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.

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

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

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

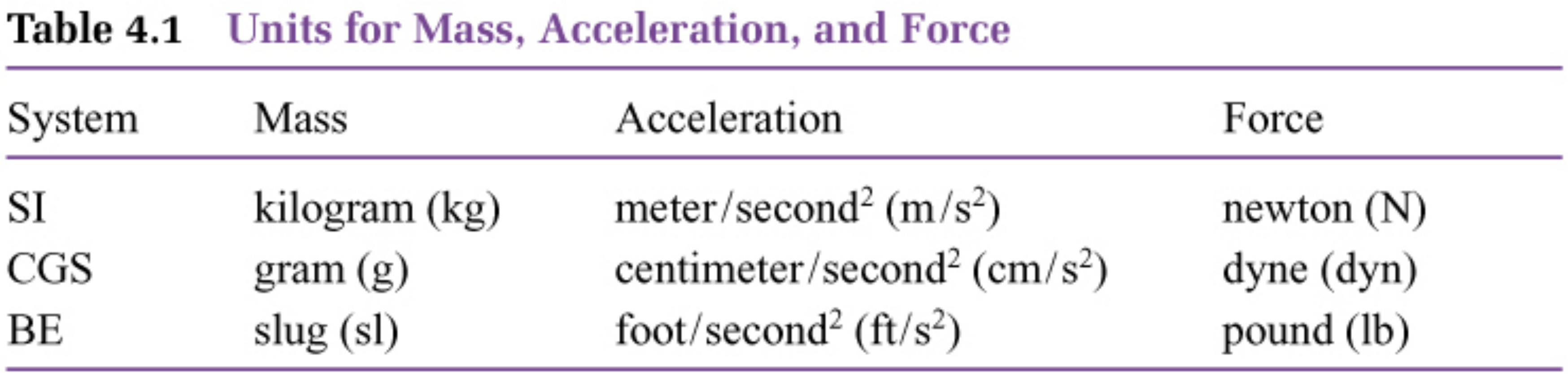


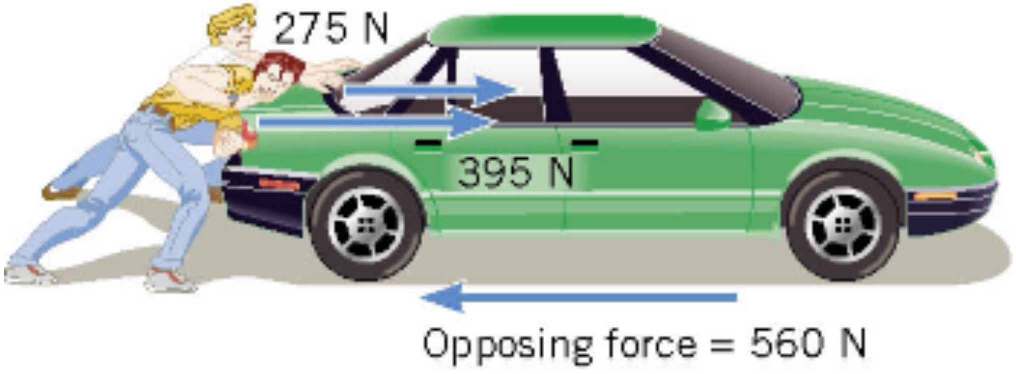
Table 4.1 Units for Mass, Acceleration, and Force

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)

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

4.3 Newton's Second Law of Motion

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



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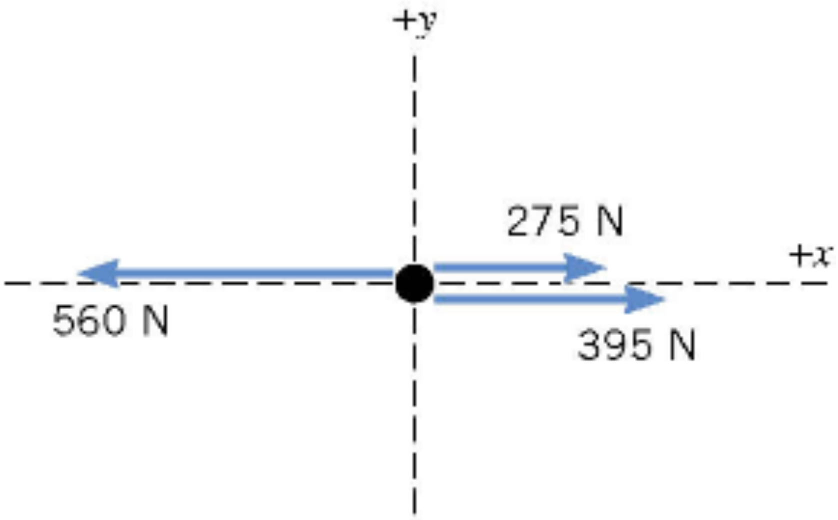
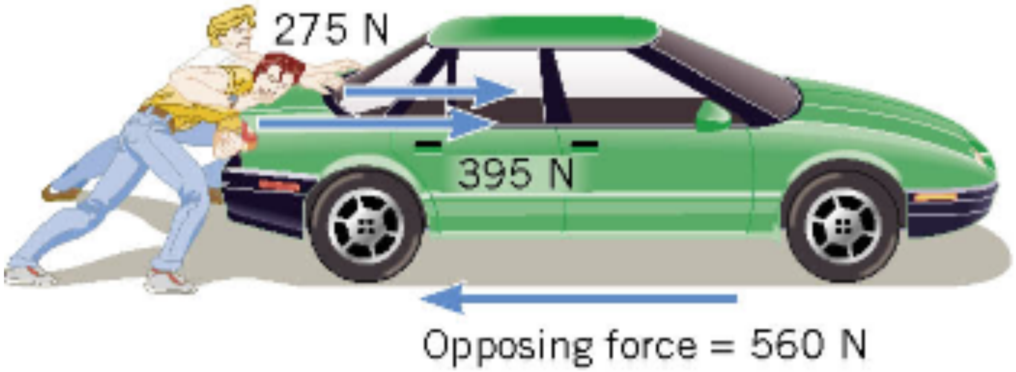


