- Homework 2 due next time; Exam review (Sept. 19)
- Exam I on Sept. 24 (one week from today)

Correct homework due dates (printed syllabus self-contradictory):

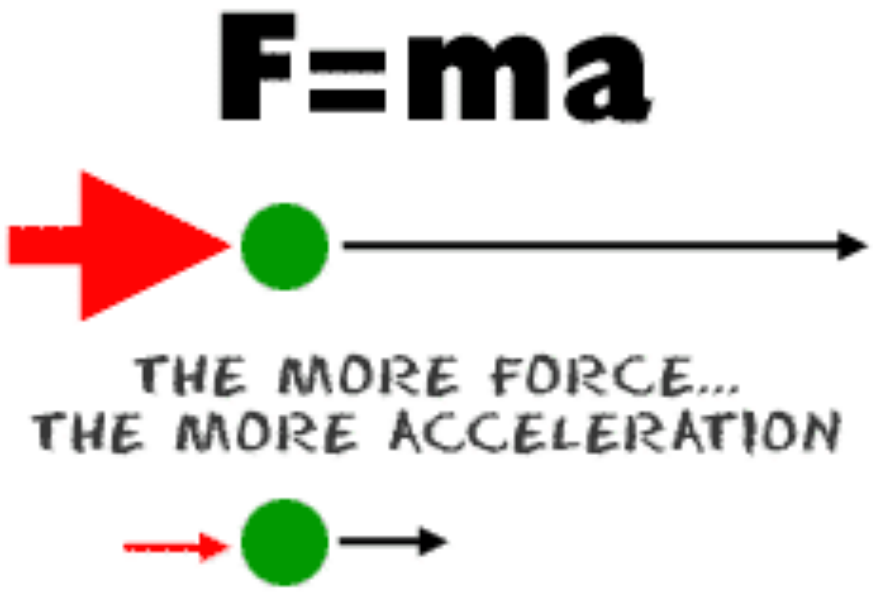
1. HW1: Tuesday, September 10
2. HW2: Thursday, September 19
3. HW3: Tuesday, October 8
4. HW4: Thursday, October 17
5. HW5: Tuesday, November 12
6. HW6: Tuesday, December 3

Exam dates are

1. Exam I: Tuesday, September 24
2. Exam II: Thursday, October 29
3. Exam III: Thursday, December 5

Today

- Laws of Motion
- Conservation Laws
- Gravity
  - tides



How did Newton change our view of the universe?

Sir Isaac Newton
(1642–1727)

- He realized the same physical laws that operate on Earth also operate in the heavens:
  ⇒ one *universe*
- He discovered laws of motion and gravity.
- Much more: Experiments with light; first reflecting telescope (using mirrors rather than lenses), invented calculus…

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.

In the absence of an applied force, an object at rest remains at rest. An object in motion remains in motion.

Newton's second law of motion

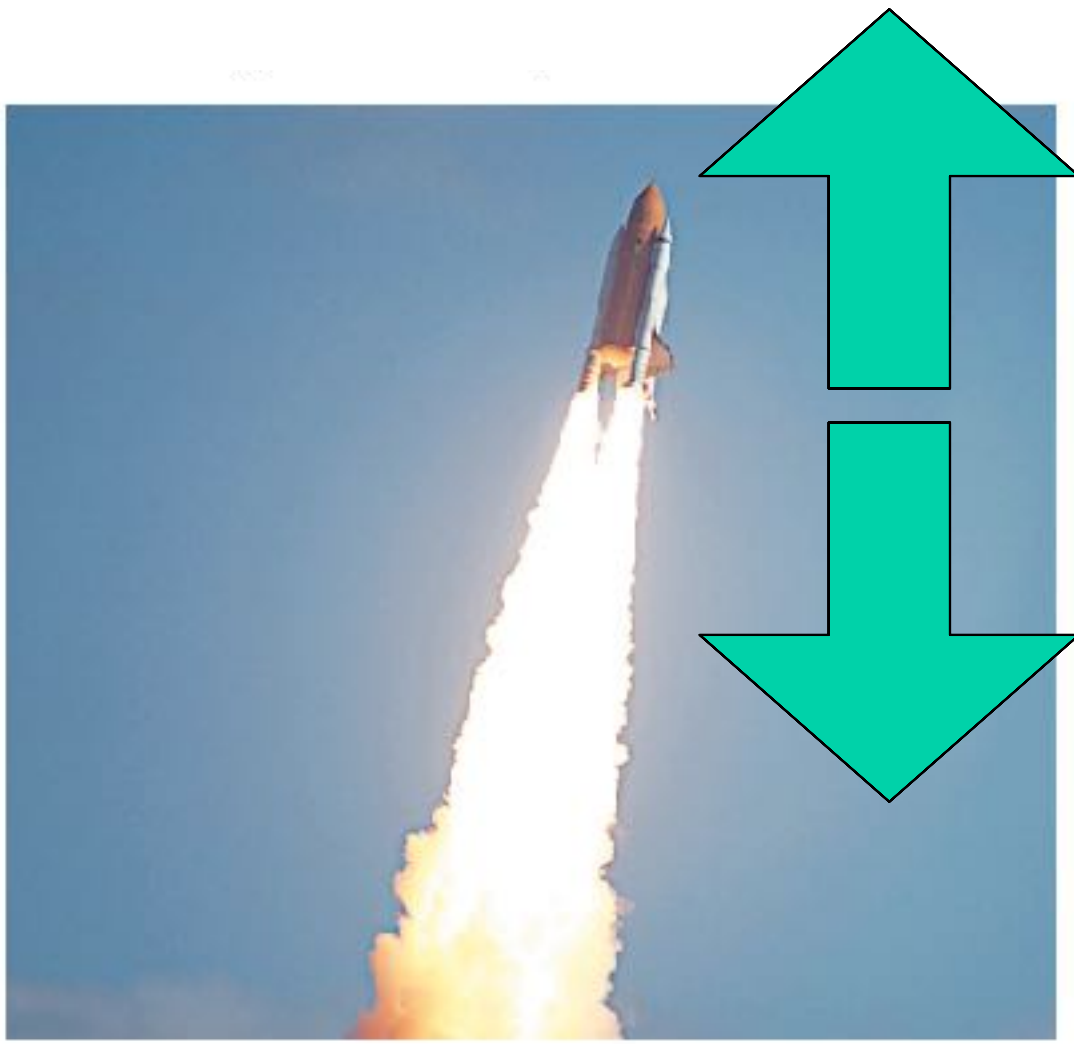
Force = mass × acceleration

$$F = ma$$

A force must be applied to change an object's state of motion (its momentum).

Newton’s third law of motion

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



As the rocket fires, the shuttle doesn’t just sit there. It accelerates in reaction to the applied force.

