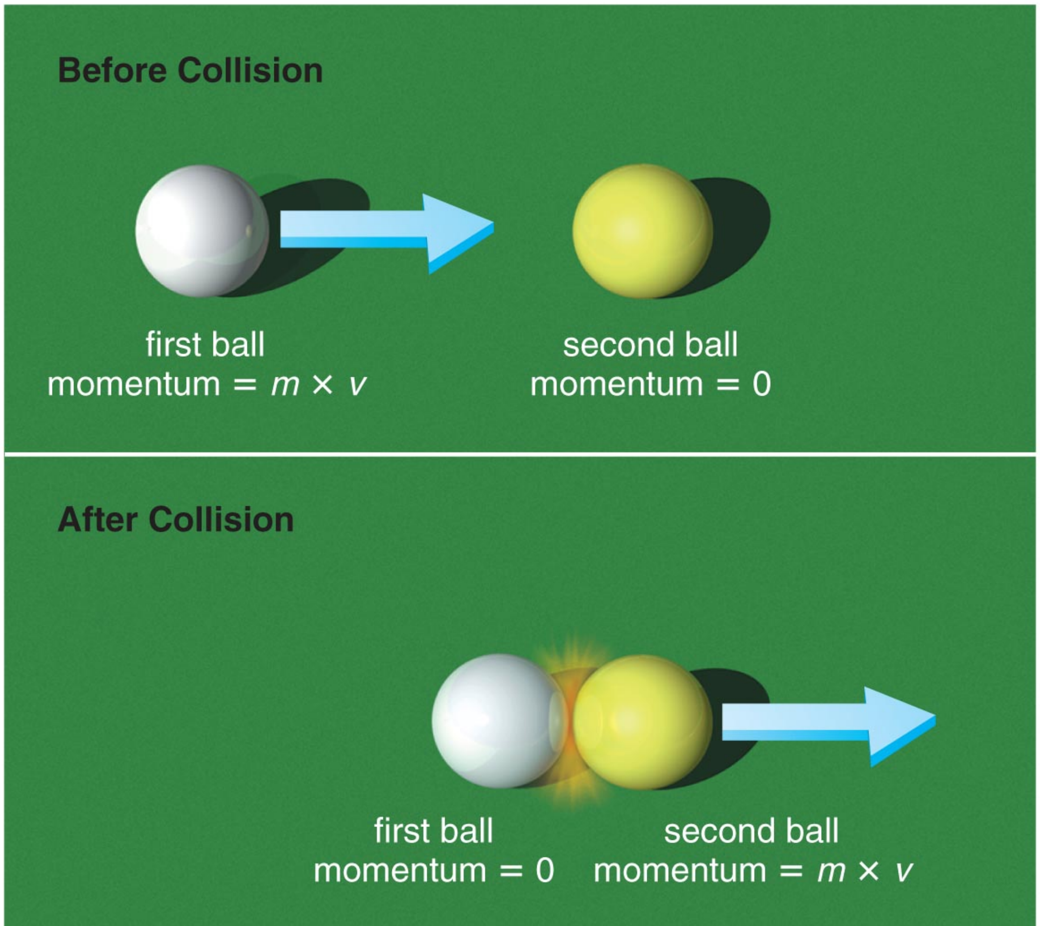
4.3 Conservation Laws in Astronomy

- 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?**

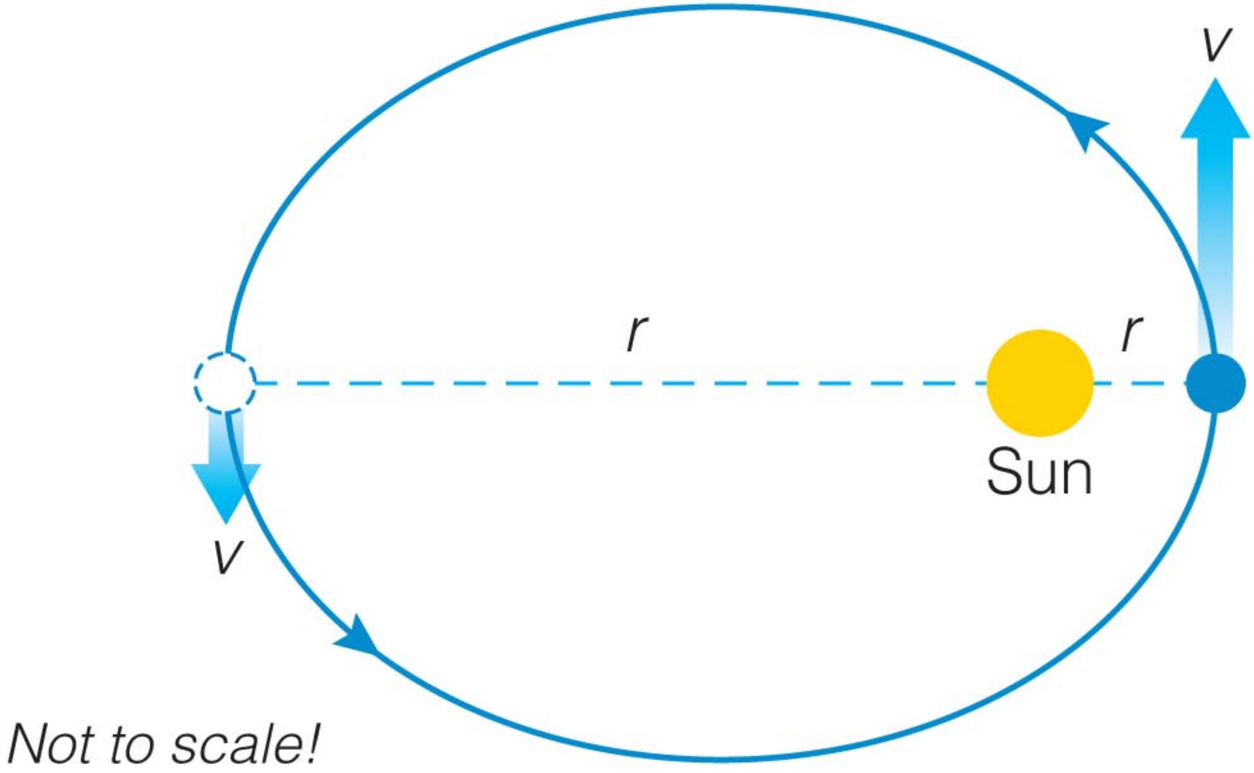
Why do objects move at constant velocity if no force acts on them?

