Chapter 4

Forces and Newton's Laws of Motion

Prof. Bromberg will miss Wed. Office hrs. Please email for appt. on Thurs-Fri

4.1 The Concepts of Force and Mass

A ***force*** is a push or a pull acting on an object. A force is a vector!

Contact forces arise from physical contact, and are due to a stretch or compression at the point of contact.

Action-at-a-distance forces do not require contact and include gravity and forces due to charged particles

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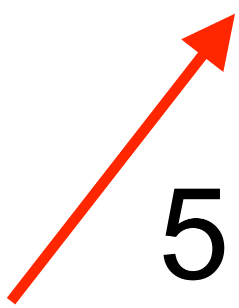
4.1 *The Concepts of Force and Mass*

Arrows are used to represent force vectors.
The length of the arrow is proportional
to the magnitude of the force.

15 N = fifteen newtons



5 N

force

5 N ~ 1 lb

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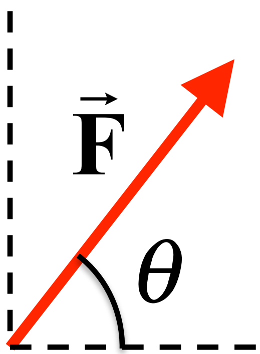
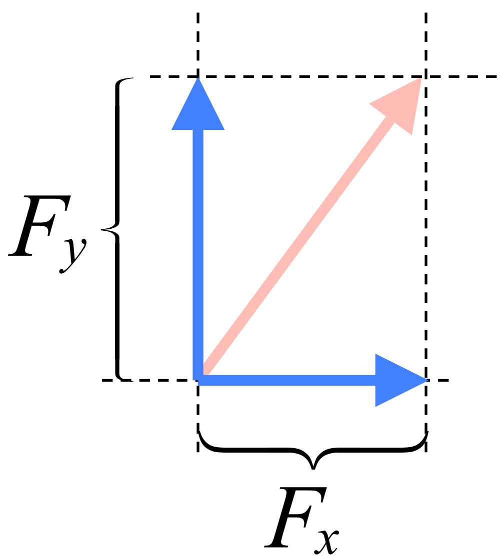
4.1 The Concepts of Force and Mass

Bold letter with arrow is the symbol, $\vec{\mathbf{F}}$, for a force vector: has magnitude and direction.

Direction is given as an angle, θ, or coded in components, F_x, F_y.



$$F = |\vec{\mathbf{F}}|$$



$$\boxed{\begin{aligned} F_x &= F\cos\theta \\ F_y &= F\sin\theta \end{aligned}}$$

$$\boxed{\begin{aligned} \theta &= \tan^{-1}(F_y / F_x) \\ F &= \sqrt{F_x^2 + F_y^2} \end{aligned}}$$

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4.1 *The Concepts of Force and Mass*

Mass **of an object is a measure of the number and type of atoms within the object.**

Mass **can be measured without resorting to gravity/weight.**

A spring will oscillate a mass with an oscillation period,

$$T \propto \sqrt{m}. \qquad (\propto \text{ means proportional to})$$

If the period is twice as long, the mass is 4 times bigger.

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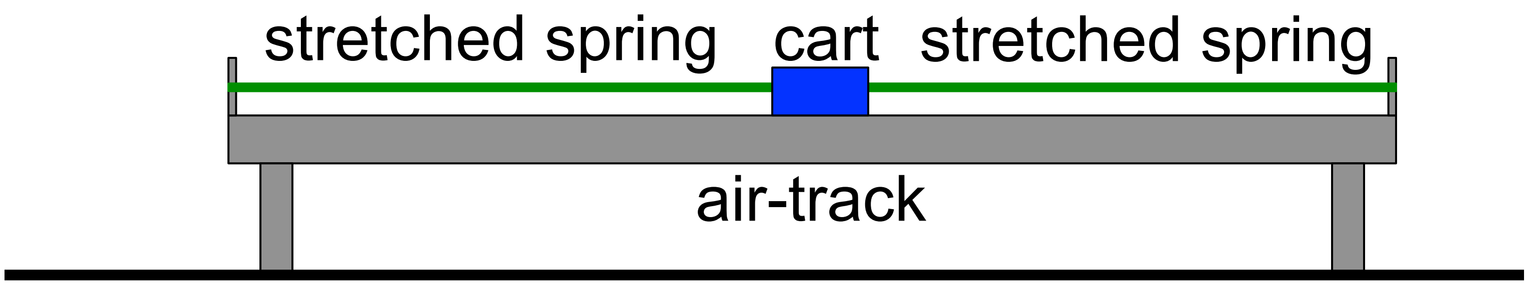
Device to measure a mass anywhere in the universe



a planet or moon
or a big spaceship (air-track unnecessary)

These springs can be taken anywhere in the universe and used to measure the mass of any cart. Also, the stretching of these springs can be used to define the unit of force.

