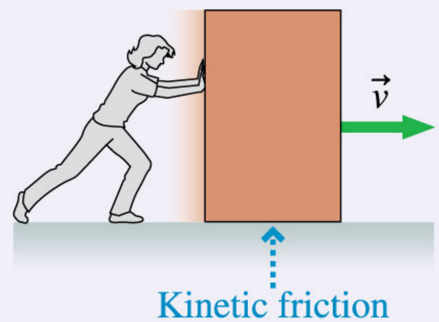
Dynamics in 1-D: Preview

How do we model friction and drag?

Friction and drag are complex forces, but we will develop simple models of each.

- Static, kinetic, and rolling friction depend on the coefficients of friction but not on the object's speed.
- Drag depends on the *square* of an object's speed and on its cross-section area.
- Falling objects reach terminal speed when drag and gravity are balanced.



Dynamics in 1-D: Preview

Same strategy as before. See a pattern?
For the solve part we now have another tool: Newton's laws

How do we solve problems?

We will develop and use a four-part problem-solving strategy:

- Model the problem, using information about objects and forces.
- Visualize the situation with a pictorial representation.
- Set up and solve the problem with Newton's laws.
- Assess the result to see if it is reasonable.

Newton’s first law can be applied to

What is each one?

A. Static equilibrium.
B. Newtonian equilibrium.
C. Dynamic equilibrium.
D. Both A and B.
E. Both A and C.

Newton’s first law can be applied to

A. Static equilibrium.
B. Newtonian equilibrium.
C. Dynamic equilibrium.
D. Both A and B.
E. Both A and C.

Mass is

A. An intrinsic property.
B. A force.
C. A measurement.

Mass is

A. **An intrinsic property.**
B. A force.
C. A measurement.

Which means?

Gravity is

A. An intrinsic property.
B. A force.
C. A measurement.

Gravity is

A. An intrinsic property.
B. A force.
C. A measurement.

Weight is

A. An intrinsic property.
B. A force.
C. A measurement.

Weight is

A. An intrinsic property.

B. A force.

C. A measurement.

You can’t feel your own weight, and it depends on the mass, acceleration due to gravity, and acceleration due to other forces

The coefficient of static friction is

A. Smaller than the coefficient of kinetic friction.
B. Equal to the coefficient of kinetic friction.
C. Larger than the coefficient of kinetic friction.
D. Depends on the specific situation.

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It is easier to continue moving objects when they are already moving than starting from rest. Why?

The force of friction is described by

A. The law of friction.
B. The theory of friction.
C. A model of friction.
D. The friction hypothesis.
E. The friction ultimatum.

What is the definition of law, theory, hypothesis, model?

The force of friction is described by

A. The law of friction.
B. The theory of friction.
C. **A model of friction.**
D. The friction hypothesis.

When an object moves through the air, the magnitude of the drag force on it

A. Increases as the object's speed increases.
B. Decreases as the object's speed increases.
C. Does not depend on the object's speed.

When an object moves through the air, the magnitude of the drag force on it

A. Increases as the object’s speed increases.

B. Decreases as the object’s speed increases.

C. Does not depend on the object’s speed.

What is a reasonable explanation?

Terminal speed is

A. Equal to the speed of sound.
B. The minimum speed an object needs to escape the earth's gravity.
C. The speed at which the drag force cancels the gravitational force.
D. The speed at which the drag force reaches a minimum.
E. Any speed that can result in a person's death.

Terminal speed is

A. Equal to the speed of sound.

B. The minimum speed an object needs to escape the earth's gravity.

C. The speed at which the drag force cancels the gravitational force.

D. The speed at which the drag force reaches a minimum.

E. Any speed that can result in a person's death.

We just looked at the elements that we will be dealing with in this part of the course:
mass, gravity, weight, friction, drag

Now let's use them for dynamics calculations

The Equilibrium Model

Axes are independent, for example, you can be accelerating in x and not in y

- In the absence of a net force, an object is at rest or moves with constant velocity.
- Its acceleration is zero, and we say that it is **in equilibrium**.

- The concept of equilibrium is essential for the engineering analysis of stationary objects such as bridges.
- When the acceleration is zero, then Newton's second law in two dimensions becomes:

$$(F_{\text{net}})_x = \sum_i (F_i)_x = 0 \quad \text{and} \quad (F_{\text{net}})_y = \sum_i (F_i)_y = 0$$

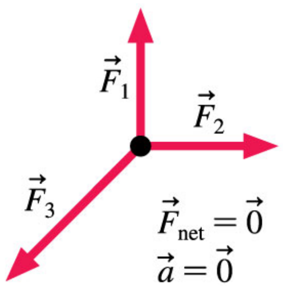
Mechanical Equilibrium

MODEL 6.1

Mechanical equilibrium

For objects on which the net force is zero.

- Model the object as a particle with no acceleration.
  - A particle at rest is in equilibrium.
  - A particle moving in a straight line at constant speed is also in equilibrium.
- Mathematically: $\vec{a} = \vec{0}$ in equilibrium; thus
  - **Newton's second law** is $\vec{F}_{\text{net}} = \sum_i \vec{F}_{\text{i}} = \vec{0}$.
  - The forces are "read" from the free-body diagram,
- Limitations: Model fails if the forces aren't balanced.



The object is at rest or moves with constant velocity.

A ring, seen from above, is pulled on by three forces. The ring is not moving. How big is the force F?

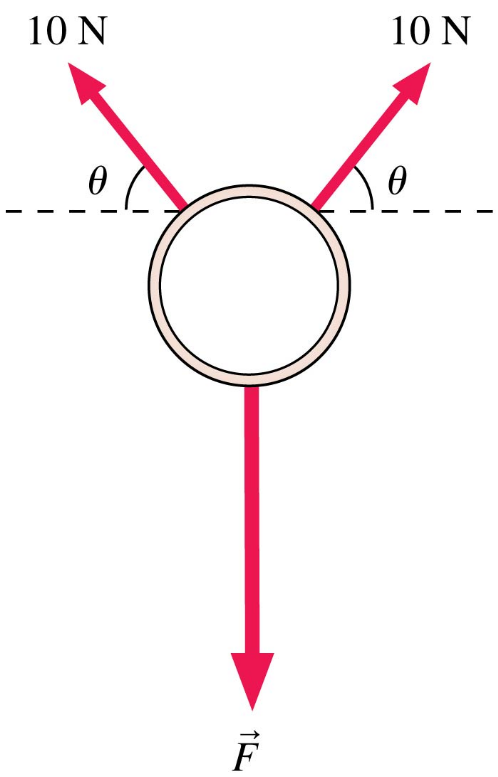
A. 20 N

B. $10\cos\theta$ N

C. $10\sin\theta$ N

D. $20\cos\theta$ N

E. $20\sin\theta$ N



This is a typical, straightforward, mechanical equilibrium problem: keep in mind that the sum of forces in each individual direction is zero.
Let's work it out.

A ring, seen from above, is pulled on by three forces. The ring is not moving. How big is the force F?

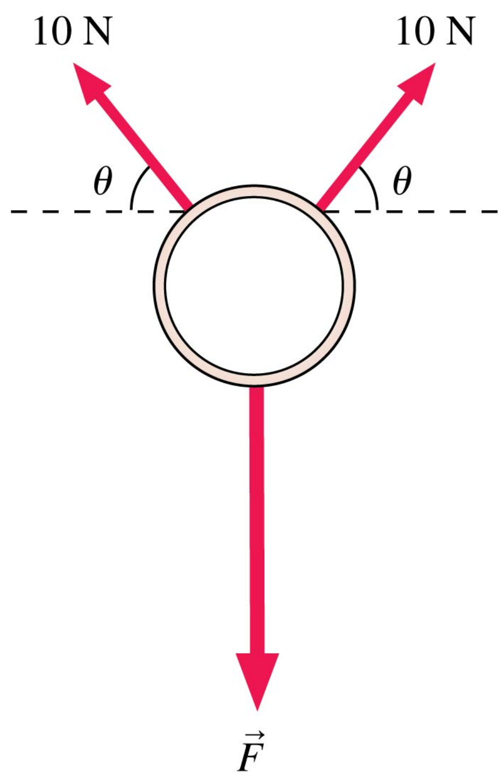
A. 20 N

B. $10\cos\theta$ N

C. $10\sin\theta$ N

D. $20\cos\theta$ N

✔ **E. $20\sin\theta$ N**



Towing a Car up a Hill

EXAMPLE 6.2 | **Towing a car up a hill**

A car with a weight of 15,000 N is being towed up a 20° slope at constant velocity. Friction is negligible. The tow rope is rated at 6000 N maximum tension. Will it break?

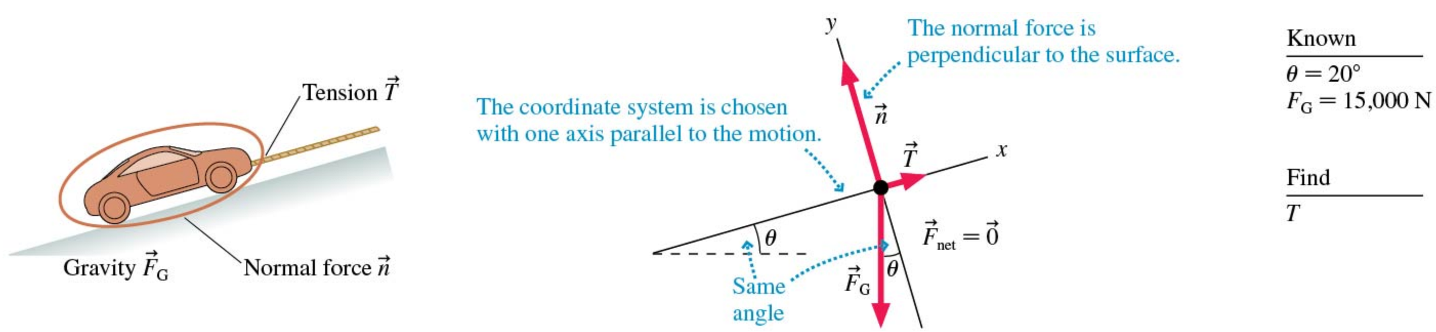
MODEL Model the car as a particle in equilibrium.

Towing a Car up a Hill

EXAMPLE 6.2 **Towing a car up a hill**

VISUALIZE Part of our analysis of the problem statement is to determine which quantity or quantities allow us to answer the yes-or-no question. In this case, we need to calculate the tension in the rope. **FIGURE 6.2** shows the pictorial representation. Note the similarities to Examples 5.2 and 5.6 in Chapter 5, which you may want to review.

We noted in Chapter 5 that the weight of an object at rest is the magnitude F_G of the gravitational force acting on it, and that information has been listed as known.



