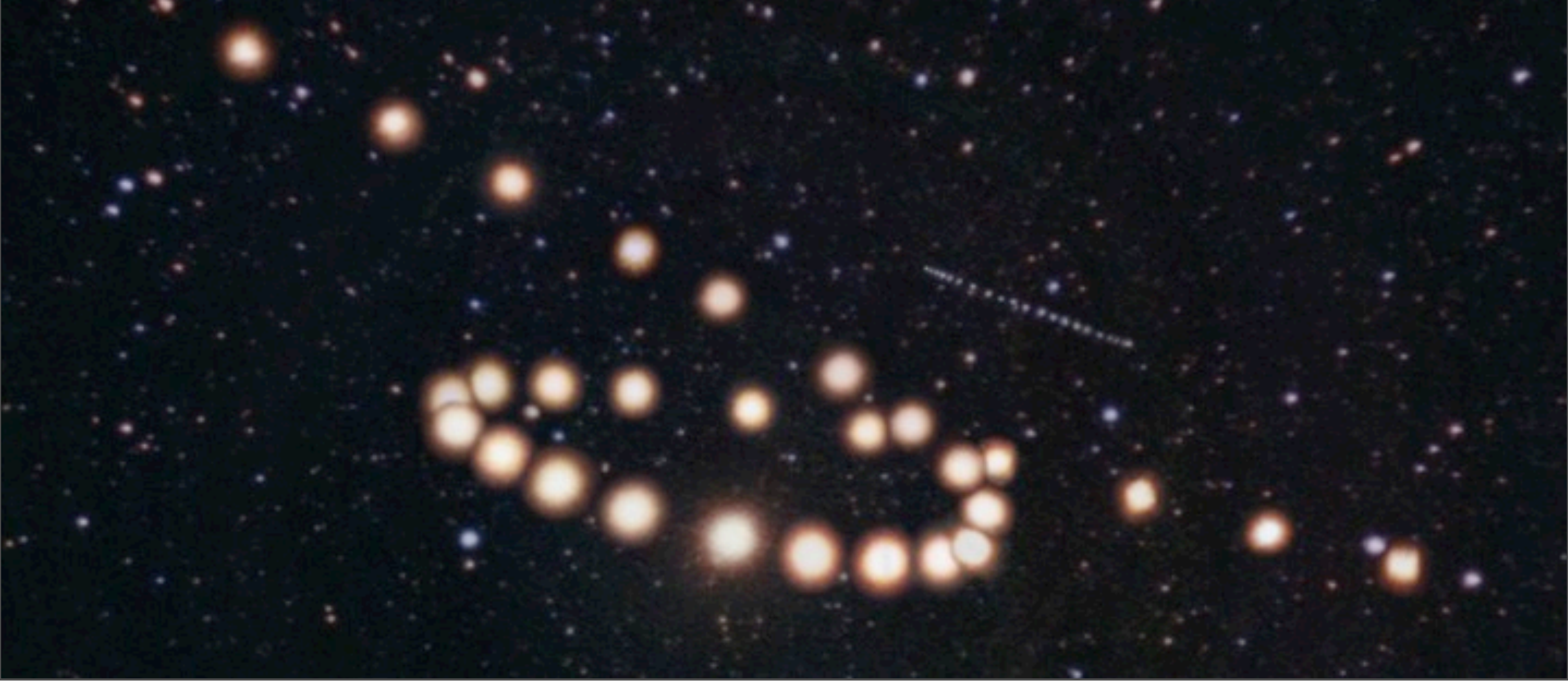
Making Sense of the Universe: Understanding Motion, Energy, and Gravity

1. Newton’s Laws
2. Conservation Laws
   - Energy
   - Angular momentum
3. Gravity


DON'T
LET
GO
SANDRA BULLOCK
GEORGE CLOONEY
FROM DIRECTOR ALFONSO CUARÓN
GRAVITY

Review from last time

- Ancient Greeks: Ptolemy; the geocentric model
  - addressed problem of retrograde motion with complicated explanations: circles on circles (on circles, ad nauseam)

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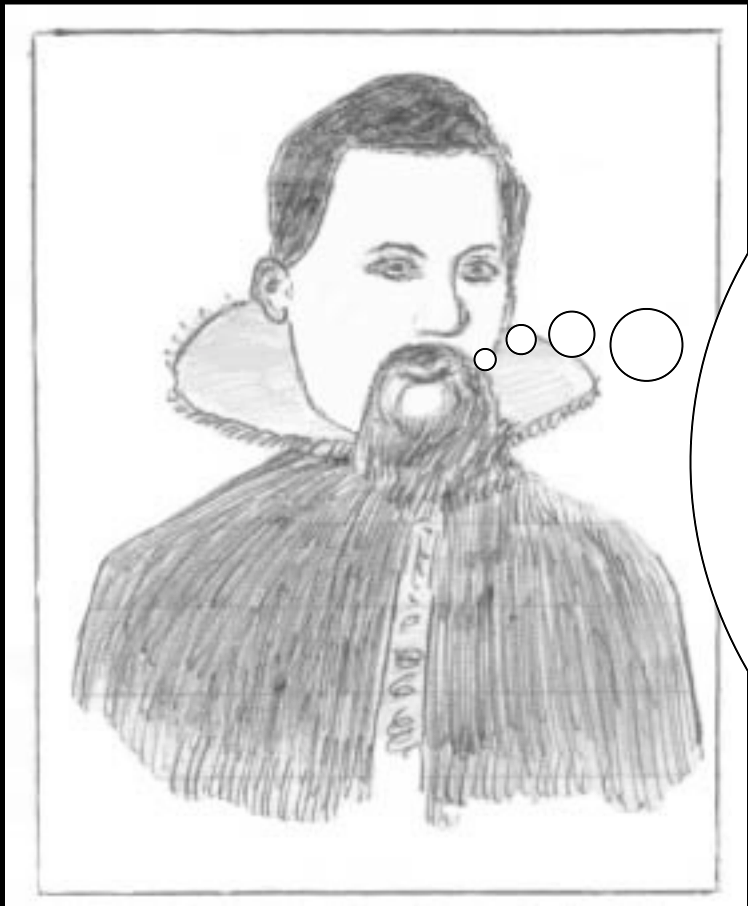


1. ellipses
2. equal areas in equal times
3. $p^2 = a^3$

p = orbital period in years

a = avg. distance from Sun in AU

4.1 Describing Motion: Examples from Daily Life

- Our goals for learning:
  - **How do we describe motion?**
  - **How is mass different from weight?**

How do we describe motion?

Speed: Rate at which an object moves

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

e.g. 10 m/s

Velocity: Speed and direction

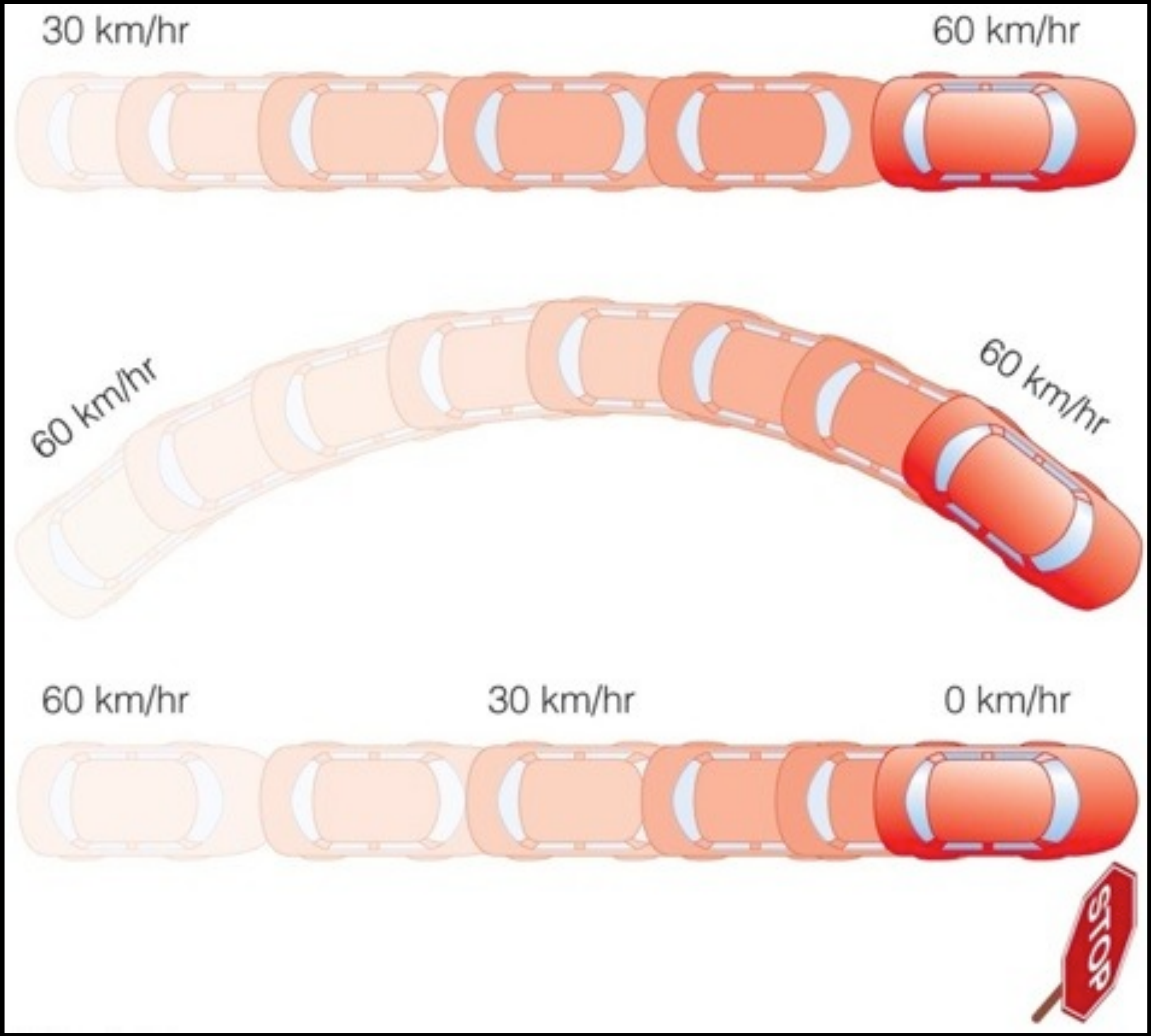
e.g. 10 m/s, due east

Acceleration: Any change in velocity even if only direction is changing

$$\text{acceleration} = \frac{\text{speed}}{\text{time}} = \frac{\text{distance/time}}{\text{time}}$$