SI Unit of Mass: kilogram (kg)

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Newton's First Law

An object continues in a state of rest or in a state of motion at a constant speed *along a straight line*, unless compelled to change that state by a net force.

The *net force* is the vector sum of all of the forces acting on an object.

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Net Force acting on ONE object

Mathematically, the net force is written as

$$\sum_{i=1}^{N} \vec{\mathbf{F}}_i = \vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 + \vec{\mathbf{F}}_3 + \cdots + \vec{\mathbf{F}}_N$$

where the Greek letter sigma denotes the vector sum of all forces acting on an object.

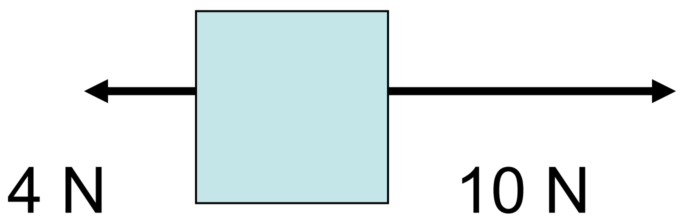
ONE object!

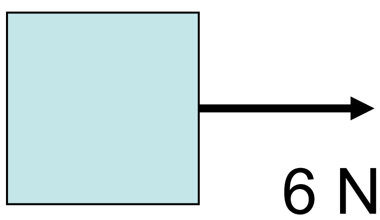
4.2 Newton’s Laws of Motion (First Law)

The net force on an object is the vector sum of all forces acting on that object.

The SI unit of force is the Newton (N).

Individual Forces   Top views   Net Force





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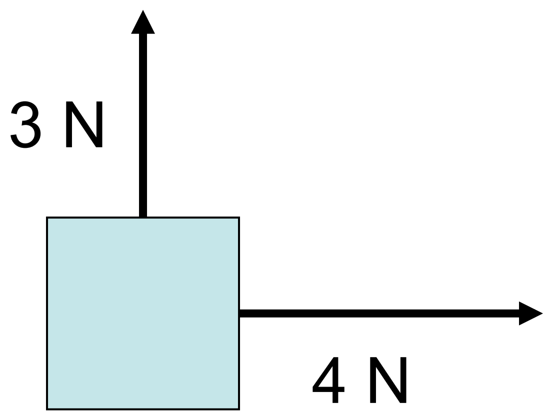
4.2 Newton's Laws of Motion (First Law)

Individual Forces

Top view

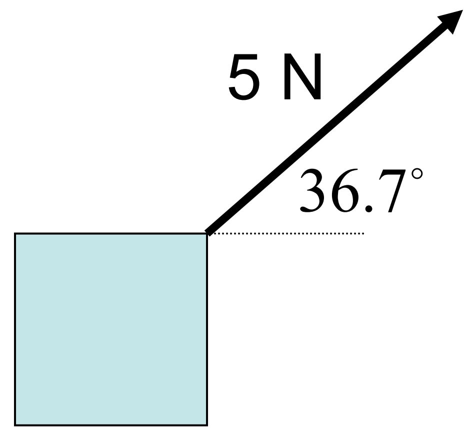


No friction

No Gravity

Net Force

Top view



θ is an angle with respect to x-axis

$$\tan\theta = \frac{F_y}{F_x} \quad \Rightarrow \quad \theta = \tan^{-1}\left(\frac{F_y}{F_x}\right)$$

$$\theta = \tan^{-1}\left(\frac{3}{4}\right) = 36.7^\circ$$

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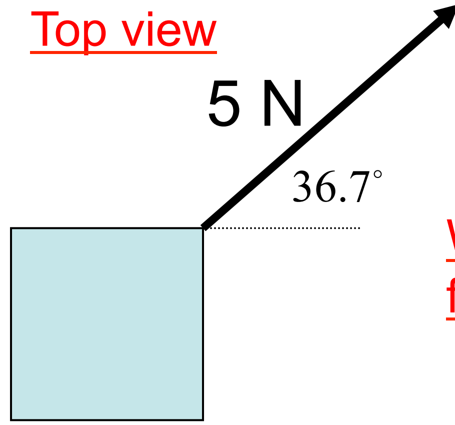
4.2 Newton's Laws of Motion (First Law)

Net Force

Top view

No friction

No Gravity

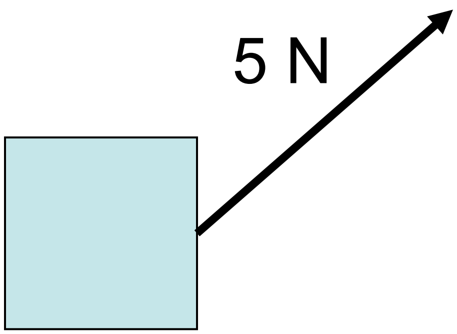


You will see this
in most textbooks.

Why does the picture show the force vector attached to a corner ?

