Causes of Motion

"Never confuse **motion** with action."

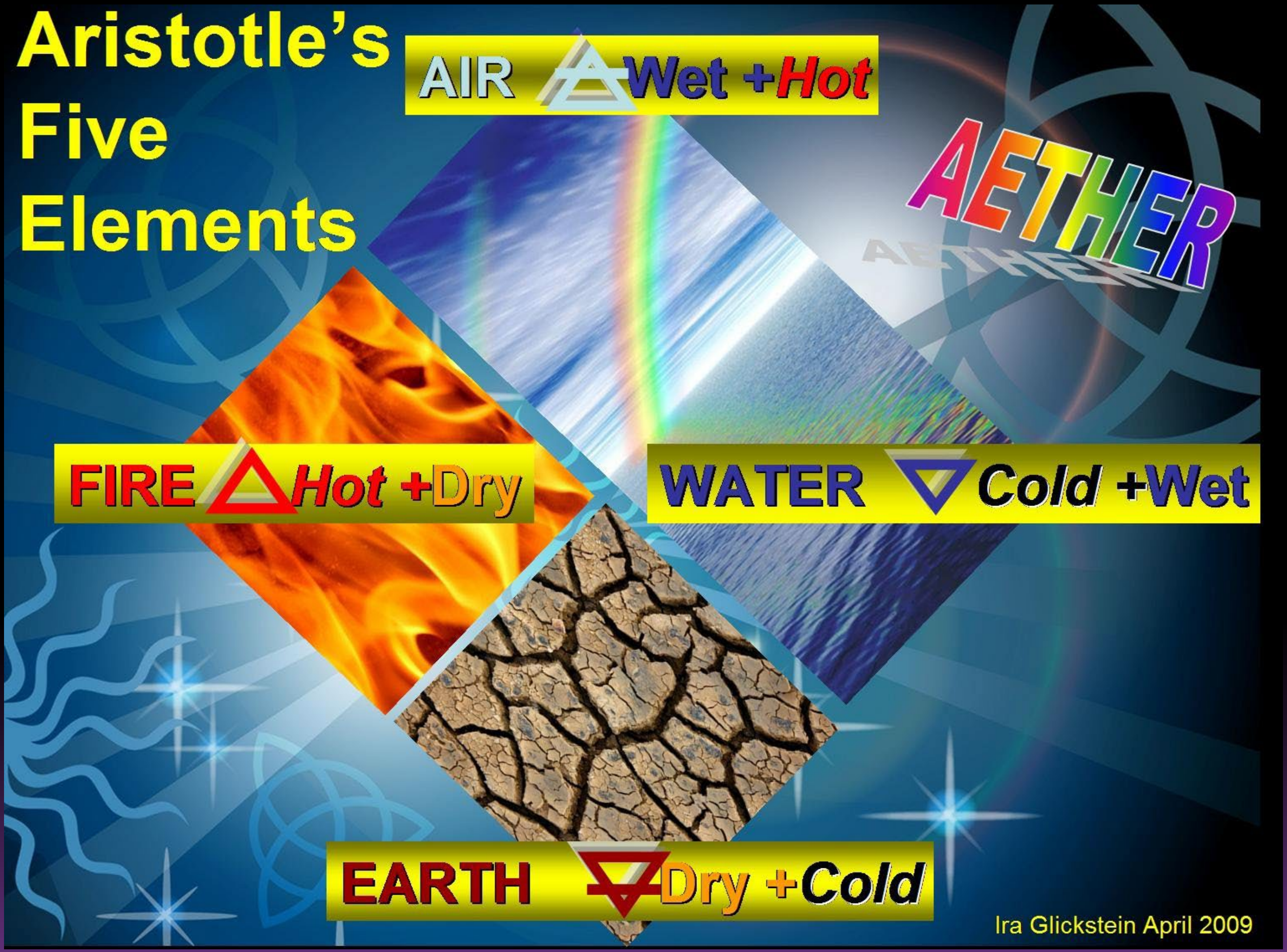
-- Benjamin Franklin

- The first attempt at describing the causes of motion was by Aristotle (~400 BC).
  - Based on his World View that everything was made up of FIVE Elements:

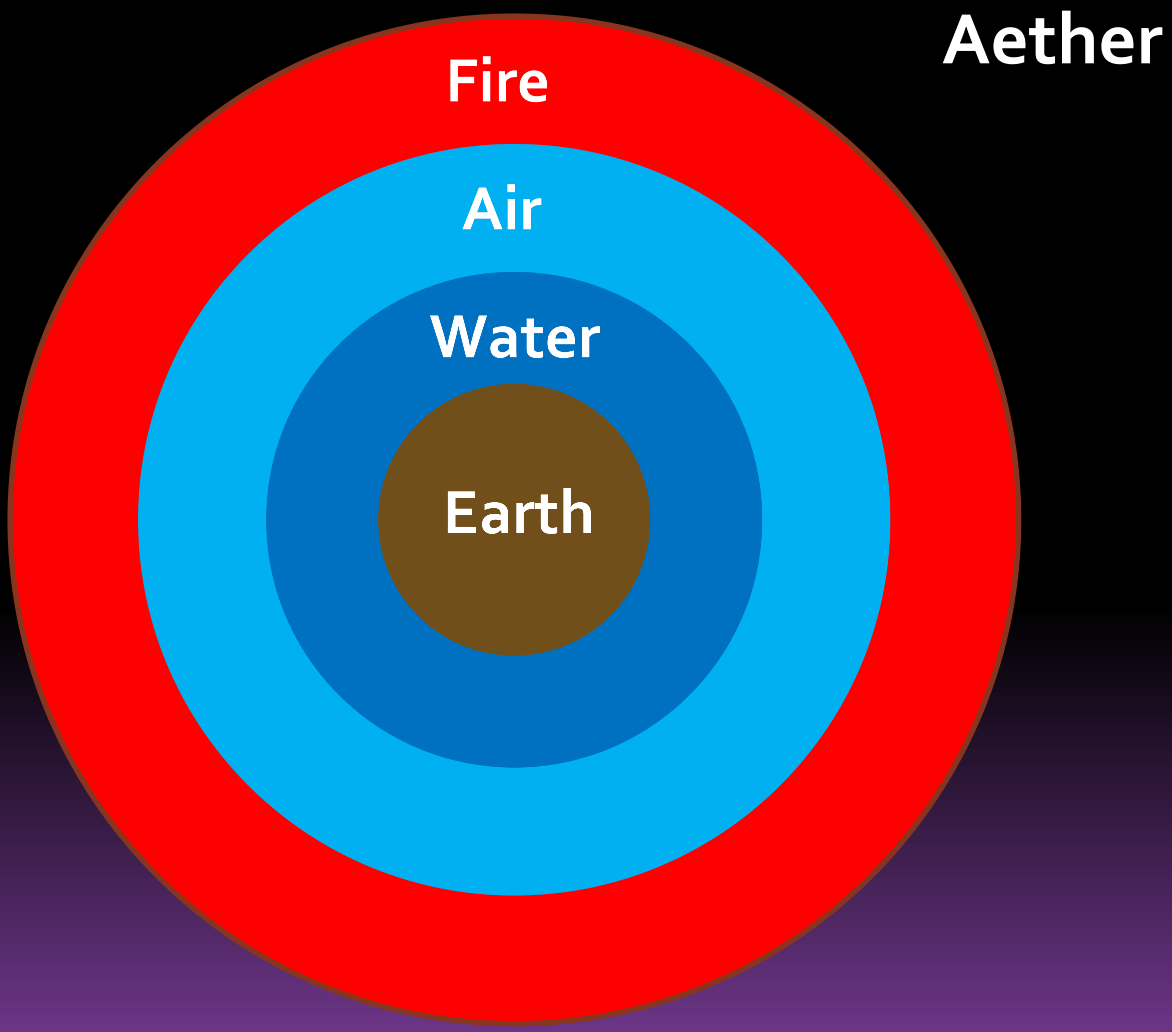
Aether, Earth, Water, Air, Fire

  - Every object in the universe was composed of one of these elements or some combination of them

- Each element had distinct properties….



