Astronomy 100
Chapter 5
Gravity

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Plan for this lesson:

Quantities describing motion
Newton's Laws of Motion
Universal Law of Gravitation
Conservation Laws
Theory of Relativity

Quantities describing motion

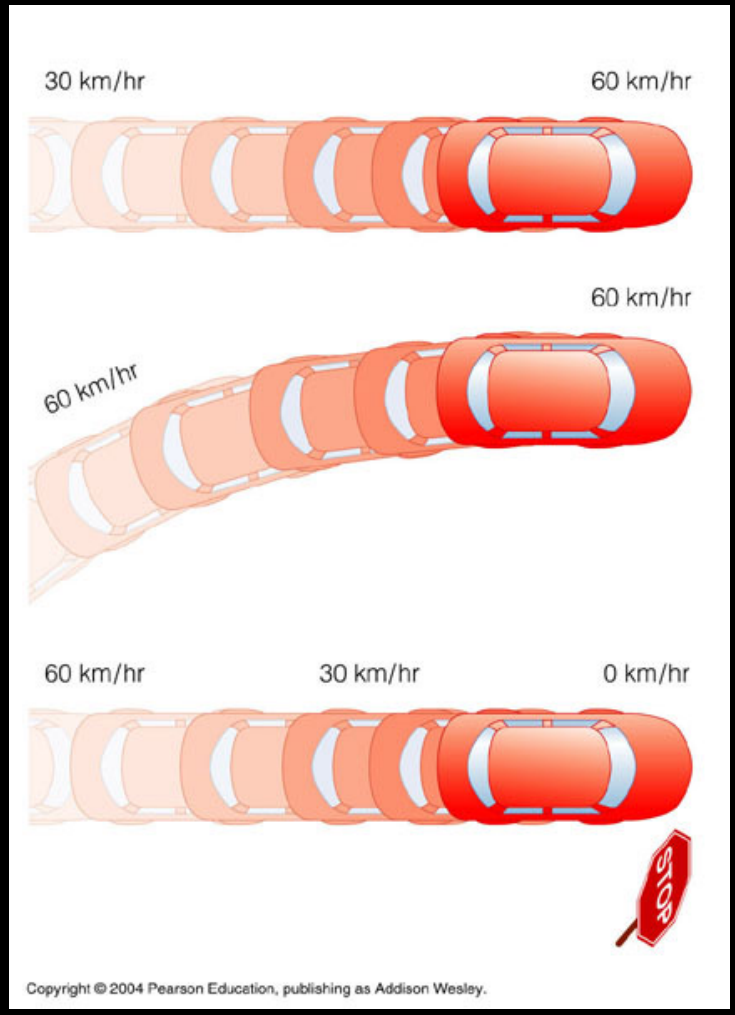
Speed tells us how far we will travel in a given amount of time. Speed is measured in units of distance divided by time:

miles per hour,
kilometers per hour,
meters per second.

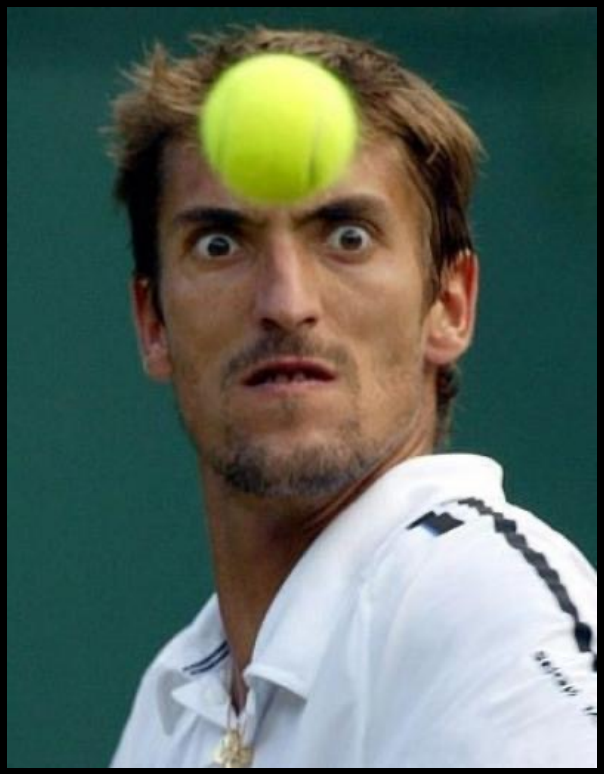
Velocity has the additional information: the direction of the speed. Velocity is a "**vector**."

Acceleration is a rate of change in velocity. This could be a change in speed or in direction.

(units of speed divided by time, e.g. km/s^2).



- **Mass** is the measure of the amount of matter in an object. Units are kilograms.
- **Momentum** is the product of mass and velocity. For the same speed, the higher the mass, the more momentum an object has.

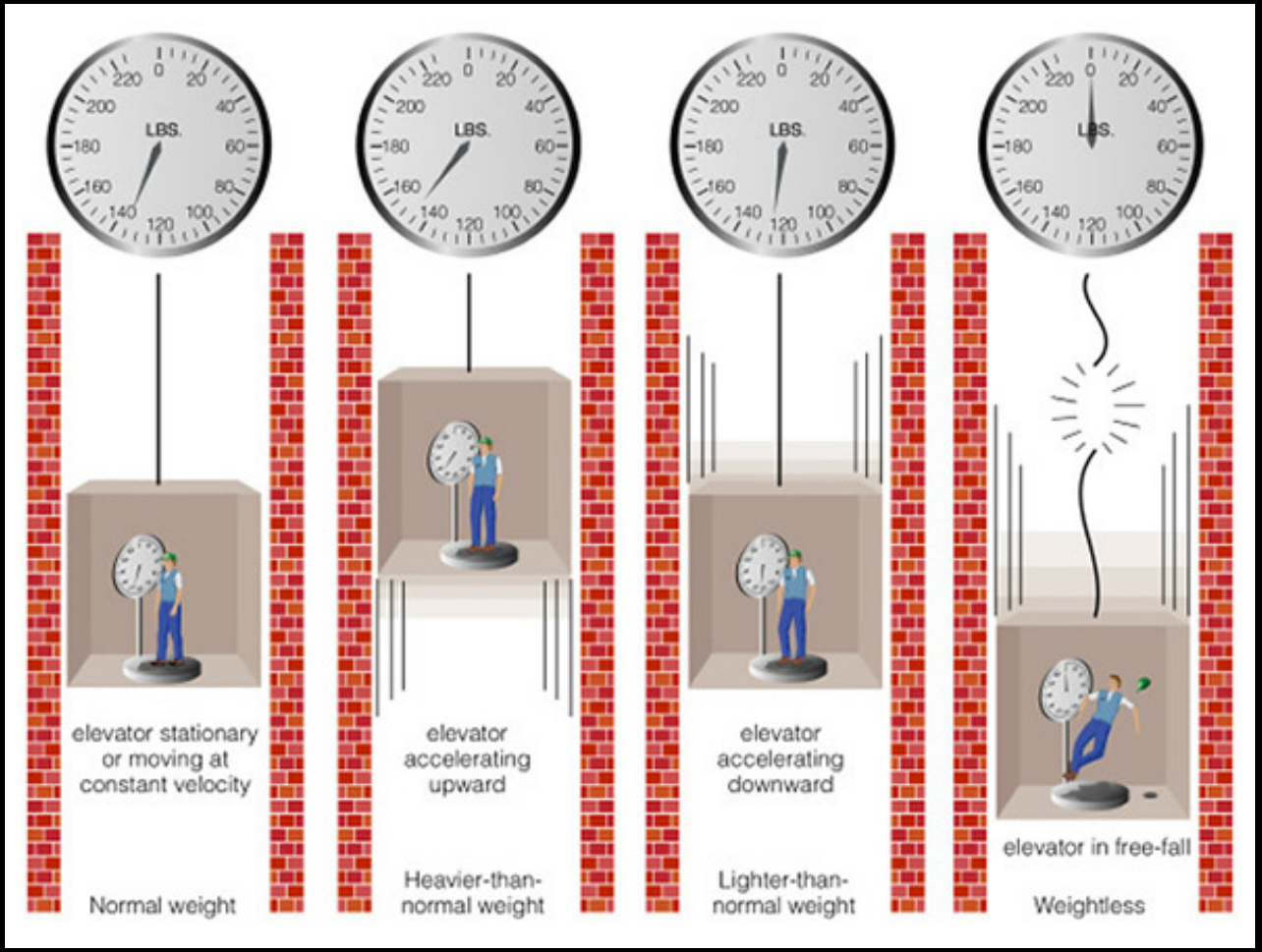


vs.

Force is a rate of change in momentum. It takes force to accelerate an object, or to slow it down.

