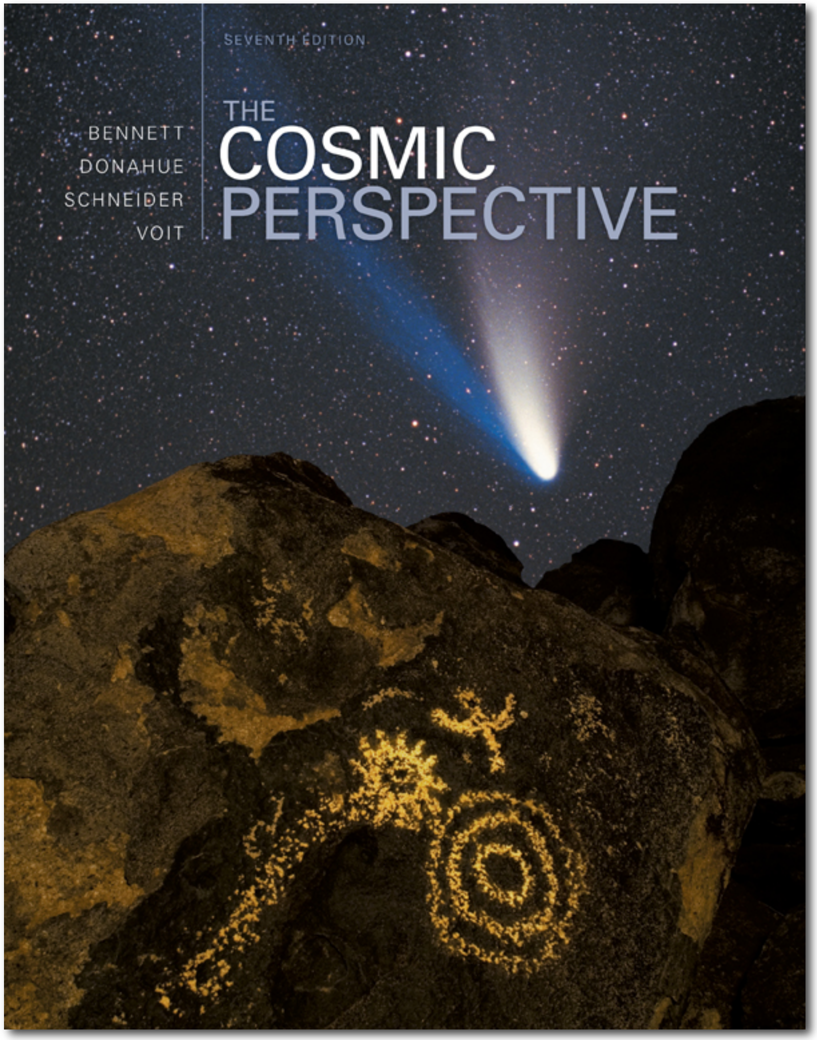
Chapter 4 Lecture

The Cosmic Perspective

Seventh Edition



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

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

4.1 Describing Motion: Examples from Daily Life

- Our goals for learning:
  - **How do we describe motion?**

    We will define speed, velocity, linear momentum, angular momentum, acceleration

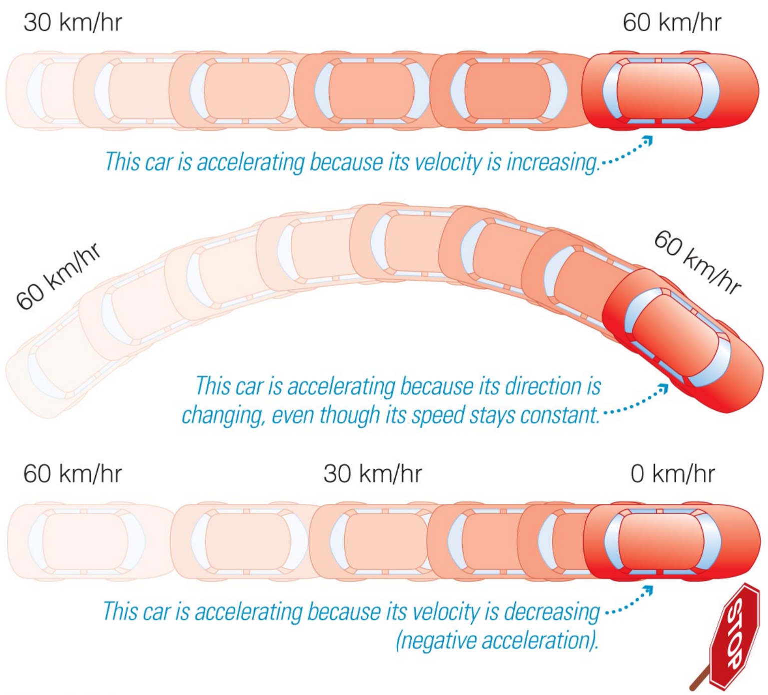
    We will introduce the laws of conservation of linear and angular momentum

  - **How is mass different from weight?**

How do we describe motion?

- Precise definitions to describe motion:
- **Speed:** Rate at which object moves

$$\text{speed} = \frac{\text{distance}}{\text{time}} \quad \left(\text{units of } \frac{\text{m}}{\text{s}}\right)$$



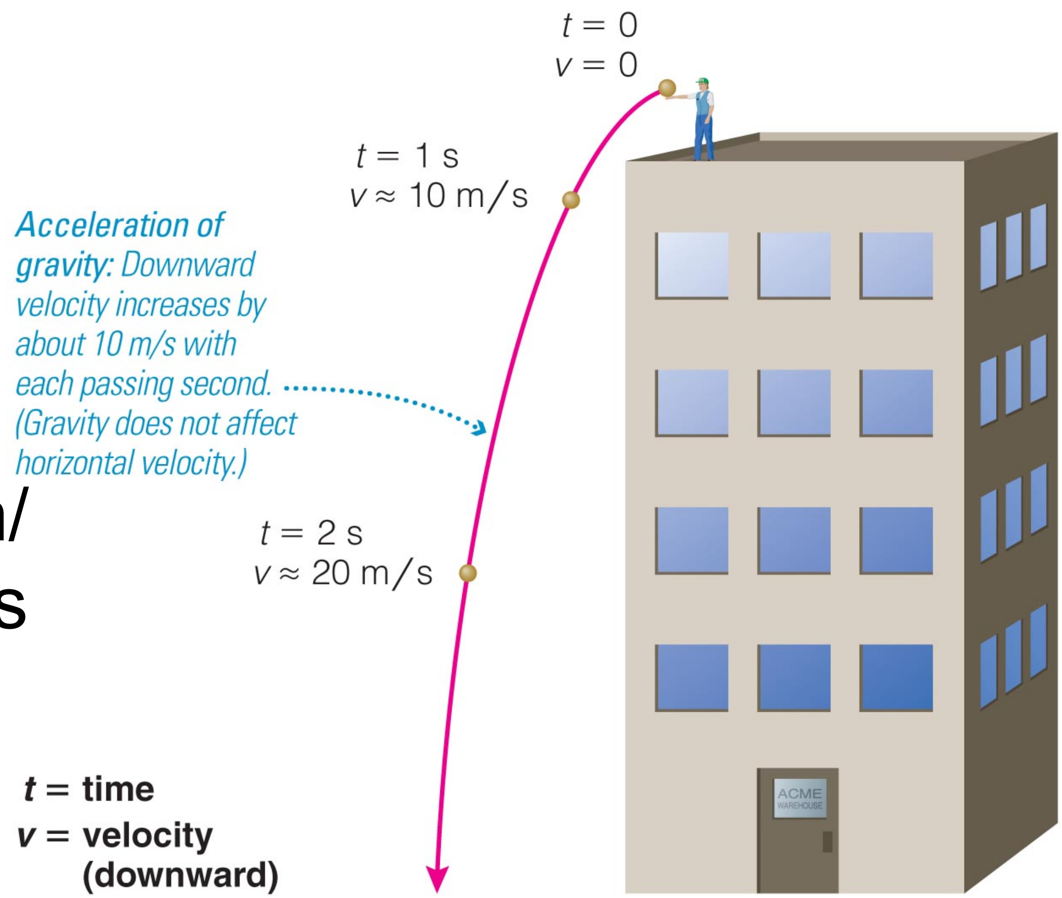
Example: 10 m/s

- **Velocity:** Speed and direction
  Example: 10 m/s, due east

- **Acceleration:** Any change in velocity
  units of speed/time (m/s^2)

The Acceleration of Gravity

- All falling objects accelerate at the same rate (not counting friction of air resistance).
- On Earth, $g \approx 10$ m/s^2: speed increases 10 m/s with each second of falling.