Objects continue at constant velocity because of **conservation of momentum**.



- 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 orbit will continue indefinitely.

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

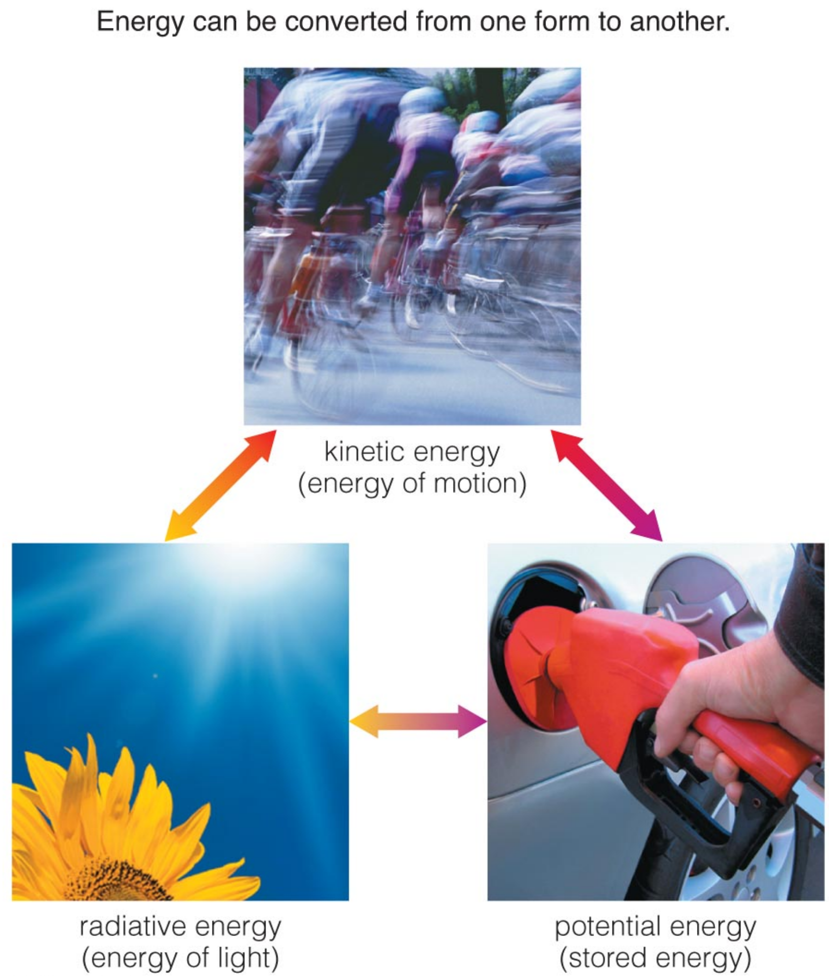
Where do objects get their energy?

- Energy makes matter move.
- Energy is conserved, but it can:
  - transfer from one object to another
  - change in form

Basic Types of Energy

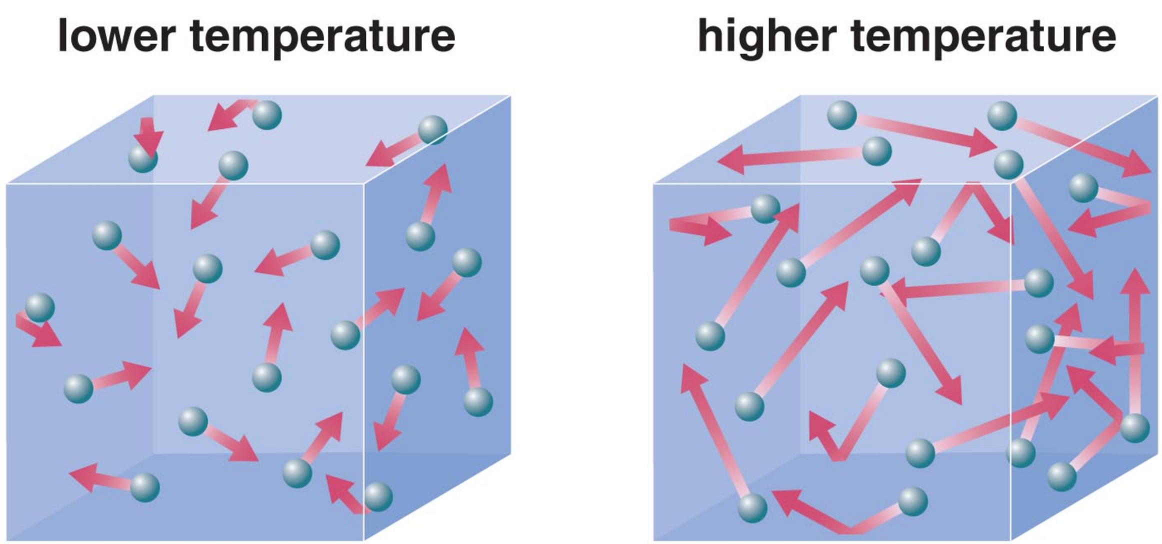
- Kinetic (motion)
- Radiative (light)
- Potential (stored)