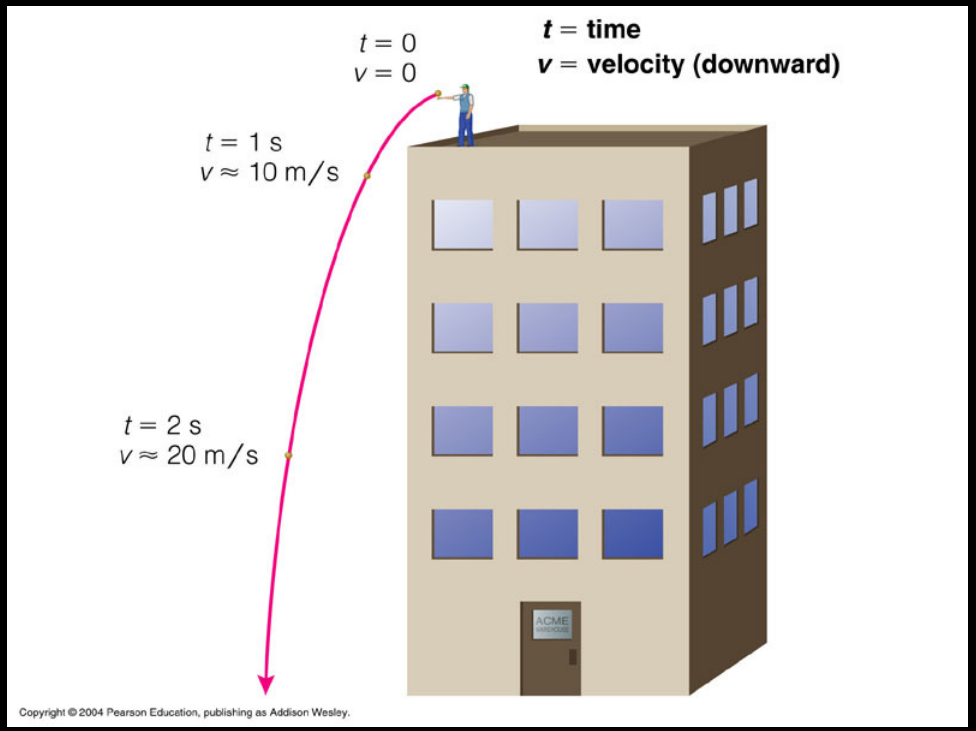
- **Weight** is the force of gravity on an object.
- Your weight is your mass times the acceleration due to gravity, g.
- A person's weight on the Moon is 6 times less than that on Earth, since the Moon's gravity is 6 times weaker.

Freefall, or weightlessness, occurs when there isn't any force to oppose your fall.



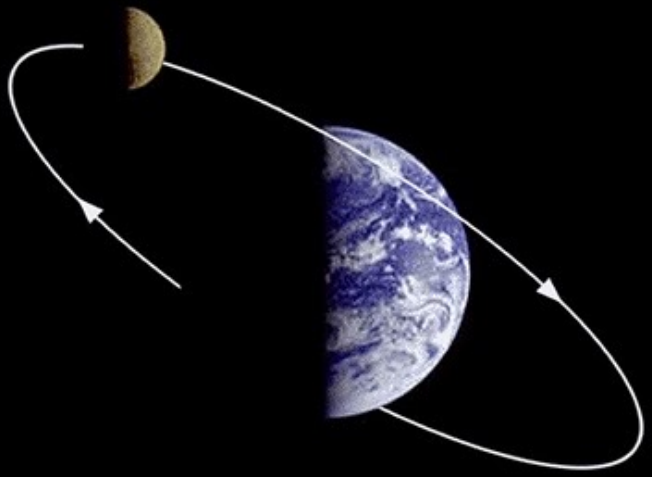
Freefall

- The force of gravity gives an acceleration, for Earth: g = 9.8 m/s^2
- Gravity accelerates all objects equally, regardless of their mass.
- On Earth, gravity increases a falling object's speed by about 10 meters per second everynsecond (about 22 miles per hour each second).



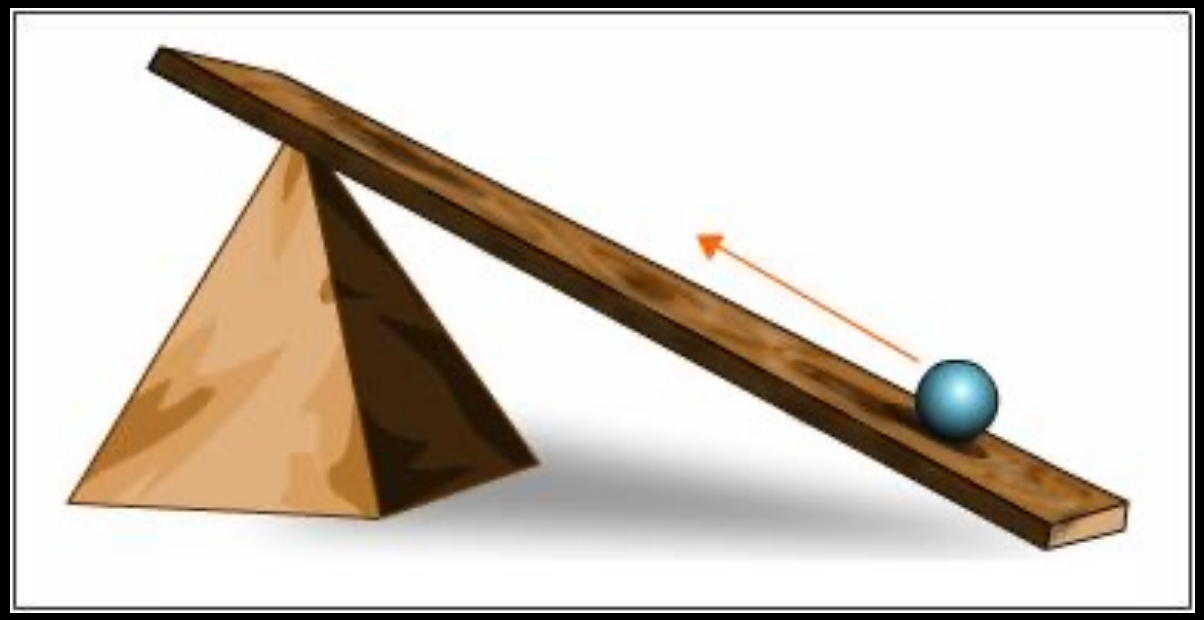
Where is gravity?

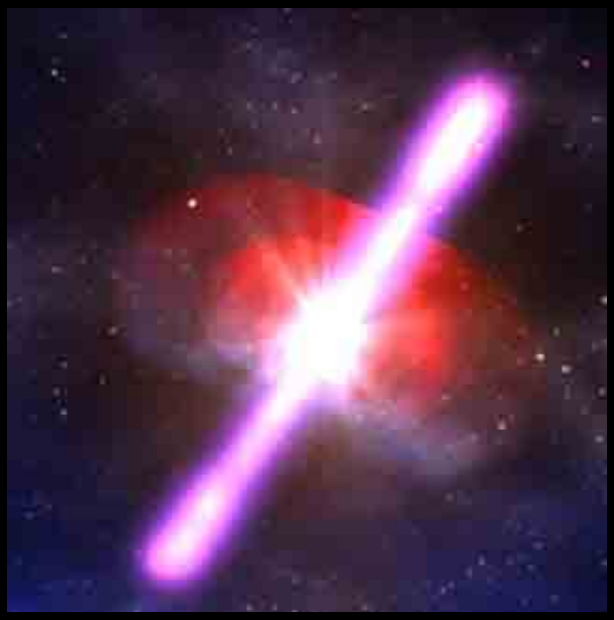
Objects in orbit around Earth are in a constant state of freefall!



Energy

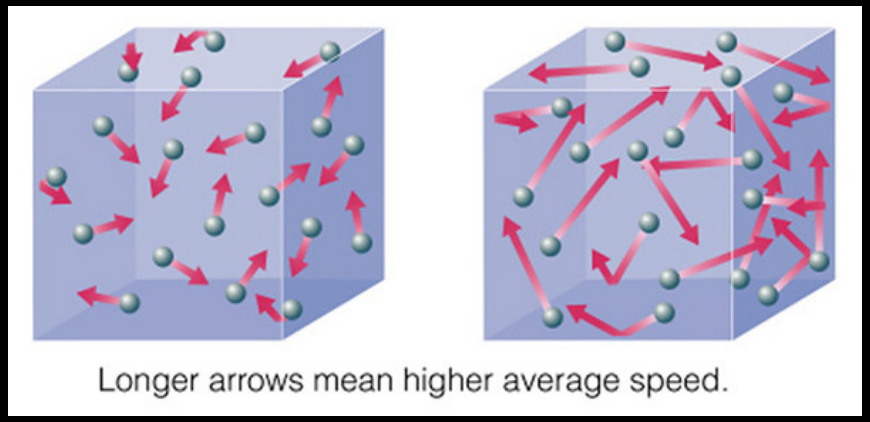
Every phenomenon in the Universe involves energy, energy transfer, or transformation (units are Joules, or Calories).