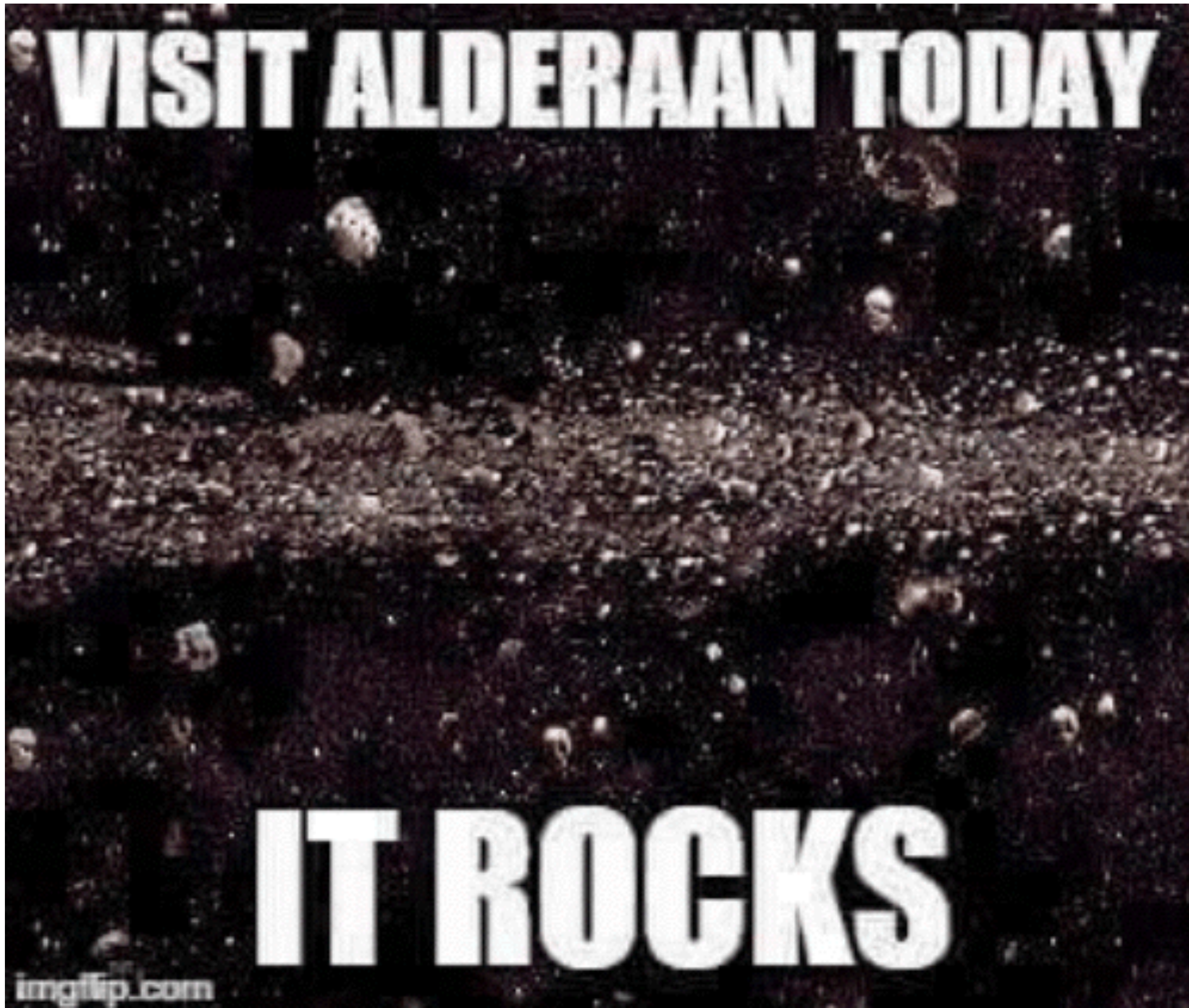
When seated, your weight is balanced by the reaction force of the chair.

- Newton's Three Laws of Motion
  1. An object moves at constant velocity (constant speed in the same direction) if no net force is acting on it.
  2. Force = mass × acceleration ($F = ma$).
  3. For every force, there is an equal and opposite reaction force.

Conserved Quantities

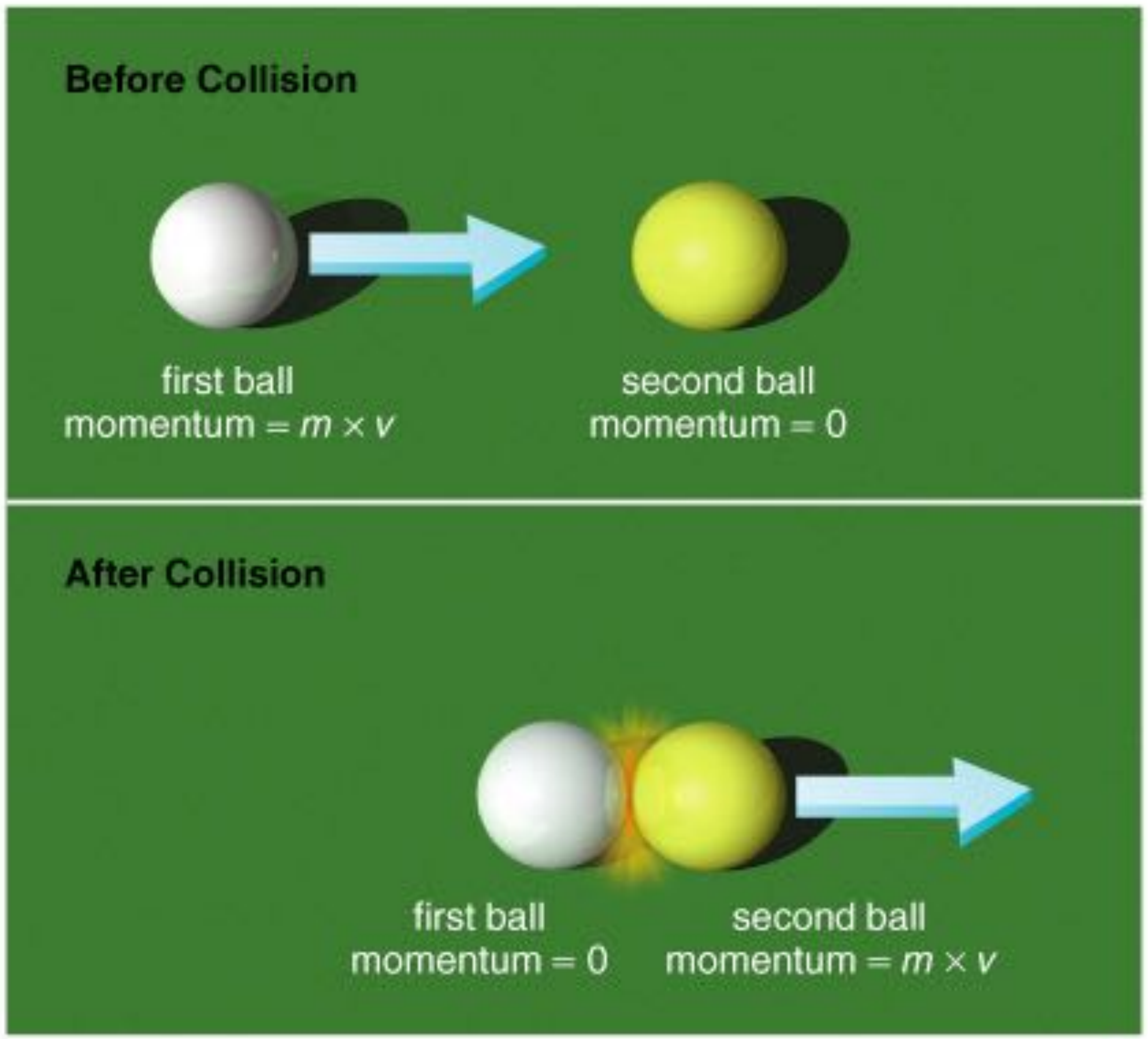
You can not destroy conserved quantities, only transfer them from one object to another.