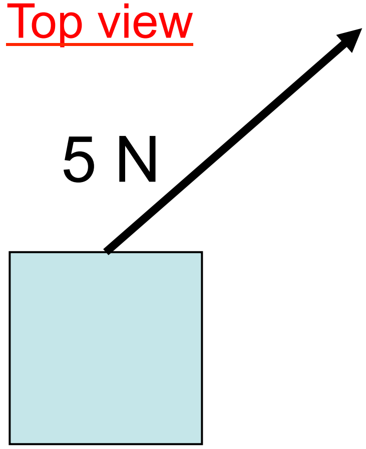
Why not

Top view



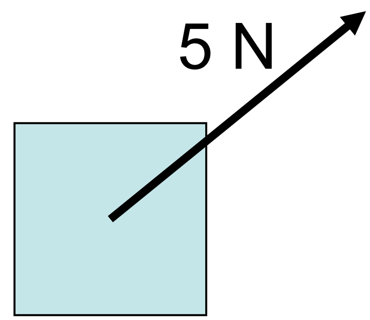
or this

Top view



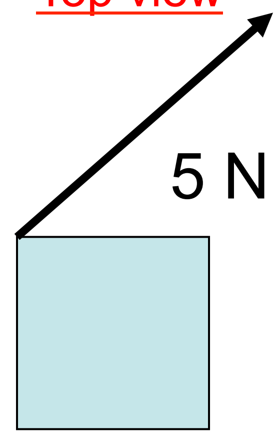
or this

Top view



or this

Top view



Best would be this,
attached to the center of object.

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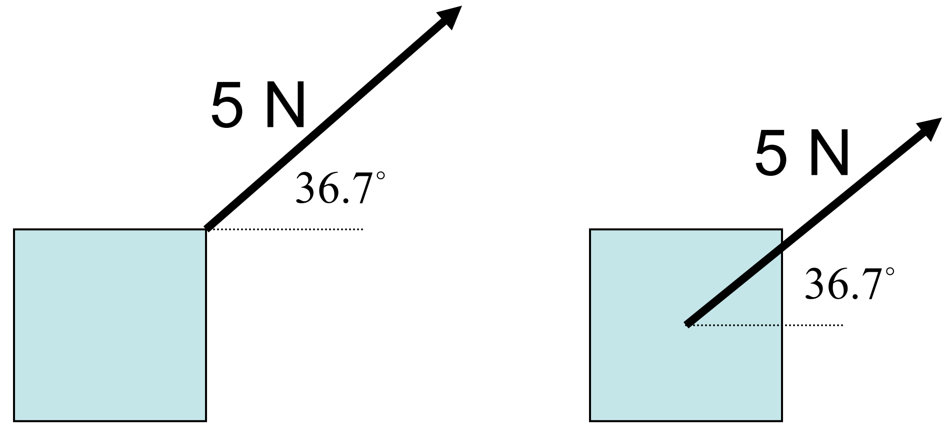
4.2 Newton's Laws of Motion (First Law)

No friction

No Gravity

Top view



Both drawings lead to the same linear motion of the object

The object will not maintain a constant $\underbrace{\text{speed \& direction}}_{\text{velocity}}$.

The object will accelerate in this direction: $\vec{\mathbf{a}}$

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4.2 Newton's Laws of Motion (First Law)

Newton's 1st law: for an object to remain at rest, or move with constant speed & direction, the Net Force acting on it must be ZERO.

So

Newton's 1st law: if the Net Force acting on a object is NOT ZERO, the velocity (magnitude, or direction, or both) must change.

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4.2 Newton's Laws of Motion (First Law)

Newton's 1st law is often called the law of inertia.

Inertia is the natural tendency of an object to remain at rest or in motion at a constant speed along a straight line.

The *mass* of an object is a quantitative measure of inertia.

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4.2 Newton’s Laws of Motion (First Law)

An *inertial reference frame* is one in which Newton’s law of inertia is valid.

All accelerating reference frames are non-inertial.

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4.2 *Newton's Laws of Motion (First Law)*

Warning:

Newton's 1st law can appear to be violated if you don't recognize the existence of contact forces.

Newton's 1st law: for an object to *remain at rest*, or *move with constant speed & direction*, the Net Force acting on it <u>must be</u> ZERO.

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4.2 Newton's Laws of Motion (First Law)

Examples (4 clicker questions):

A mass hanging from a string.

A mass at rest on a table.

A mass at rest on a ramp.

A mass sliding on a table.

