Chapter 4

Forces and Newton's Laws of Motion

continued

Net Force acting on ONE object

Mathematically, the net force is written as

$$\sum \vec{\mathbf{F}}$$

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

ONE object!

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).

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

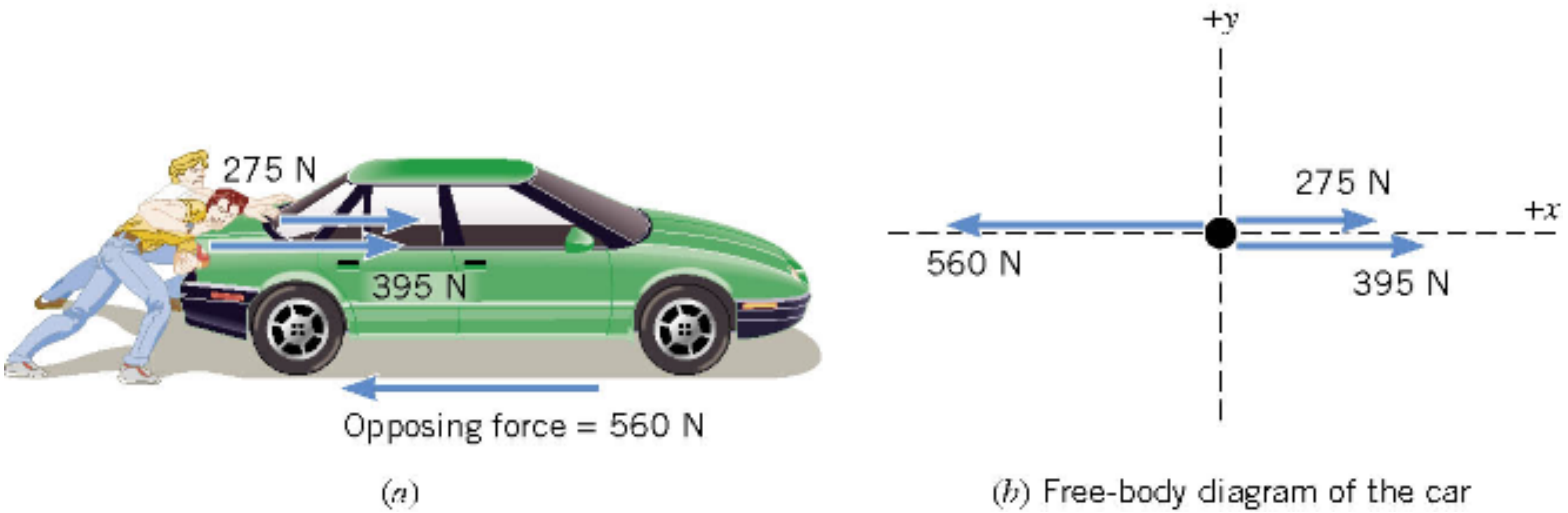
4.3 Newton's Second Law of Motion

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)

