

# Newton's Laws of Motion & Forces

Chapters 5 & 6

**NEWTON'S LAWS OF MOTION**

# Force

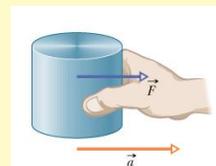
A force is a push or a pull.

Vector quantity (magnitude and direction)

units: N (Newton)

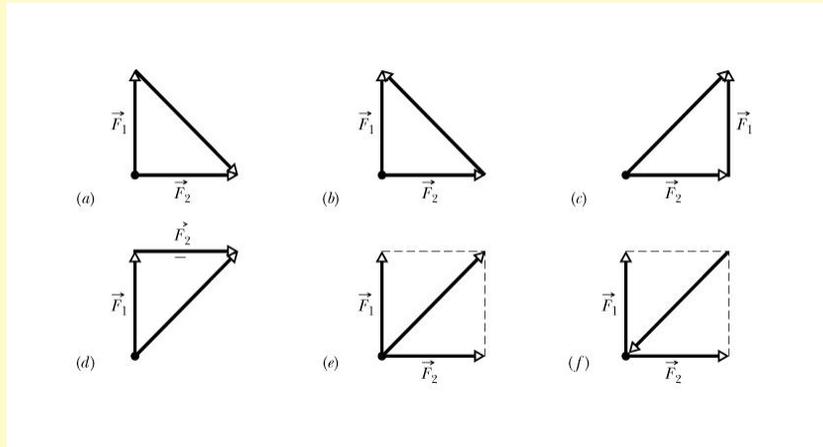
## 1<sup>st</sup> Law of Motion

- If no net force acts on a body, the body's velocity cannot change; that is, the body cannot accelerate.
- i.e. An object in motion stays in motion and object at rest stays at rest unless acted upon by a net force.
- Principle of superposition of forces
  - “Net” force, or resultant force, is found by adding the individual forces vectorially. It is a single force that has a magnitude and direction that has the same effect as all of the individual forces combined.
- Also referred to as the Law of Inertia
- Inertia is a property of matter that resists changes in motion



### Checkpoint 1

Which of the figure's six arrangements correctly show the vector addition of force  $\vec{F}_1$  and  $\vec{F}_2$  to yield the third vector, which is meant to represent their net force  $\vec{F}_{net}$ ?



## Inertial Reference Frames

- Newton's laws first law is not true in all reference frames, but you can always find a reference frame in which it is true.
- An inertial reference frame is one in which Newton's laws hold.

## 2<sup>nd</sup> Law of motion

- The net force on a body is equal to the product of the body's mass and its acceleration.

$$\vec{F}_{net} = m\vec{a}$$

- In component form:

$$F_{net,x} = ma_x \quad F_{net,y} = ma_y$$

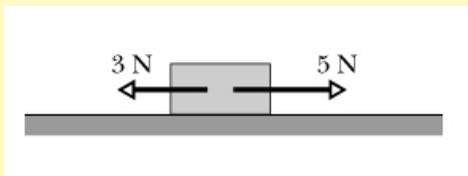
- Only forces that act on *that* body are to be included in the vector sum
- The acceleration component along a given axis is caused only by the sum of the force components along that *same* axis, and not by force components along any other axis.

## Equilibrium, Systems, & FBDs

- If the net force on a body is zero, the body is said to be in equilibrium
  - Caution: An object in equilibrium does NOT have to be at rest
- A system consists of one or more bodies, and any force on the bodies inside the system from bodies outside the system is called an **external force**. Forces between bodies in the system are called **internal forces**.
- When applying Newton's second law to systems of particles, **only external forces are considered**.
- When solving force problems, always start by drawing a free-body diagram (FBD)
  - A diagram that shows ALL of the forces acting on a body

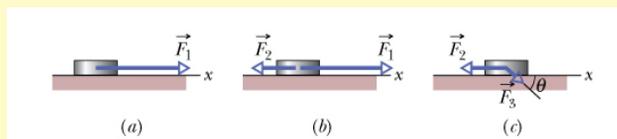
### Checkpoint 2

The figure here shows two horizontal forces acting on a block on a frictionless floor. If a third horizontal force  $F_3$  also acts on the block, what are the magnitude and direction of  $F_3$  when the block is (a) stationary and (b) moving to the left with a constant speed of 5 m/s?