Towing a Car up a Hill

EXAMPLE 6.2 | **Towing a car up a hill**

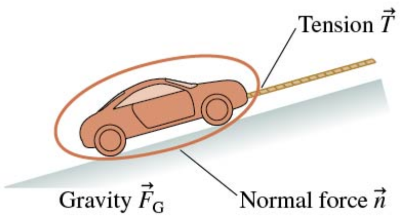
SOLVE The free-body diagram shows forces $\vec{T}$, $\vec{n}$, and $\vec{F}_G$ acting on the car. Newton's second law with $\vec{a} = \vec{0}$ is

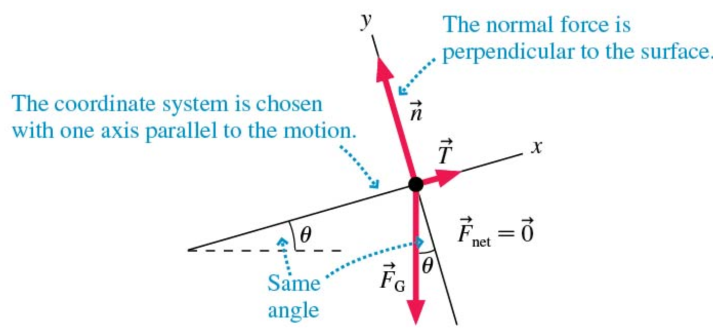
$$(F_{net})_x = \sum F_x = T_x + n_x + (F_G)_x = 0$$
$$(F_{net})_y = \sum F_y = T_y + n_y + (F_G)_y = 0$$

From here on, we'll use $\sum F_x$ and $\sum F_y$, without the label i, as a simple shorthand notation to indicate that we're adding all the x-components and all the y-components of the forces.

We can find the components directly from the free-body diagram:

$$T_x = T \qquad T_y = 0$$
$$n_x = 0 \qquad n_y = n$$
$$(F_G)_x = -F_G \sin\theta \qquad (F_G)_y = -F_G \cos\theta$$





Known
$\theta = 20°$
$F_G = 15{,}000$ N

Find
T

Towing a Car up a Hill

EXAMPLE 6.2 **Towing a car up a hill**

NOTE The gravitational force has both x- and y-components in this coordinate system, both of which are negative due to the direction of the vector $\vec{F}_G$. You'll see this situation often, so be sure you understand where $(F_G)_x$ and $(F_G)_y$ come from.

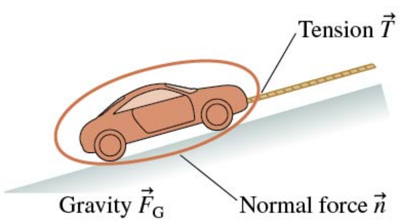
With these components, the second law becomes

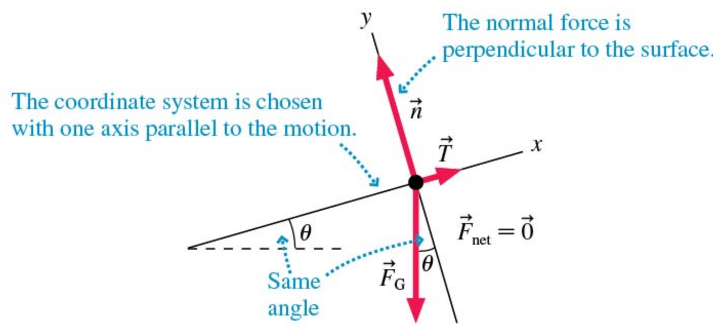
$$T - F_G \sin\theta = 0$$
$$n - F_G \cos\theta = 0$$

The first of these can be rewritten as

$$T = F_G \sin\theta = (15{,}000\ \text{N}) \sin 20° = 5100\ \text{N}$$

Because $T < 6000$ N, we conclude that the rope will *not* break. It turned out that we did not need the y-component equation in this problem.





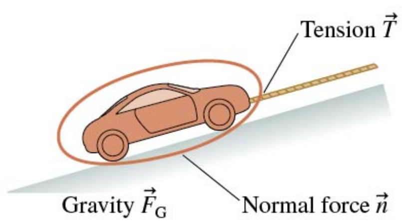
Known
$\theta = 20°$
$F_G = 15{,}000$ N

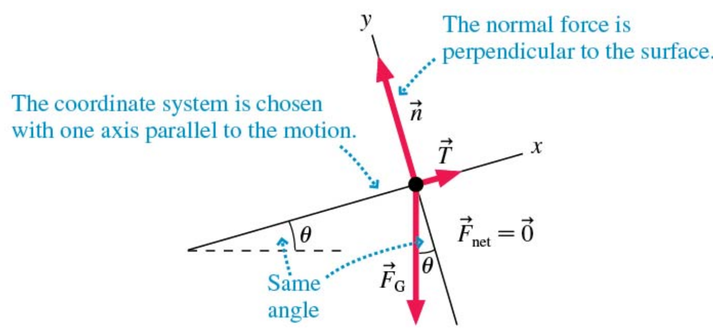
Find
T

Towing a Car up a Hill

EXAMPLE 6.2 | **Towing a car up a hill**

ASSESS Because there's no friction, it would not take *any* tension force to keep the car rolling along a horizontal surface ($\theta = 0°$). At the other extreme, $\theta = 90°$, the tension force would need to equal the car's weight ($T = 15{,}000$ N) to lift the car straight up at constant velocity. The tension force for a 20° slope should be somewhere in between, and 5100 N is a little less than half the weight of the car. That our result is reasonable doesn't prove it's right, but we have at least ruled out careless errors that give unreasonable results.



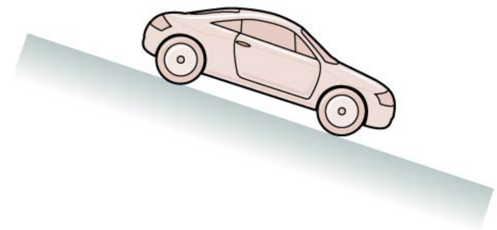


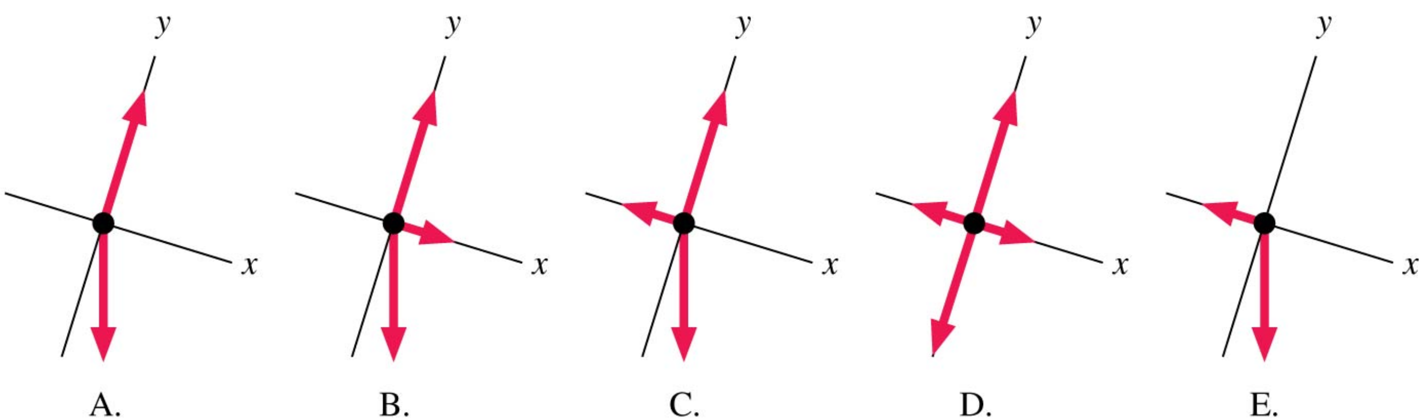
Known
$\theta = 20°$
$F_G = 15{,}000$ N

Find
T

Quick Check 3

A car is parked on a hill. Which is the correct free-body diagram?

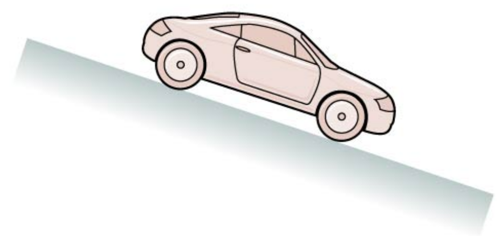


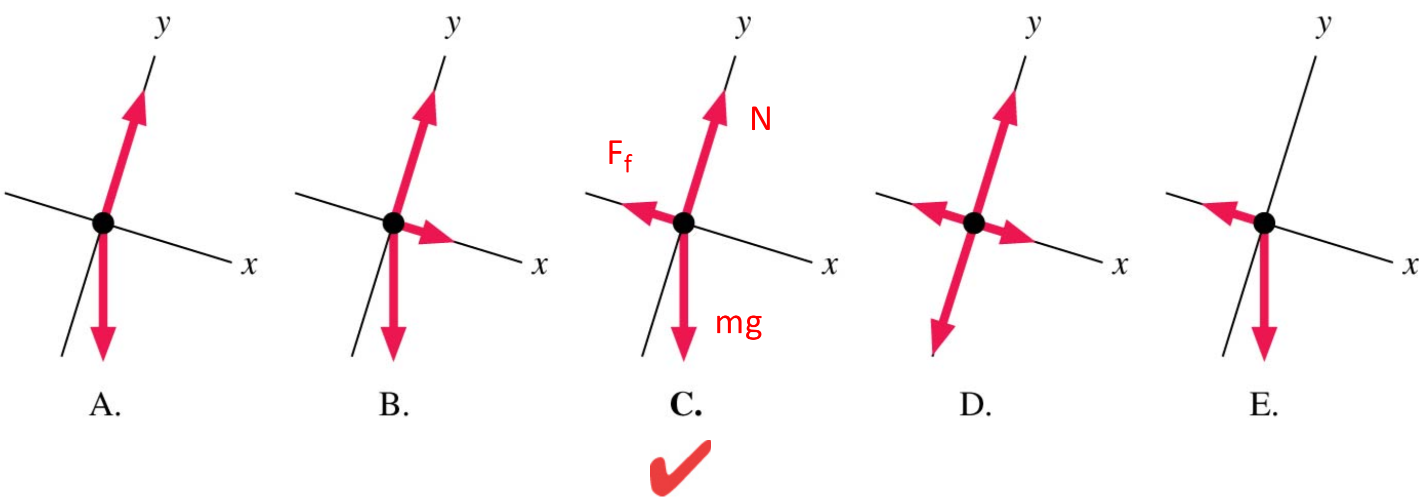


What forces are acting on the car and in which directions?
What is the sum of forces in x? In y?

Quick Check 3

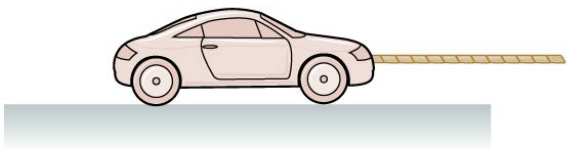
A car is parked on a hill. Which is the correct free-body diagram?