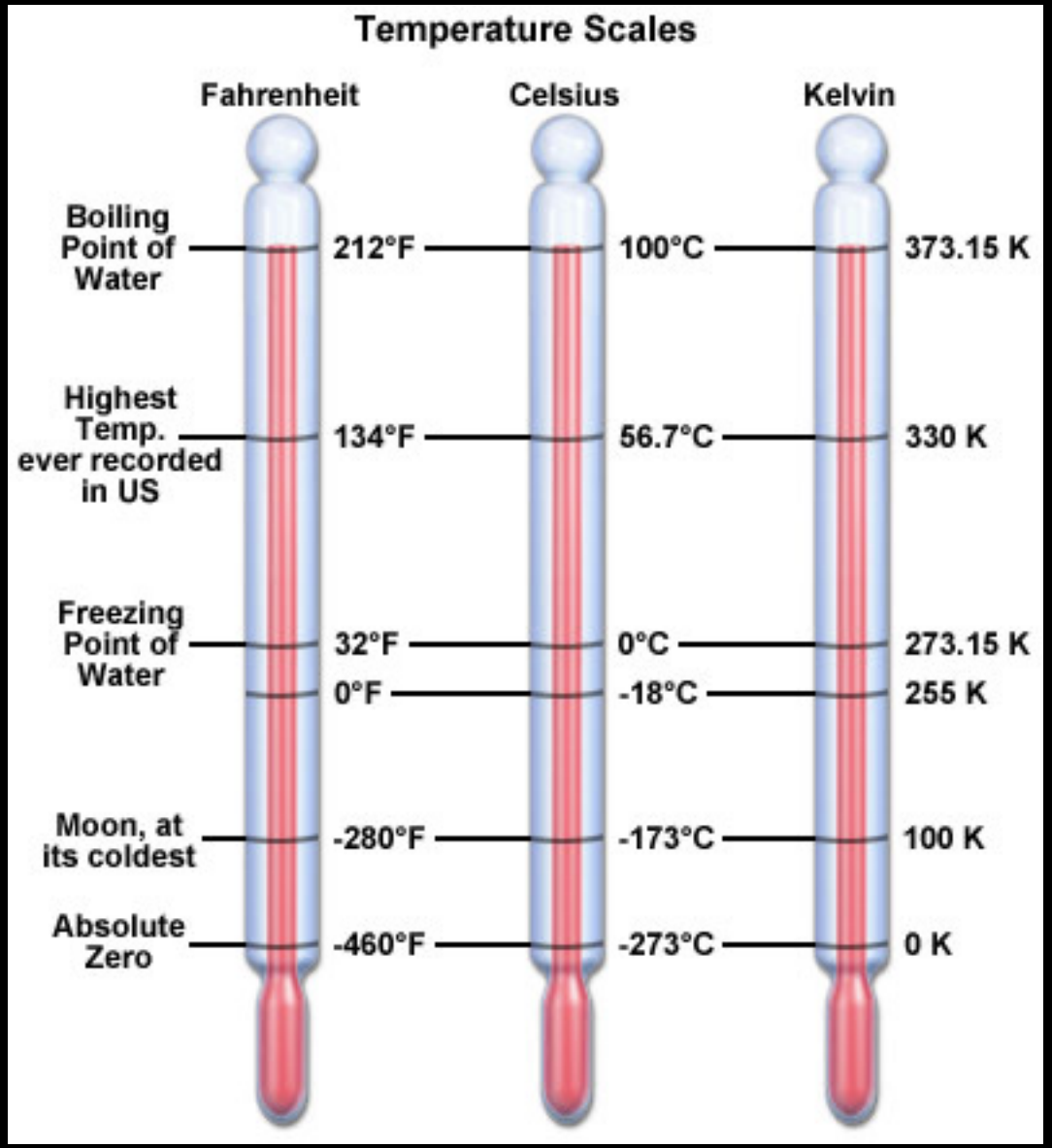
Thermal Energy

Thermal energy is a type of kinetic energy and measures the total kinetic energy of an object's constituent particles. The hotter the object, the more thermal energy.



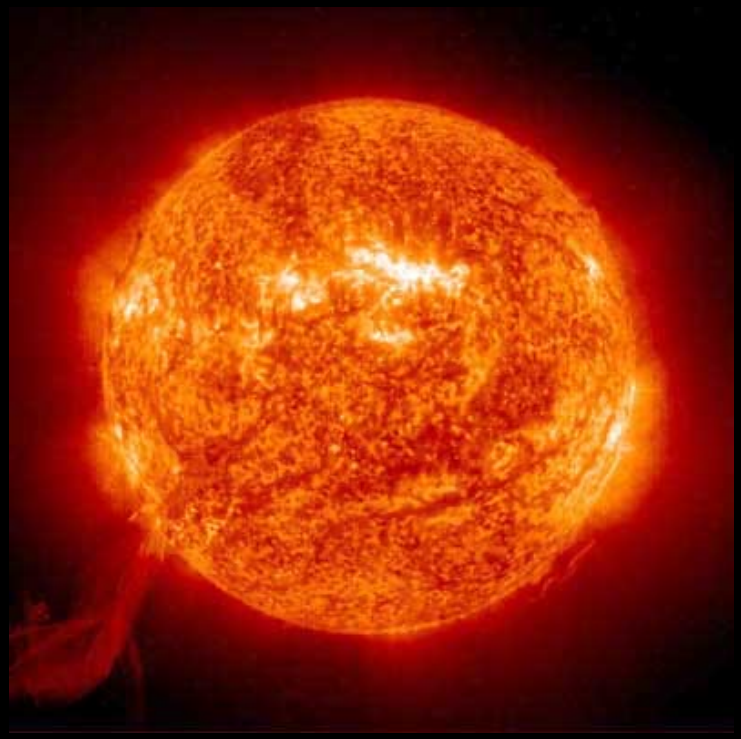
Temperature Scales

- Three scales: Celsius, Fahrenheit, Kelvin.
- 100 degrees between freezing and boiling points of water in Kelvin and Celsius scales.
- 180 degrees between freezing and boiling points of water in Fahrenheit scale.
- **Absolute zero = 0 K.**



Radiative energy

Radiative energy is the energy carried by radiation (or light). This is the energy that warms the surface of a planet.