(*b*) Free-body diagram of the car

4.3 Newton’s Second Law of Motion



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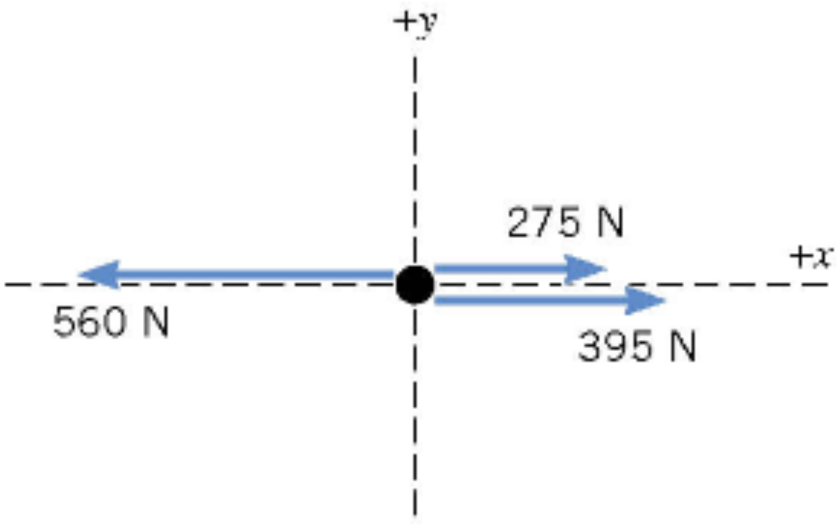


(*b*) Free-body diagram of the car

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

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

4.4 *The Vector Nature of Newton's Second Law*

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

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

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

AND

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

4.4 The Vector Nature of Newton's 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!

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

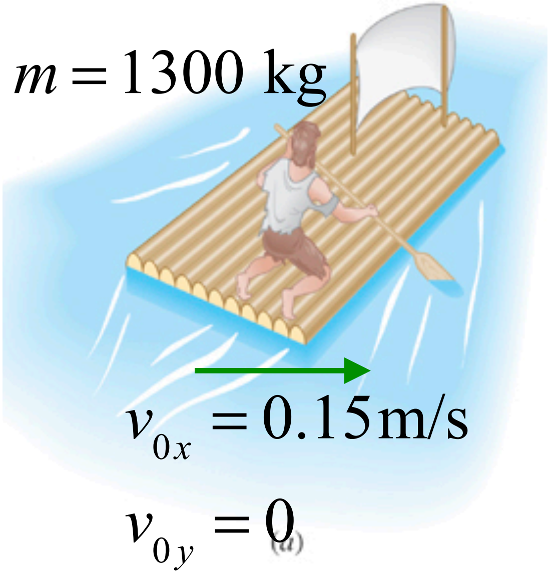
⇓

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.

