Chapter 6

Force and Motion–II

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6-1 Friction

Learning Objectives

6.01 Distinguish between friction in a static situation and a kinetic situation.

6.02 Determine direction and magnitude of a frictional force.

6.03 For objects on horizontal, vertical, or inclined planes in situations involving friction, draw free-body diagrams and apply Newton's second law.

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6-1 Friction

- 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

6-1 Friction

- Three experiments:
  - Slide a book across a counter. The book slows and stops, so there must be an acceleration parallel to the surface and opposite the direction of motion.
  - Push a book at a constant speed across the counter. There must be an equal and opposite force opposing you, otherwise the book would accelerate. Again the force is parallel to the surface and opposite the direction of motion.
  - Push a crate or other heavy object that does not move. To keep the crate stationary, an equal and opposite force must oppose you. If you push harder, the opposing force must also increase to keep the crate stationary. Keep pushing harder. Eventually the opposing force will reach a maximum, and the crate will slide.

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6-1 Friction

- Two types of friction
- The **static frictional force**:
  - The opposing force that prevents an object from moving
  - Can have any magnitude from 0 N up to a maximum
  - Once the maximum is reached, forces are no longer in equilibrium and the object slides
- The **kinetic frictional force**:
  - The opposing force that acts on an object in motion
  - Has only one value
  - Generally smaller than the maximum static frictional force