- ...and a natural place in the hierarchy of a Universe made of perfect spheres.



Aristotle's Explanation of 'Natural' Motion

- IF any element where out of its natural position, its natural motion would be to return
  - Motion occurred in straight lines toward or away from the center of the earth

  (which back then was seen as the center of the universe)

- Testing this explanation matches observation
  - Muddy water separates (water on top, dirt on bottom)
  - A rock falls through air to get back to the earth

- Aristotle's Explanation of 'Non-Natural' Motion
  - Things move because effort is being applied
    - Stop applying effort, the motion stops

- **Thus, the natural state of motion of any object is to be at rest (*in its sphere*)!**

- Aristotle's explanations seem to explain all the causes of motion and thus was used for 2000 years!

Just one problem: IT'S WRONG!

Problems with Aristotle's Theory

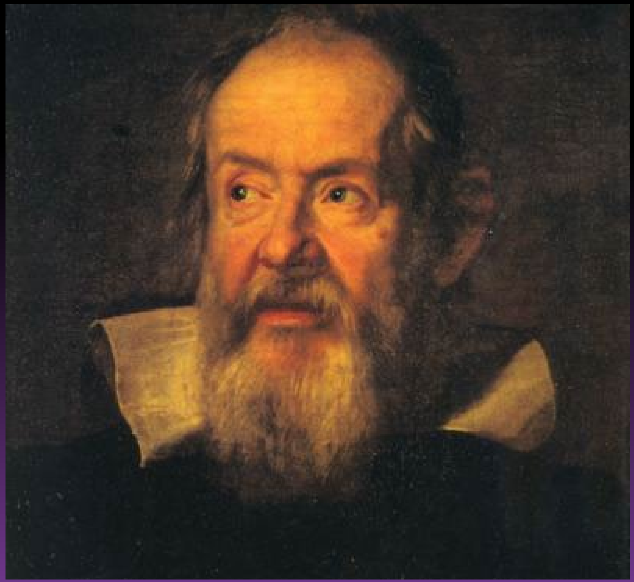
- #1
  - Objects don't stop immediately
- #2
  - Implies interaction between objects and elements

    Thus, there could be no motion in a vacuum…

    (..but what about the planets?)

Galileo (1564-1642)

- First person to challenge the Aristotelian explanation
- Did so with simple experiments



- Galileo found that an objects natural state of motion was **NOT** to be at rest, but to be in a state of constant velocity (*uniform motion*), which *includes* being at rest (v = 0).

Constant Velocity = straight line at fixed speed

- Galileo called this property or behavior of objects inertia.

Inertia – the natural tendency of an object to remain at rest or in uniform motion

Ex. Riding a Bike and then hitting a curb

NOTE:

We often overlook inertia because of the presence of ***friction***. Without ***friction***, it is much easier to see inertia's effects/behavior.

So what causes motion then?

Forces

- By definition, a **Force** is a *push* or a *pull*.

Types of Forces

- Contact Force
  - Requires direct physical contact

- Action-At-A-Distance Force
  - Doesn't require physical contact

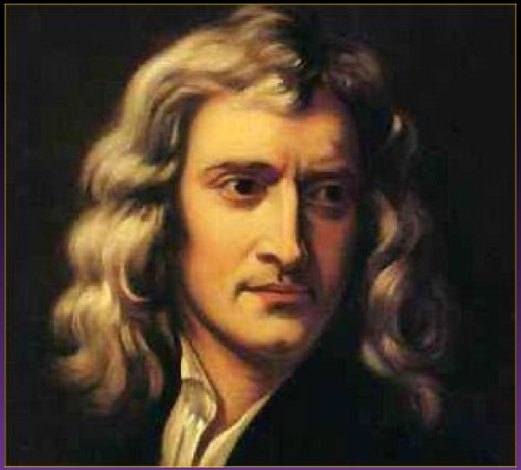
Balanced & Unbalanced Forces

- *Balanced forces – equal but opposite forces acting on the same object that result in **NO** change in motion of the object*

- *Unbalanced forces* – *two or more forces of unequal strength and/or direction acting upon on the same object that results in a change in motion of the object*

Newton (1642-1727)

- Studied motion and forces extensively
- Invented Calculus to help solve motion problems
- Conclusions can be summarized in 3 Laws



Newton's 1st Law of Motion

- Extension of the work done by Galileo

An object at rest will remain at rest, and an object in motion will remain in motion, *with constant velocity*, unless acted upon by an external, non-zero force.

a.k.a. The Law of Inertia

Ex. Bumper Cars

- What makes your body “jerk” when you hit something?

Inertia

- Car Stops but you don’t

Another interpretation of Inertia

- Think of inertia as being “naturally” resistant to changes in motion

More inertia = more resistant to change in motion

- Why didn’t Galileo get credit for 1st Law?
  - Did not associate inertia to any measureable physical quantity of an object

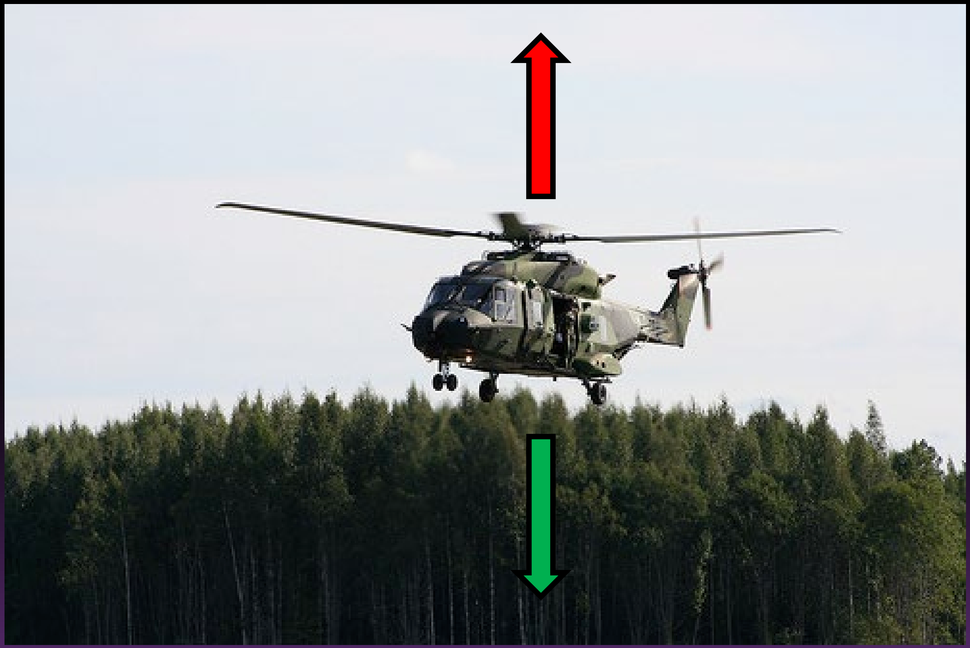
- Newton related inertia to something measureable

  Mass

- Mass (*inertia*) is an inherent <u>scalar</u> property of an object that is independent of the objects location or surroundings

  1 kg on Earth = 1 kg on Jupiter

- Newton's 1st Law is our model for explaining the motion of objects that experience a net force of zero (*balanced force*).



Rotors provide a push up

Gravity provides a pull down

IF Forces balance, helicopter hovers

Producing a Change in Motion

- In order to produce a change in motion, you must exert an **unbalanced force** on an object long enough for it to overcome its inertia
- If the inertia is large and the amount of force applied is small, there will be no or very little change in motion

Producing a Change in Motion

Contact Forces can **ONLY** be transmitted over 'long' distances if the medium is *rigid* and the force is applied for a 'long' enough period of time.

Demo

Table cloth and Dishes

Newton's 2^{nd} Law of Motion

- Newton's 2^{nd} Law is our model for explaining the motion of objects that experience a non-zero net force of zero (*unbalanced force*).