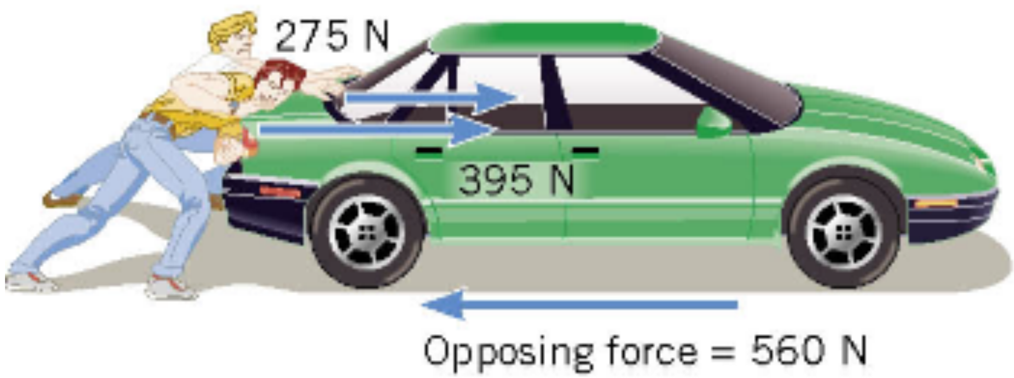
$\sim 5\,\mathrm{N} = 1\,\mathrm{lb}$

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

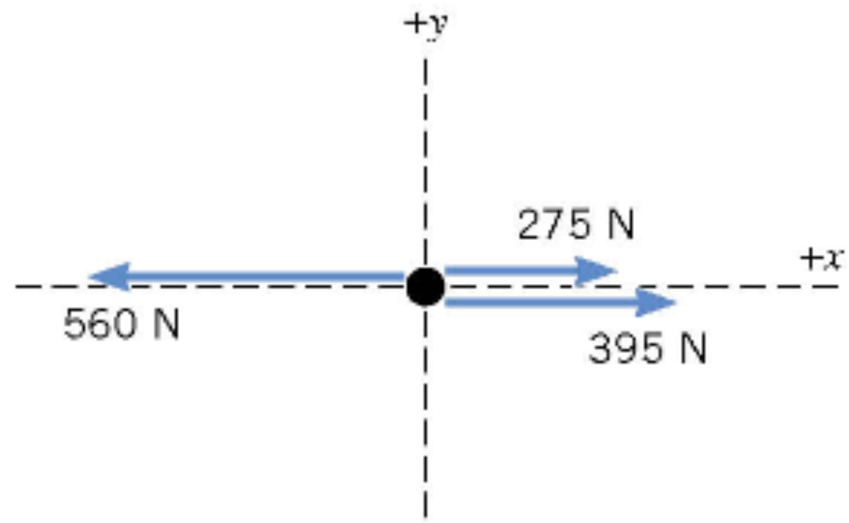


(b) Free-body diagram of the car

4.3 Newton's Second Law of Motion



(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

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

Clicker Question 4.5

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

a) 0.059 m

b) 10 m

c) 0.59 m

d) 3.0 m

e) 0.3 m

Clicker Question 4.5

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

a) $0.059\ \text{m}$

b) $10\ \text{m}$

c) $0.59\ \text{m}$

d) $3.0\ \text{m}$

e) $0.3\ \text{m}$

$$x = v_0 t + \tfrac{1}{2} a t^2$$

$$= 0 + 0.5(0.059\ \text{m/s}^2)(10\ \text{s})^2$$

$$= 3.0\,\text{m}$$

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

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!

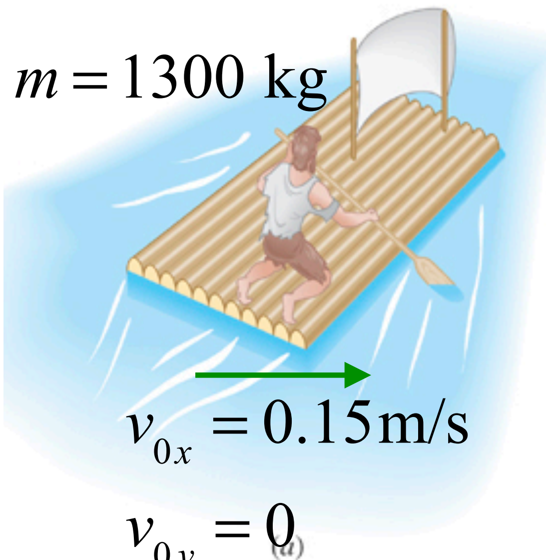
A) If mass of the object is known, *and* all forces acting on the object are known, then the acceleration vector can be calculated.

$\Downarrow$

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.

The ability to predict the future can be very useful.

Drifting Raft



$m = 1300\ \text{kg}$

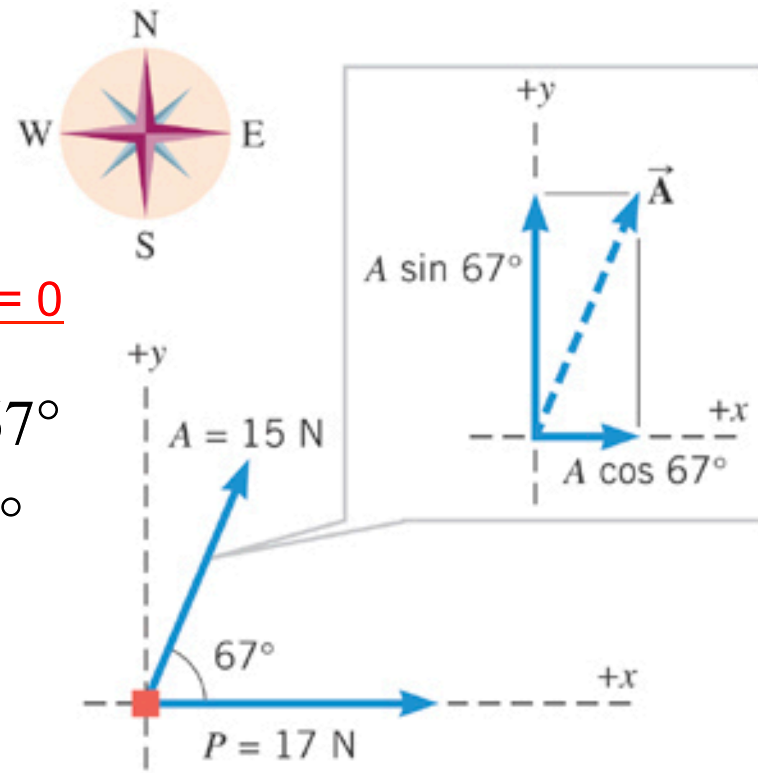
$v_{0x} = 0.15\,\text{m/s}$

$v_{0y} = 0$

Forces start acting at *t* = 0

$\vec{\mathbf{A}}: A = 15\,\text{N}, \theta = 67°$

$\vec{\mathbf{P}}: P = 17\,\text{N}, \theta = 0°$



Free-body diagram of the raft

	x-component	y-component
$\vec{\mathbf{A}}$:	$(15\,\text{N})\cos 67°$	$(15\,\text{N})\sin 67°$
$\vec{\mathbf{P}}$:	$17\,\text{N}$	$0\,\text{N}$