4.4 The Vector Nature of Newton's Second Law

Drifting Raft



$m = 1300 \text{ kg}$

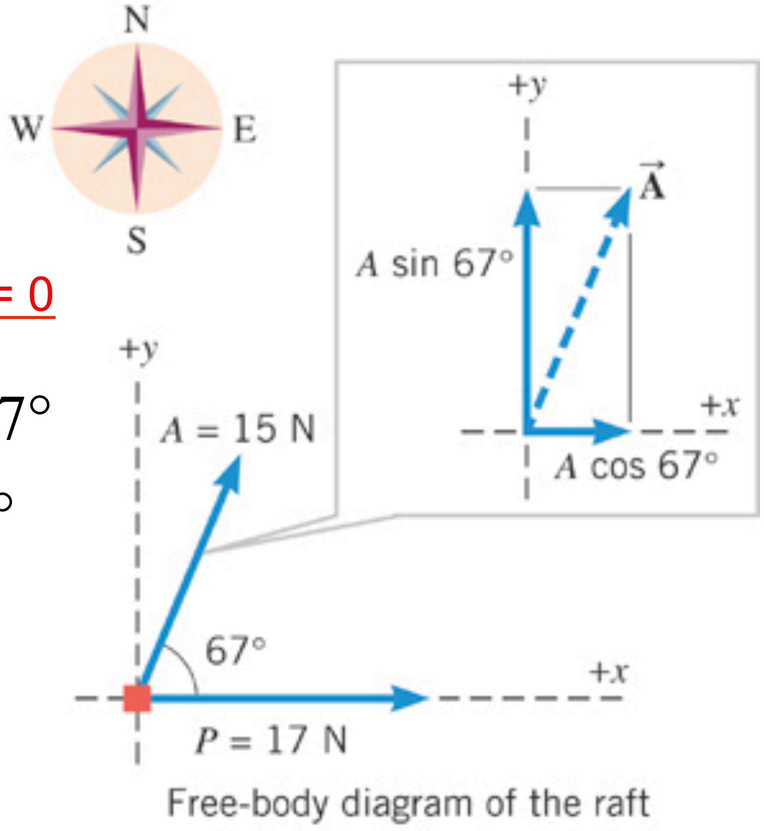
$v_{0x} = 0.15 \text{m/s}$

$v_{0y} = 0$

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

Force components

	x-component	y-component
$\vec{\mathbf{A}}$:	$(15\text{N})\cos 67°$	$(15\text{N})\sin 67°$
$\vec{\mathbf{P}}$:	$17\,\text{N}$	$0\,\text{N}$
$\vec{\mathbf{A}} + \vec{\mathbf{P}}$:	$(5.9 + 17)\,\text{N}$ $23\,\text{N}$	$(14 + 0)\,\text{N}$ $14\,\text{N}$

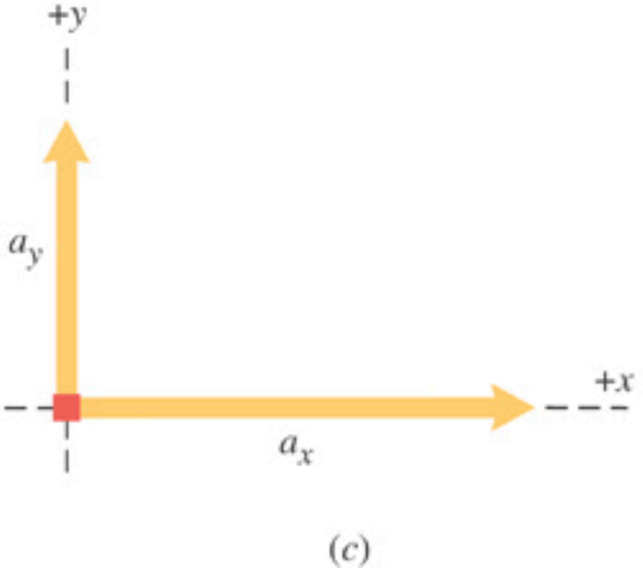
Net Force after *t* = 0

4.4 The Vector Nature of Newton's Second Law

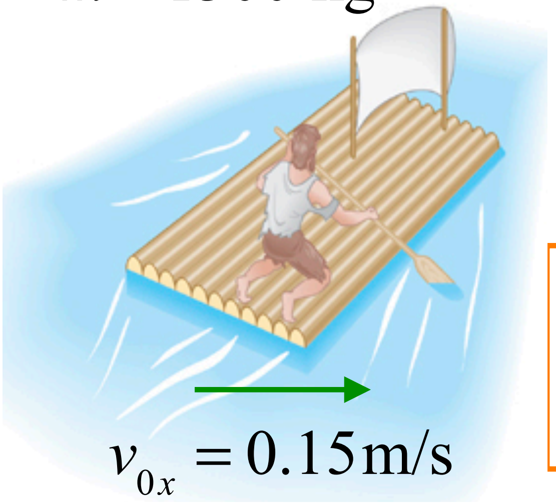
Acceleration after $t = 0$

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

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



$m = 1300\ \text{kg}$



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

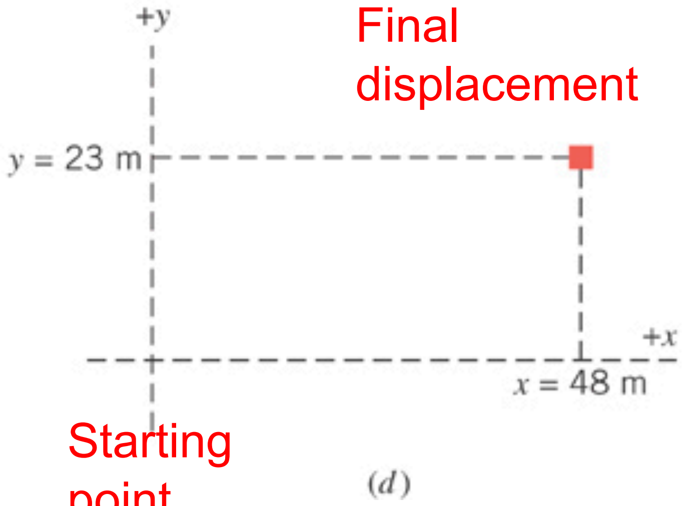
$v_{0y} = 0$

Predict the future:

Displacement at $t = 65$ s

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

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



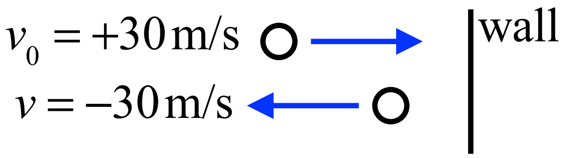
Final displacement

Starting point

one object

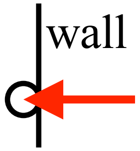
B) If the acceleration vector and mass of an object are known, then the Net Force acting on the object can be calculated.