The Acceleration of Gravity (g)

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

Apollo 15 demonstration

Momentum and Force

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

1. A car coming to a stop
2. A bus speeding up
3. An elevator moving up at constant speed
4. A bicycle going around a curve
5. A moon orbiting Jupiter

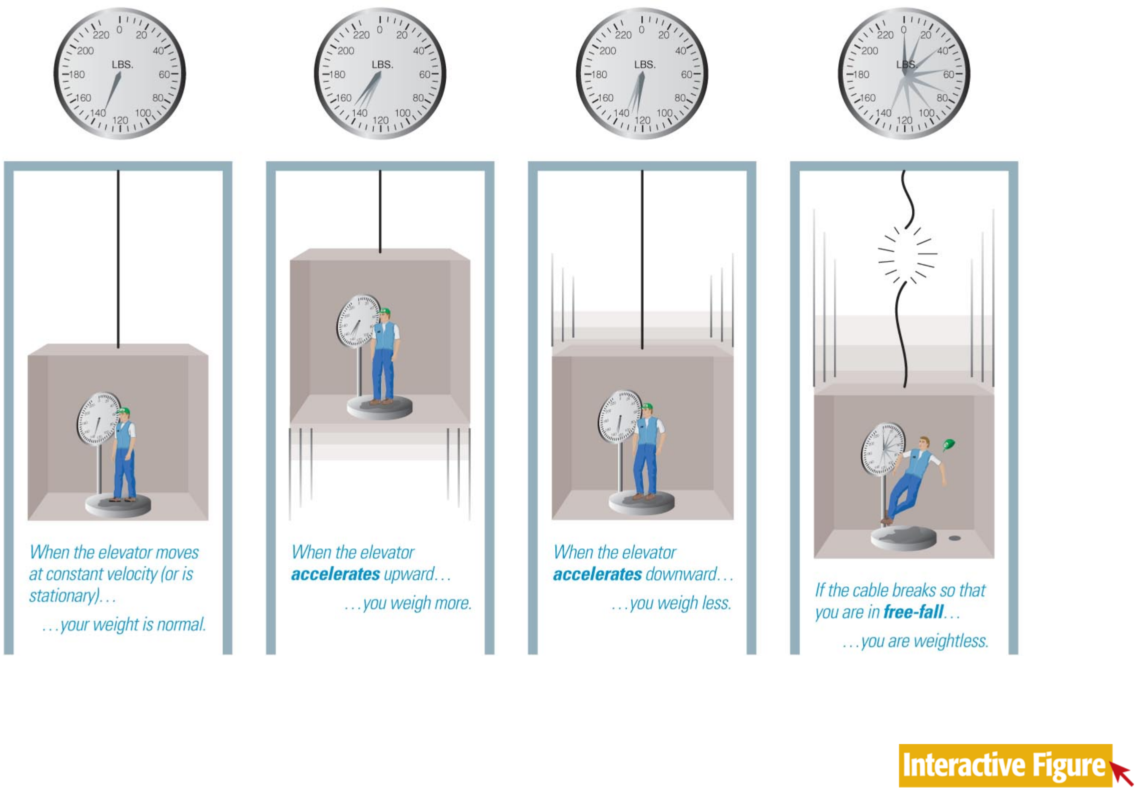
Thought Question

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

1. A car coming to a stop: Y
2. A bus speeding up: Y
3. An elevator moving at constant speed: N
4. A bicycle going around a curve: Y
5. 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



Your apparent weight is zero in free-fall, however, the force of gravity acting on you is still equal to F = mg, where m is your mass.

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.

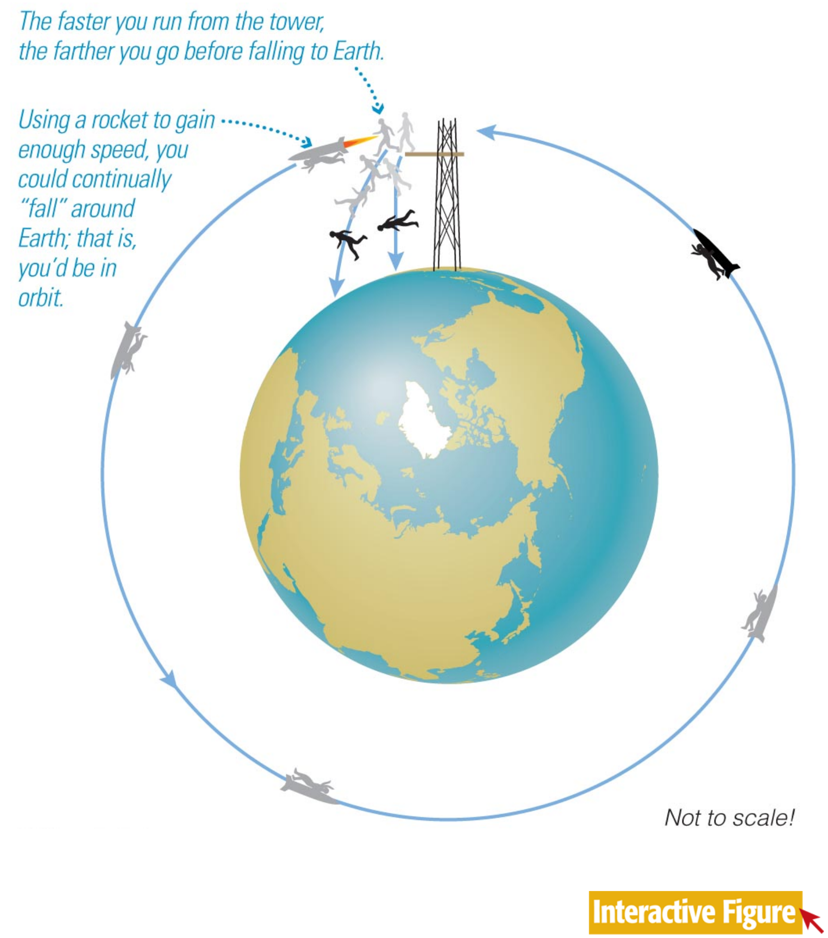
Thought Question

On the Moon:

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.

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

4.2 Newton's Laws of Motion

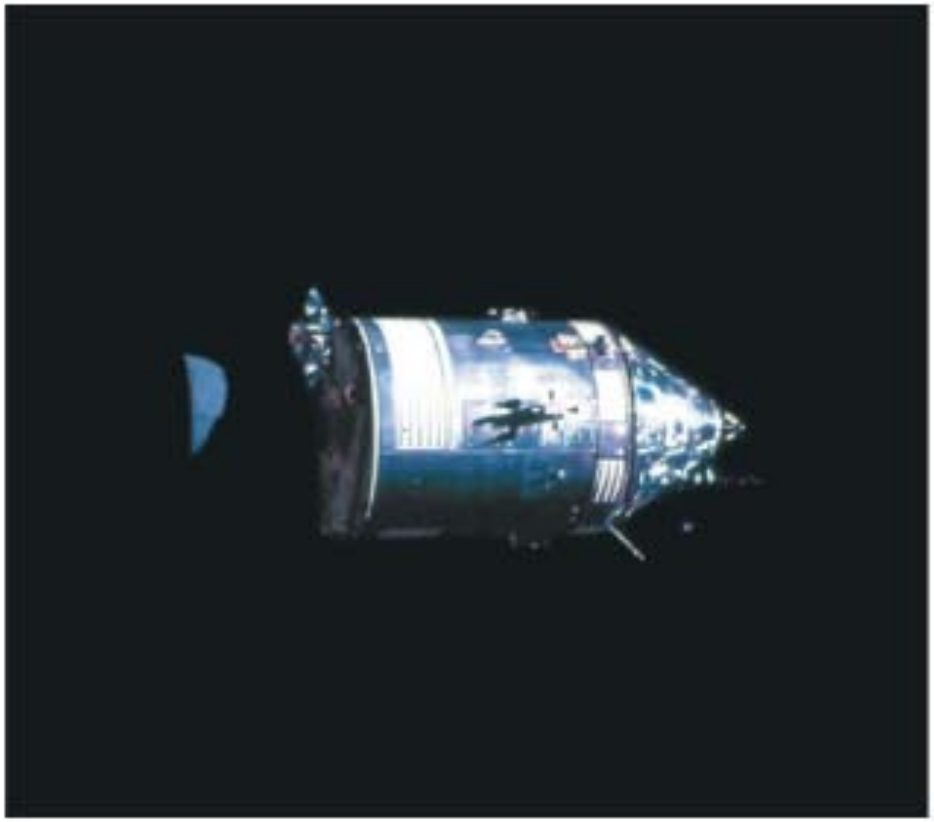
- Our goals for learning:
  - **How did Newton change our view of the universe?**
  - **What are Newton's three laws of motion?**

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*
- Discovered 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 stays at rest or 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

    (The acceleration of an object is proportional to the net force on that object and inversely proportional to its mass.

  - Force = rate of change in momentum

Units of Force: **kg m/s^2 = Newton**

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**?

1. The *force* of the car on the truck is equal and opposite to the force of the truck on the car.
2. The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck.
3. 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**?