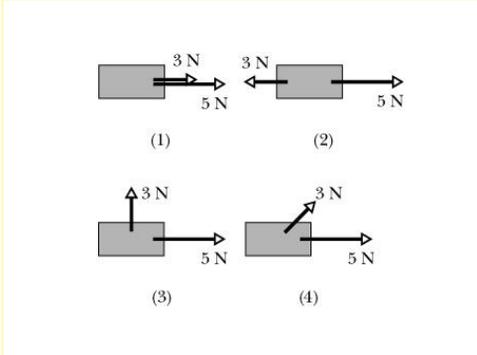
### Sample 1

The figure below shows three situations in which one or two forces act on a puck that moves over frictionless ice along an  $x$  axis, in one-dimensional motion. The puck's mass is  $m = 0.20$  kg. Forces  $F_1$  and  $F_2$  are directed along the axis and have magnitudes  $F_1 = 4.0$  N and  $F_2 = 2.0$  N. Force  $F_3$  is directed at angle  $\theta = 30^\circ$  and has magnitude  $F_3 = 1.0$  N. In each situation, what is the acceleration of the puck?



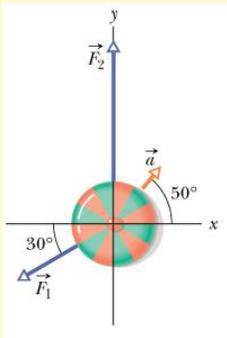
### Checkpoint 3

The figure shows *overhead* views of four situations in which two forces accelerate the same block across a frictionless floor. Rank the situations according to the magnitudes of (a) the net force on the block and (b) the acceleration of the block, greatest first.



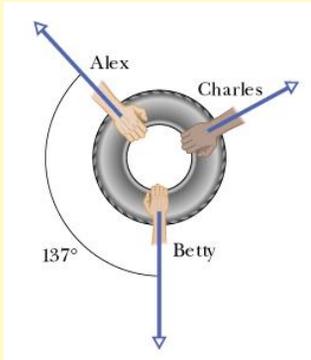
### Sample 2

A 2.0 kg cookie tin is accelerated at  $3.0 \text{ m/s}^2$  in the direction shown by  $\mathbf{a}$ , over a frictionless horizontal surface. The acceleration is caused by three horizontal forces, only two of which are shown:  $\mathbf{F}_1$  of magnitude 10 N and  $\mathbf{F}_2$  of magnitude 20 N. What is the third force  $\mathbf{F}_3$  in unit-vector notation and in magnitude-angle notation.



### Sample 3

In a two-dimensional tug-of-war, Alex, Betty, and Charles pull horizontally on an automobile tire at the angles shown in the overhead view below. The tire remains stationary in spite of the three pulls. Alex pulls the force  $F_A$  of magnitude 220 N, and Charles pulls with force  $F_C$  of magnitude 170 N. The direction of  $F_C$  is not given. What is the magnitude of Betty's force  $F_B$ ?



## Problem-Solving Tactics

- Dimensions & Vectors
  - When you are dealing with forces, you cannot just add or subtract their magnitudes to find their net force unless they happen to be directed along the same axis. If they are not, you must use vector addition.
- What is your System?
  - If you are using Newton's second law, you must know what body or system you are applying it to.
- Choose your Axes Wisely
  - Often, we can save a lot of work by choosing one of our coordinate axes to coincide with one of the forces.