- Can get to this model by playing with the 1^{st}

1st Law States:

A balanced force acting on an object results in uniform motion

Thus,

A balanced force = uniform motion

or

A balanced force = constant velocity

The opposite of the 1st Law would read

An unbalanced force = non-uniform motion

or

An unbalanced force = change in velocity

But

change in velocity = acceleration

Therefore,

An unbalanced force = acceleration

In math terms, our statement looks like this:

$F \propto a$

This implies that the amount of force applied is directly related to the acceleration produced.

More force = more acceleration

less force = less acceleration

- What about an objects inertia? How does that fit in the 2nd Law?

- Recall, mass is a measure of an objects inertia

  (*resistance to changes in motion*)

- In order for an object to accelerate when you apply a force, you must first overcome its inertia.

  more mass (inertia) = less acceleration

  less mass (inertia) = more acceleration

- This behavior can be stated using math as:

$$a \propto \frac{1}{m}$$

Combining both expressions we get:

$$a \propto \frac{F}{m}$$

This is Newton's 2^{nd} Law (*in mathematical form*)

Officially stated, it reads:

The acceleration of an object is directly proportional to the net force acting on an object and inversely proportional to its mass

Rearranging…

$$F \propto ma$$

While this is a useful expression, it can not be used to calculate anything until we make it an equality!

➔ replace $\propto$ with =

How do we do that?

- Math “trick”

$$F = kma$$

k = constant of proportionality

(has the exact value and units necessary to make both sides **exactly** equal)

Determined:

- Theoretically
- Experimentally

- It turns out in this case, k = 1:

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

- From this expression we can now determine the units of FORCE:

$$units = kg\left(\frac{m}{s^2}\right) \quad \text{or} \quad 1N = \frac{kg\ m}{s^2}$$

"Newton"

- Since force is a vector, it can be written in component form:

$$\mathbf{F} = F_x\ \hat{\mathbf{x}} + F_y\ \hat{\mathbf{y}} + F_z\ \hat{\mathbf{z}}$$

with

$$F_x = ma_x$$

$$F_y = ma_y$$

$$F_z = ma_z$$

Important aspects of *F=ma*

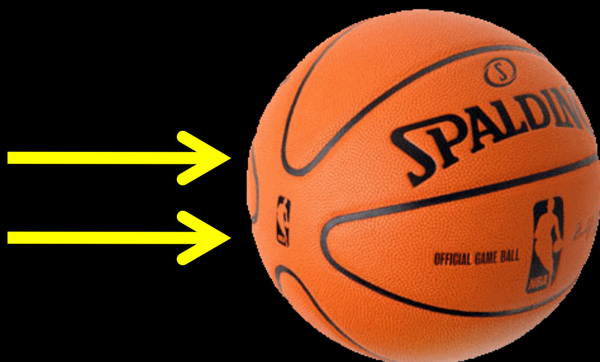
- Since *a* is a vector, ***F*** must be a vector
- The net or resultant force is **always** the vector sum of **ALL** the forces acting **ON** an object

$$F_{net} = F_1 + F_2 + F_3 \ldots$$

- The **net force always** determines the magnitude and direction of the motion

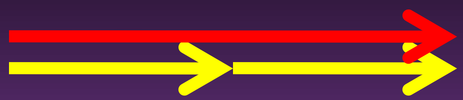
(Net force and acceleration are always in the same direction)

Individual Unbalanced Forces



Net/Resultant Force

Vector Addition



Individual Unbalanced Forces

Net/Resultant Force

Vector Addition

Important aspects of *F=ma*

- Just because the Net Force is zero, that does NOT mean there are NO forces acting on an object!

Individual Unbalanced Forces

No Motion

Net/Resultant Force

Vector Addition

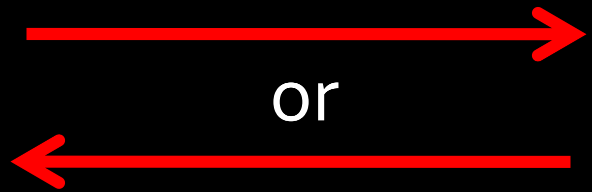
Cancel Out

Ex. Tug of War

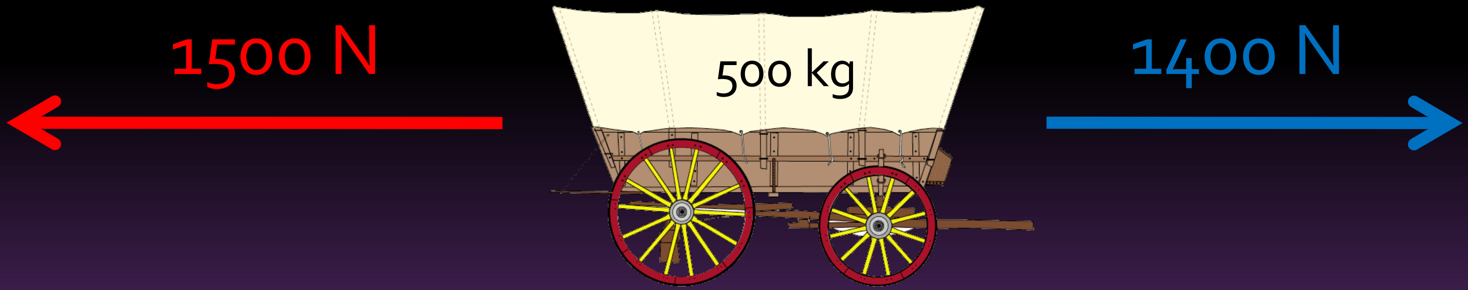
Two teams, the Red and the Blue, are engaged in an tug of war involving a 500 kg wagon. The Red team pulls with a force of 1500 N to the left and the Blue team pulls with a force of 1400 N to the right.

a) What is the net Force on the wagon?
b) What is the acceleration of the wagon?

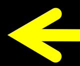
First need coordinate system:



Pick one.



a) Graphical Solution:



Motion

Analytic Solution…

b) Wagon's acceleration…

Example:

A car accelerates at 5 m/s^2 under the influence of a constant 5000 N force. What is the cars mass?

Example:

How much force is required to accelerate a 1500 kg truck from 20 m/s to 25 m/s in 4 s.

Important aspects of *F=ma*

- F_{net} is the CAUSE of the motion of an object or system and *m*a is the RESPONSE of the object or system to the applied force.
- F = ma makes NO distinction in whether the net force is a contact or action-at-a-distance force

  (*will work for both types of forces*)
- F = ma will only work in an inertial reference frame.

Inertial Reference Frame

- Inertial Reference Frame

  A reference frame that is stationary or moving at a constant velocity relative to the object you are observing

- Earlier, we said that we could choose any reference frame that was stationary relative to the object that was in motion in order to describe its motion.

- An inertial reference frame is more general in that is says **ANY** reference frame that is stationary **OR** moving at constant velocity relative to the object will work.

