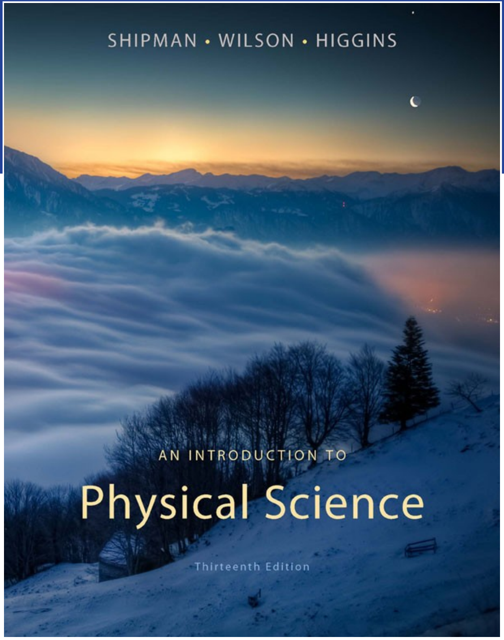

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Chapter 3

Force and Motion

Force and Motion – *Cause and Effect*

- In chapter 2 we studied motion but not its cause.
- In this chapter we will look at both force and motion – the cause and effect.
- We will consider Newton’s:
  - *Newton’s three laws of motion*
  - *Newton’s law of universal gravitation*
  - *Buoyancy and momentum*

Audio Link

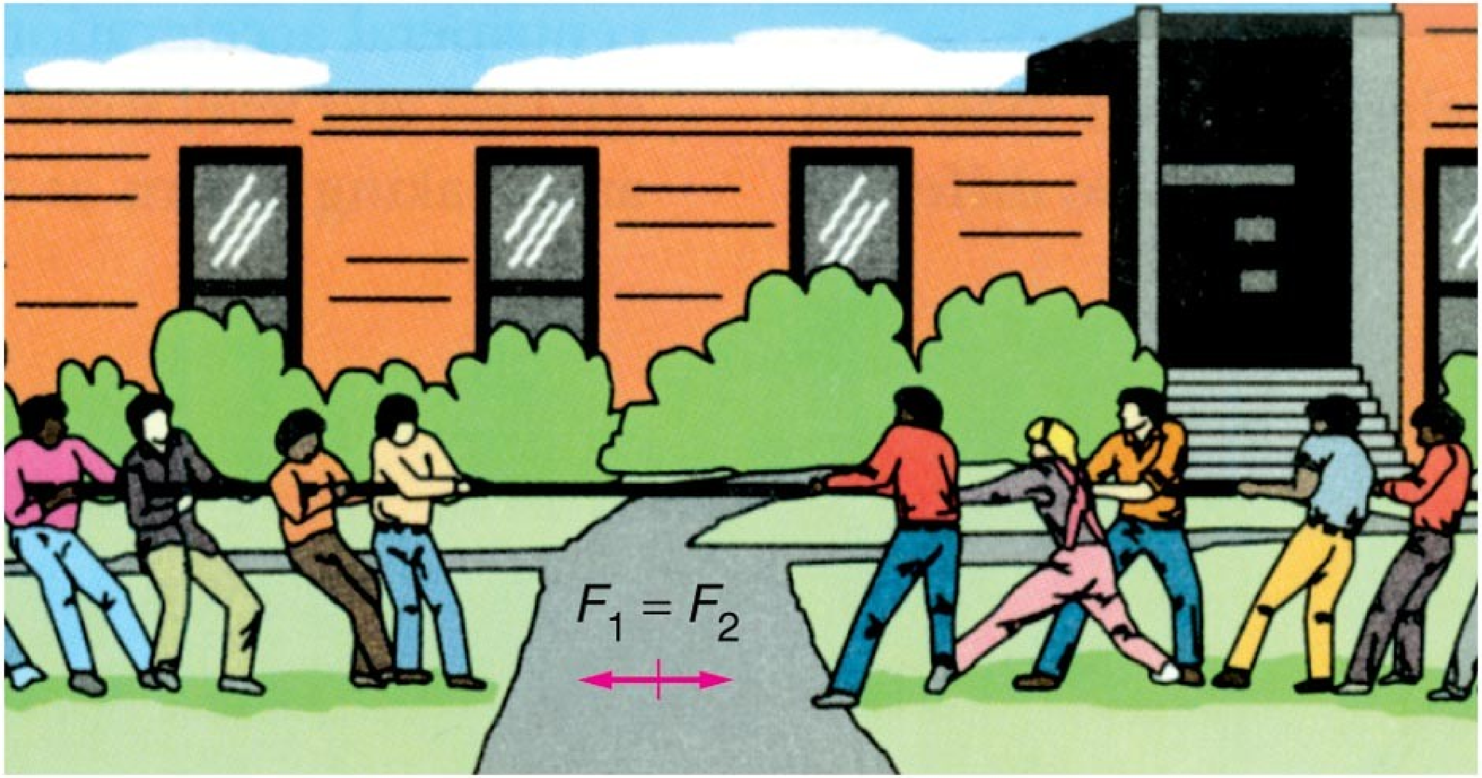
Sir Isaac Newton (1642 – 1727)

- Only 25 when he formulated most of his discoveries in math and physics
- His book *Mathematical Principles of Natural Philosophy* is considered to be the most important publication in the history of Physics.
- Alchemist
- Invented Reflecting Telescope

Force and Net Force

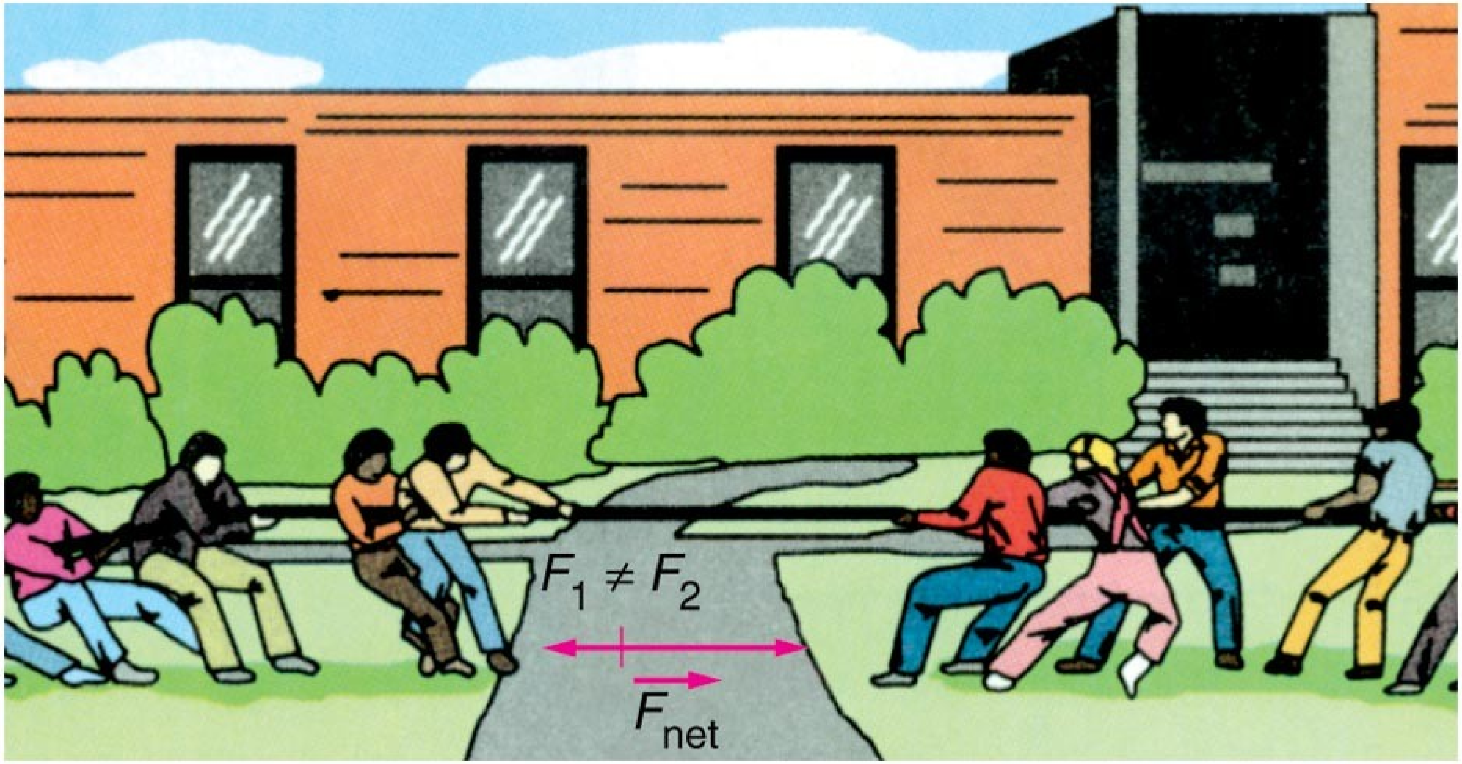
- Force – a vector quantity capable of producing motion or a change in motion
  - *A force is capable of changing an object’s velocity and thereby producing acceleration.*
- A given force may not actually produce a change in motion because other forces may serve to balance or cancel the effect.