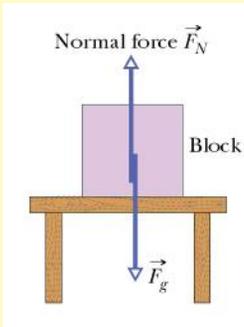
## SOME PARTICULAR FORCES

### Some Particular Forces

- **The Gravitational Force ( $F_g$ )**
  - Due to the mass of the Earth
  - Pulls objects toward the center of the Earth
  - Given by  $F = mg$
- **Weight ( $W$ )**
  - The magnitude of the net force required to prevent the body from falling freely
  - The weight  $W$  of a body is equal to the magnitude  $F_g$  of the gravitational force ( $W = mg$ )
- **The Normal Force ( $F_N$ )**
  - When a body presses on a surface the surface pushes back on the body with a supportive force that is perpendicular to the surface.

#### Checkpoint 4

In the figure below, is the normal force  $F_N$  greater than, less than, or equal to  $mg$  if the block and table are in an elevator moving upward (a) at constant speed and (b) at increasing speed?

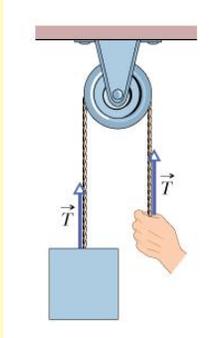


## Some Particular Forces

- **Friction ( $f_k$  or  $f_s$ )**
  - The force that opposes the motion of an object.
  - Always parallel to the surface and opposite the direction of the motion.
- **Tension ( $F_T$ )**
  - The force present when a cord, rope, cable, or other such unstretchable object is attached to a body and pulled taut.
  - Directed along the rope and away from the object.
- **Air Resistance ( $F_{air}$  or  $F_{ar}$ )**
  - Fluid friction that acts on a body due to the air around it.
  - Always opposes the motion of the object.
- **Applied Force ( $F$  or  $F_{app}$ )**
  - Any force applied to a body that cannot be categorized as any other type of force

### Checkpoint 5

The suspended body weighs 75 N. Is  $T$  equal to, greater than, or less than 75 N when the body is moving upward (a) at constant speed, (b) at increasing speed, and (c) at decreasing speed?



### Sample 4

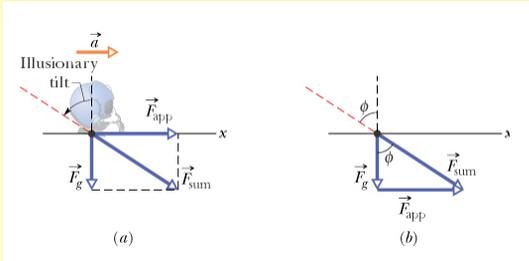
A jet plane taking off from an aircraft carrier is propelled by its powerful mechanism installed in the carrier deck. The resulting high acceleration allows the plane to reach takeoff speed in a short distance on the deck. However, that high acceleration also compels the pilot to angle the plane sharply nose-down as it leaves the deck. Pilots are trained to ignore this compulsion, but occasionally a plane is flown straight into the ocean.

Your sense of vertical depends on visual clues and the vestibular system located in your inner ear. That system contains tin hair cells in a fluid. When you hold your head upright, the hairs are vertical in line with the gravitational force  $F_g$  on you and the system signals your brain that your head is upright. When you tilt your head backward by some angle  $\phi$ , the hairs are bent and the system signals your brain about the tilt. The hairs are also bent when you are accelerated forward by an applied horizontal force  $F_{app}$ . The signal sent to your brain then indicates, erroneously, that your head is tilted back, to be in line with an extension through the vector sum  $F_{net} = F_g + F_{app}$ . However, the erroneous signal is ignored when visual clues clearly indicate no such tilt, such as when you are accelerated in a car.

A pilot being hurled along the deck of an aircraft carrier at night has almost no visual clues. The illusion of tilt is strong and very convincing, with the result that the pilot feels as though the plane leaves the deck headed sharply upward. Without proper training, a pilot will attempt to level the plane by bringing its nose sharply down, sending the plane into the ocean.