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

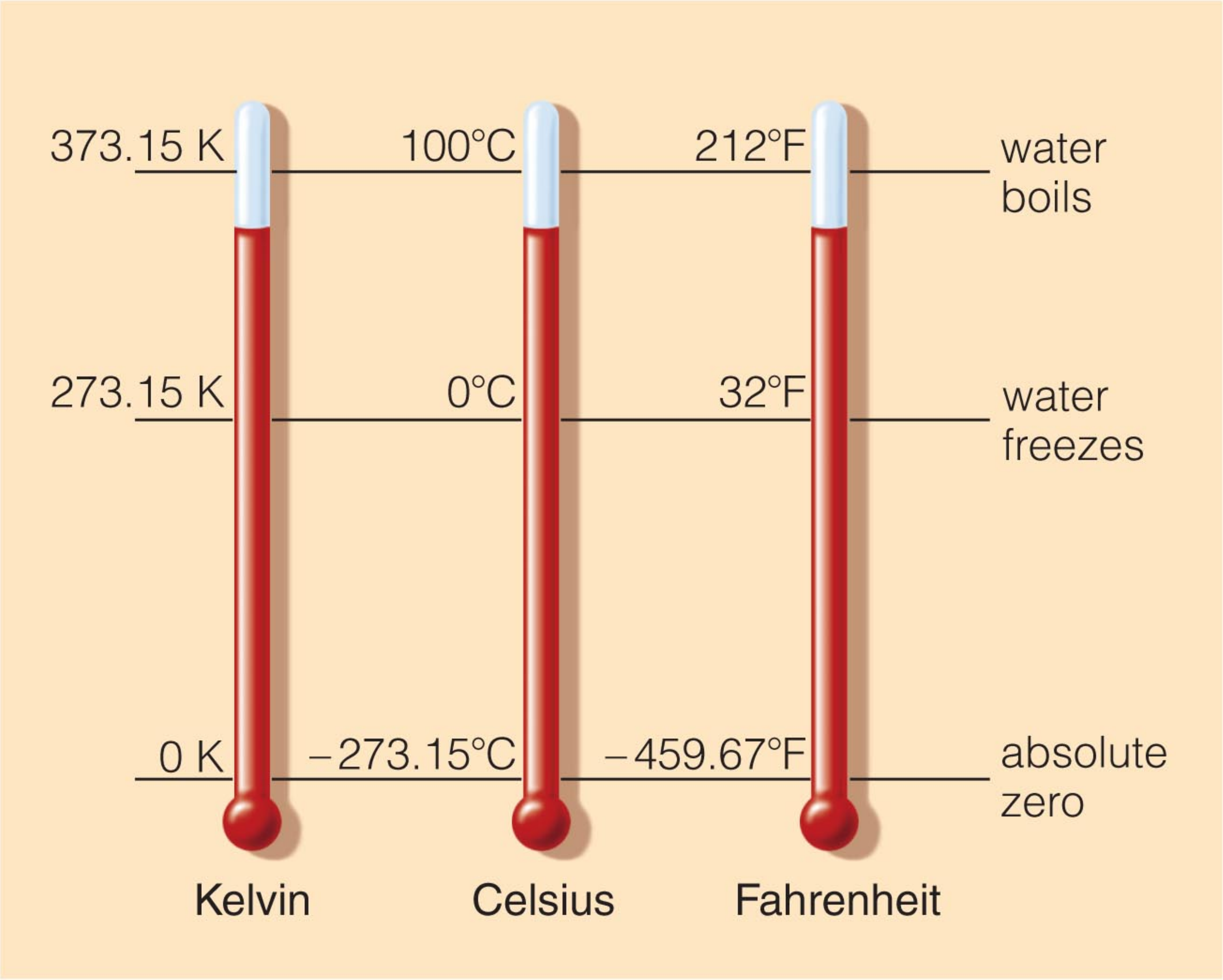


Thermal Energy:

- 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.