- Mass
- Energy
- Momentum
- Angular momentum



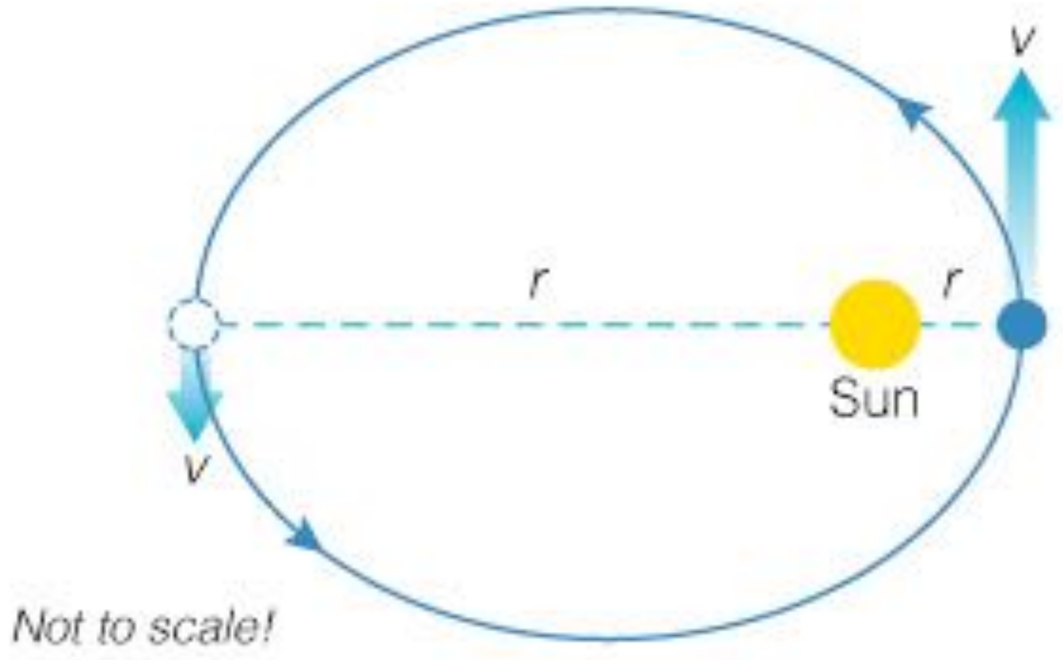
If you blow up Alderaan, all the pieces add up to the same mass.

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 × velocity × radius

$$\mathbf{L = mvr}$$

- 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:

L = mvr

e.g, kinetic energy:

- Energy makes matter move.

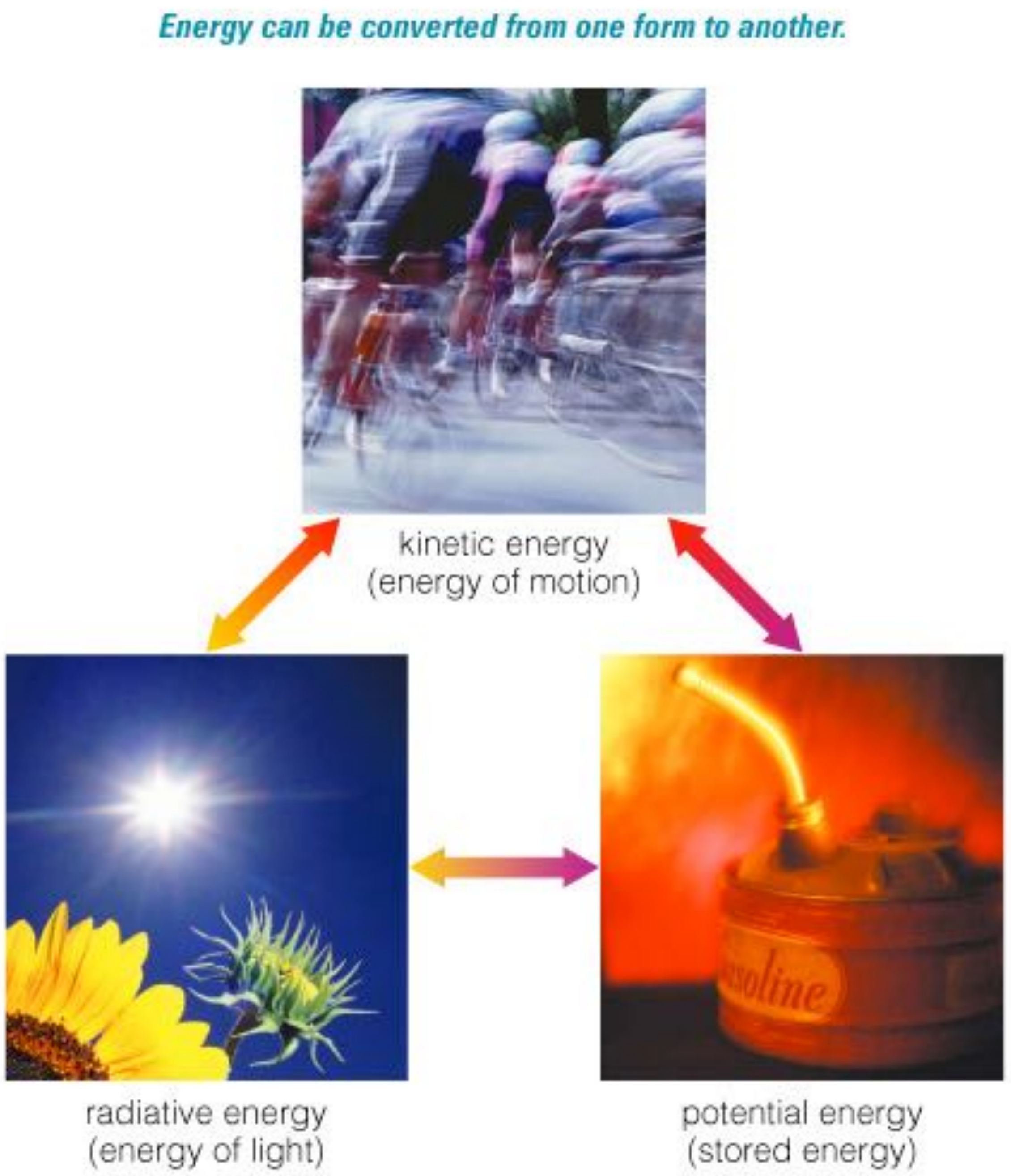
$$E_K = \frac{1}{2}mv^2$$

- Energy is conserved, but it can…
  - — transfer from one object to another.
  - — change in form.

