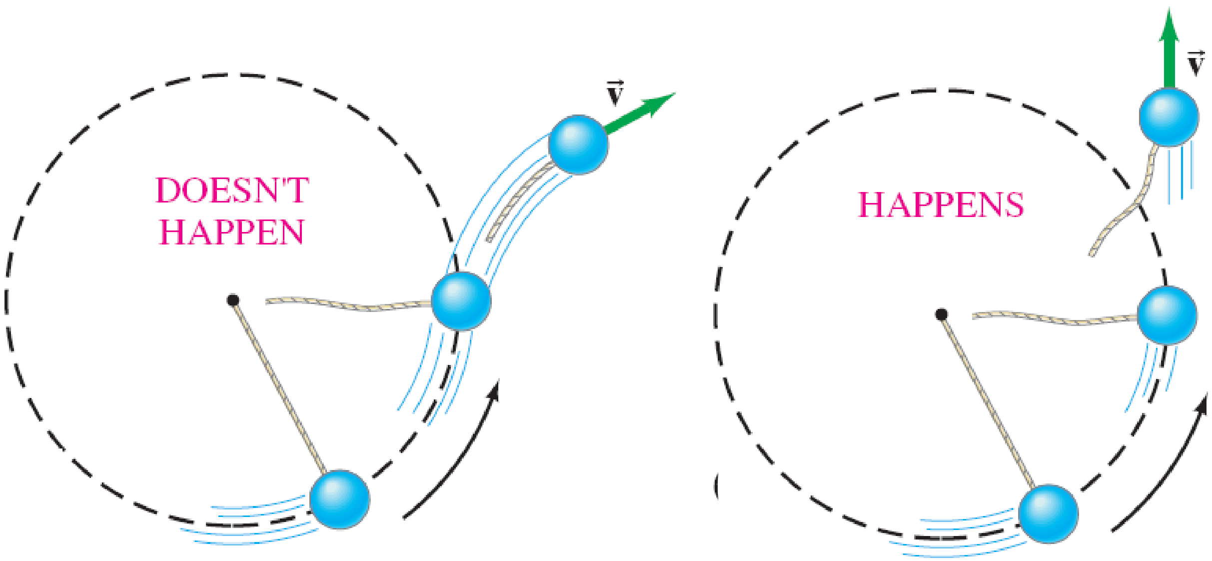
We can see that the force must be **inward** by thinking about a ball on a string. Strings only pull; they never push.



5-3 Dynamics of Uniform Circular Motion

There is no **centrifugal** force pointing outward; what happens is that the natural tendency of the object to move in a straight line must be overcome.

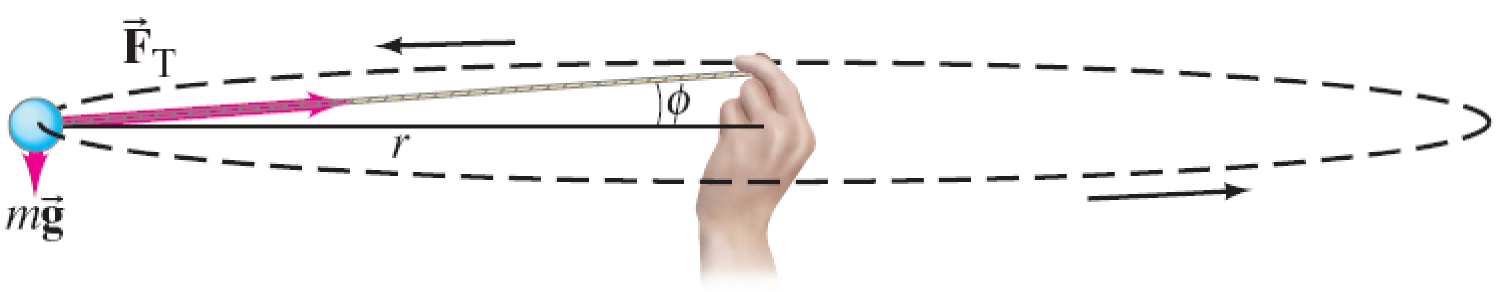
If the centripetal force vanishes, the object flies off at a **tangent** to the circle.