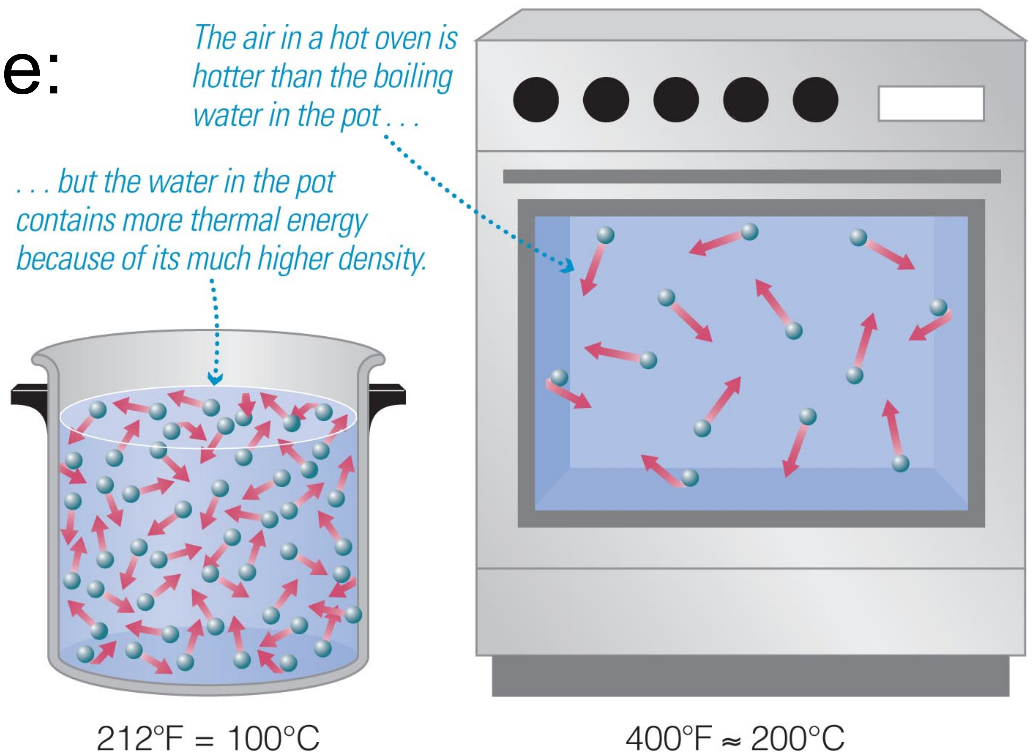
Temperature Scales



Temperature Scales

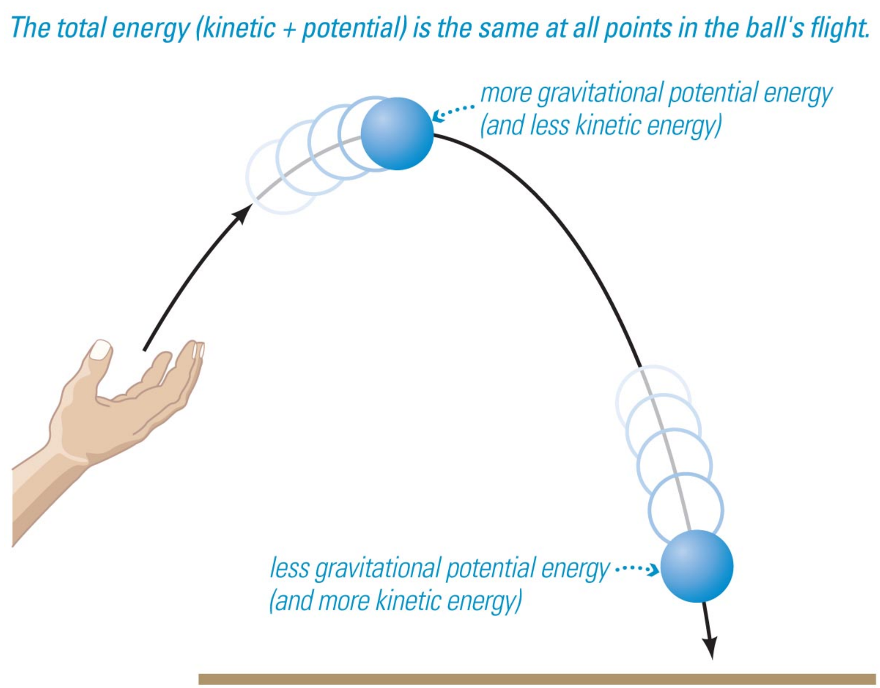
- Thermal energy is a measure of the total kinetic energy of all the particles in a substance. It therefore depends on both *temperature* AND *density.*

Example:



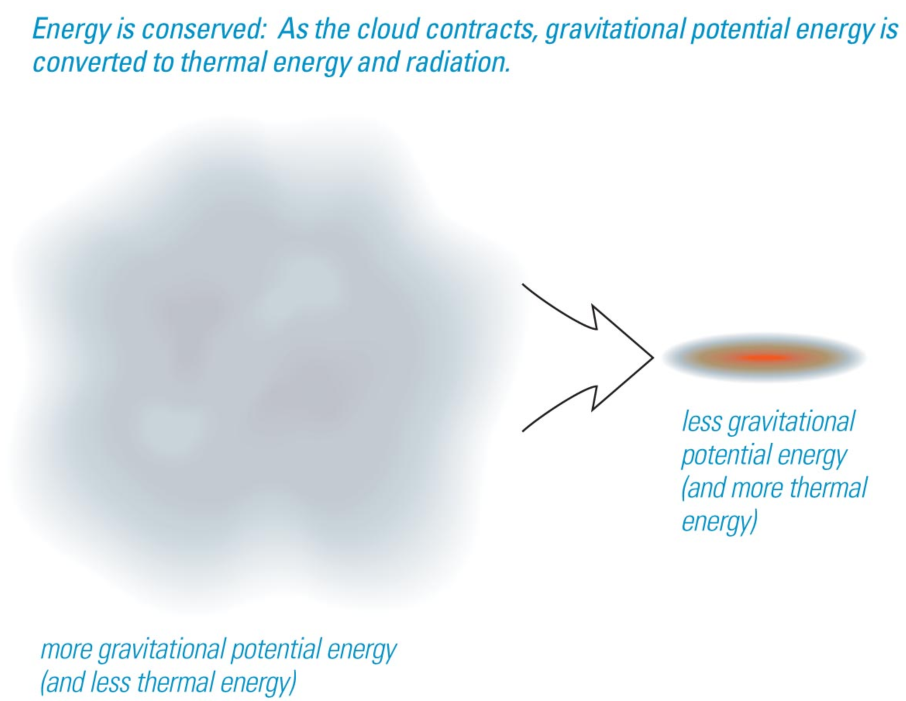
Gravitational Potential Energy

- 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.