Balanced (equal) forces, therefore no motion.



Equal in magnitude but in opposite directions.

Unbalanced forces result in motion



Net force to the right

Before there was Newton

- Aristotle considered the natural state of most matter to be at rest.
- Galileo (1564 – 1642) concluded that objects could naturally remain in motion indefinitely.
- Galileo introduced the idea of inertia, showed the Aristotelean models were wrong (discovered Jupiter's moons, Venus had phases like the moon, Sunspots).
- Galileo would probably be credited with Newton's first law except for the conflict with the Roman Catholic Church hierarchy.

Newton's First Law of Motion

- Newton's 1st Law of Motion – *An object will remain at rest or in uniform motion in a straight line unless acted on by an external, unbalanced force.*

Objects and Newton's 1st Law

- An object will remain at rest or in uniform motion in a straight line unless acted on by an external, unbalanced force.
- Balanced forces have equal magnitude in opposite directions
- An external force is a force applied to the entire object or system.

Motion and Inertia

- Inertia - the natural tendency of an object to remain in a state of rest or in uniform motion in a straight line *(first introduced by Galileo)*
- Basically, objects tend to maintain their state of motion and resist change.
- Newton went one step further and related an object's mass to its inertia.
  - *The greater the mass of an object, the greater its inertia.*
  - *The smaller the mass of an object, the less its inertia.*

Mass and Inertia

The large man has more inertia – more force is necessary to start him swinging and also to stop him – due to his greater inertia

Mass and Inertia

Quickly pull the paper and the stack of quarters tend to stay in place due to inertia.

“Law of Inertia”

- Because of the relationship between motion and inertia:
- Newton’s *First Law of Motion* is sometimes called the *Law of Inertia*.
- Seatbelts help ’correct’ for this law during sudden changes in speed.

Newton's Second law of Motion

- $\textit{Acceleration} \;\alpha\; \dfrac{\textit{Force}}{\textit{mass}}$
- Acceleration (change in velocity) produced by a force acting on an object is directly proportional to the magnitude of the force *(the greater the force the greater the acceleration.)*
- Acceleration of an object is inversely proportional to the mass of the object *(the greater the mass of an object the smaller the acceleration.)*
- $a = F/m$ or $F = ma$

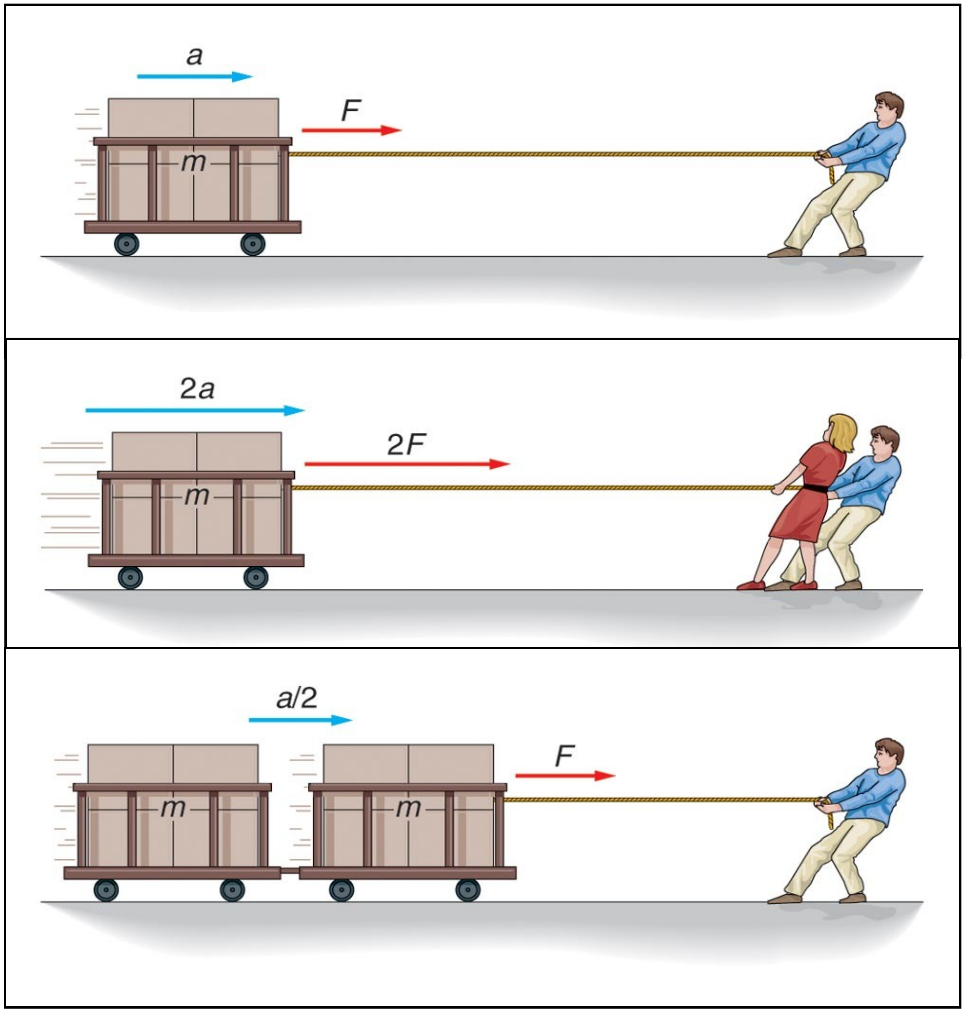
Force, Mass, Acceleration

a) Original situation

$$a \;\alpha\; \frac{F}{m}$$

b) If we double the force we double the acceleration.