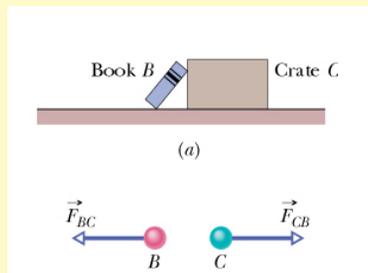
### Sample 4 continued

Suppose that, starting from rest, a pilot undergoes constant horizontal acceleration to reach a takeoff speed of 85 m/s in 90 m. what is the angle  $\phi$  of the illusory tilt experienced by the pilot?



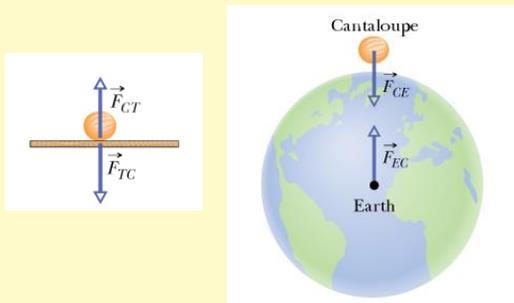
## 3<sup>rd</sup> Law of Motion

- When two bodies interact, the forces on the bodies from each other are always equal in magnitude and opposite in direction.
- i.e. Every action has an equal and opposite reaction.
- The forces between two interacting bodies are called a **third-law force pair**



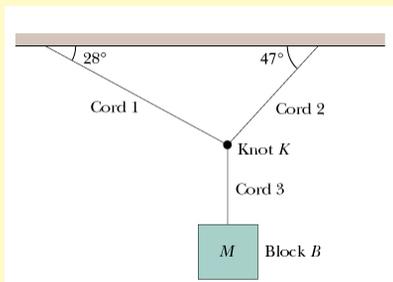
### Checkpoint 6

Suppose that a cantaloupe is sitting on a table inside an elevator cab that begins to accelerate upward. (a) Do the magnitudes of  $F_{TC}$  and  $F_{CT}$  increase, decrease, or stay the same? (b) Are those two forces still equal in magnitude and opposite in direction? (c) Do the magnitudes of  $F_{CE}$  and  $F_{EC}$  increase, decrease, or stay the same? (d) Are those two forces still equal in magnitude and opposite in direction?



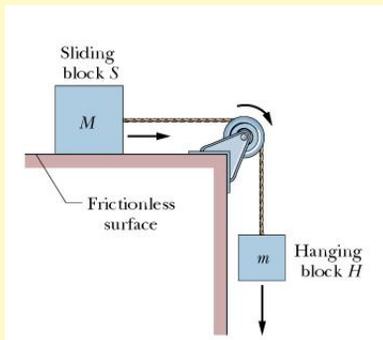
### Sample 5

A block  $B$  of mass  $M = 15.0$  kg hangs by a cord from a knot  $K$  of mass  $m_K$ , which hangs from a ceiling by means of two other cords. The cords have negligible mass, and the magnitude of the gravitational force on the knot is negligible compared to the gravitational force on the block. What are the tensions in the three cords?



### Sample 6

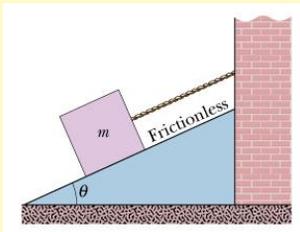
The figure shows a block  $S$  (the sliding block) with mass  $M = 3.3$  kg. The block is free to move along a horizontal frictionless surface and connected, by a cord that wraps over a frictionless pulley, to a second block  $H$  (the hanging block), with mass  $m = 2.1$  kg. The cord and pulley have negligible masses compared to the blocks (they are “massless”). The hanging block  $H$  falls as the sliding block  $S$  accelerates to the right. Find (a) the acceleration of the block  $S$ , (b) the acceleration of block  $H$ , and (c) the tension in the cord?



### Sample 7

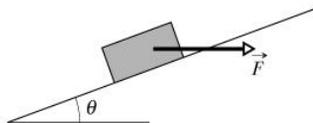
In the figure, a cord holds a 15 kg block stationary on a frictionless plane inclined at angle  $\theta = 27^\circ$ .

