PHYS121 Integrated Science-Physics

W2T1 Application of Newton's laws of motion

References:

[1] David Halliday, Jearl Walker, Resnick Jearl, 'Fundamentals of Physics', (Wiley, 2018)
[2] Doug Giancoli, 'Physics for Scientists and Engineers with modern physics', (Pearson, 2009)
[3] Hugh D. Young, Roger A. Freedman, 'University Physics with Modern Physics', (Pearson, 2012)
And others specified when needed.

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5.7.5. An astronaut, whose mass on the surface of the Earth is m, orbits the Earth in the space shuttle at an altitude of 450 km. What is her mass while orbiting in the space shuttle?

a) $0.125m$

b) $0.25m$

c) $0.50m$

d) $0.75m$

e) m

Learning outcomes

- Solve problems using Newton's laws of motion involving friction force, drag force, uniform and non-uniform circular motions.

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Friction, static/kinetic (revisited)

- Friction forces are essential:
  - Picking things up
  - Walking, biking, driving anywhere
  - Writing with a pencil
  - Building with nails, weaving cloth
- But overcoming friction forces is also important:
  - Efficiency in engines
  - (20% of the gasoline used in an automobile goes to counteract friction in the drive train)
  - Roller skates, fans
  - Anything that we want to remain in motion

- Microscopic picture: surfaces are bumpy
- Friction occurs as contact points slide over each other
- Two specially prepared metal surfaces can cold-weld together and become impossible to slide, because there is so much contact between the surfaces
- Greater force normal to the contact plane increases the friction because the surfaces are pressed together and make more contact
- Sliding that is jerky, due to the ridges on the surface, produces squeaking/squealing/sound

