# Chapter 4
# Making Sense of the Universe:
## Understanding Motion, Energy, and Gravity

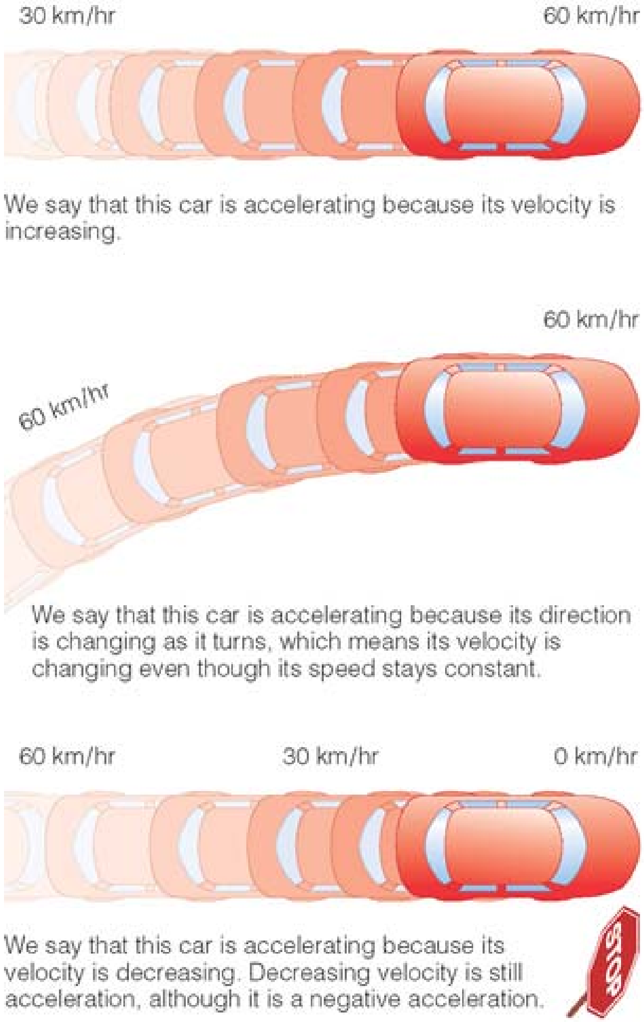


"*If I have seen farther than others, it is because I have stood on the shoulders of giants.*" — Sir Isaac Newton (1642 – 1727)

# 4.1 Describing Motion

- Our goals for learning:
- How do we describe motion?
- 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: speed of 10 m/s

- **velocity**: speed and direction

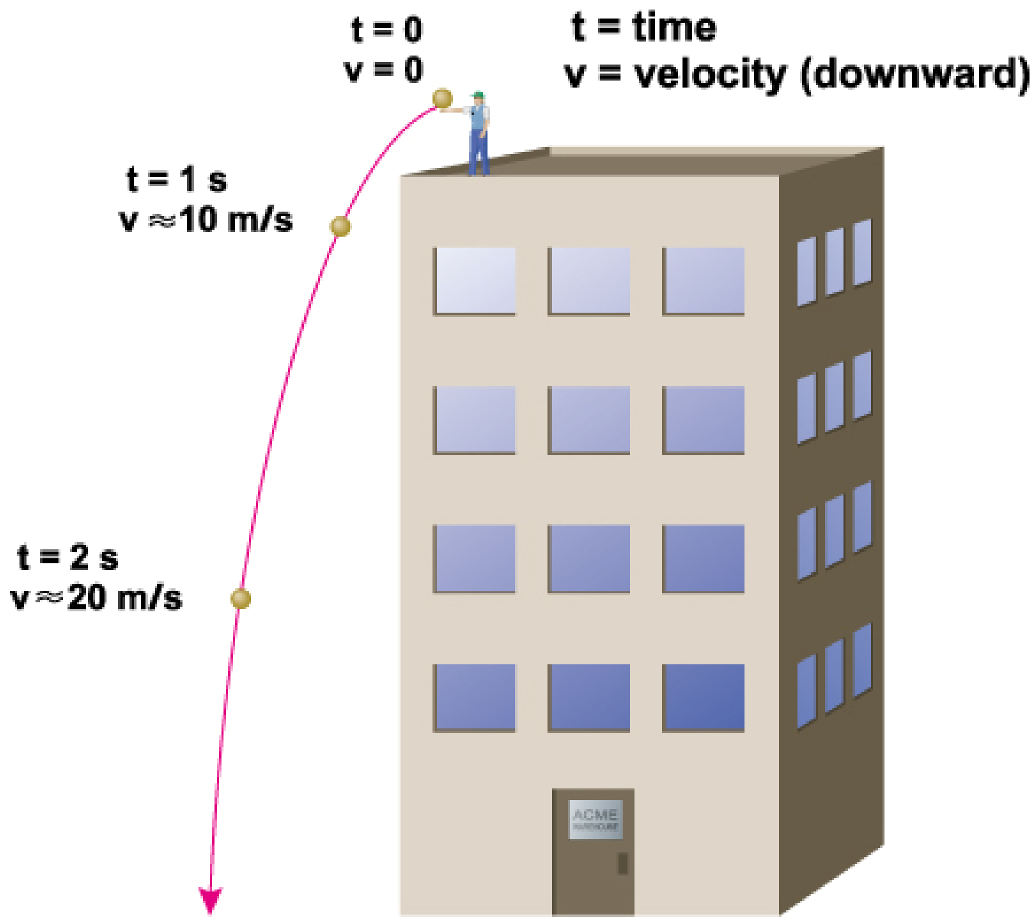
  example: 10 m/s, due east

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

# Thought Question: Is there a net force? Y/N

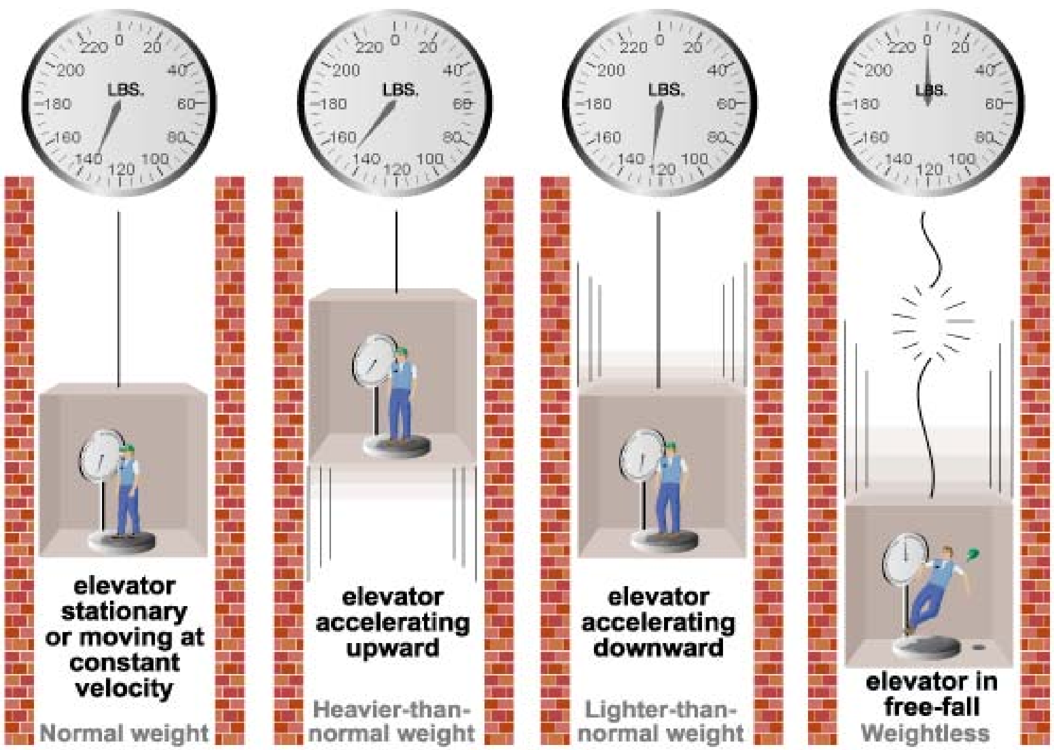
1. A car coming to a stop.
2. A bus speeding up.
3. An elevator moving up at constant speed.
4. A bicycle going around a curve.
5. A moon orbiting Jupiter.

# 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






Interactive Figure

You are weightless in free-fall!