Basic Types of Energy

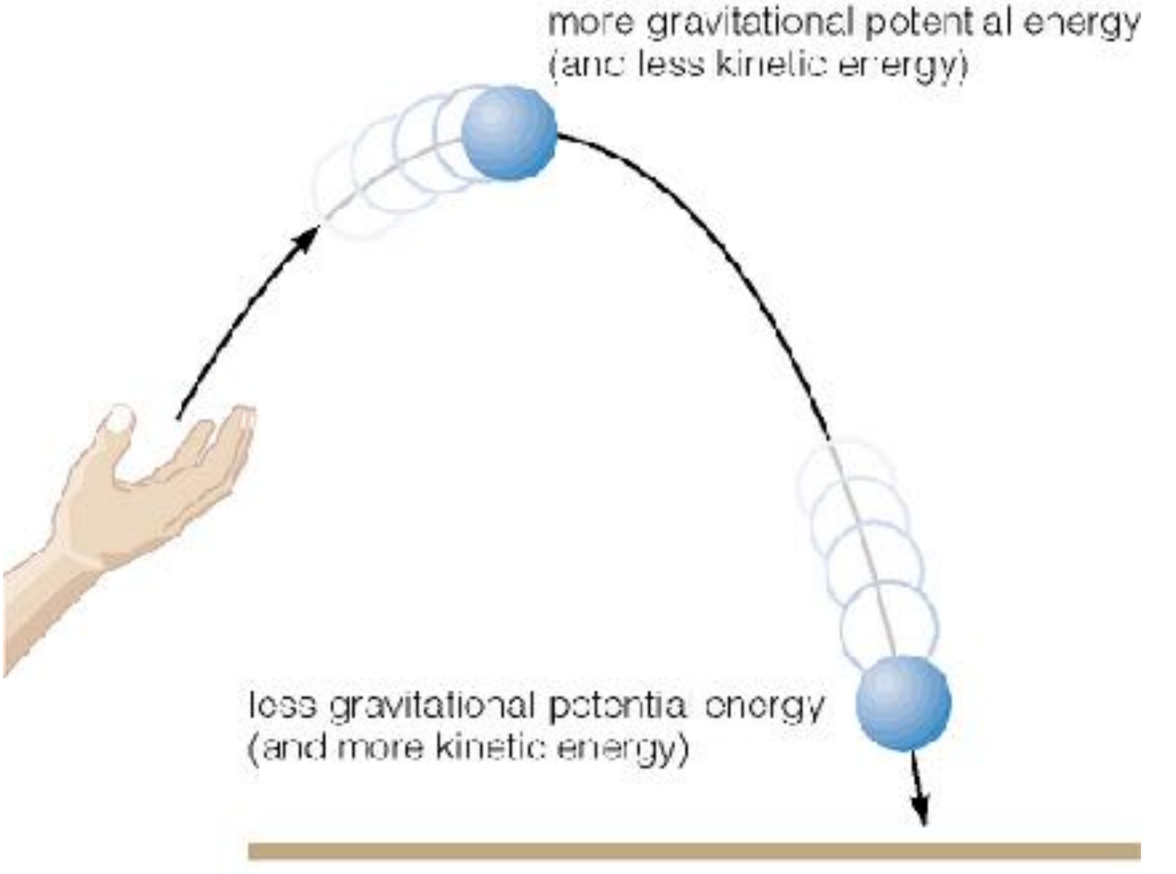
- Kinetic (motion)
- Radiative (light)
- Stored or potential

Energy can change type but cannot be destroyed.



Gravitational Potential Energy

- On Earth, it depends on…
  - — an object's mass (*m*).
  - — the strength of gravity (*g*).
  - — the distance an object could potentially fall.