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

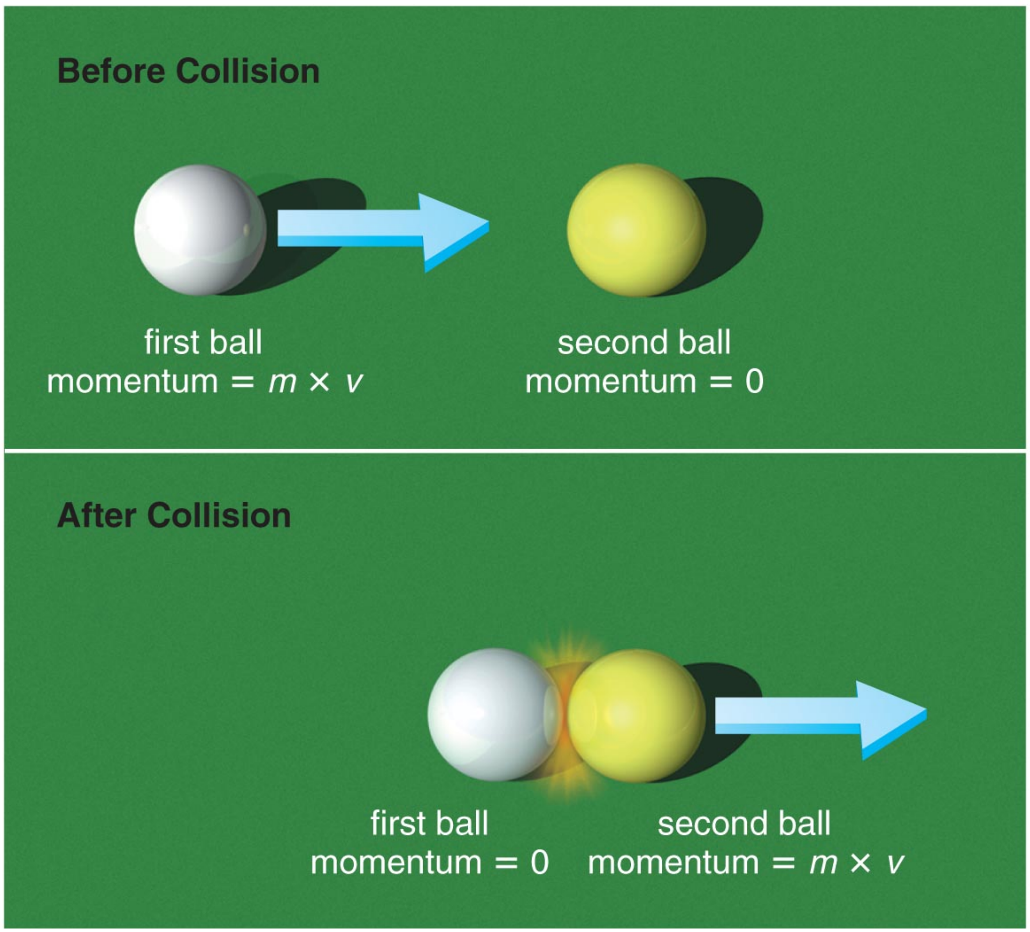
What have we learned?

- **How did Newton change our view of the universe?**
  - He discovered laws of motion and gravitation.
  - He realized these same laws of physics were identical in the universe and on Earth.
- **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.

4.3 Conservation Laws in Astronomy

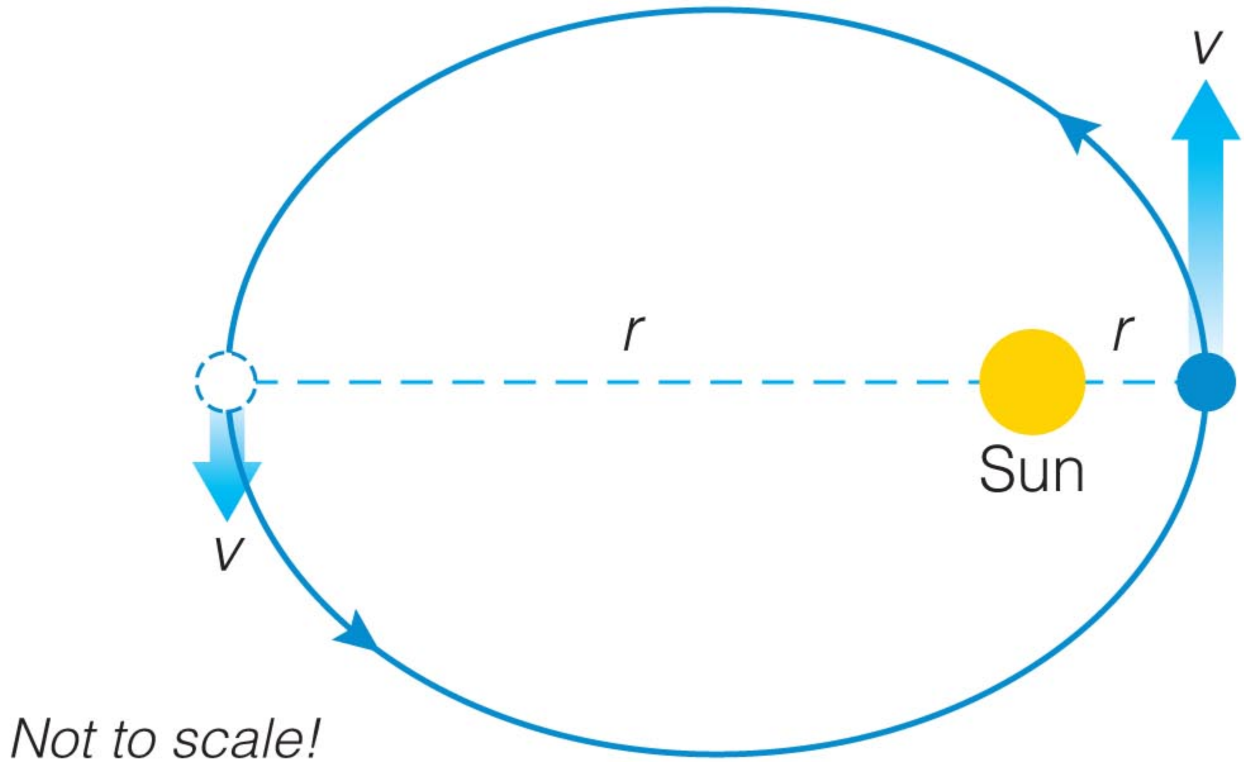
- Our goals for learning:
  - **What is conservation of momentum?**
  - **What keeps a planet rotating and orbiting the Sun?**
  - **Where do objects get their energy?**

From Newton's 2nd law, if the net force on an object (or system) is zero its momentum is conserved.



- 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 (L) = mass x velocity x radius

(more general: L = moment of inertia x angular velocity)

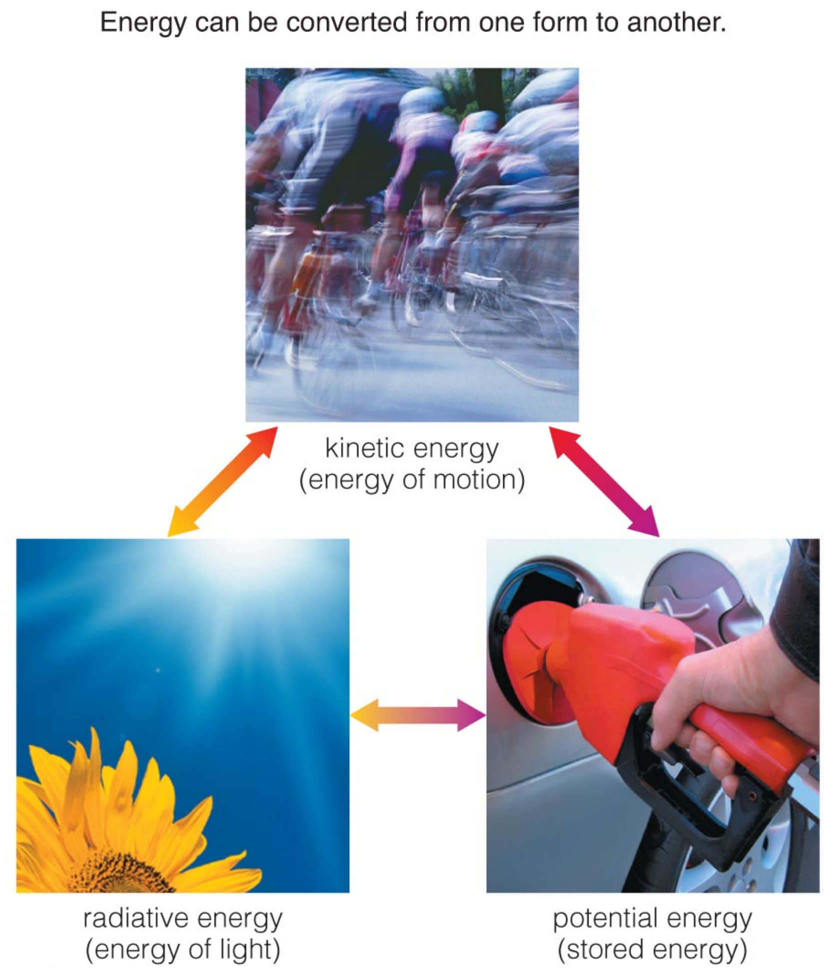
- The angular momentum of an object cannot change unless an external twisting force (torque) is acting on it.
- Earth experiences no twisting force as it orbits the Sun, so its rotation and orbit will continue indefinitely.