Force components

$\vec{\mathbf{A}} + \vec{\mathbf{P}}$:	$(5.9 + 17)\,\text{N}$	$(14 + 0)\,\text{N}$
	$23\,\text{N}$	$14\,\text{N}$

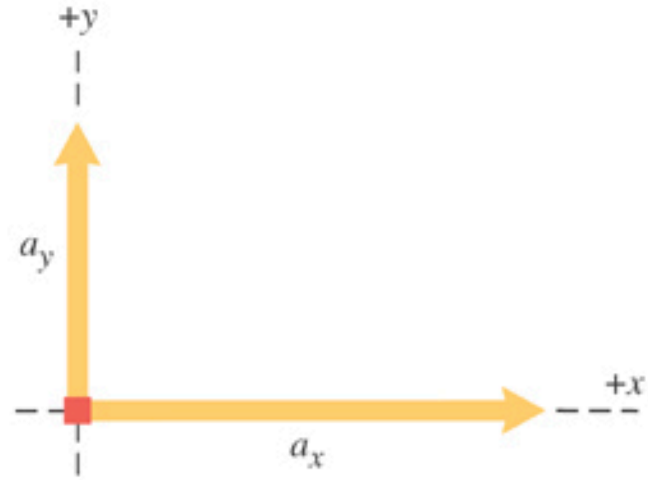
Net Force after *t* = 0

4.4 The Vector Nature of Newton's Second Law

Acceleration after $t = 0$

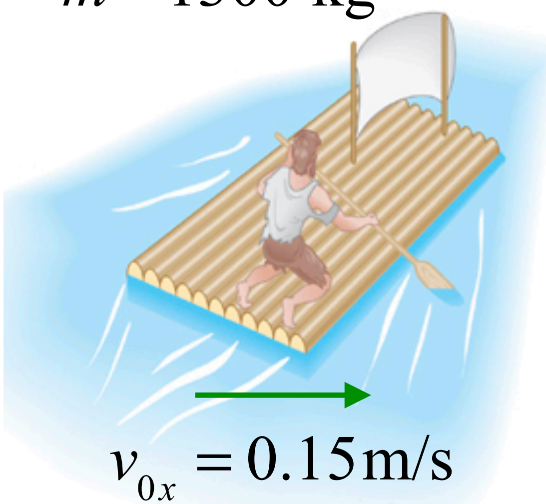
$$a_x = \frac{\sum F_x}{m} = \frac{+23\text{ N}}{1300\text{ kg}} = +0.018\text{ m/s}^2$$

$$a_y = \frac{\sum F_y}{m} = \frac{+14\text{ N}}{1300\text{ kg}} = +0.011\text{ m/s}^2$$



(c)

$m = 1300\text{ kg}$



$v_{0x} = 0.15\text{m/s}$

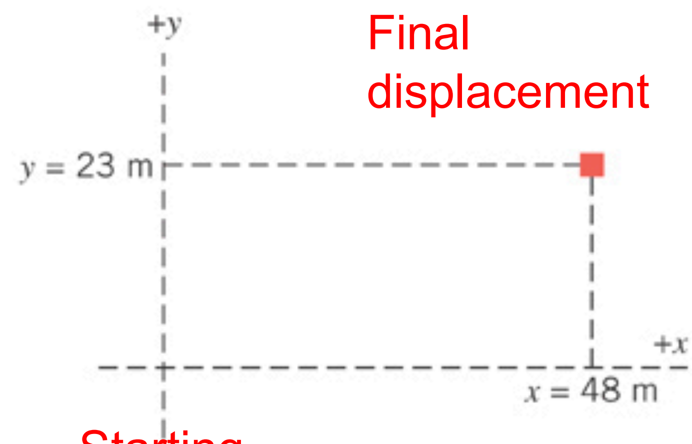
$v_{0y} = 0$

Predict the future:

Displacement at $t = 65$ s

$$x = v_{0x}t + \tfrac{1}{2}a_x t^2 = 48\text{m}$$

$$y = v_{0y}t + \tfrac{1}{2}a_y t^2 = 23\text{m}$$



Final displacement

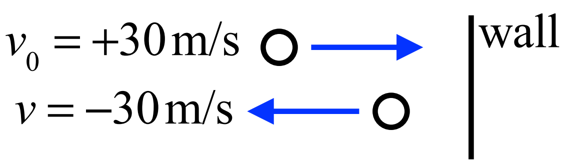
Starting point

(d)

one object

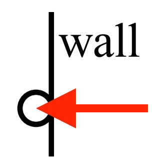
B) If the acceleration vector and mass of an object are known, then the Net Force acting on the object can be calculated.

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?



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

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



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

$$\begin{aligned}(\text{1D vectors})\ F &= ma \\ &= (0.2\ \text{kg})(-3000\ \text{m/s}^2) \\ &= -600\ \text{kg-m/s}^2\ \text{ or }\ -600\ \text{N}\end{aligned}$$

Force on ball is to the LEFT

Magnitude of 600 N

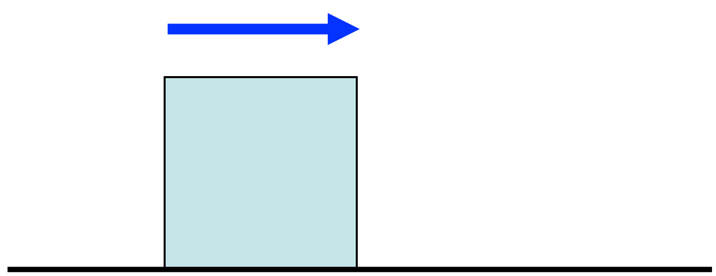
(~120 lbs)

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

A mass sliding on a table.