# 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.

# 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?

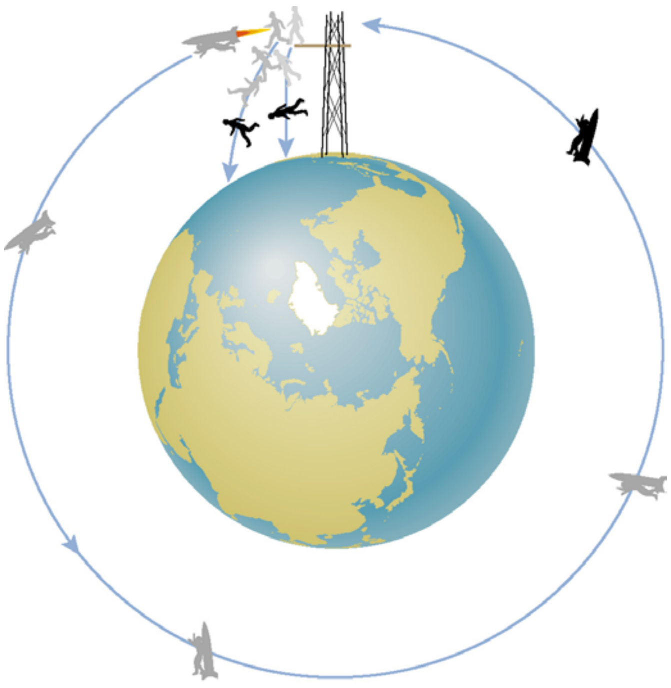
- There IS gravity in space…
- weightlessness is due to a constant state of free-fall:

# What have we learned?

- How do we describe motion?
  - Speed = distance/time
  - Speed + direction => **velocity (v)**
  - Change in velocity => **acceleration (a)**
  - **Momentum** = mass × velocity
  - **Force** causes a change in momentum, which means acceleration.

# What have we learned?

- How is mass different from weight?
  - Mass = quantity of matter
  - Weight = force acting on mass
  - Objects are weightless when 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?



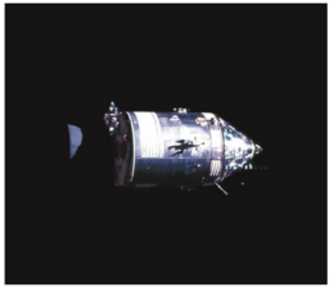
Sir Isaac Newton
(1642-1727)

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

# 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.

A spaceship needs no fuel to keep moving in space.

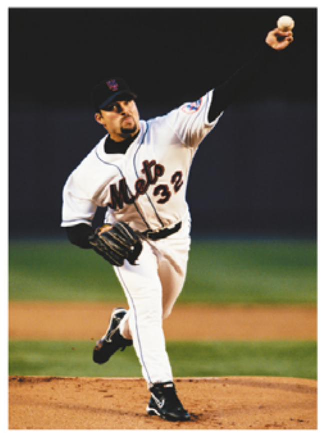


**Newton's first law of motion:** An object moves at constant velocity unless a net force acts to change its speed or direction.

# Newton's second law of motion:

Force = mass × acceleration

A baseball accelerates as the pitcher applies a force by moving his arm. (Once released, this force and acceleration cease, so the ball's path changes only due to gravity and effects of air resistance.)



**Newton's second law of motion:**
Force = mass × acceleration

Newton's third law of motion:

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

A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.

**Newton's third law of motion:**
For any force, there is always an equal and opposite reaction force.

# Thought Question:
# Is the force the Earth exerts on you larger, smaller, or the same as the force you exert on it?

A. Earth exerts a larger force on you.
B. I exert a larger force on Earth.
C. Earth and I exert equal and opposite forces on each other.

Is the force the Earth exerts on you larger, smaller, or the same as the force you exert on it?

A. Earth exerts a larger force on you.
B. I exert a larger force on Earth.
**C. Earth and I 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**?

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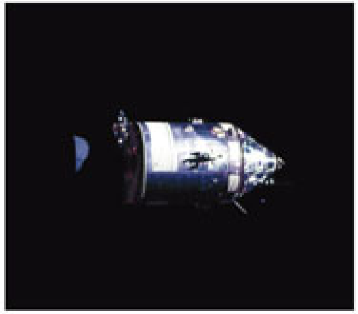
2. The *momentum* transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck. **T**
3. The *change of velocity* of the car is the same as the change of velocity of the truck. **F**

# What have we learned?

- How did Newton change our view of the universe?
  - He discovered laws of motion & 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 × acceleration
  3) For every force there is an equal and opposite reaction force.

A spaceship needs no fuel to keep moving in space.



A baseball accelerates as the pitcher applies a force by moving his arm. (Once released, this force and acceleration cease, so the ball's path changes only due to gravity and effects of air resistance.)

A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.

# 4.3 Conservation Laws in Astronomy:

Our goals for learning:

- What keeps a planet rotating and orbiting the Sun?
- Where do objects get their energy?

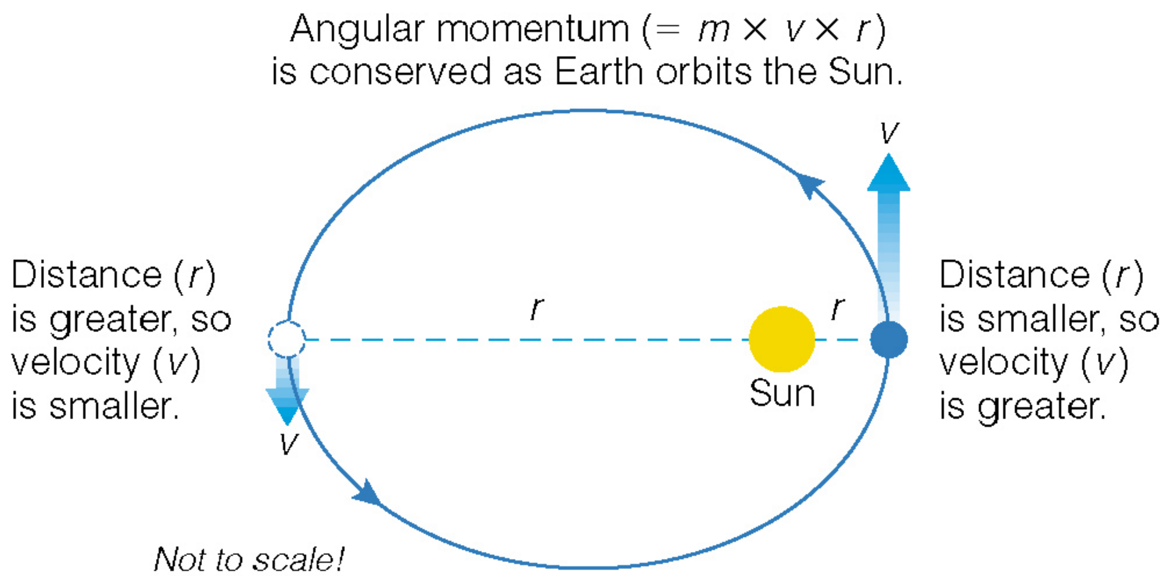
Three important conservation laws:

- Conservation of momentum
- Conservation of angular momentum
- Conservation of energy

These laws are embodied in Newton's laws, but offer a different and sometimes more powerful way to consider motion.