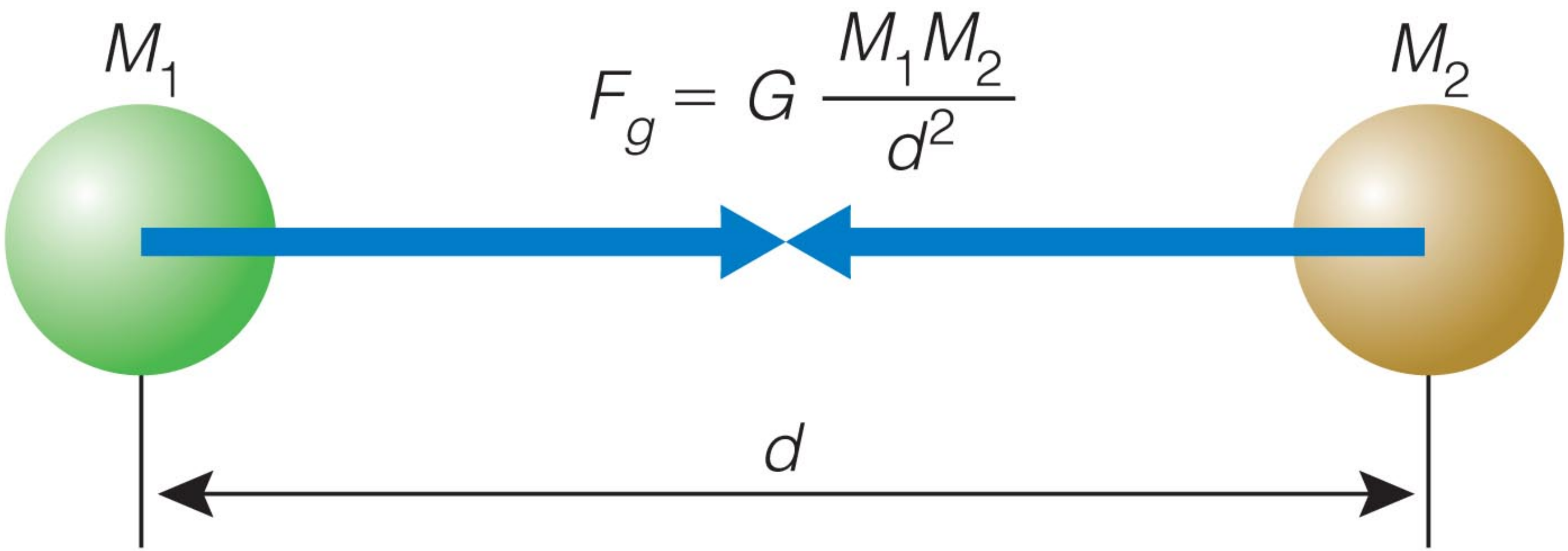
4.4 The Universal Law of Gravitation

- 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?