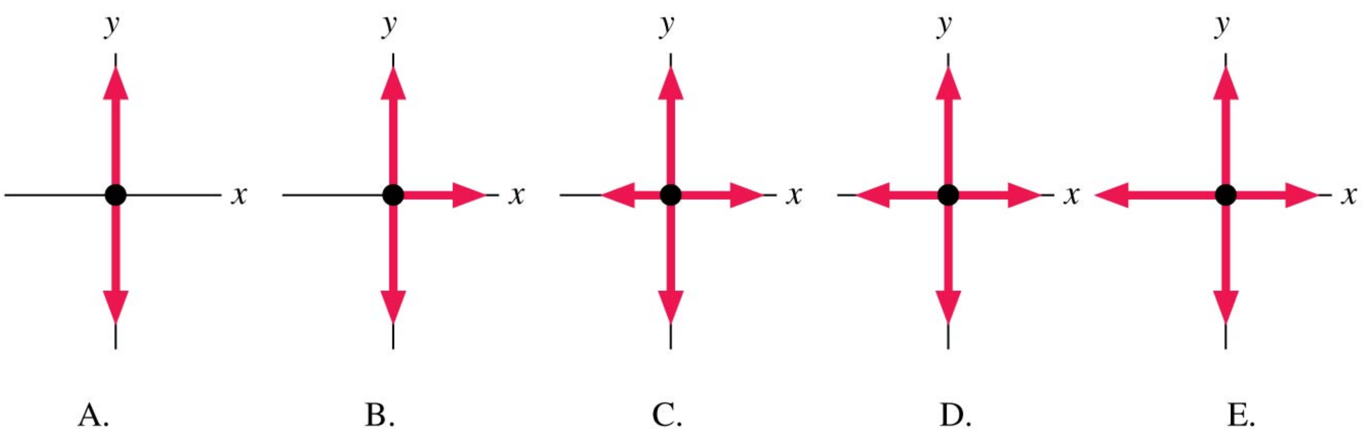




Quick Check 4

A car is towed to the right at constant speed. Which is the correct free-body diagram?





What forces are acting on the car and in which directions?
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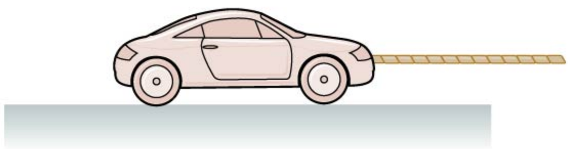
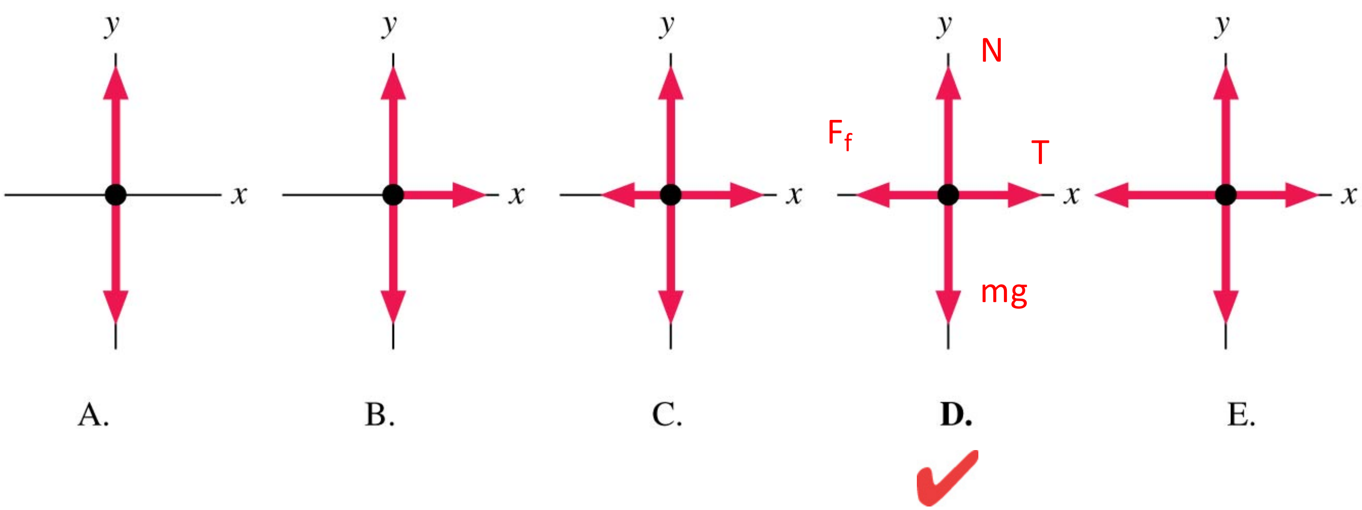
Quick Check 4

A car is towed to the right at constant speed. Which is the correct free-body diagram?





Using Newton's Second Law

- The essence of Newtonian mechanics can be expressed in two steps:
  - The forces on an object determine its acceleration $\vec{a} = \vec{F}_{\text{net}}/m$
  - The object's trajectory can be determined by using $\vec{a}$ in the equations of kinematics.

PROBLEM-SOLVING STRATEGY 6.1

SOLVE The mathematical representation is based on Newton's second law:

$$\vec{F}_{\text{net}} = \sum_i \vec{F}_i = m\vec{a}$$

The forces are "read" directly from the free-body diagram. Depending on the problem, either

- Solve for the acceleration, then use kinematics to find velocities and positions; or
- Use kinematics to determine the acceleration, then solve for unknown forces.

The cart is initially at rest. Force $\vec{F}$ is applied to the cart for time Δt, after which the car has speed v. Suppose the same force is applied for the same time to a second cart with twice the mass. Friction is negligible. Afterward, the second cart's speed will be

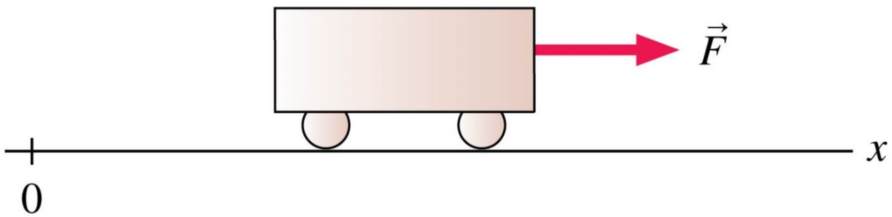
A. $\frac{1}{4}v$

B. $\frac{1}{2}v$

C. v

D. $2v$

E. $4v$



$v = v_0 + a\Delta t$ $\quad a = \frac{F}{m}$ $\quad v_0 = 0$

$v = \frac{F}{m}\Delta t$

The cart is initially at rest. Force $\vec{F}$ is applied to the cart for time Δt, after which the car has speed v. Suppose the same force is applied for the same time to a second cart with twice the mass. Friction is negligible. Afterward, the second cart's speed will be

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✔ **B.** $\frac{1}{2} v$

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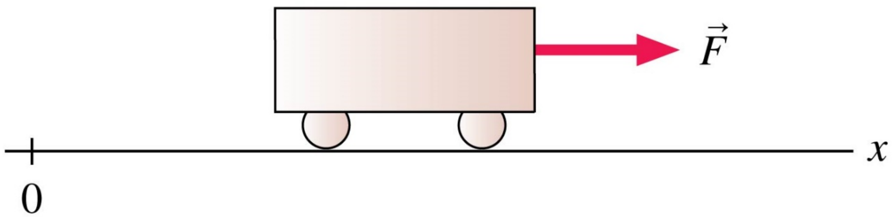


$$v = v_0 + a\Delta t \qquad a = \frac{F}{m} \qquad v_0 = 0$$

$$v = \frac{F}{m}\Delta t$$

Example: Speed of a Towed Car

EXAMPLE 6.3 | **Speed of a towed car**

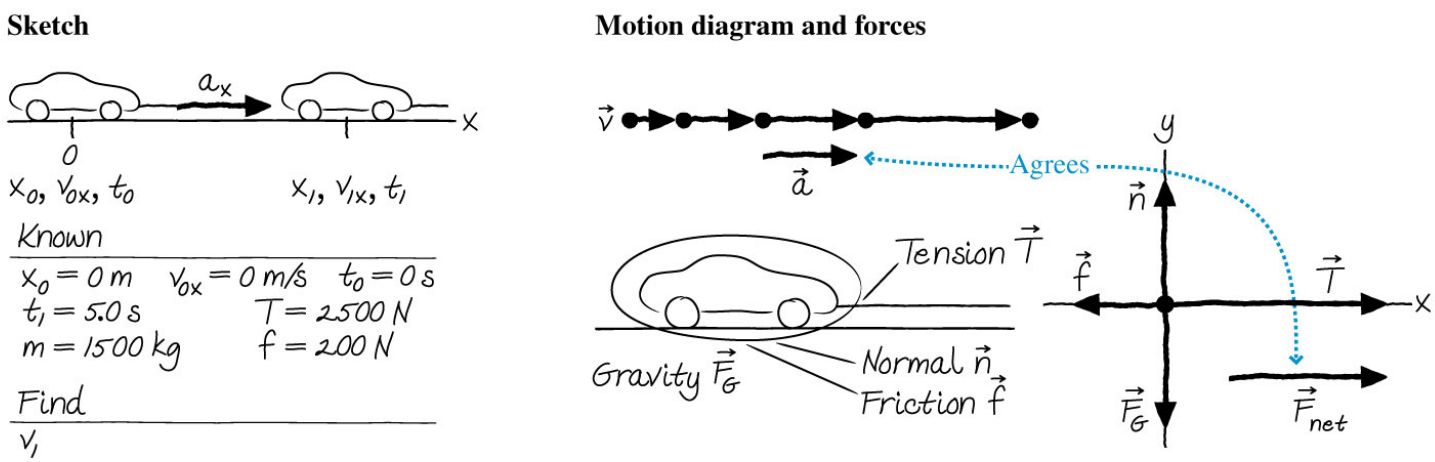
A 1500 kg car is pulled by a tow truck. The tension in the tow rope is 2500 N, and a 200 N friction force opposes the motion. If the car starts from rest, what is its speed after 5.0 seconds?

MODEL Model the car as an accelerating particle. We'll assume, as part of our *interpretation* of the problem, that the road is horizontal and that the direction of motion is to the right.

Example: Speed of a Towed Car

EXAMPLE 6.3 | **Speed of a towed car**

VISUALIZE **FIGURE 6.3** shows the pictorial representation. We've established a coordinate system and defined symbols to represent kinematic quantities. We've identified the speed v_1, rather than the velocity v_{1x}, as what we're trying to find.