- (a) What are the magnitudes of the force  $T$  on the block from the cord and the normal force  $F_N$  on the block from the plane?
- (b) We now cut the cord. Does the block accelerate as it slides down the inclined plane? If so, what is its acceleration?



### Checkpoint 7

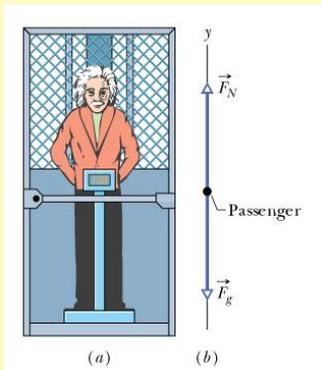
In the figure, horizontal force  $F$  is applied to a block on a ramp. (a) Is the component of  $F$  that is perpendicular to the ramp  $F\cos\theta$  or  $F\sin\theta$ ? (b) Does the presence of  $F$  increase or decrease the magnitude of the normal force on the block from the ramp?



### Sample 8

A passenger of mass  $m = 72.2$  kg stands on a platform scale in an elevator cab. We are concerned with the scale readings when the cab is stationary and when it is moving up or down.

- Find a general solution for the scale reading, whatever the vertical motion of the cab.
- What does the scale read if the cab is stationary or moving upward at a constant  $0.50$  m/s?
- What does the scale read if the cab accelerates upward at  $3.20$  m/s<sup>2</sup> and downward at  $3.20$  m/s<sup>2</sup>?
- During the upward acceleration in part (c), what is the magnitude  $F_{net}$  of the net force on the passenger, and what is the magnitude  $a_{p,cab}$  of his acceleration as measured from the frame of the cab? Does  $F_{net} = ma_{p,cab}$ ?



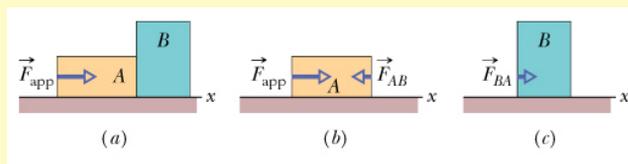
### Checkpoint 8

In the sample problem, what does the scale read if the elevator cable breaks so that the cab falls freely; that is, what is the apparent weight of the passenger in free fall?

### Sample 9

A constant horizontal force  $F_{app}$  of magnitude 20 N is applied to block A of mass  $m_A = 4.0$  kg, which pushes against block B of mass  $m_B = 6.0$  kg. The blocks slide over a frictionless surface, along an  $x$  axis.

- (a) What is the acceleration of the blocks?
- (b) What is the (horizontal) force  $F_{BA}$  on block B from block A?



## MORE FORCES

### Friction

Surface Friction ( $f$ ) depends on:

- 1) The weight of the object
  - The force between the object and the surface ( $F_N$ )
- 2) The type of surface
  - How rough/smooth the object and the surface are
  - “roughness” is scientifically described using the coefficient of friction “ $\mu$ ”

\*Note  $\mu$  is a unitless quantity!

# Friction

Every object has two  $\mu$  values:

**Static** coefficient (not moving):  $\mu_s$

**Kinetic** coefficient (moving):  $\mu_k$

The **static** coefficient is ALWAYS larger than the **kinetic** coefficient

I.e. It takes more force to **JUST START** moving than to **CONTINUE** moving

## Friction Equations

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

**NOT MOVING**

$$f_s \leq \mu_s F_N$$

**MOVING**

$$f_k = \mu_k F_N$$

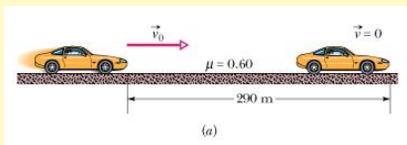
$f_{s,\max}$  must be exceeded for an object to begin moving

### Checkpoint 9

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 no 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)?