5-3 Dynamics of Uniform Circular Motion

Example 5-11: Force on revolving ball (horizontal).

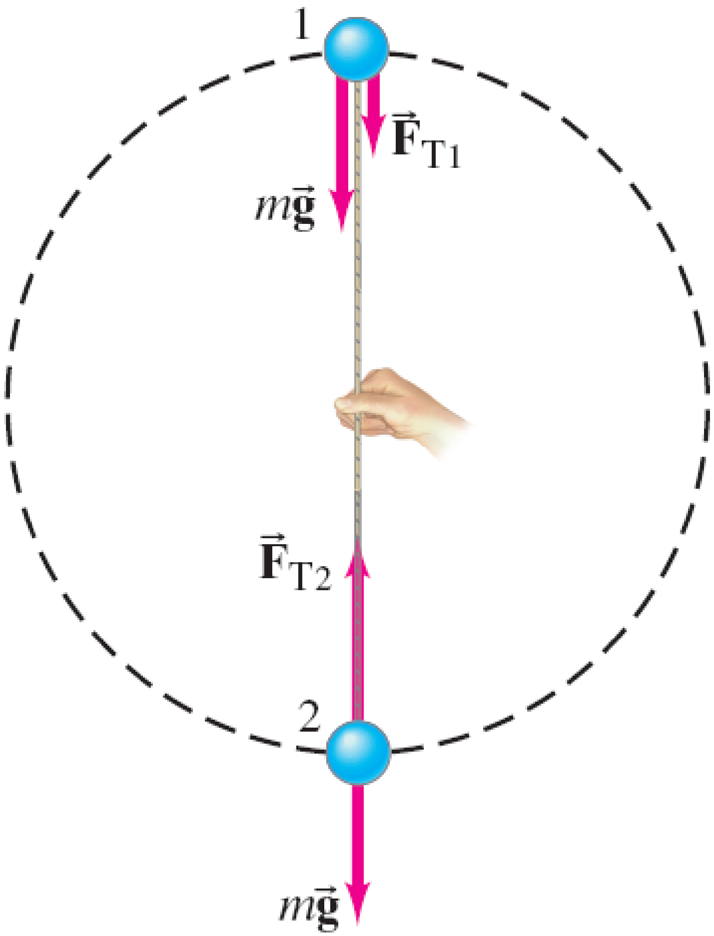
Estimate the force a person must exert on a string attached to a 0.150-kg ball to make the ball revolve in a horizontal circle of radius 0.600 m. The ball makes 2.00 revolutions per second. Ignore the string's mass.



5-3 Dynamics of Uniform Circular Motion

Example 5-12: Revolving ball (vertical circle).

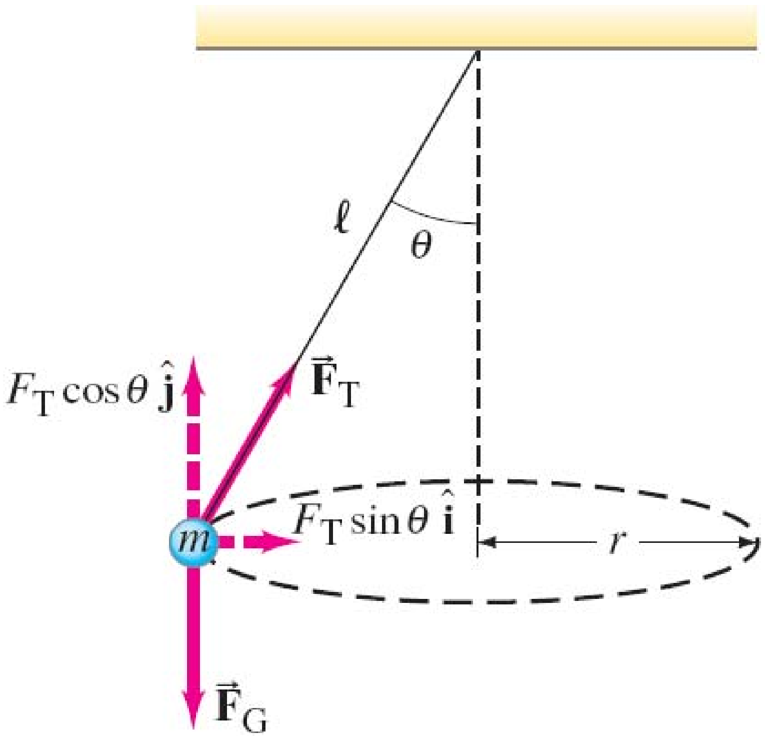
A 0.150-kg ball on the end of a 1.10-m-long cord (negligible mass) is swung in a vertical circle. (a) Determine the minimum speed the ball must have at the top of its arc so that the ball continues moving in a circle. (b) Calculate the tension in the cord at the bottom of the arc, assuming the ball is moving at twice the speed of part (a).