# What keeps a planet rotating and orbiting the Sun?

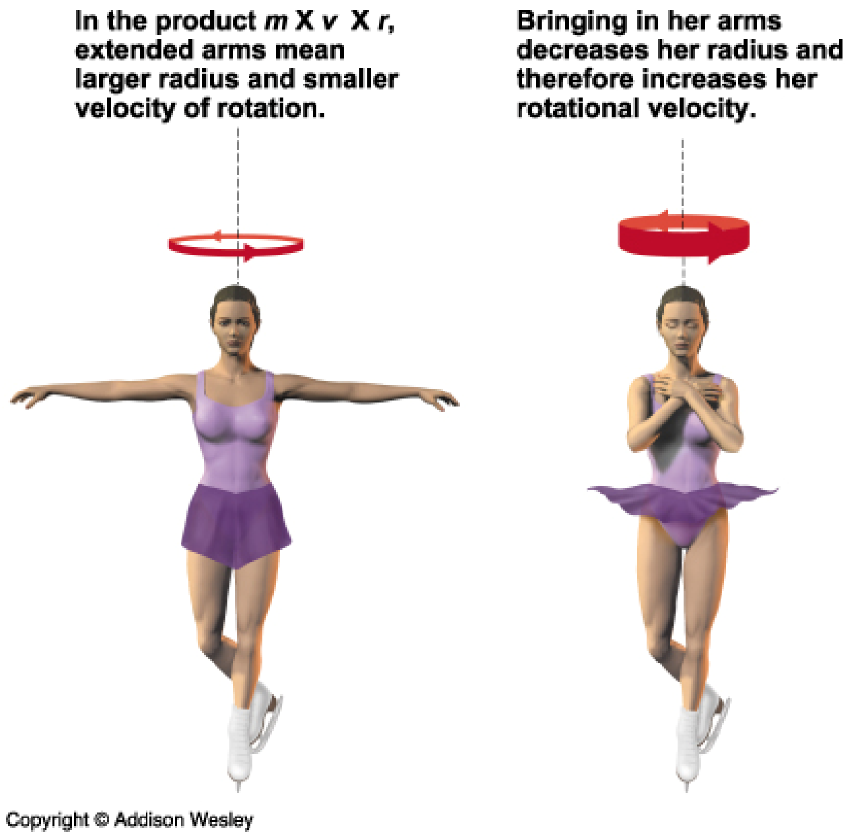
## Conservation of Angular Momentum






As long as Earth doesn't transfer angular momentum to other objects, its rotation and orbit cannot change.

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)
- Stored or potential

Energy can change type but cannot be destroyed.

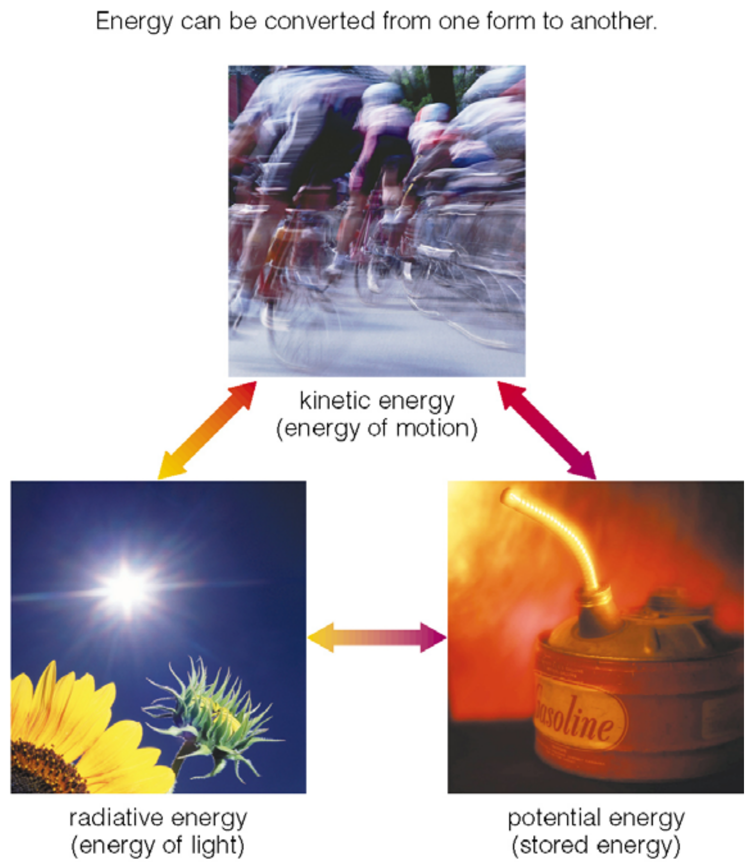
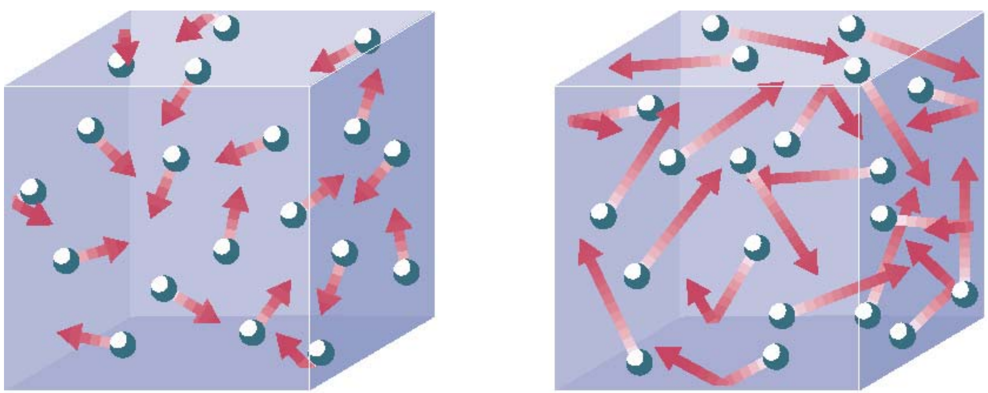


**Table 4.1 Energy Comparisons**

| Item | Energy (joules) |
|---|---|
| Average daytime solar energy striking Earth, per $m^2$ per second | $1.3 \times 10^3$ |
| Energy released by metabolism of one average candy bar | $1 \times 10^6$ |
| Energy needed for 1 hour of walking (adult) | $1 \times 10^6$ |
| Kinetic energy of average car traveling at 60 mi/hr | $1 \times 10^6$ |
| Daily energy needs of average adult | $1 \times 10^7$ |
| Energy released by burning 1 liter of oil | $1.2 \times 10^6$ |
| Energy released by fission of 1 kg of uranium-235 | $5.6 \times 10^{13}$ |
| Energy released by fusion of hydrogen in 1 liter of water | $7 \times 10^{13}$ |
| Energy released by 1-megaton H-bomb | $5 \times 10^{15}$ |
| Energy released by major earthquake (magnitude 8.0) | $2.5 \times 10^{16}$ |
| U.S. annual energy consumption | $10^{20}$ |
| Annual energy generation from the Sun | $10^{34}$ |
| Energy released by supernova (explosion of a star) | $10^{44}–10^{46}$ |

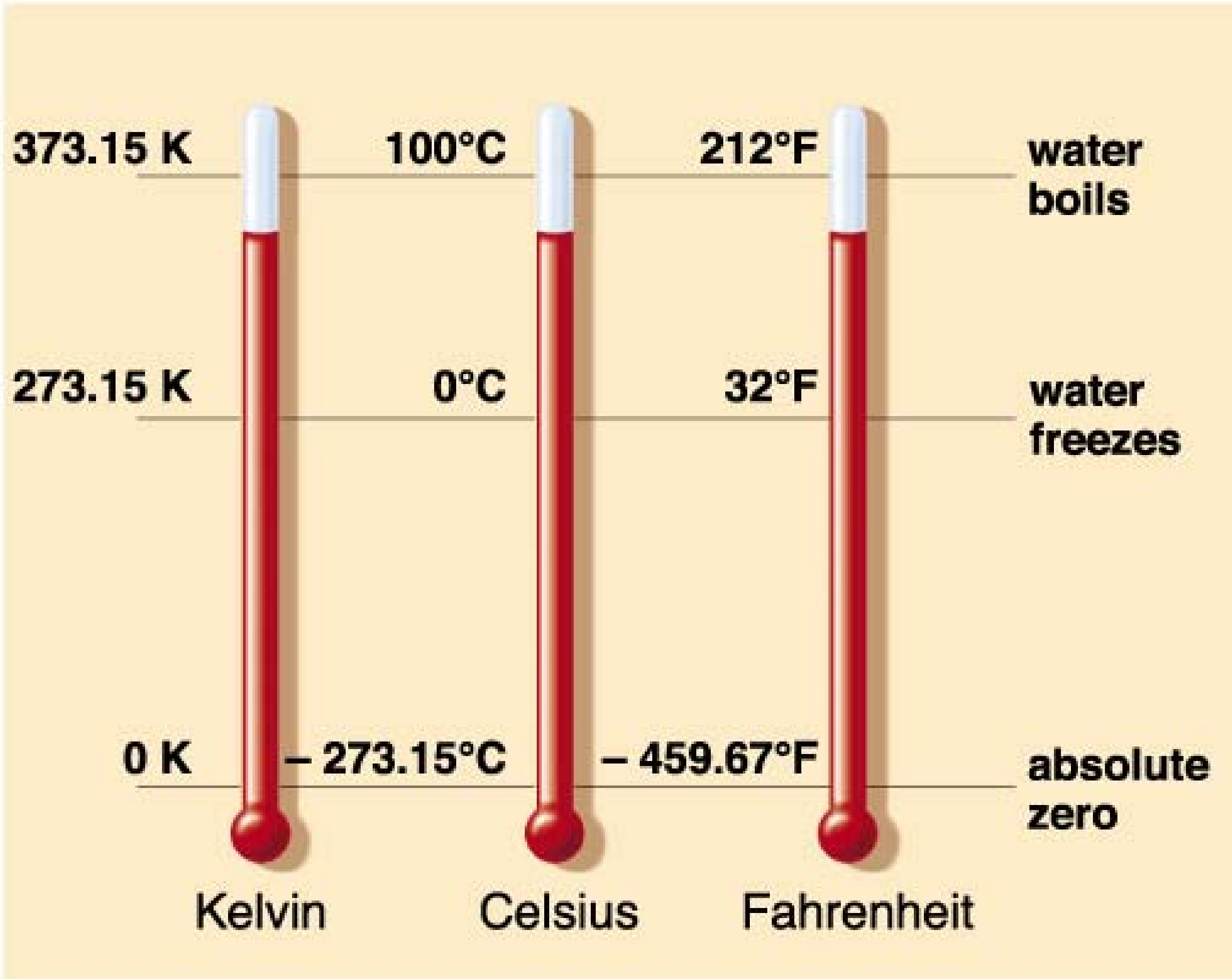
**thermal energy:**
the collective kinetic energy of many particles (for example, in a rock, in air, in water)