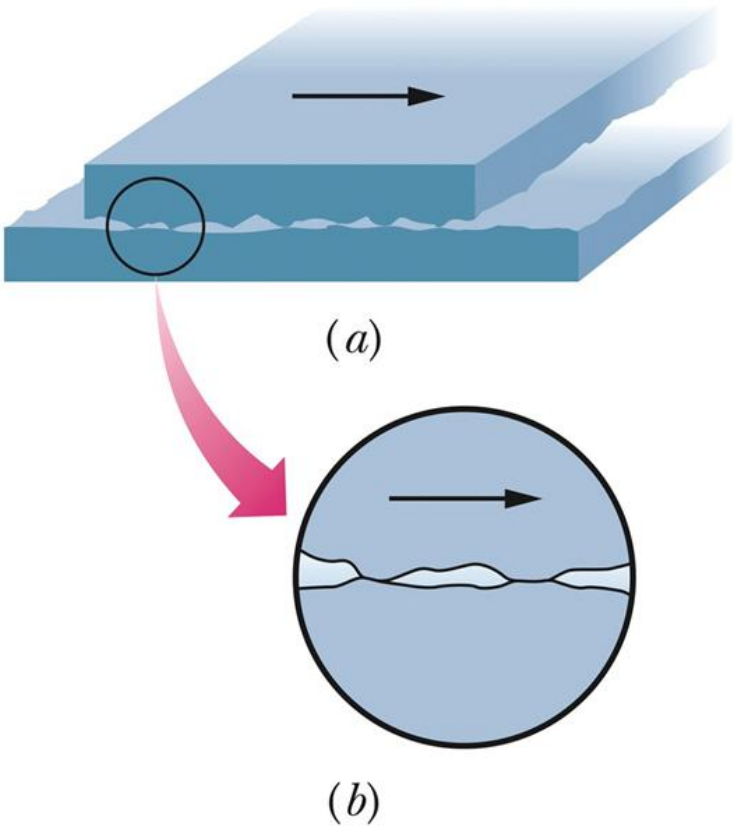


Figure 6-2

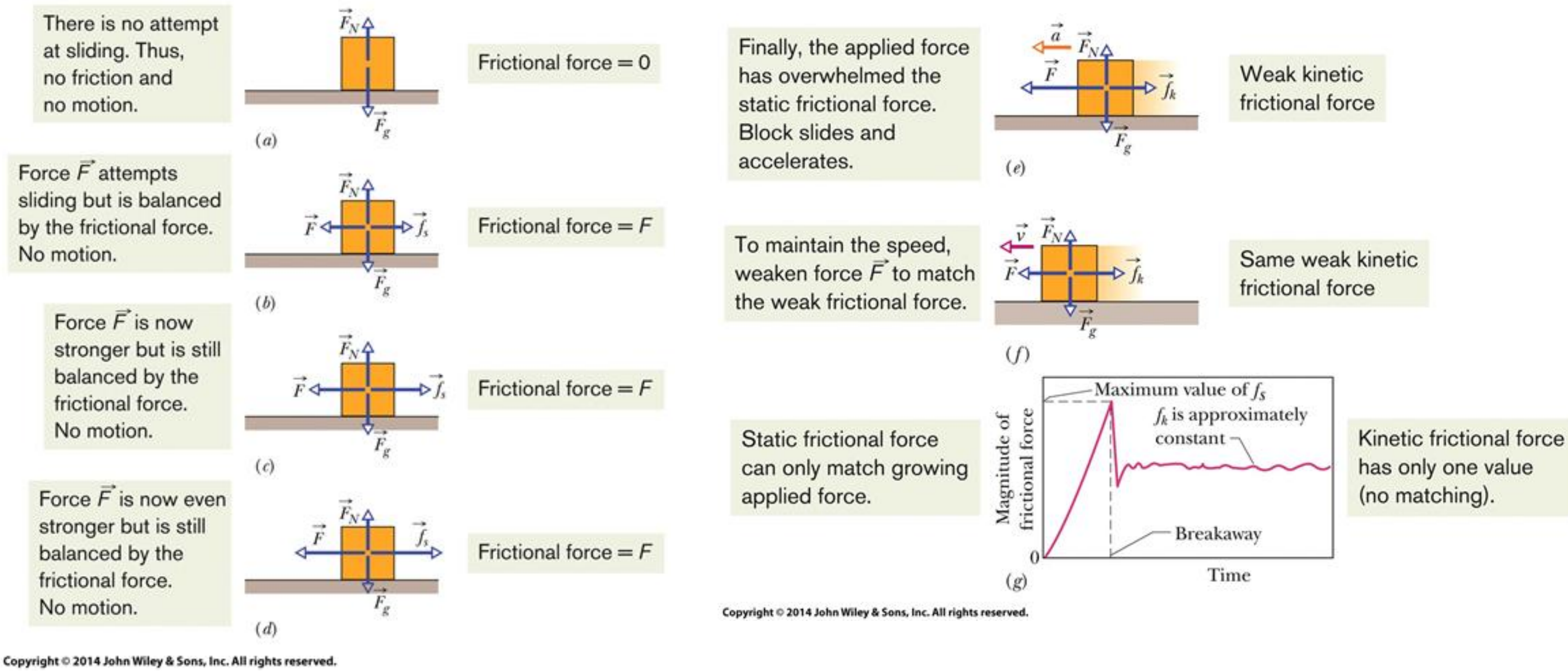


Figure 6-1

PhET demo, https://phet.colorado.edu/en/simulation/legacy/forces-1d

- The properties of friction
  1. If the body does *not move* (*with respect to the contacting surface*), then the applied force and frictional force balance along the direction parallel to the surface: equal in magnitude, opposite in direction
  2. The magnitude of f_s has a maximum $f_{s,\max}$ given by:

$$f_{s,\max} = \mu_s F_N,$$

Equation (6-1)

where μ_s is the **coefficient of static friction**.

If the applied force increases past $f_{s,\max}$, sliding begins.

  3. Once *sliding begins*, the frictional force decreases to f_k given by:

$$f_k = \mu_k F_N,$$

Equation (6-1)

where μ_k is the **coefficient of kinetic friction**.

- *Magnitude F_N of the normal force measures how strongly the surfaces are pushed together*

- Assume that μ_k does not depend on velocity
- Note that these equations are *not vector equations*

Checkpoint 1

A block lies on a floor, (a) What is the magnitude of the frictional force on it from the floor? (b) If a horizontal force of 5 N is now applied to the block, but the block does not move, what is the magnitude of the frictional force on it? (c) If the maximum value $f_{s,\ max}$ of the static frictional force on the block is 10 N, will the block move if the magnitude of the horizontally applied force is 8 N? (d) If it is 12 N? (e) What is the magnitude of the frictional force in part (c)?

Answer:

(a) 0

(b) 5 N

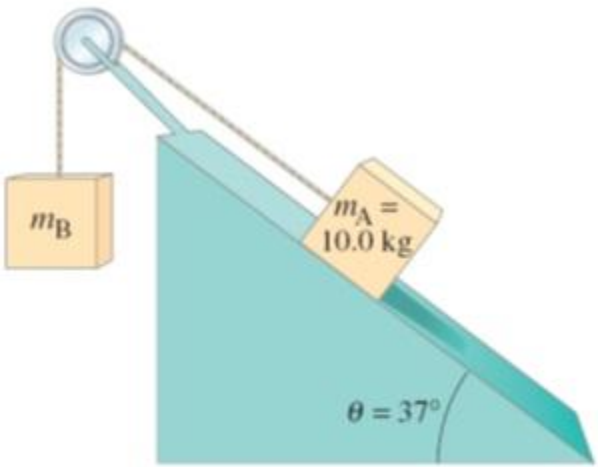
(c) no

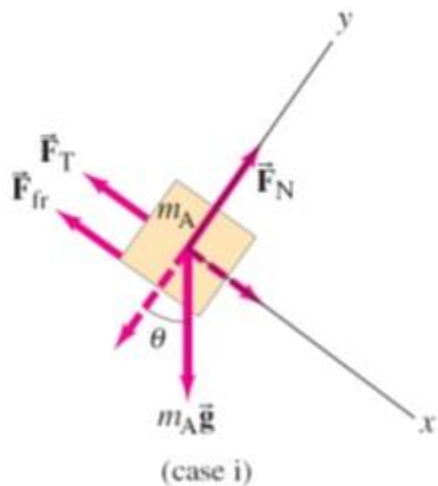
(d) yes

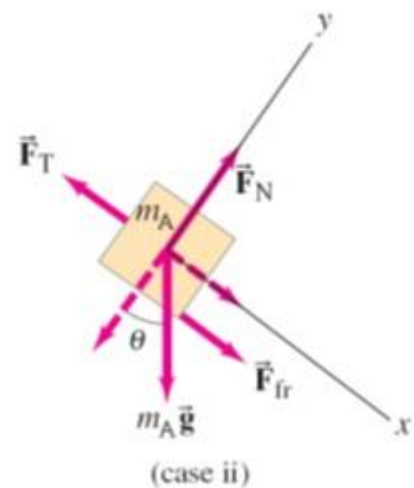
(e) 8 N

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 滑轮, 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.