5-3 Dynamics of Uniform Circular Motion

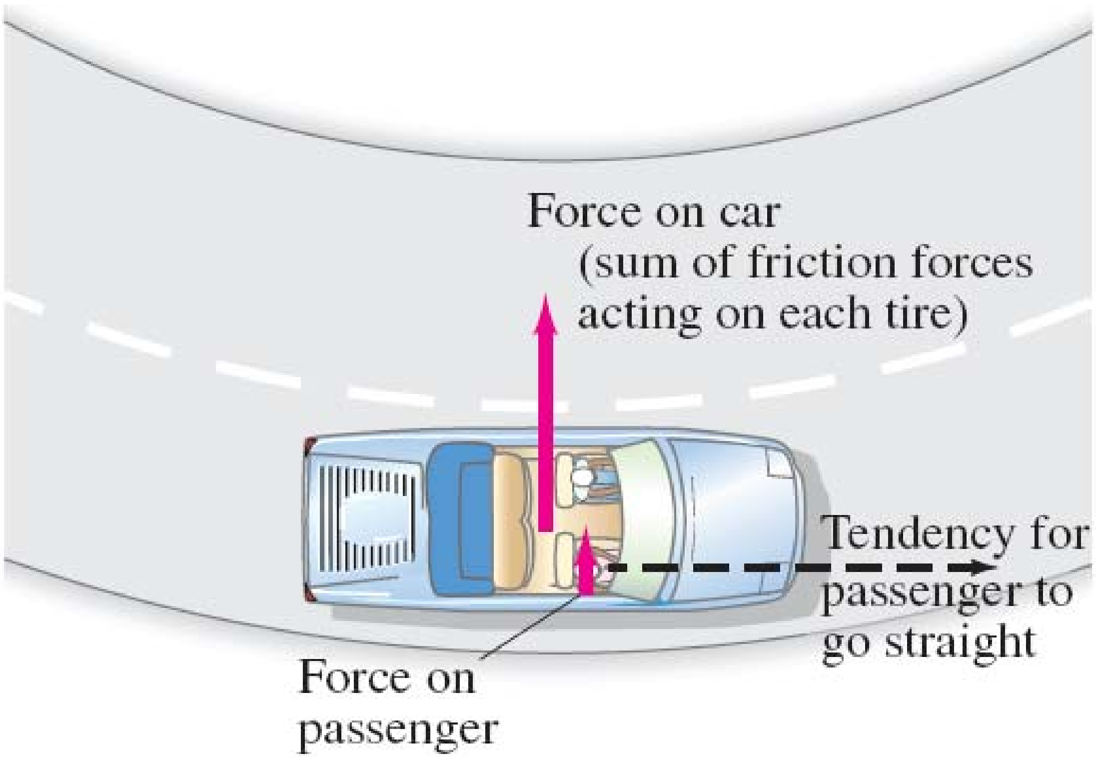
Example 5-13: Conical pendulum.

A small ball of mass m, suspended by a cord of length l, revolves in a circle of radius $r = l \sin \theta$, where θ is the angle the string makes with the vertical. (a) In what direction is the acceleration of the ball, and what causes the acceleration? (b) Calculate the speed and period (time required for one revolution) of the ball in terms of l, θ, g, and m.