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.

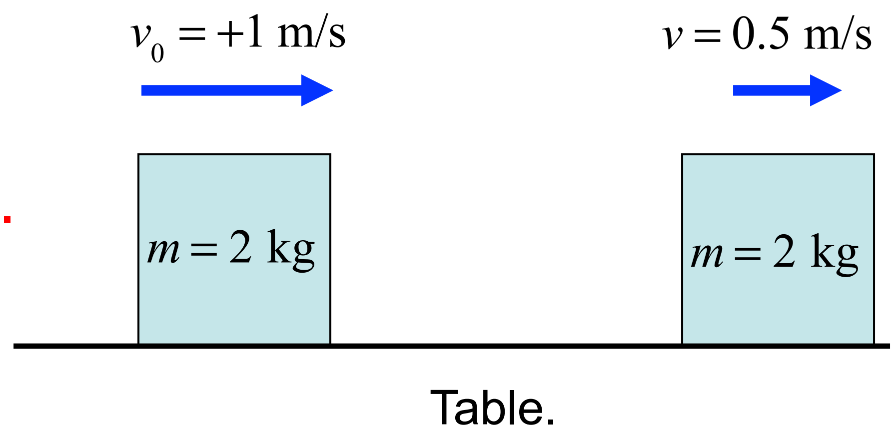
$v_0 = +1 \text{ m/s}$



1) Calculate the acceleration vector
2) Use Newton's 2^{nd} 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) $F = -0.5\,\text{N}$

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

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

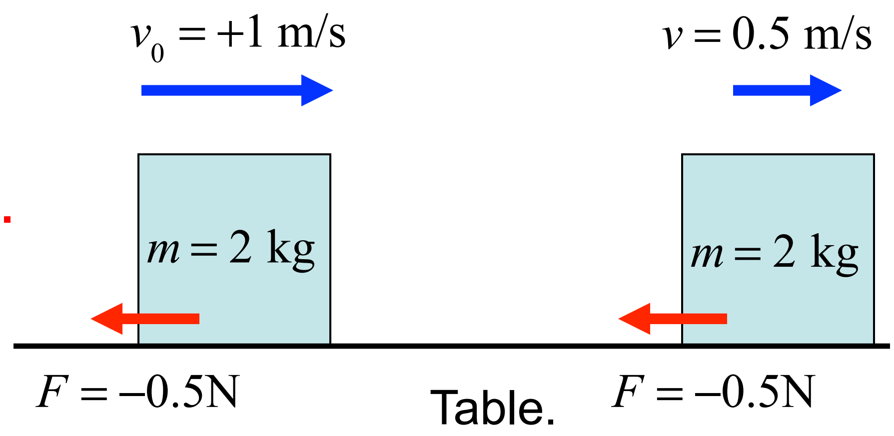
d) $F = +1.0\,\text{N}$

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

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.

Acting on the mass is what force (magnitude and direction) that causes it to lose speed?



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

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

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

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

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

$$a = \frac{(v - v_0)}{t} = \frac{[0.50 - 1.0]\,\text{m/s}}{2.0\text{ s}} = -0.25\text{ m/s}^2$$