Slide based on Ref. [2]

The Drag Force and Terminal Speed

- A **fluid** is anything that can flow (gas or liquid)
- When there is relative velocity between fluid and an object there is a **drag force**:
  - That opposes the relative motion
  - And points along the direction of the flow, relative to the body
- Here we examine the drag force for
  - Air
  - With a body that is not streamlined
  - For motion fast enough that the air becomes turbulent (breaks into swirls)

- For this case (large object, not too slow), the drag force is:

$$D = \frac{1}{2} C \rho A v^2,$$ **Equation (6-14)**

- Where:
  - v is the relative velocity
  - ρ is the air density (mass/volume)
  - C is the experimentally determined drag coefficient
  - A is the effective cross-sectional area of the body (the area taken perpendicular to the relative velocity)
- In reality, C is not constant for all values of v

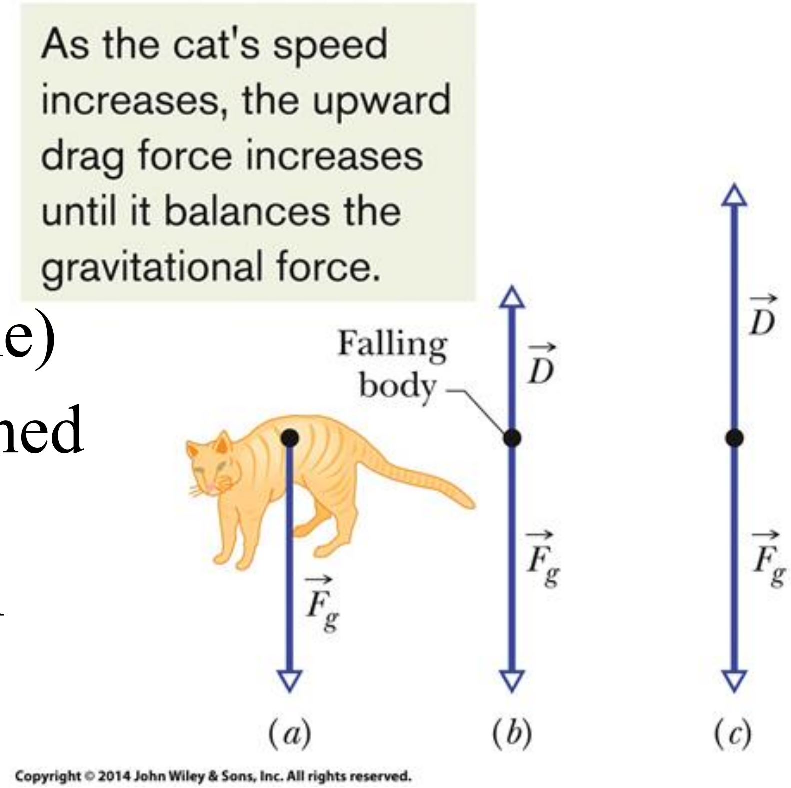


Figure 6-6

- The drag force from the air opposes a falling object

$$-D + F_g = +ma$$ **Equation (6-15)**

- Once the drag force equals the gravitational force, the object falls at a constant **terminal speed:**

$$v_t = \sqrt{\frac{2F_g}{C\rho A}}.$$ **Equation (6-16)**

- Terminal speed can be increased by reducing A
- Terminal speed can be decreased by increasing A
- Skydivers use this to control descent

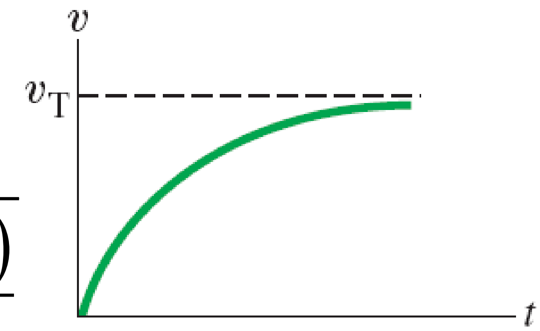
Example Speed of a rain drop:

- Spherical drop feels gravitational force $F = mg$:
  - Express in terms of density of water

$$F_g = V\rho_w g = \frac{4}{3}\pi R^3 \rho_w g.$$

- So plug in to the terminal velocity equation (6-16):
  - Use $A = \pi R^2$ for the cross-sectional area

$$\begin{aligned} v_t &= \sqrt{\frac{2F_g}{C\rho_a A}} = \sqrt{\frac{8\pi R^3 \rho_w g}{3C\rho_a \pi R^2}} = \sqrt{\frac{8R\rho_w g}{3C\rho_a}} \\ &= \sqrt{\frac{(8)(1.5\times10^{-3}\,\text{m})(1000\,\text{kg/m}^3)(9.8\,\text{m/s}^2)}{(3)(0.60)(1.2\,\text{kg/m}^3)}} \\ &= 7.4\,\text{m/s} \approx 27\,\text{km/h.} \quad (\text{Answer}) \end{aligned}$$



Uniform Circular Motion

- A particle is in **uniform circular motion** if
  - It travels around a circle or circular arc
  - At a constant speed
- Since the velocity changes, the particle is accelerating!
- Velocity and acceleration have:
  - Constant magnitude
  - Changing direction