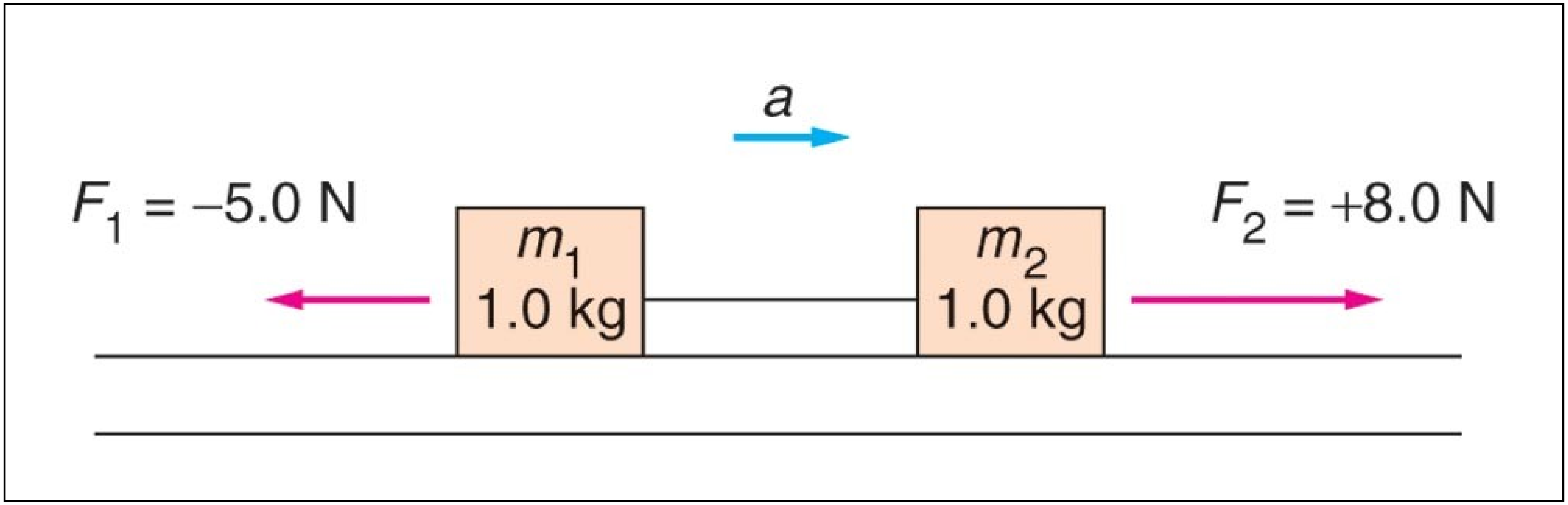
c) If we double the mass we half the acceleration.



F = *ma*

- "*F*" is the net force (unbalanced), which is likely the vector sum of two or more forces.
- "*m*" & "*a*" concern the whole system
- <u>*Units*</u>
- Force = mass x acceleration = kg x m/s^2 = N
- N = kg x m/s^2 = newton -- this is a derived unit and is the metric system (SI) unit of force

Net Force and Total Mass - Example



- *Forces are applied to blocks connected by a string (weightless) resting on a frictionless surface. Mass of each block = 1 kg; F_1 = 5.0 N; F_2 = 8.0 N*
- *What is the acceleration of the system?*

Net Force and Total Mass - Example

- *Forces are applied to blocks connected by a string (weightless) resting on a frictionless surface. Mass of each block = 1 kg; F_1 = 5.0 N; F_2 = 8.0 N. What is the acceleration of the system?*
- GIVEN:
  - m_1 = 1 kg; m_2 = 1 kg
  - F_1 = -5.0 N; F_2 = 8.0 N
- a = ?
- $$\boldsymbol{a} = \frac{F}{m} = \frac{F_{net}}{m_1 + m_2} = \frac{8.0\text{ N} - 5.0\text{ N}}{1.0\text{ kg} + 1.0\text{ kg}} = \mathbf{1.5\ m/s^2}$$

Mass & Weight

- Mass = amount of matter present
- Weight = related to the force of gravity
- Earth: weight = mass x acc. due to gravity
- w = mg (special case of $F = ma$) Weight is a force due to the pull of gravity.
- Therefore, one’s weight changes due to changing pull of gravity – like between the Earth and Moon.
- Moon’s gravity is only 1/6th that of Earth’s.

Computing Weight – an example

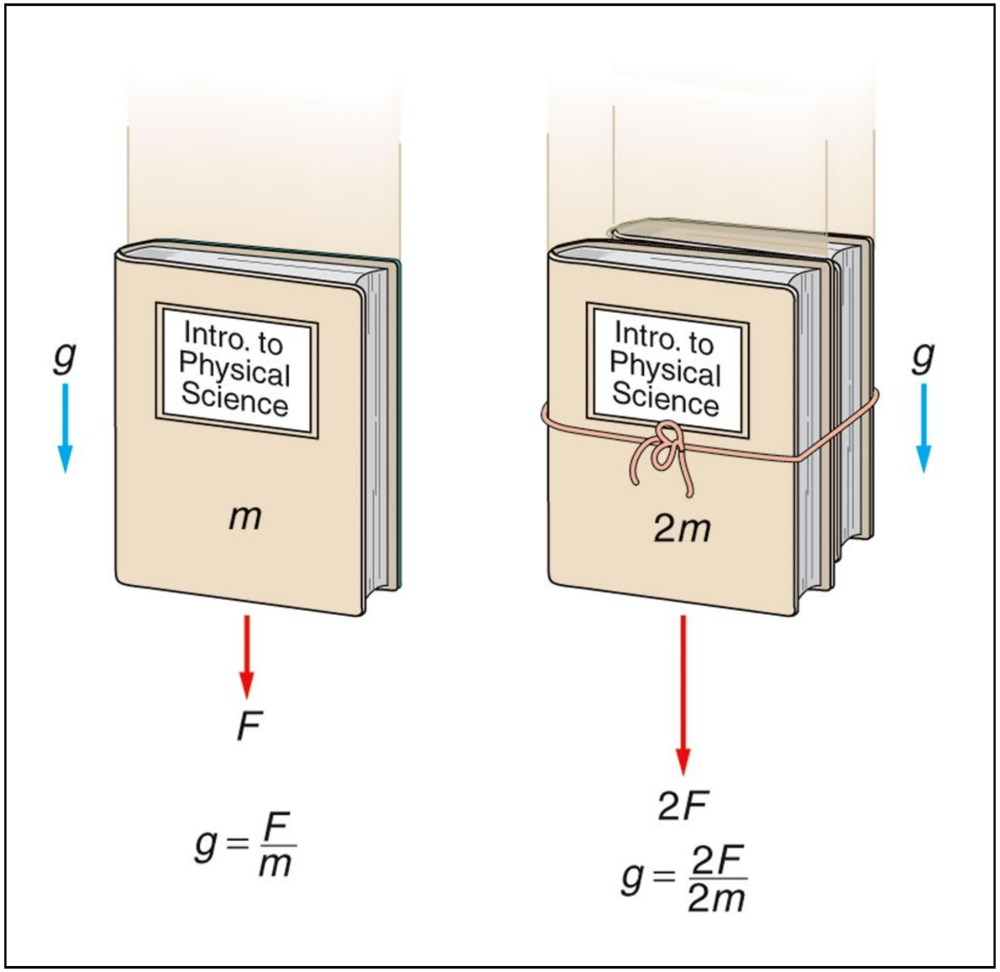
What is the weight of a 2.45 kg mass on (a) Earth, and (b) the Moon?

Computing Weight – *an example*

- *What is the weight of a 2.45 kg mass on (a) Earth, and (b) the Moon?*
- Use Equation $w = mg$
- Earth: $w = mg$ = (2.45 kg) (9.8 m/s^2) = $\underline{\text{24.0 N}}$ (*or* 5.4 lb. Since 1 lb = 4.45 N)
- Moon: $w = mg$ = (2.45 kg) [(9.8 m/s^2)/6] = $\underline{\text{4.0 N}}$ (*or* 0.9 lb.)

Acceleration due to gravity is *independent* of the mass.

Both *F* & *m* are doubled, resulting in *g* remaining constant.



Friction

- <u>Friction</u> – resistance to relative motion that occurs whenever two materials are in contact with each other.
  - Ever-present and found in all states (solids, liquids, and gases) of matter
- In some cases we want to increase friction (sand on ice), in other cases we want to reduce friction (motor oil).

Audio Link

Two Types of Friction

- Static friction occurs when the frictional force is sufficient to prevent relative motion between surfaces
- Kinetic (or sliding) friction occurs when there is relative motion between surfaces in contact.
- Kinetic friction is generally less than static friction
  - Usually it takes less force to keep something moving than to start it moving.

Coefficients of Friction

- Coefficients of friction (μ) are dimensionless quantities used to characterize particular contact situations.
- Both, coefficients of static friction (μ_s) and coefficients of kinetic friction (μ_k) are determined experimentally for a wide range of contact surfaces.
- Usually (μ_s) > (μ_k).

Approximate values for Coefficients of Static and Kinetic Friction between several surfaces

Table 3.1 Approximate Values for Coefficients of Static and Kinetic Friction between Certain Surfaces

Friction between Materials	μ_s	μ_k
Aluminum on aluminum	1.90	1.40
Aluminum on steel	0.61	0.47
Teflon on steel	0.04	0.04
Rubber on concrete		
dry	1.20	0.85
wet	0.80	0.60
Wood on wood	0.58	0.40
Lubricated ball bearings	< 0.01	< 0.01

Newton's Third Law of Motion

- For every action there is an equal and opposite reaction.