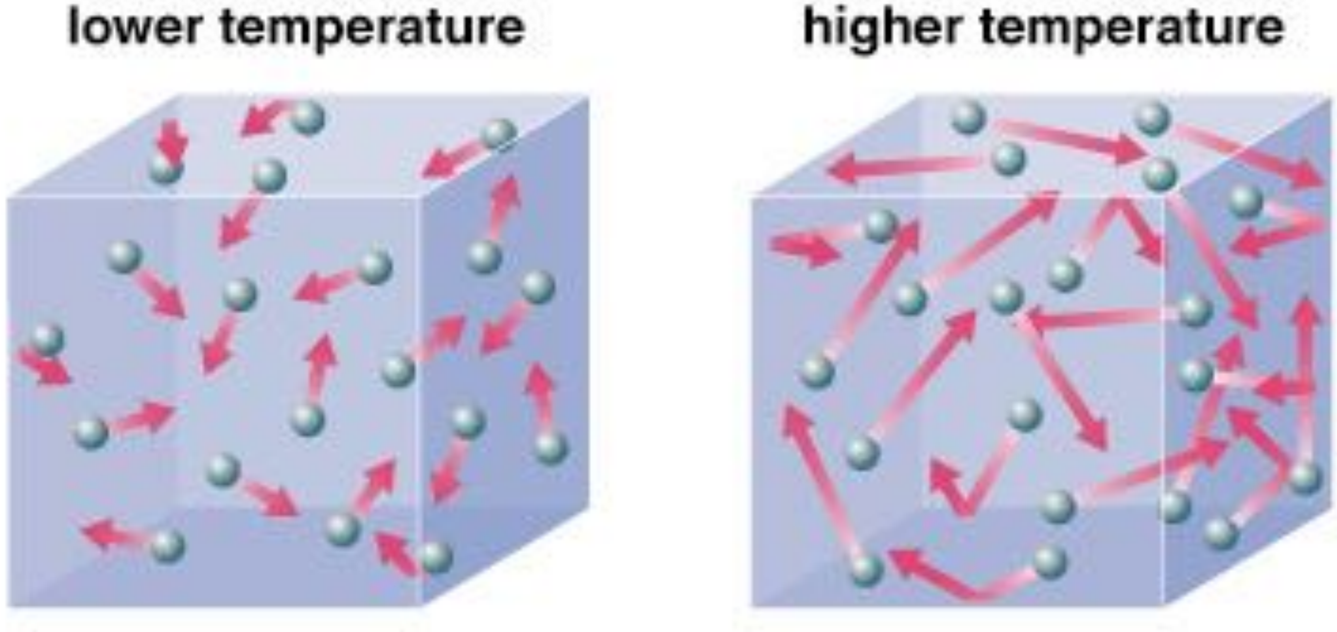
$$E_P = mgh$$

Play Canon Ball Drop

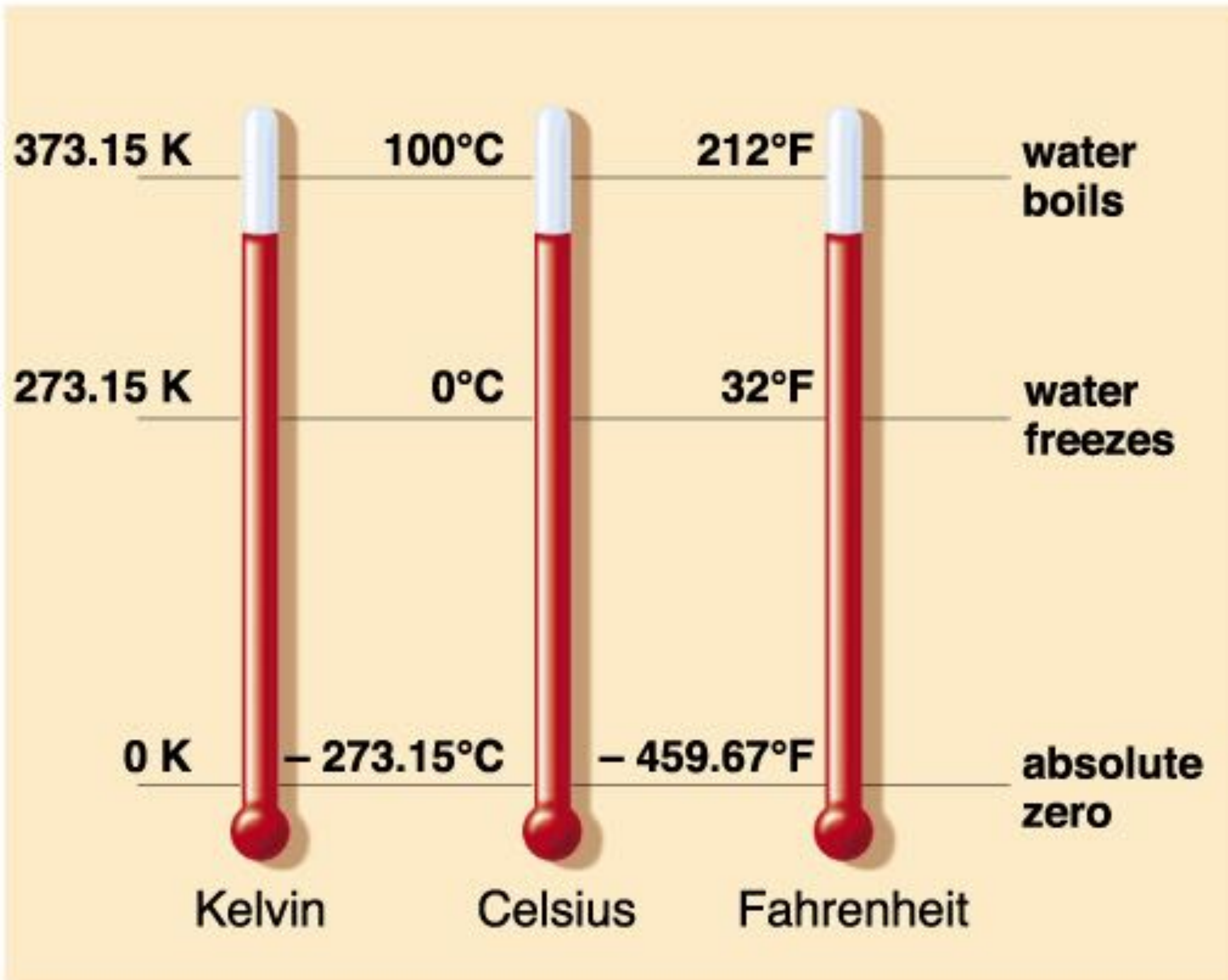
Thermal Energy:

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.

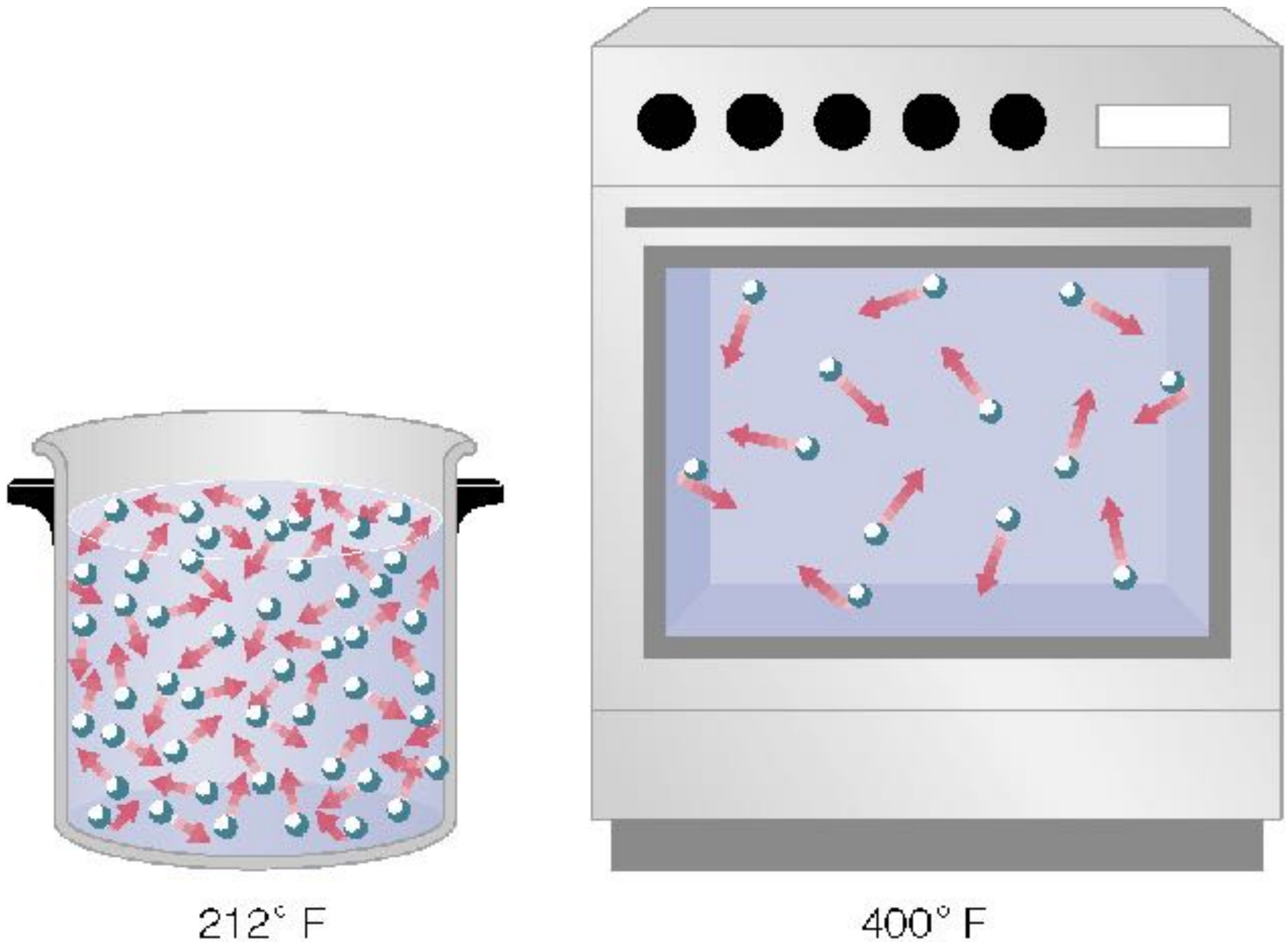


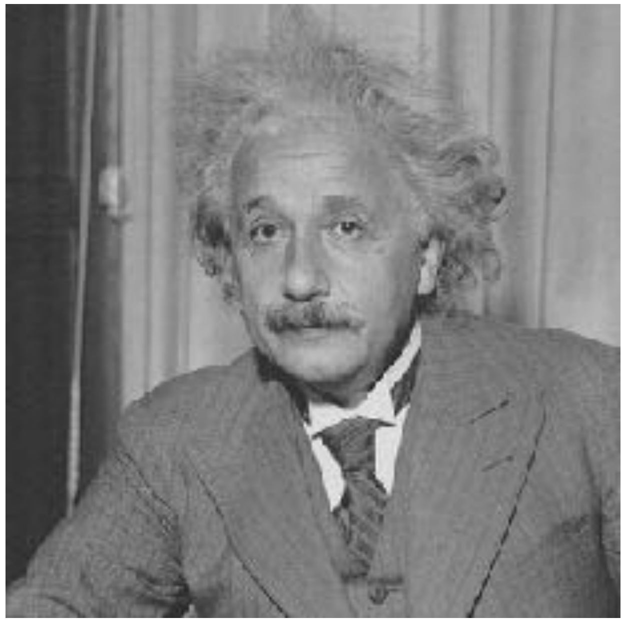
Temperature Scales



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:





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.
- 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 is the same today as it was at the beginning of time.

4.4 The Force of Gravity

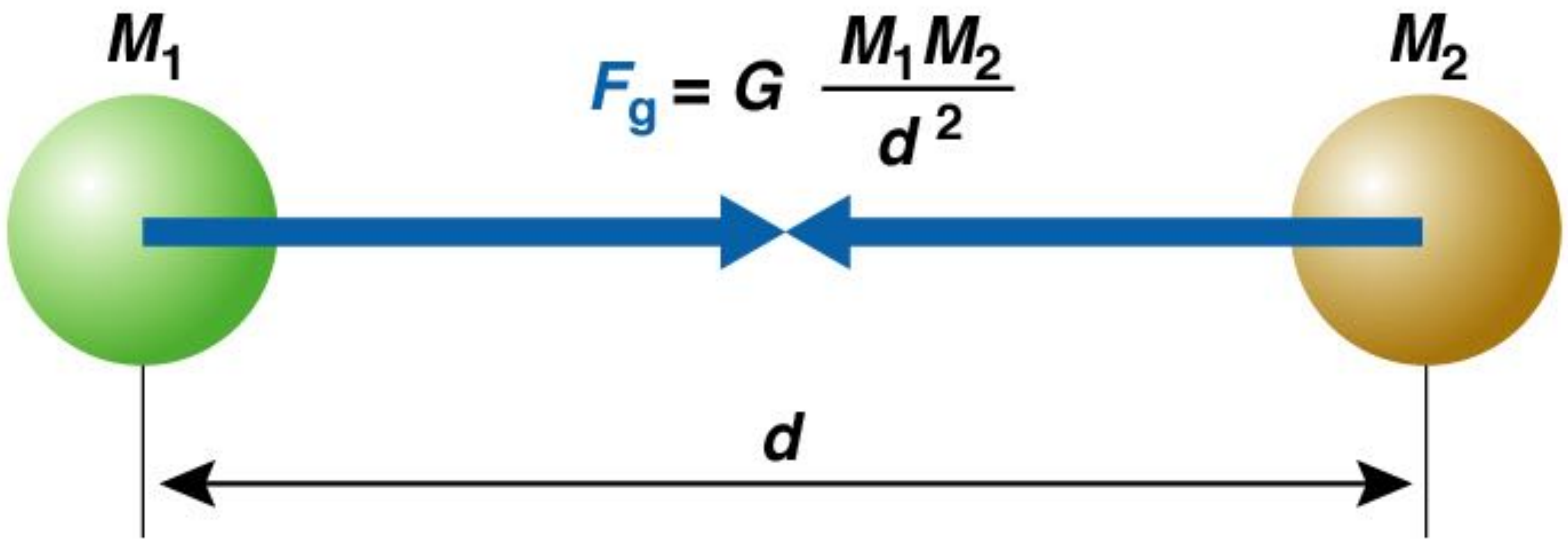
Our goals for learning:

- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?
- How do gravity and energy together allow us to understand orbits?
- Why are large objects spherical?
- How does gravity cause tides?

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.

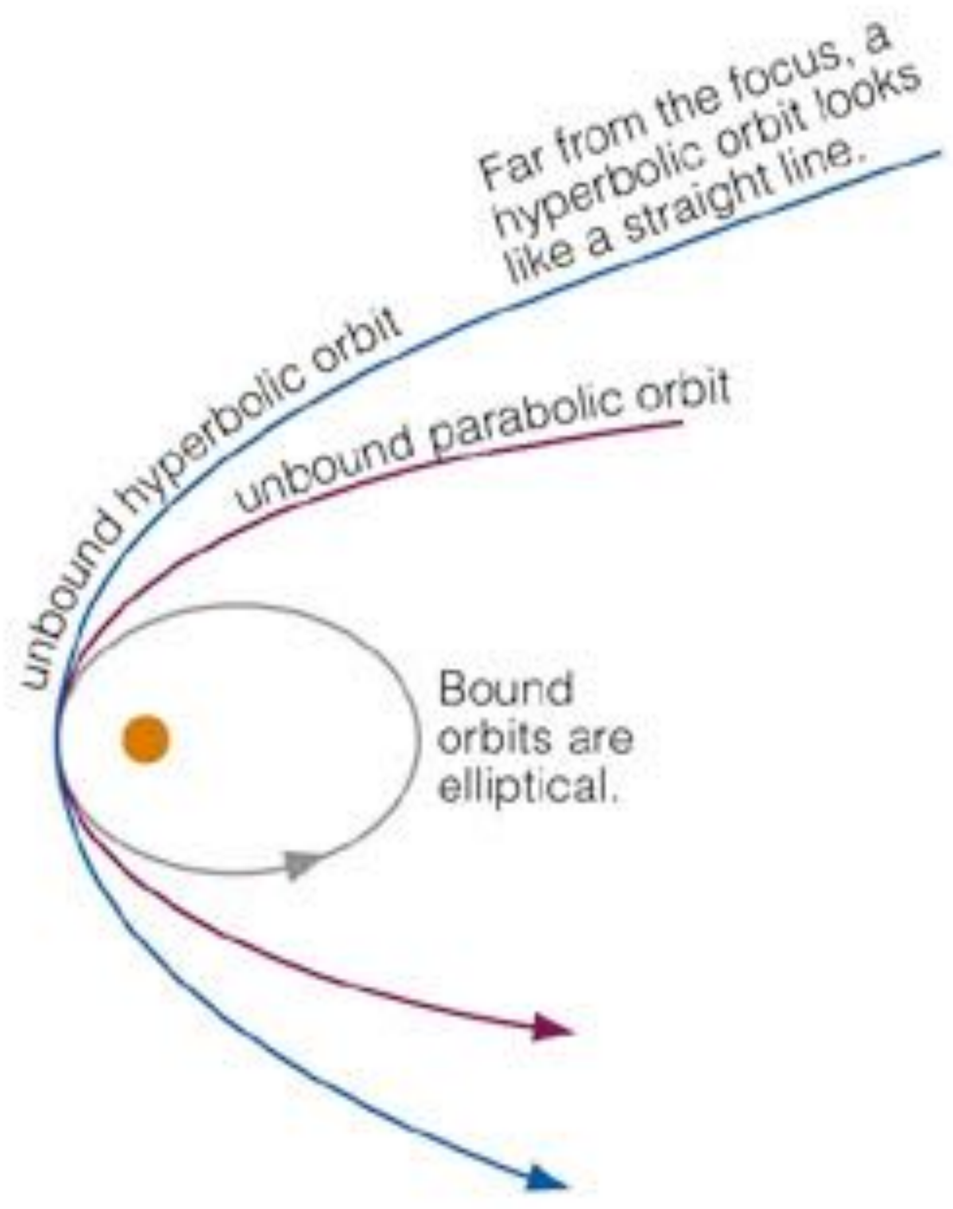


04_18_CenterMBinaryStar.htm

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

- Kepler's first two laws apply to all orbiting objects, not just planets.