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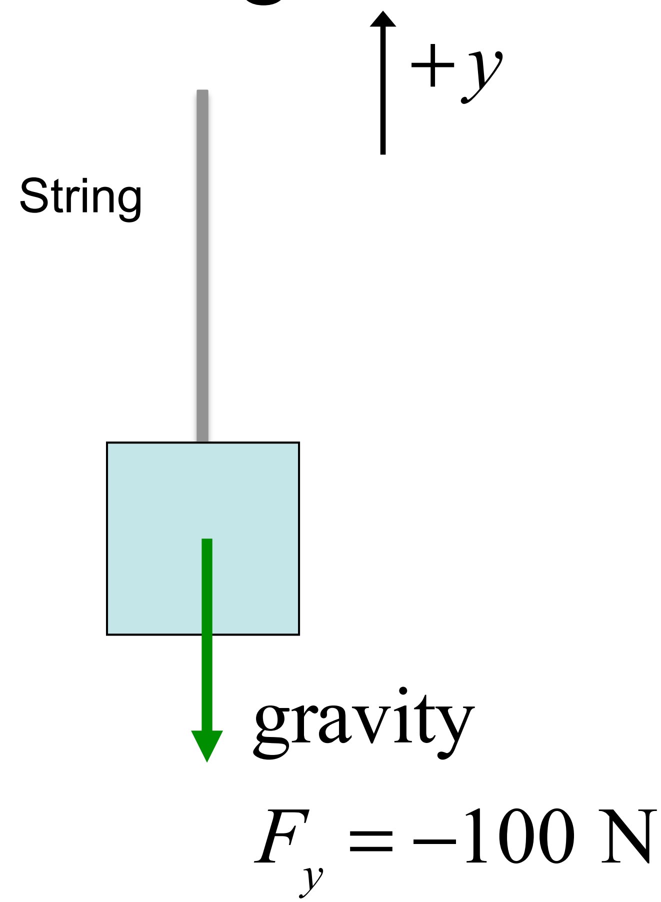
Clicker Question 4.1

A mass hanging from a string.

Gravity applies a 100 N gravitational force to the object. What force component does the string apply to the object?



a) string $F_y = -100$ N

b) string $F_y = +100$ N

c) string $F_y = \;\; 0$ N

d) string $F_y = \;\; 1$ N

e) A string can't make a force

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Clicker Question 4.2

A mass resting on a table.

At rest: Net force must be zero

Gravity applies a 100 N gravitational force to the object. What force does the table apply to the object?

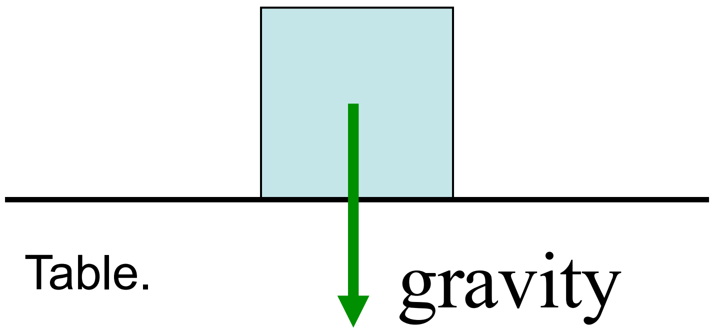
a) table $F_y = -100\ \mathrm{N}$

b) table $F_y = +100\ \mathrm{N}$

c) table $F_y = \ \ 0\ \mathrm{N}$

d) table $F_y = \ \ 1\ \mathrm{N}$

e) A table can't make a force



$F_y = -100\ \mathrm{N}$

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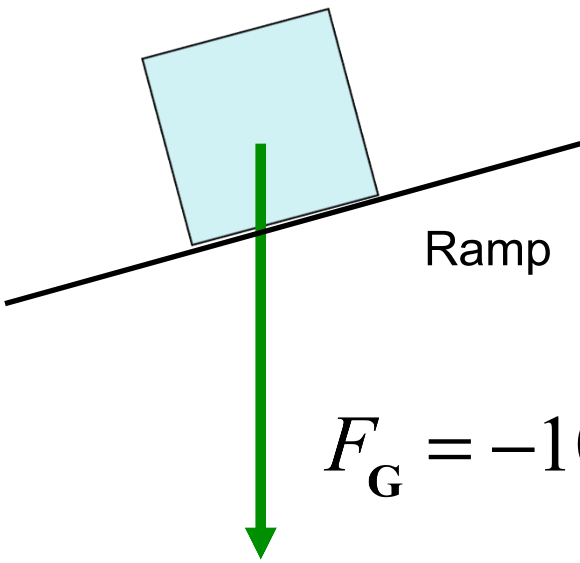
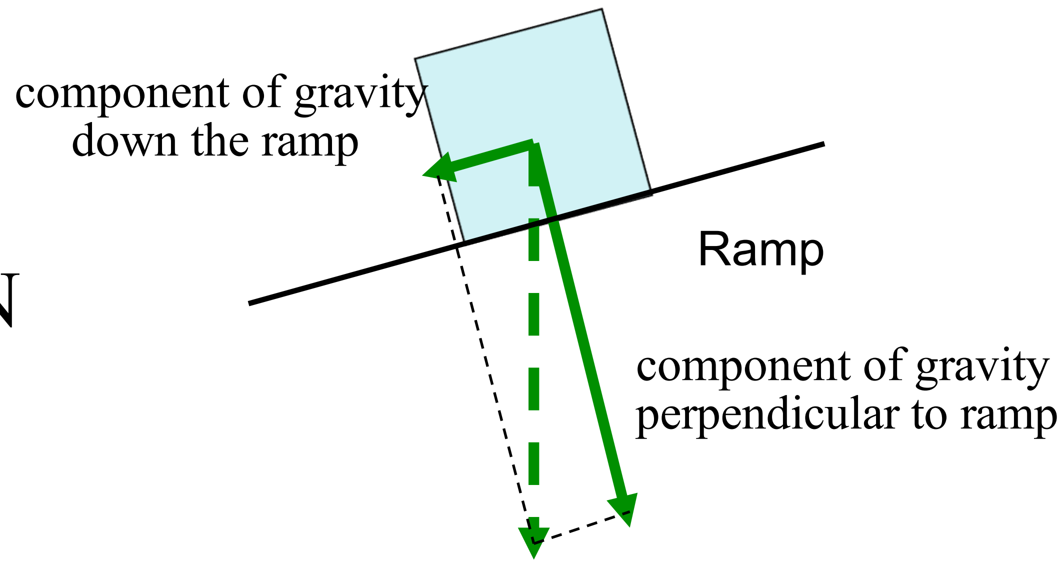
A mass at rest on a ramp.