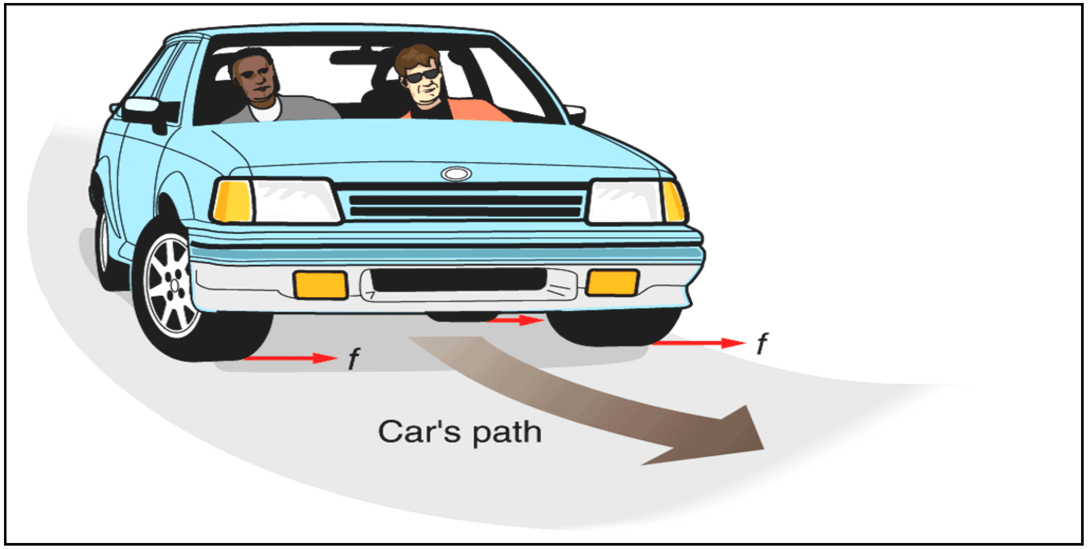
or

- Whenever on object exerts a force on a second object, the second object exerts an equal and opposite force on the first object.
- action = opposite reaction
- $F_1 = -F_2$ or $m_1a_1 = -m_2a_2$

Newton’s Third Law of Motion

- $F_1 = -F_2$ or $m_1 a_1 = -m_2 a_2$
- <u>Jet propulsion</u> – exhaust gases in one direction and the rocket in the other direction
- <u>Gravity</u> – jump from a table and you will accelerate to Earth. In reality BOTH you and the Earth are accelerating towards each other
  - *You – small mass, huge acceleration* $(m_1 a_1)$
  - *Earth – huge mass, very small acceleration* $(-m_2 a_2)$
  - *BUT* → $m_1 a_1 = -m_2 a_2$

Newton's Laws in Action



- Friction on the tires provides necessary centripetal acceleration.
- Passengers continue straight ahead in original direction and as car turns the door comes toward passenger – 1st Law
- As car turns you push against door and the door equally pushes against you – 3rd Law

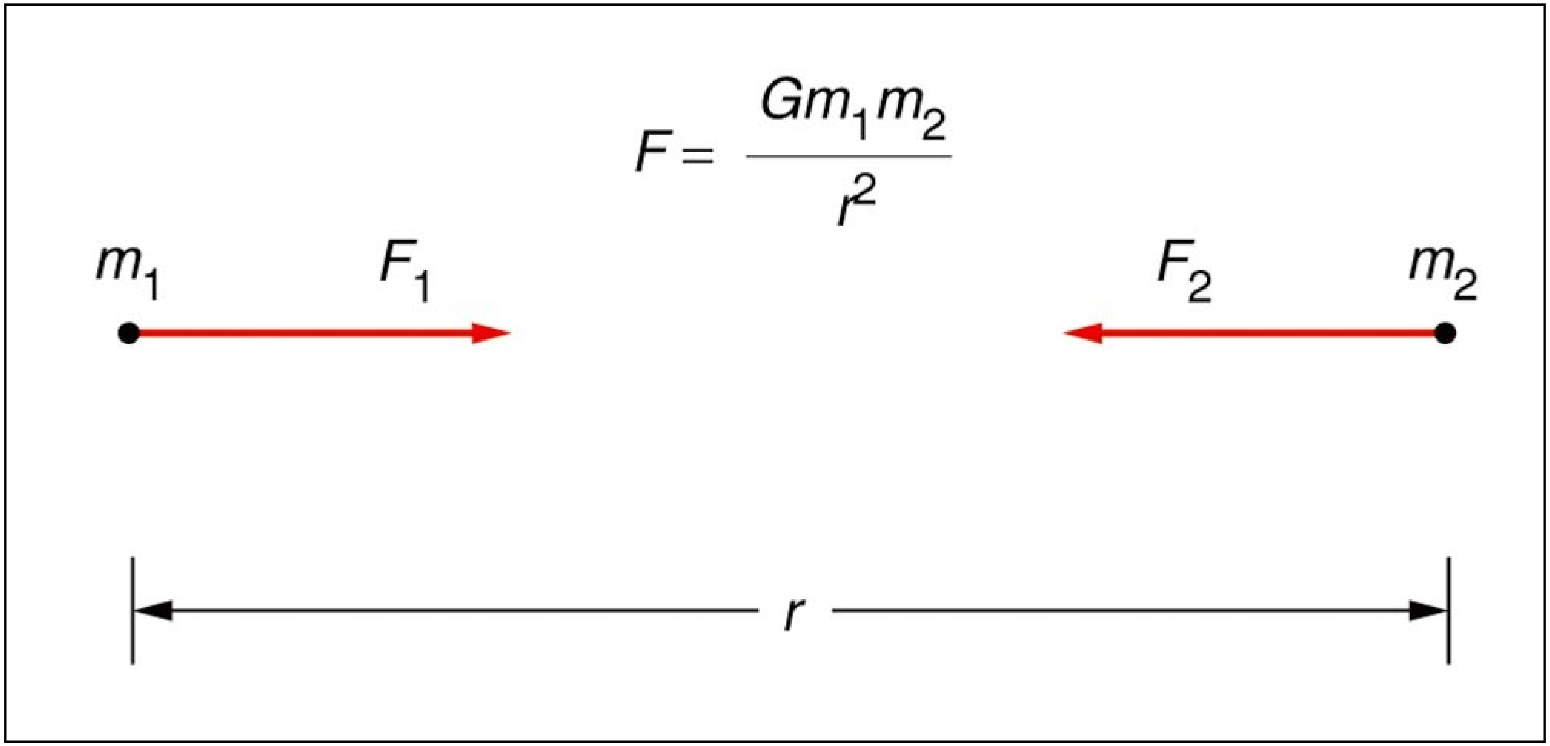
Newton’s Law of Gravitation

- Gravity is a *fundamental force* of nature
  - We do not know what causes it
  - We can only describe it
- Law of Universal Gravitation – Every particle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them

Newton’s Law of Gravitation

- Equation form: $F = \dfrac{Gm_1m_2}{r^2}$
- G is the universal gravitational constant
- $G = 6.67 \times 10^{-11}\ N{\cdot}m^2/kg^2$
- G:
  - *is a very small quantity*
  - *thought to be valid throughout the universe*
  - *was measured by Cavendish 70 years after Newton’s death*
  - *not equal to “g” and not a force*