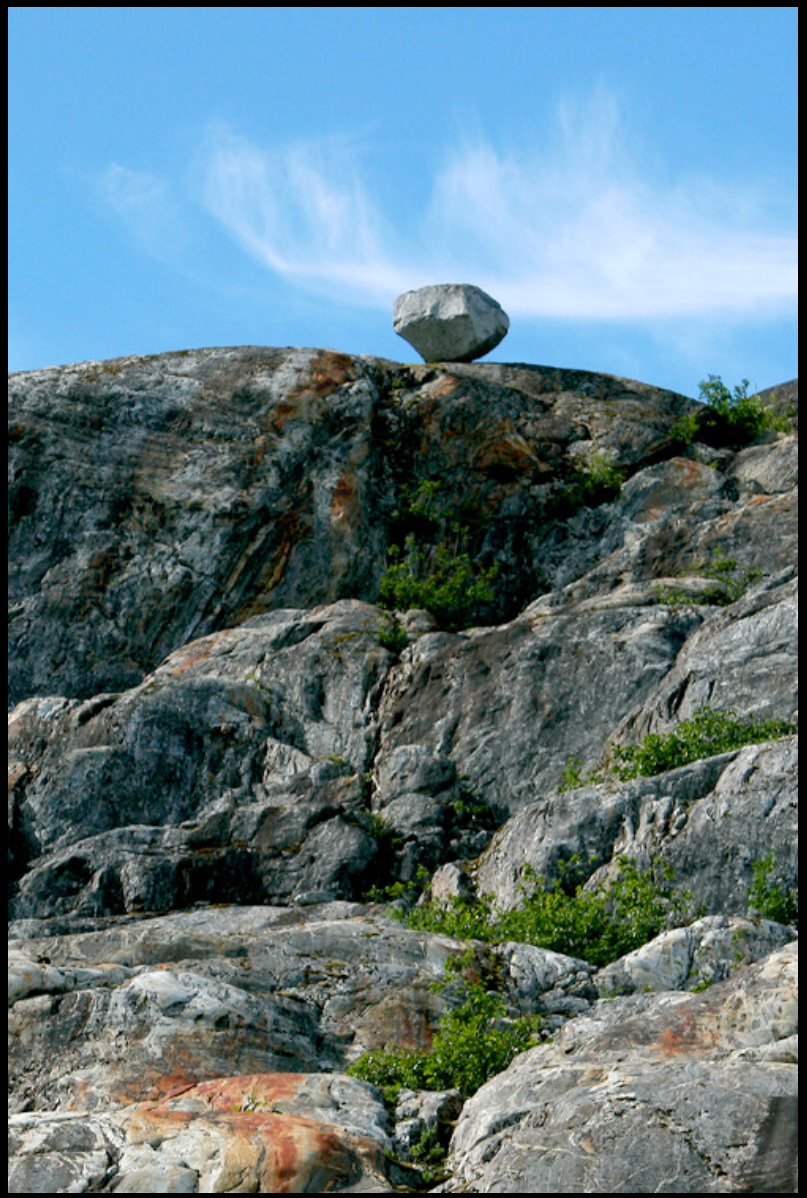


Kinetic energy

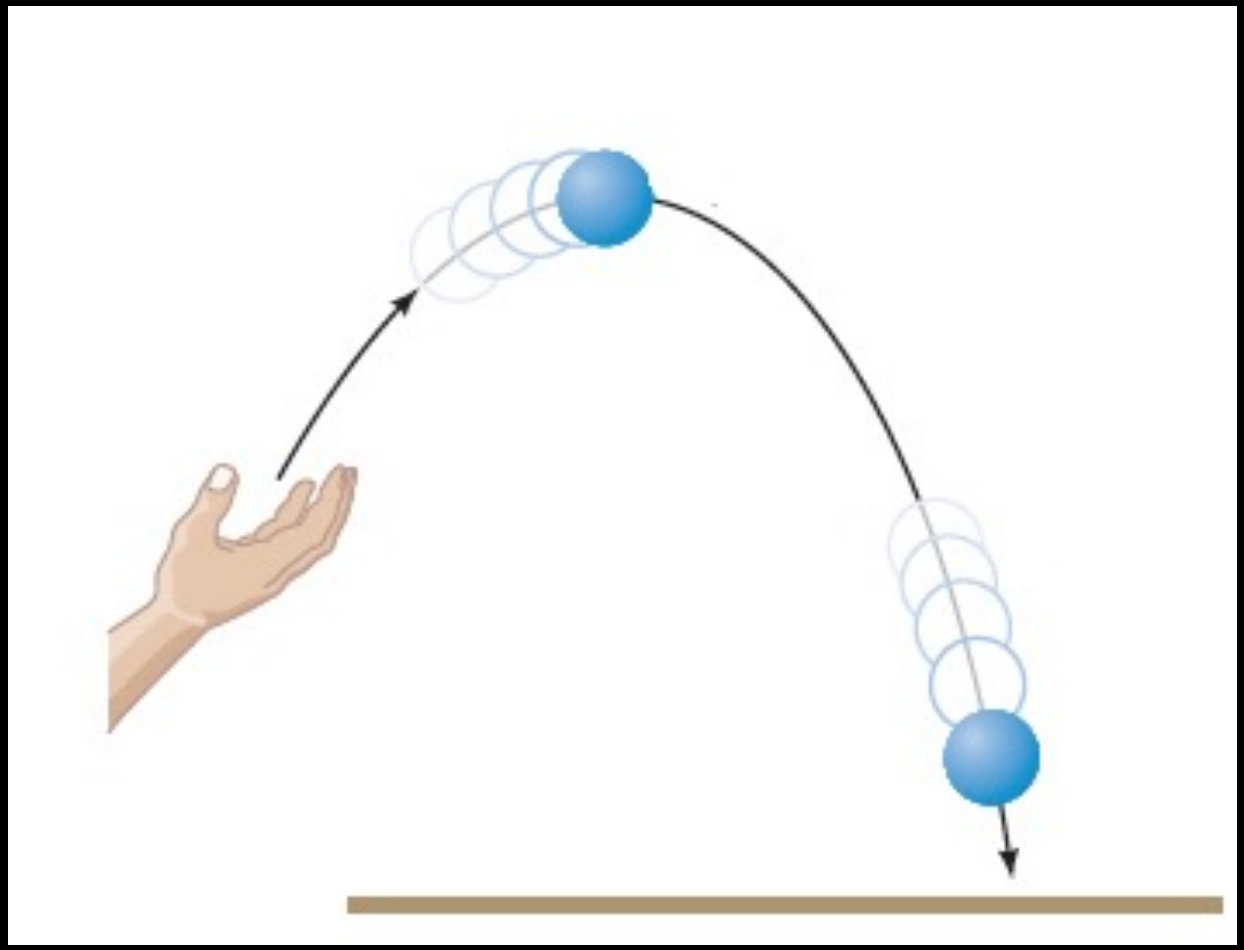
Kinetic energy is the energy of motion. The faster you move, the more kinetic energy you have.

Potential energy

- Potential energy is stored energy, which can be converted to kinetic or other form of energy.
- Gravitational potential energy is larger at larger distances from a gravitating body.



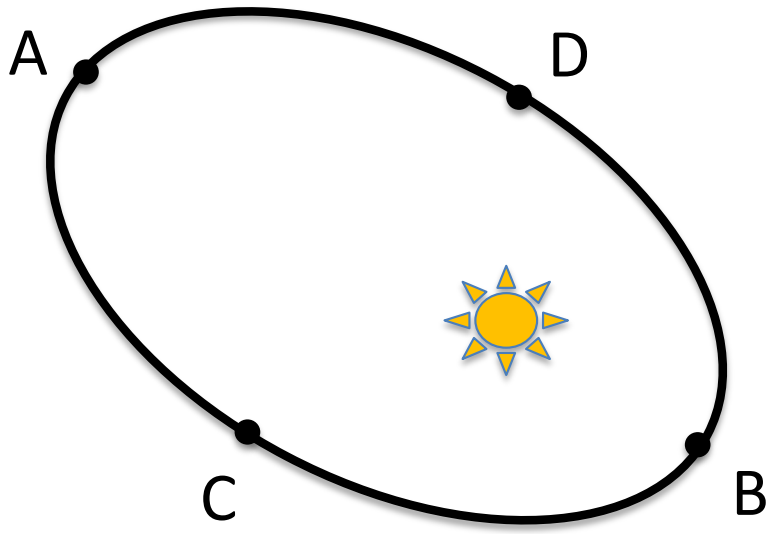
Throwing a ball upward: Kinetic energy to gravitational potential energy back to kinetic energy.



question for you

Shown below is an orbit of a planet around the Sun. At which point is its potential energy maximal?

A. A
B. B
C. C and D
D. It's always the same.
E. I have no idea.



Newton's Laws of Motion

Newton's Laws of Motion

First Law:

An object remains rest or in uniform motion unless acted upon by a force.

Voyager 1

Newton's Laws of Motion

<u>Second Law:</u>

Force = mass x acceleration

Newton's Laws of Motion

Third Law:

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

question for you

If the Earth pulls me with its force of gravity, how strongly am I pulling the Earth?

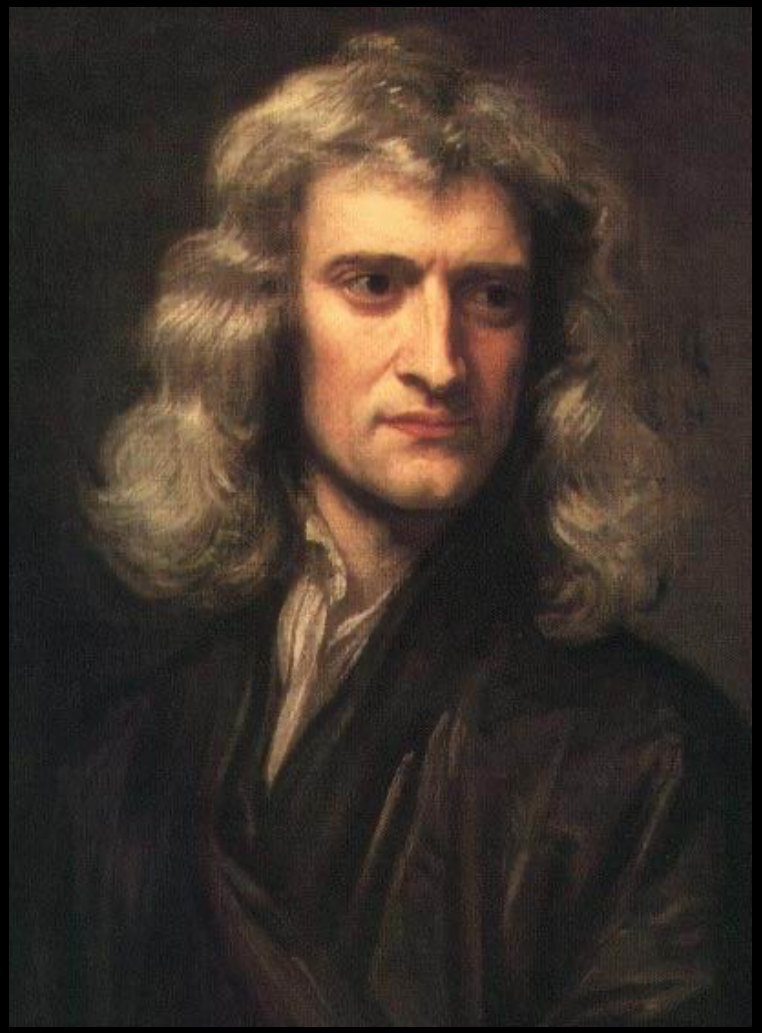
A. With the same force
B. With a much, much smaller force
C. With no force at all, the Earth isn't moving.
D. It depends on the time of the day.
E. I have no idea.

Law of Universal Gravitation

Sir Isaac Newton (1643 – 1727)

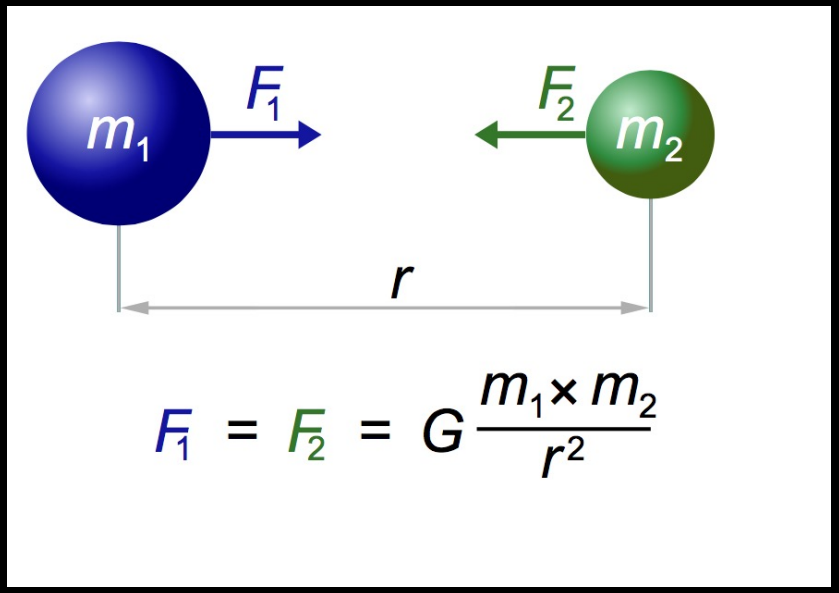
Introduced:

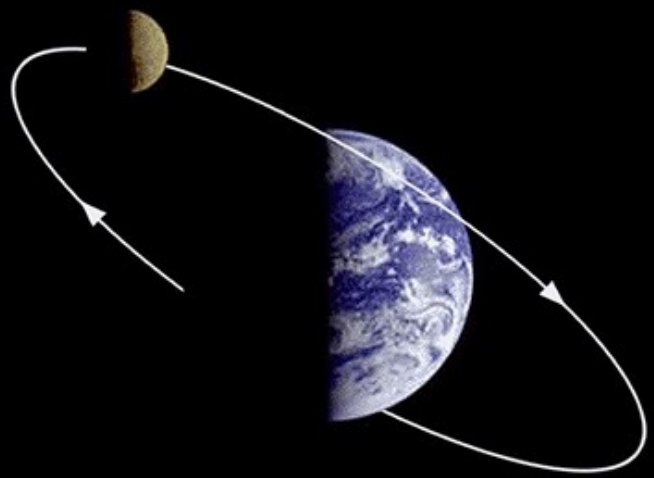
- **Calculus**
- **Universal law of gravitation**: the same gravitational force that makes an apple fall from a tree is responsible for keeping the Moon in orbit.