5-4 Highway Curves: Banked and Unbanked

When a car goes around a **curve**, there must be a net force toward the center of the circle of which the curve is an arc. If the road is flat, that force is supplied by **friction**.



5-4 Highway Curves: Banked and Unbanked

If the frictional force is **insufficient**, the car will tend to move more nearly in a **straight line**, as the skid marks show.

5-4 Highway Curves: Banked and Unbanked

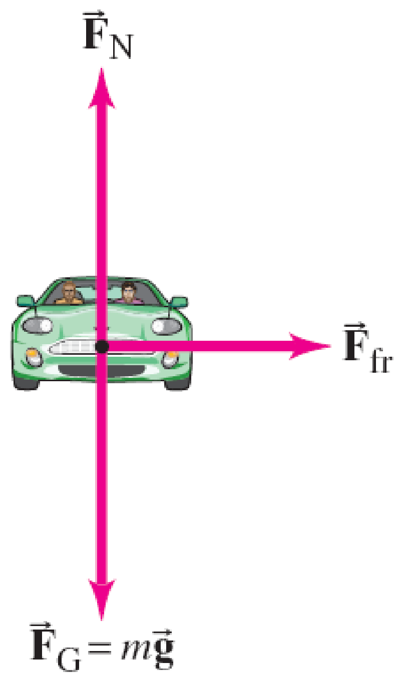
As long as the tires do not slip, the friction is **static**. If the tires do start to slip, the friction is **kinetic**, which is bad in two ways:

1. The kinetic frictional force is **smaller** than the static.

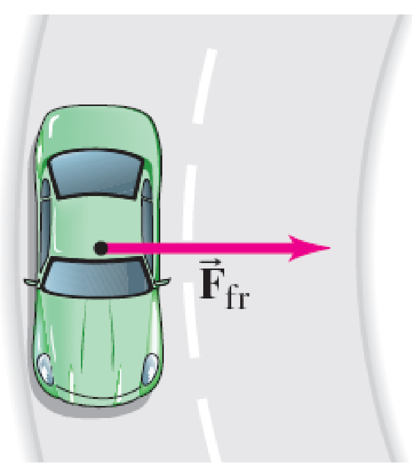
2. The static frictional force can point toward the center of the circle, but the kinetic frictional force **opposes** the direction of motion, making it very difficult to regain control of the car and continue around the curve.

5-4 Highway Curves: Banked and Unbanked

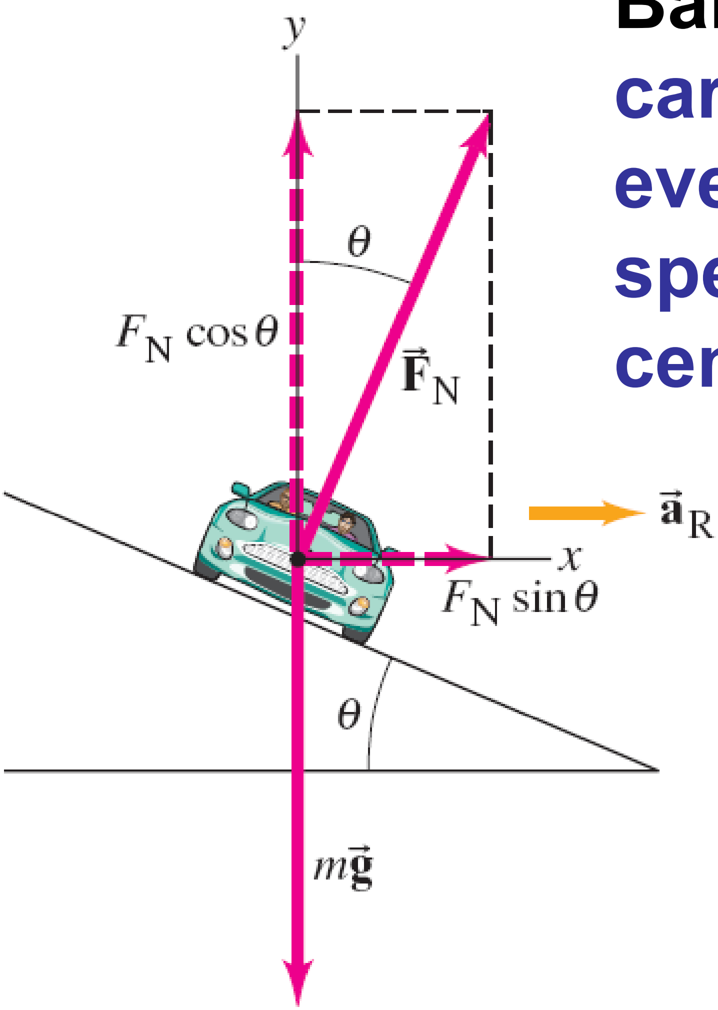
Example 5-14: Skidding on a curve.