Gravity applies a 100 N gravitational force to an object at rest on a 15° ramp.



$$F_{\mathbf{G}} = -100 \text{ N}$$

Component of gravity pulls the mass down the the ramp



$$F_{\mathbf{G}} = -100 \text{ N}$$

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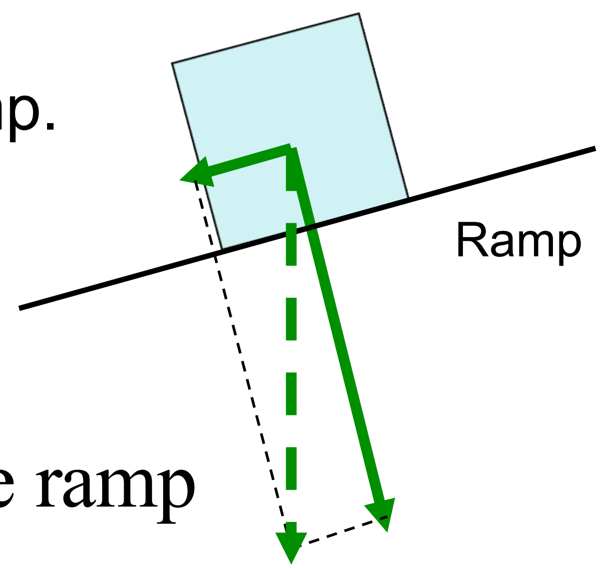
Clicker Question 4.3

A mass at rest on a ramp.

At rest: Net force must be zero

Gravity applies a 100 N gravitational force to an object at rest on a 15° ramp. The friction between ramp and object applies a force on the mass in what direction?



$$F_G = -100\ \text{N}$$

a) Frictional force > 100 N, up the ramp

b) Frictional force = 100 N, up the ramp

c) Frictional force = 100 N, down the ramp

d) Frictional force < 100 N, up the ramp

e) A ramp can't make a force

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Clicker Question 4.4

A mass sliding on a table.

Gravity applies a force to a mass.
It is sliding on a table with an initial velocity of +1 m/s. It slows while sliding to +0.5 m/s. To slow it the friction between them applies a force to the mass in what direction?

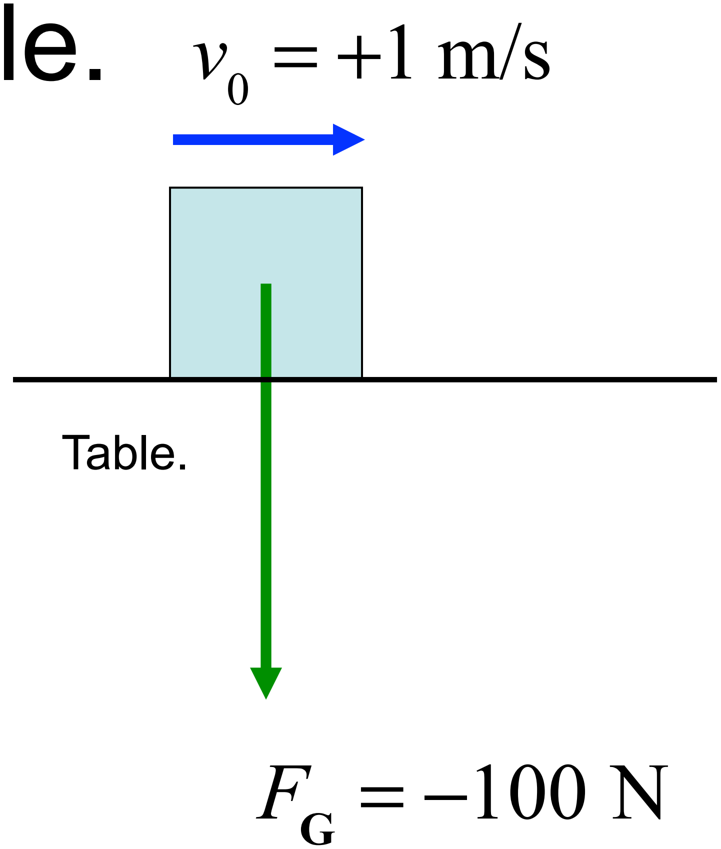
a) Upward

b) Downward

c) To the right (+)

d) To the left (–)

e) A table can't make a force.