$$F = ma = (2.0\text{ kg})(-0.25\text{ m/s}^2) = -0.5\text{ kg-m/s}^2$$

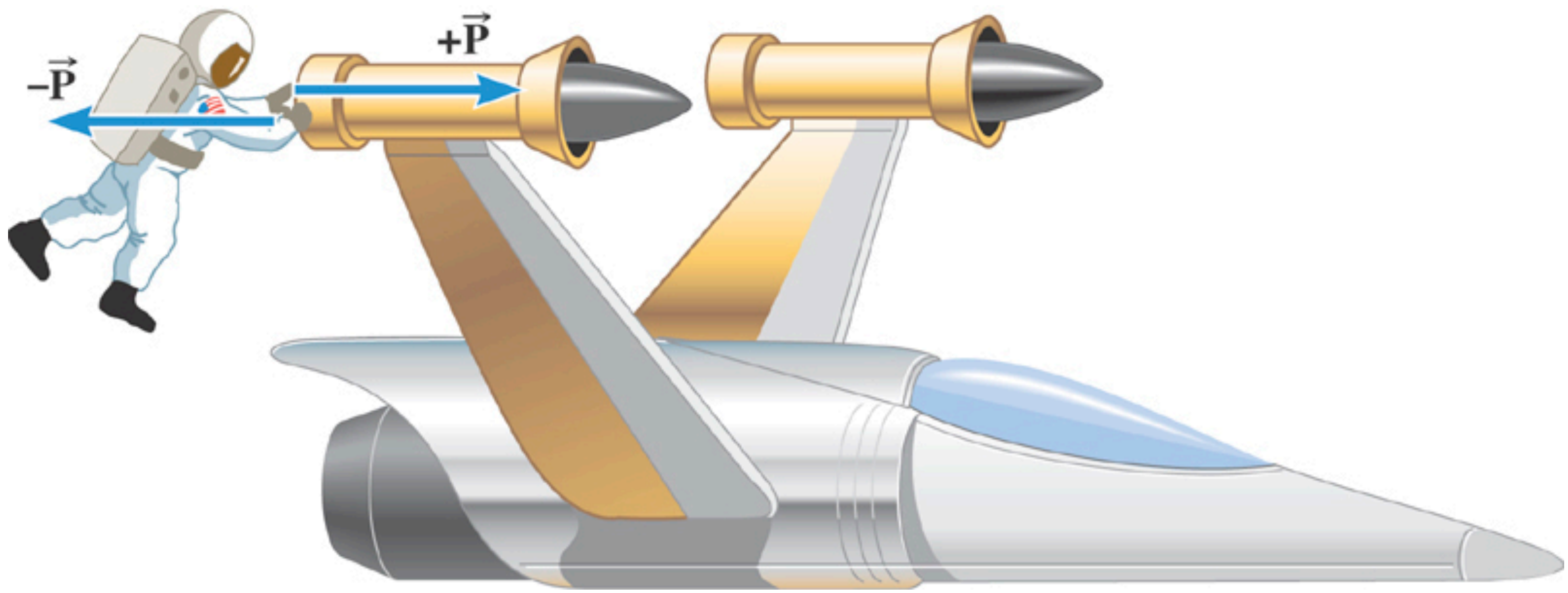
$$= -0.5\text{ N}$$

Newton's Third Law of Motion

Whenever one body exerts a force on a second body, the second body exerts an oppositely directed force of equal magnitude on the first body.

There are 2 and ONLY 2 objects involved in applying Newton's 3^{rd} law.

4.5 Newton's Third Law of Motion



Suppose that the magnitude of the force is 36 N. If the mass of the spacecraft is 11,000 kg and the mass of the astronaut is 92 kg, what are the accelerations?

On the spacecraft $\sum \vec{\mathbf{F}} = \vec{\mathbf{P}}.$ (one object)

On the astronaut $\sum \vec{\mathbf{F}} = -\vec{\mathbf{P}}.$ (another object)

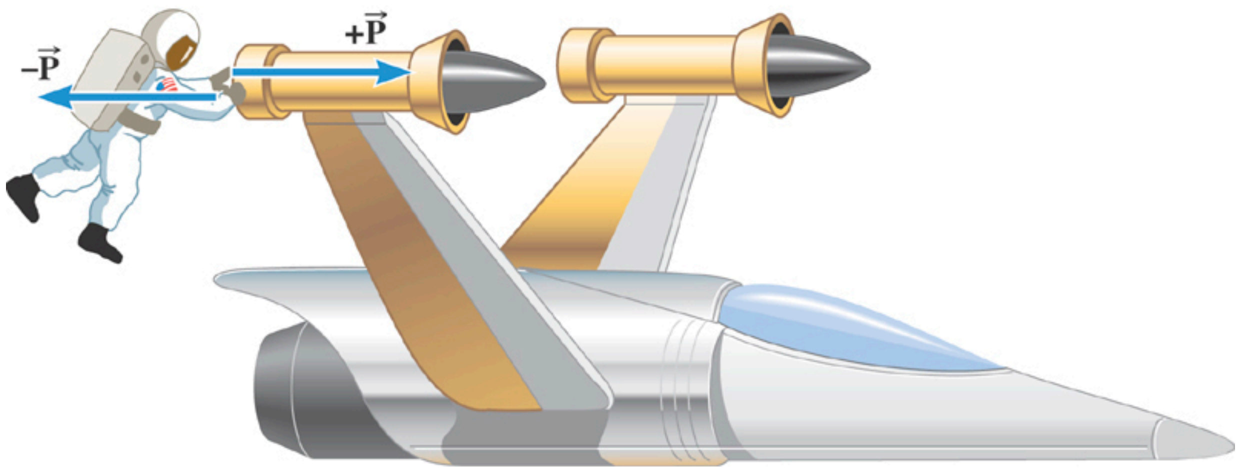
$$\vec{\mathbf{a}}_S = \frac{\vec{\mathbf{P}}}{m_S} = \frac{+36\text{ N}}{11{,}000\text{ kg}} = +0.0033\,\text{m/s}^2$$

Really tiny, and would not be noticed except over a very long time

$$\vec{\mathbf{a}}_A = \frac{-\vec{\mathbf{P}}}{m_A} = \frac{-36\text{ N}}{92\text{ kg}} = -0.39\,\text{m/s}^2$$

4.5 Newton's Third Law of Motion

How long will these forces be able to act? Not very long!
As soon as the astronaut's arms are fully extended,
the contact with the space craft is lost and NO MORE FORCES.