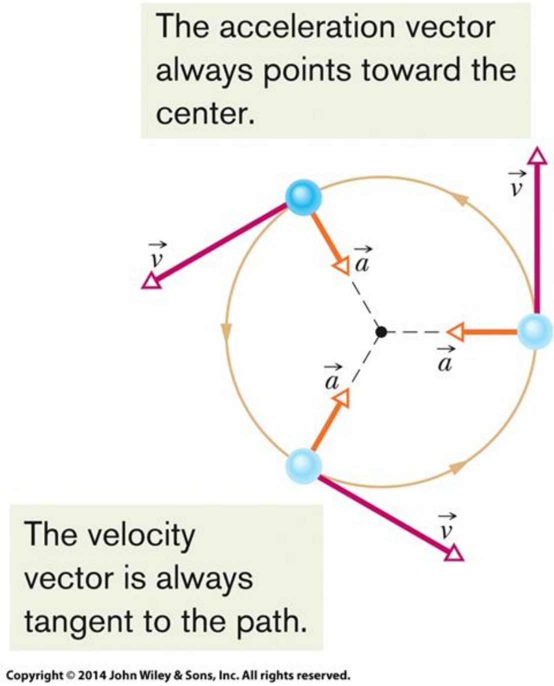
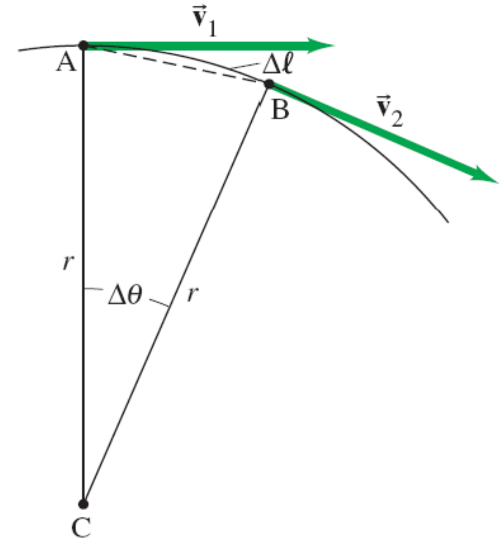
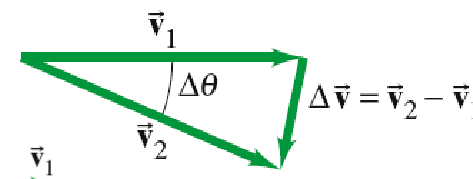


Figure 4-16

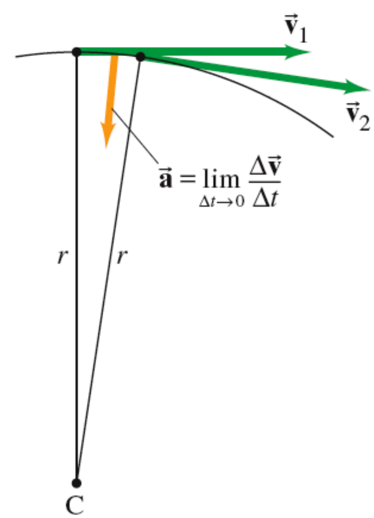
- The acceleration is called **centripetal acceleration**
  - Means “center seeking”
  - Directed radially inward

$$a = \frac{v^2}{r}$$ **Equation (4-34)**





- The **period of revolution** is:
  - The time it takes for the particle go around the closed path (one revolution) exactly once



$$T = \frac{2\pi r}{v}$$ **Equation (4-35)**

- The centripetal acceleration comes from a centripetal force which is not a new kind of force, it is simply an application of force

$$F_R = m\frac{v^2}{r}$$

Equation (6-18)

<u>A centripetal force accelerates a body by changing the direction of the body's velocity without changing the body's speed.</u>

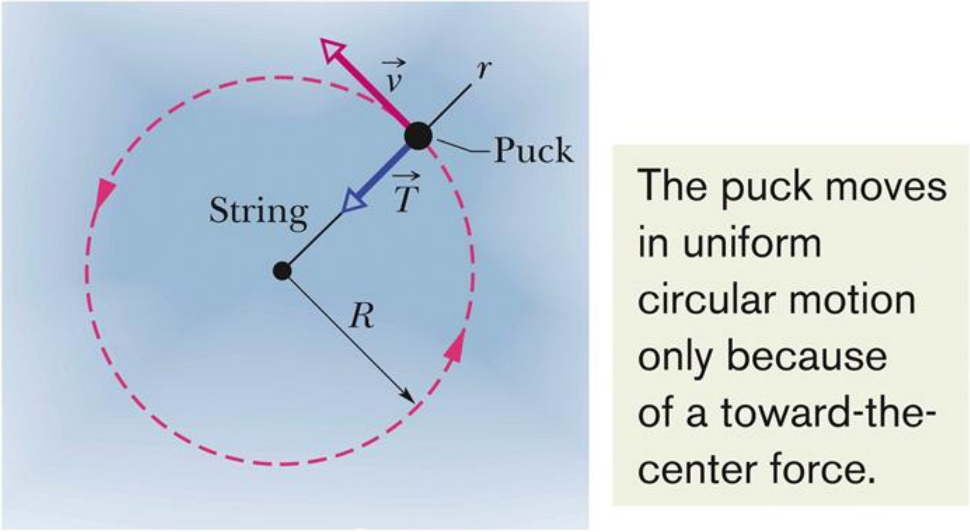
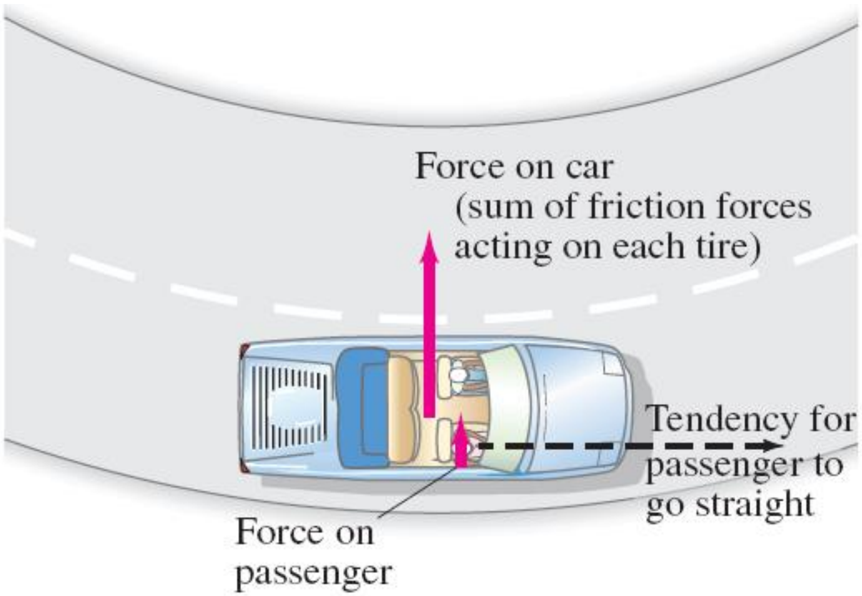