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Newton’s Second Law

When a net external force acts on an object of mass *m*, the acceleration that results is directly proportional to the net force and has a magnitude that is inversely proportional to the mass. The direction of the acceleration is the same as the direction of the net force.

$$\vec{\mathbf{a}} = \frac{\sum \vec{\mathbf{F}}}{m} \qquad \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

Sum of forces acting on 1 object

SI Unit for Force

$$(\mathrm{kg})\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right) = \frac{\mathrm{kg}\cdot\mathrm{m}}{\mathrm{s}^2}$$

Note: it has the same units as ma.

This combination of units is called a *newton* (N).

$$1\,\mathrm{kg}\cdot\mathrm{m/s}^2 = 1\,\mathrm{N}$$

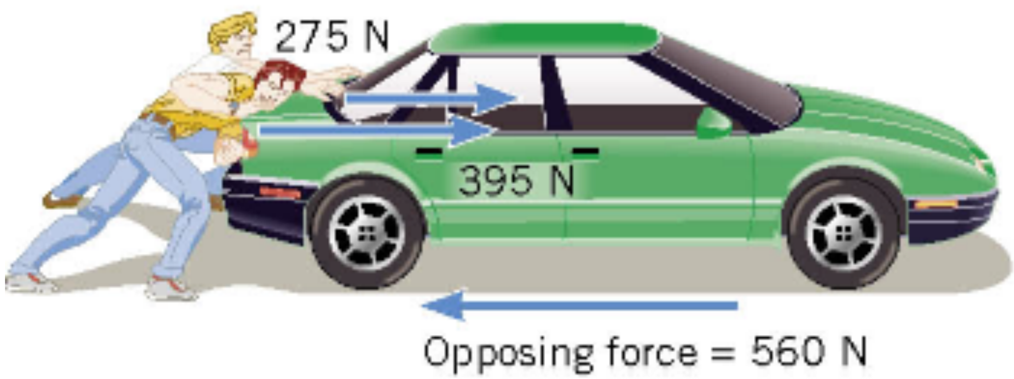
4.2 Newton's Laws of Motion (Second Law)

Table 4.1 Units for Mass, Acceleration, and Force

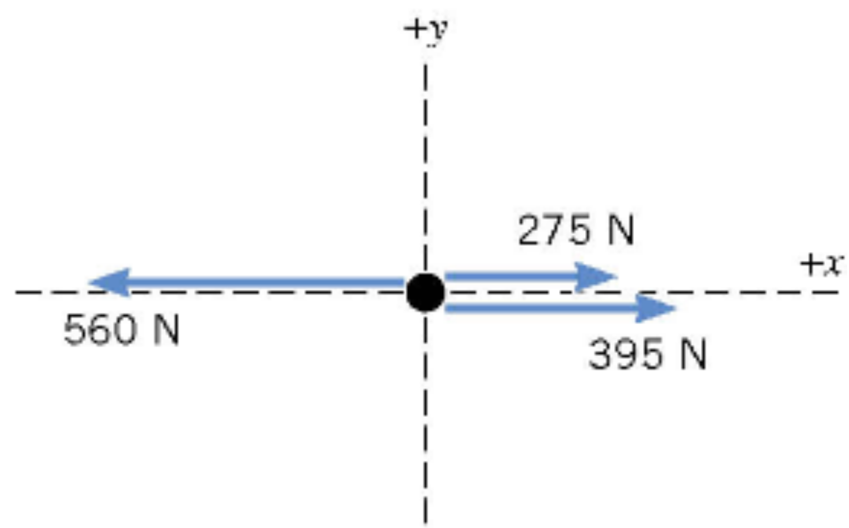
System	Mass	Acceleration	Force
SI	kilogram (kg)	meter/second^2 (m/s^2)	newton (N)
CGS	gram (g)	centimeter/second^2 (cm/s^2)	dyne (dyn)
BE	slug (sl)	foot/second^2 (ft/s^2)	pound (lb)

$\sim 5\,\mathrm{N} = 1\,\mathrm{lb}$

A ***free-body-diagram*** is a diagram that represents the object and the forces that act on it.