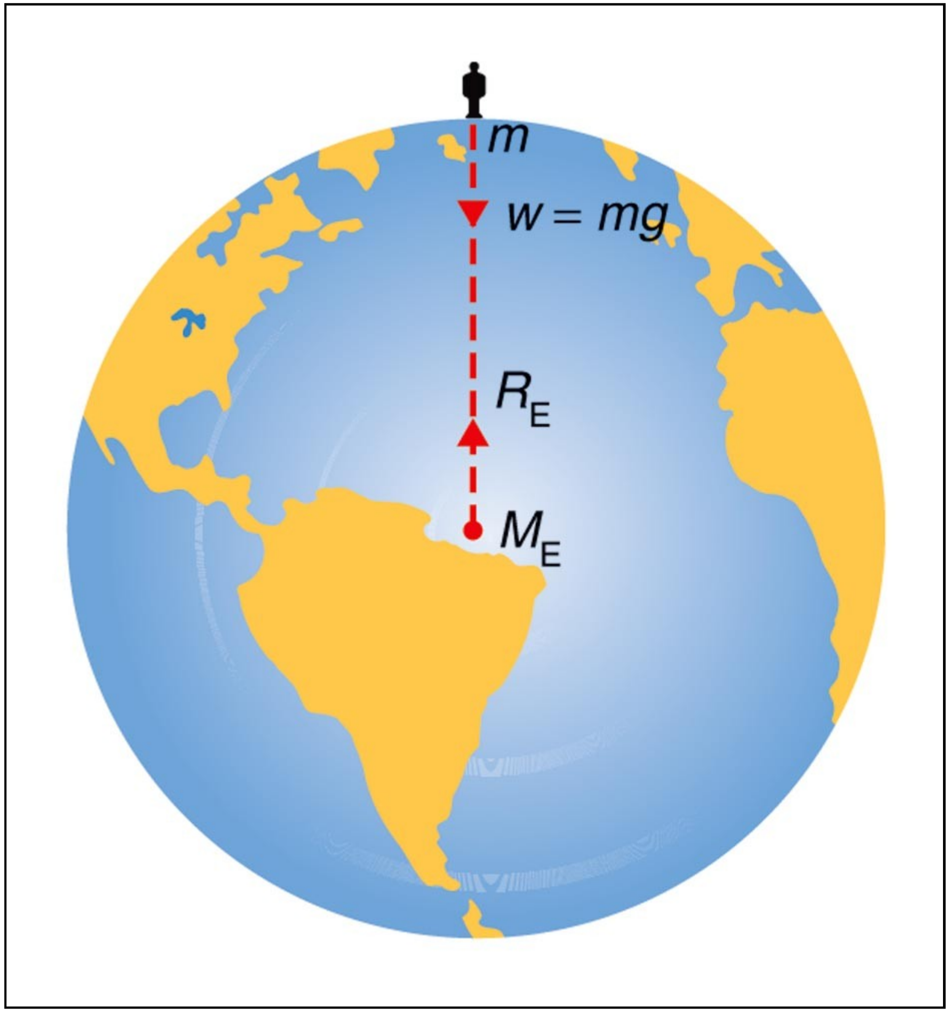
Newton's Law of Gravitation



- The forces that attract particles together are equal and opposite
- $F_1 = -F_2$ or $m_1a_1 = -m_2a_2$

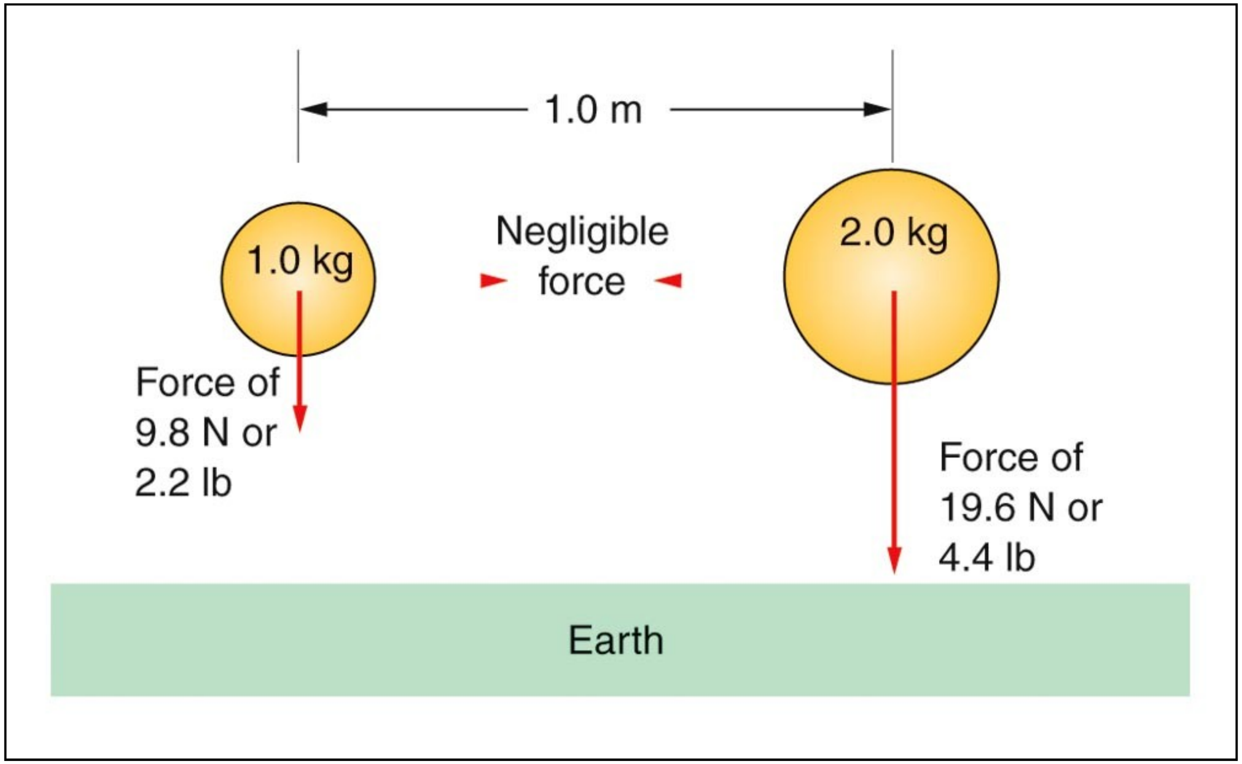
Newton's Law of Gravitation

- $F = \dfrac{Gm_1m_2}{r^2}$
- For a homogeneous sphere the gravitational force acts as if all the mass of the sphere were at its center



Applying Newton's Law of Gravitation

- Two objects with masses of 1.0 kg and 2.0 kg are 1.0 m apart. What is the magnitude of the gravitational force between the masses?



Applying Newton's Law of Gravitation – *Example*

- Two objects with masses of 1.0 kg and 2.0 kg are 1.0 m apart. What is the magnitude of the gravitational force between the masses?
- $F = \dfrac{Gm_1m_2}{r^2}$
- $F = \dfrac{(6.67 \times 10^{-11}\ \text{N-}\cancel{\text{m}^2}/\cancel{\text{kg}^2})(1.0\ \cancel{\text{kg}})(2.0\ \cancel{\text{kg}})}{(1.0\ \cancel{\text{m}})^2}$
- $F = \underline{1.3 \times 10^{-10}\ \text{N}}$

Force of Gravity on Earth

- $F = \dfrac{GmM_E}{R^2_E}$ [force of gravity on object of mass m]
- M_E and R_E are the mass and radius of Earth
- This force is just the object's weight ($w = mg$)
- $\therefore\ w = \cancel{m}g = \dfrac{G\cancel{m}M_E}{R_E^{\,2}}$
- $g = \dfrac{GM_E}{R^2_E}$
- m cancels out $\therefore$ g is independent of mass

"Weightlessness" in space is the result of both the astronaut and the spacecraft 'falling' to Earth at the same rate

Buoyancy

- Buoyant force – the upward force resulting from an object being wholly or partially immersed in a fluid.
- The Archimedes' Principle – An object immersed in a fluid experiences a buoyant force equal to the weight of the volume of fluid displaced.
- Both liquids and gases are considered fluids.

Buoyancy

- The buoyant force depends on the weight of the fluid displaced.
  - The weight of the fluid displaced depends on the density of the fluid and the volume displaced.
- Salt water is denser than fresh water.
  - Therefore, one floats higher in salt water, since one needs to displace less salt water to equal one’s weight.