### Sample 10

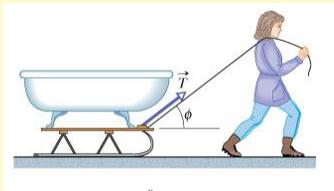
If a car's wheels are "locked" (kept from rolling) during emergency braking, the car slides along the road. Ripped-off bits of tire and small melted sections of road form the "skid marks" that reveal that cold-welding occurred during the slide. The record fro the longest skid marks on a public road was reportedly set in 1960 by a Jaguar on the M1 highway in England. The marks were 290 m long! Assuming that  $\mu_k = 0.60$  and the car's acceleration was constant during the braking, how fast was the car going when the wheels became locked?



### Sample 11

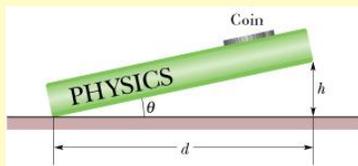
A woman pulls a loaded sled of mass  $m = 75 \text{ kg}$  along a horizontal surface at constant velocity. The coefficient of kinetic friction  $\mu_k$  between the runners and the snow is 0.10, and the angle  $\phi$  is  $42^\circ$ .

- (a) What is the magnitude of the force  $T$  on the sled from the rope?
- (b) If the woman increases her pull on the rope, so that  $T$  is greater than 91 N, is the magnitude  $f_k$  of the frictional force greater than, less than, or the same as in (a)?



### Sample 12

The figure shows a coin of mass  $m$  at rest on a book that has been tilted at an angle  $\theta$  with the horizontal. By experimenting, you find that when  $\theta$  is increased to  $13^\circ$ , the coin is on the *verge* of sliding down the book, which means that even a slight increase beyond  $13^\circ$  produces sliding. What is the coefficient of static friction  $\mu_s$  between the coin and the book?

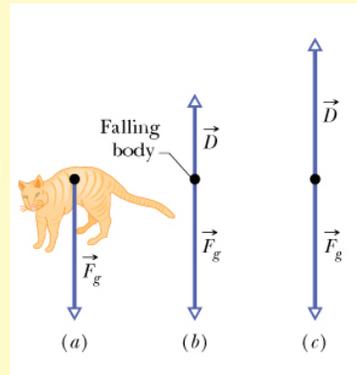


## Drag Force and Terminal Speed

- The drag force, or air resistance, is sometimes known as “fluid” friction. It is the resistive force experienced by an object traveling through air.
- Air resistance/drag depends on multiple things
  - Air density, drag coefficient, cross-sectional area of the moving object, and most importantly, its speed

$$D = \frac{1}{2} C \rho A v^2 \quad D = k v^2$$

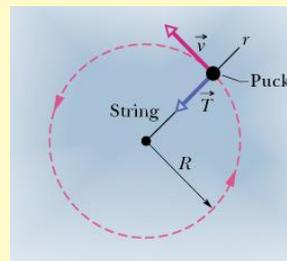
- Terminal velocity is achieved when the drag force is equal to the gravitational force on a falling object and it ceases to accelerate and continues falling at a constant speed.



## Uniform Circular Motion

- Object's undergoing centripetal acceleration experiences something we call the centripetal force
  - **Caution: a centripetal force is not a new kind of force, it is a name we give to any force causing centripetal acceleration**
- A centripetal force accelerates a body by changing the direction of the body's velocity without changing the body's speed

$$a_c = \frac{v^2}{R} \quad F_c = m \frac{v^2}{R}$$



### Checkpoint 10

When you ride in a Ferris wheel at constant speed, what are the directions of your acceleration  $\mathbf{a}$  and the motion force  $\mathbf{F}_N$  on you (from the always upright seat) as you pass through (a) the highest point and (b) the lowest point of the ride?

### Sample 13

Igor is a cosmonaut on the International Space Station, in a circular orbit around Earth, at an altitude  $h$  of 520 km with a constant speed  $v$  of 7.6 km/s. Igor's mass  $m$  is 79 kg.

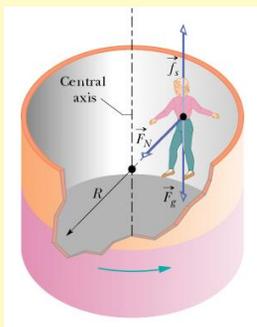
- (a) What is his acceleration?
- (b) What force does Earth exert on Igor?