Inertial Reference Frame

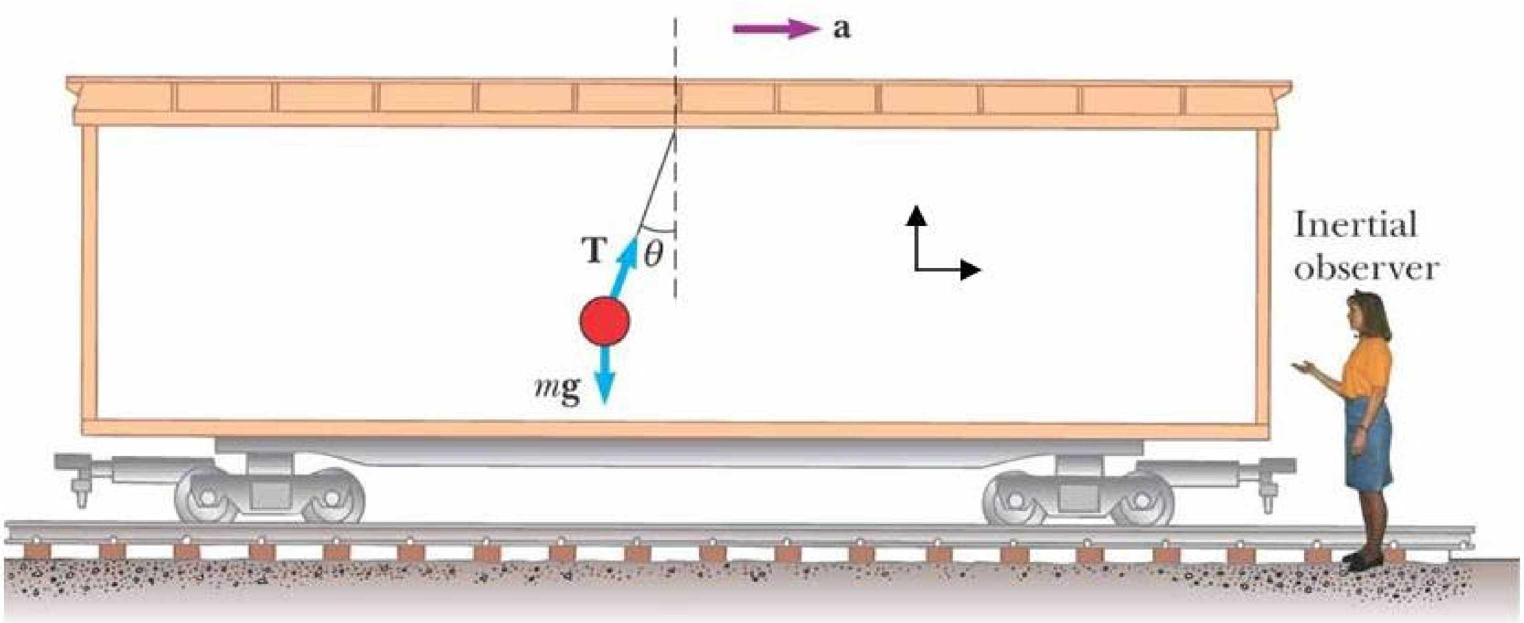
- Warning!

  The reference frame can **NOT** be accelerating, only moving at a constant velocity (*uniform motion*)

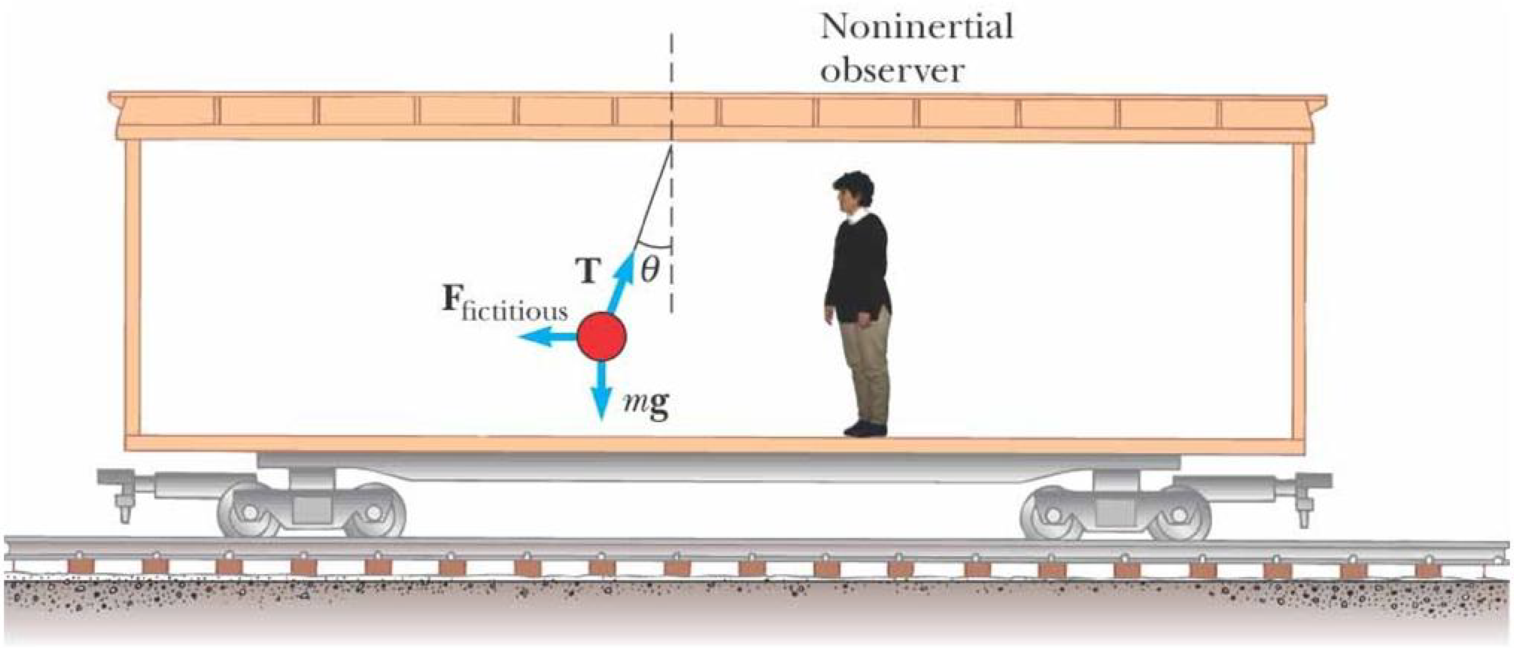
- **Why?**

  If the reference frame is accelerating, it could lead to the illusion that a force is acting on an object when if fact there isn't.

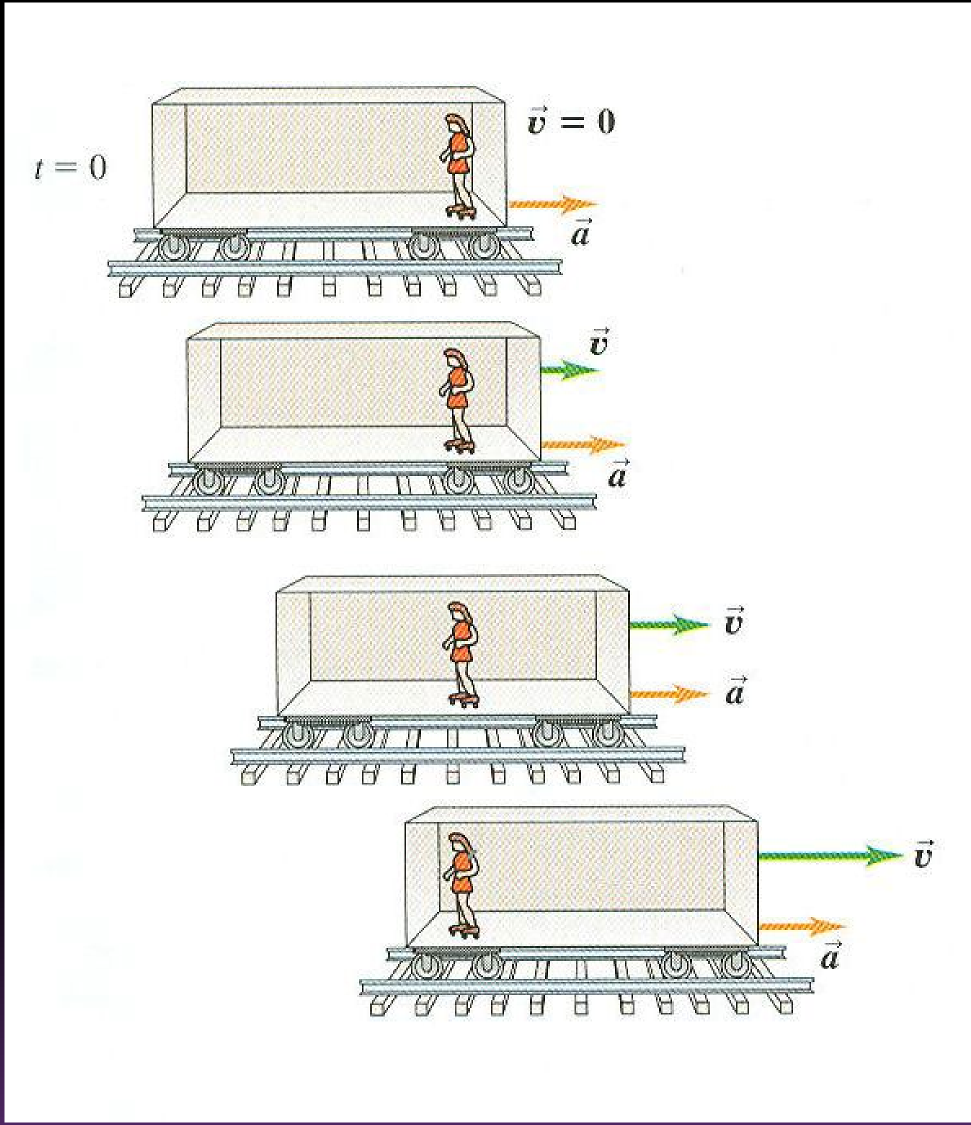
  ➔ An object "moves" because of its inertia, not because of an applied force!