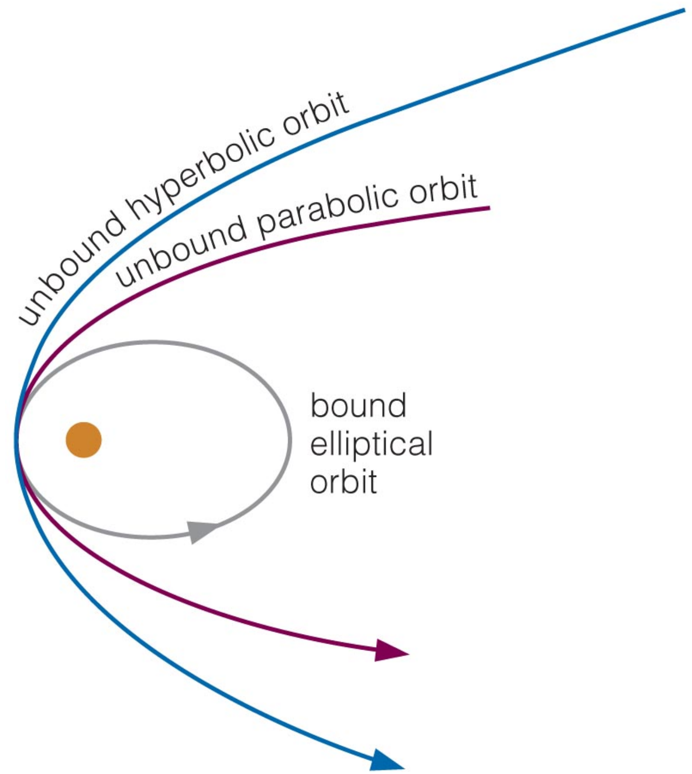
The **universal law of gravitation:**

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



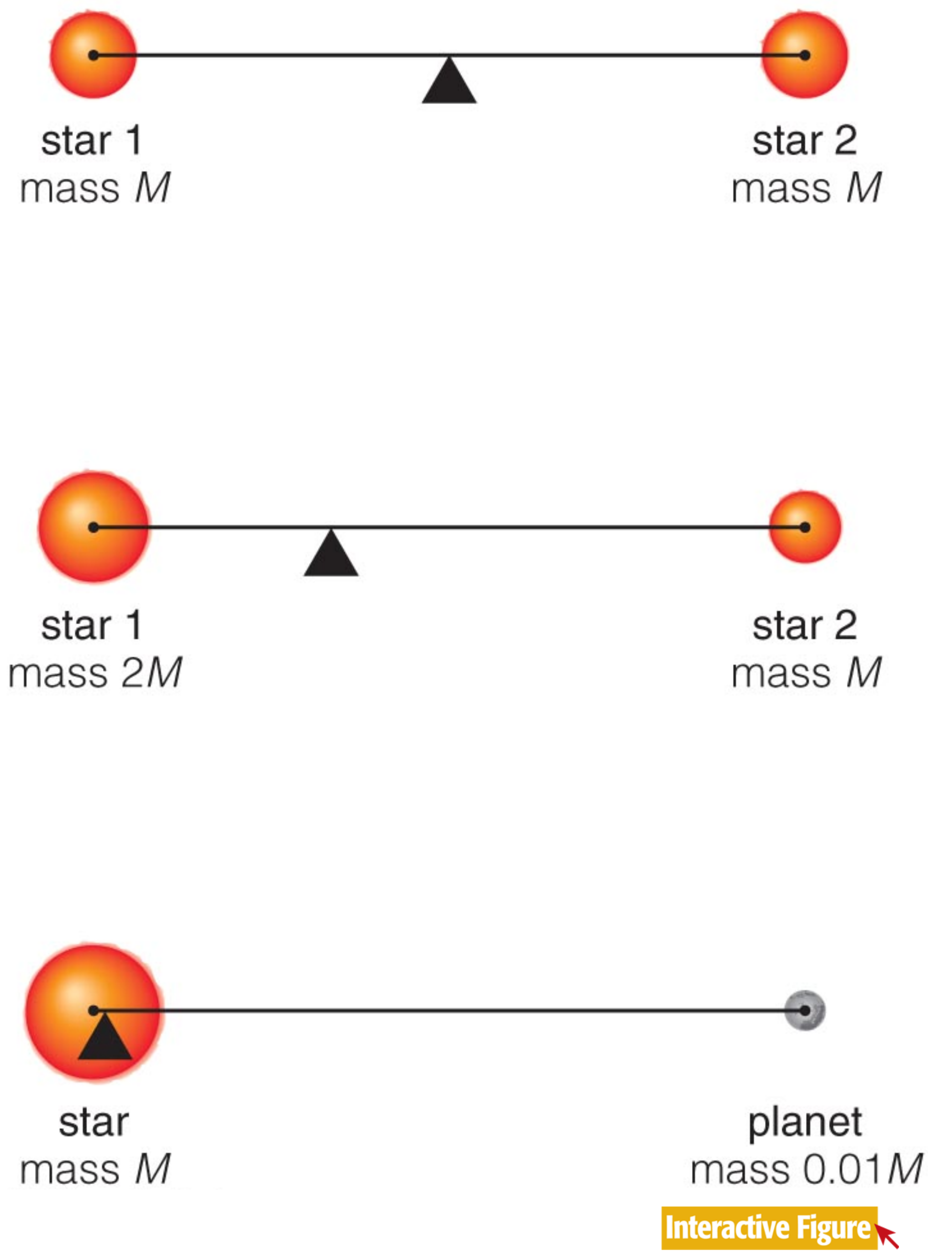
How does Newton's law of gravity extend Kepler's laws?

- 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.

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

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

- G = Newton's gravitational constant
- p = orbital period
- a = average orbital distance (between centers)
- $(M_1 + M_2)$ = sum of object masses

Newton's Version of Kepler's Third Law

$$P^2 = \frac{a^3}{M_1 + M_2}$$

p = orbital period **in years**

a = average orbital distance **in AU** (between centers)

$(M_1 + M_2)$ = sum of object masses **in Sun masses**

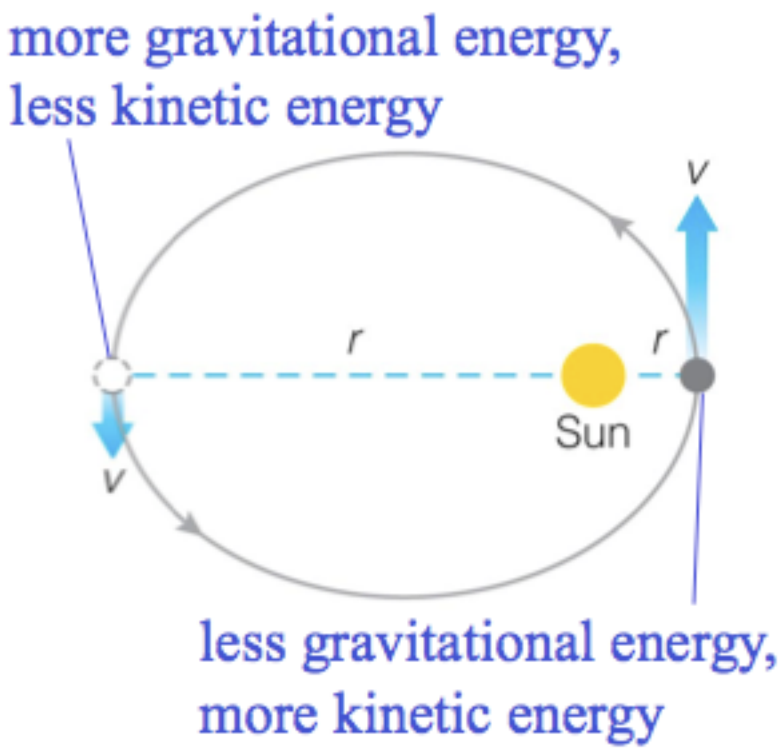
What have we learned?

- **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?