### Sample 14

Even some seasoned roller-coaster riders blanch at the thought of riding the Rotor, which is essentially a large, hollow cylinder that is rotated rapidly around its central axis. Before the ride begins, a rider enters the cylinder through a door on the side and stands on a floor, up against a canvas-covered wall. The door is closed, and as the cylinder begins to turn, the rider, wall and floor move in unison. When the rider's speed reaches some predetermined value, the floor abruptly and alarmingly falls away. The rider does not fall with it but instead is pinned to the wall while the cylinder rotates, as if an unseen agent is pressing the body to the wall. Later, the floor is eased back to the rider's feet, the cylinder slows, and the rider sinks a few centimeters to regain footing on the floor.

Suppose that the coefficient of static friction  $\mu_s$  between the rider's clothing and the canvas is 0.40 and that the cylinder's radius  $R$  is 2.1 m.

- What minimum speed  $v$  must the cylinder and the rider have if the rider is not to fall when the floor drops?
- If the rider's mass is 49 kg, what is the magnitude of the centripetal force on her?

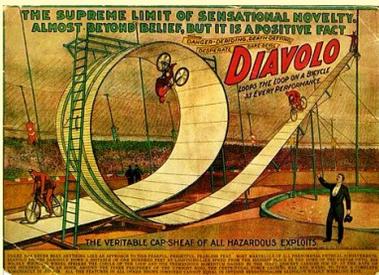


### Checkpoint 11

If the Rotor initially moves at the minimum required speed for the rider not to fall and then its speed is increased in steps, do the following increase, decrease, or remain the same: (a) the magnitude of  $f_s$ ; (b) the magnitude of  $F_N$ ; (c) the value of  $f_{s,max}$ ?

### Sample 15

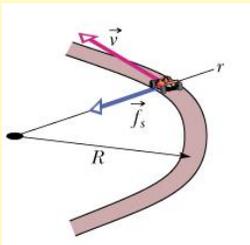
In a 1901 circus performance, Allo “Dare Devil” Diavolo introduced the stunt of riding a bicycle in a loop-the-loop. Assuming that the loop is a circle with radius  $R = 2.7$  m, what is the least speed  $v$  Diavolo could have at the top of the loop to remain in contact with it there?



### Sample 16

A modern race car is designed so that the passing air pushes down on it, allowing the car to travel much faster through a flat turn in a Grand Prix without friction failing. This downward push is called *negative lift*. Can a race car have so much negative lift that it could be driven upside down on a long ceiling, as done fictionally by a sedan in the first *Men in Black* movie? The figure represents a Grand Prix race car of mass  $m = 600$  kg as it travels on a flat track in a circular arc of radius  $R = 100$  m. Because of the shape of the car and the wings on it, the passing air exerts a negative lift  $F_L$  downward on the car. The coefficient of static friction between the tires and the track is 0.75. (Assume that the forces on the four tires are identical.)

- If the car is on the verge of sliding out of the turn when its speed is 28.6 m/s, what is the magnitude of  $F_L$ ?
- The magnitude  $F_L$  of the negative lift on a car depends on the square of the car's speed  $v^2$ , just as the drag force does. Thus, the negative lift on the car here is greater when the car travels faster, as it does on a straight section of track. What is the magnitude of the negative lift for a speed of 90 m/s?



### Sample 17

Curved portions of highways are always banked (tilted) to prevent cars from sliding off the highway. When a highway is dry, the frictional force between the tires and the road surface may be enough to prevent sliding. When the highway is wet, however, the frictional force may be negligible, and banking is then essential. The figure below represents a car of mass  $m$  as it moves at a constant speed  $v$  of 20 m/s around a banked circular track of radius  $R = 190$  m. (It is a normal car, rather than a race car, which means any vertical force from the passing air is negligible.) If the frictional force from the track is negligible, what bank angle  $\theta$  prevents sliding?