An inertial observer <u>correctly</u> reports that the inertia of the ball causes it to deflect ***to the left*** as the boxcar accelerates ***to the right***.

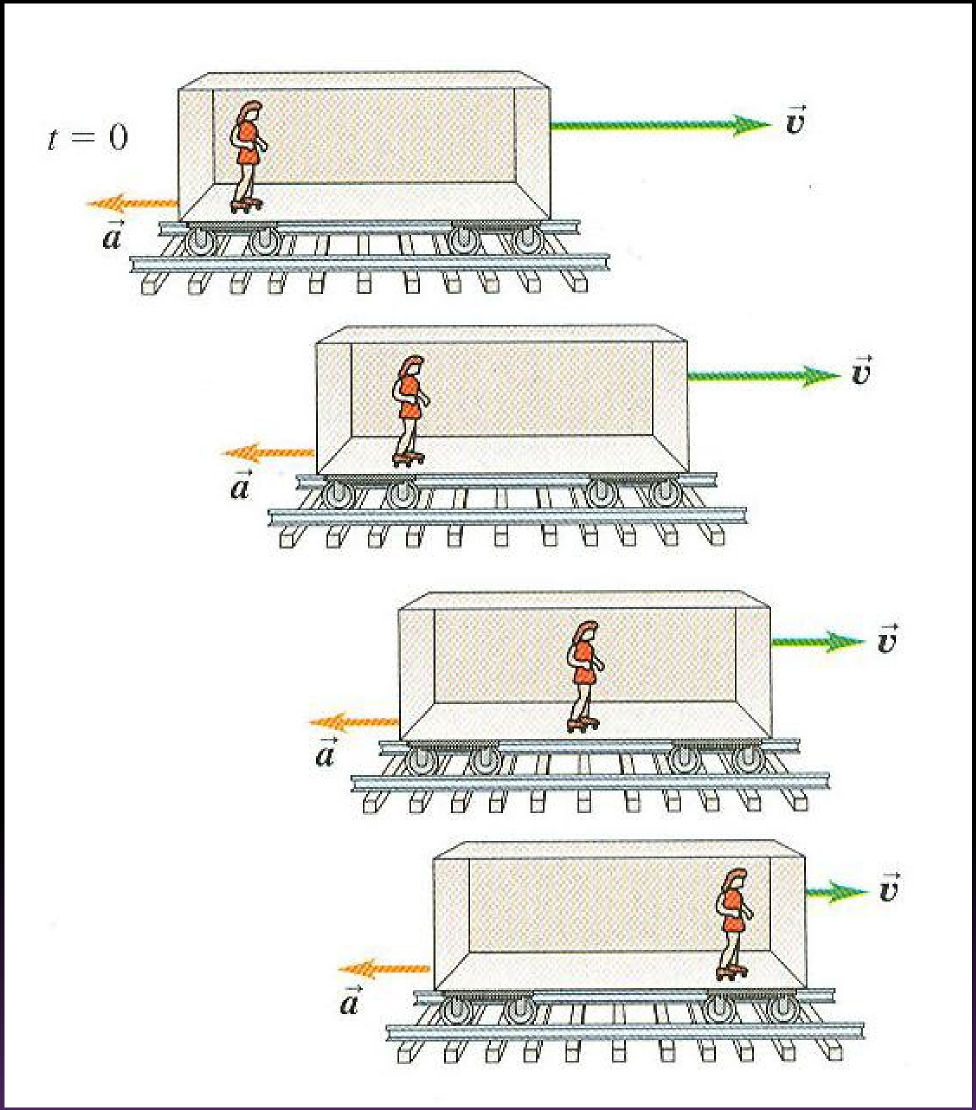


A non-inertial observer incorrectly reports that the net force on the ball is zero and that it is deflected ***to the left*** because it is being acted upon by a force $\mathbf{F}_{fictitious}$ ***to the left*** which eventually gets balanced by the horizontal component of **T** acting to the right.



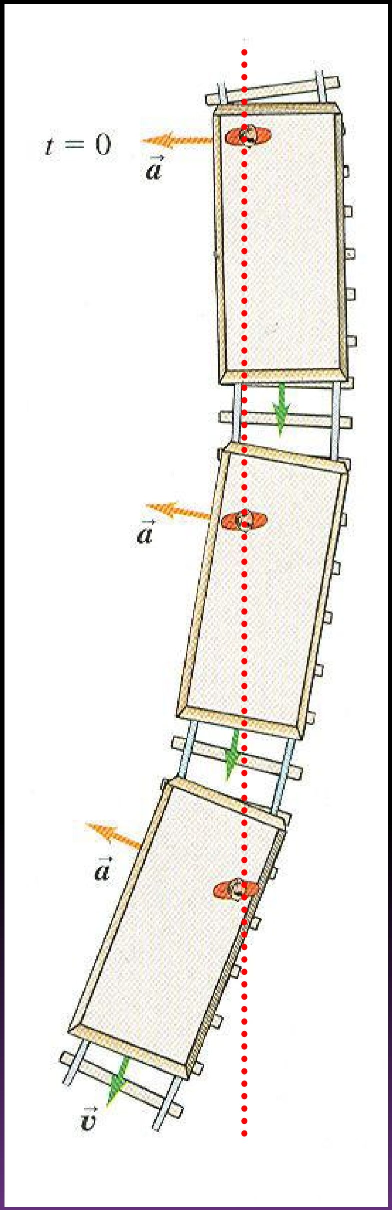
If you and the vehicle are initially at rest, you will remain at rest as the vehicle accelerates around you.

An observer ON THE TRAIN *would see you accelerating to the* ***left*** *and assume a force is acting on you* ***to the left****, when in fact they are the one that is accelerating* *<u>to the right</u>*.



If you and the vehicle are initially moving, you will continue moving with a constant velocity as the vehicle slows down (decelerates) around you.

An observer ON THE TRAIN *would see you accelerating to the* ***right*** *and assume a force is acting on you* ***to the right****, when in fact they are the one that is accelerating* *to the left.*



If you and the vehicle are initially moving, you will continue moving with a constant velocity (*in a straight line*) as the vehicle turns around you (centripetal acceleration) .

Newton's 3rd Law of Motion

- This one is a little tricky.
- The first two laws explain the motion of an object experiencing a zero net force (1st law) or a non-zero net force (2nd law).
- The 3rd law doesn't relate to motion at all, but rather describes where the forces used in the first two laws come from.

Consider…

- What causes motion?

  A force

- Where does this force come from?

  outside the object

- PROOF

  DEMO

  Push off in a rolling chair

- Something had to PUSH you to cause you to move.
  - That force came from the table
- You can push on yourself all you want, but you will not move. Something external has to act on you to cause motion.

Newton's genius was to realize that ALL forces come in **PAIRS**!