6-1 Friction

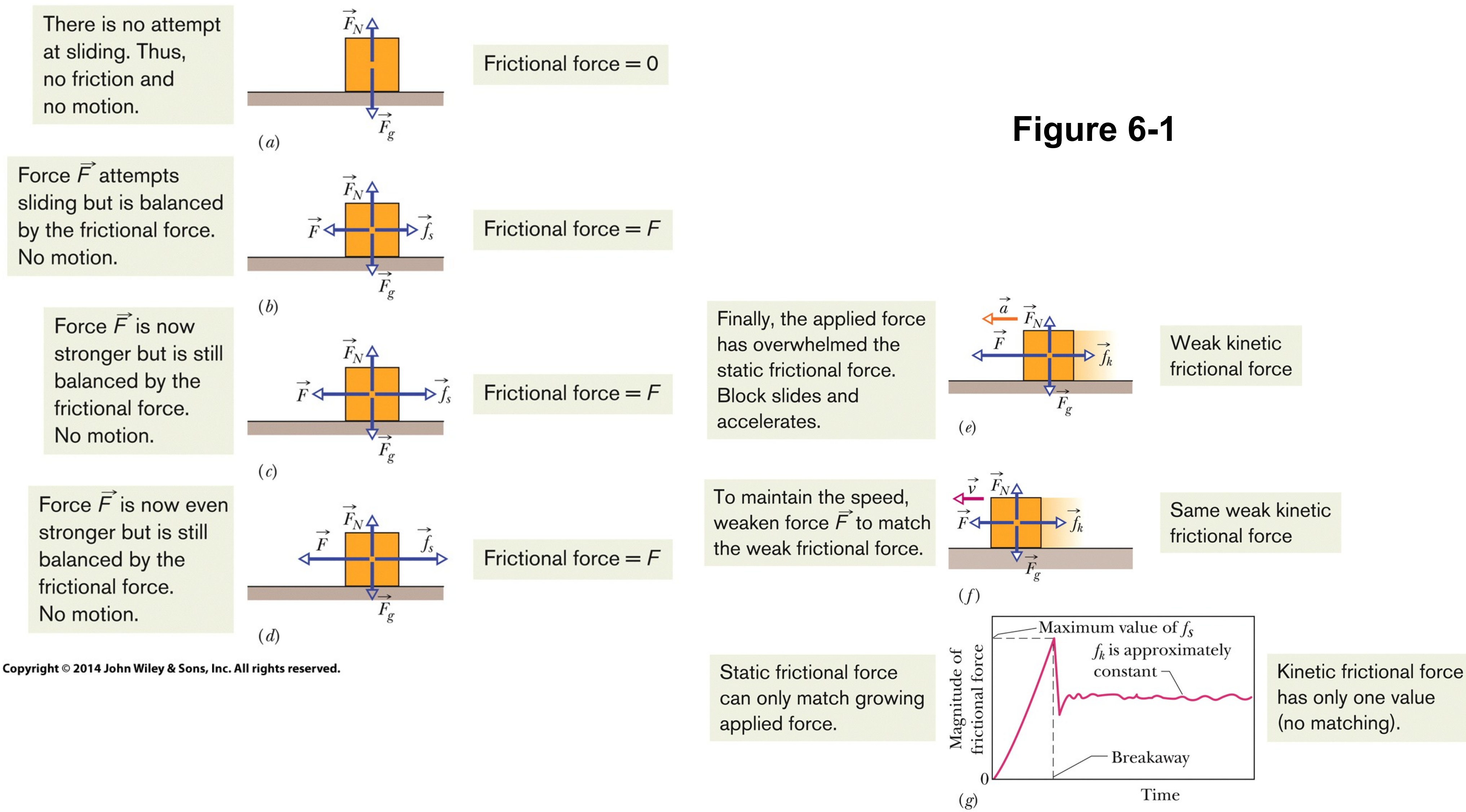

Figure 6-1

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6-1 Friction

- 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

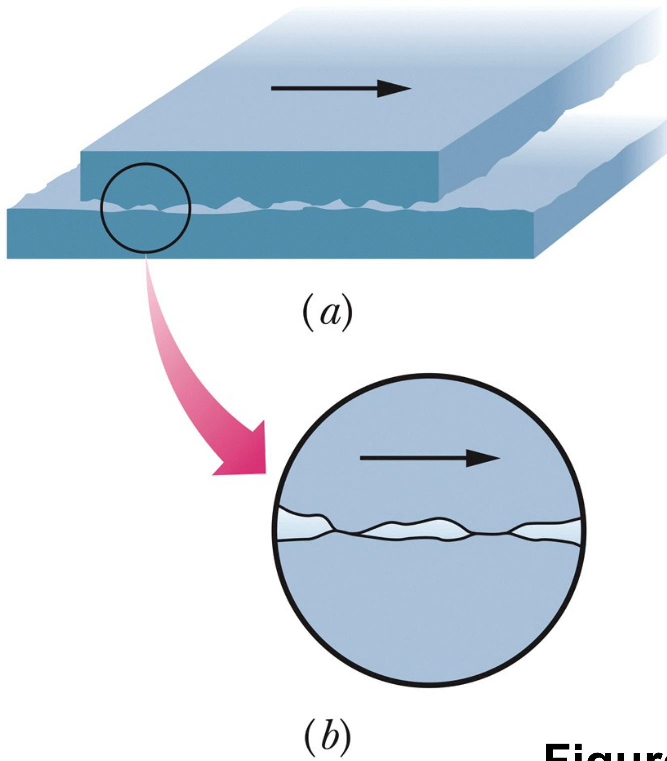

Figure 6-2

6-1 Friction

- The properties of friction
  1. If the body does not move, 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:

$$f_{s,\max} = \mu_s F_N, \qquad \textbf{Eq. (6-1)}$$

where μ_s is the **coefficient of static friction**. If the applied force increases past $f_{s,max}$, sliding begins.

6-1 Friction

- The properties of friction

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

$$f_k = \mu_k F_N, \qquad \textbf{Eq. (6-2)}$$

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

- Magnitude F_N of the normal force measures how strongly the surfaces are pushed together
- The values of the friction coefficients are unitless and must be determined experimentally

6-1 Friction

- 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

6-1 Friction

Example For a force applied at an angle:

- Decompose the force into *x* and *y* components
- Balance the vertical components (F_N, F_g, F_y)
- Balance the horizontal components (f, F_x)
- Solve for your unknown, noting that F_N and f are related

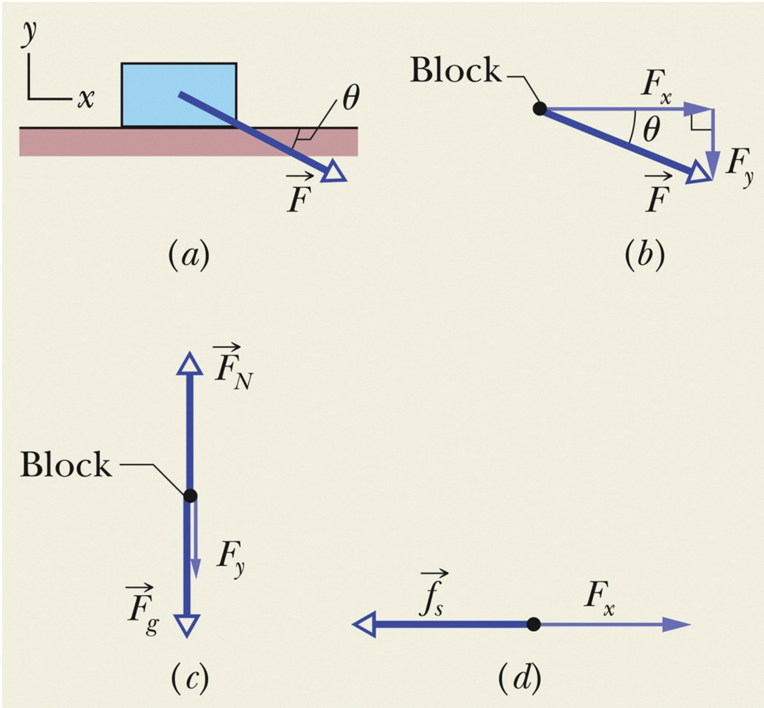

Figure 6-3

6-2 The Drag Force and Terminal Speed

Learning Objectives

6.04 Apply the relationship between the drag force on an object moving through the air and the speed of the object.

6.05 Determine the terminal speed of an object falling through the air.

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6-2 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)