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.



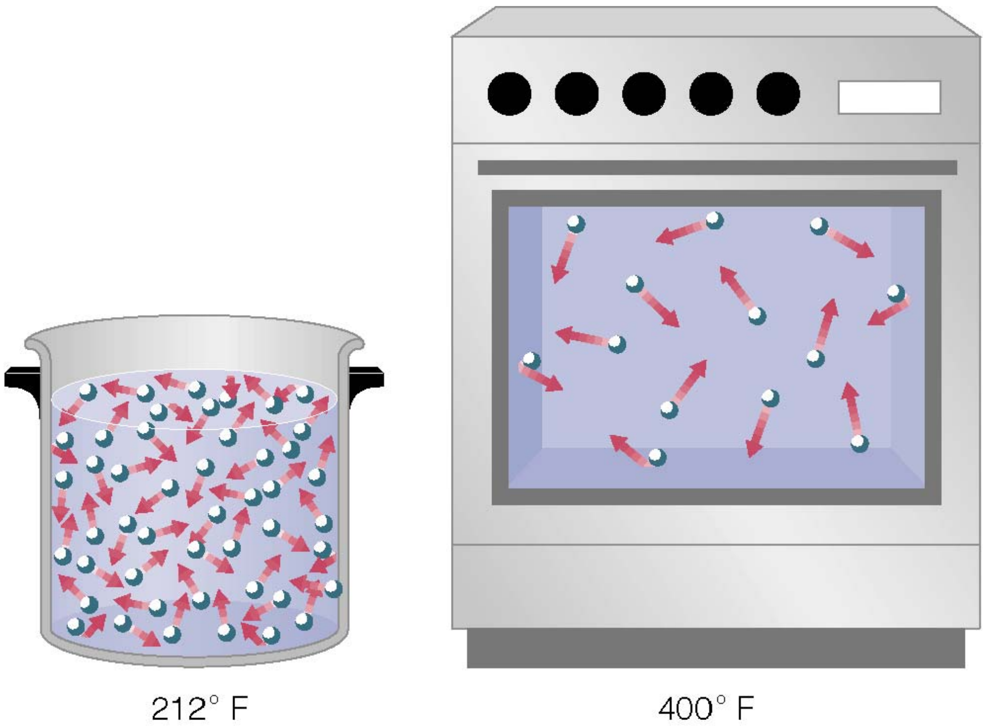
Longer arrows mean higher average speed.

# Temperature Scales



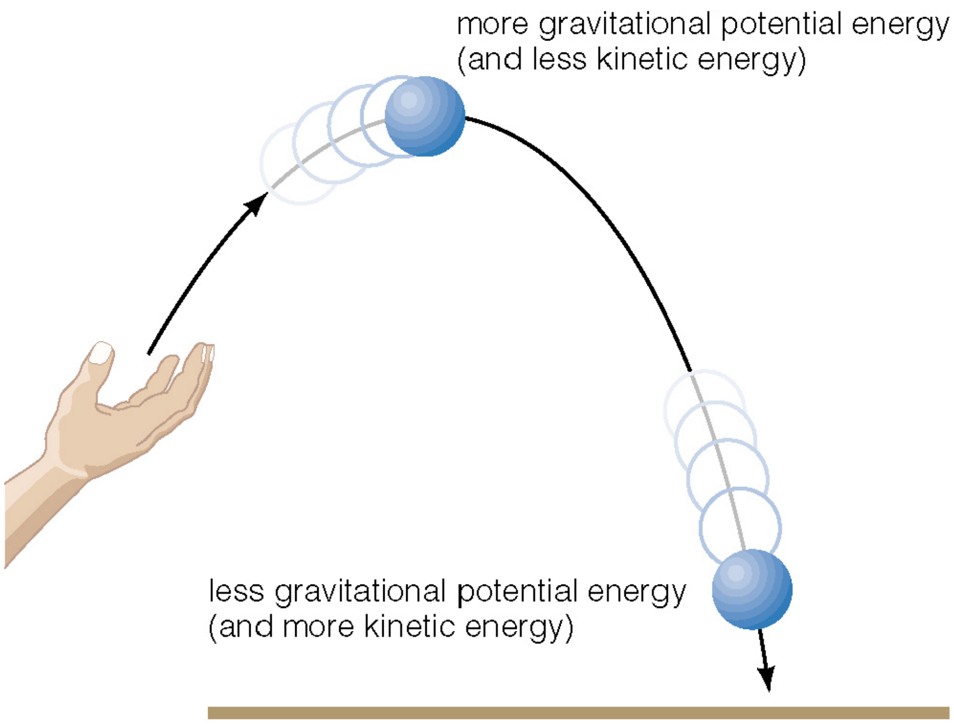
Thermal energy is a measure of the total kinetic energy of all the particles in a substance. It therefore depends both on *temperature* AND *density*

Example:



# Gravitational Potential Energy

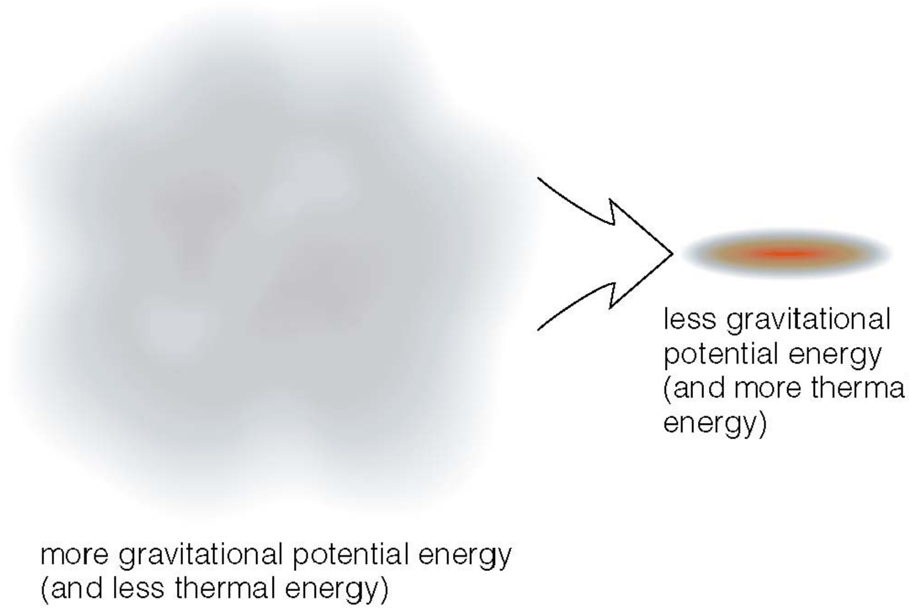
- On Earth, depends on:
  - object's mass (m)
  - strength of gravity (*g*)
  - distance object could potentially fall

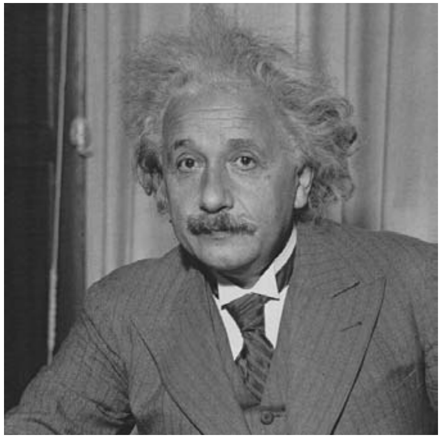


# Gravitational Potential Energy

- In space, an object or gas cloud has more gravitational energy when it is spread out than when it contracts.