Newton's 3rd Law officially states:

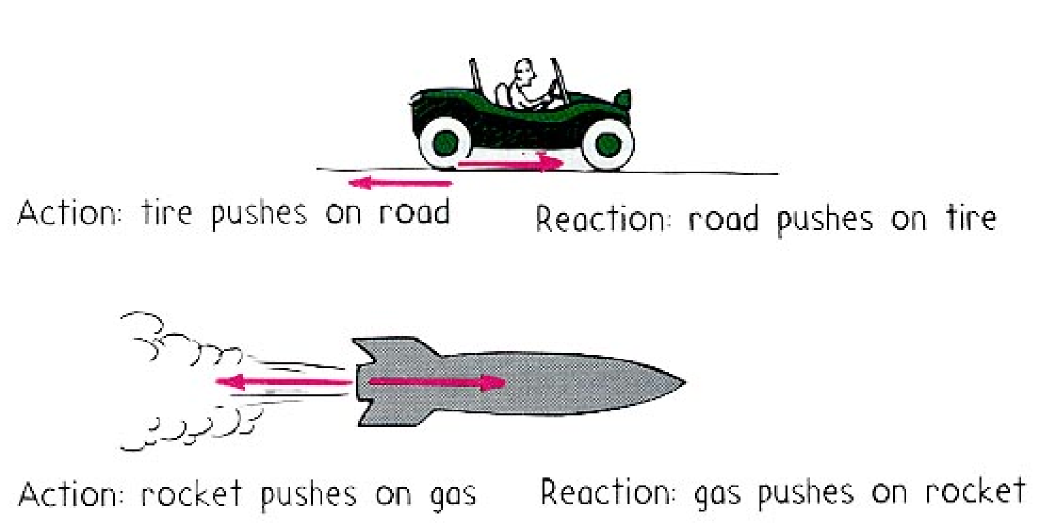
When two objects interact, the force exerted by the 1st object on the 2nd is equal in magnitude, but opposite in direction to the forced exerted by the 2nd object back on the 1st.

In mathematical form:

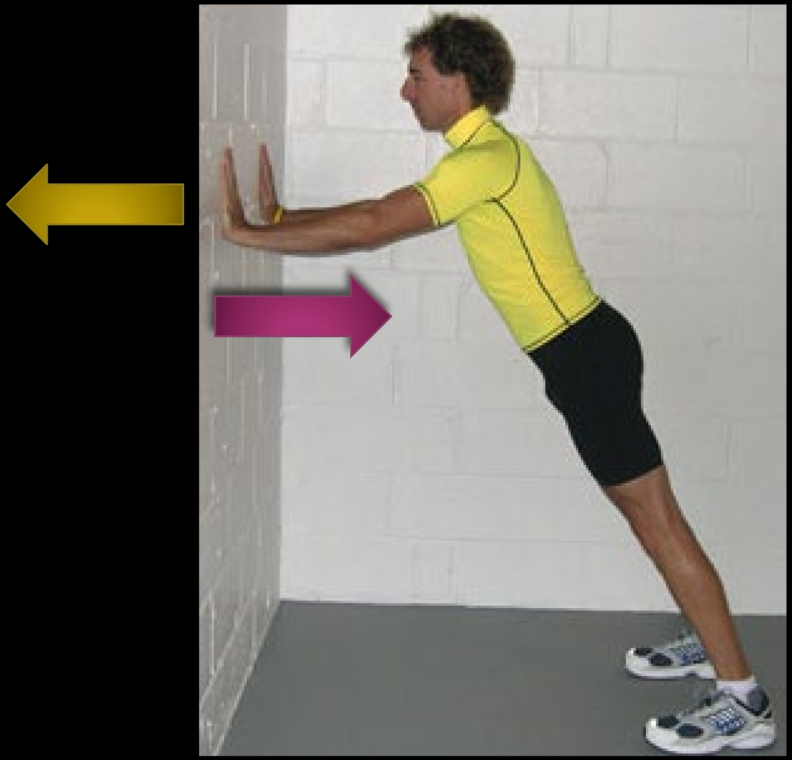
$$\mathbf{F}_{1\text{ on }2} = -\mathbf{F}_{2\text{ on }1}$$

Sometimes called *Action-Reaction* Law

- For every action there is an equal and opposite reaction



- Warning:
  - The action and reaction forces act on **DIFFERENT** objects!



Why doesn’t he fall through the wall?

The wall is pushing back with the same amount of force he is exerting on it!

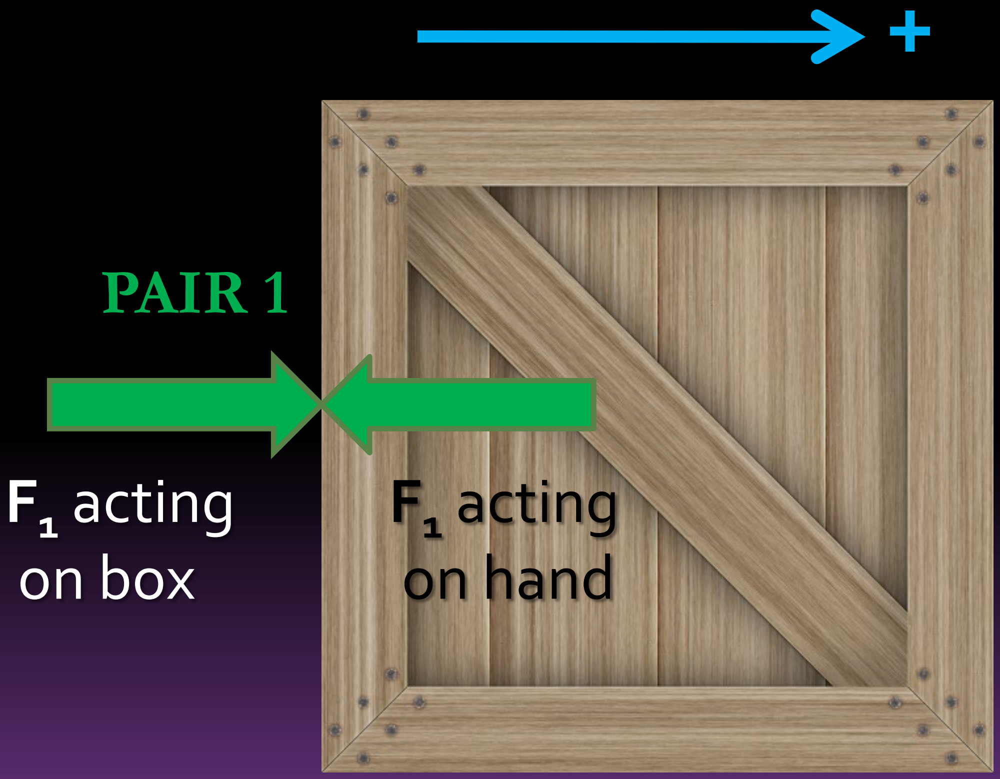
What does this all mean…

- It means that you can only use one force from the force pair at a time per interaction in the 1st or 2nd law.

- Analogy
  - Viewing a quarter (*can only see one side at a time*)