Suppose contact is maintained for 1 second. How fast will each object be moving? Both start at rest.

$$\vec{\mathbf{a}}_S = +0.0033\,\mathrm{m/s^2} \qquad v = a_S t = +0.0033\ \mathrm{m/s}\ (= 3.3\ \mathrm{mm/s})$$ Really tiny

$$\vec{\mathbf{a}}_A = -0.39\,\mathrm{m/s^2} \qquad v = a_A t = -0.39\ \mathrm{m/s}\ (= -390\ \mathrm{mm/s})$$ About 1 ft/s !

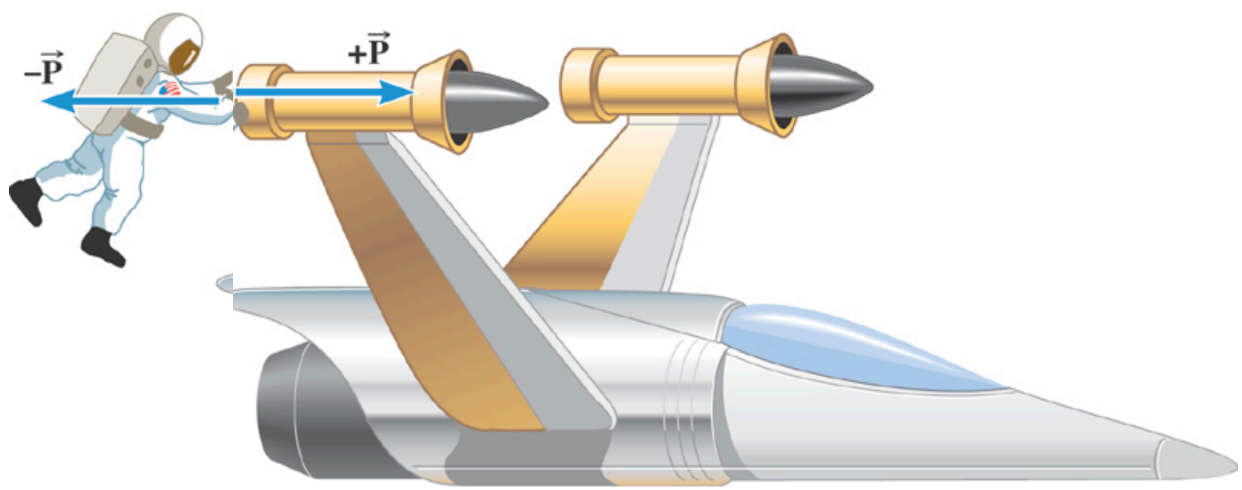
4.5 Newton's Third Law of Motion

These two forces do not have a Net Force = 0!

$+\mathbf{P}$ acts on the spacecraft

$-\mathbf{P}$ acts on the astronaut

To use the Net force and Newton's 2nd law, all the forces being summed must act on the same object.



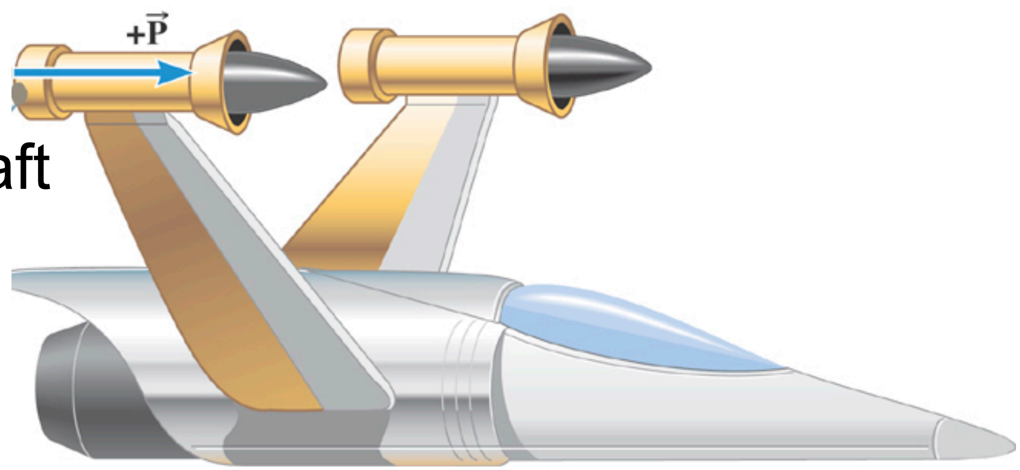
These two forces do not have a Net Force = 0!

$+\mathbf{P}$ acts on the spacecraft

$-\mathbf{P}$ acts on the astronaut

To use the Net force and Newton's 2nd law, all the forces being summed must act on the same object.

Astronaut's push
Acting on spacecraft



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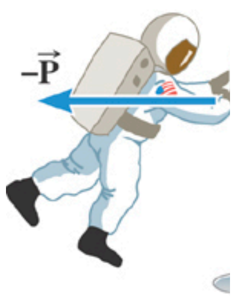


Spacecraft's push acting on the astronaut.

Warning:

Newton's 3st law can appear to be violated if you can't see the resulting movement (too small) of one of the two objects.