- Ellipses are not the only orbital paths. Orbits can be:
  - — bound (ellipses)
  - — unbound
    - parabola
    - hyperbola



Newton's version of Kepler's Third Law

$$P^2 = \frac{4\pi^2}{G}\frac{a^3}{M}$$

p = orbital period

a = average orbital distance (between centers)

$(M_1 + M_2)$ = sum of object masses

(e.g., the mass of the sun)

derive

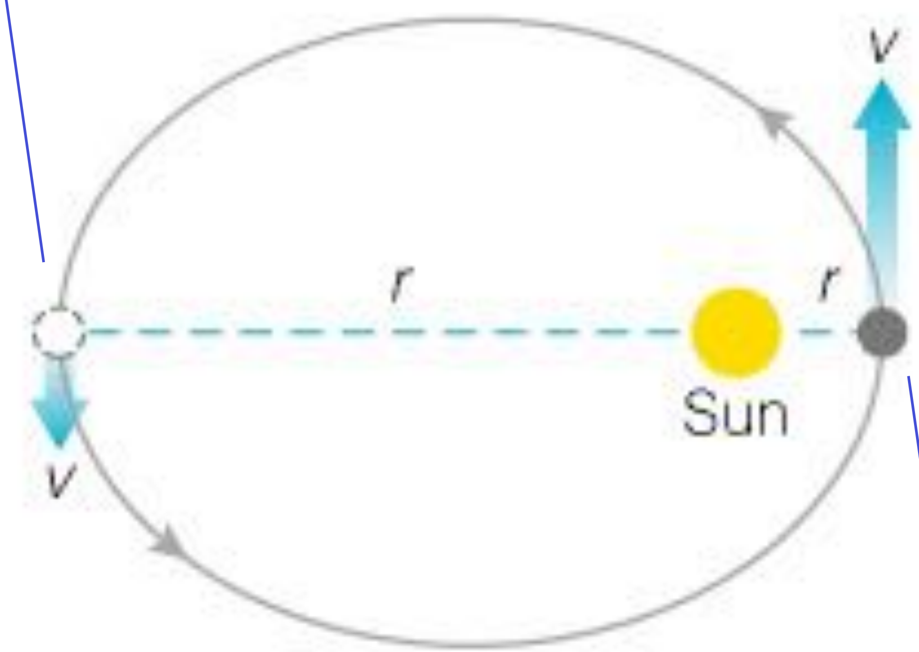
Orbits of the Moons of Jupiter

Moon	P (days)	a (km)	a^3/P^2 (solar masses)
Io	1.8	4×10^5	0.001
Europa	3.6	7×10^5	0.001
Ganymede	7.2	1×10^6	0.001
Callisto	16.7	2×10^6	0.001

The mass of Jupiter is 0.001 times the mass of the Sun

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

More gravitational energy;
Less kinetic energy



Less gravitational energy;
More kinetic energy

Total orbital energy stays constant.

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

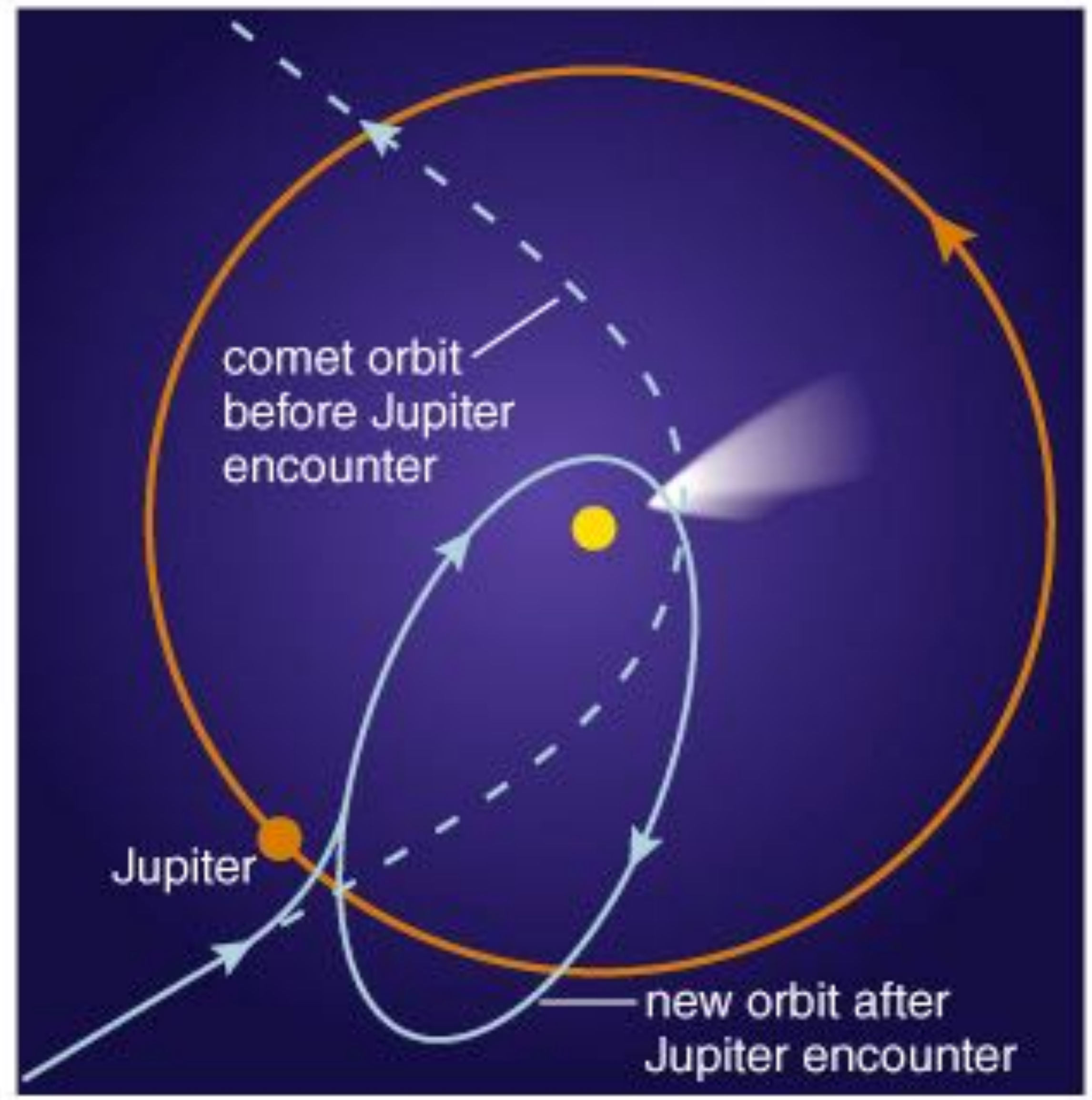
04_CannonballOrbit.htm

Changing an Orbit

⇒ So what can make an object gain or lose orbital energy?