Examples of Buoyancy

- Ships float because the average density of the ship is less than the water it would displace.
- Oil floats on water, since oil is less dense than water
- Cream floats on milk, since cream is less dense than milk.
- By taking in, or pumping out water, submarines can vary their buoyancy.

Momentum

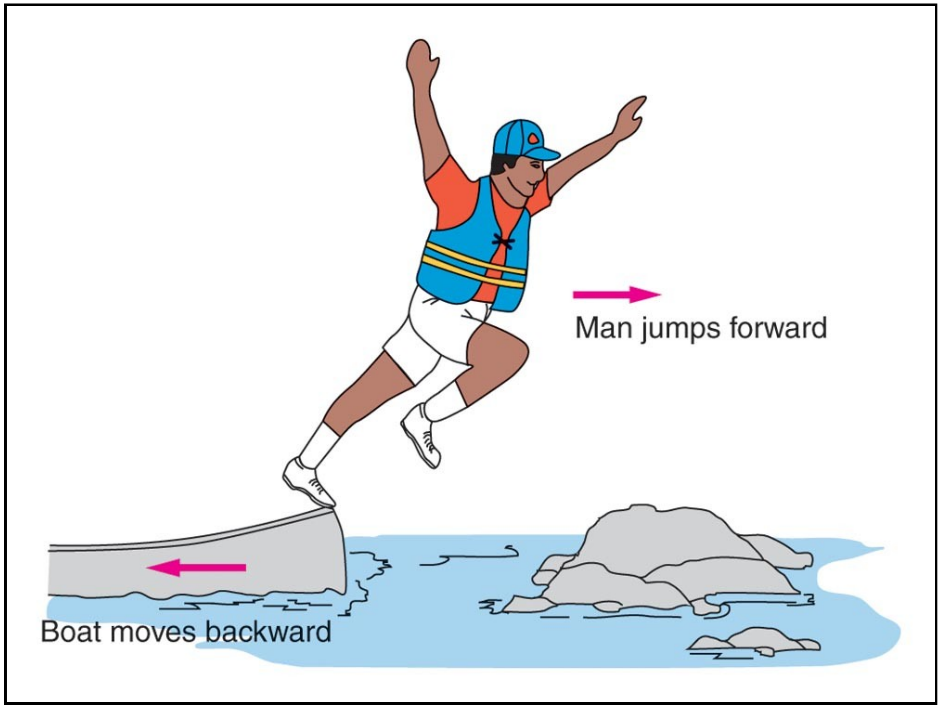
- <u>Linear momentum</u> = mass x velocity
- $p = mv$
- If we have a system of masses, the linear momentum is the sum of all individual momentum vectors.
- $P_f = P_i$ (final = initial)
- $P = p_1 + p_2 + p_3 + \ldots$ (sum of the individual momentum vectors)

Audio Link

Law of Conservation of Linear Momentum

- <u>Law of Conservation of Linear Momentum</u> - the total linear momentum of an isolated system remains the same if there is no external, unbalanced force acting on the system
- Linear Momentum is ’conserved’ as long as there are no external unbalanced forces.
  - *It does not change with time.*

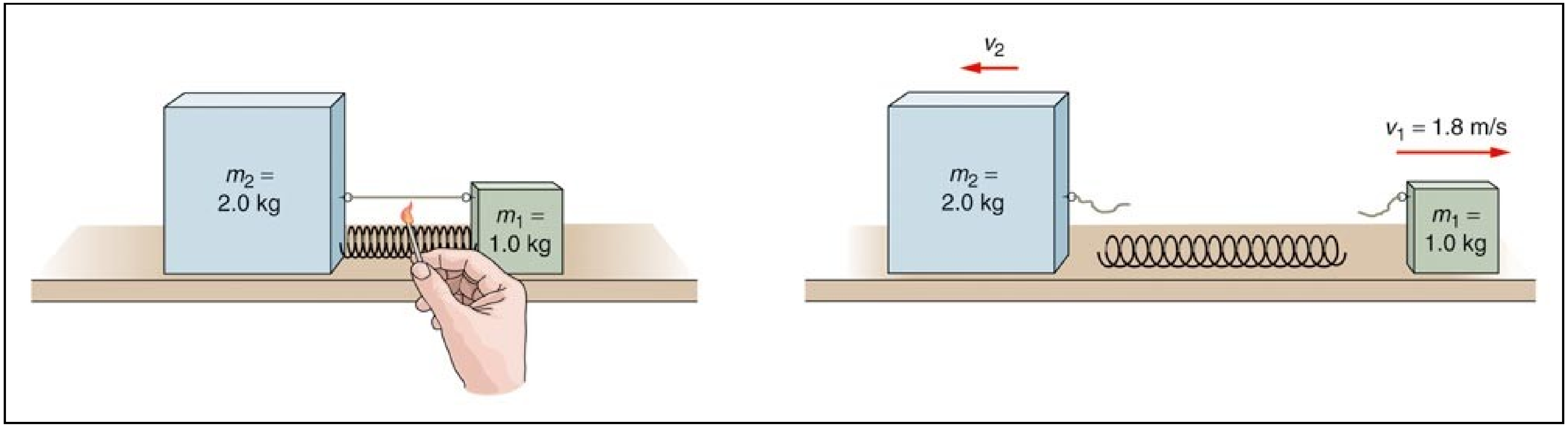
Conservation of Linear Momentum



- $P_i = P_f = 0$ (for man and boat)
- When the man jumps out of the boat he has momentum in one direction and, therefore, so does the boat.
- Their momentums must cancel out! (= 0)

Applying the Conservation of Linear Momentum

- *Two masses at rest on a frictionless surface. When the string (weightless) is burned the two masses fly apart due to the release of the compressed (internal) spring (v_1 = 1.8 m/s).*



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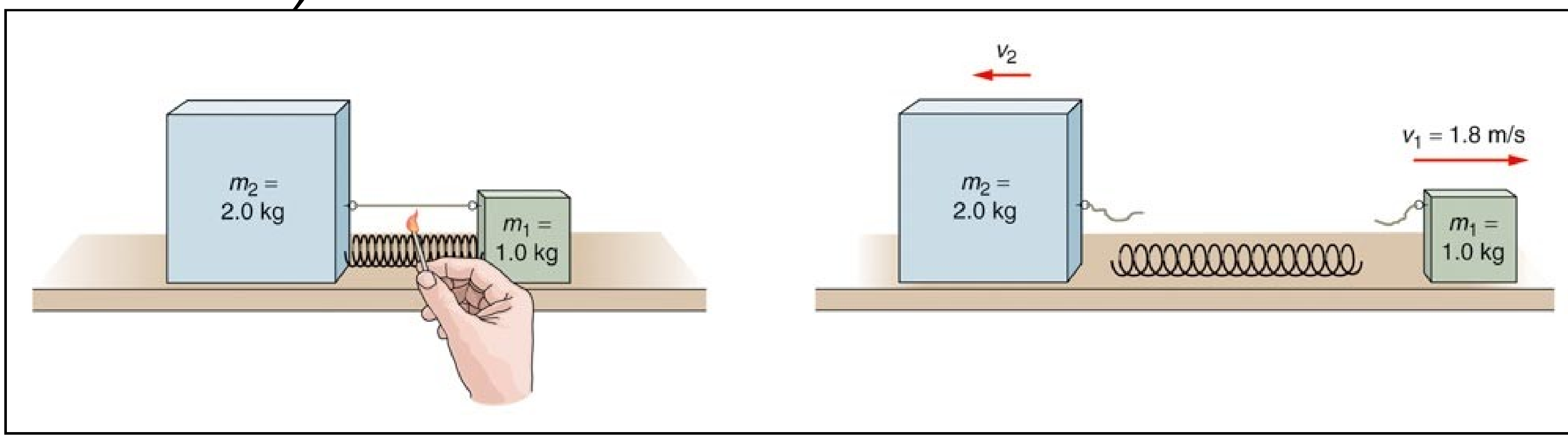
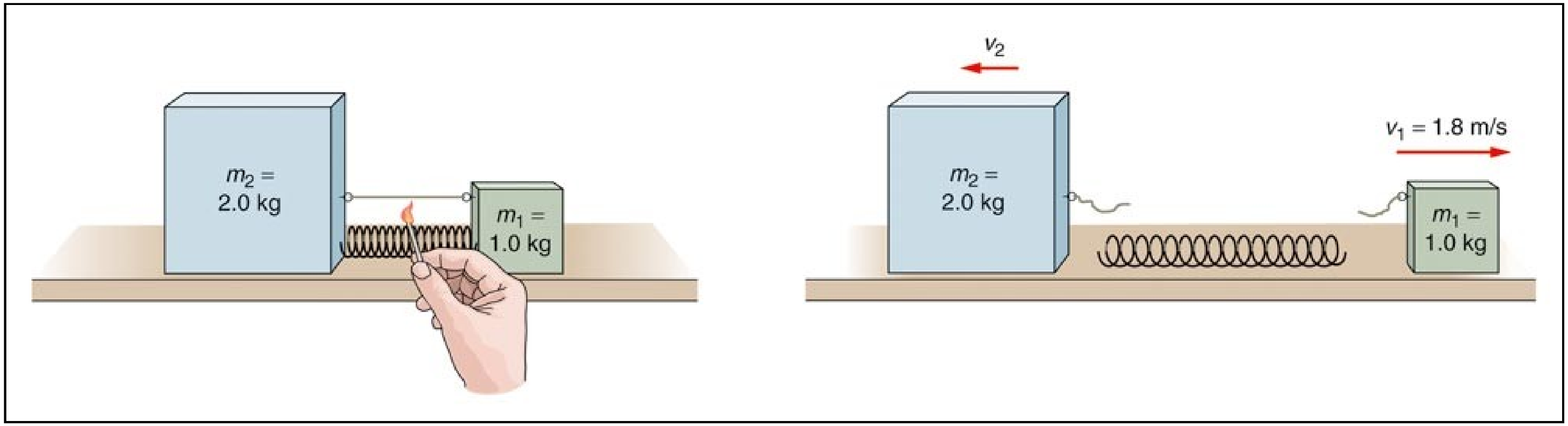