e.g. 2 m/s^2

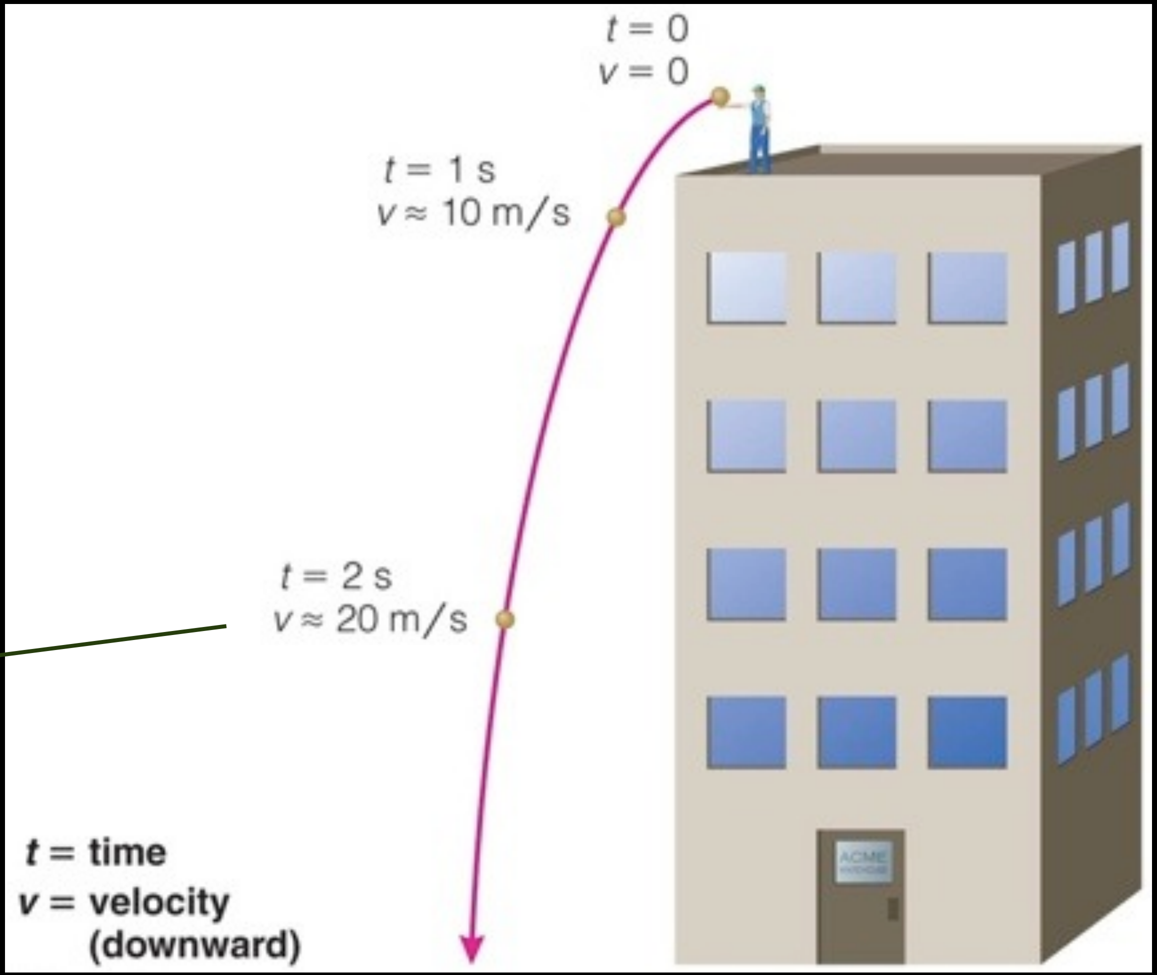
Speed, Velocity, Acceleration



Acceleration Due to Gravity

- All falling objects accelerate at the same rate (if you ignore air resistance):

$g \approx 10\ m/s^2$



The Acceleration of Gravity (g)

- Galileo showed that *g* is the *same* for all falling objects, regardless of their mass.

Momentum and Force

momentum = mass x velocity

- A **net force** changes momentum, which generally means an acceleration (change in velocity).

net force ⟶ change in momentum

- Rotational momentum of a spinning or orbiting object is known as **angular momentum.**

Thought Question

For each of the following is there a net force? Y/N

A car coming to a stop

A bus speeding up

An elevator moving up at constant speed

A bicycle going around a curve

A moon orbiting Jupiter

Thought Question

For each of the following is there a net force? Y/N

A car coming to a stop: Y

A bus speeding up: Y

An elevator moving up at constant speed: N

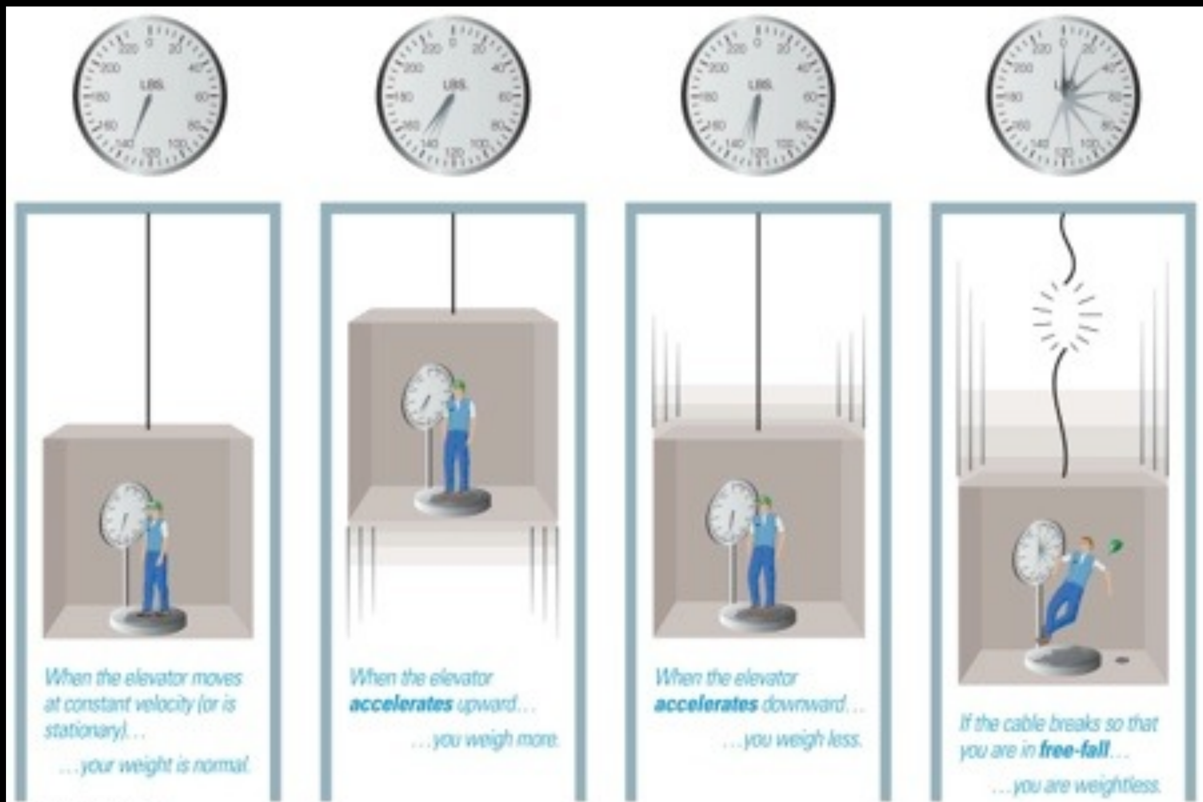
A bicycle going around a curve: Y

A moon orbiting Jupiter: Y

How is mass different from weight?

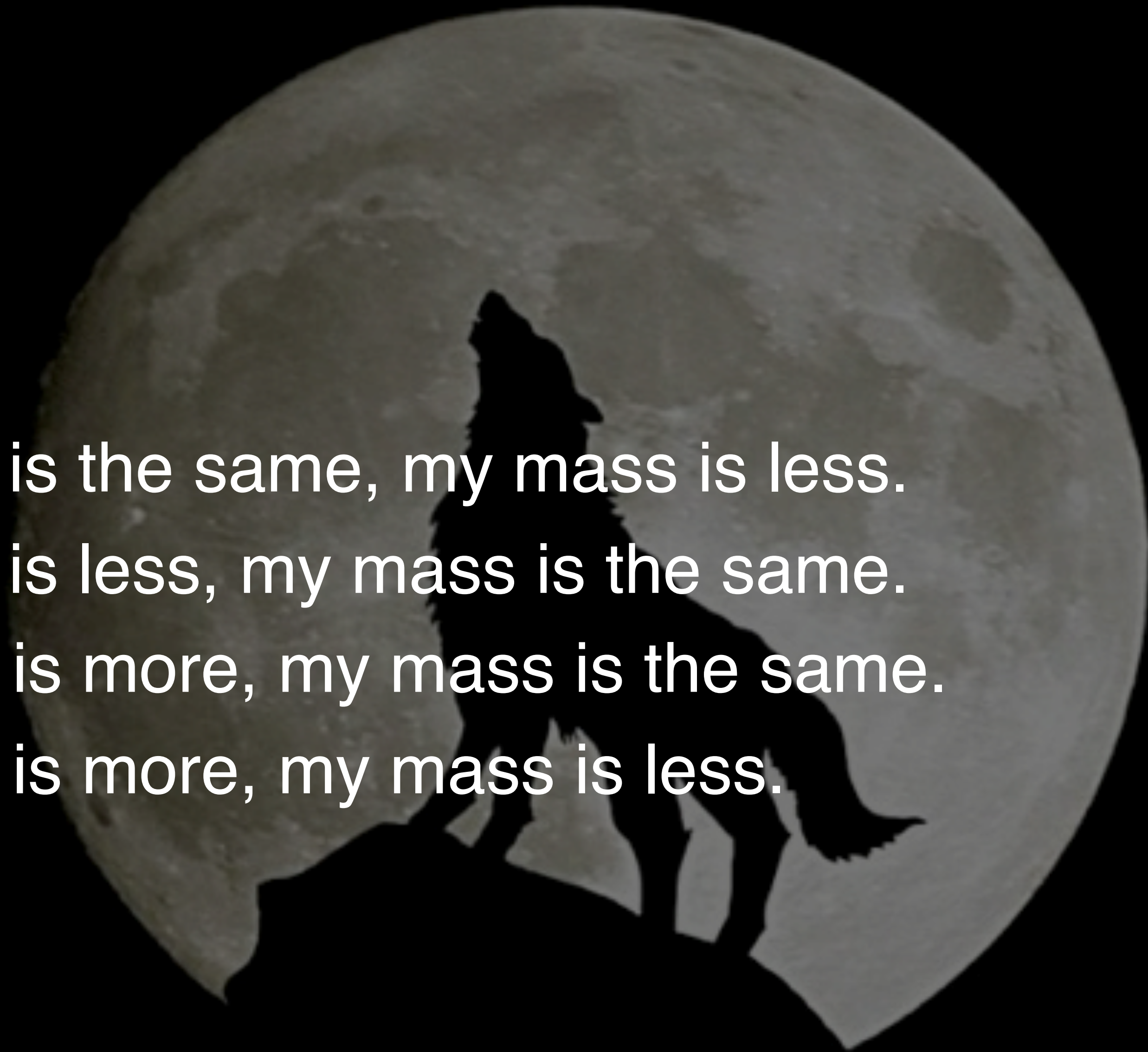
Mass – the amount of matter in an object

Weight – the *force* that acts upon an object



You are weightless in freefall.

Thought Question



On the Moon:

A. My weight is the same, my mass is less.
B. My weight is less, my mass is the same.
C. My weight is more, my mass is the same.
D. My weight is more, my mass is less.

Thought Question

On the Moon:

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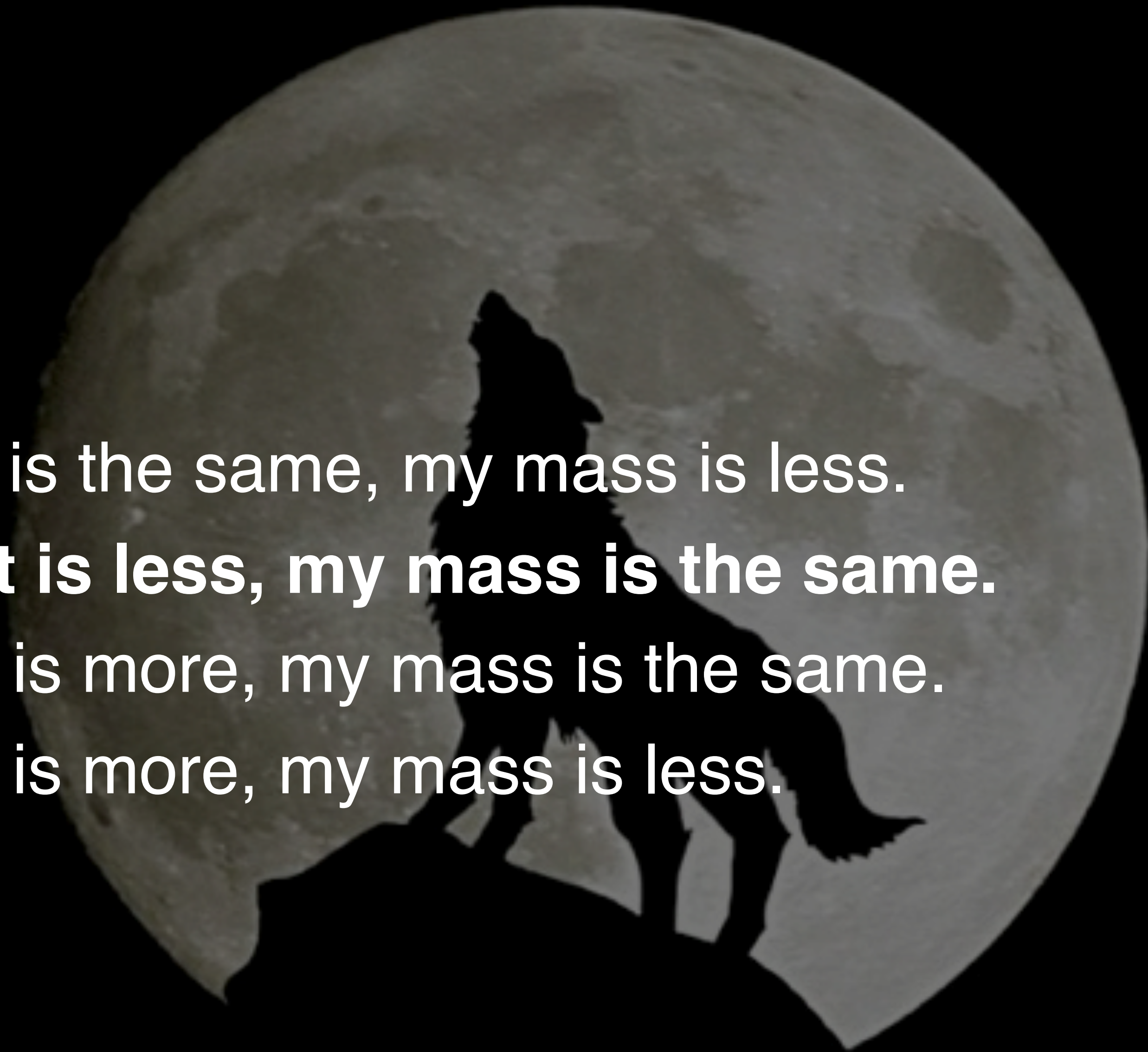
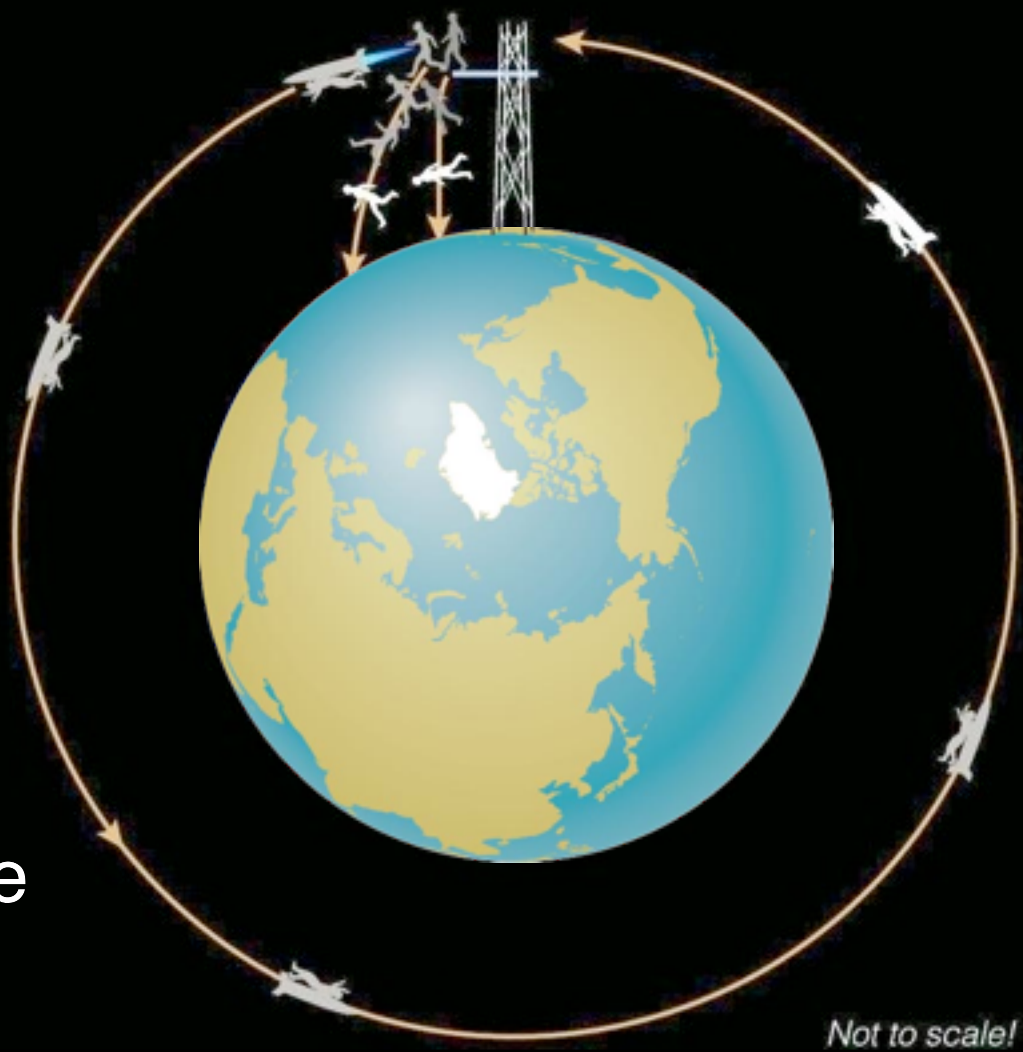


Why are astronauts weightless in space?

Why are astronauts weightless in space?



- There *is* gravity in space.
- Weightlessness is due to a constant state of free-fall.

What have we learned?

How do we describe motion?

– Speed = distance/time

– Speed and direction => **velocity**

– Change in velocity => **acceleration**

Momentum = mass x velocity

Force causes change in momentum, producing acceleration.

What have we learned?

How is mass different from weight?

– Mass = quantity of matter

– Weight = force acting on mass

– Objects are weightless in free-fall.

4.2 Newton's Laws of Motion

- Our goals for learning:
  - **How did Newton change our view of the universe?**
  - **What are Newton's three laws of motion?**

How did Newton change our view of the universe?

- Realized the same physical laws that operate on Earth also operate in the heavens
  - one *universe*
- Realized laws of motion and gravity
- Much more: experiments with light, first reflecting telescope, calculus…

Sir Isaac Newton (1642–1727)

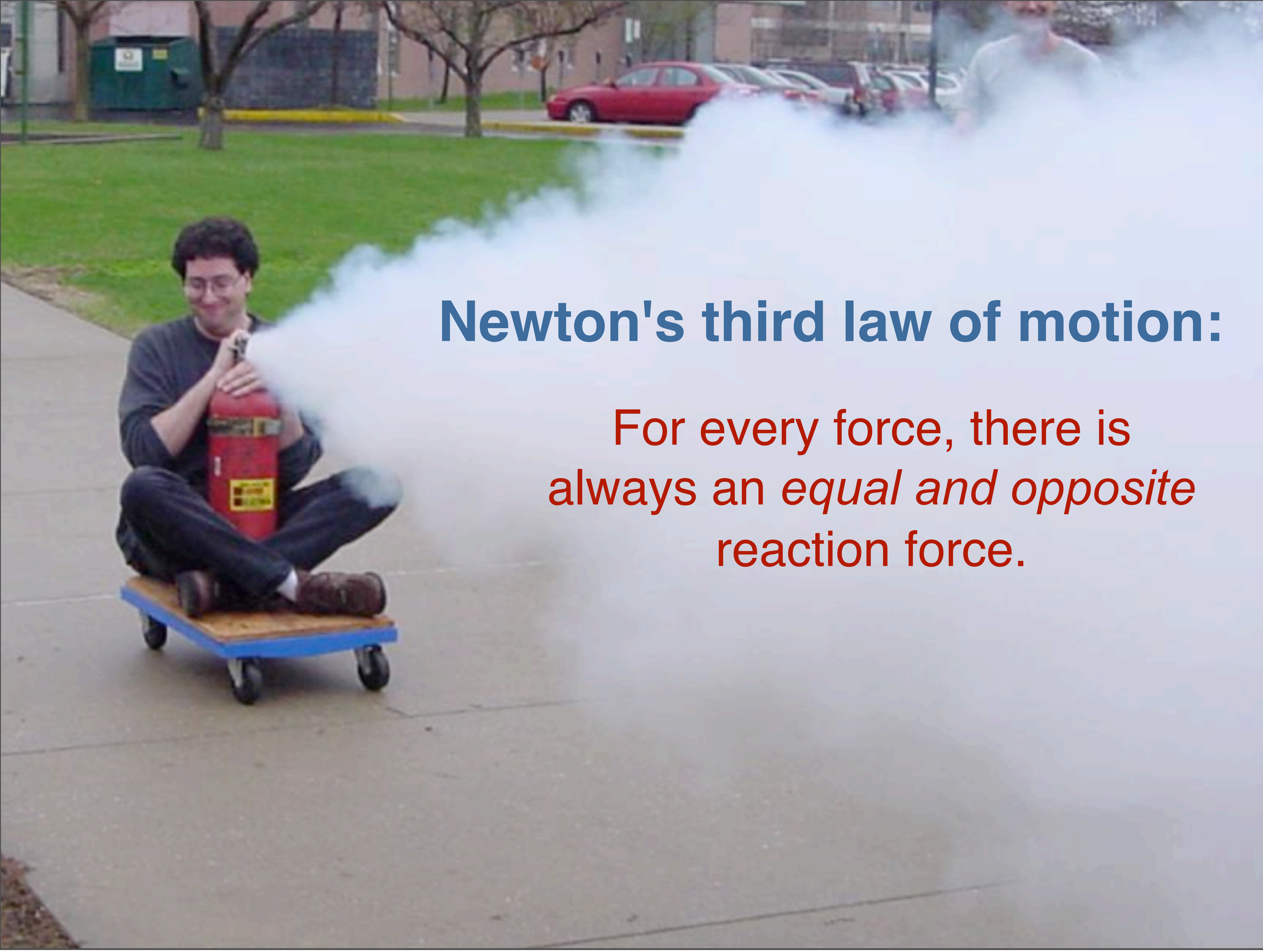
What are Newton's three laws of motion?

Newton's first law of motion: An object moves at constant velocity unless a net force acts to change its speed or direction.

Newton's Second Law of Motion

- There are two equivalent ways to express Newton's Second Law of Motion
  - Force = mass x acceleration
  - Force = rate of change in momentum

$$F = ma$$



Newton's third law of motion:

For every force, there is always an *equal and opposite* reaction force.

Thought Question

How does the force the Earth exerts on you compare with the force you exert on it?

A. Earth exerts a larger force on you.

B. You exert a larger force on Earth.

C. Earth and you exert equal and opposite forces on each other.

Thought Question

How does the force the Earth exerts on you compare with the force you exert on it?

A. Earth exerts a larger force on you.

B. You exert a larger force on Earth.

C. Earth and you exert equal and opposite forces on each other.

Thought Question

A compact car and a Mack truck have a head-on collision. Are the following **true** or **false**?

- The *force* of the car on the truck is equal and opposite to the force of the truck on the car.
- The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck.
- The *change of velocity* of the car is the same as the change of velocity of the truck.

Thought Question

A compact car and a Mack truck have a head-on collision. Are the following **true** or **false**?

- The *force* of the car on the truck is equal and opposite to the force of the truck on the car. **T**
- The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck.
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Thought Question

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- The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck. **T**
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Thought Question

A compact car and a Mack truck have a head-on collision. Are the following **true** or **false**?

- The *force* of the car on the truck is equal and opposite to the force of the truck on the car. **T**
- The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck. **T**
- The *change of velocity* of the car is the same as the change of velocity of the truck. **F**

Thought Question

A co… n
colli…

- T… d
  c… T
- T…
  tl… um
  tr…
- T… e as
  t… the change of velocity of the truck? …

What have we learned?