⇒A contracting cloud converts grav. potential energy to thermal energy.





# Mass-Energy

Mass itself is a form of potential energy

$$E = mc^2$$

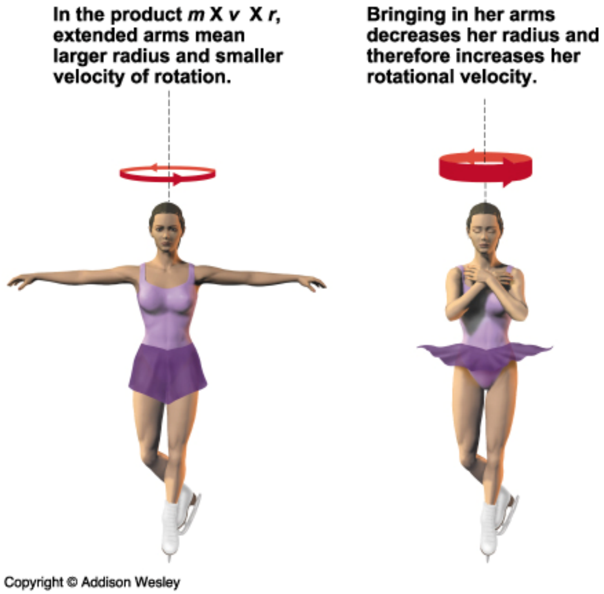
- A small amount of mass can release a great deal of energy
- Concentrated energy can spontaneously turn into particles (for example, in particle accelerators)

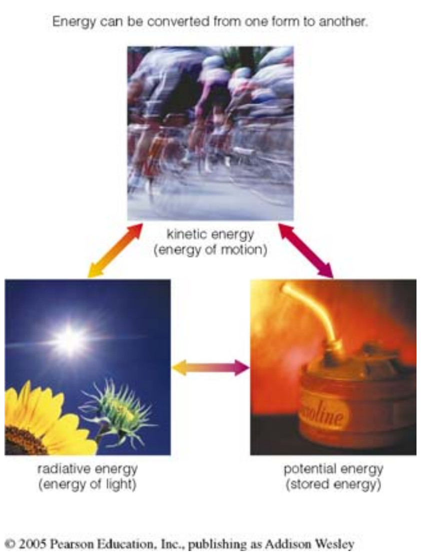
# Conservation of Energy

- 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?

- What keeps a planet rotating and orbiting the Sun?
  - The law of conservation of angular momentum
- Where do objects get their energy?
  - Conservation of energy: energy cannot be created or destroyed; it can only be transformed from one type to another.
  - Energy comes in 3 basic types: kinetic, potential, radiative. Some subtypes important in astronomy: thermal energy, grav. Potential energy, mass-energy ($E = mc^2$).



# 4.4 The Force of Gravity

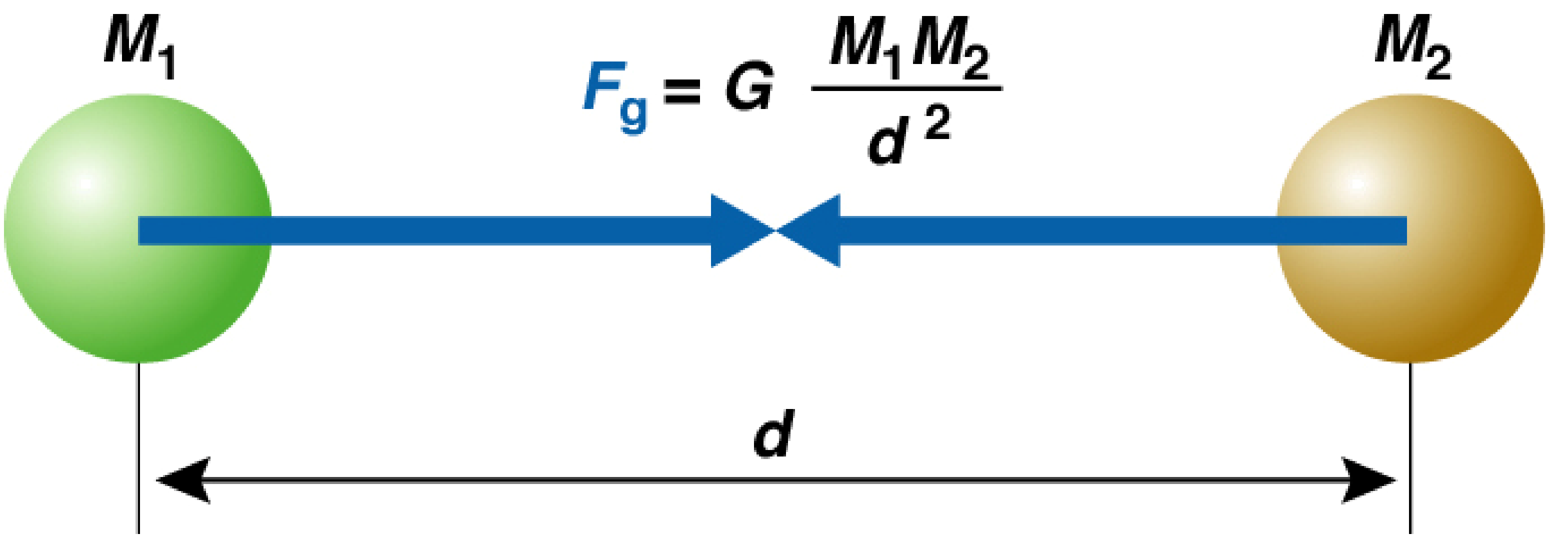
Our goals for learning:

- 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?
- How does gravity cause tides?

## What determines the strength of gravity?

The **Universal Law of Gravitation**

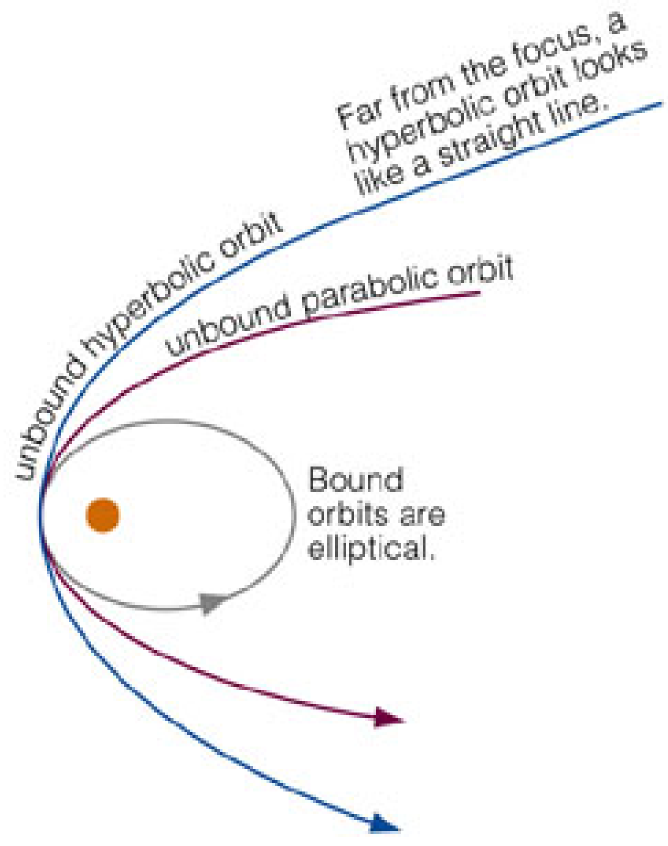
1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers..



# 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 generalized Kepler's Third Law:

**Newton's version of Kepler's Third Law**:
*If* a small object orbits a larger one and you measure the orbiting object's
*orbital period* AND *average orbital distance*
THEN you can calculate the mass of the larger object.