Newton's Law of Universal Gravitation

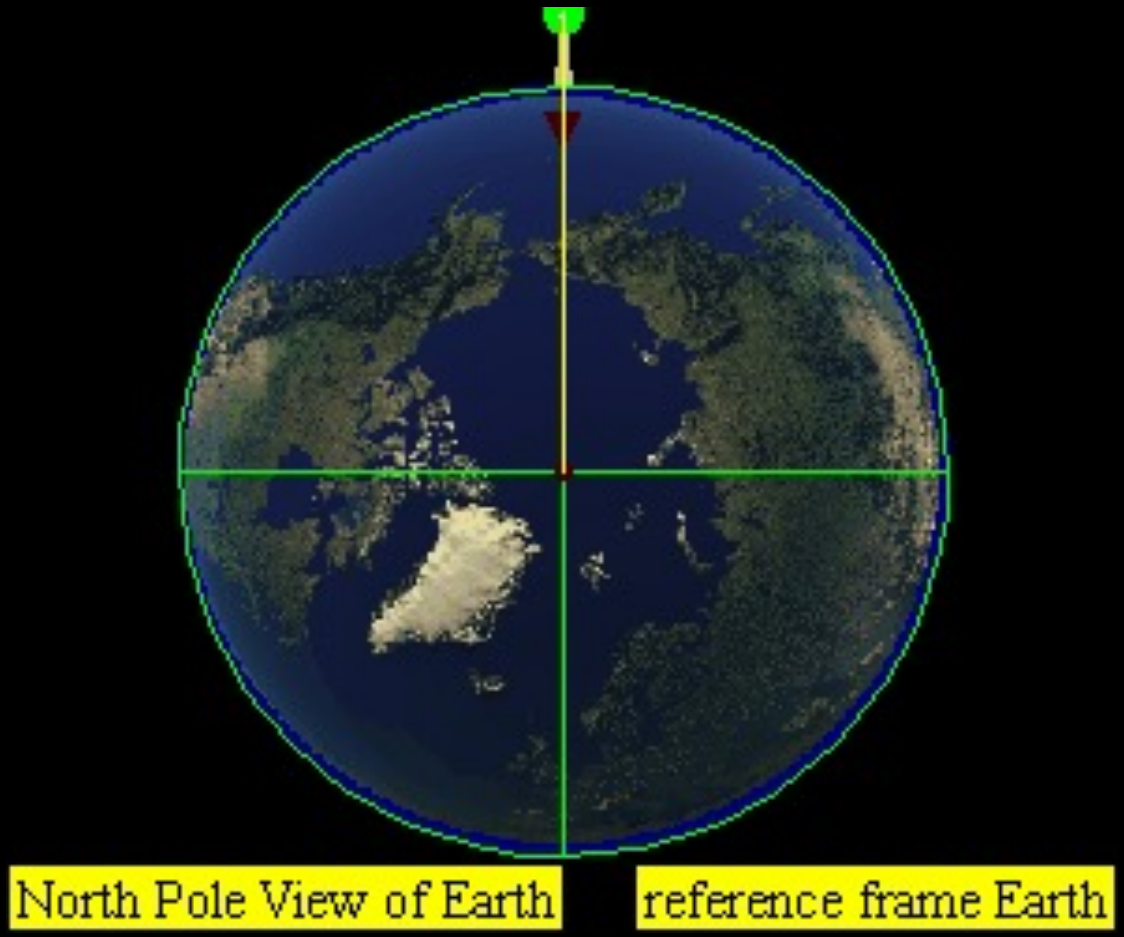
Any two bodies in the universe attract each other with a force that is larger the more massive they are and the closer they are to each other.





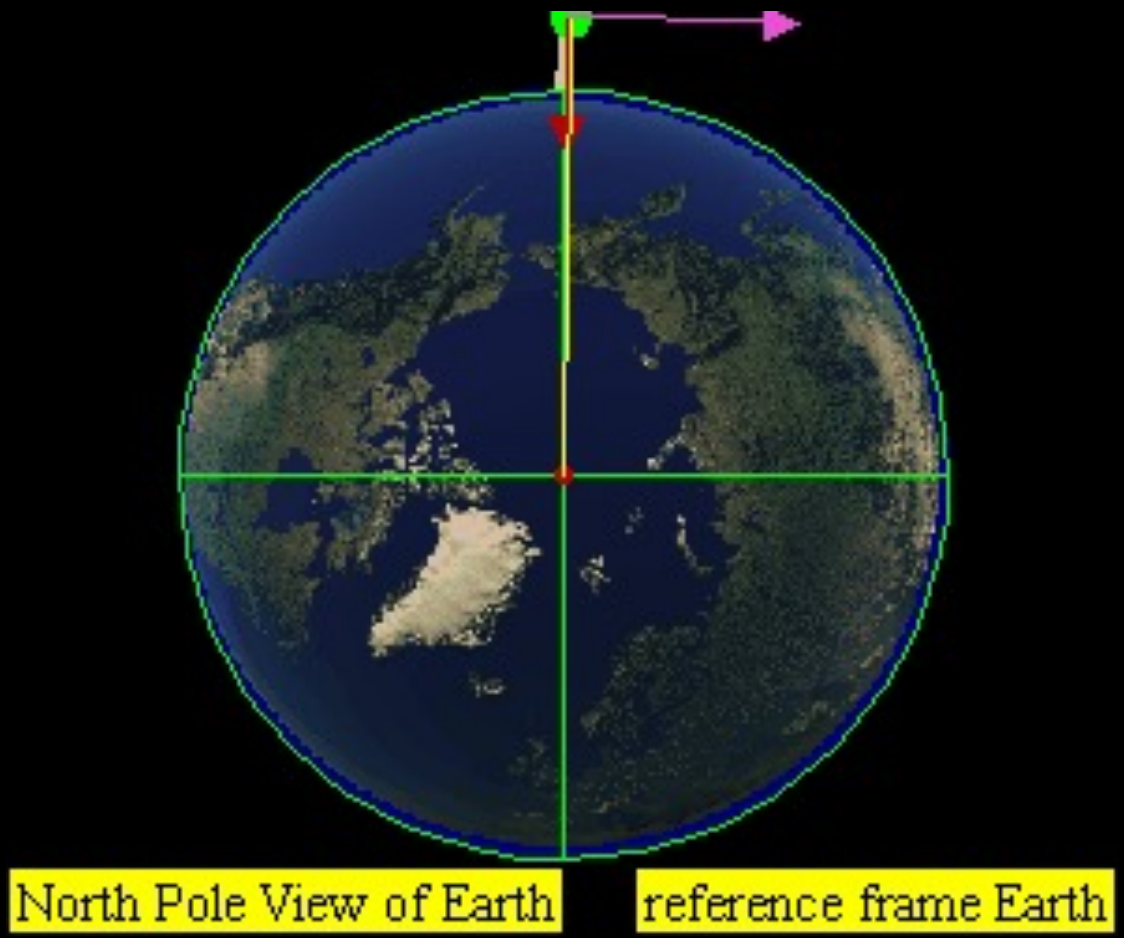
I am pulling the Earth with the same force it is pulling me...