6-2 The Drag Force and Terminal Speed

- For this case, the drag force is:

$$D = \tfrac{1}{2}C\rho A v^2,$$

Eq. (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

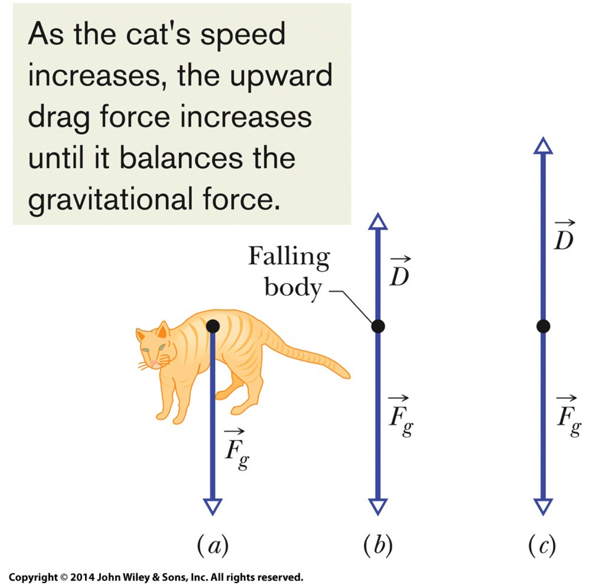

Figure 6-6

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6-2 The Drag Force and Terminal Speed

- The drag force from the air opposes a falling object

$$D - F_g = ma, \qquad \text{Eq. (6-15)}$$

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

$$v_t = \sqrt{\frac{2F_g}{C\rho A}}. \qquad \text{Eq. (6-16)}$$

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

6-2 The Drag Force and Terminal Speed

Example Speed of a rain drop:

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

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

- So plug in to the terminal velocity equation using the values provided in the text:
  - Use $A = \pi R^2$ for the cross-sectional area

$$v_t = \sqrt{\frac{2F_g}{C\rho_a A}} = \sqrt{\frac{8\pi R^3 \rho_w g}{3C\rho_a \pi R^2}} = \sqrt{\frac{8R\rho_w g}{3C\rho_a}}$$

$$= \sqrt{\frac{(8)(1.5 \times 10^{-3}\ \text{m})(1000\ \text{kg/m}^3)(9.8\ \text{m/s}^2)}{(3)(0.60)(1.2\ \text{kg/m}^3)}}$$

$$= 7.4\ \text{m/s} \approx 27\ \text{km/h}. \qquad \text{(Answer)}$$

6-3 Uniform Circular Motion

Learning Objectives

6.06 Sketch the path taken in uniform circular motion and explain the velocity, acceleration, and force vectors (magnitudes and directions) during the motion.

6.07 Identify that unless there is a radially inward net force (a centripetal force), an object cannot move in circular motion.

6.08 For a particle in uniform circular motion, apply the relationship between the radius of the path, the particle's speed and mass, and the net force acting on the particle.

6-3 Uniform Circular Motion

- Recall that circular motion requires a centripetal acceleration

$$a = \frac{v^2}{R}$$ Eq. (6-17)

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.

6-3 Uniform Circular Motion

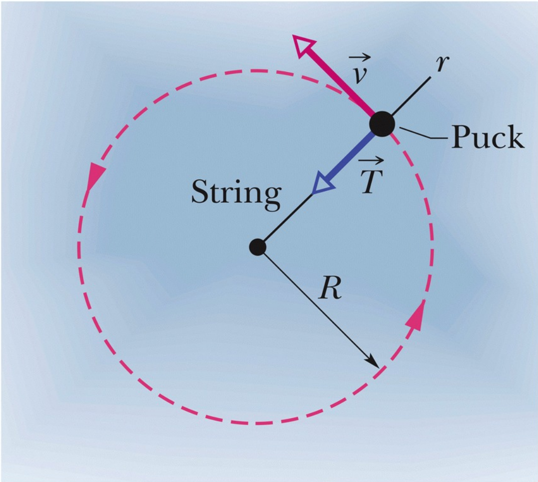
- Centripetal force is not a new *kind* of force, it is simply an application of force

$$F = m\frac{v^2}{R}$$

Eq. (6-18)

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

- For the puck on a string, the string tension supplies the centripetal force necessary to maintain circular motion



The puck moves in uniform circular motion only because of a toward-the-center force.