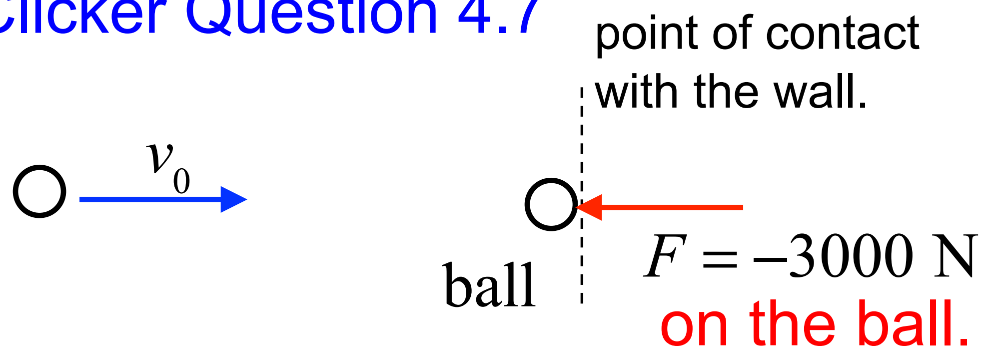
Examples (clicker questions):

- **Ball** bouncing off a **wall**.
- **Mass** sliding on a **table** w/friction.
- **Bat** hitting a **baseball**
- **Gun** firing a **bullet**

Newton’s Third Law of Motion

Whenever one body exerts a force on a second body, the second body exerts an oppositely directed force of equal magnitude on the first body.

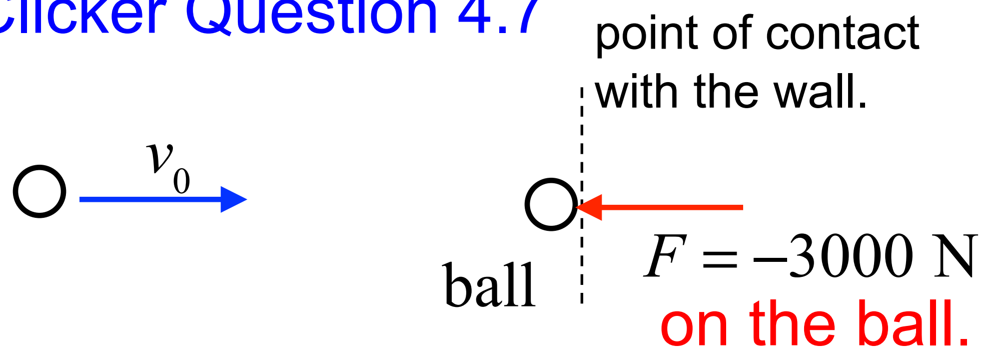
Clicker Question 4.7



A ball heads horizontally toward a wall. While in contact with the wall, the wall applies a force, $F = -3000$ N on the ball, as shown.
At the same time, the ball must apply what force on the wall?

a) $F = -3000$ N
b) $F = +3000$ N
c) $F = 0$ N
d) $F = 60$ N
e) A ball cannot make a force.

Clicker Question 4.7



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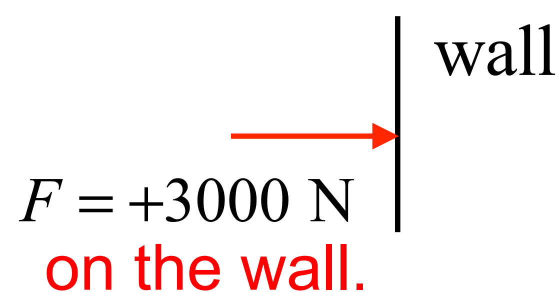
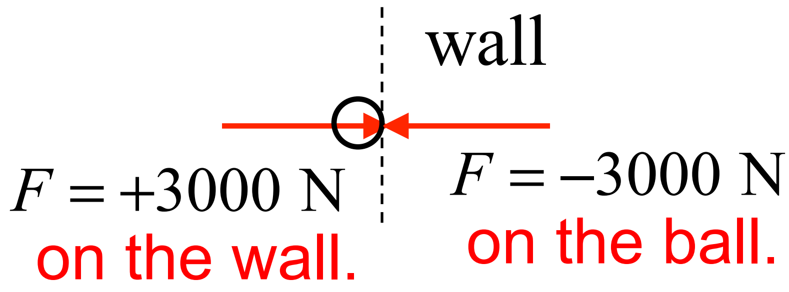
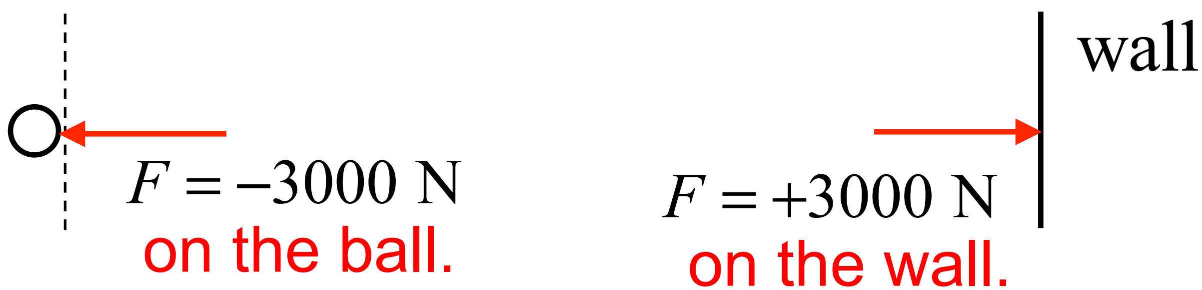