- Friction or atmospheric drag
- A gravitational encounter
- The thrust of a rocket

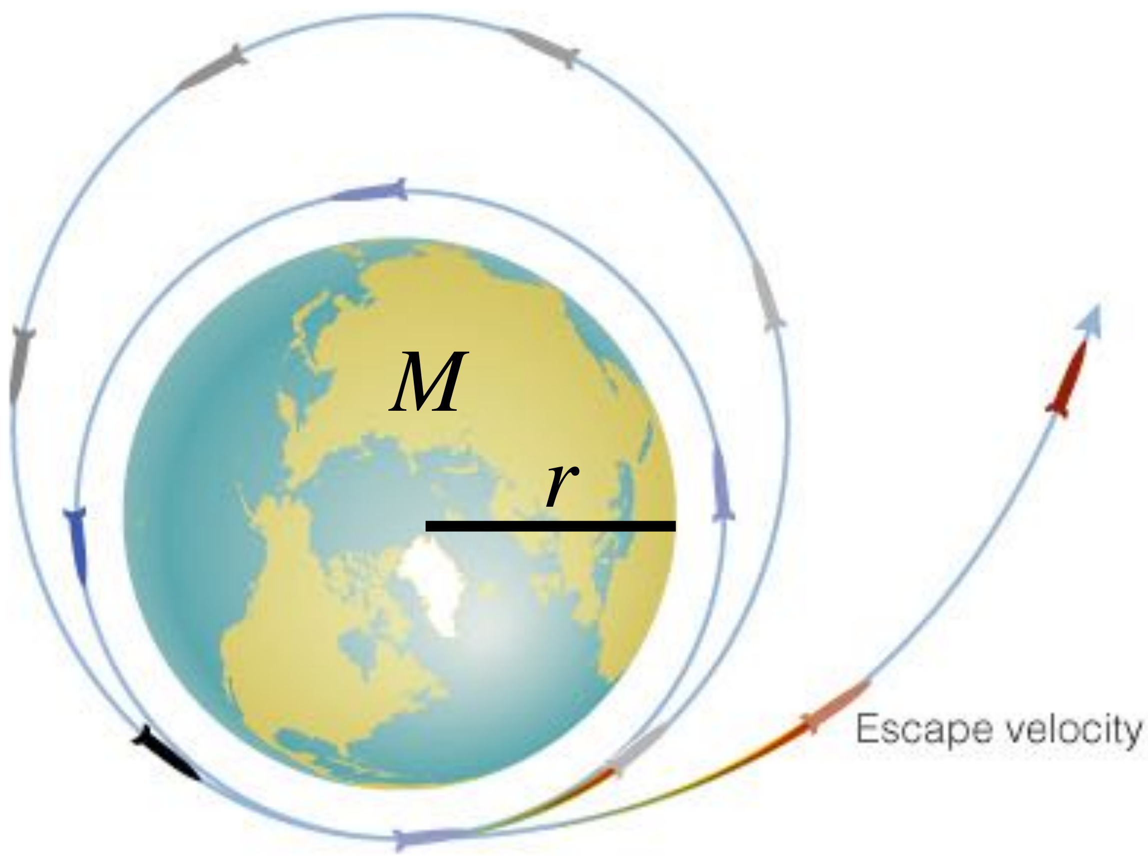
i.e., some external force



movie: Messenger orbit

https://www.theplanetstoday.com/messenger_flight_path.html

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).

PLAY 04_02 canon ball 04_EscapeVEarth

Circular & Escape velocity

Circular velocity:

$$v_{circ} = \sqrt{\frac{GM}{r}}$$

Escape velocity:

$$v_{esc} = \sqrt{\frac{2GM}{r}} = \sqrt{2}v_{circ}$$

Examples:

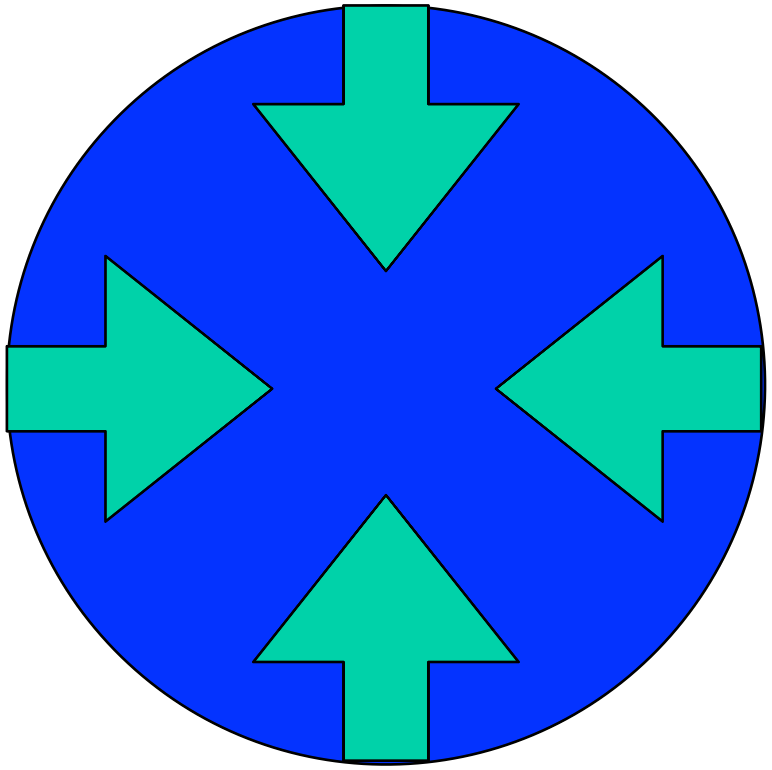
Object	circular speed at surface	escape speed from surface
Earth	7.8 km/s	11 km/s
Sun	436 km/s	617 km/s
Moon	1.7 km/s	2.4 km/s

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 as well as bound ellipse (all conic sections)
  - Can be used to measure mass of orbiting systems

Why are stars and planets spherical?

- Gravity pulls - it is an attractive force
- IF self-gravity is the most important force holding an object together, it must be spherical.



Example: Earth

- Diameter of Earth: 12,756 km
- Mt. Everest: 8.848 km above sea level
- Marianas Trench: 10.934 km below
- Maximum variation: 19.782 km

$$\frac{\text{maximum variation}}{\text{diameter}} = \frac{19.782}{12,756}$$

$$= 0.0015$$

- a very smooth sphere!

- Gravity makes individual objects round
  - about 100 km in diameter is where objects start to become dominated by self-gravity
    - planets round
    - asteroids still lumpy

This holds for individual objects.
What about multiple objects?