A 1000-kg car rounds a curve on a flat road of radius 50 m at a speed of 15 m/s (54 km/h). Will the car follow the curve, or will it skid? Assume: (a) the pavement is dry and the coefficient of static friction is $\mu_s = 0.60$; (b) the pavement is icy and $\mu_s = 0.25$.



5-4 Highway Curves: Banked and Unbanked



Banking the curve can help keep cars from skidding. In fact, for every banked curve, there is one speed at which the entire centripetal force is supplied by the horizontal component of the **normal** force, and no friction is required. This occurs when:

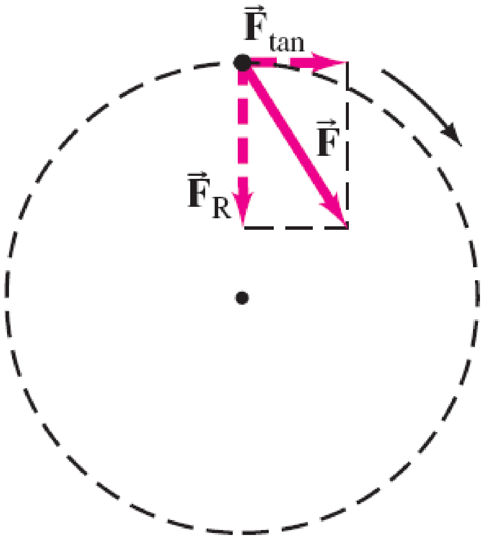
$$F_N \sin\theta = m\frac{v^2}{r}.$$

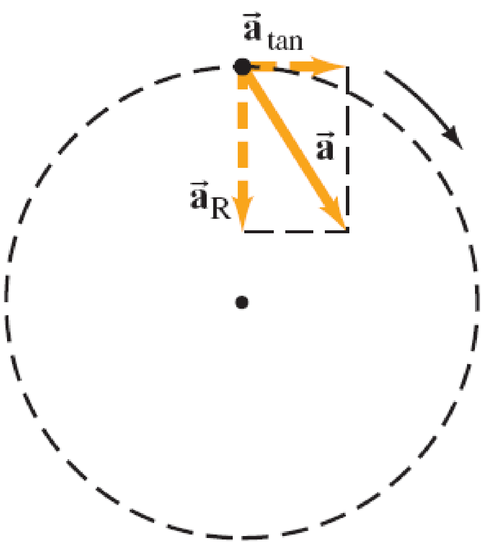
5-4 Highway Curves: Banked and Unbanked

Example 5-15: Banking angle.

(a) For a car traveling with speed v around a curve of radius r, determine a formula for the angle at which a road should be banked so that no friction is required. (b) What is this angle for an expressway off-ramp curve of radius 50 m at a design speed of 50 km/h?