Figure 6-8

Examples You are a passenger:

- For a car, rounding a curve, the car accelerates toward the center of the curve due to a **centripetal force** provided by the inward friction on the tires. Your inertia makes you want to go straight ahead so you may feel friction from your seat and may also be pushed against the side of the car. These inward forces keep you in uniform circular motion in the car.



- For a space shuttle, the shuttle is kept in orbit by the gravitational pull of Earth acting as a centripetal force. This force also acts on every atom in your body, and keeps you in orbit around the Earth. You float with no sensation of force, but are subject to a centripetal acceleration.

Checkpoint 2

As every amusement park fan knows, a Ferris wheel is a ride consisting of seats mounted on a tall ring that rotates around a horizontal axis. When you ride in a Ferris wheel at constant speed, what are the directions of your acceleration $\vec{a}$ and the normal force $\vec{F}_N$ on you (from the always upright seat) as you pass through (a) the highest point and (b) the lowest point of the ride? (c) How does the magnitude of the acceleration at the highest point compare with that at the lowest point? (d) How do the magnitudes of the normal force compare at those two points?

Answer:

(a) accel downward, F_N upward

(b) accel upward, F_N upward

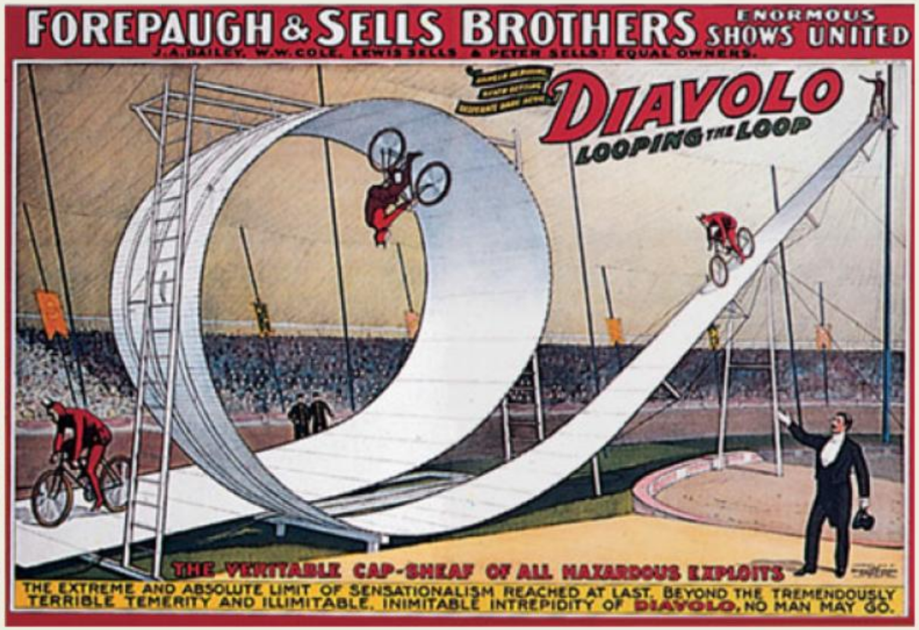
(c) the magnitudes must be equal for the motion to be uniform

(d) F_N is greater in (b) than in (a)

A centripetal force accelerates a body by changing the direction of the body's velocity without changing the body's speed. It is NOT a new kind of force. The name merely indicates the direction of the force.

Example Bicycle going around a vertical loop:

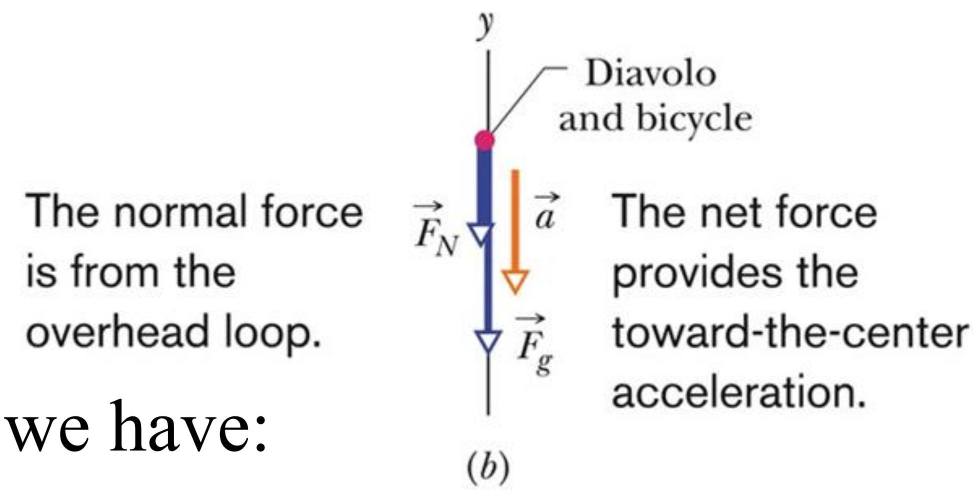
In a 1901 circus performance, Allo "Dare Devil" Diavolo introduced the stunt of riding a bicycle in a loop-the-loop (Fig. 6-9*a*). Assuming that the loop is a circle with radius $R = 2.7$ m, what is the least speed v that Diavolo and his bicycle could have at the top of the loop to remain in contact with it there?