Newton's Cannonball



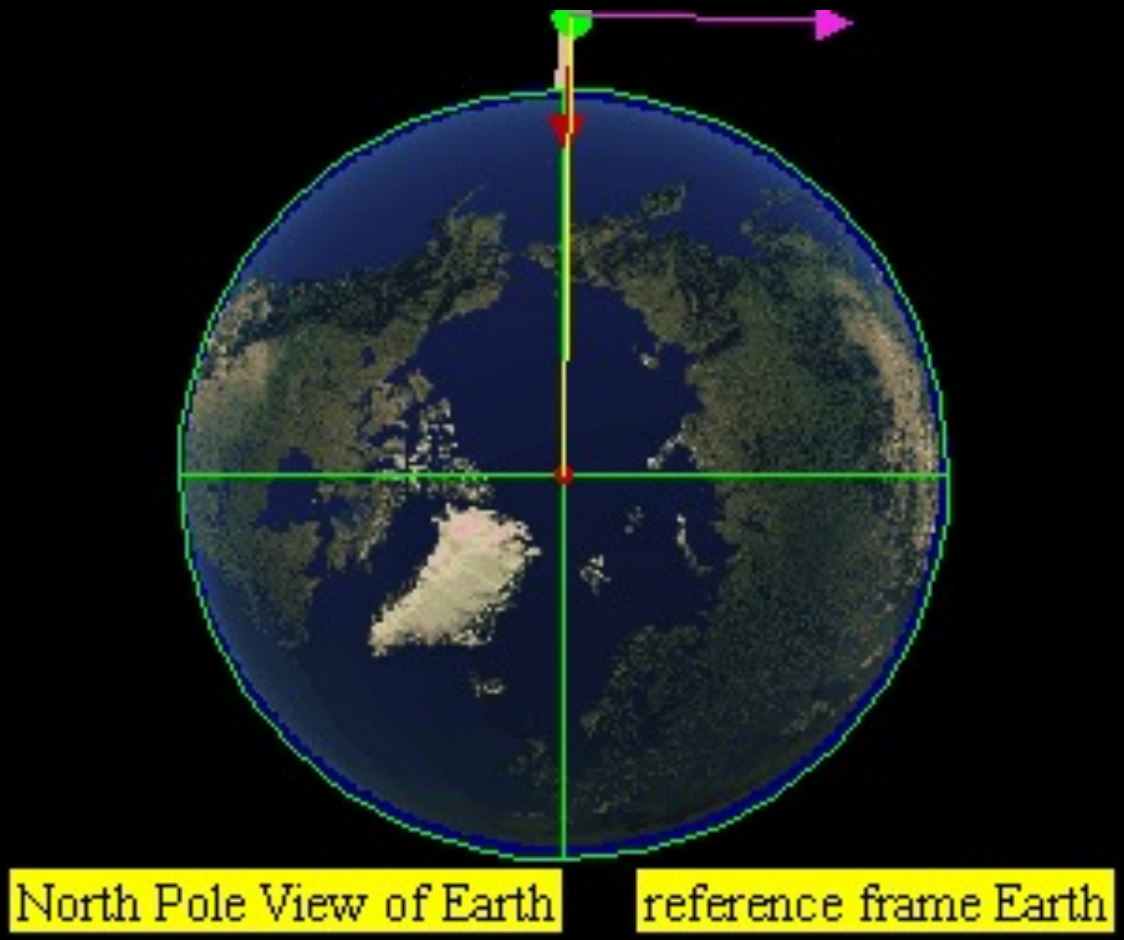
Cannonball fired with zero velocity from high mountain (ignore air resistance) [source: wikipaedia]

Newton's Cannonball



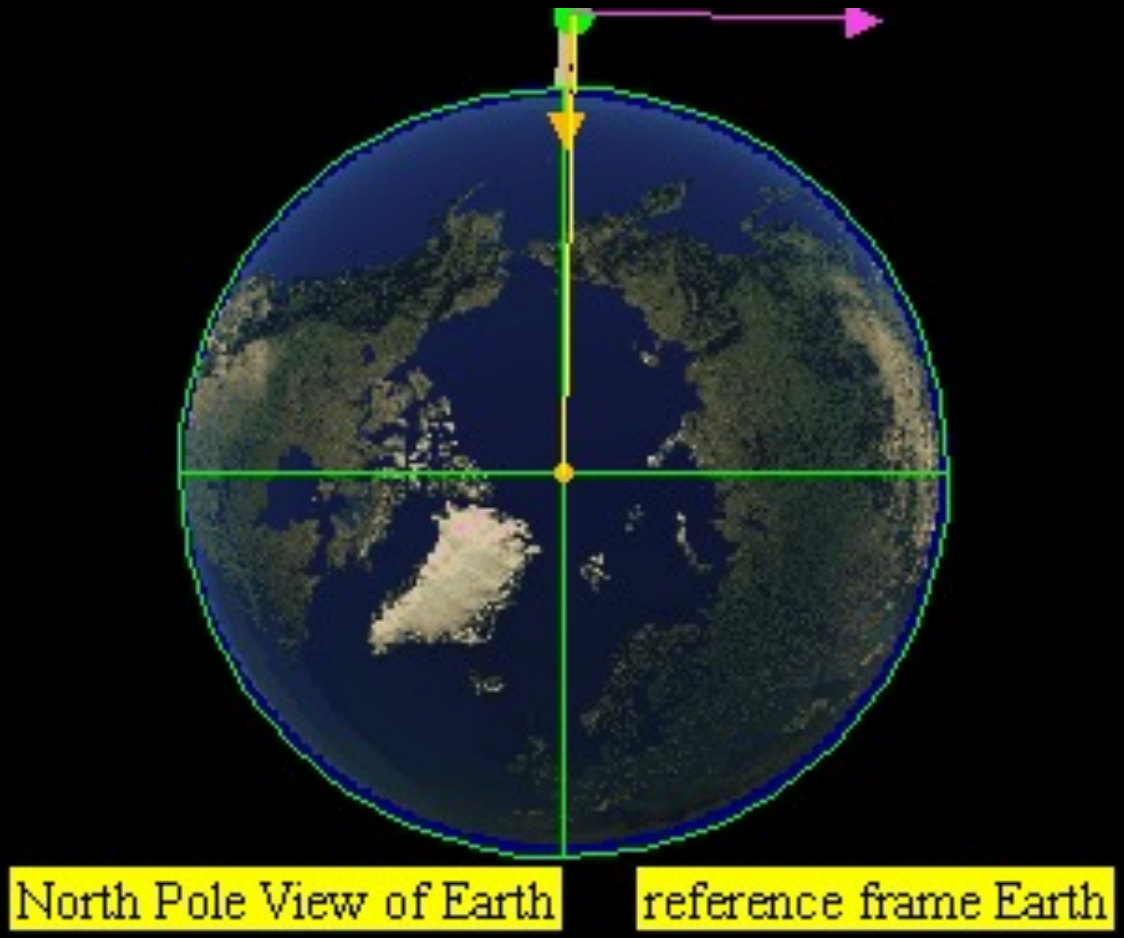
v = 6 km/s

Newton's Cannonball



v = 7.3 km/s

Newton's Cannonball



v = 8 km/s

Newton's Cannonball

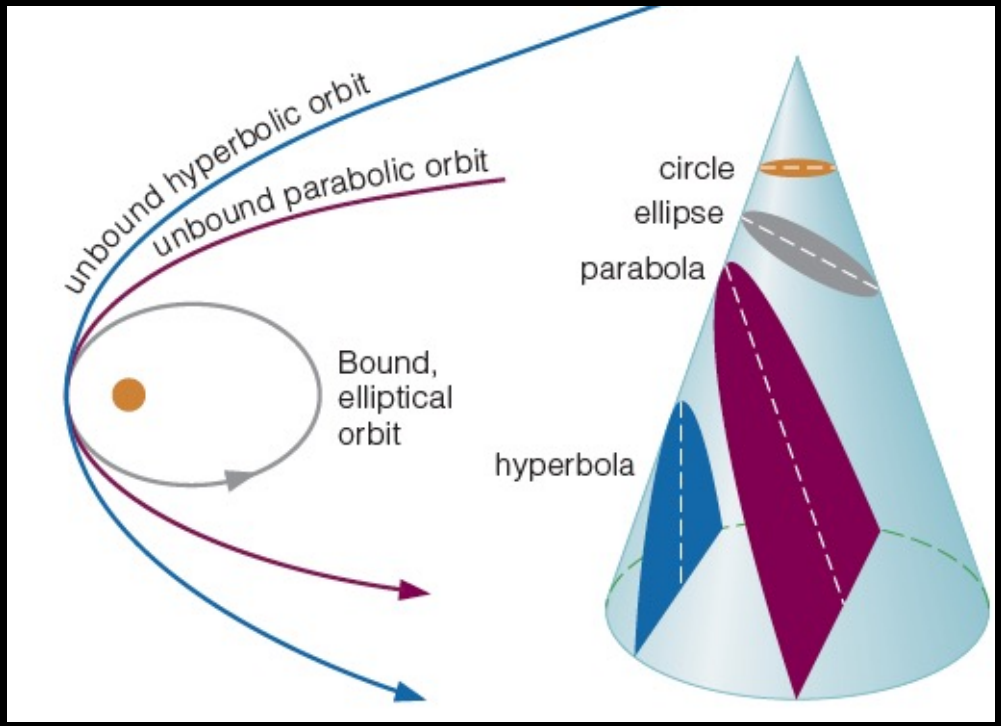
v = 11.2 km/s

Escape Velocity

- Escape velocity from Earth is 11.2 km/s.