GIVEN:

- m_1 = 1.0 kg
- m_2 = 2.0 kg
- v_1 = 1.8 m/s, v_2 = ?

- $P_f = P_i = 0$
- $P_f = p_1 + p_2 = 0$
- $p_1 = -p_2$
- $m_1v_1 = -m_2v_2$

Applying the Conservation of Linear Momentum



$$m_1 v_1 = -m_2 v_2$$

$$\rightarrow \; v_2 = -\frac{m_1 v_1}{m_2} = -\frac{(1.0\ \text{kg})\,(1.8\ \text{m/s})}{2.0\ \text{kg}} = \underline{-0.90\ \text{m/s}}$$

Jet Propulsion

- Jet Propulsion can be explained in terms of both Newton's 3rd Law & Linear Momentum
- $p_1 = -p_2 \rightarrow m_1 v_1 = -m_2 v_2$
- The exhaust gas molecules have small *m* and large *v*.
- The rocket has large *m* and smaller *v*.
- BUT $\rightarrow$ $m_1 v_1 = -m_2 v_2$ (momentum is conserved)

Angular Momentum

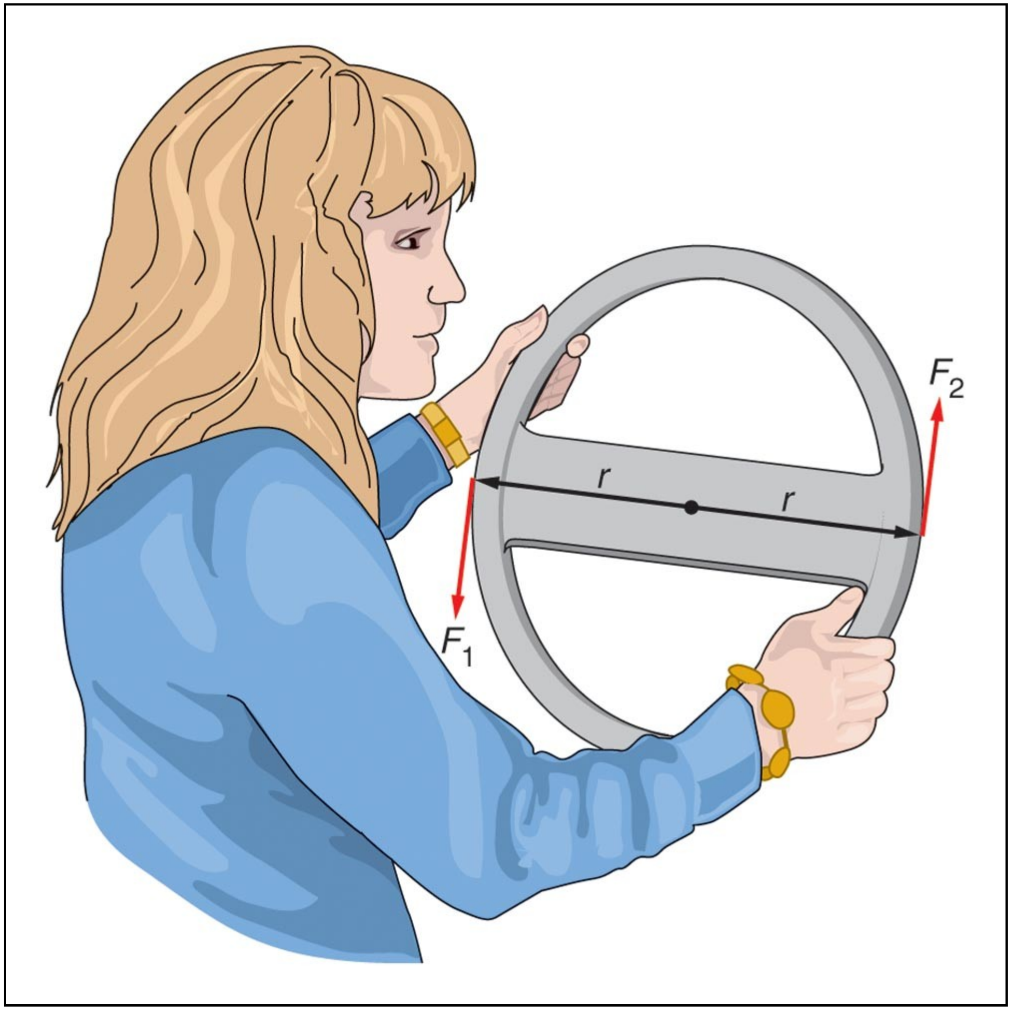
- $L = mvr$
- L = angular momentum, m = mass, v = velocity, and r = distance to center of motion
- $L_1 = L_2$
- $m_1v_1r_1 = m_2v_2r_2$

Torque

- Torque – the twisting effect caused by one or more forces
- As we have learned, the linear momentum of a system can be changed by the introduction of an external unbalanced force.
- Similarly, angular momentum can be changed by an external unbalanced torque.