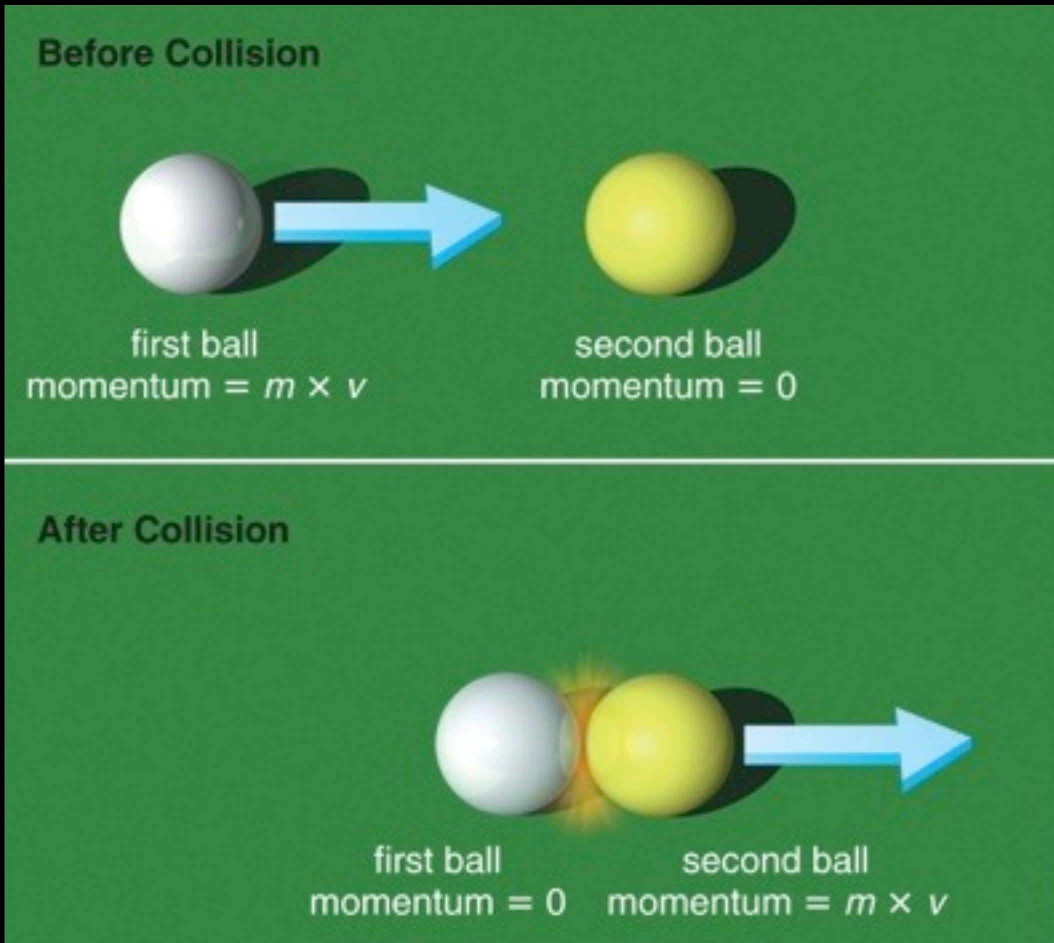
- **How did Newton change our view of the universe?**
  - He discovered laws of motion and gravitation.
  - He realized these same laws of physics were operating everywhere in the Universe.
- **What are Newton's three laws of motion?**
  1. Object moves at constant velocity if no net force is acting.
  2. Force = mass x acceleration
  3. For every force there is an equal and opposite reaction force.

5 minute break :^)

4.3 Conservation Laws in Astronomy

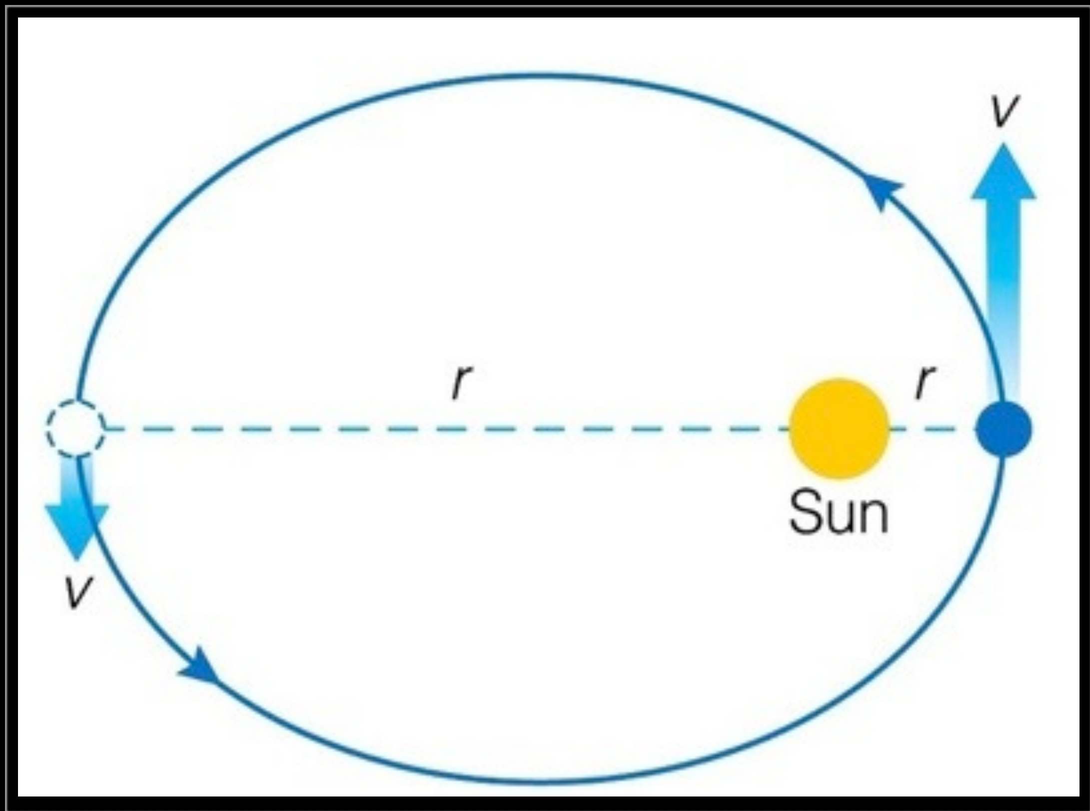
- Our goals for learning:
  – **Why do objects move at constant velocity if no force acts on them?**
  – **What keeps a planet rotating and orbiting the Sun?**
  – **Where do objects get their energy?**

Why do objects move at constant velocity if no force acts on them?



- The total momentum of interacting objects cannot change unless an external force is acting on them.
- Interacting objects exchange momentum through equal and opposite forces.

What keeps a planet rotating and orbiting the Sun?



Conservation of Angular Momentum

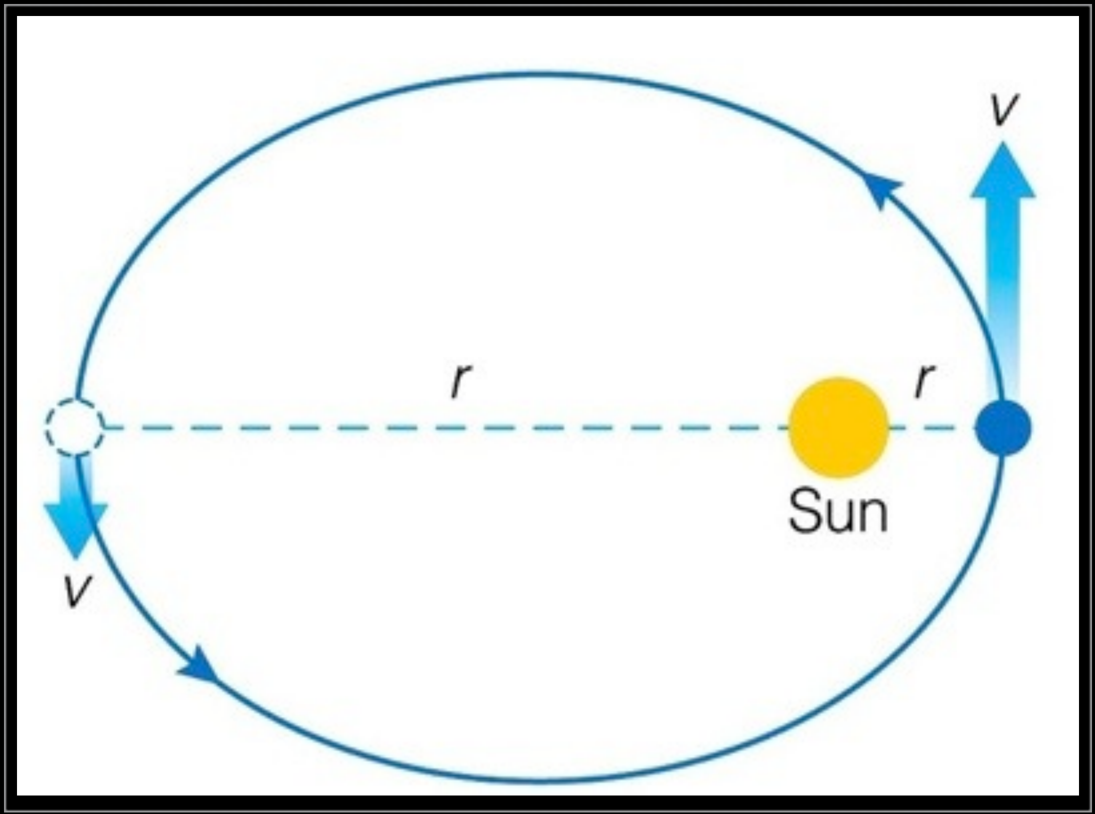
angular momentum = mass x velocity x radius

- The angular momentum of an object cannot change unless an external twisting force (torque) is acting on it.
- Earth experiences no twisting force as it orbits the Sun, so its rotation and orbit will continue indefinitely.

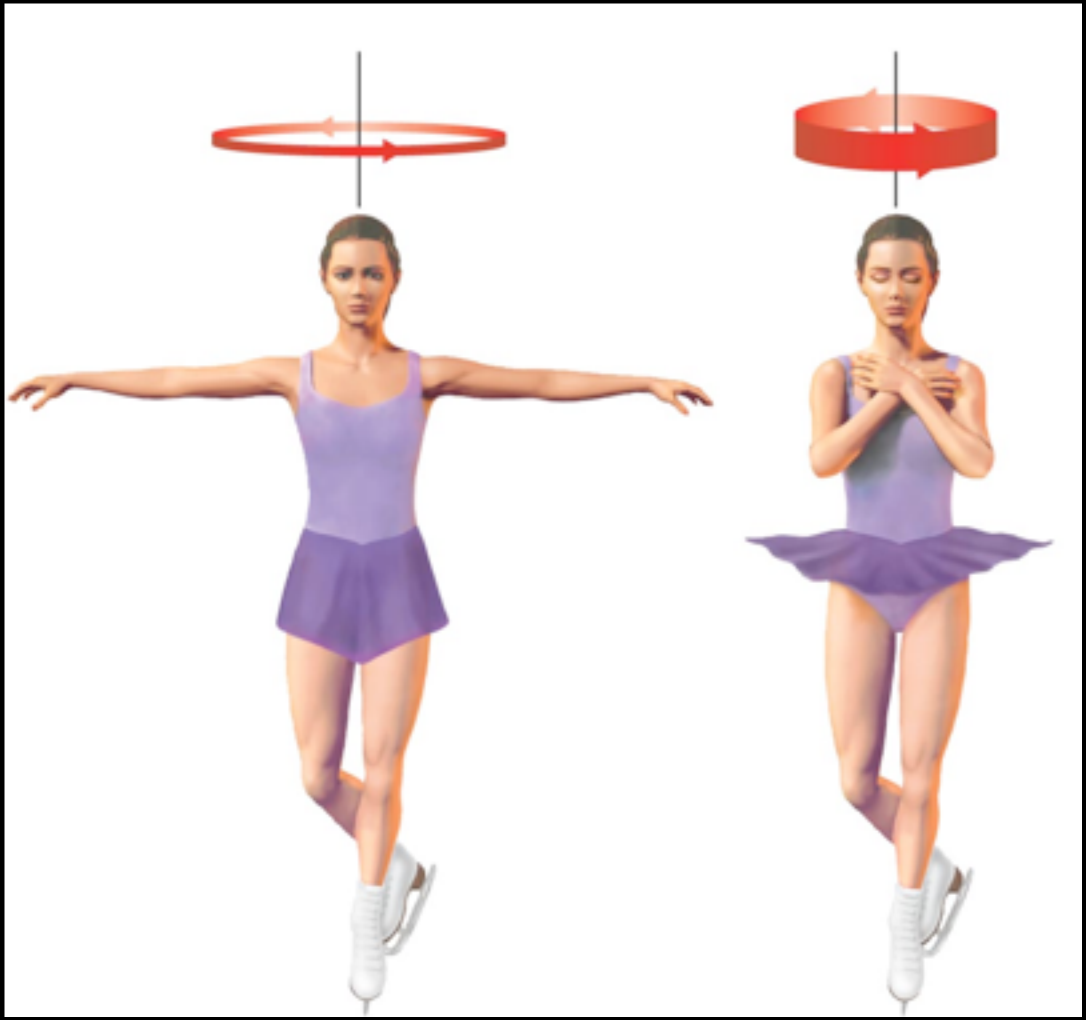
What keeps a planet rotating and orbiting the Sun?

angular momentum = mass x velocity x radius

net torque ↔ change in angular momentum



Angular momentum conservation also explains why objects rotate faster as they shrink in radius.