Orbits are conic sections

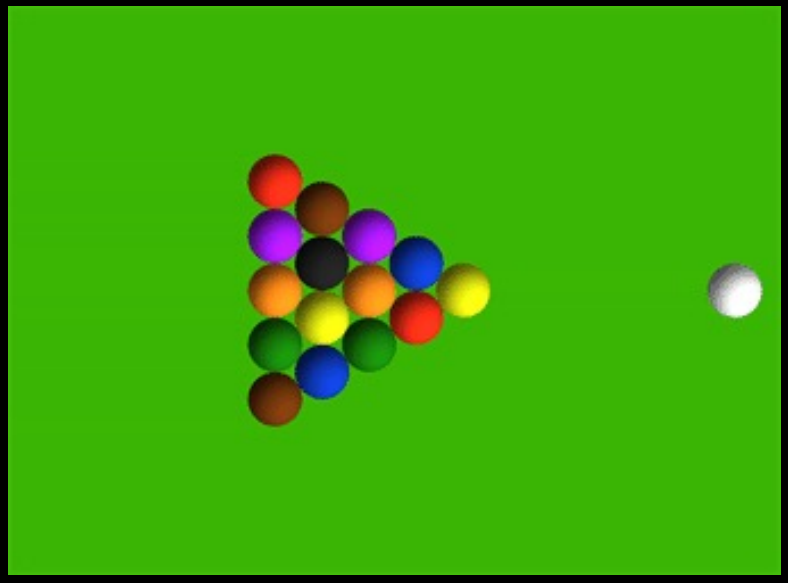
- Kepler's first two laws directly follow from the Law of Universal Gravitation and apply to all orbiting objects.
- Ellipses aren't the only possible orbits.
- Orbit shape depends on the initial "kick".



Conservation Laws

Conservation laws

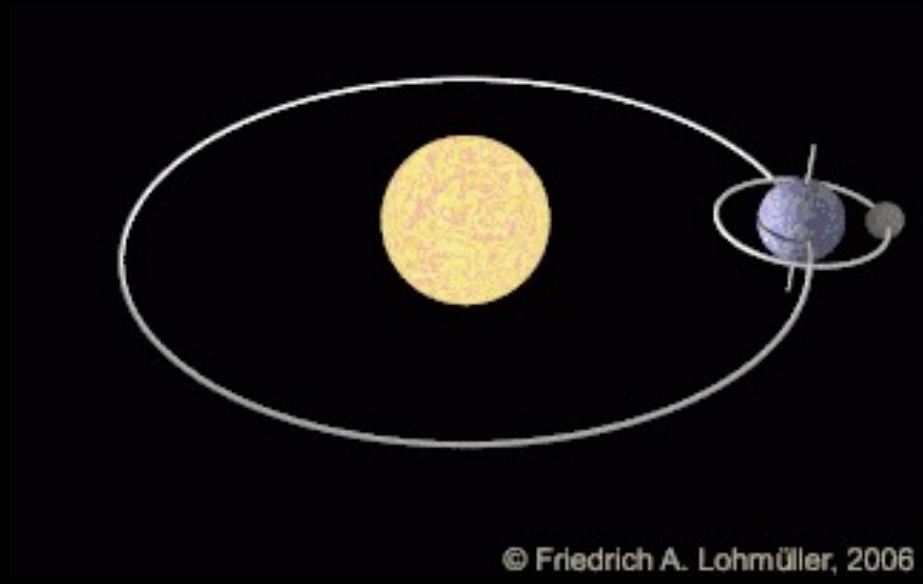
Energy, momentum, and angular momentum are conserved, unless there is an outside influence on the system.



Conservation of Angular Momentum

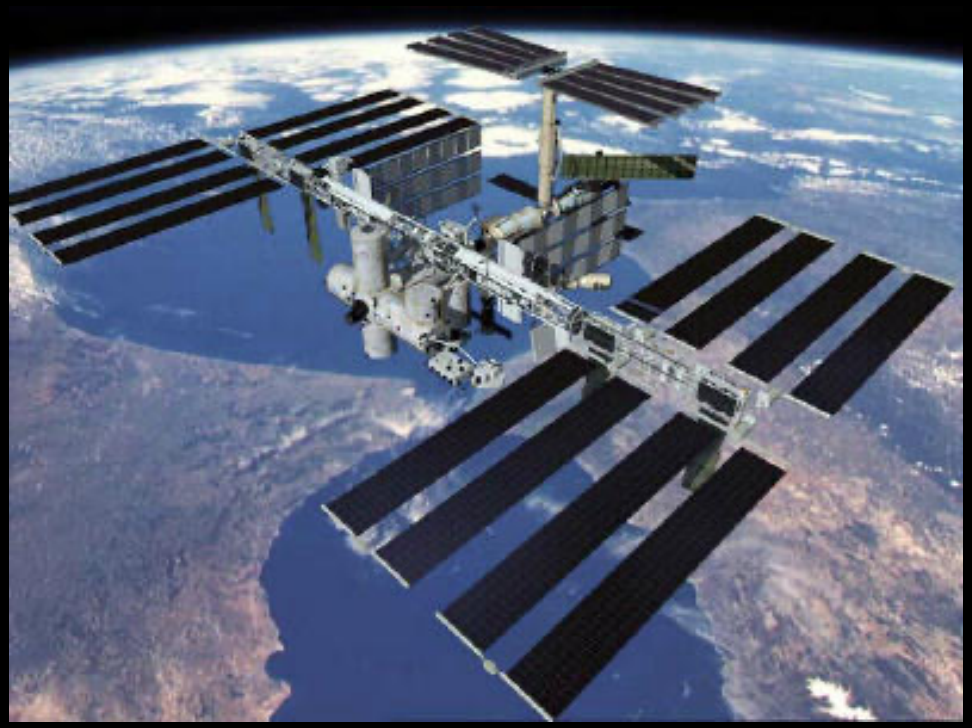
Conservation of angular momentum keeps a planet rotating and orbiting the Sun **in a plane**.

Angular momentum = mass × velocity × distance



Energy conservation

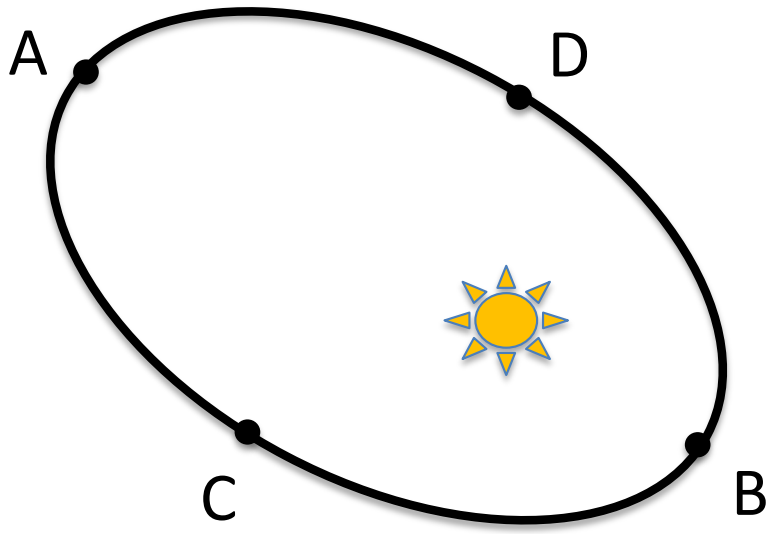
Energy can be transferred from one object to another, or transformed/converted from one form into another.



question for you

Shown below is an orbit of a planet around the Sun. At which point is its momentum maximal?

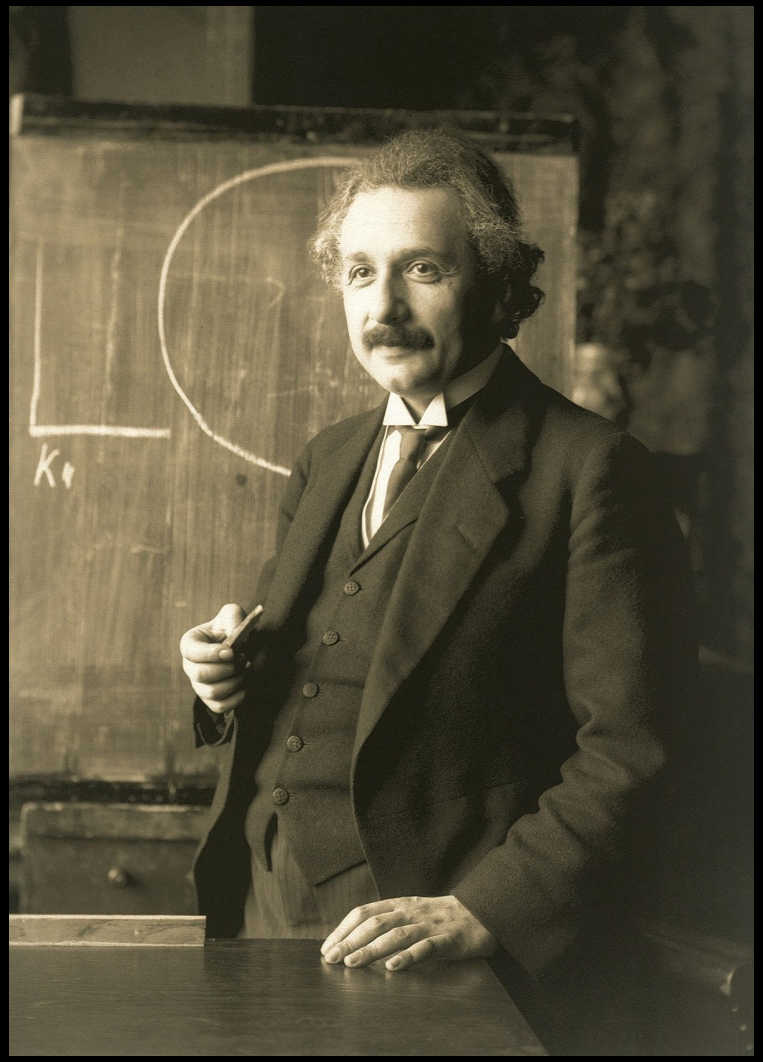
A. A
B. B
C. It always increases.
D. It's always the same.
E. I have no idea.