Examples:

• Calculate mass of Sun from Earth's orbital period (1 year) and average distance (1 AU).
• Calculate mass of Earth from orbital period and distance of a satellite.
• Calculate mass of Jupiter from orbital period and distance of one of its moons.

# Newton's version of Kepler's Third Law

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

$p$ = orbital period

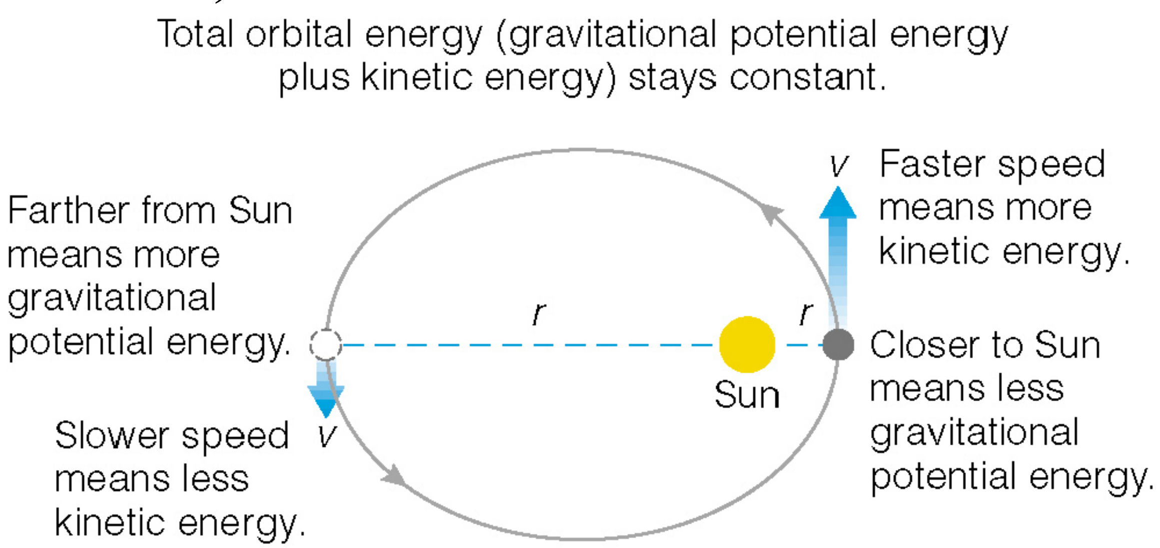
$a$=average orbital distance (between centers)

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

# How do gravity and energy together explain orbits?

- Orbits cannot change spontaneously.
- An object's orbit can only change if it somehow gains or loses **orbital energy =**

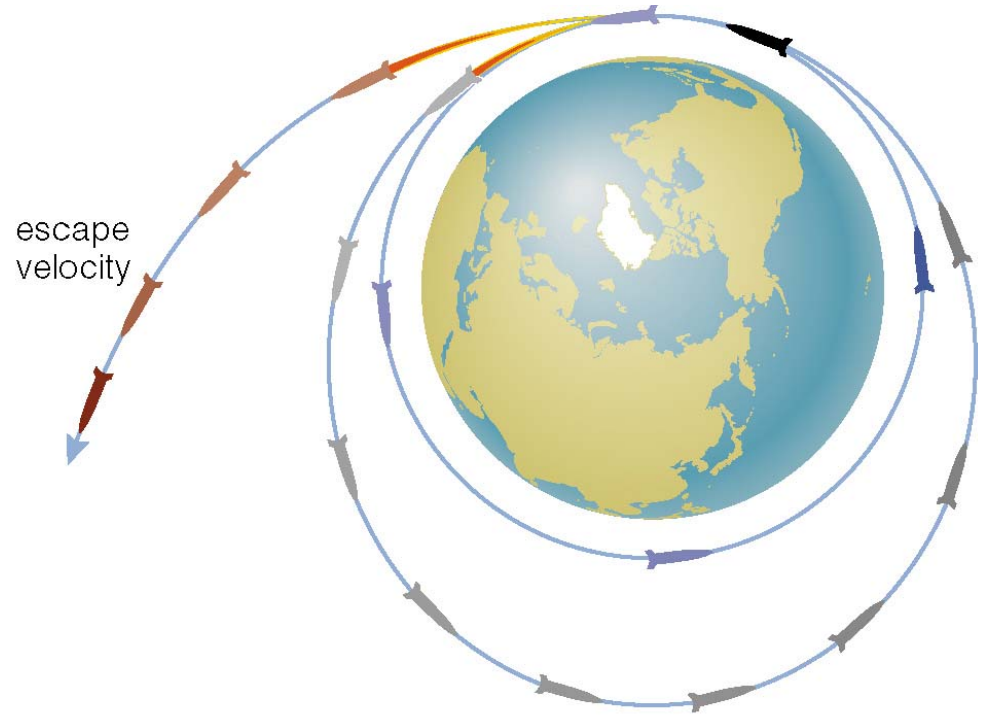
  kinetic energy + gravitational potential energy (due to orbit).



$\Rightarrow$ So what can make an object gain or lose orbital energy?

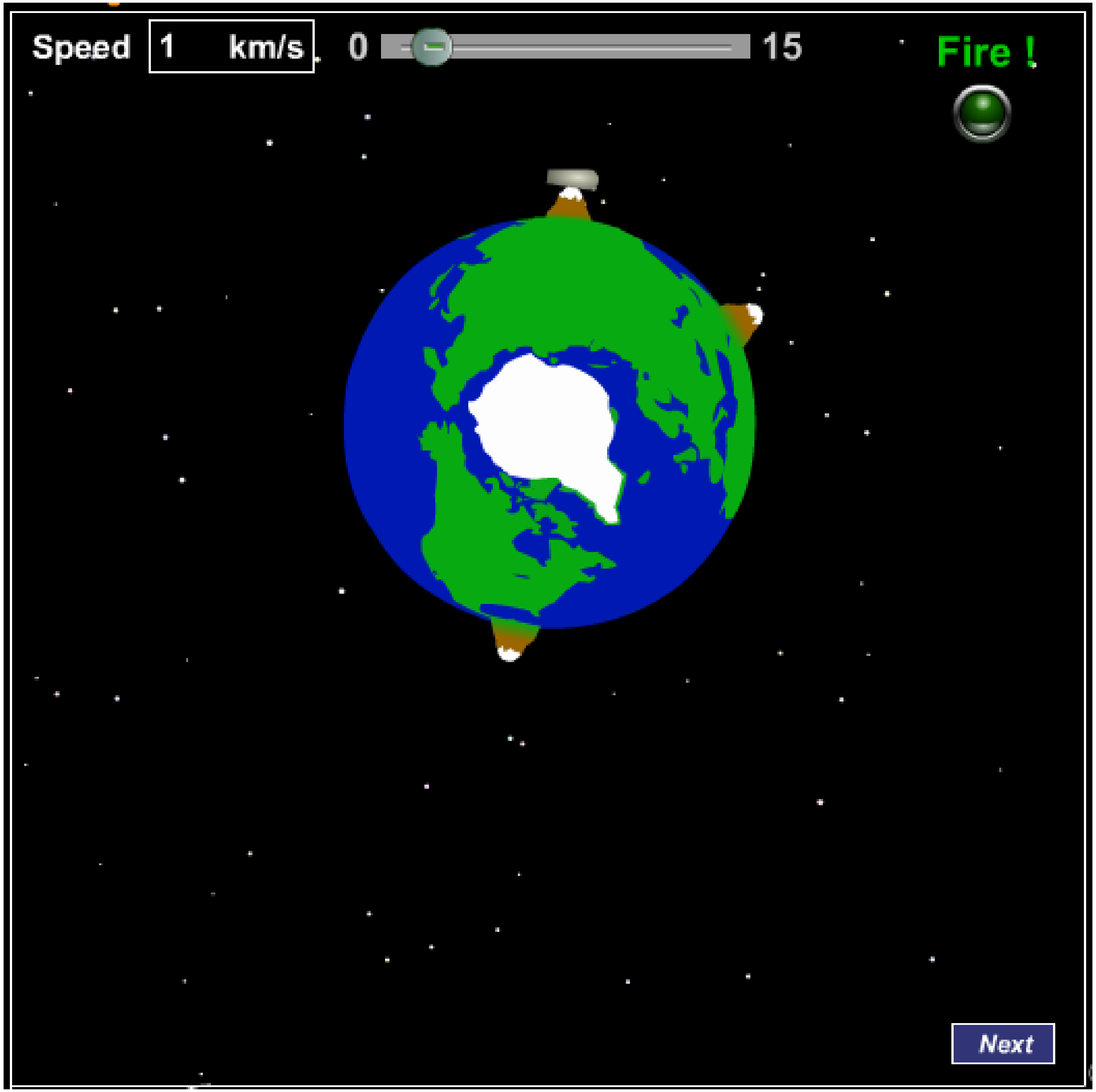
- Friction or atmospheric drag
- A gravitational encounter.