Where do objects get their energy?

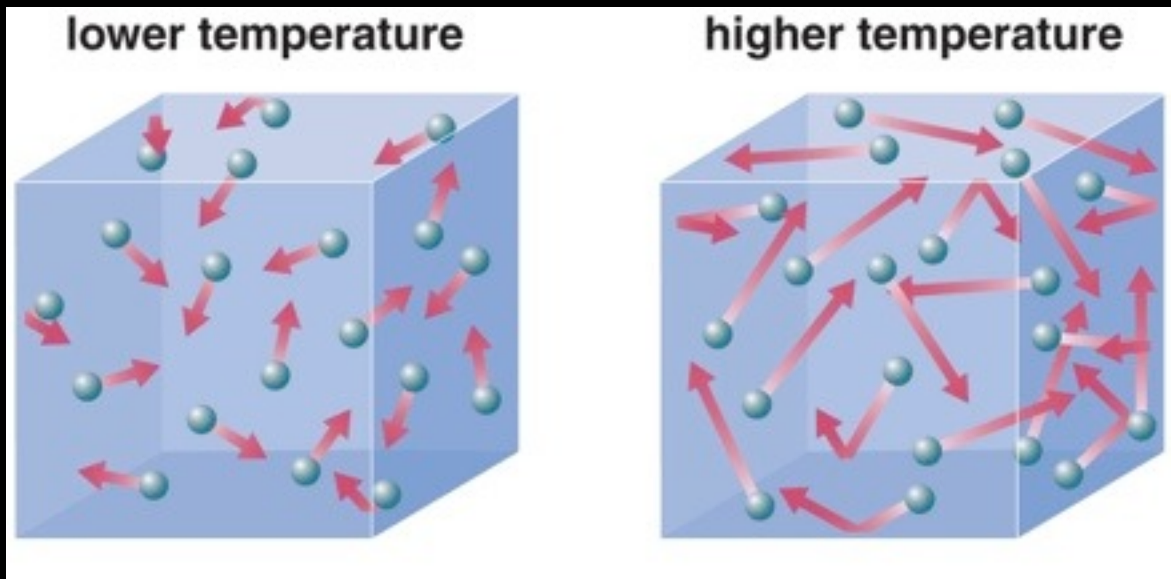
- Energy is the capacity to make matter move.
- Energy is neither created nor destroyed, but it can:
  - transfer from one object to another
  - change in form

Basic Types of Energy

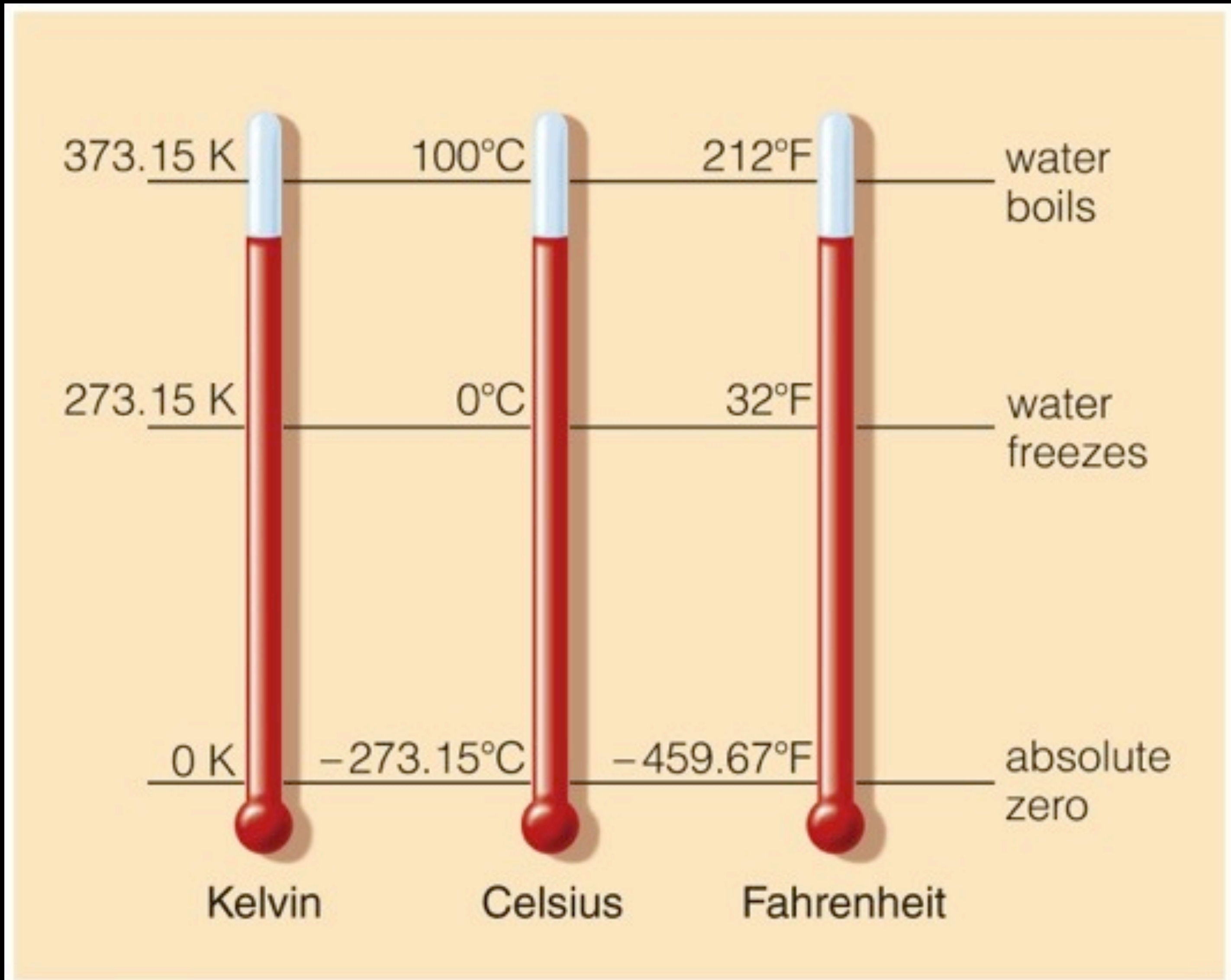
- Kinetic (motion)
- Radiative (light)
- Potential (stored)

Thermal Energy:

- The collective kinetic energy of many particles
  - Thermal energy is related to temperature but not exactly the same thing:
    - **Temperature** is the *average* kinetic energy of the many particles in a substance.

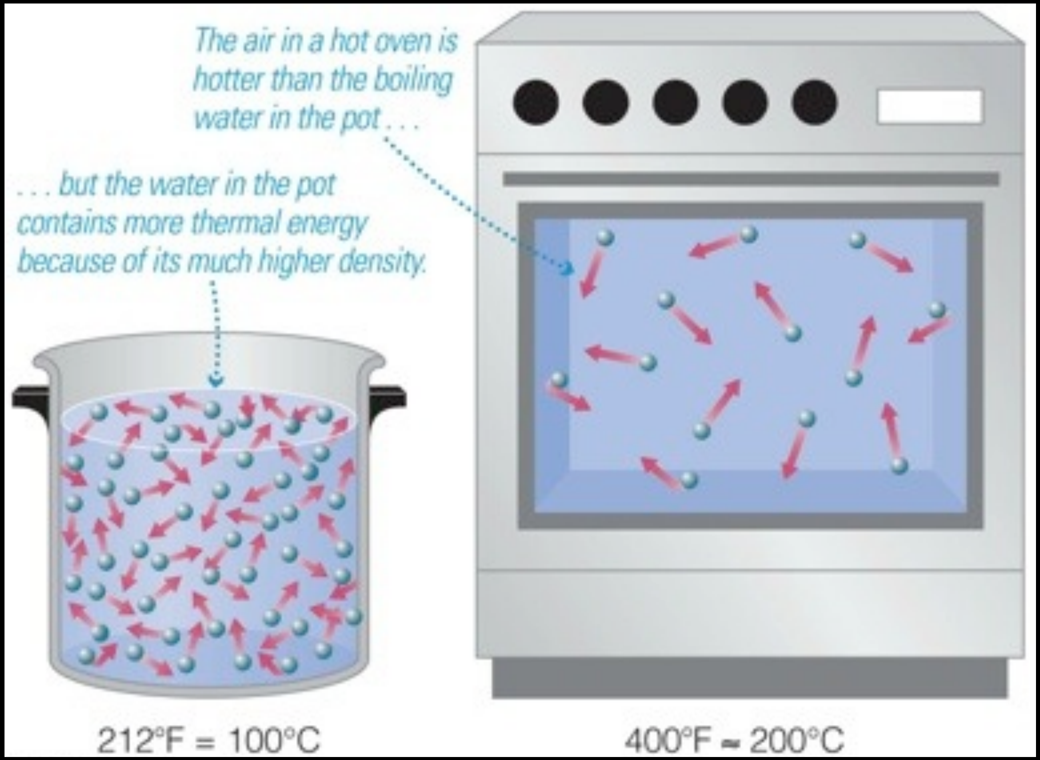


Temperature Scales



Temperature Scales

Thermal energy is a measure of the total kinetic energy of all the particles in a substance. It therefore depends on both *temperature* AND *density.*



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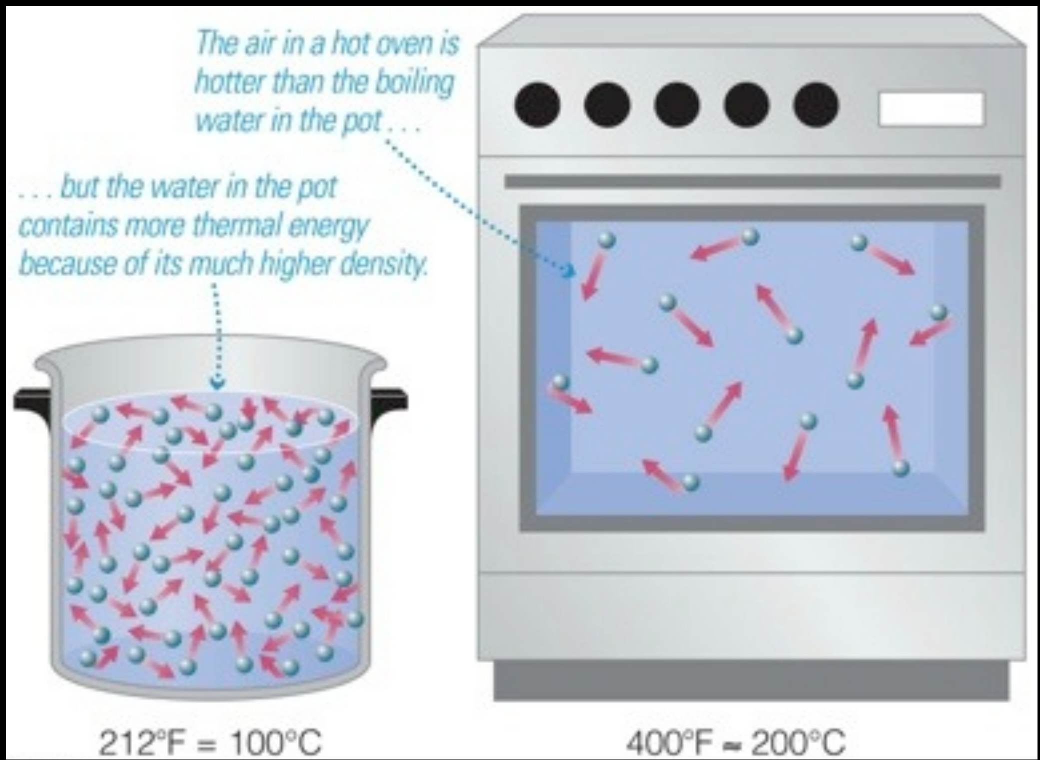
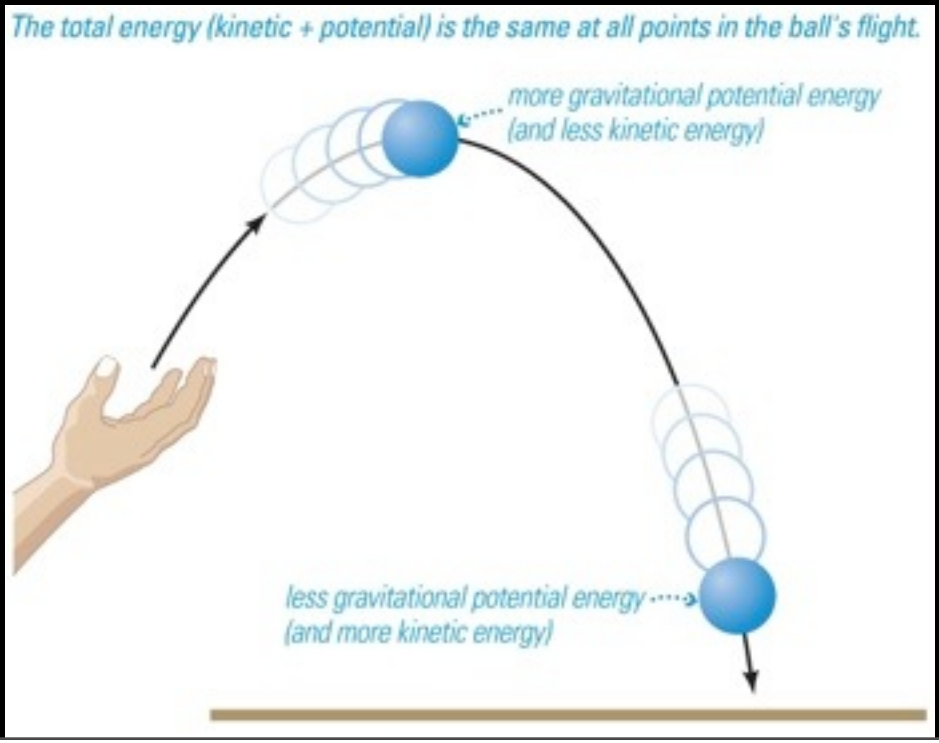