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

Basic Types of Energy

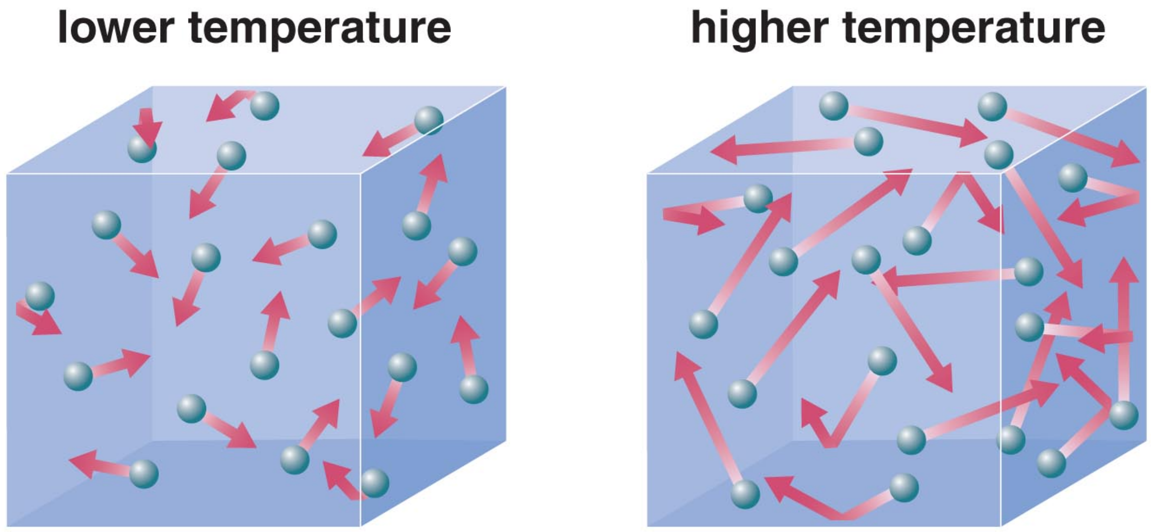
- Kinetic (motion)
- Radiative (light)
- Potential (stored)

- Energy can change type, but cannot be created or destroyed.

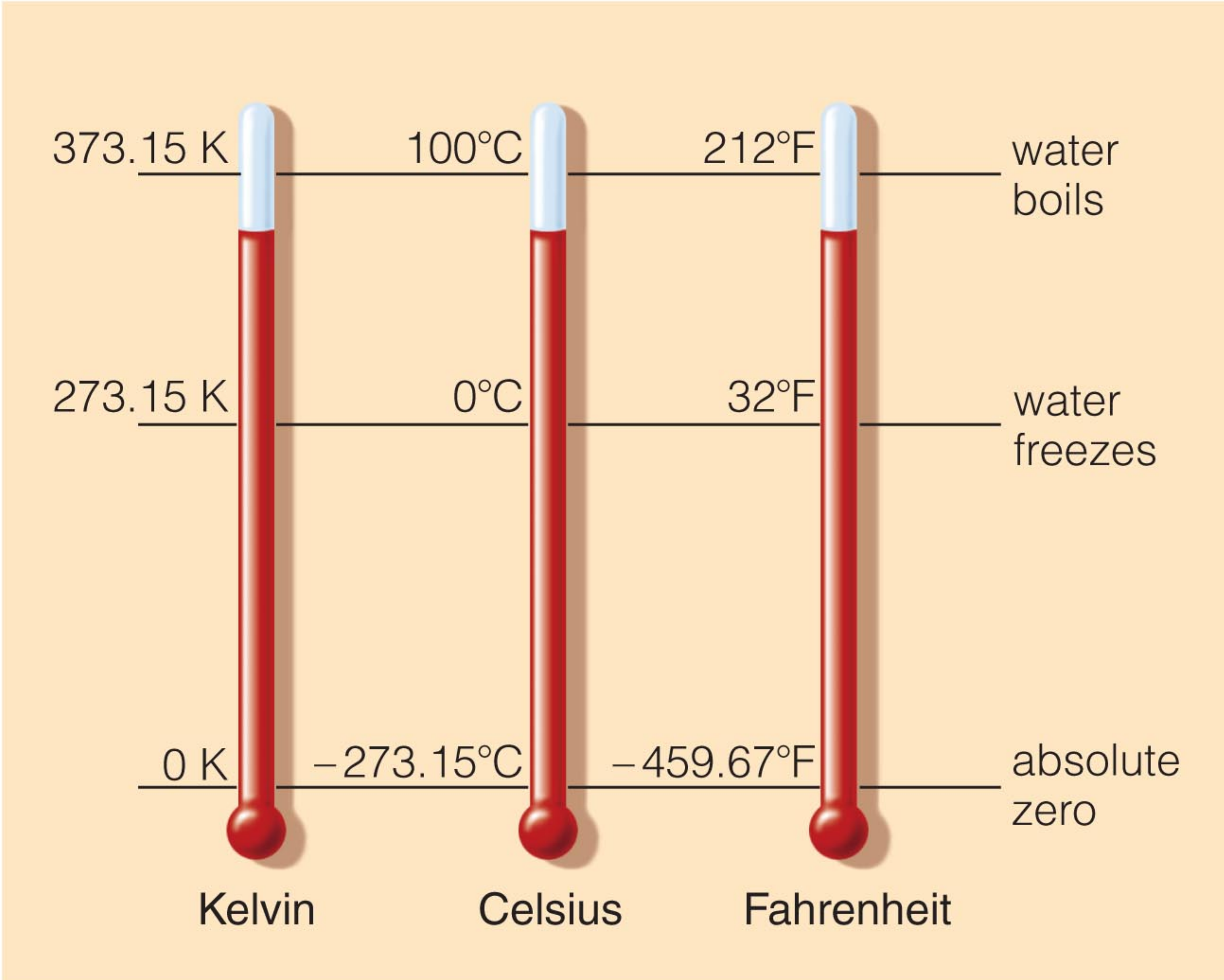


Thermal Energy:

- The collective kinetic energy of many particles (for example, in a rock, in air, in water)
  - Thermal energy is related to temperature but it is NOT the same.
  - **Temperature** is the *average* kinetic energy of the many particles in a substance.