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?



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

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



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

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

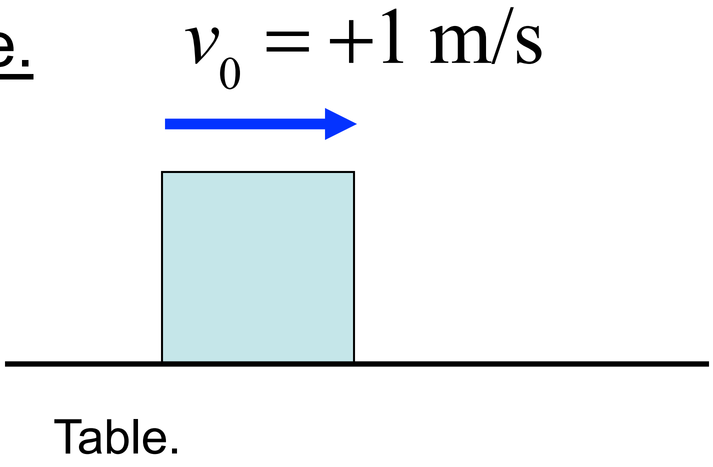
Force on ball is to the LEFT

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.

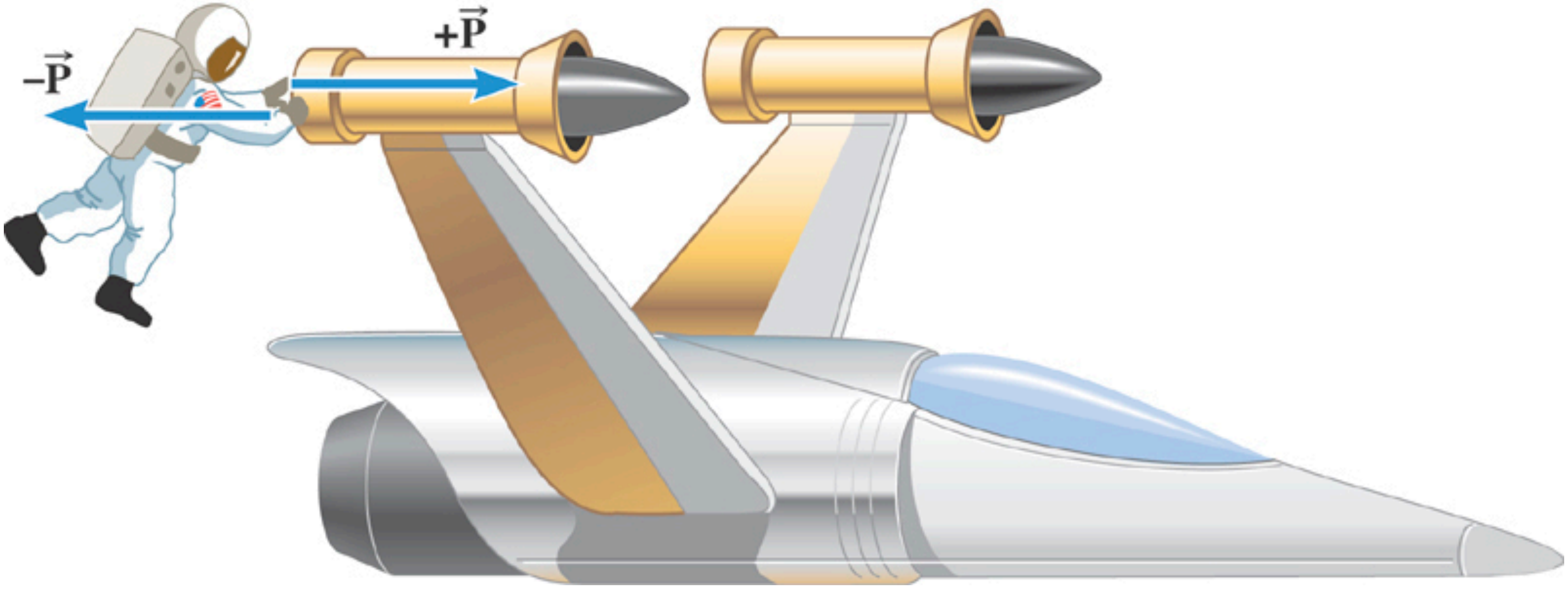
1) Calculate the acceleration vector
2) Use Newton's 2^{nd} law, to calculate the frictional force that must act on the mass.