Clicker Question 4.7

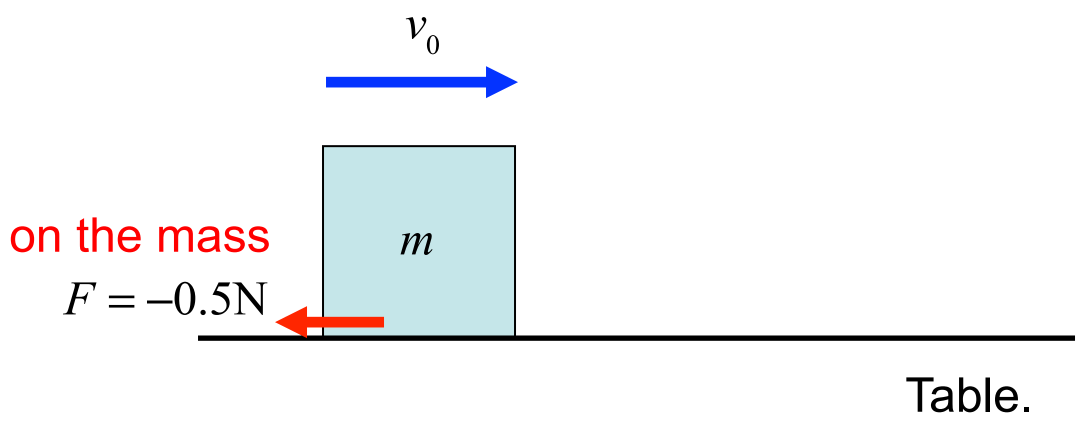
Simultaneously showing both forces that act the objects at the point of contact



These two forces do not result in a Net Force = 0.
There is one force on the wall and one force on the ball.



Clicker Question 4.8



While the mass is sliding, a friction force, $F = -0.5\,\text{N}$, acts on the mass. What friction force acts on the table?

a) $F = +0.5\,\text{N}$

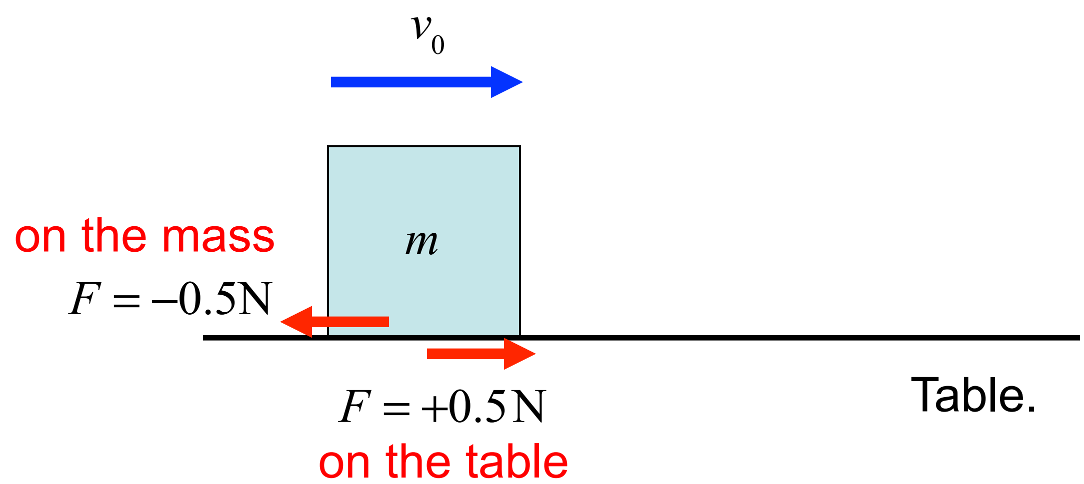
b) $F = -0.5\,\text{N}$

c) $F = 0\,\text{N}$

d) $F = 60\,\text{N}$

e) A mass cannot make a force.

Clicker Question 4.8



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a) $F = +0.5\,\text{N}$

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c) $F = 0\,\text{N}$

d) $F = 60\,\text{N}$

e) A mass cannot make a force.

Bat hitting a baseball

Newton's 3^{rd} law: Whatever magnitude of force the bat applies to the ball, the ball applies the same magnitude of force back (opposite direction) onto the bat.

The bat is slowed by the force of the ball on the bat, and the ball is accelerated by the force of the bat

A gun firing a bullet

Newton's 3^{rd} law: Whatever force the explosion applies to the bullet, it applies an equal magnitude force back (opposite direction) onto the gun.

The bullet is accelerated by the force of the explosion, and the gun is accelerated in the opposite direction by the same magnitude of force.

4.6 *Types of Forces: An Overview*

In nature there are two general types of forces, fundamental and nonfundamental.

Fundamental Forces

1. Gravitational force

2. Strong Nuclear force

3. Electroweak force

Examples of nonfundamental forces:

friction

tension in a rope

normal or support forces