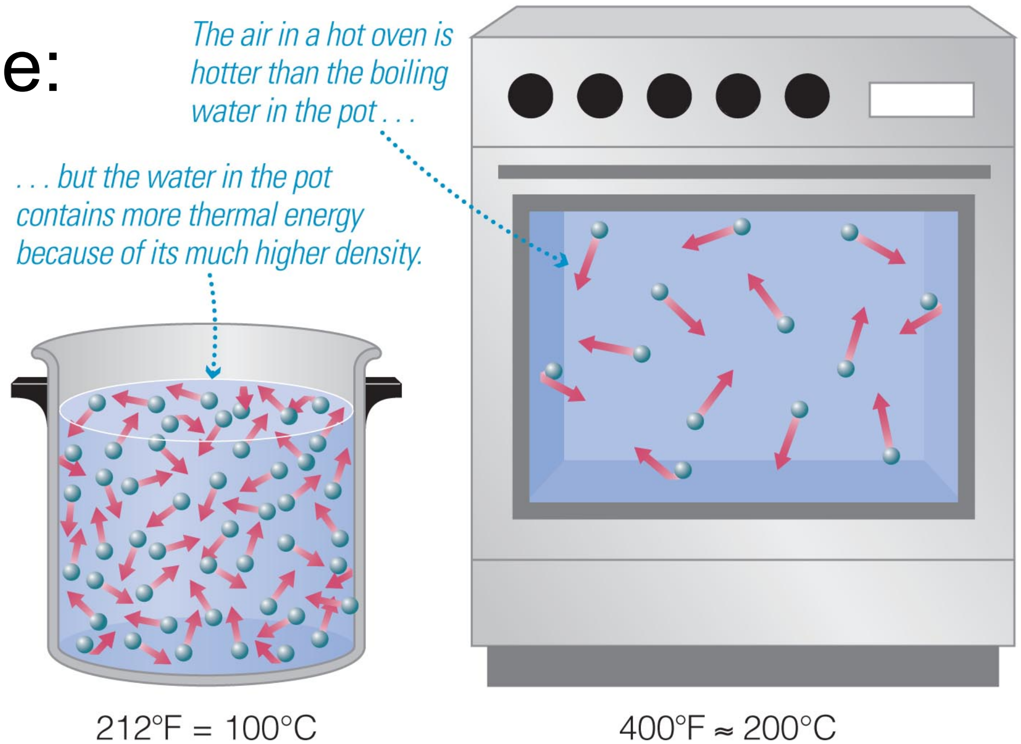
Temperature Scales



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.*

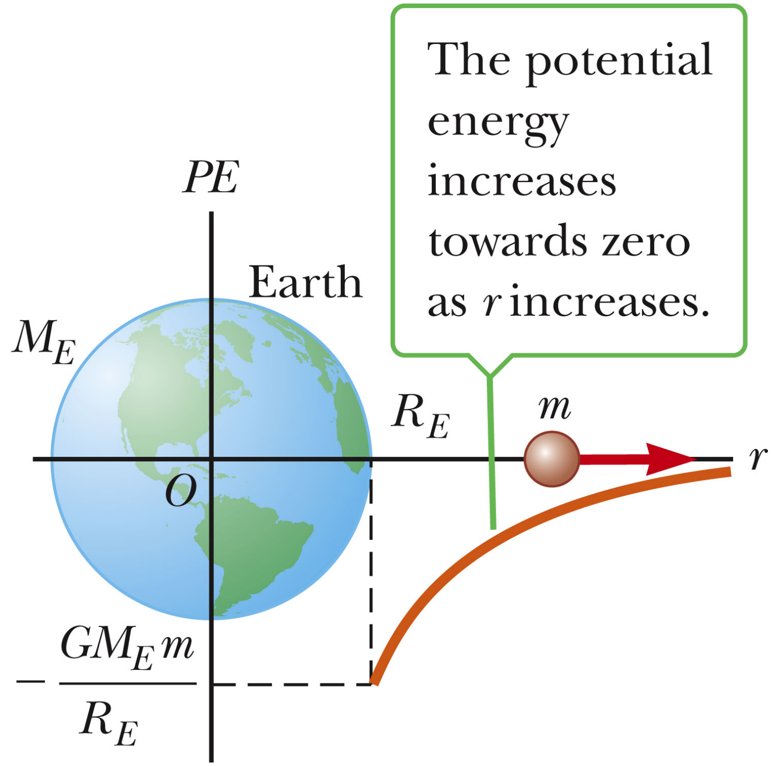
Example:



Gravitational Potential Energy, PE

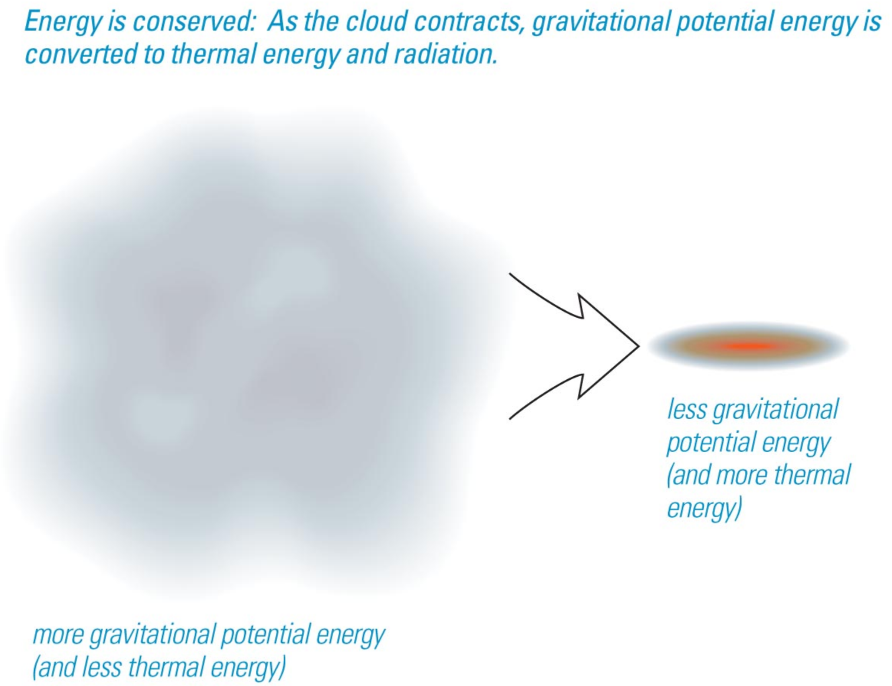
- On Earth, PE = mgh
  - object's *mass (m)*
  - strength of gravity *(g)*
  - distance object could potentially fall

- More accurate: $PE = -G\dfrac{M_E m}{r}$



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:

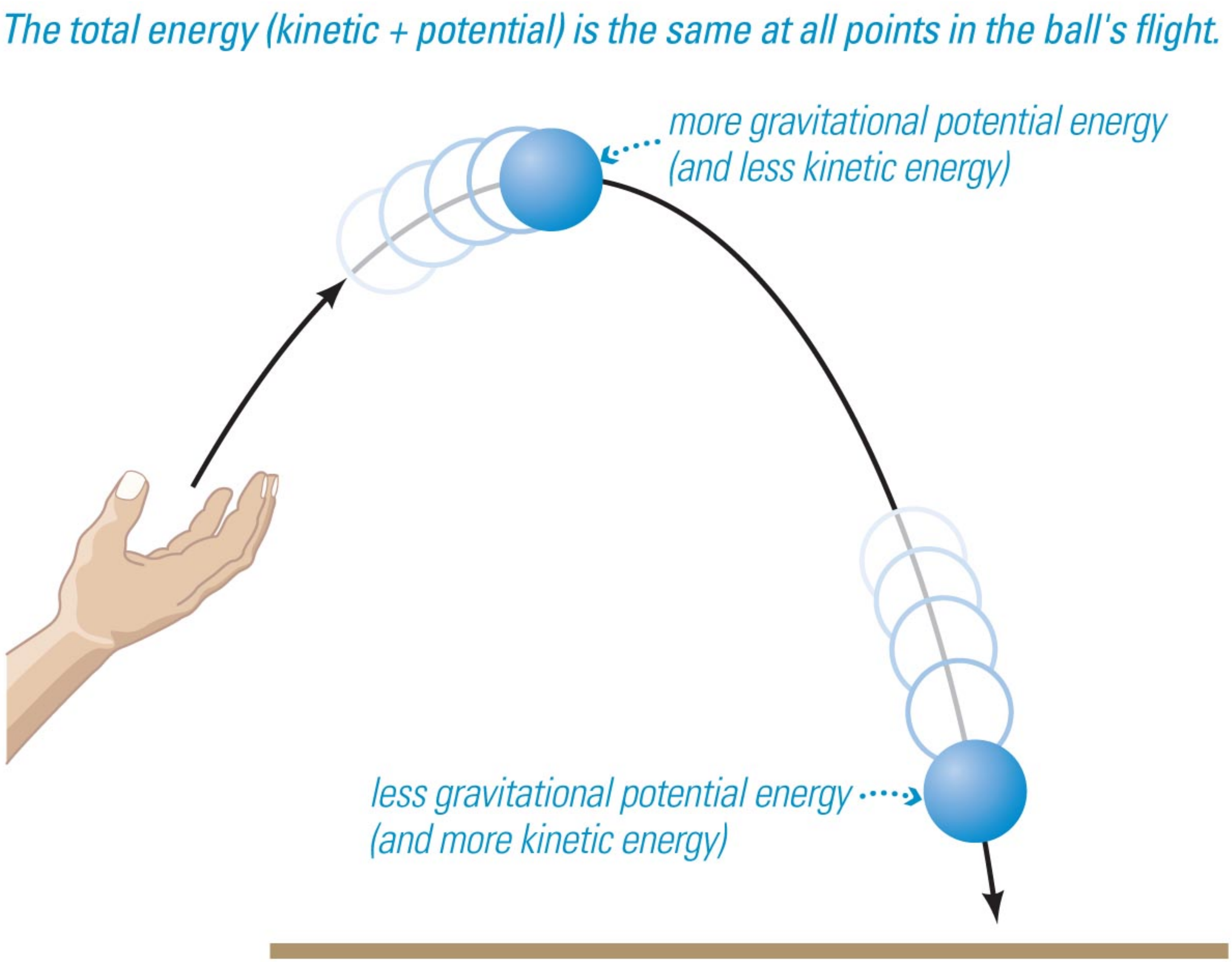
$$E = mc^2$$

- 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.

Conservation of Total Energy



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.