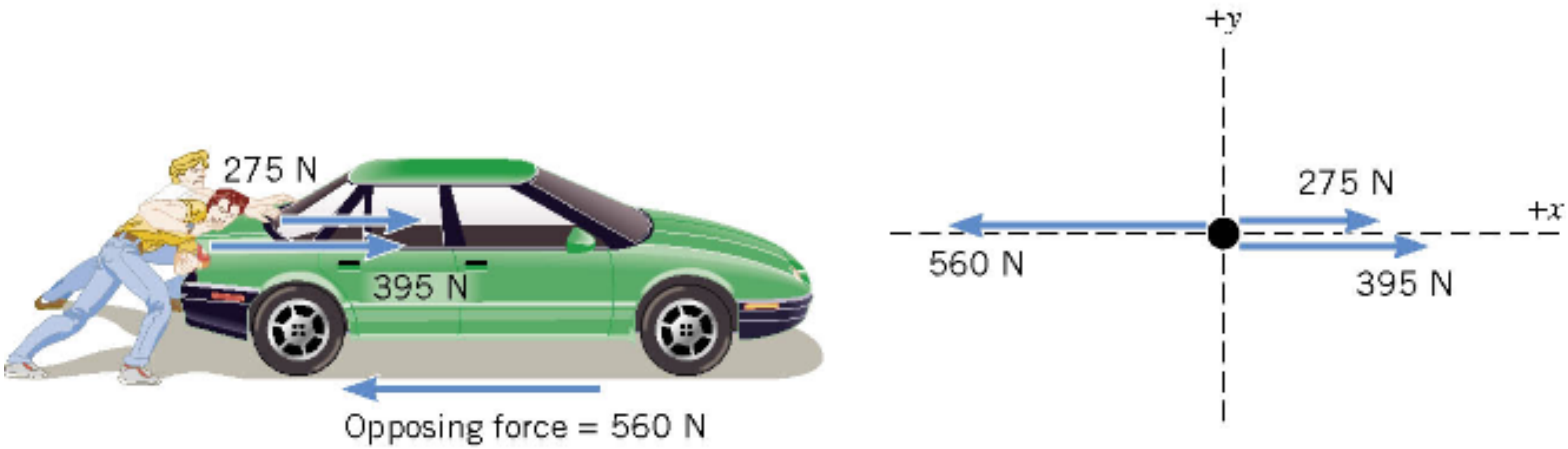


(*a*)



(*b*) Free-body diagram of the car

4.2 Newton's Laws of Motion (Second Law)



(a) (b) Free-body diagram of the car

The net force in this case is:

275 N + 395 N – 560 N = +110 N

and is directed along the + x axis of the coordinate system.

If the mass of the car is 1850 kg then, by Newton's second law, the acceleration is

$$a = \frac{\sum F}{m} = \frac{+110\,\mathrm{N}}{1850\,\mathrm{kg}} = +0.059\,\mathrm{m/s^2}$$

Clicker Question 4.5

With the acceleration just calculated $a = 0.059\ \mathrm{m/s^2}$ and starting at rest, how far has the car gone after 10s of pushing?

a) $0.059\ \mathrm{m}$

b) $10\ \mathrm{m}$

c) $0.59\ \mathrm{m}$

d) $3.0\ \mathrm{m}$

e) $0.3\ \mathrm{m}$

The direction of force and acceleration vectors can be taken into account by using *x* and *y* components.

$$\sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

is equivalent to

$$\sum F_x = ma_x \quad \& \quad \sum F_y = ma_y$$

Net Force in x-direction
= *m* times *a* in x-direction

AND

Net Force in y-direction
= *m* times *a* in y-direction

4.2 ***Newton's Laws of Motion (Second Law)***

How to use Newton's 2nd law, $\sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$ one object

A) If mass of the object is known, *and* all forces acting on the object are known, then the acceleration vector can be calculated.

B) If the acceleration vector and mass of an object are known, then the Net Force acting on the object can be calculated. It may surprise you!

C) If the acceleration vector and mass of an object are known, but the calculated Net Force and the identified forces disagree, at least one additional force must act on the object. Find it!

4.2 Newton's Laws of Motion (Second Law)

A) If mass of the object is known, *and* all forces acting on the object are known, then the acceleration vector can be calculated.

$$\Downarrow$$

Once the Net Force acting on an object and Newton's 2nd law are used to calculate the object's acceleration vector, future changes of the position and velocity can be predicted.

$$a_x = \frac{\sum F_x}{m} \qquad a_y = \frac{\sum F_y}{m}$$

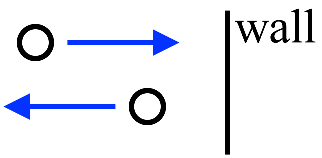
one object

B) If the acceleration vector and mass of an object are known, then the Net Force acting on the object can be calculated.

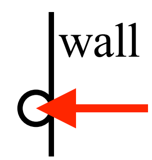
A paddle ball travelling horizontally bounces off a wall. The *speed* of the ball was 30 m/s before and after hitting the wall. If contact with the wall was for 0.02 s, what was the ball's acceleration during the contact?