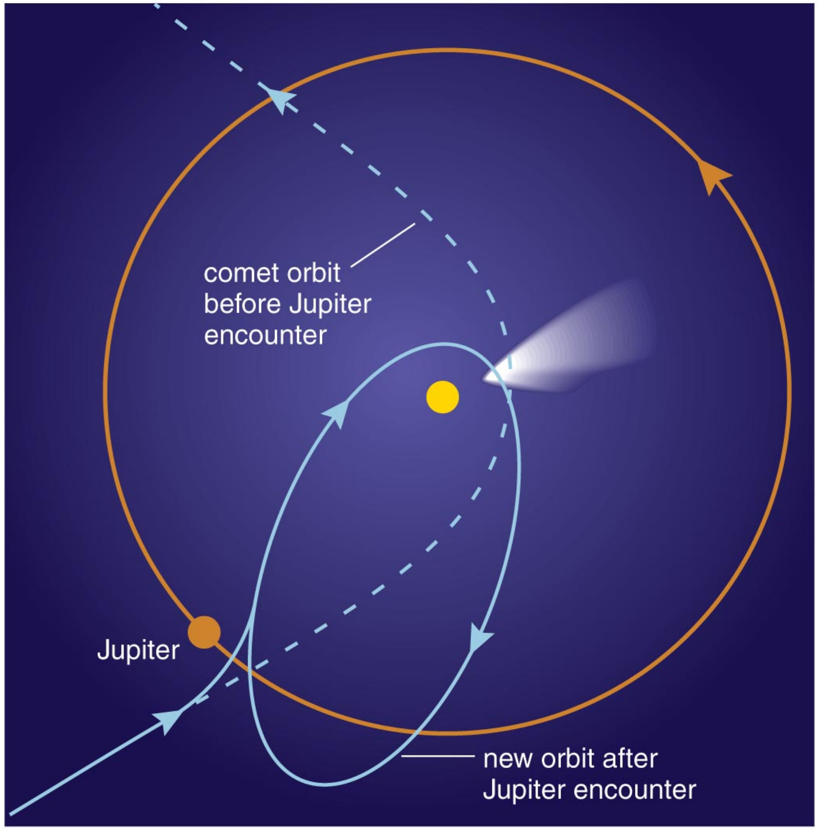


- Total orbital energy (gravitational + kinetic) stays constant if there is no external force.
- Orbits cannot change spontaneously.

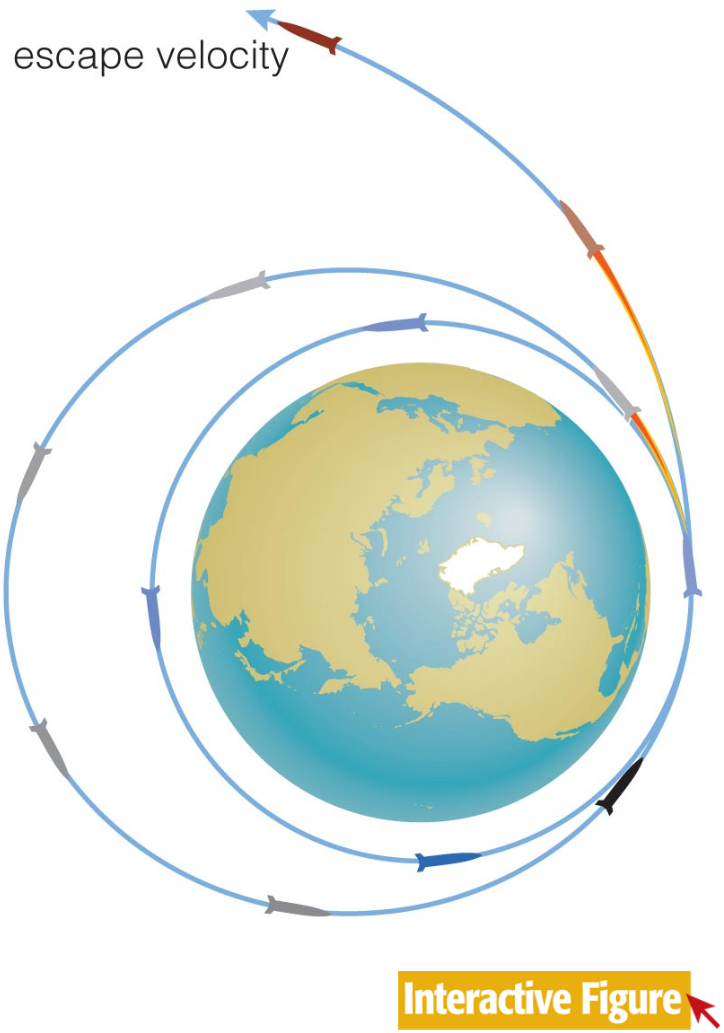
Total orbital energy stays constant.