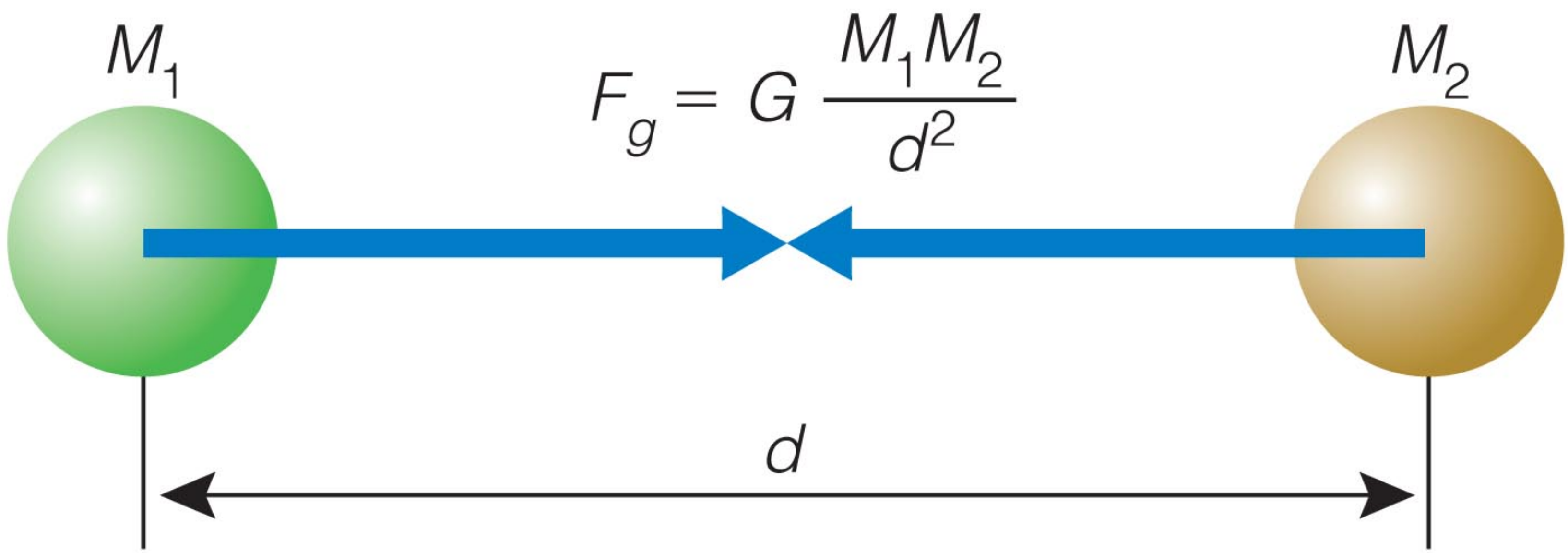
4.4 The Universal Law of Gravitation

- 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. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.



Newton's Law of Gravity

Example 1: What is the gravitational force between the Sun and Earth?

Earth's mass = 5.98×10^{24} kg
Sun's mass = 1.99×10^{30} kg
1 AU = 1.5×10^{11} m
$G = 6.67 \times 10^{-11}$ Newton $\cdot$ m^2/kg^2

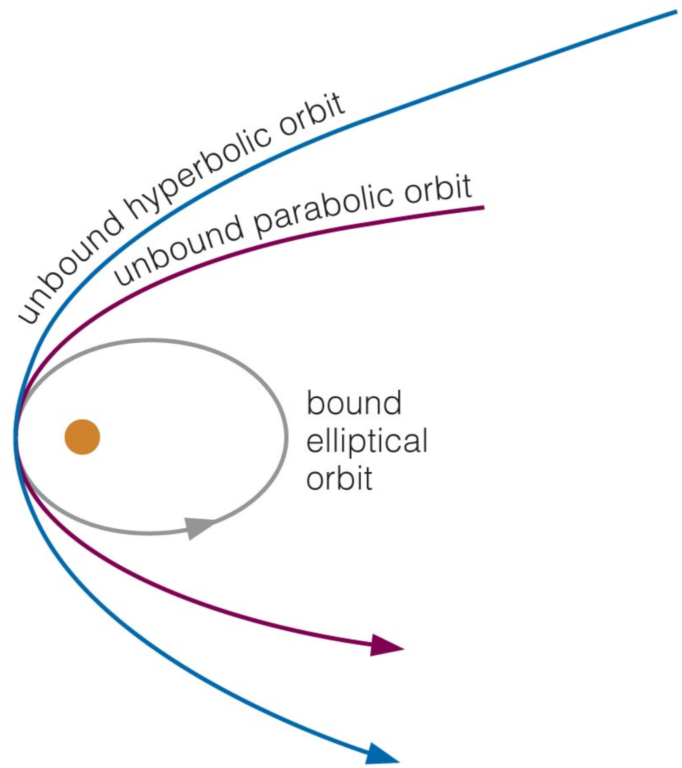
Newton's Law of Gravity

Example 2: What is the ratio of your weight to your mass?

Earth's mass = 5.98×10^{24} kg
Sun's mass = 1.99×10^{30} kg
Earth's radius = 6378 km
$G = 6.67 \times 10^{-11}$ Newton $\cdot$ m^2/kg^2

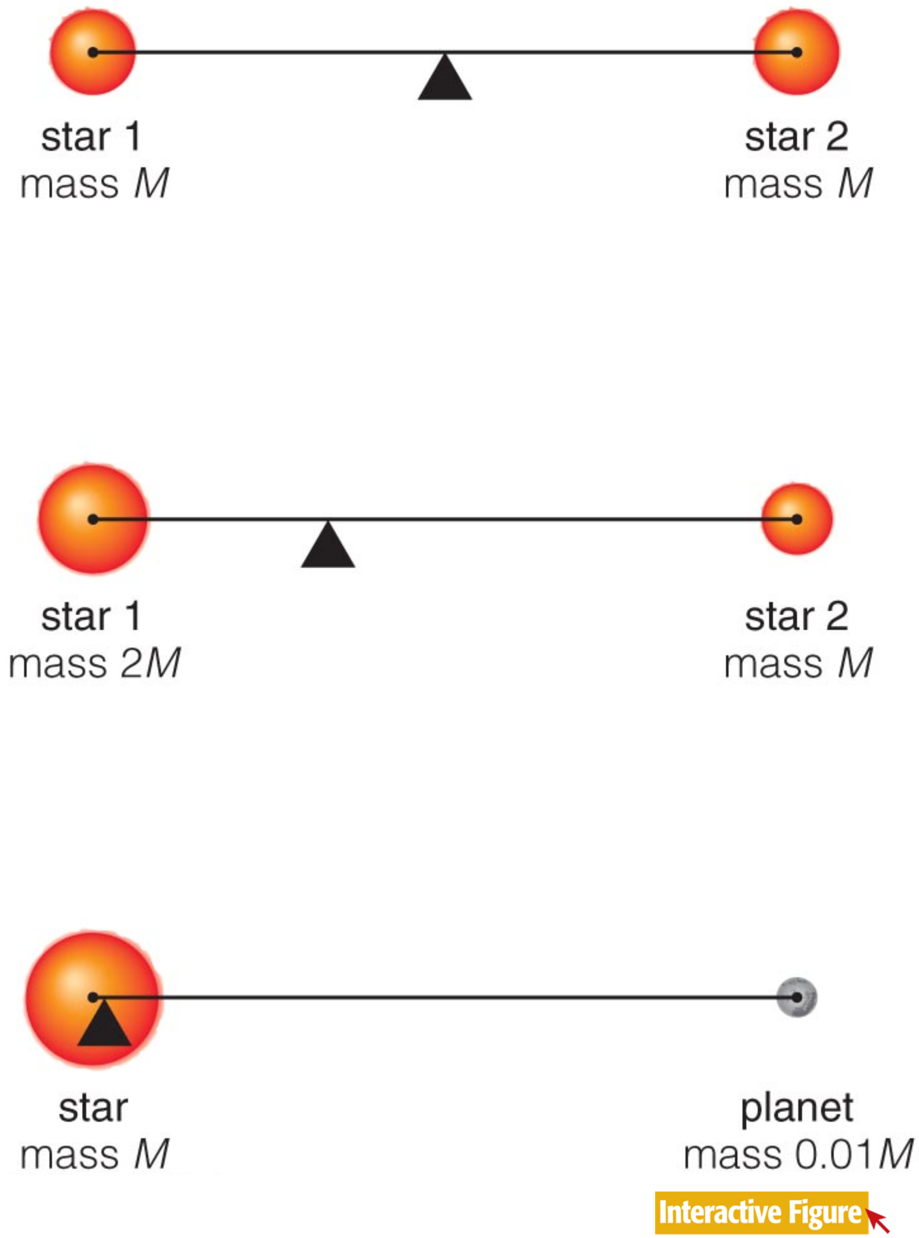
How does Newton's law of gravity extend Kepler's laws?

- 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.

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.