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 3rd 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)

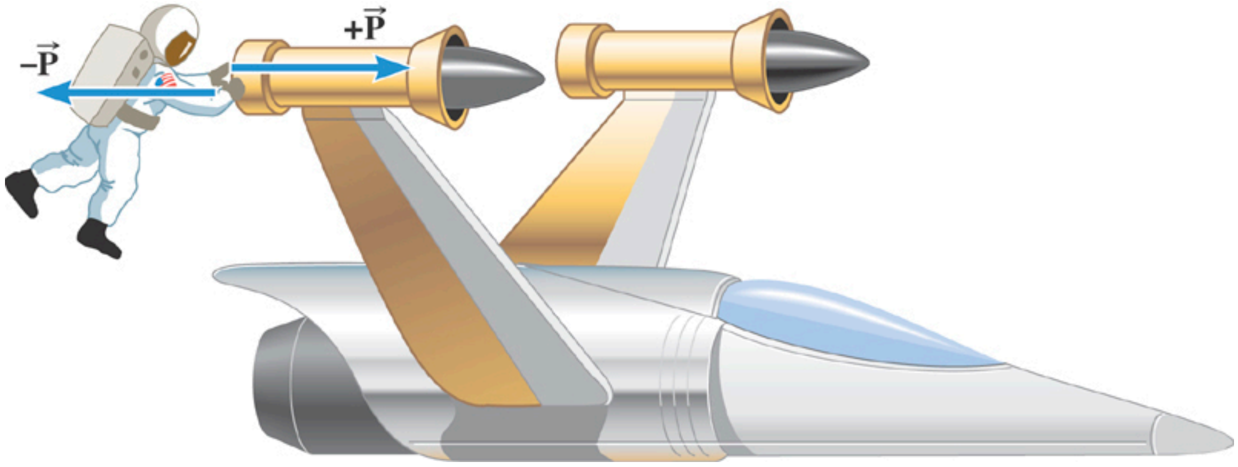
$$\vec{\mathbf{a}}_S = \frac{\vec{\mathbf{P}}}{m_S} = \frac{+36\ \mathrm{N}}{11{,}000\ \mathrm{kg}} = +0.0033\,\mathrm{m/s^2}$$

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

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

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.

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

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

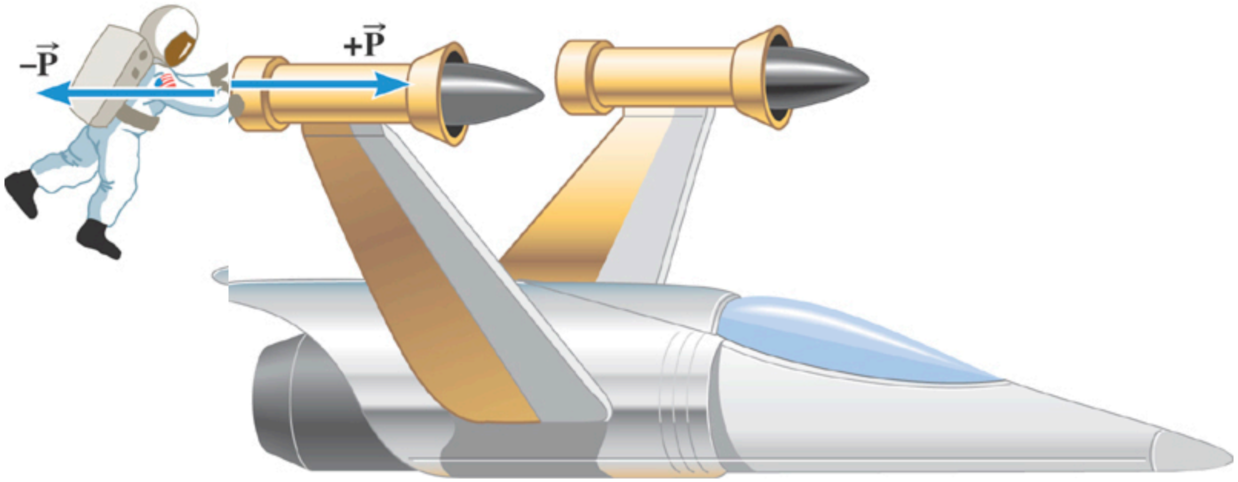
4.5 Newton’s Third Law of Motion

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.



4.5 Newton's Third Law of Motion

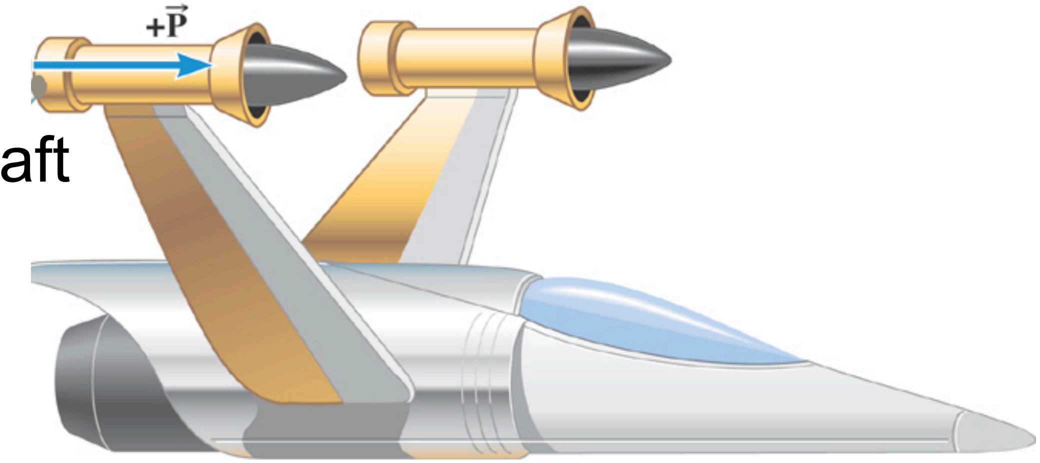
These two forces do not have a Net Force = 0!