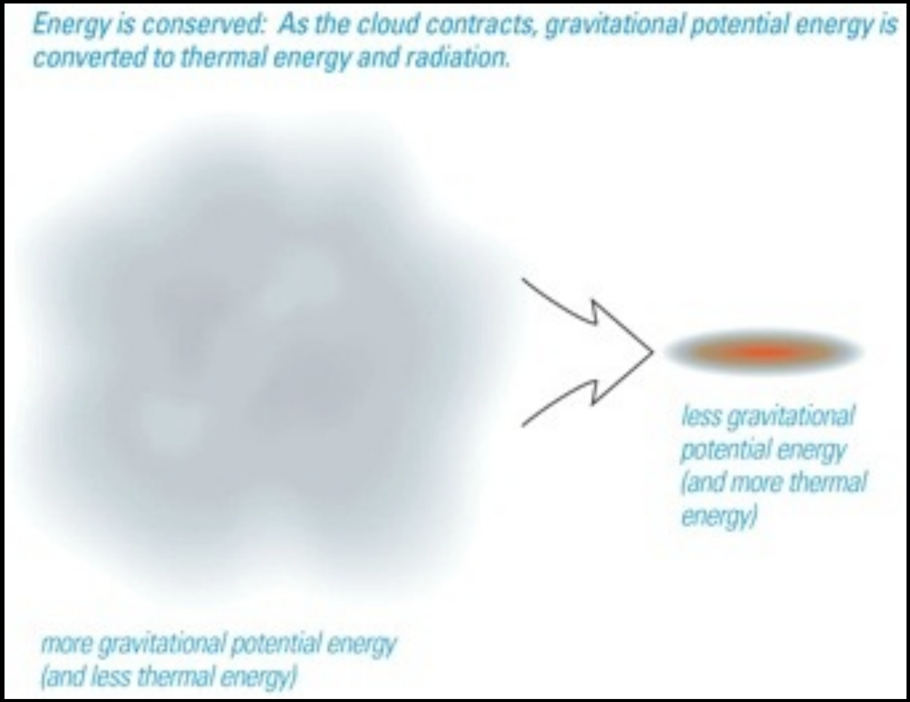
Gravitational Potential Energy

- On Earth, depends on:
  - object's *mass (m)*
  - strength of gravity *(g)*
  - distance object could potentially fall



Gravitational Potential Energy

- In space, an object or gas cloud has more gravitational energy when it is spread out than when it contracts.
  - A contracting cloud converts gravitational potential energy to thermal energy.

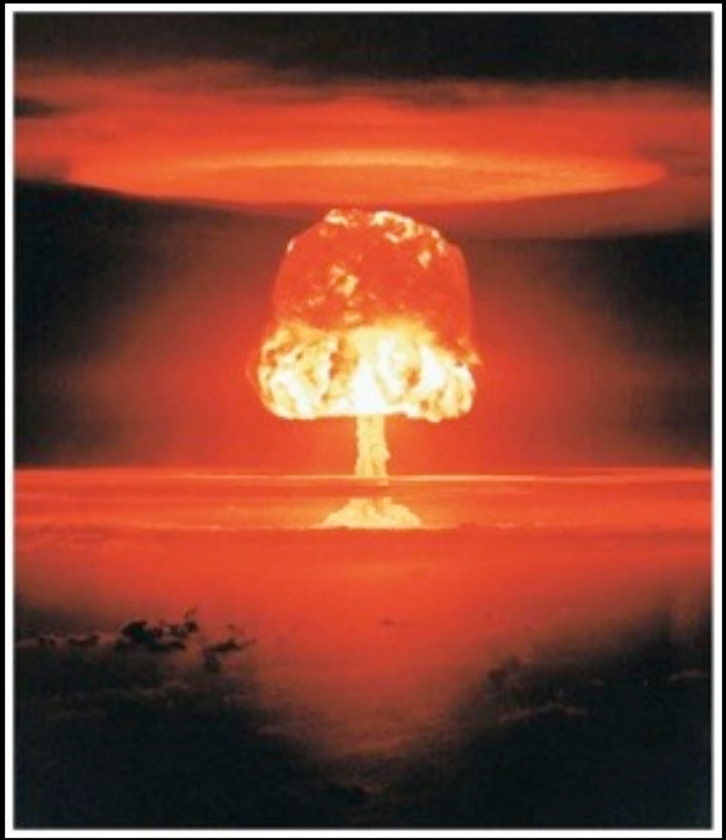


Mass-Energy

- Mass itself is a form of potential energy:

$$E = mc^2$$

- A small amount of mass can release a great deal of energy (for example, an H-bomb).
- Concentrated energy can spontaneously turn into particles (for example, in particle accelerators).



Conservation of Energy

- Energy can be neither created nor destroyed.
- It can change form or be exchanged between objects.
- The total energy content of the universe was determined in the Big Bang and remains the same today.

What have we learned?

Why do objects move at constant velocity if no force acts on them?

– Conservation of momentum

What keeps a planet rotating and orbiting the Sun?

– Conservation of angular momentum

Where do objects get their energy?

– Conservation of energy: energy cannot be created or destroyed but only transformed from one type to another.

– Energy comes in three basic types: kinetic, potential, radiative.

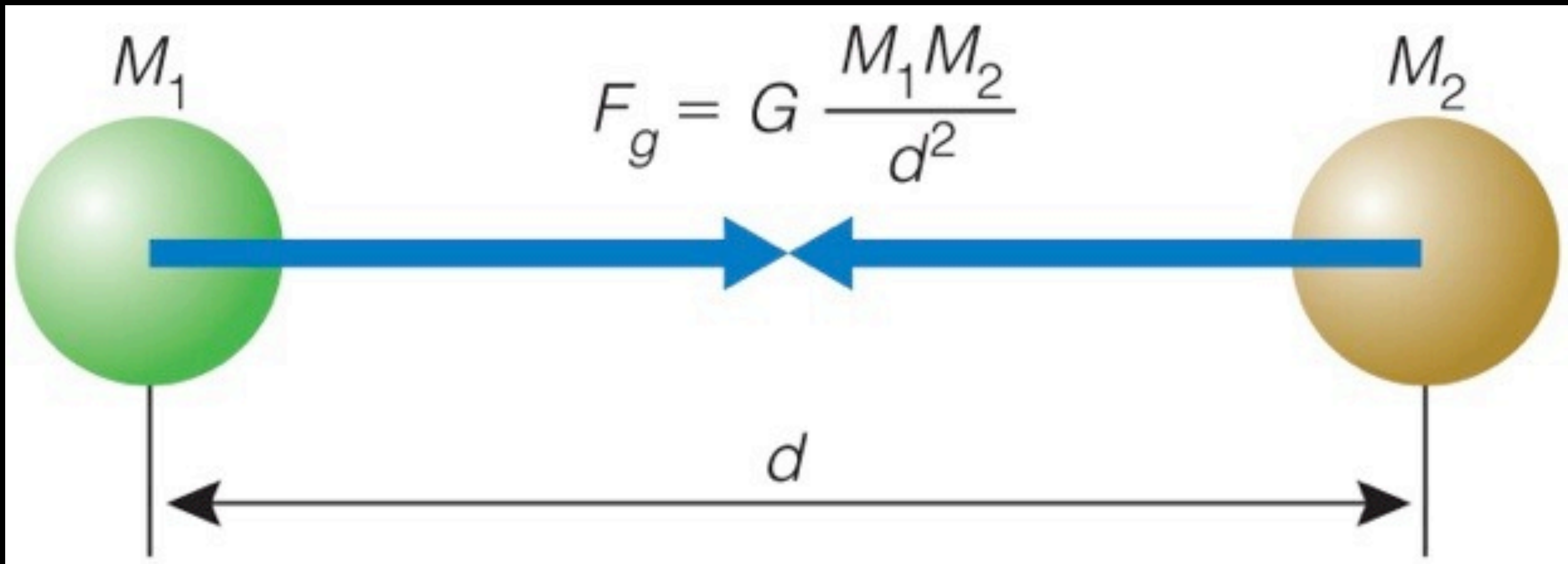
4.4 The Universal Law of Gravitation

- Our goals for learning:
  - **What determines the strength of gravity?**
  - **How does Newton's law of gravity extend Kepler's laws?**

What determines the strength of gravity?

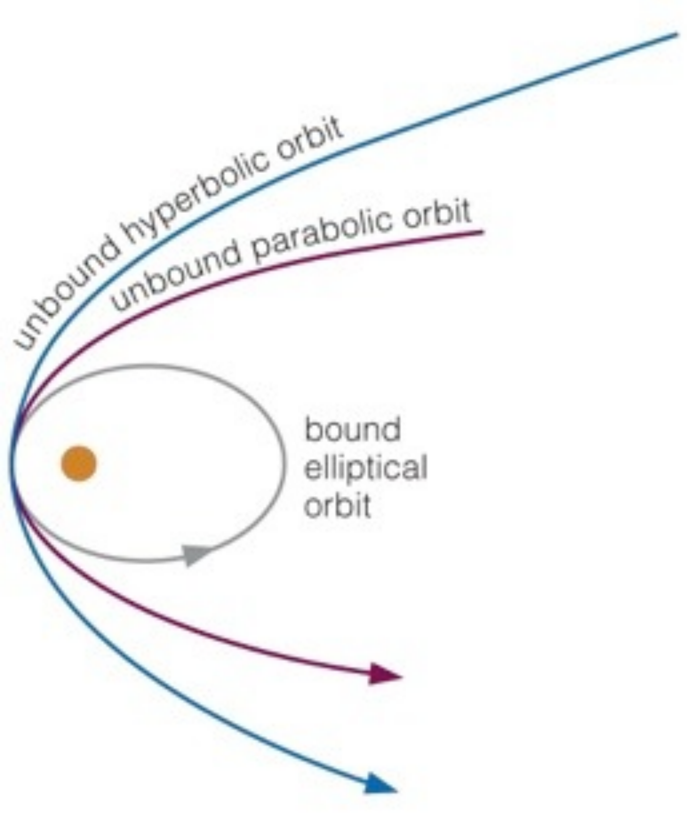
The **universal law of gravitation:**

1. Every mass attracts every other mass.
2. Attractive force is *directly* proportional to the product of their masses.
3. Attractive force is *inversely* proportional to the *square* of the distance between their centers.