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

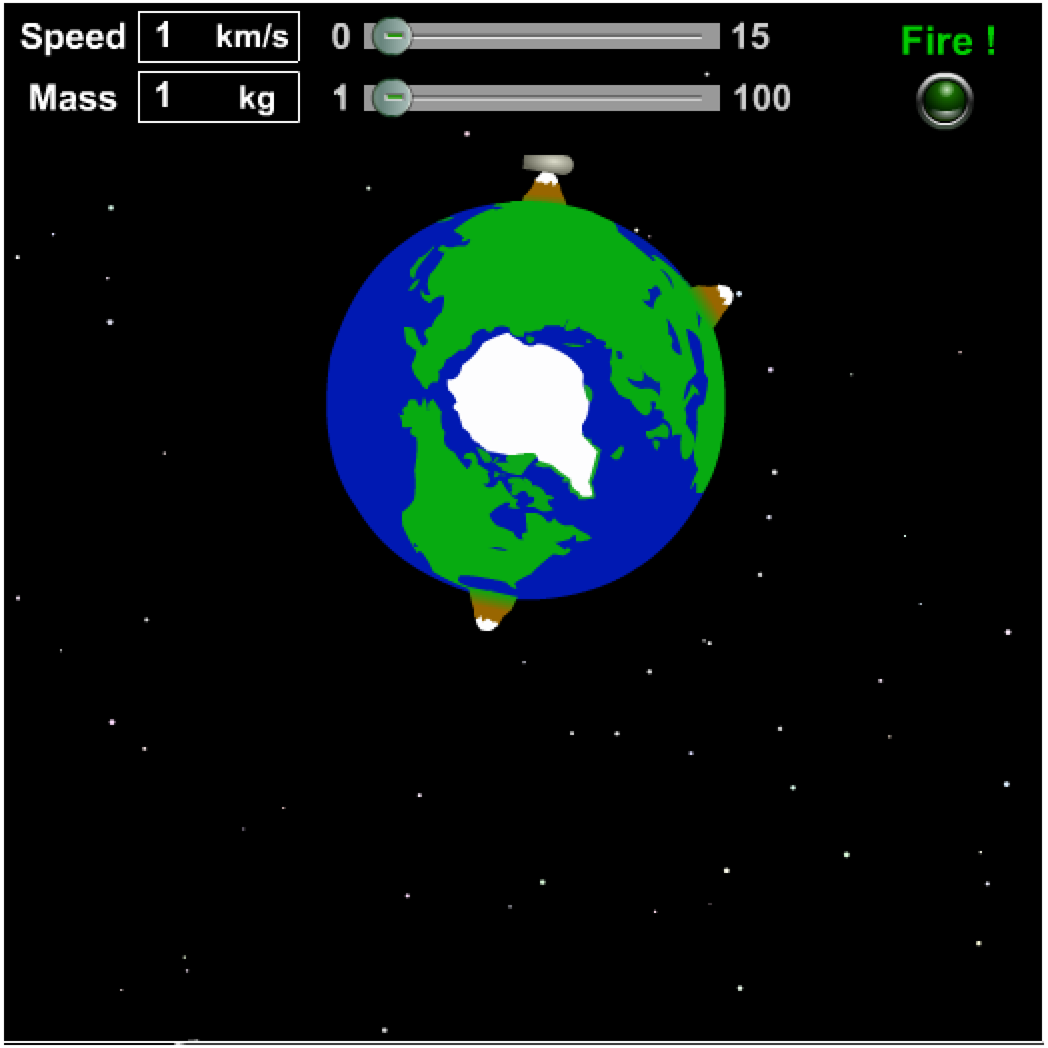




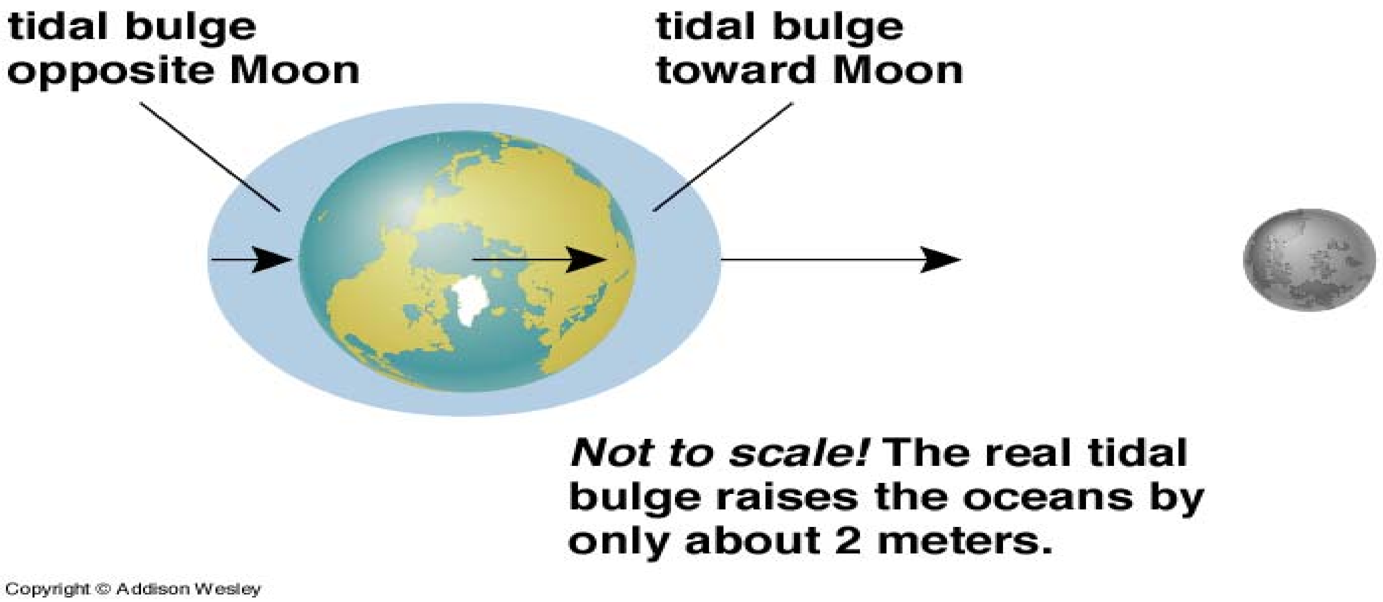

- **escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)