Example: Speed of a Towed Car

EXAMPLE 6.3 | **Speed of a towed car**

SOLVE We begin with Newton's second law:

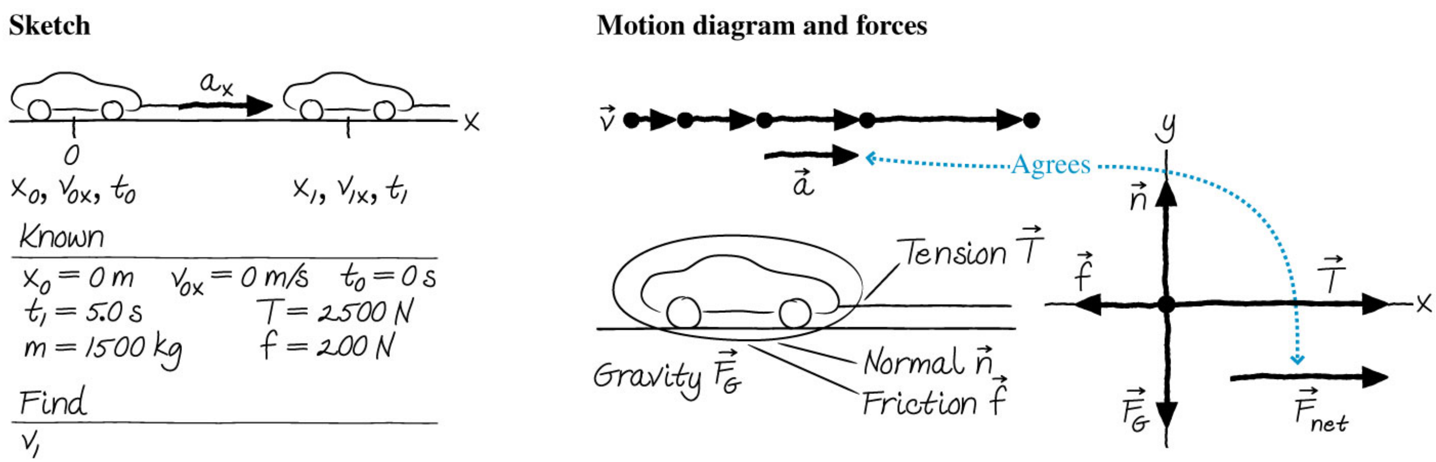
$$(F_{\text{net}})_x = \sum F_x = T_x + f_x + n_x + (F_G)_x = ma_x$$

$$(F_{\text{net}})_y = \sum F_y = T_y + f_y + n_y + (F_G)_y = ma_y$$

All four forces acting on the car have been included in the vector sum. The equations are perfectly general, with + signs every-where, because the four vectors are *added* to give $\vec{F}_{\text{net}}$. We can now "read" the vector components from the free-body diagram:

$$T_x = +T \qquad T_y = 0 \qquad n_x = 0 \qquad n_y = +n$$

$$f_x = -f \qquad f_y = 0 \qquad (F_G)_x = 0 \qquad (F_G)_y = -F_G$$



Example: Speed of a Towed Car

EXAMPLE 6.3 | **Speed of a towed car**

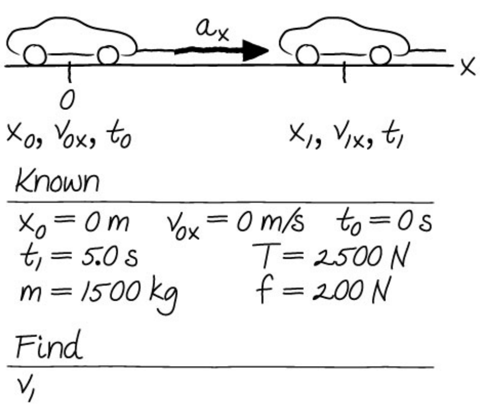
SOLVE The signs, which we had to insert by hand, depend on which way the vectors point. Substituting these into the second-law equations and dividing by m give

$$a_x = \frac{1}{m}(T - f)$$

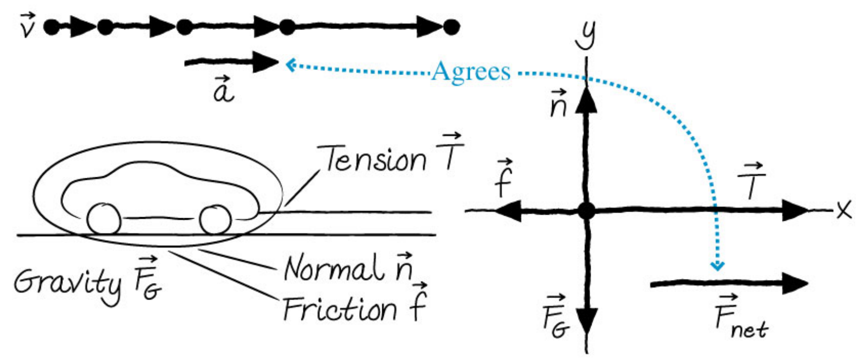
$$= \frac{1}{1500\text{ kg}}(2500\text{ N} - 200\text{ N}) = 1.53\text{ m/s}^2$$

$$a_y = \frac{1}{m}(n - F_G)$$

Sketch



Motion diagram and forces



Example: Speed of a Towed Car

EXAMPLE 6.3 | **Speed of a towed car**

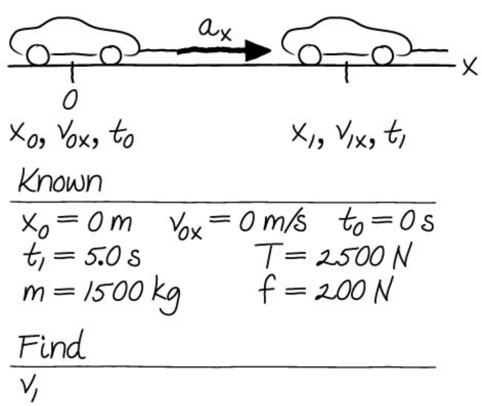
NOTE Newton's second law has allowed us to determine a exactly but has given only an algebraic expression for a_y. However, we know *from the motion diagram* that $a_y = 0$! That is, the motion is purely along the x-axis, so there is *no* acceleration along the y-axis. The requirement $a_y = 0$ allows us to conclude that $n = F_G$.

Because a_x is a constant 1.53 m/s^2, we can finish by using constant-acceleration kinematics to find the velocity:

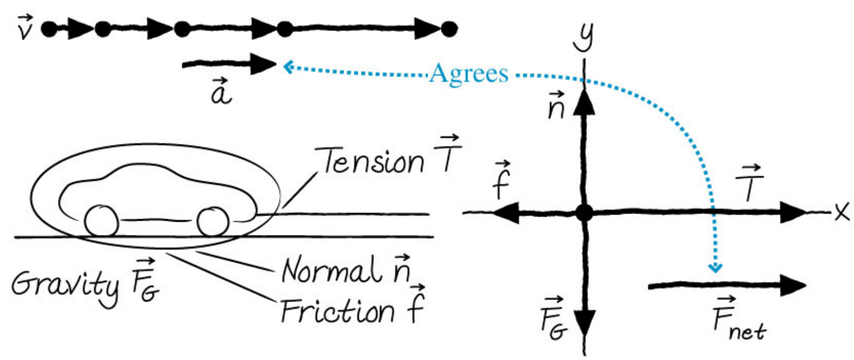
$$v_{1x} = v_{0x} + a_x \Delta t$$
$$= 0 + (1.53 \text{ m/s}^2)(5.0 \text{ s}) = 7.7 \text{ m/s}$$

The problem asked for the *speed* after 5.0 s, which is $v_1 = 7.7$ m/s.

Sketch



Motion diagram and forces

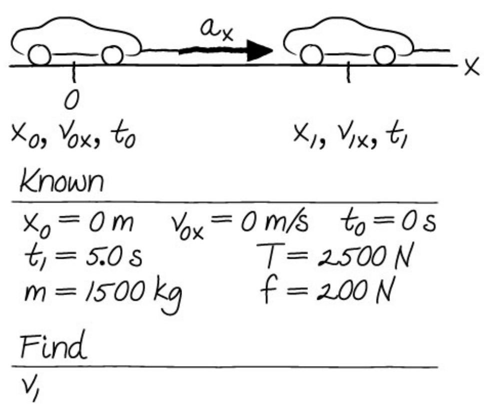


Example: Speed of a Towed Car

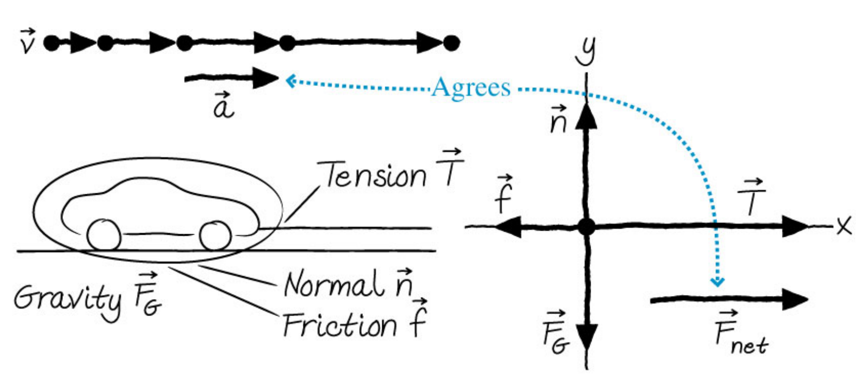
EXAMPLE 6.3 | **Speed of a towed car**

ASSESS 7.7 m/s ≈ 15 mph, a quite reasonable speed after 5 s of acceleration.

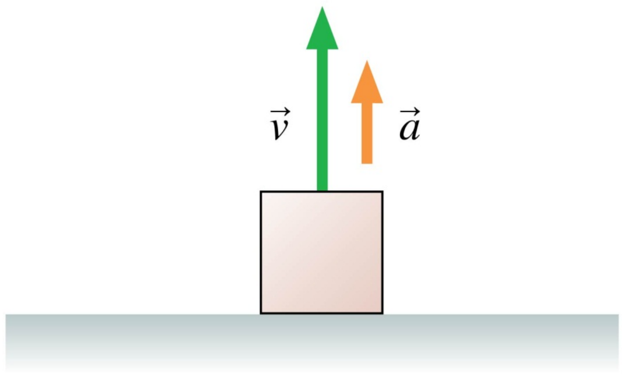
Sketch



Motion diagram and forces



The box is sitting on the floor of an elevator. The elevator is accelerating upward. The magnitude of the normal force on the box is



A. $n > mg.$

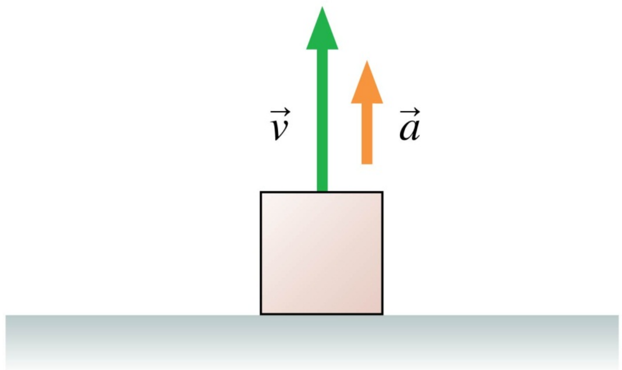
B. $n = mg.$

C. $n < mg.$

D. $n = 0.$

E. Not enough information to tell.

The box is sitting on the floor of an elevator. The elevator is accelerating upward. The magnitude of the normal force on the box is



✔ **A.** $n > mg$.

B. $n = mg$.

C. $n < mg$.

D. $n = 0$.

E. Not enough information to tell.

There is upward acceleration because there is a net force upward

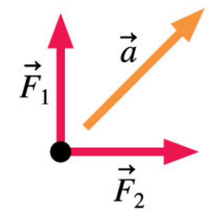
Constant Force

MODEL 6.2

Constant force

For objects on which the net force is constant.