Changing an Orbit

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



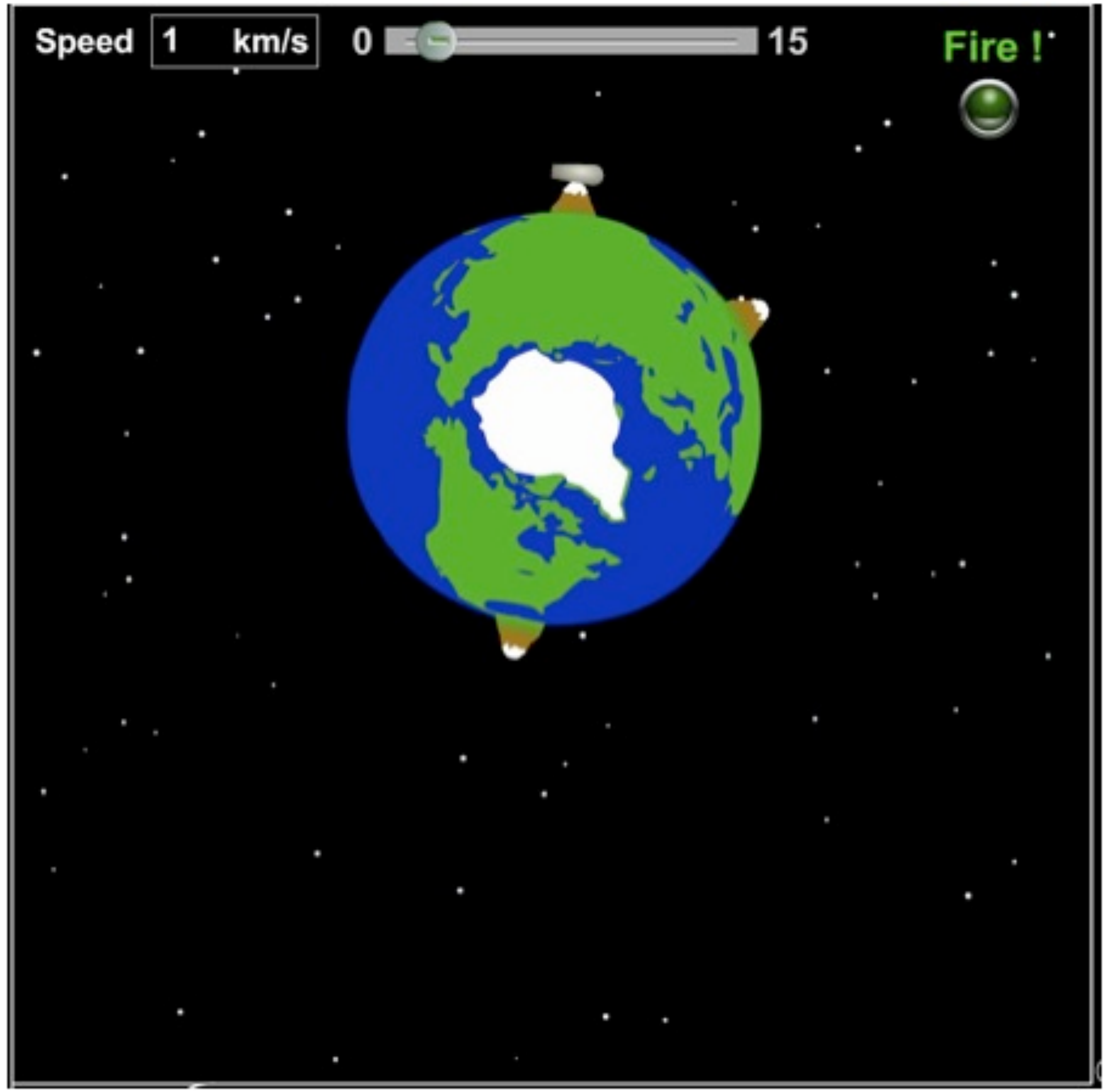
Escape Velocity



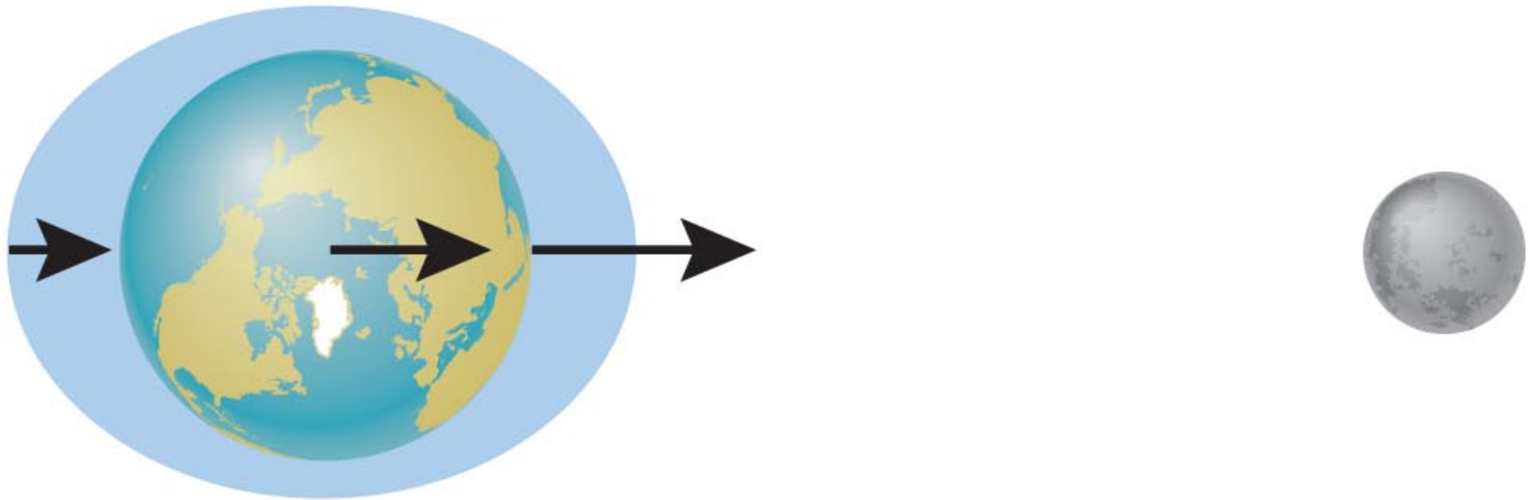
- If an object gains orbital energy, it moves to a more distant orbit.
- If an object gains enough energy, it may escape (change from a bound to unbound orbit).
- **Escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)

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 from one side to the other “stretches” the Earth.

Tides and Phases

- Since the tidal stretching is two-sided, as the Earth rotates, there are *two* high tides and *two* low tides a day.
- Strength of tides depends on phase of Moon.