- Examples:
  - 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

$$P^2 = \left[\frac{4\pi^2}{G(m_1 + m_2)}\right] a^3$$

P = sidereal period of orbit, in seconds
a = average orbital distance between centers, in meters
m_1 = mass of first object, in kilograms
m_2 = mass of second object, in kilograms
G = universal constant of gravitation = 6.67×10^{-11} Newton · m^2/kg^2

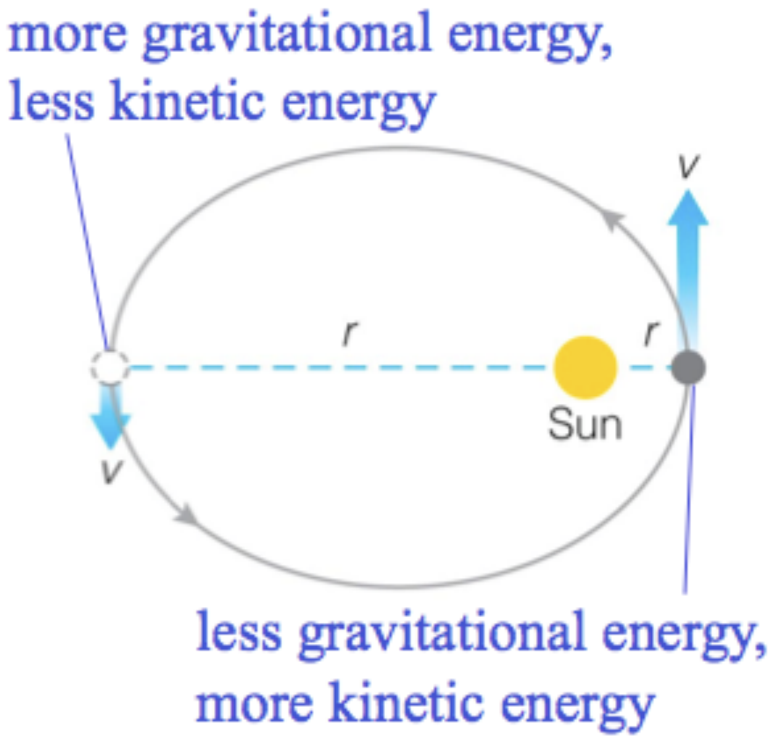
What have we learned?

- **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.

Total orbital energy stays constant.

Questions on Gravity

Sample questions:

Why does a person orbiting Earth in the Space Shuttle feel weightless?

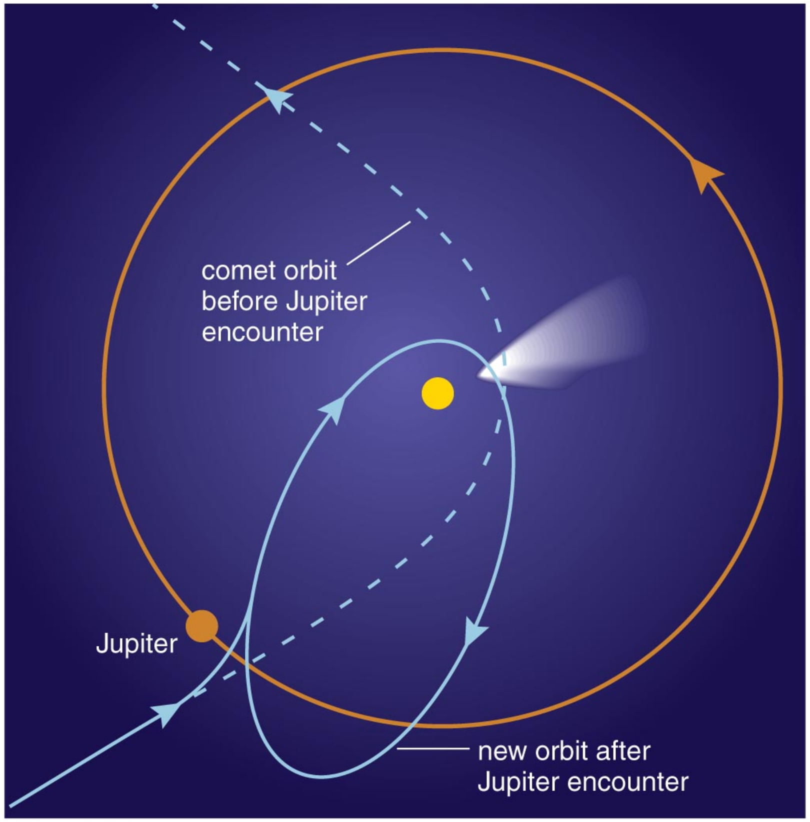
A feather and a boulder are left to fall under the influence of gravity in a vacuum. Compare their accelerations.

You throw a ball straight up in the air. At its highest point what are the ball's acceleration and velocity.

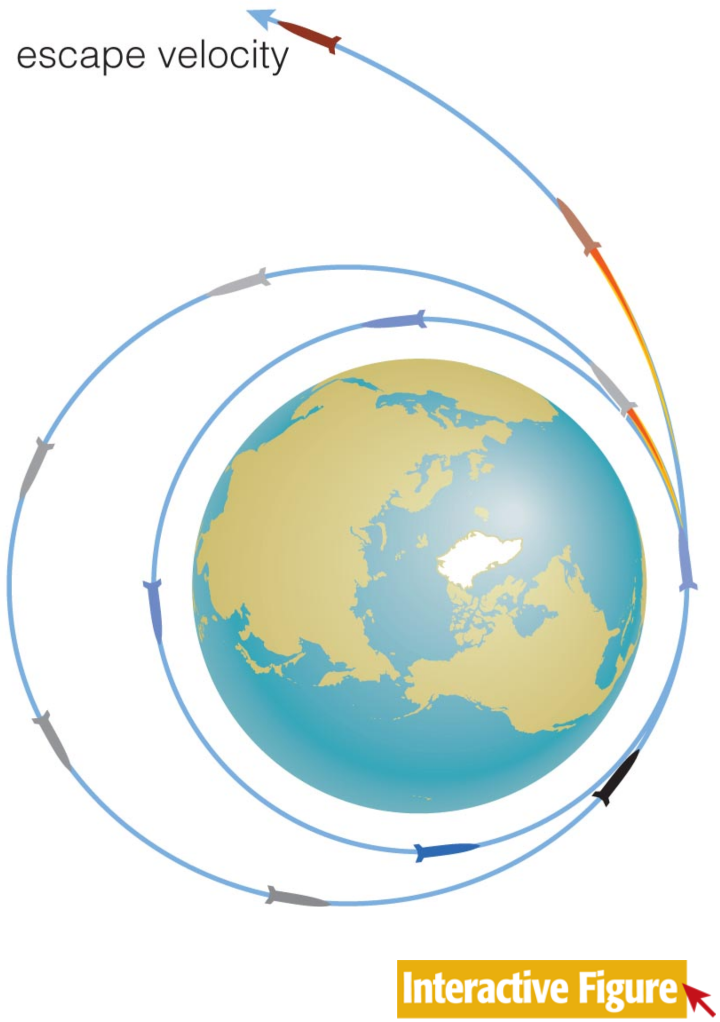
Suppose that a planet of the same mass as Earth were orbiting the Sun at a distance of 3 AU. By how much would the gravitational force on this planet due to the Sun change.

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)

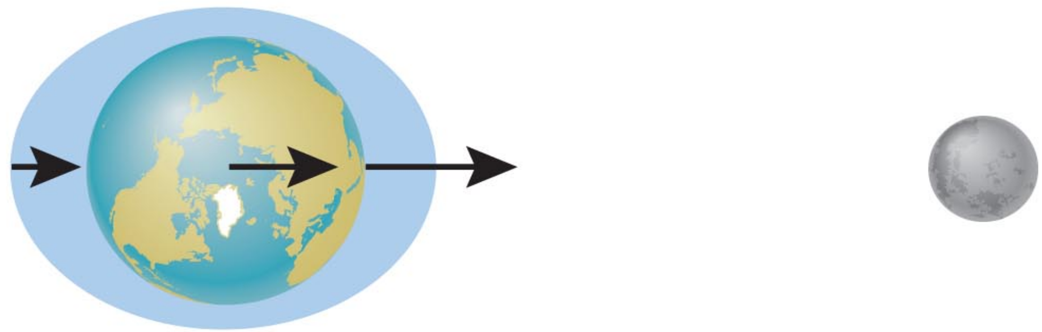
The Gravity Probe B EXPERIMENT

Gravity in Newton’s Universe

The Gravity Probe B EXPERIMENT

Gravity in Einstein's Universe

How does gravity cause tides?