- Model the object as a particle with uniform acceleration.
  - The particle accelerates in the direction of the net force.
- Mathematically:
  - **Newton's second law** is $\vec{F}_{\text{net}} = \sum_i \vec{F}_{\text{i}} = m\vec{a}$.
  - Use the kinematics of constant acceleration.
- Limitations: Model fails if the forces aren't constant.



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

The object undergoes uniform acceleration.

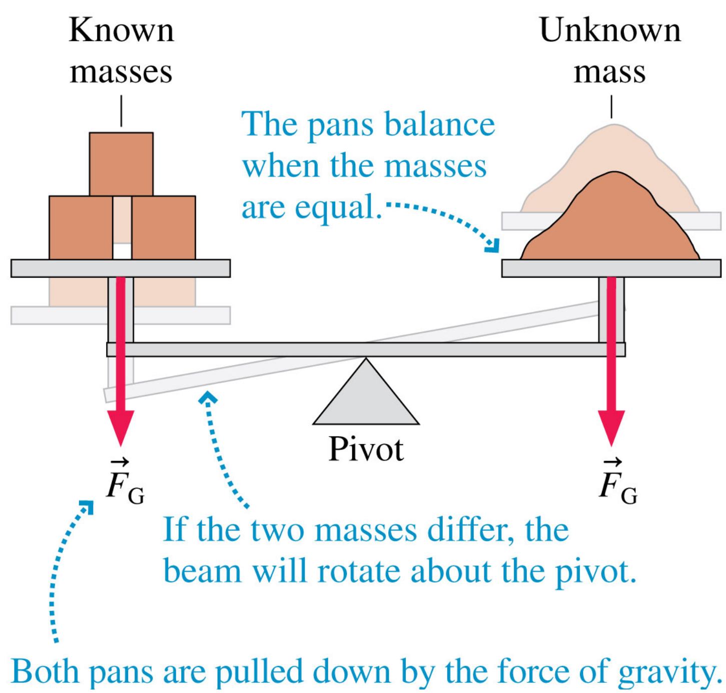
Mass: An Intrinsic Property

This has gravitas

- A *pan balance*, shown in the figure, is a device for measuring **mass**.
- The measurement does not depend on the strength of gravity.

Why?

- Mass is a scalar quantity that describes an object's inertia.
- Mass describes the amount of matter in an object.
- **Mass is an intrinsic property of an object.**



[Higgs boson in 2 minutes!]

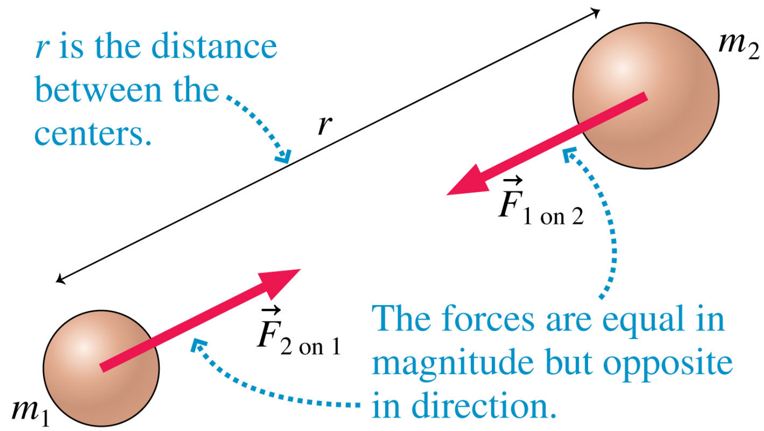
So a not horrible way to think about why mass ‘increases’ as objects move closer to the speed of light (and hence you need a larger force to continue accelerating them) is that they are moving in a fluid (the Higgs field) so there is a drag force.

Very loosely speaking, mass is a measure of this drag. We don’t notice this drag at the tiny speeds we move just like we don’t notice drag from the atmosphere when we walk. We feel it at large speeds, for example the drag of the atmosphere eventually leads to a terminal velocity.

Gravity: A Force

Let that sink in

- Gravity is an attractive, long-range force between any two objects.
- The figure shows two objects with masses m_1 and m_2 whose centers are separated by distance r.
- Each object pulls on the other with a force:

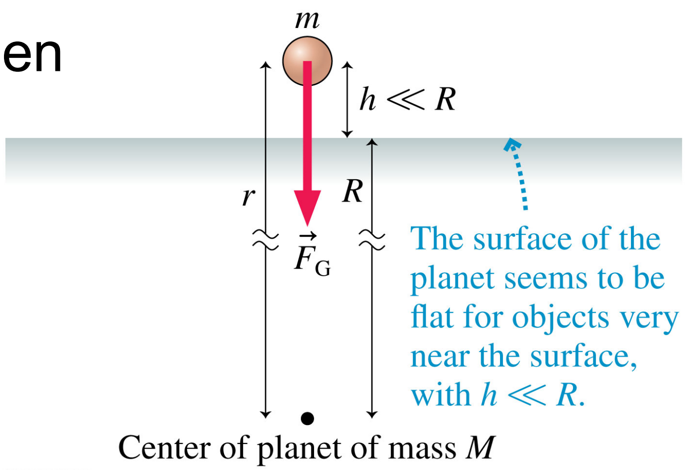


$$F_{1 \text{ on } 2} = F_{2 \text{ on } 1} = \frac{Gm_1 m_2}{r^2} \qquad \text{(Newton's law of gravity)}$$

where $G = 6.67 \times 10^{-11}$ N m^2/kg^2 is the gravitational constant.

Gravity: A Force

- The gravitational force between two human-sized objects is very small.
- Only when one of the objects is planet-sized or larger does gravity become an important force.



- For objects near the surface of the planet earth,

$$\vec{F}_G = \vec{F}_{\text{planet on } m} = \left(\frac{GMm}{R^2}, \text{straight down}\right) = (mg, \text{straight down})$$

where M and R are the mass and radius of the earth, and $g = 9.80\ \text{m/s}^2$.

What is g at sea level at the equator?
Sea level at the north pole? Himalayas?

Gravity: A Force

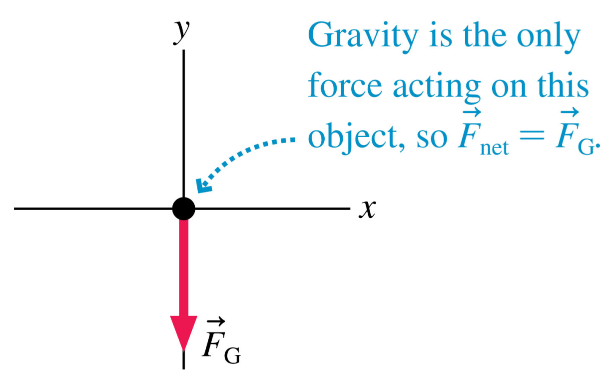
Why is R^2 the radius of the earth? What does that mean?

- The magnitude of the gravitational force is $F_G = mg$, where

$$g = \frac{GM}{R^2}$$

- The figure shows the free-body diagram of an object in free fall near the surface of a planet.
- With $\vec{F}_{\text{net}} = \vec{F}_{\text{G}}$, Newton's second law predicts the acceleration to be

$$\vec{a}_{\text{free fall}} = \frac{\vec{F}_{\text{net}}}{m} = \frac{\vec{F}_{\text{G}}}{m} = (g, \text{straight down})$$



- All objects on the same planet, regardless of mass, have the same free-fall acceleration!

Force of gravity is tiny but measurable!

Mass bends space, so a not horrible way to think about why gravity is an attractive force that can keep objects in orbit is that this bending, in two dimensions looks like a banked curve. The heavier the object, the more it bends space, the greater the bank angle, and the smaller the radius of curvature. This banked curve exerts a ‘centripetal force‘ and the centripetal acceleration is what we understand as acceleration due to gravity.

Of course, this bending happens in the three dimensions we seem to live in and not in two, but it is difficult for us humans who evolved in what we see as a flat surface to imagine a three dimensional banked curve.

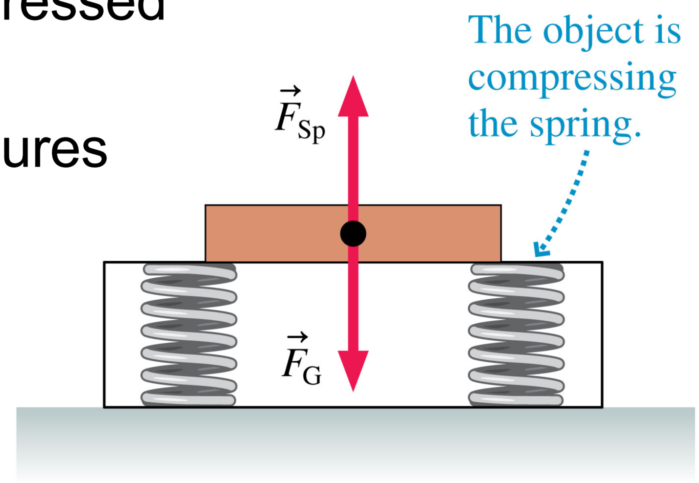
Weight: A Measurement

Wait… what?

- When you weigh yourself, you stand on a spring scale and compress a spring.
- The reading of a spring scale is F_{Sp}, the magnitude of the upward force the spring is exerting. To keep you in place
- Let's define the **weight** of an object to be the reading F_{Sp} of a calibrated spring scale when the object is at rest relative to the scale.
- That is, **weight is a measurement, the result of "weighing" an object**.
- Because F_{Sp} is a force, weight is measured in newtons.

Weight: A Measurement

- A bathroom scale uses compressed springs which push up.
- When any spring scale measures an object at rest, $\vec{F}_{\text{net}} = \vec{0}$.
- The upward spring force exactly balances the downward gravitational force of magnitude mg:



$$F_{\text{Sp}} = F_{\text{G}} = mg$$

- Weight is defined as the magnitude of F_{Sp} when the object is at rest relative to the stationary scale:

$$w = mg \qquad \text{(weight of a stationary object)}$$

An astronaut takes her bathroom scales to the moon, where $g = 1.6\ \mathrm{m/s^2}$. On the moon, compared to at home on earth,

A. Her weight is the same and her mass is less.

B. Her weight is less and her mass is less.

C. Her weight is less and her mass is the same.

D. Her weight is the same and her mass is the same.

E. Her weight is zero and her mass is the same.

An astronaut takes her bathroom scales to the moon, where $g = 1.6\ \mathrm{m/s^2}$. On the moon, compared to at home on earth,

A. Her weight is the same and her mass is less.

B. Her weight is less and her mass is less.

✔ C. **Her weight is less and her mass is the same.**

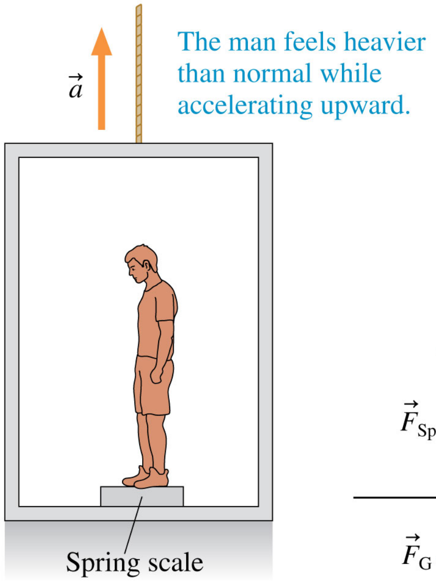
D. Her weight is the same and her mass is the same.