Figure 6-8

6-3 Uniform Circular Motion

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)

6-3 Uniform Circular Motion

Example Bicycle going around a vertical loop:

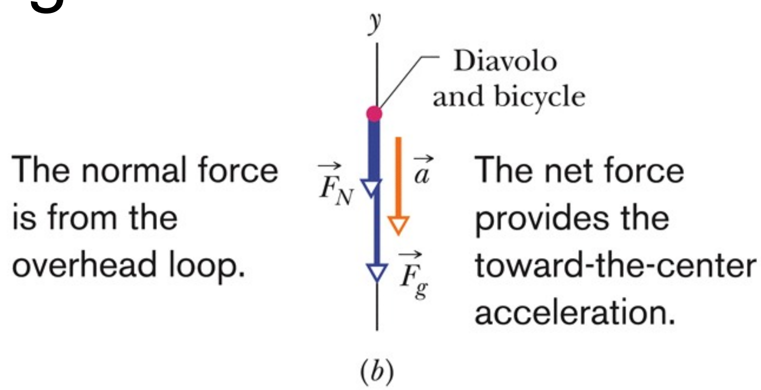


Figure 6-9

- At the top of the loop we have:

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

Eq. (6-19)

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

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

6-3 Uniform Circular Motion

Example Car in a banked circular turn:

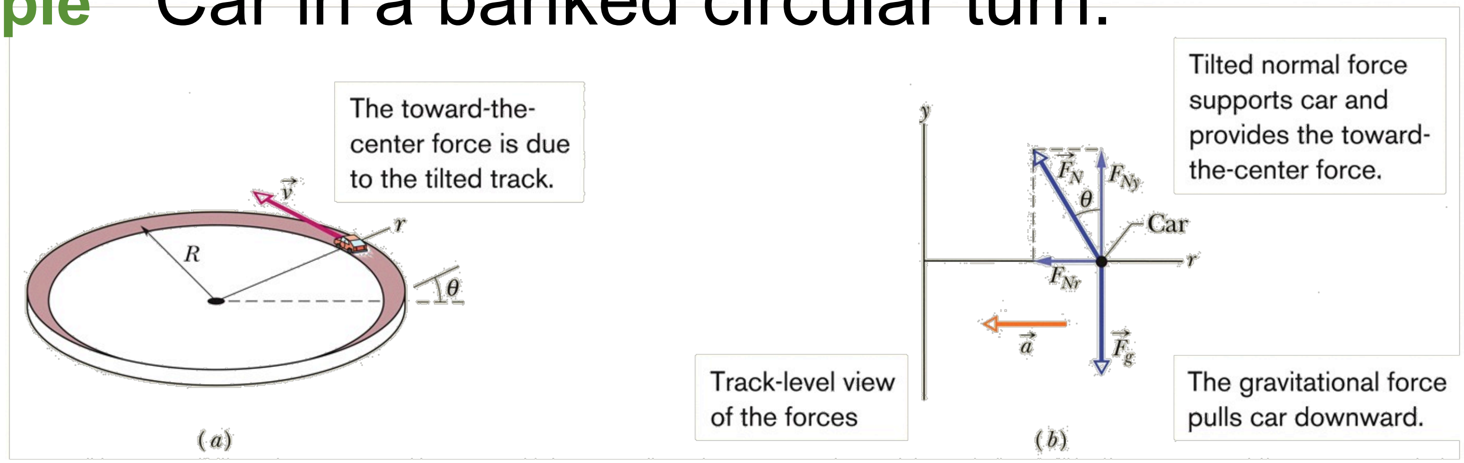


Figure 6-11

- Sum components along the radial direction:

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

- Sum components along the vertical direction:

$$F_N \cos\theta = mg.$$ **Eq. (6-24)**

- Divide and replace (sin θ)/(cos θ) with tangent.

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

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6 Summary

Friction

- Opposes the direction of motion or attempted motion
- Static if the object does not slide
- Static friction can increase to a maximum

$$f_{s,\max} = \mu_s F_N, \quad \textbf{Eq. (6-1)}$$

- Kinetic if it does slide

$$f_k = \mu_k F_N, \quad \textbf{Eq. (6-2)}$$

Drag Force

- Resistance between a fluid and an object
- Opposes relative motion
- Drag coefficient *C* experimentally determined

$$D = \frac{1}{2} C \rho A v^2, \quad \textbf{Eq. (6-14)}$$

- Use the effective cross-sectional area (area perpendicular to the velocity)

6 Summary

Terminal Speed

- The maximum velocity of a falling object due to drag

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

Uniform Circular Motion

- Centripetal acceleration required to maintain the motion

$$a = \frac{v^2}{R}$$ **Eq. (6-17)**

- Corresponds to a centripetal force

$$F = m\frac{v^2}{R}$$ **Eq. (6-18)**

- Force points toward the center of curvature