$+\mathbf{P}$ 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.

Astronaut's push
Acting on spacecraft



4.5 Newton's Third Law of Motion

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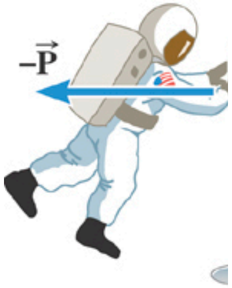


Spacecraft's push
acting on the astronaut.

4.5 Newton's Third Law of Motion

Warning:

Newton's 3st law can appear to be violated if you can't see the resulting change of velocity of one of the two objects.

Examples (clicker questions):

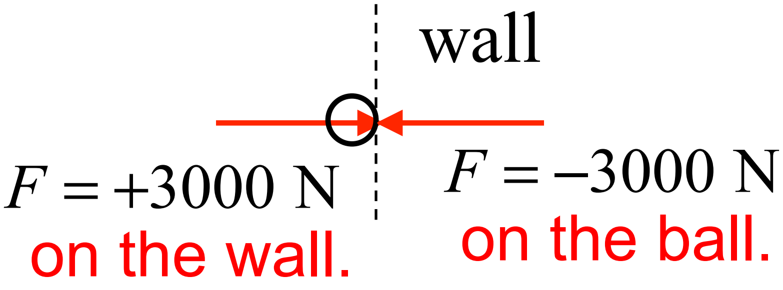
Ball bouncing off a **wall**.
Mass sliding on a **table** w/friction.
Bat hitting a **baseball**
Gun firing a **bullet**

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

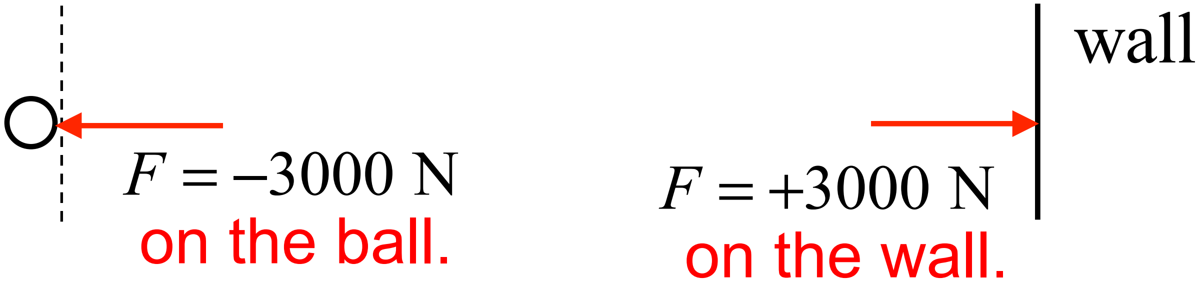
Simultaneously showing both forces
that act the objects at the point of contact



$F = +3000\ \mathrm{N}$
on the wall.

$F = -3000\ \mathrm{N}$
on the ball.

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



$F = -3000\ \mathrm{N}$
on the ball.

$F = +3000\ \mathrm{N}$
on the wall.

Bat hitting a baseball

Newton’s 3rd 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 3rd 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

4.6 Types of Forces: An Overview

Examples of nonfundamental forces:

friction

tension in a rope

normal or support forces

Newton’s Law of Universal Gravitation

Every particle in the universe exerts an attractive force on every other particle.

A particle is a piece of matter, small enough in size to be regarded as a mathematical point.

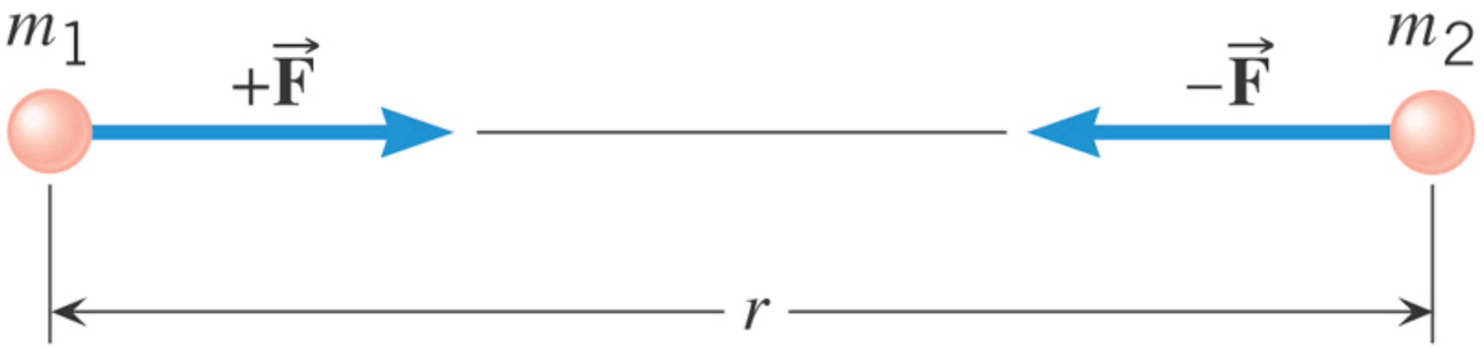
The force that each exerts on the other is directed along the line joining the particles.