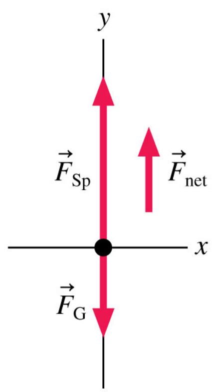
E. Her weight is zero and her mass is the same.

Weight: A Measurement

- The figure shows a man weighing himself in an accelerating elevator.
- Looking at the free-body diagram, the y-component of Newton's second law is:

$$(F_{\text{net}})_y = (F_{\text{Sp}})_y + (F_{\text{G}})_y = F_{\text{Sp}} - mg = ma_y$$





- The man's weight as he accelerates vertically is

$$w = \text{scale reading } F_{\text{Sp}} = mg + ma_y = mg\left(1 + \frac{a_y}{g}\right)$$

- You weigh *more* as an elevator accelerates upward!

A 50-kg student ($mg = 490$ N) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. As the elevator accelerates upward, the scale reads

A. > 490 N

B. 490 N

C. < 490 N but not 0 N

D. 0 N

A 50-kg student ($mg = 490$ N) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. As the elevator accelerates upward, the scale reads

✔ **A. > 490 N**

B. 490 N

C. < 490 N but not 0 N

D. 0 N

A 50-kg student ($mg = 490$ N) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. As the elevator accelerates upward, the student's weight is

A. > 490 N

B. 490 N

C. < 490 N but not 0 N

D. 0 N

A 50-kg student ($mg = 490\ \mathrm{N}$) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. As the elevator accelerates upward, the student's weight is

✔ **A.** **> 490 N**

B. 490 N

C. < 490 N but not 0 N

D. 0 N

Weight is reading of a scale on which the object is stationary *relative to the scale*.

Weightlessness

- The weight of an object which accelerates vertically is

$$w = \text{scale reading } F_{\text{Sp}} = mg + ma_y = mg\left(1 + \frac{a_y}{g}\right)$$

- If an object is accelerating downward with $a_y = {}^{-}g$, then $w = 0$.
- An object in free fall *has no weight!*
- Astronauts while orbiting the earth are also weightless.
- Does this mean that they are in free fall?

Astronauts are weightless as they orbit the earth.

A 50-kg student ($mg = 490\ \text{N}$) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. Sadly, the elevator cable breaks. What is the student's weight during the few second it takes the student to plunge to his doom?

A. $> 490\ \text{N}$

B. $490\ \text{N}$

C. $< 490\ \text{N}$ but not $0\ \text{N}$

D. $0\ \text{N}$

A 50-kg student ($mg = 490$ N) gets in a 1000-kg elevator at rest and stands on a metric bathroom scale. Sadly, the elevator cable breaks. What is the student's weight during the few second it takes the student to plunge to his doom?

A. > 490 N

B. 490 N

C. < 490 N but not 0 N

✔ **D. 0 N** The bathroom scale would read 0 N. Weight is reading of a scale on which the object is stationary *relative to the scale.*

A 50-kg astronaut ($mg = 490$ N) is orbiting the earth in the space shuttle. Compared to on earth:

A. His weight is the same and his mass is less.
B. His weight is less and his mass is less.
C. His weight is less and his mass is the same.
D. His weight is the same and his mass is the same.
E. His weight is zero and his mass is the same.

A 50-kg astronaut ($mg = 490\ \mathrm{N}$) is orbiting the earth in the space shuttle. Compared to on earth:

A. His weight is the same and his mass is less.

B. His weight is less and his mass is less.

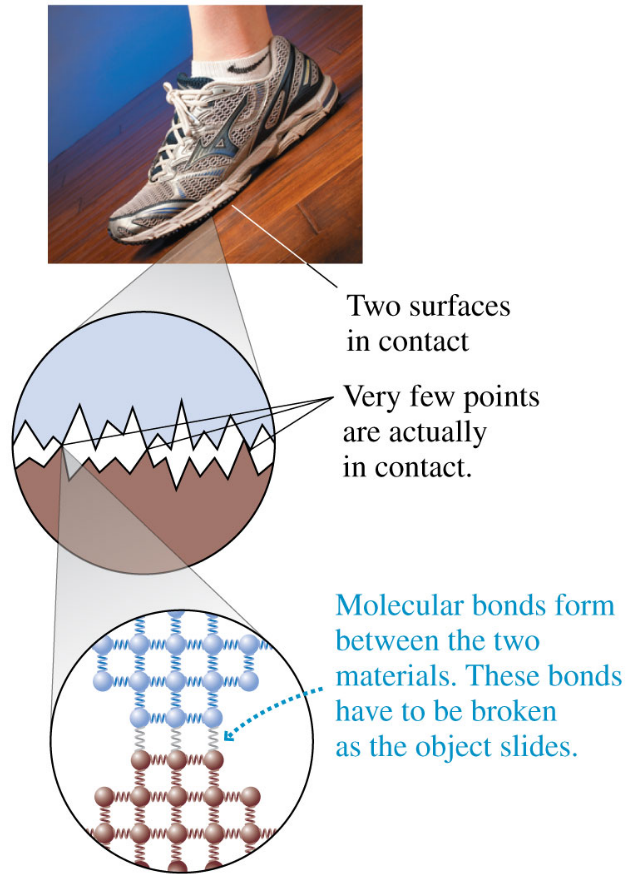
C. His weight is less and his mass is the same.

D. His weight is the same and his mass is the same.

✔E. **His weight is zero and his mass is the same.**

Static Friction

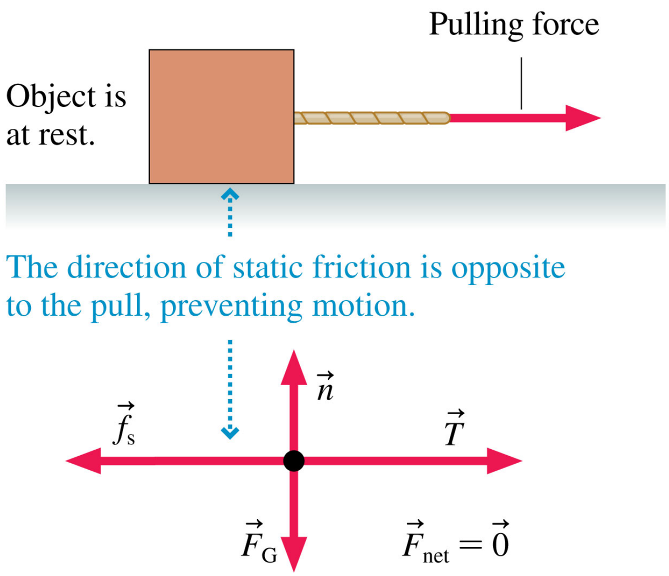
- A shoe pushes on a wooden floor but does not slip.
- On a microscopic scale, both surfaces are “rough” and high features on the two surfaces form molecular bonds.
- These bonds can produce a force *tangent* to the surface, called the **static friction** force.
- Static friction is a result of many molecular springs being compressed or stretched ever so slightly.



The friction model is phenomenological, it hides much of the the physics and replaces it with a measurement. All models are wrong, some models are useful

Static Friction

- The figure shows a rope pulling on a box that, due to static friction, isn't moving.
- Looking at the free-body diagram, the x-component of Newton's first law requires that the static friction force must exactly balance the tension force:



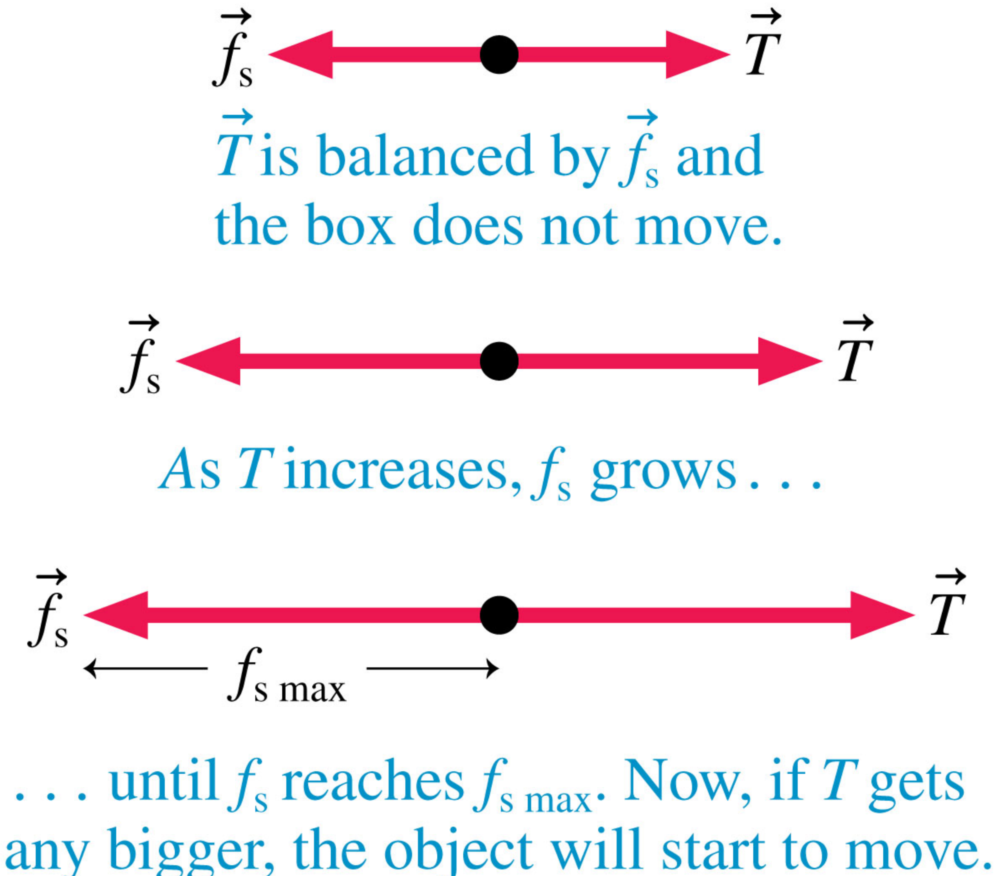
$$f_s = T$$

So the static friction is *variable*?

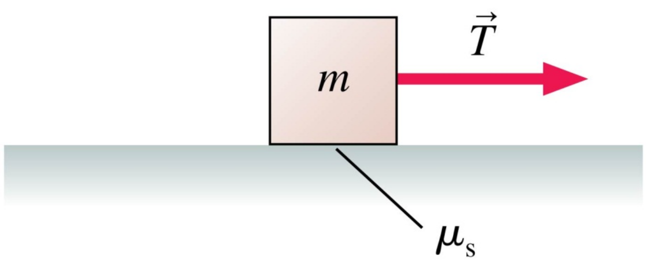
- $\vec{f}_s$ points in the direction *opposite* to the way the object would move if there were no static friction.