- Newton's force pairs always occur or exist at interaction or contact points

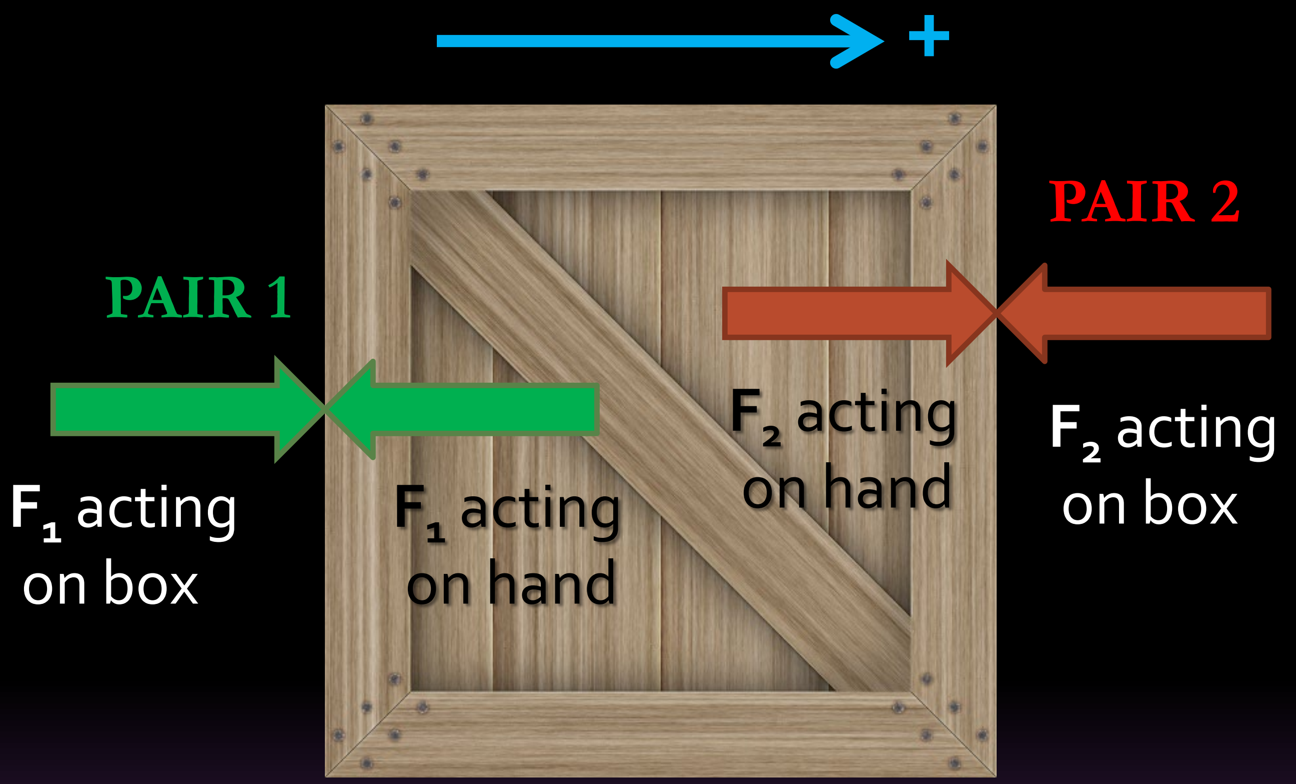
- Consider…



F = *ma* for the motion of the box is:

$$F_{1\ acting\ on\ box} = m_{box} a_{box}$$

- Now Consider…



$F = ma$ for the motion of the box is:

$$F_{1\ acting\ on\ box} - F_{2\ acting\ on\ box} = m_{box}a_{box}$$

Only use forces acting on the box in $F = ma$, **NOT** forces the box is exerting on something else.

- One useful application of the 3rd law is to explain the resultant motion of two interacting objects that do **NOT** interact with anything else.

$$\vec{F}_{1\ on\ 2} + \vec{F}_{2\ on\ 1} = 0$$

For a closed system

- Consider

Two figure skaters in the middle of a frozen lake

* If the two figure skates face each other, hands touching , and then push off, what is the motion?

- They move apart…

- But how can this be if the sum of the forces is zero (Newton's 3rd Law)?

$$\vec{F}_{1\ on\ 2} + \vec{F}_{2\ on\ 1} = 0$$

- Remember, each force in the force pair acts on a different object!

$\vec{F}_{guy\ on\ girl}$

$\vec{F}_{girl\ on\ guy}$

$$\vec{F}_{girl\ on\ guy} + \vec{F}_{guy\ on\ girl} = 0$$

Newton's 3rd Law

$\vec{F}_{guy\ on\ girl}$

$\vec{F}_{girl\ on\ guy}$

Newton's 2nd Law

$$\vec{F}_{guy\ on\ girl} = m_{girl}\vec{a}_{girl}$$

or

$$\vec{F}_{girl\ on\ guy} = m_{guy}\vec{a}_{guy}$$

Motion of the girl

Motion of the guy

- Which skater exerted the larger force as they pushed off?

neither, the magnitude of the force was the same, only in opposite directions

(Newton's 3rd Law)

$$\vec{F}_{girl\ on\ guy} = -\vec{F}_{guy\ on\ girl}$$

Example

Two skaters, initially at rest, push off by exerting a force of 250 N on each other. If m_{guy} = 125 *kg* and m_{girl} = 45 *kg*, what are their velocities as they separate from each other if the push off Force lasts for 0.5 sec (*assuming no friction*).

NOTE: Once they separate, the push off force is gone and inertia (friction) takes over!

- What causes the shuttle to rocket skyward?

- The force of **ALL** the gas particles pushing on the shuttle

Summary of Newton's Laws

- The 3rd Law explains the source of all the forces that get everyday objects started in motion

- The 2nd Law explains the motion of everyday objects under the influence of a non-zero or *unbalanced* force

- The 1st Law explains the motion of everyday objects under the influence of a zero or *balanced* net force **OR** NO applied forces at all

Quick Summary

- Newton's 1st Law

  Law of Inertia or Zero Force Law

- Newton's 2nd Law

  $F = ma$ or Non-Zero Force Law

- Newton's 3rd Law

  Action-Reaction Law or Force Pairs

Newton's Law of Gravitation

- Newton studied the effects of forces on falling objects on the earth along with the motions of planets and can to a very important conclusion:

Newton's Law of Gravitation

- Every object in the universe with mass attracts every other object in the universe with mass with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

$$F \propto \frac{m_1 m_2}{r^2}$$

Gravity

- Gravity is the term we use to describe the mutual attraction between **ANY** two objects with mass!

- *Summary of Gravity*:
  - Gravity is produced by **ANY** object that has <u>mass</u>
  - Gravity is an <u>action-at-a-distance</u> force
  - Gravity is always <u>attractive</u>

Gravity

$$F \propto \frac{m_1 m_2}{r^2}$$

- Not useful for calculating. Needs to be an equality (=) statement.

- Convert using a constant of proportionality. Since we are talking gravity, lets use G.

Gravity

$$F = \frac{Gm_1 m_2}{r^2}$$

- G is called the *Universal Gravitational Constant*

$$G = 6.67x10^{-11} \frac{N\,m^2}{kg^2}$$

Gravity

- What is the gravitational attraction between two people 1 *m* apart?

  (assume 1 person as a mass of 90 kg and the other 60 kg)

$$F = \frac{\left(6.67x10^{-11}\,\frac{N\,m^2}{kg^2}\right)(90\,kg)(60\,kg)}{(1m)^2}$$

$$F = 3.6x10^{-8}\,N$$

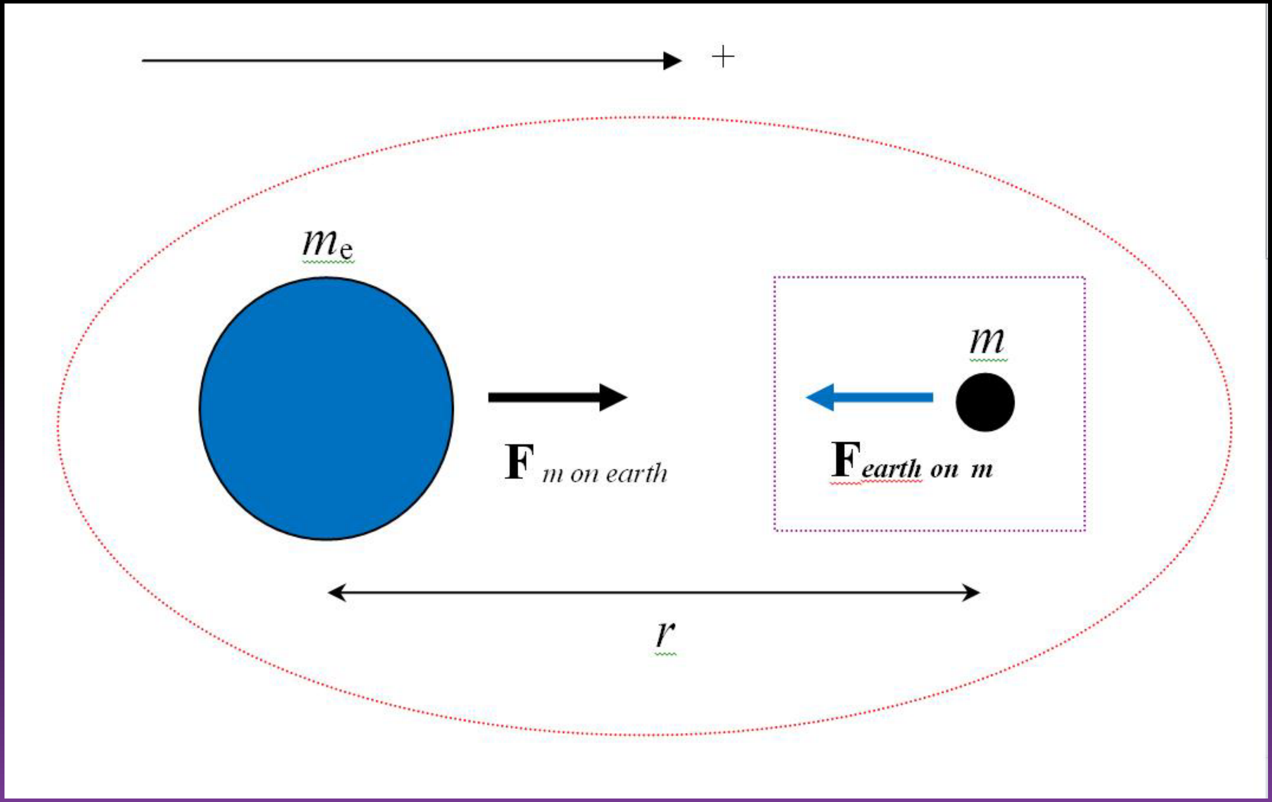
The gravitational force is very small. So why are we so strongly attracted to the earth?