4.7 The Gravitational Force

For two particles that have masses m_1 and m_2 and are separated by a distance r, the force has a magnitude given by

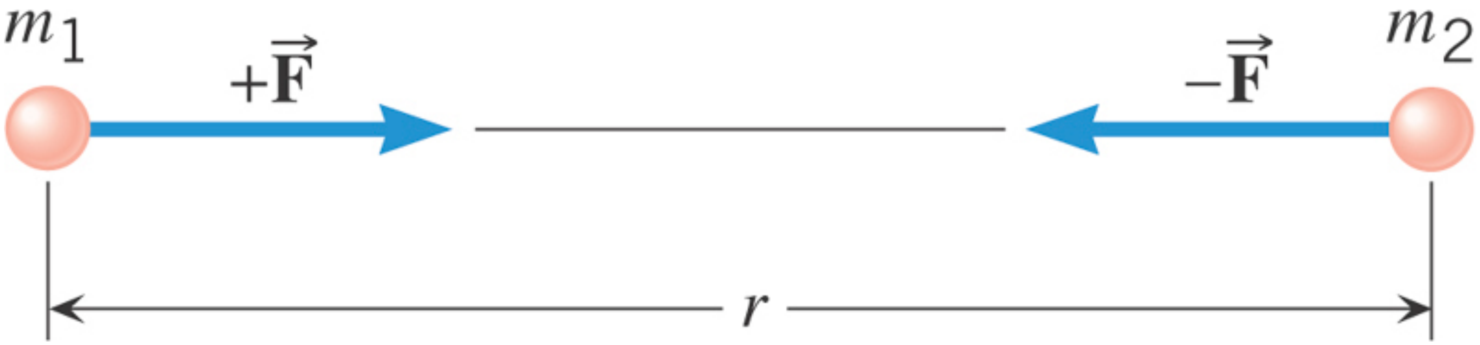
$$F = G\frac{m_1 m_2}{r^2}$$

$$G = 6.673\times10^{-11}\ \mathrm{N\cdot m^2/kg^2}$$



the same magnitude of force acts on each mass, no matter what the values of the masses.