$v_0 = +30\,\mathrm{m/s}$

$v = -30\,\mathrm{m/s}$



If the paddle ball has a mass of 0.2 kg, what is the force that the wall applied to the ball?

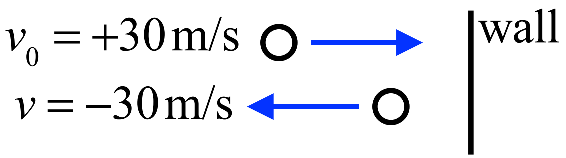


$F = ?$

one object

B) If the acceleration vector and mass of an object are known, then the Net Force acting on the object can be calculated.

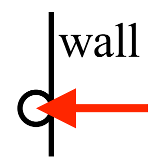
A paddle ball travelling horizontally bounces off a wall. The *speed* of the ball was 30 m/s before and after hitting the wall. If contact with the wall was for 0.02 s, what was the ball's acceleration during the contact?



$$a = \frac{(v - v_0)}{t} = \frac{\left[-30 - (+30)\right]\text{m/s}}{.02\text{ s}} = -3000\text{ m/s}^2$$

If the paddle ball has a mass of 0.2 kg, what is the force that the wall applied to the ball?

$$\begin{aligned} F_x &= ma_x \\ &= (0.2\text{ kg})(-3000\text{ m/s}^2) \\ &= -600\text{ kg-m/s}^2 \text{ or } -600\text{ N} \end{aligned}$$



$$F = -600\,\text{N}$$

Force on ball is to the LEFT

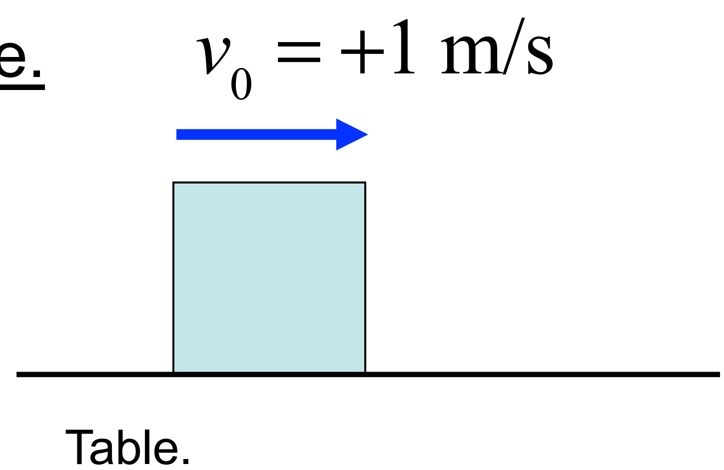
Magnitude of 600 N

(~120 lbs)

C) If the acceleration vector and mass of an object are known, <u>but</u> the calculated Net Force and the identified forces disagree, at least one <u>additional force</u> must act on the object. Likely you will not know the origin of this force, but it must be there.

<u>A mass sliding on a table.</u>

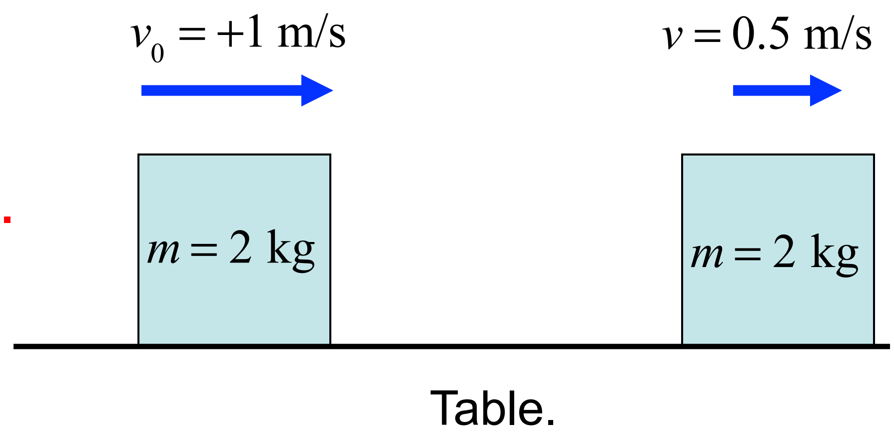
A 2 kg mass slides on a table with an initial velocity of +1 m/s. It slows while sliding to +0.5 m/s, in 2 seconds.



1) Calculate the acceleration vector
2) Use Newton's 2nd law, to calculate the frictional force that must act on the mass.

Clicker Question 4.6

A 2.0 kg mass sliding on a table with an initial velocity of +1.0 m/s, slows to +0.5 m/s, in 2.0 seconds.



A force acting on the mass causes it to lose speed. What is the magnitude and direction of this force?

a) $F = -0.5\,\mathrm{N}$

b) $F = +0.5\,\mathrm{N}$

c) $F = -1.0\,\mathrm{N}$

d) $F = +1.0\,\mathrm{N}$

e) $F = -2.0\,\mathrm{N}$