The earth has a very large mass

Gravity

- *What is the magnitude of our observed acceleration for an object of mass m near the surface of the earth?*

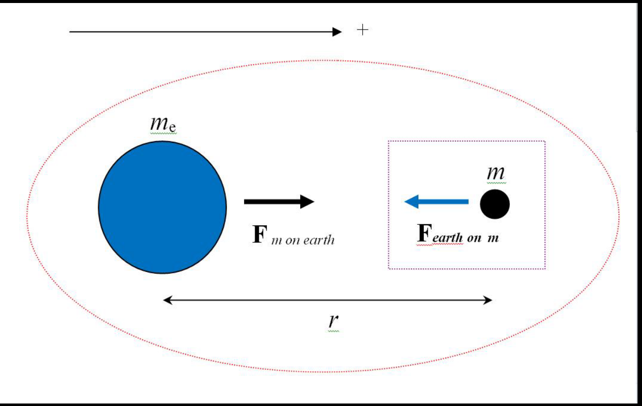
Consider a simplified depiction:



Gravity

From Newton's Law of Gravitation and Newton's 2[nd] Law,

$$F_{earth\ on\ m} = -\frac{Gm_e m}{r_e^2} = -ma$$



with $\mathbf{r} = \mathbf{r_e}$ *near the* *surface* *of the earth*

➔ $$a = \frac{Gm_e}{r_e^2}$$ *acceleration of* $\mathbf{m}$ *due to* $\mathbf{m_e}$ *a distance* $\mathbf{r_e}$ *away*

Notice this expression doesn't contain ***m*** at all!

Gravity

- The magnitude of the acceleration due to the gravity of the earth on an object of mass ***m*** near its surface is:

$m_e = 5.96 \times 10^{24}\ kg$
$r_e = 6.37 \times 10^{6}\ m$

$G = 6.67 \times 10^{-11}\ N\ m^2 / kg^2$
m = mass of the object

$$a = \frac{\left(6.67x10^{-11}\ \frac{N\,m^2}{kg^2}\right)\left(5.96x10^{24}\,kg\right)}{\left(6.37x10^{6}\ m\right)^2}$$

$$a \approx 9.8\frac{m}{s^2} \equiv g$$

g is what we call the acceleration due to '*the*' gravity '*of the earth*'

[*In general, g can represent the acceleration due to gravity of any massive object.*]

Gravity

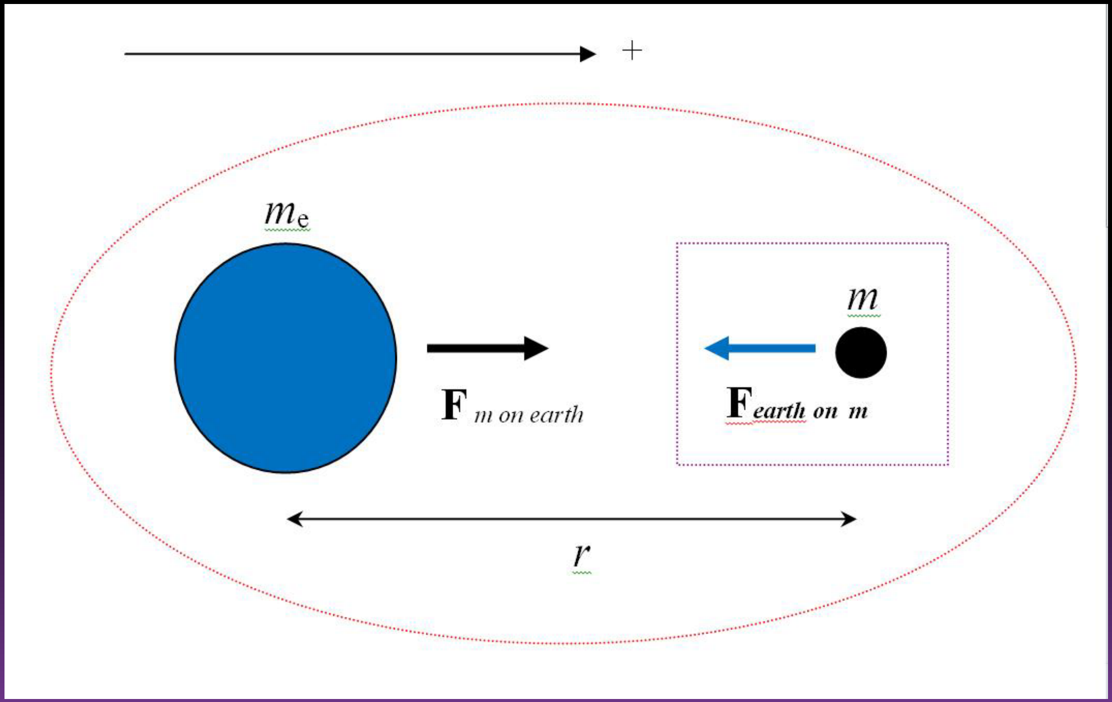
- In general, the acceleration due to gravity produced by ANY object of mass m a distance r away from the center of the mass can be determined by:

$$g \equiv \frac{Gm}{r^2}$$

Gravity

- Is the value of earth's g constant?

$$a \approx 9.8\frac{m}{s^2} \equiv g$$



No, it depends on r_e

$$a = \frac{Gm_e}{r_e^{\,2}}$$

Gravity

- When dealing with the force of gravity on objects, we often use the term weight.

- The weight of an object is a measure of the gravitational force exerted on an object of mass m near the surface of a much larger object

$$F = ma = mg$$

- But we will use the model

$$W = mg$$

Units of weight are the same as force (N)

In the US, we use *lbs* instead of N

$$1\,lb = 4.45N$$

Gravity

- Will an objects weight always be the same?

    No

- Will an objects mass always be the same?

    Yes

Gravity

- What is your weight on Jupiter if you weigh 200 *lbs* (91 *kg*) on the earth?

$m_j = 1.7 \times 10^{27}\ kg$

$r_j = 6.99 \times 10^{7}\ m$

$G = 6.67 \times 10^{-11}\ N\ m^2 / kg^2$

$$g_{jupiter} = \frac{\left(6.67x10^{-11} \frac{N\,m^2}{kg^2}\right)\left(1.7x10^{27}\,kg\right)}{\left(6.99x10^{7}\,m\right)^2}$$

$$g_{jupiter} \approx 25.9 \frac{m}{s^2}$$

2.6 times that of the earth

Gravity

- Your weight would then be:

$$W = mg_{jupiter}$$

$$W = (91kg)\left(25.9\frac{m}{s^2}\right)$$

$$W \approx 2357N$$ (~530 lbs)

For our struggle is not against flesh and blood, but against the rulers, against the authorities, against the powers of this dark world and against the spiritual forces of evil in the heavenly realms.

Ephesians 6:12