Static Friction

- Static friction acts in *response* to an applied force.



A box on a rough surface is pulled by a horizontal rope with tension T. The box is not moving. In this situation,



A. $f_s > T$

B. $f_s = T$

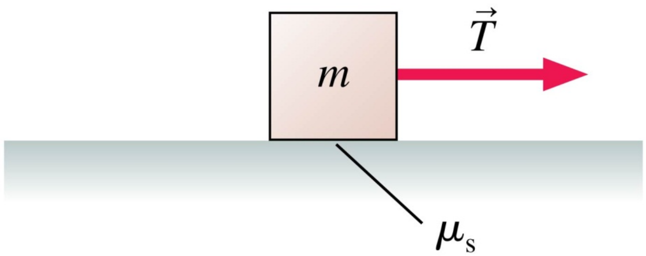
C. $f_s < T$

D. $f_s = \mu_s mg$

E. $f_s = 0$

What can we say about the static friction?

A box on a rough surface is pulled by a horizontal rope with tension T. The box is not moving. In this situation,



A. $f_s > T$

✔ **B. $\boldsymbol{f_s = T}$** Newton's first law.

C. $f_s < T$

D. $f_s = \mu_s mg$

E. $f_s = 0$

Static Friction

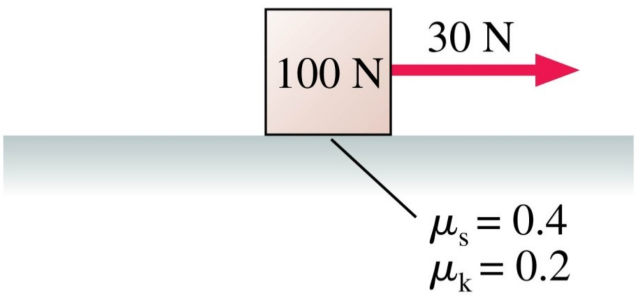
- Static friction force has a *maximum* possible size $f_{\text{s max}}$.
- An object remains at rest as long as $f_{\text{s}} < f_{\text{s max}}$.
- The object just begins to slip when $f_{\text{s}} = f_{\text{s max}}$.
- A static friction force $f_{\text{s}} > f_{\text{s max}}$ is not physically possible:

$$f_{\text{s max}} = \mu_{\text{s}} n$$

where the proportionality constant μ_{s} is called the **coefficient of static friction**.

A box with a weight of $100\ \mathrm{N}$ is at rest. It is then pulled by a $30\ \mathrm{N}$ horizontal force.

Does the box move?

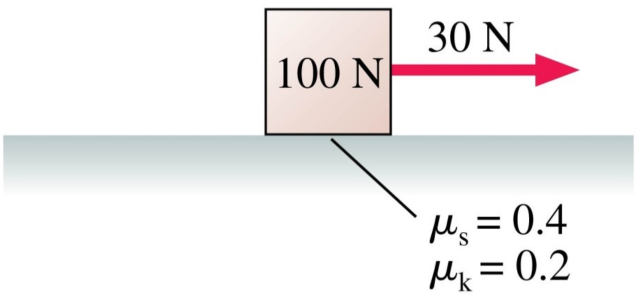


A. Yes

B. No

C. Not enough information to say.

A box with a weight of 100 N is at rest. It is then pulled by a 30 N horizontal force.



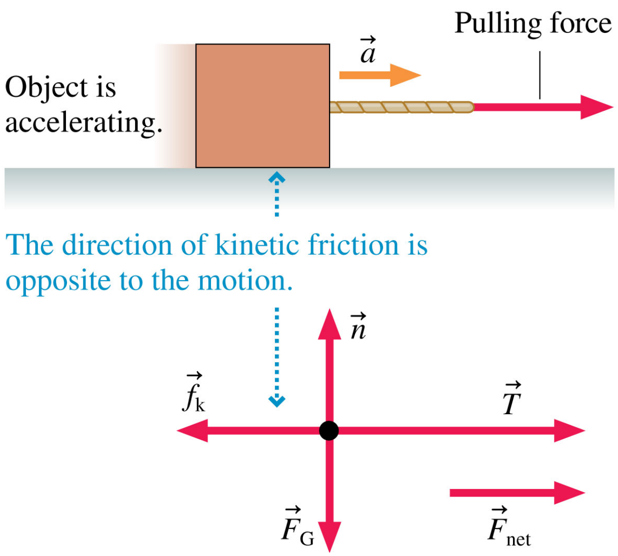
Does the box move?

A. Yes

✔ **B. No** $30 \text{ N} < f_{s\ max} = 40 \text{ N}$

C. Not enough information to say.

Kinetic Friction



Is the kinetic friction *variable*?

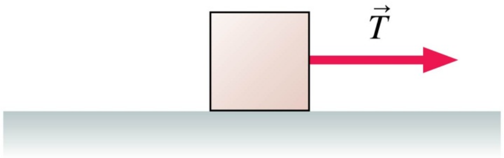
- The **kinetic friction** force is proportional to the magnitude of the normal force:

$$f_k = \mu_k n$$

where the proportionality constant μ_k is called the **coefficient of kinetic friction.**

- The kinetic friction direction is opposite to the velocity of the object relative to the surface.
- For any particular pair of surfaces, $\mu_k < \mu_s$.

A box is being pulled to the right over a rough surface. $T > f_k$, so the box is speeding up. Suddenly the rope breaks.



What happens? The box

A. Stops immediately.

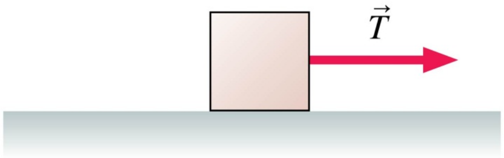
B. Continues with the speed it had when the rope broke.

C. Continues speeding up for a short while, then slows and stops.

D. Keeps its speed for a short while, then slows and stops.

E. Slows steadily until it stops.

A box is being pulled to the right over a rough surface. $T > f_k$, so the box is speeding up. Suddenly the rope breaks.



What happens? The box

1st law?

A. Stops immediately.

Without friction

B. Continues with the speed it had when the rope broke.

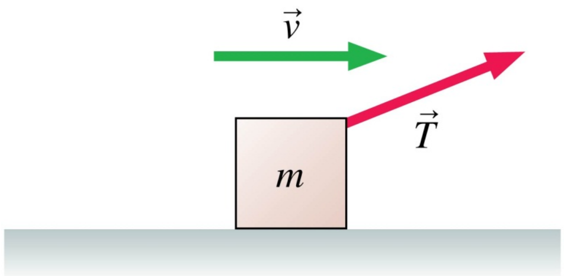
C. Continues speeding up for a short while, then slows and stops.

What?

D. Keeps its speed for a short while, then slows and stops.

✔ **E. Slows steadily until it stops.**

A box is being pulled to the right at steady speed by a rope that angles upward. In this situation:



What can we say about the normal force?

A. $n > mg$

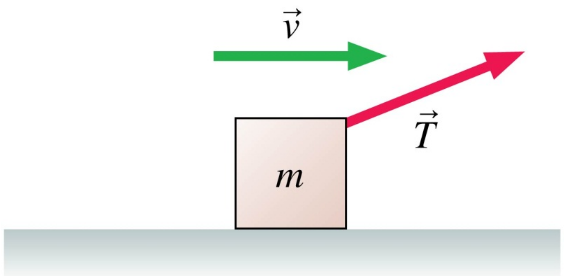
B. $n = mg$

C. $n < mg$

D. $n = 0$

E. Not enough information to judge the size of the normal force.

A box is being pulled to the right at steady speed by a rope that angles upward. In this situation:



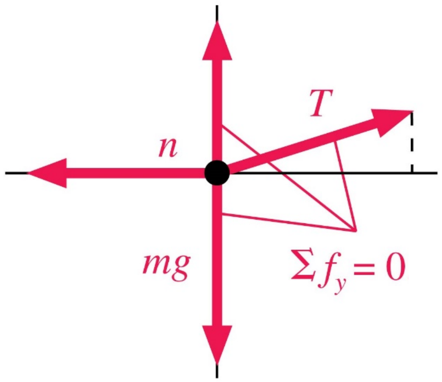
A. $n > mg$

B. $n = mg$

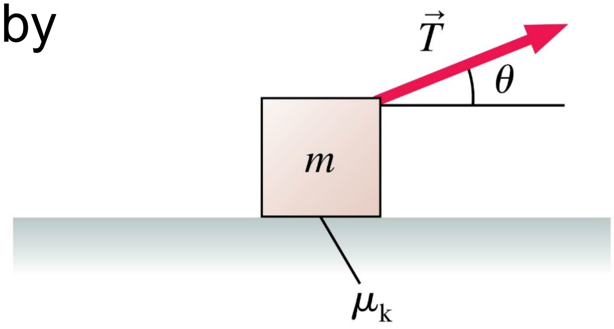
✔ **C. $\boldsymbol{n < mg}$**

D. $n = 0$

E. Not enough information to judge the size of the normal force.



A box is being pulled to the right by a rope that angles upward. It is accelerating. Its acceleration is



A. $\dfrac{T}{m}(\cos\theta + \mu_k \sin\theta) - \mu_k g$

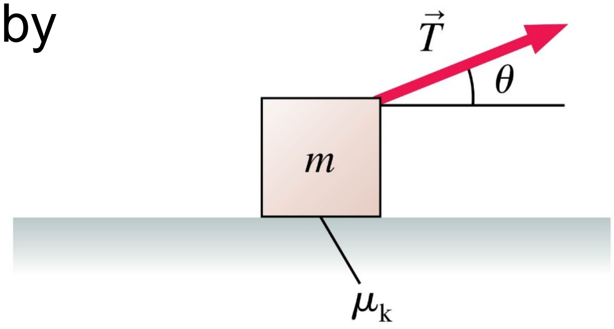
B. $\dfrac{T}{m}(\cos\theta - \mu_k \sin\theta) - \mu_k g$

C. $\dfrac{T}{m}(\sin\theta + \mu_k \cos\theta) - \mu_k g$

D. $\dfrac{T}{m} - \mu_k g$

E. $\dfrac{T}{m}\cos\theta - \mu_k g$

A box is being pulled to the right by a rope that angles upward. It is accelerating. Its acceleration is



✔ **A.** $\boldsymbol{\frac{T}{m}(\cos\theta + \mu_k \sin\theta) - \mu_k g}$

B. $\frac{T}{m}(\cos\theta - \mu_k \sin\theta) - \mu_k g$

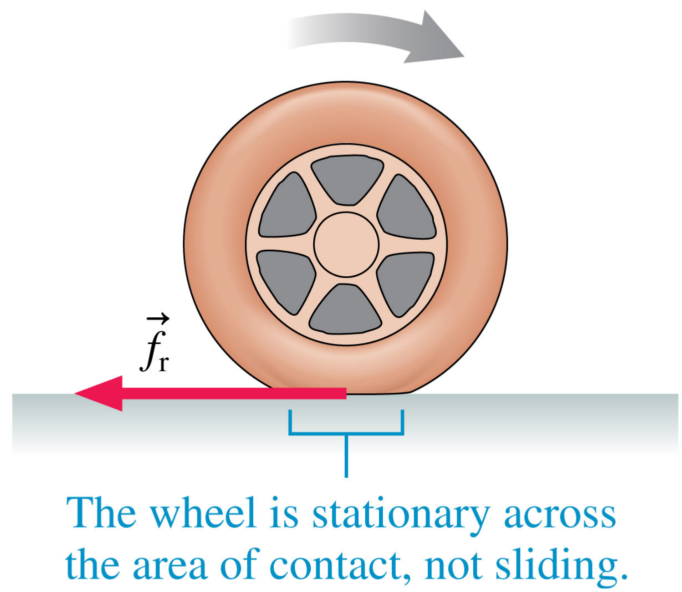
C. $\frac{T}{m}(\sin\theta + \mu_k \cos\theta) - \mu_k g$