Photograph reproduced with permission of Circus World Museum

(*a*)

Figure 6-9



(b)

- At the top of the loop we have:

$$-F_N - mg = m\left(-\frac{v^2}{R}\right).$$ **Equation (6-19)**

- Solve for v and plug in our known values, including $F_N = 0$ for the minimum answer:

$$\begin{aligned} v &= \sqrt{gR} = \sqrt{(9.8\ \mathrm{m/s^2})(2.7\ \mathrm{m})} \\ &= 5.1\ \mathrm{m/s}. \end{aligned}$$

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.

Slide based on Ref. [2]

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.

Slide based on Ref. [2]

Unbanked/flat road

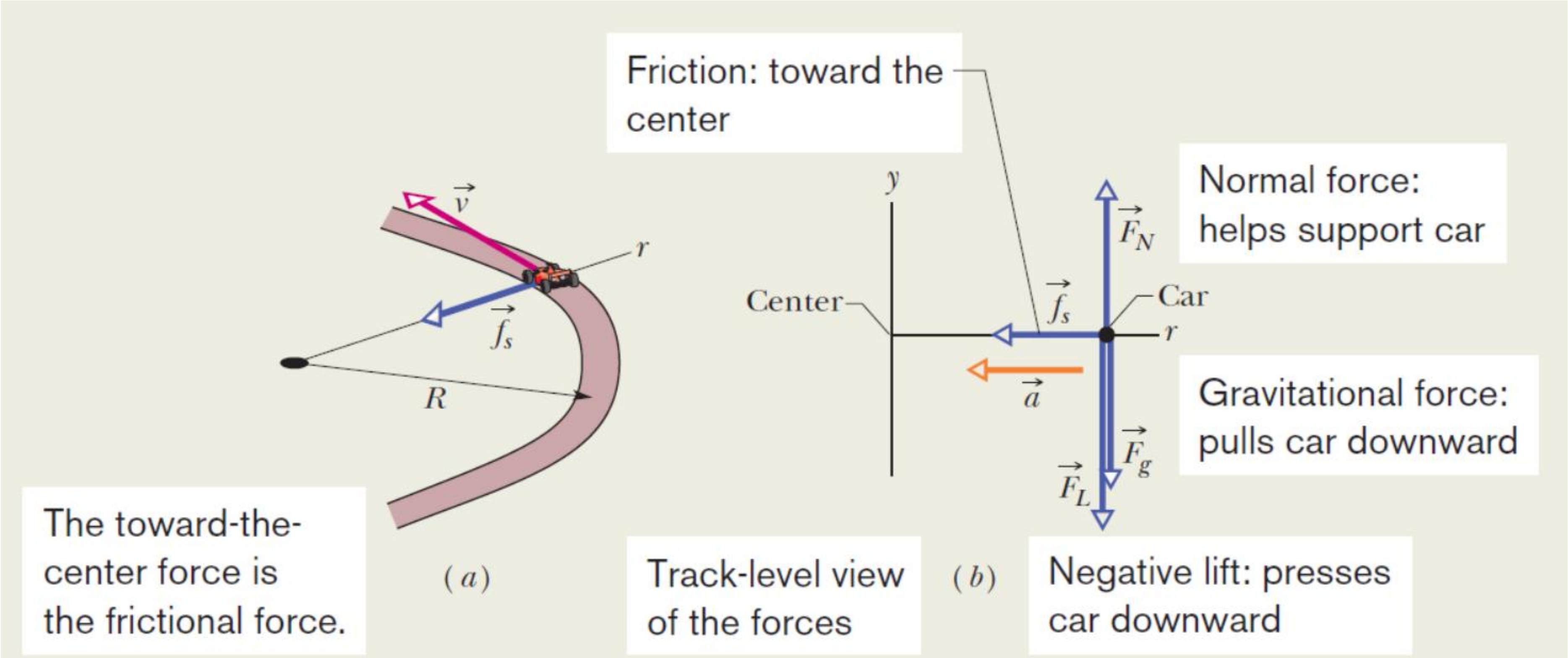


Figure 6-10 (*a*) A race car moves around a flat curved track at constant speed *v*. The frictional force $\vec{f}_s$ provides the necessary centripetal force along a radial axis *r*. (*b*) A free-body diagram (not to scale) for the car, in the vertical plane containing *r*.

Example Car in a banked circular turn, what bank angle prevents sliding if the frictional force from the track is negligible?