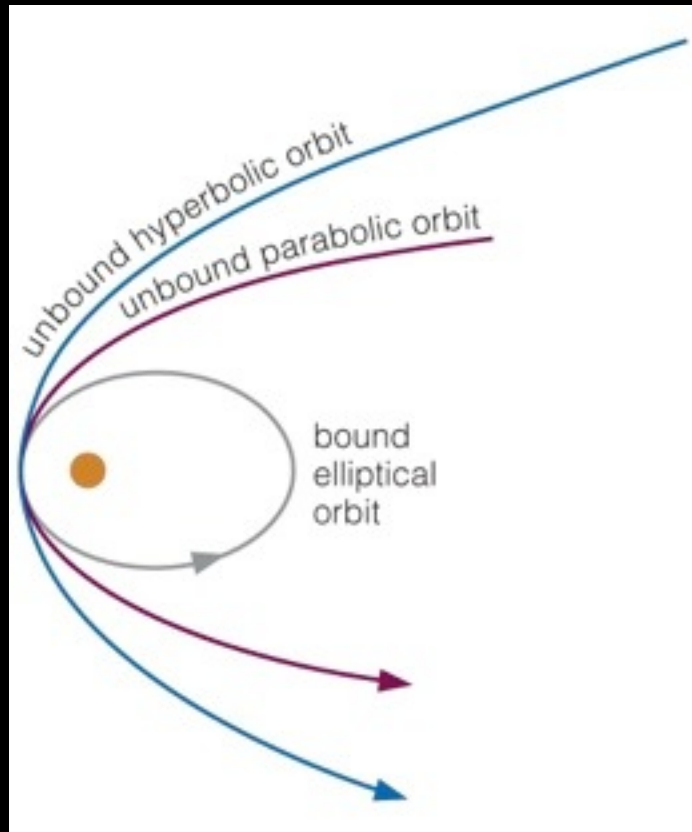
How does Newton's law of gravity extend Kepler's laws?

- Kepler's laws apply to all orbiting objects, not just planets.
- Ellipses are not the only orbital paths. Orbits can be:
  - bound (ellipses)
  - unbound
    - parabola
    - hyperbola



a Orbits allowed by the law of gravity.

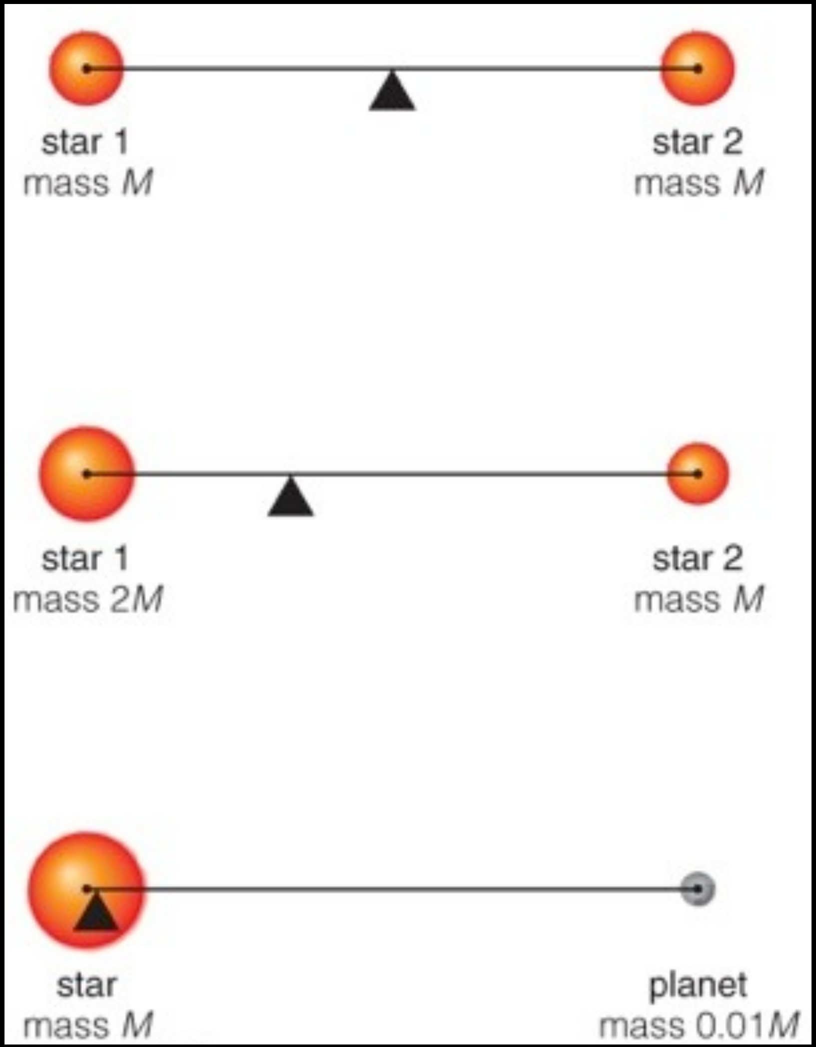
How does Newton's law of gravity extend Kepler's laws?



a Orbits allowed by the law of gravity.

– unbound
  - parabola
  - hyperbola

Center of Mass



- Because of momentum conservation, orbiting objects orbit around their center of mass.

Newton and Kepler's Third Law

- Newton's laws of gravity and motion showed that the relationship between the *orbital period* and *average orbital distance* of a system tells us the *total mass* of the system.
  - Earth's orbital period (1 year) and average distance (1 AU) tell us the Sun's mass.
  - Orbital period and distance of a satellite from Earth tell us Earth's mass.
  - Orbital period and distance of a moon of Jupiter tell us Jupiter's mass.

Newton's Version of Kepler's Third Law

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \qquad \text{OR} \qquad M_1 + M_2 = \frac{4\pi^2}{G} \frac{a^3}{p^2}$$

p = orbital period

- α = average orbital distance (between centers)
- $(M_1 + M_2)$ = sum of object masses

What have we learned?

What determines the strength of gravity?

– Directly proportional to the *product* of the masses $(M \times m)$

Inversely proportional to the *square* of the separation

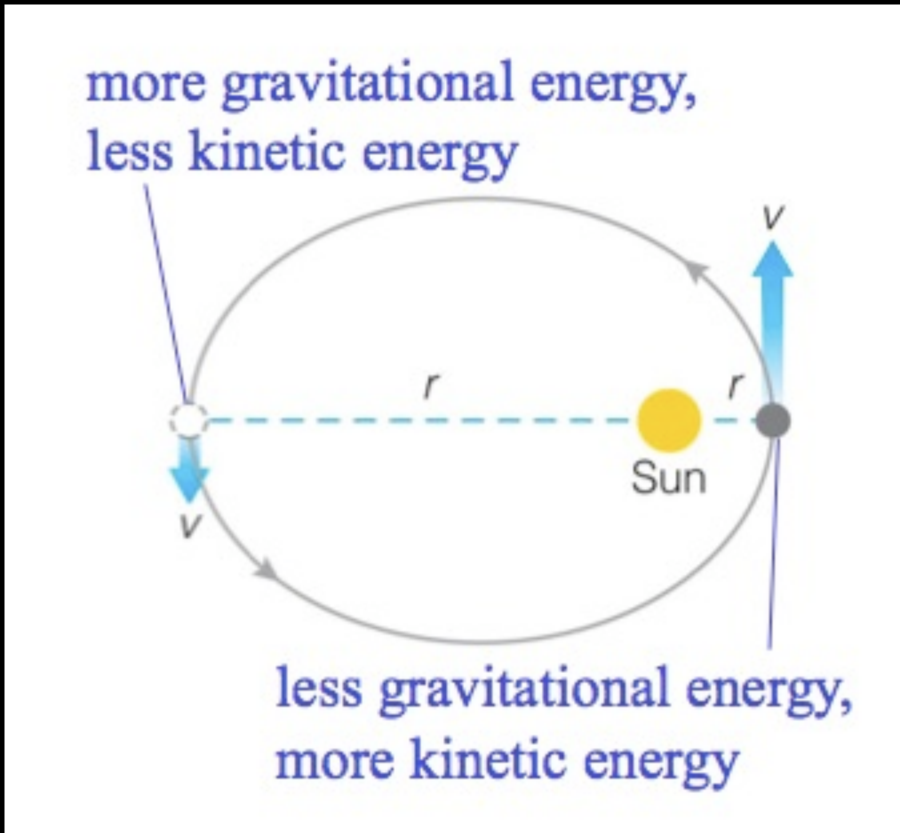
How does Newton's law of gravity allow us to extend Kepler's laws?

– Applies to other objects, not just planets
– Includes unbound orbit shapes: parabola, hyperbola
– Can be used to measure mass of orbiting systems

4.5 Orbits, Tides, and the Acceleration of Gravity

- Our goals for learning:
  - **How do gravity and energy together allow us to understand orbits?**
  - **How does gravity cause tides?**
  - **Why do all objects fall at the same rate?**

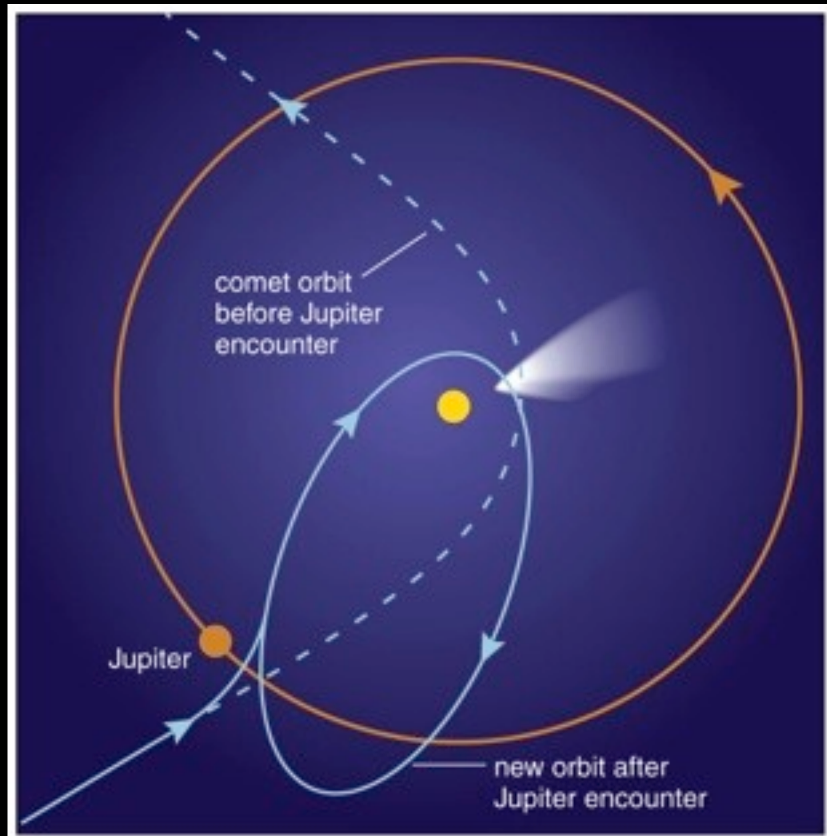
How do gravity and energy together allow us to understand orbits?



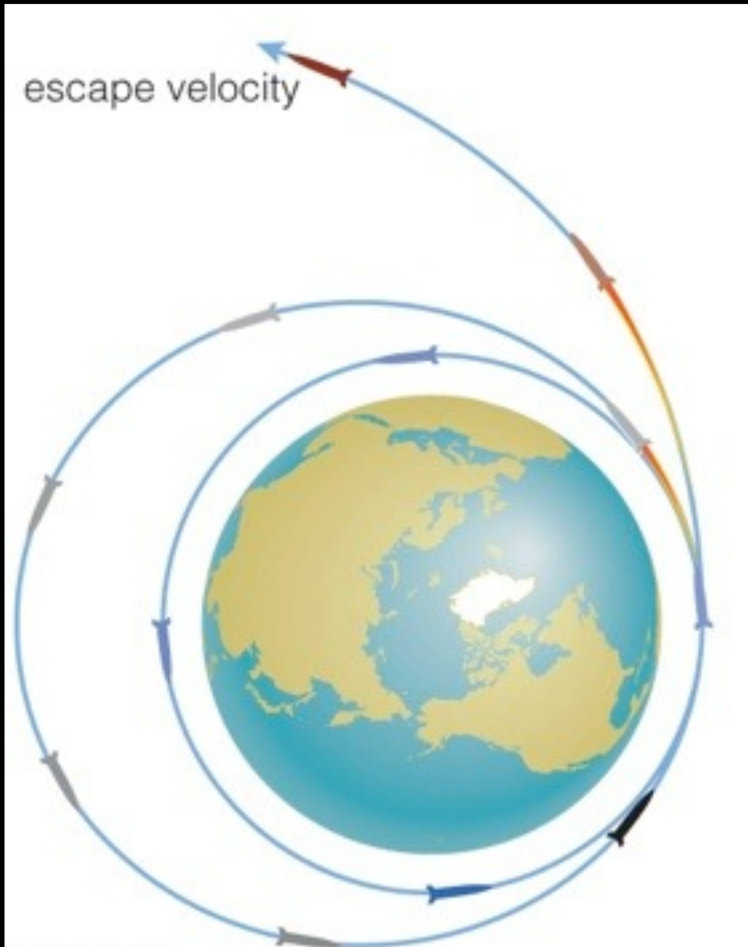
- Total orbital energy (gravitational + kinetic) stays constant if there is no external force.
- Orbits cannot change spontaneously.