D. $\frac{T}{m} - \mu_k g$

E. $\frac{T}{m}\cos\theta - \mu_k g$

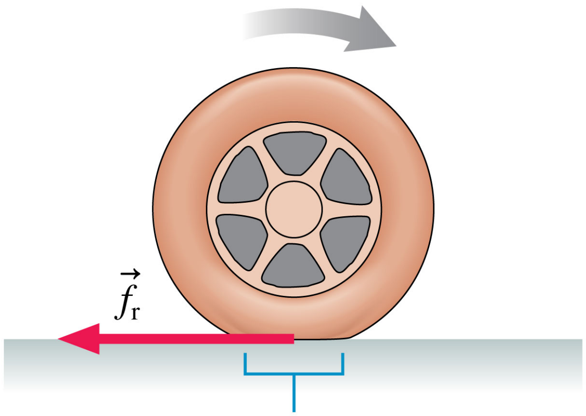
Rolling Motion

- If you slam on the brakes hard enough, your car tires slide against the road surface and leave skid marks. This is kinetic friction.
- A wheel *rolling* on a surface also experiences friction, but not kinetic friction.



- The portion of the wheel that contacts the surface is stationary with respect to the surface, not sliding.
- The interaction of this contact area with the surface causes **rolling friction**.

Rolling Friction



- A car with no engine or brakes applied does not roll forever; it gradually slows down.
- This is due to **rolling friction**.

- The force of rolling friction can be calculated as

$$f_r = \mu_r n$$

where μ_r is called the coefficient of rolling friction.

- The rolling friction direction is opposite to the velocity of the rolling object relative to the surface.

Coefficients of Friction

TABLE 6.1 Coefficients of friction

Materials	Static μ_s	Kinetic μ_k	Rolling μ_r
Rubber on dry concrete	1.00	0.80	0.02
Rubber on wet concrete	0.30	0.25	0.02
Steel on steel (dry)	0.80	0.60	0.002
Steel on steel (lubricated)	0.10	0.05	
Wood on wood	0.50	0.20	
Wood on snow	0.12	0.06	
Ice on ice	0.10	0.03	

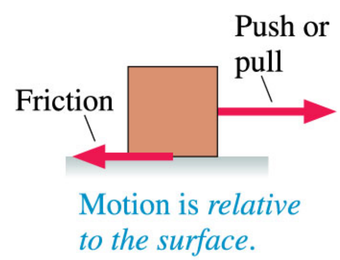
A Model of Friction

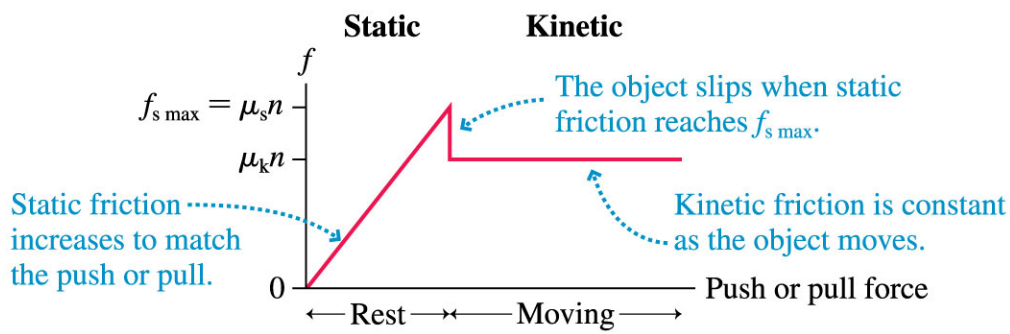
MODEL 6.3

Friction

The friction force is *parallel* to the surface.

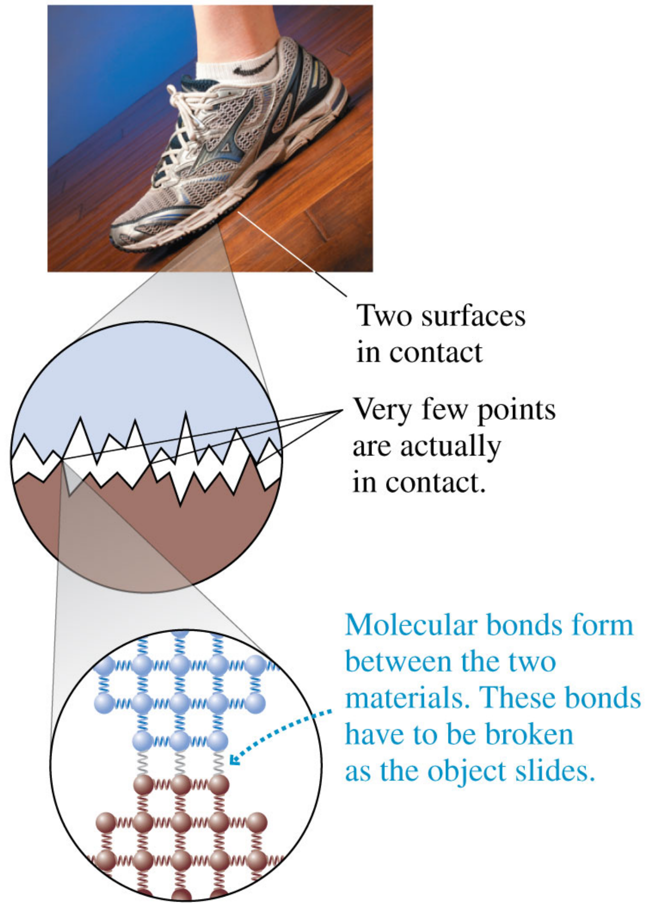
- Static friction: Acts as needed to prevent motion. Can have *any* magnitude up to $f_{s\,max} = \mu_s n$.
- Kinetic friction: Opposes motion with $f_k = \mu_k n$.
- Rolling friction: Opposes motion with $f_r = \mu_r n$.
- Graphically:





Causes of Friction

- All surfaces are very rough on a microscopic scale.
- When two surfaces are pressed together, the high points on each side come into contact and form molecular bonds.
- The amount of contact depends on the normal force *n*.
- When the two surfaces are sliding against each other, the bonds don't form fully, but they do tend to slow the motion.



Drag

- The air exerts a drag force on objects as they move through the air.
- Faster objects experience a greater drag force than slower objects.
- The drag force on a high-speed motorcyclist is significant.
- The drag force direction is opposite the object's velocity.

Birds

Drag

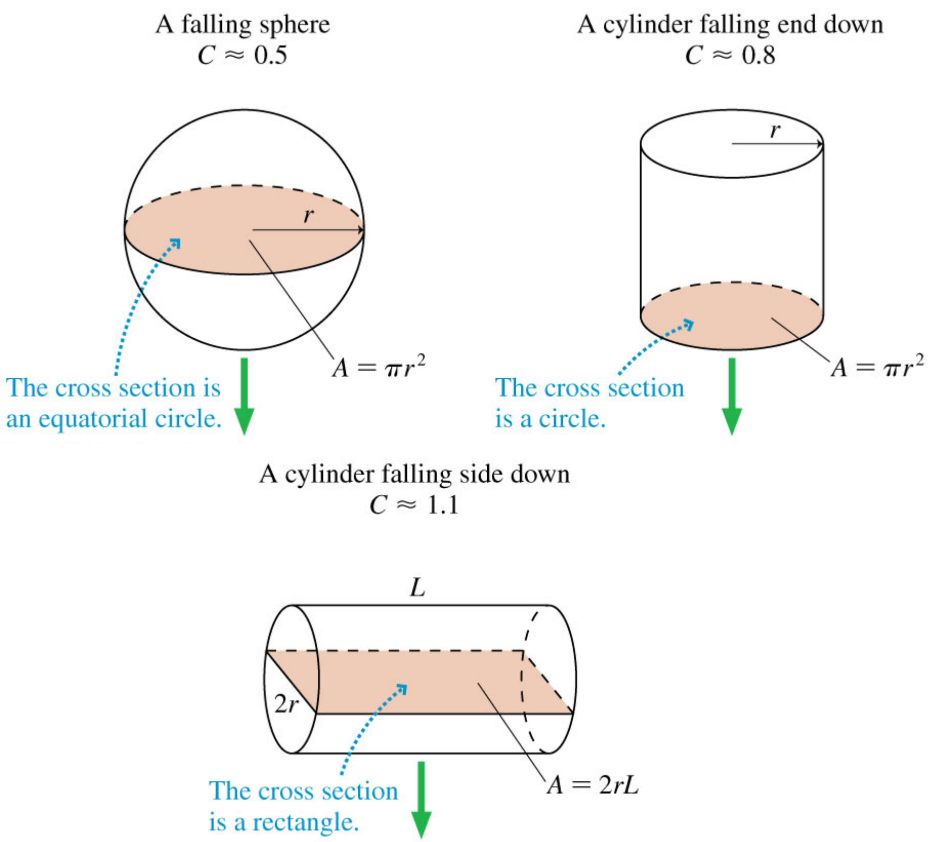
- For normal-sized objects on earth traveling at a speed v which is less than a few hundred meters per second, air resistance can be modeled as

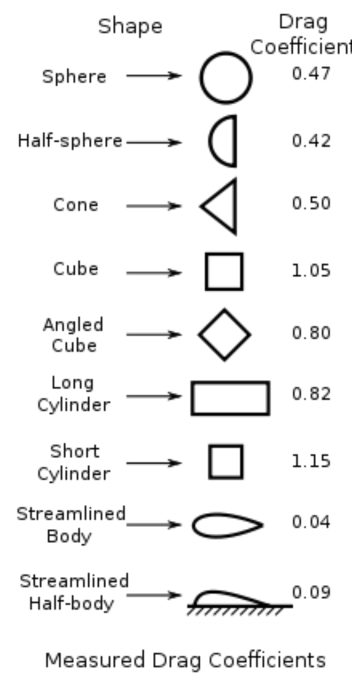
$$\vec{F}_{\text{drag}} = \left(\tfrac{1}{2}C\rho A v^2, \text{ direction opposite the motion}\right)$$

- A is the *cross-section area* of the object.
- ρ is the density of the air, which is $1.3\ \mathrm{kg/m^3}$, at atmospheric pressure and $0^{\circ}\mathrm{C}$, a common reference point of pressure and temperature.
- C is the **drag coefficient**, which is a dimensionless number that depends on the shape of the object.

Drag

- Cross-section areas for objects of different shape.





[Ferrari]