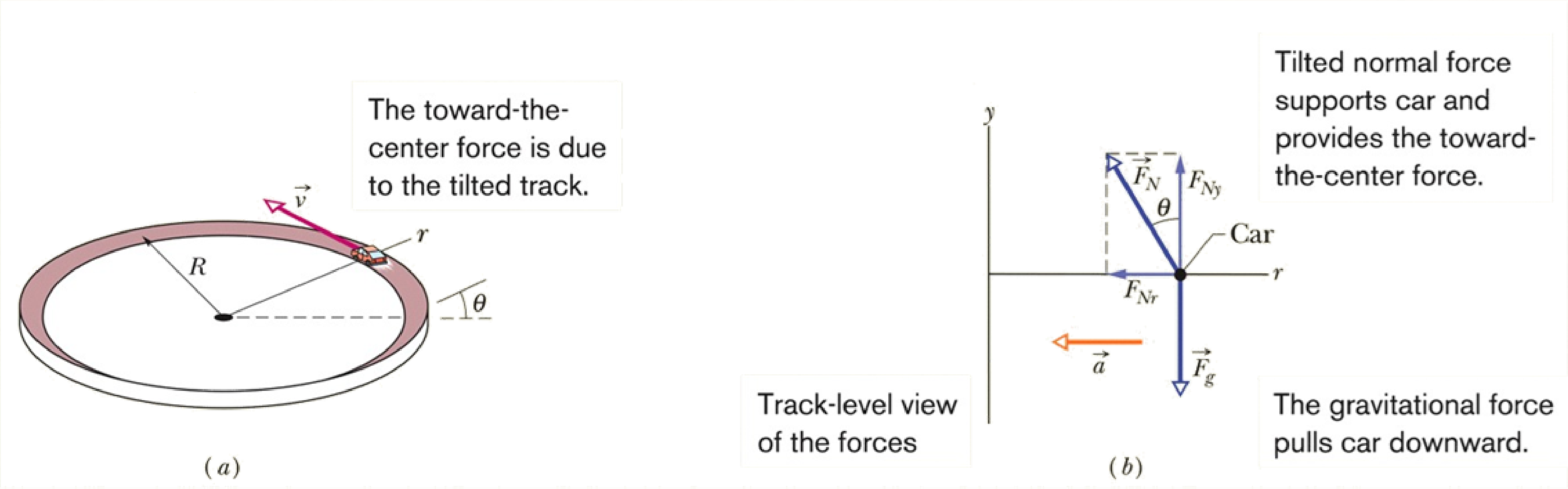


Figure 6-11

- Sum components along the radial direction:

$$-F_N \sin\theta = m\left(-\frac{v^2}{R}\right). \qquad \textbf{Equation (6-23)}$$

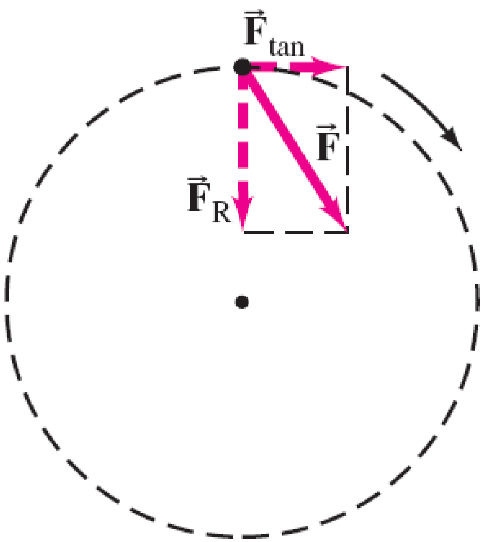
- Sum components along the vertical direction:

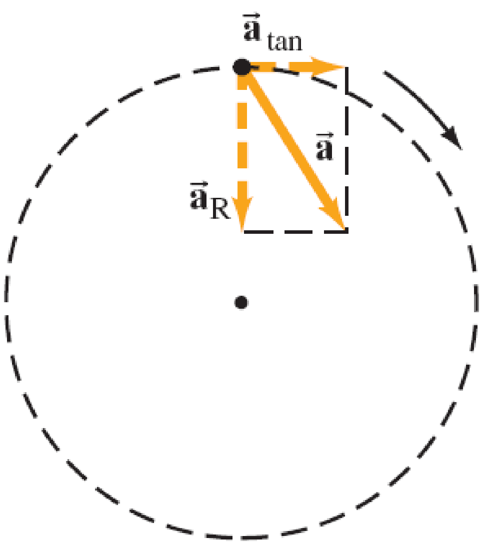
$$F_N \cos\theta = mg. \qquad \textbf{Equation (6-24)}$$

- Divide and replace $\dfrac{(\sin\theta)}{(\cos\theta)}$ with tangent.

$$\theta = \tan^{-1}\frac{v^2}{gR}$$

Nonuniform Circular Motion



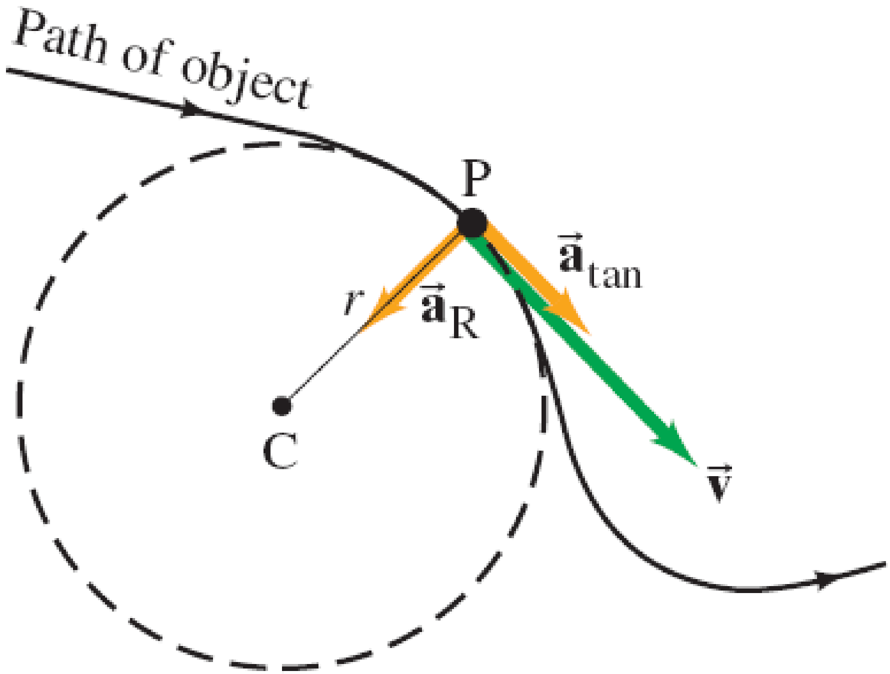


If an object is moving in a circular path but at varying speeds, it must have a tangential component to its acceleration as well as the radial one.