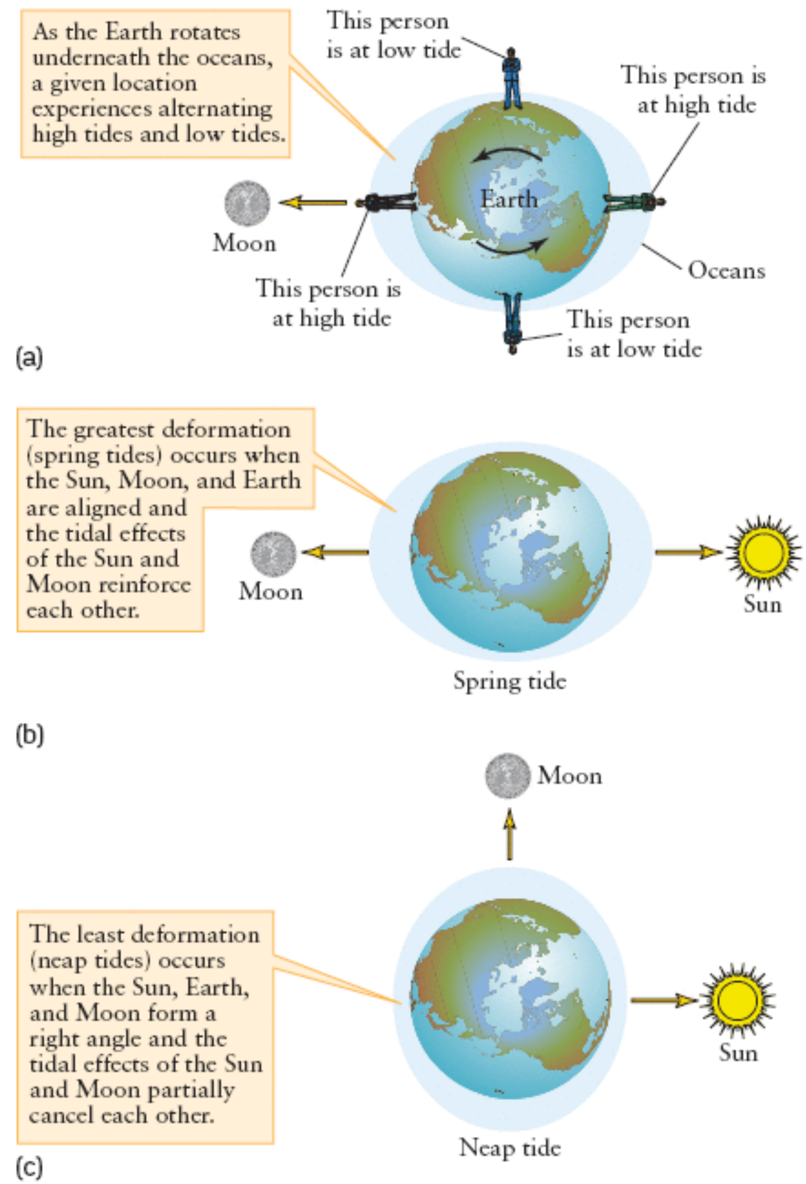
Not to scale!

- Moon's gravity pulls harder on near side of Earth than on far side.
- Difference in Moon's gravitational pull stretches the water on Earth.
- Note that due to the Earth’s rotation, there are 2 high tides and 2 low tides per day.

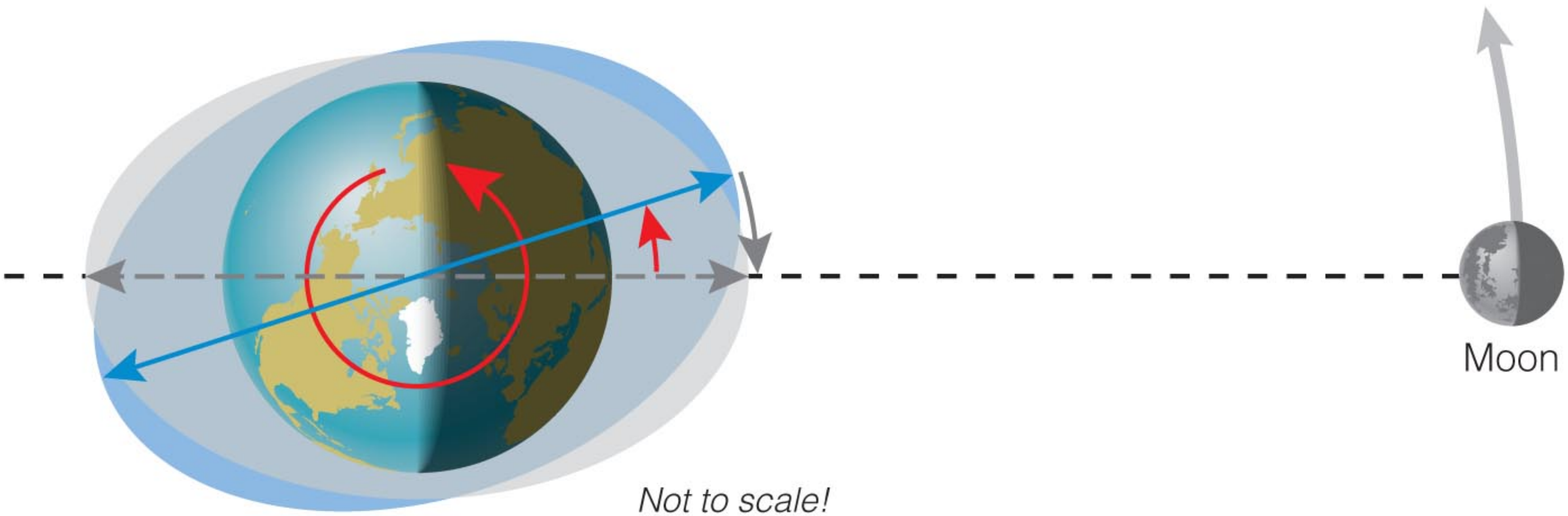
TIDES

The Sun also produces tides on the Earth, but due to its much larger distance, the solar tides are only half as strong as the lunar tides.

When the Sun, Earth, and Moon are aligned (full or new moon), you get "spring" or extra-strong tides. When the Sun, Earth, and Moon are at right angles, the solar tide partially cancels the lunar tide.This produces "neap" tides.



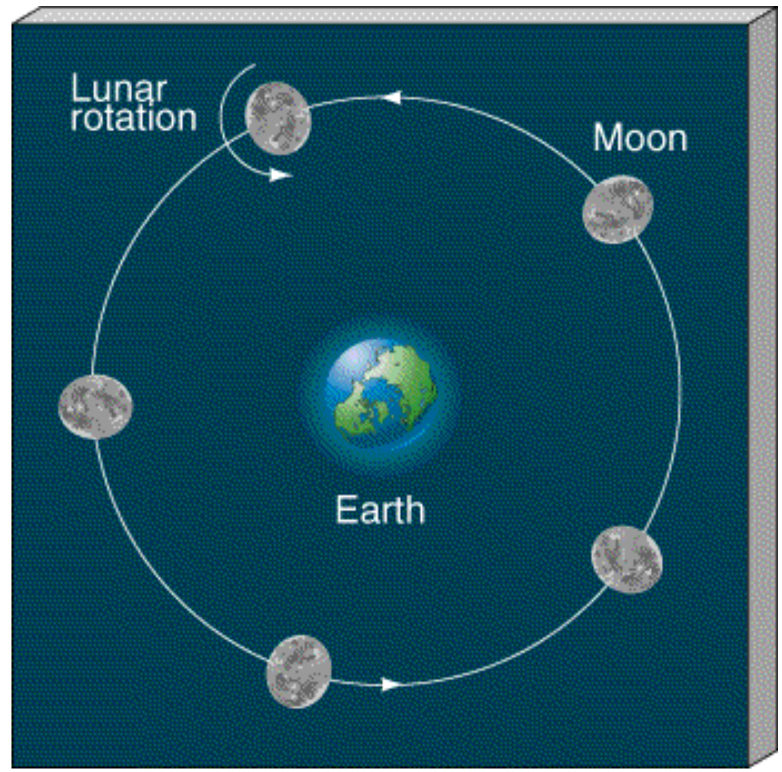
Tidal Friction



- Tidal friction gradually slows Earth's rotation (and makes the Moon get farther from Earth)

Moon’s Synchronous Orbit

Earth also produces a tidal bulge in the Moon. The Moon's much larger tidal deformation caused it to evolve into a synchronous orbit long ago, and the Moon is said to have become tidally locked to Earth.



Most of the moons in the solar system are similarly locked by the tidal fields of their parent planets.

Why do all objects fall at the same rate?

$$a_{\text{rock}} = \frac{F_g}{M_{\text{rock}}} \qquad F_g = G\frac{M_{\text{Earth}} M_{\text{rock}}}{R_{\text{Earth}}^2}$$

$$a_{\text{rock}} = G\frac{M_{\text{Earth}} \cancel{M_{\text{rock}}}}{R_{\text{Earth}}^2 \cancel{M_{\text{rock}}}} = G\frac{M_{\text{Earth}}}{R_{\text{Earth}}^2}$$

- 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.