4.7 The Gravitational Force

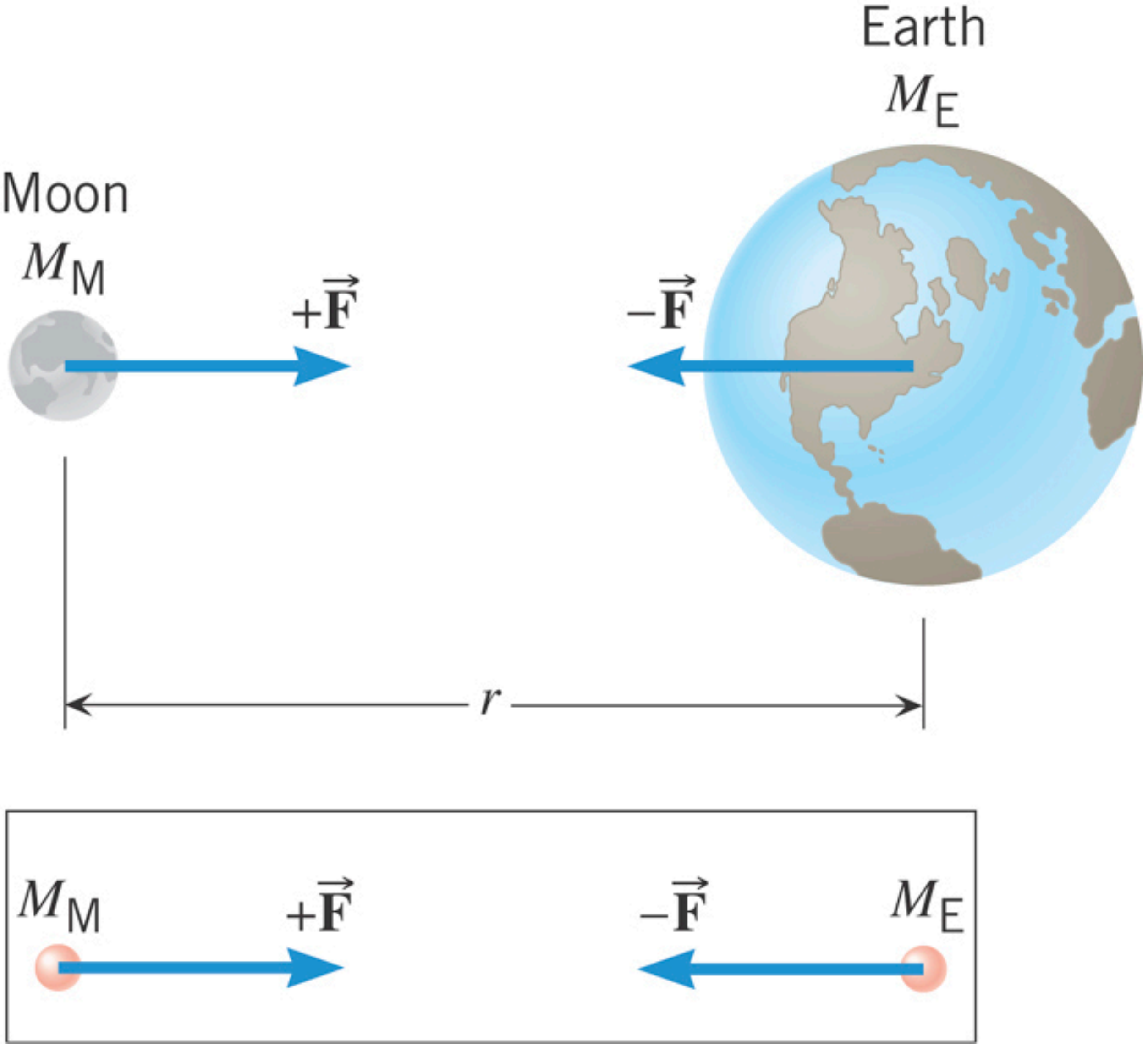


$$F = G\frac{m_1 m_2}{r^2}$$

$$= \left(6.67\times10^{-11}\ \mathrm{N\cdot m^2/kg^2}\right)\frac{(12\ \mathrm{kg})(25\ \mathrm{kg})}{(1.2\ \mathrm{m})^2}$$

$$= 1.4\times10^{-8}\ \mathrm{N}$$

4.7 The Gravitational Force



Definition of Weight

The weight of an object on or above the earth is the gravitational force that the earth exerts on the object. The weight always acts downwards, toward the center of the earth.

On or above another astronomical body, the weight is the gravitational force exerted on the object by that body.

SI Unit of Weight: newton (N)

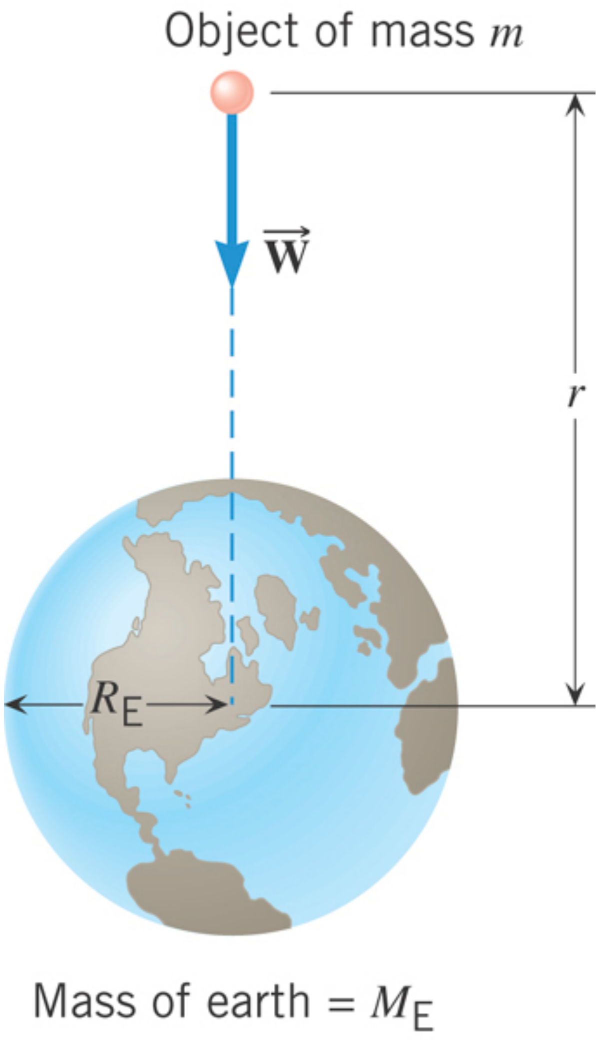
4.7 The Gravitational Force

Relation Between Mass and Weight

$$W = G\frac{M_E m}{r^2}$$

$$W = mg$$

$$g = G\frac{M_E}{r^2}$$



Near the earth's surface

$$r = R_E = 6.38 \times 10^6 \text{ m}$$

$$g = G\frac{M_E}{R_E^2}$$

$$= \left(6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2\right)\frac{\left(5.98 \times 10^{24}\ \text{kg}\right)}{\left(6.38 \times 10^6\ \text{m}\right)^2}$$

$$= 9.80\ \text{m/s}^2$$

4.7 The Gravitational Force

Can you feel gravity (the gravitational force) ?

Most people would say yes!

Consider standing on the concrete floor.

Gravity pulls down on you and compresses your body. You feel most of the compression in your legs, because most of your body mass is above them.

Consider hanging by your hands from a 100 m high diving board.

Gravity pull down on you and stretches your body.You feel most stretching in your arms, because most body mass is below them.

Let go of the 100 m high diving board.

You don’t feel stretched, and you don’t feel compressed.
While gravity makes you fall (accelerate) what do you feel ?

4.7 The Gravitational Force

The ONLY thing a person can feel is a stretch or compression of your body parts, mostly at a point of contact. If your body is not stretched or compressed, you will feel like you are floating.

Gravity ALONE will not stretch or compress your body.

Hanging from the board, the board also pulls up on your arms. Newton's 3rd law!

Standing on the ground, the ground also pushes up on the bottom of your feet. Newton's 3rd law!

While falling, the earth pulls on you and you pull on the earth. Gravity requires no contact. YOU CANNOT FEEL GRAVITY.