Changing an Orbit

- So what can make an object gain or lose orbital energy?
- Friction or atmospheric drag
- A gravitational encounter



Escape Velocity



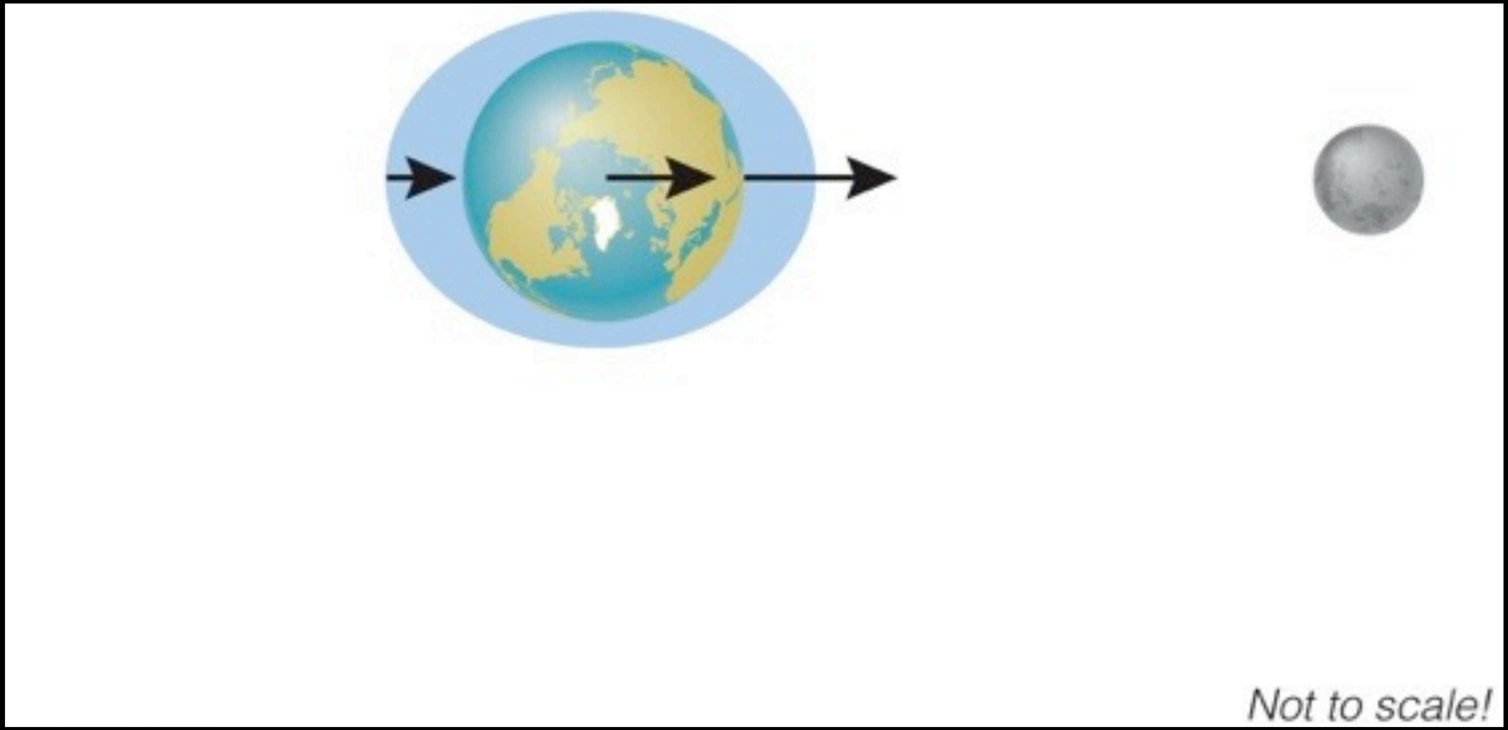
- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit).

Escape velocity from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)

Escape Velocity

- Escape and orbital velocities don't depend on the mass of the cannonball.

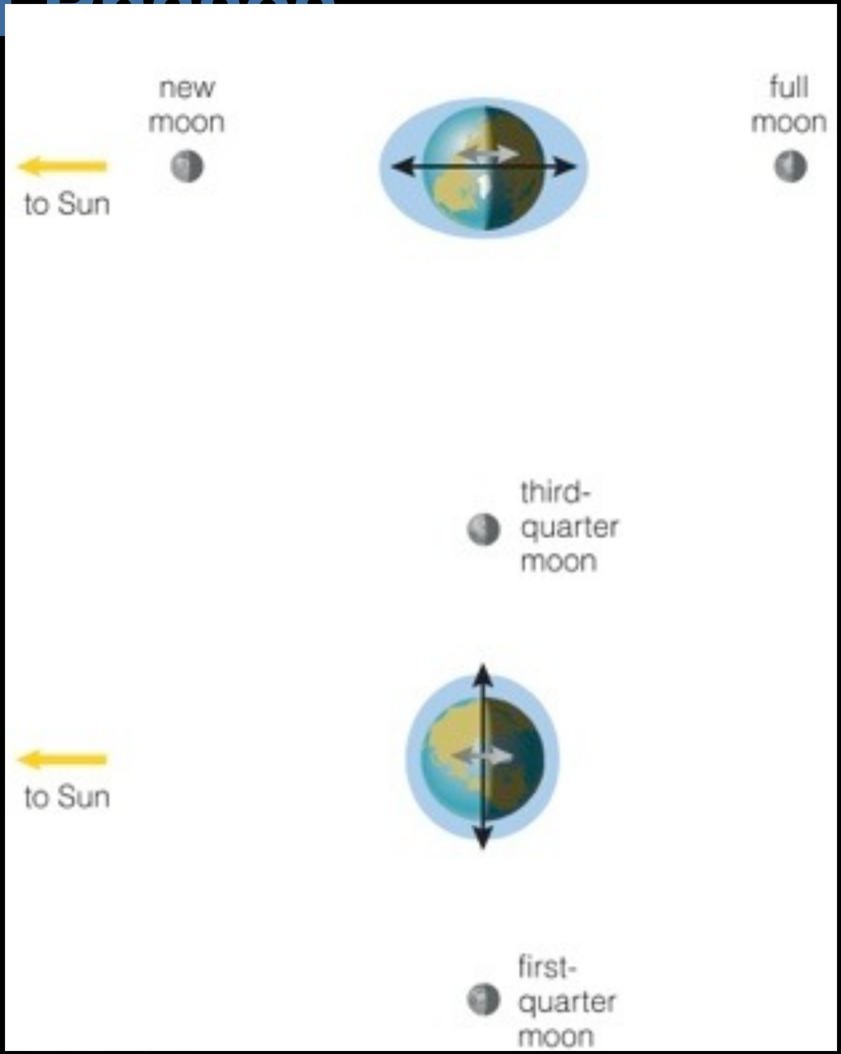
How does gravity cause tides?



- Moon's gravity pulls harder on near side of Earth than on far side.
- Difference in Moon's gravitational pull stretches Earth.

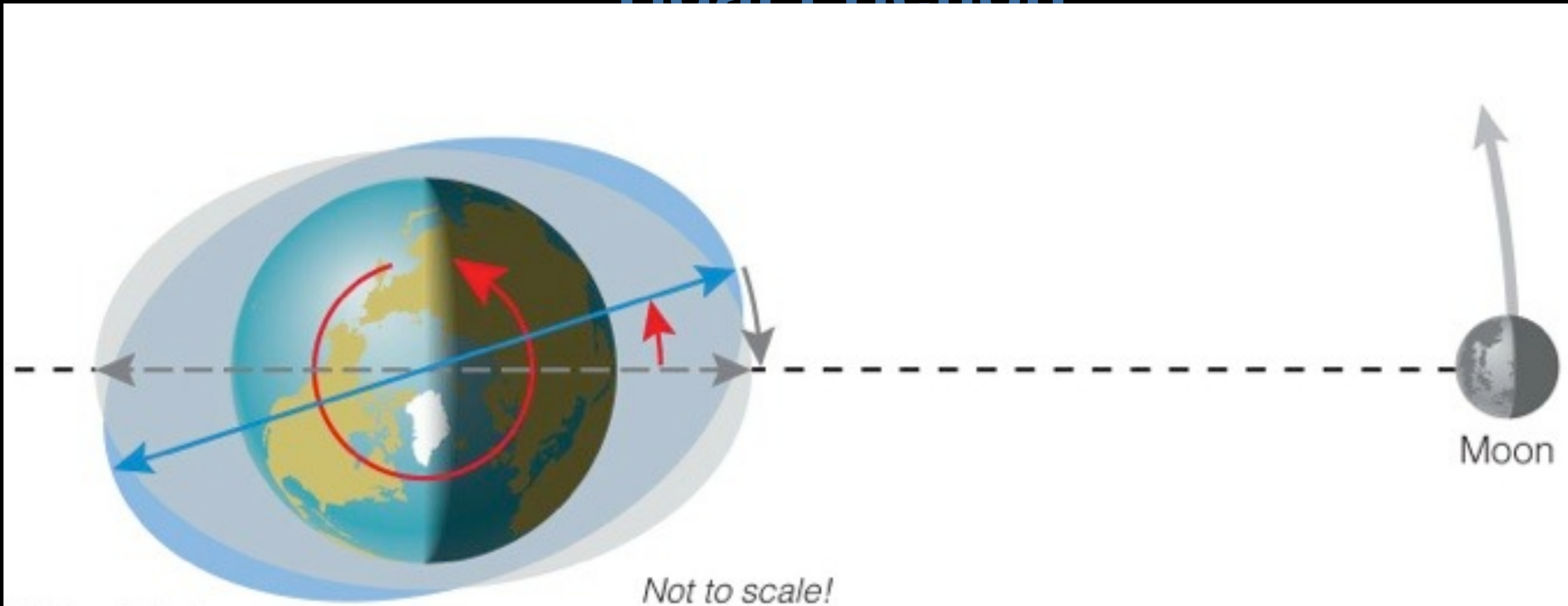
Tides and Phases

- Size of tides depends on phase of Moon.



Interactive Figure

Tidal Friction



- Tidal friction gradually slows Earth's rotation (and makes the Moon get farther from Earth).
- The Moon once orbited faster (or slower); tidal friction caused it to "lock" in synchronous rotation.

Why do all objects fall at the same rate?

$$a_{rock} = \frac{F_g}{M_{rock}} \qquad F_g = G\frac{M_{Earth} M_{rock}}{R^2_{Earth}}$$

$$a_{rock} = G\frac{M_{Earth} \cancel{M_{rock}}}{R^2_{Earth} \cancel{M_{rock}}} = G\frac{M_{Earth}}{R^2_{Earth}}$$

- The gravitational acceleration of an object like a rock does not depend on its mass because M_{rock} in the equation for acceleration cancels M_{rock} in the equation for gravitational force.
- This "coincidence" was not understood until Einstein's general theory of relativity.

What have we learned?

How do gravity and energy together allow us to understand orbits?

– Change in total energy is needed to change orbit

– Add enough energy (escape velocity) and object leaves.

How does gravity cause tides?

– The Moon's gravity stretches Earth and its oceans.

Why do all objects fall at the same rate?

– Mass of object in Newton's second law exactly cancels mass in law of gravitation.