Slide based on Ref. [2]

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.



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Nonuniform Circular Motion

EXAMPLE 5–16 **Two components of acceleration.** A race car starts from rest in the pit area and accelerates at a uniform rate to a speed of 35 m/s in 11 s, moving on a circular track of radius 500 m. Assuming constant tangential acceleration, find (*a*) the tangential acceleration, and (*b*) the radial acceleration, at the instant when the speed is $v = 15\text{ m/s}$.

APPROACH The tangential acceleration relates to the change in speed of the car, and can be calculated as $a_{\tan} = \Delta v/\Delta t$. The centripetal acceleration relates to the change in the *direction* of the velocity vector and is calculated using $a_R = v^2/r$.

SOLUTION (*a*) During the 11-s time interval, we assume the tangential acceleration $a_{\tan}$ is constant. Its magnitude is

$$a_{\tan} = \frac{\Delta v}{\Delta t} = \frac{(35\text{ m/s} - 0\text{ m/s})}{11\text{ s}} = 3.2\text{ m/s}^2.$$

(*b*) When $v = 15\text{ m/s}$, the centripetal acceleration is

$$a_R = \frac{v^2}{r} = \frac{(15\text{ m/s})^2}{(500\text{ m})} = 0.45\text{ m/s}^2.$$

Slide based on Ref. [2]

Learning outcomes

✓ Solve problems using Newton's laws of motion involving friction force, drag force, uniform and non-uniform circular motions .

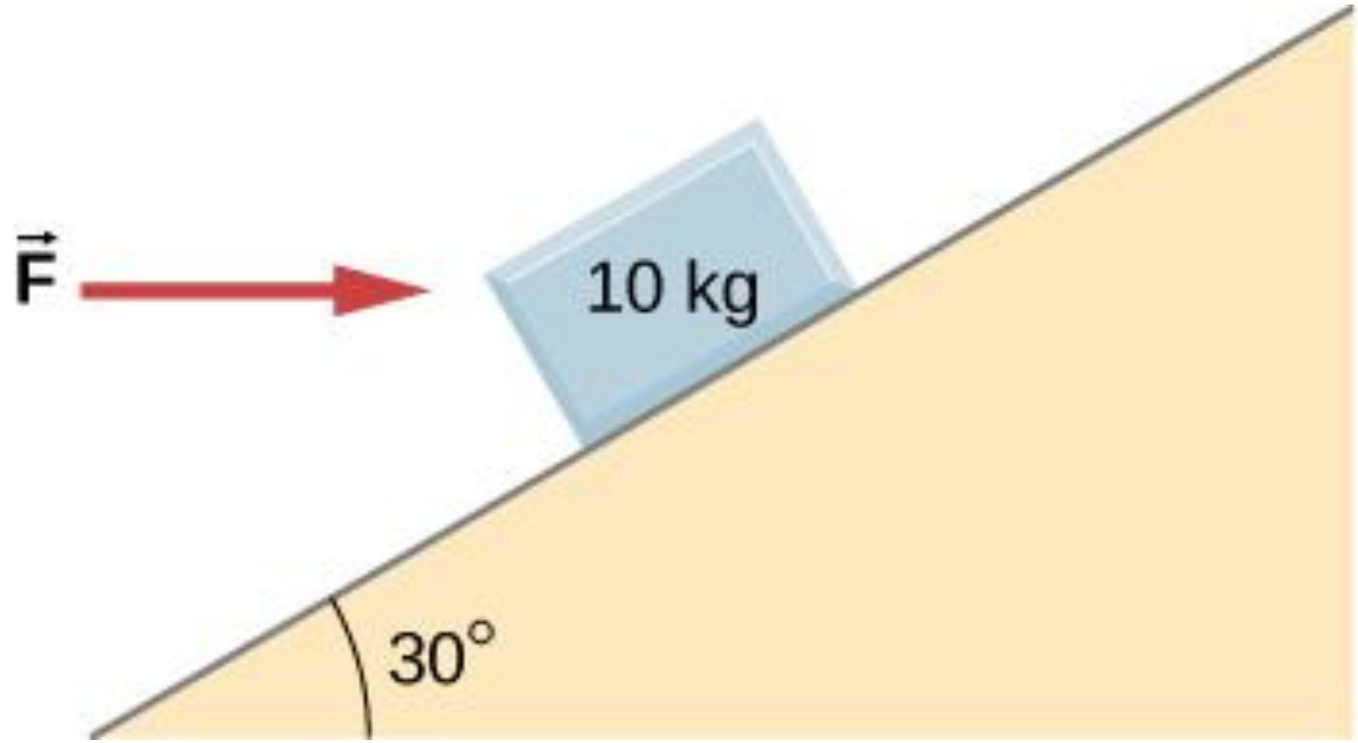
$$f_{s,\,\max} = \mu_s F_N, \qquad f_k = \mu_k F_N,$$

$$D = \frac{1}{2} C \rho A v^2, \qquad \text{(for example)}$$

$$F_R = m\frac{v^2}{r}$$

CHAPTER REVIEW AND EXAMPLES, DEMOS

https://openstax.org/books/university-physics-volume-1/pages/6-summary



$F = 200N, \mu = 0.5, a = ?$

EXERCISE 108

EXAMPLE 6.18

Effect of the Resistive Force on a Motorboat

A motorboat is moving across a lake at a speed v_0 when its motor suddenly freezes up and stops. The boat then slows down under the frictional force $f_R = -bv$. (a) What are the velocity and position of the boat as functions of time? (b) If the boat slows down from 4.0 to 1.0 m/s in 10 s, how far does it travel before stopping?

Questions