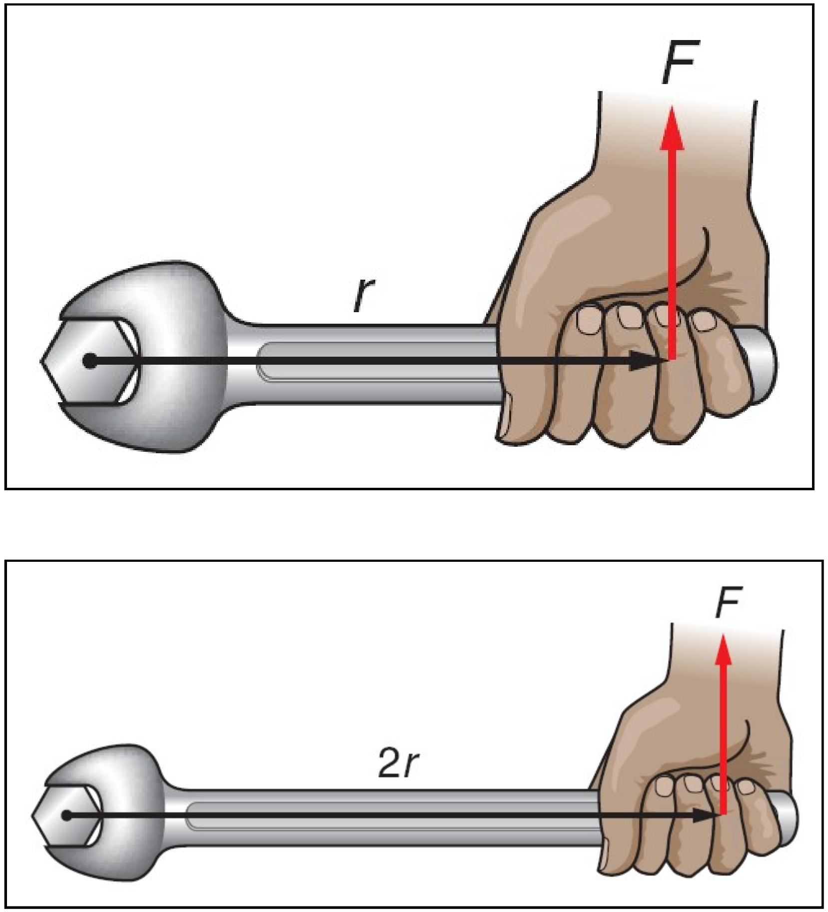
Torque

- Torque is a twisting action that produces rotational motion or a change in rotational motion.



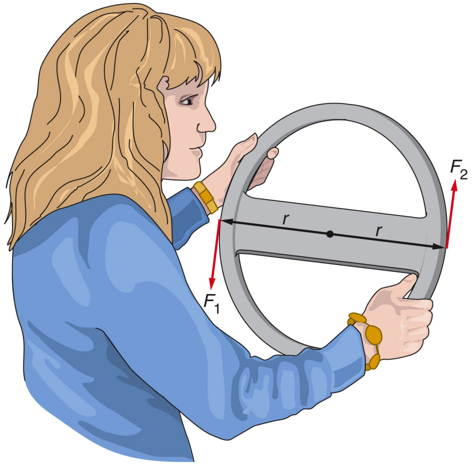
Torque and Lever Arm

- Torque varies with the length of the lever arm. As the length of the lever arm is doubled, the torque is doubled, for a given force.



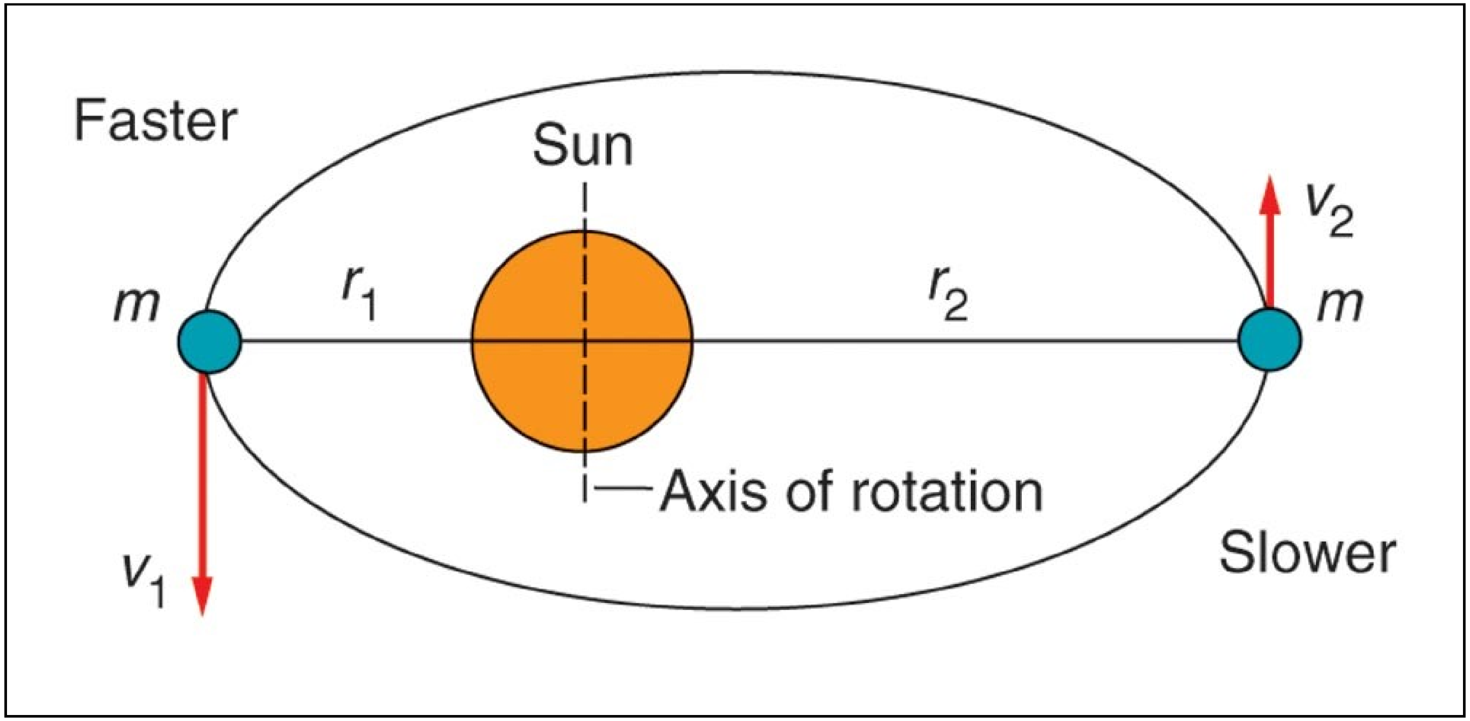
Law of Conservation of Angular Momentum

- Law of Conservation of Angular Momentum - the angular momentum of an object remains constant if there is no external, unbalanced torque (a force about an axis) acting on it



- Concerns objects that go in paths around a fixed point, for example a comet orbiting the Sun

Angular Momentum – Example planets in the Solar System



- Mass (*m*) is constant. Planet orbit paths are slightly elliptical, therefore both *r* and *v* will slightly vary during a complete orbit.
- As *r* changes so must *v*. When *r* decreases, *v* must increase so that $m_1 v_1 r_1 = m_2 v_2 r_2$

Conservation of Angular Momentum Example

- A comet at its farthest point from the Sun is 900 million miles, traveling at 6000 mi/h. What is its speed at its closest point of 30 million miles away?
- EQUATION: $m_1 v_1 r_1 = m_2 v_2 r_2$
- GIVEN: v_2, r_2, r_1, and $m_1 = m_2$
- FIND: $v_1 = \dfrac{v_2 r_2}{r_1} = \dfrac{(6.0 \times 10^3 \text{ mi/h})\ (900 \times 10^6\ \cancel{\text{mi}})}{30 \times 10^6\ \cancel{\text{mi}}}$
- 1.8×10^5 mi/h or 180,000 mi/h

Conservation of Angular Momentum

Rotors on large helicopters rotate in the opposite direction

Conservation of Angular Momentum

- Figure Skater – she/he starts the spin with arms out at one angular velocity. Simply by pulling the arms in the skater spins faster, since the average *radial distance of the mass decreases.*
- $m_1v_1r_1 = m_2v_2r_2$
- *m* is constant; *r* decreases;
- Therefore *v* increases

Chapter 3 - Important Equations

- $F = ma$ (2nd Law) or $w = mg$ (for weight)
- $F_1 = -F_2$ (3rd Law)
- $F = (Gm_1m_2)/r^2$ (Law of Gravitation)
- $G = 6.67 \times 10^{-11}$ Nm^2/kg^2 (gravitational constant)
- $g = GM/r^2$ (*acc.* of gravity, M=mass of sph. object)
- $p = mv$ (linear momentum)
- $P_f = P_i$ (conservation of linear momentum)
- $L = mvr$ (angular momentum)
- $L_1 = m_1v_1r_1 = L_2 = m_2v_2r_2$ (Cons. of Ang. Mom.)