5-5 Nonuniform Circular Motion

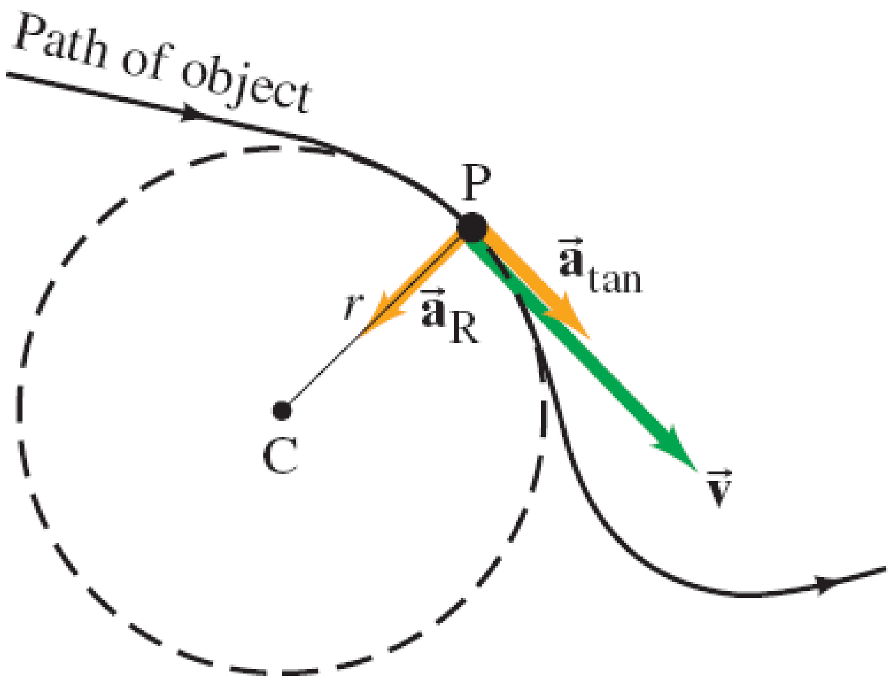




If an object is moving in a circular path but at varying **speeds**, it must have a **tangential** component to its acceleration as well as the **radial** one.

5-5 Nonuniform Circular Motion

This concept can be used for an object moving along any **curved path**, as any small segment of the path will be approximately circular.

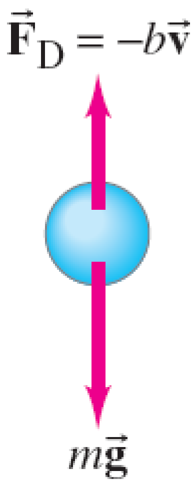


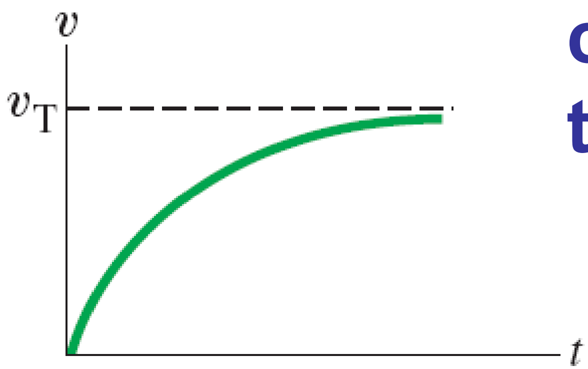
5-6 Velocity-Dependent Forces: Drag and Terminal Velocity

When an object moves through a fluid, it experiences a drag force that depends on the velocity of the object.

For small velocities, the force is approximately proportional to the velocity; for higher speeds, the force is approximately proportional to the square of the velocity.

5-6 Velocity-Dependent Forces: Drag and Terminal Velocity





If the drag force on a falling object is proportional to its velocity, the object gradually slows until the drag force and the gravitational force are equal. Then it falls with constant velocity, called the terminal velocity.

$$v_T = \frac{mg}{b}$$

Summary of Chapter 5

- **Kinetic friction:** $F_{\text{fr}} = \mu_{\text{k}} F_{\text{N}}.$

- **Static friction:** $F_{\text{fr}} \leq \mu_{\text{s}} F_{\text{N}}.$

- **An object moving in a circle at constant speed is in uniform circular motion.**

- **It has a centripetal acceleration of** $a_{\text{R}} = \dfrac{v^2}{r}.$

- **There is a centripetal force given by**

$$\Sigma F_{\text{R}} = m a_{\text{R}} = m \frac{v^2}{r}.$$