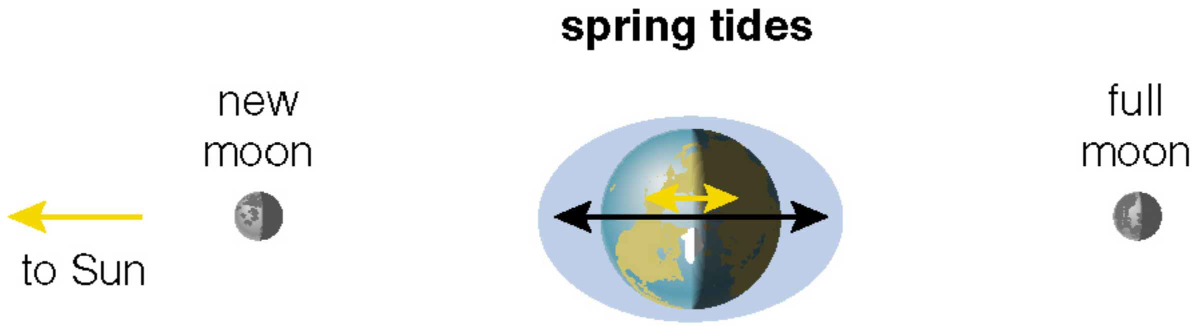

Speed
1 km/s
0
15
Fire !
Next

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



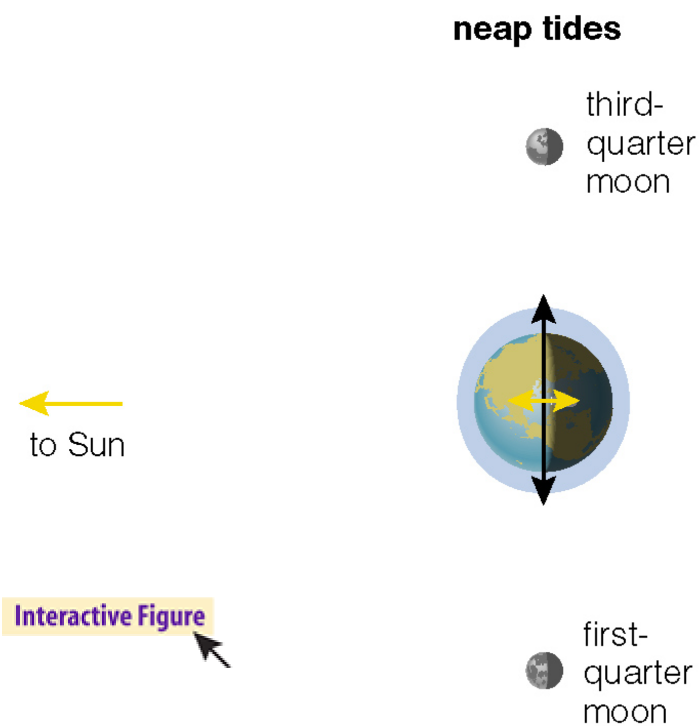
# How does gravity cause tides?








Tides vary with the phase of the Moon:

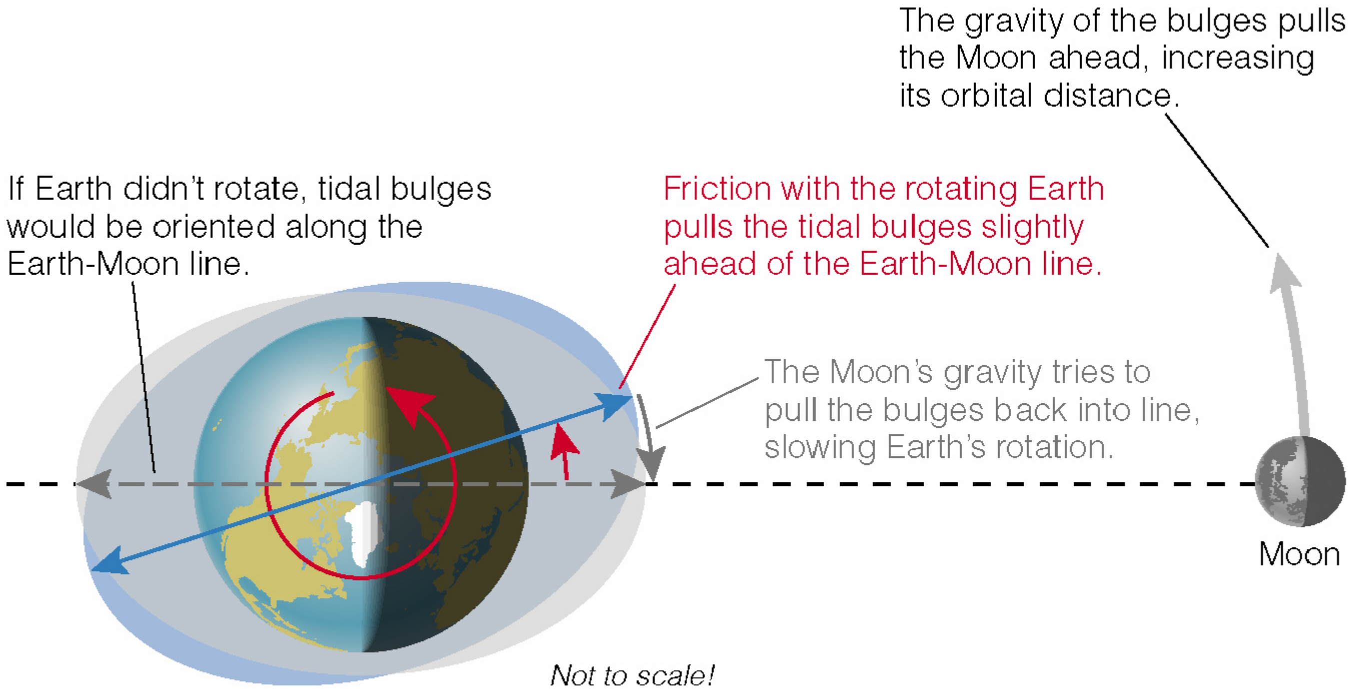


# Special Topic: Why does the Moon always show the same face to Earth?


Moon rotates in the same amount of time that it orbits…

But why?

# Tidal friction…

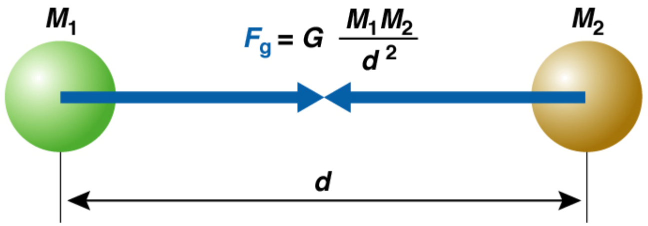




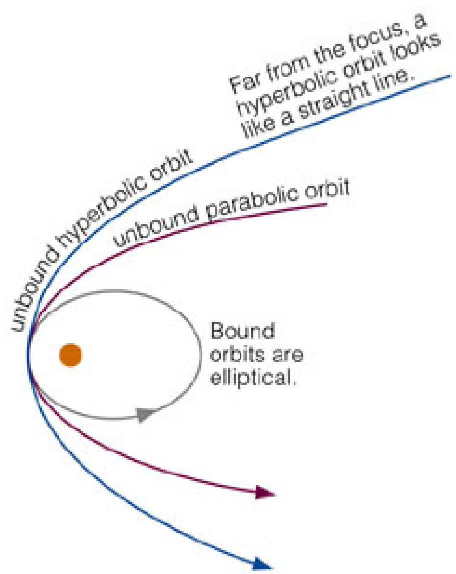

- Tidal friction gradually slows Earth rotation (and makes Moon get farther from Earth).
- Moon once orbited faster (or slower); tidal friction caused it to "lock" in synchronous rotation.

# What have we learned?

- What determines the strength of gravity?
  - Directly proportional to the *product* of the masses (M x m)
  - *Inversely* proportional to the *square* of the separation *d*

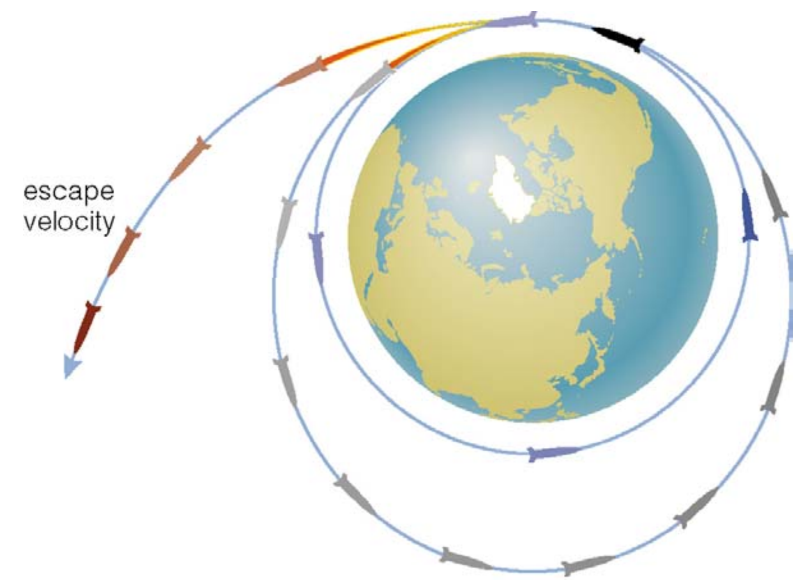



- How does Newton's law of gravity allow us to extend Kepler's laws?
  - Applies to other objects, not just planets.
  - Includes unbound orbit shapes: parabola, hyperbola
  - We can now measure the mass of other systems.



# What have we learned?

- How do gravity and energy together allow us to understand orbits?
  - Gravity determines orbits
  - Orbiting object cannot change orbit without energy transfer
  - Enough energy -> escape velocity -> object leaves.






- How does gravity cause tides?
  - Gravity stretches Earth along Earth-Moon line because the near side is pulled harder than the far side.