Theory of relativity

Albert Einstein (1879 – 1955)

- **Special** theory of relativity (1905): speed of light is independent of reference frame.
- **General** theory of relativity (1915): massive objects warp spacetime.

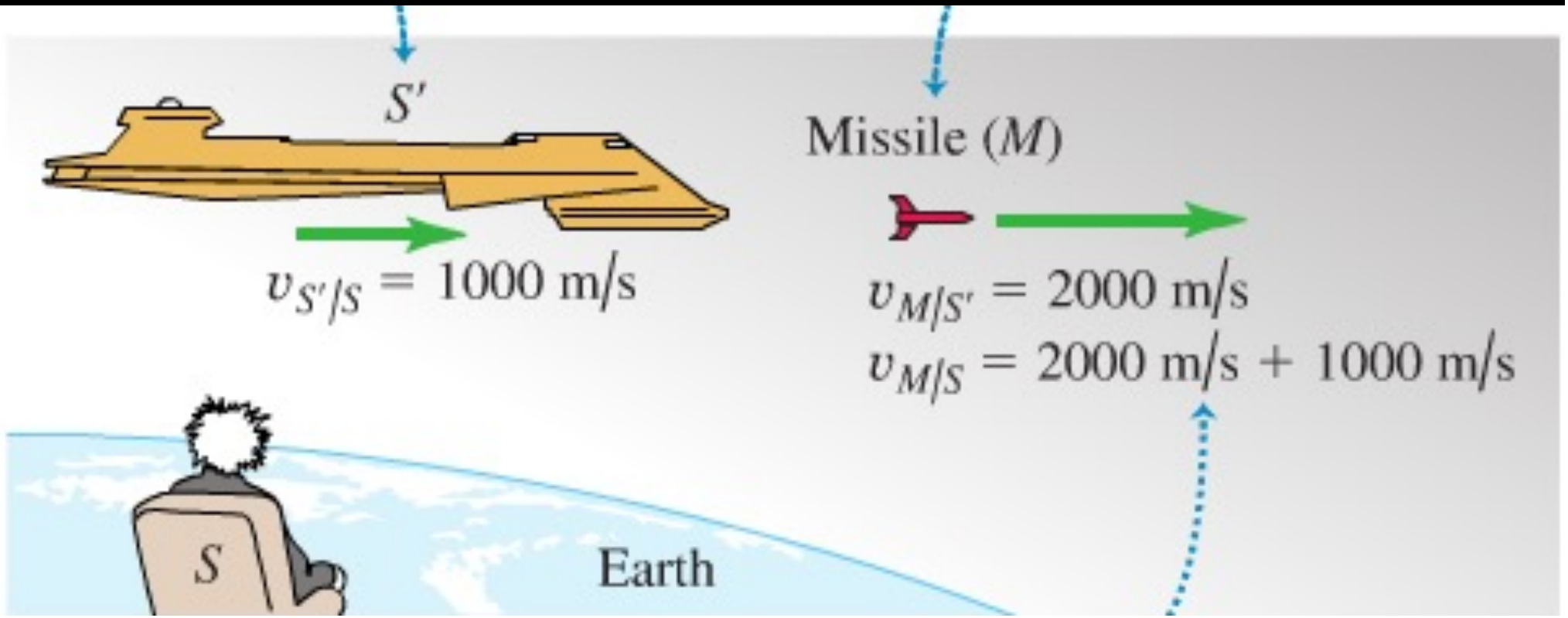


Special relativity

Equivalence principle: The laws of physics are the same in every inertial frame of reference.

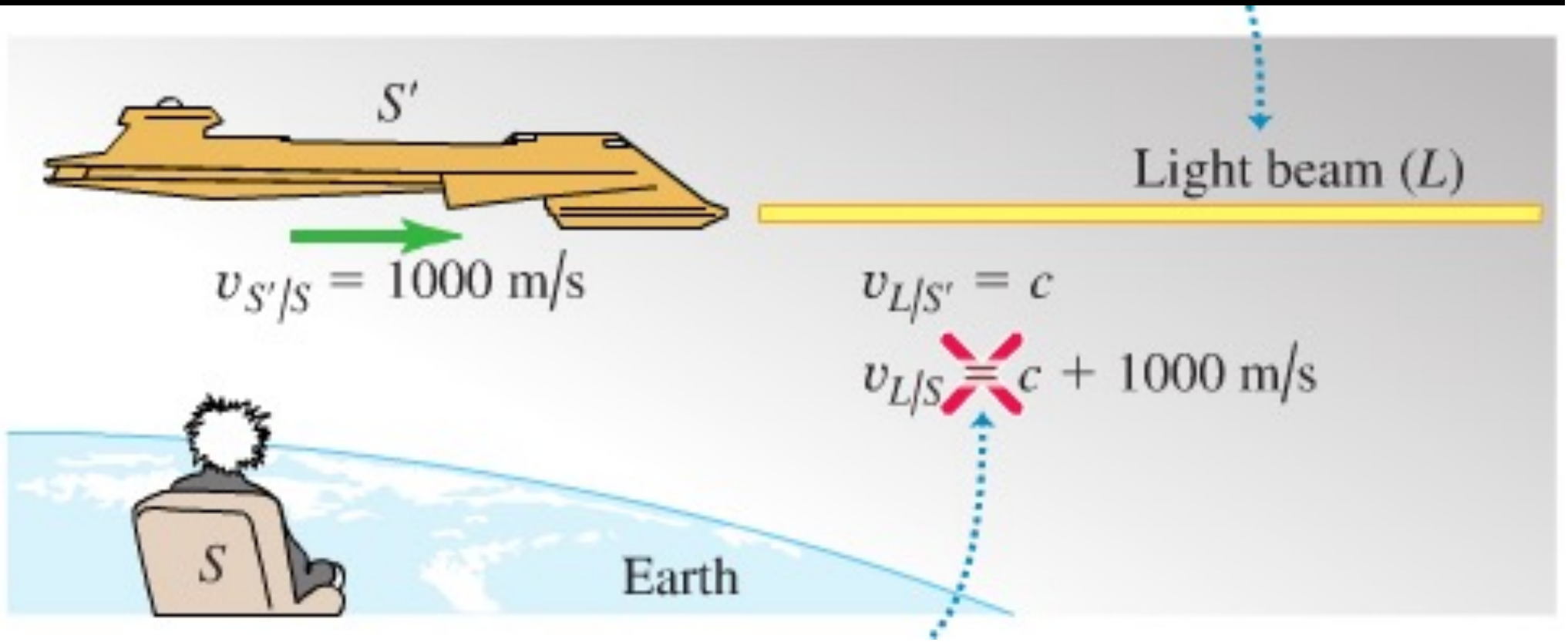
Special relativity

- A spaceship moving at 1000 meters per second fires a missile which is traveling at 2000 meters per second.
- According to an observer on Earth, the missile will be traveling at 2000 + 1000 = 3000 m /s.



Special relativity

- The same spaceship now fires a laser beam moving at the speed of light.
- According to an observer on Earth, laser beam is moving at the speed of light.

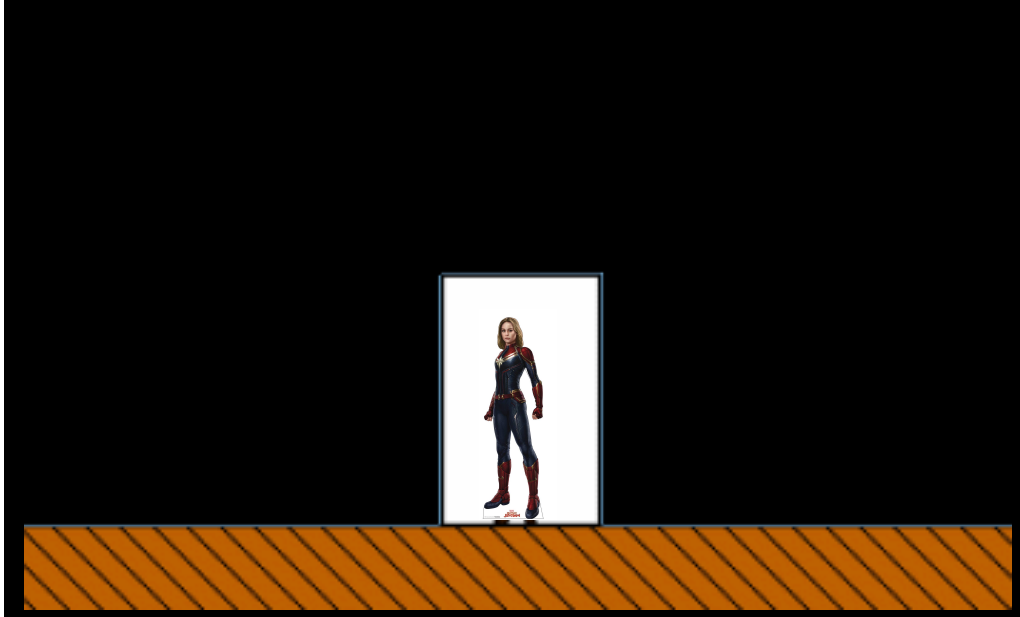


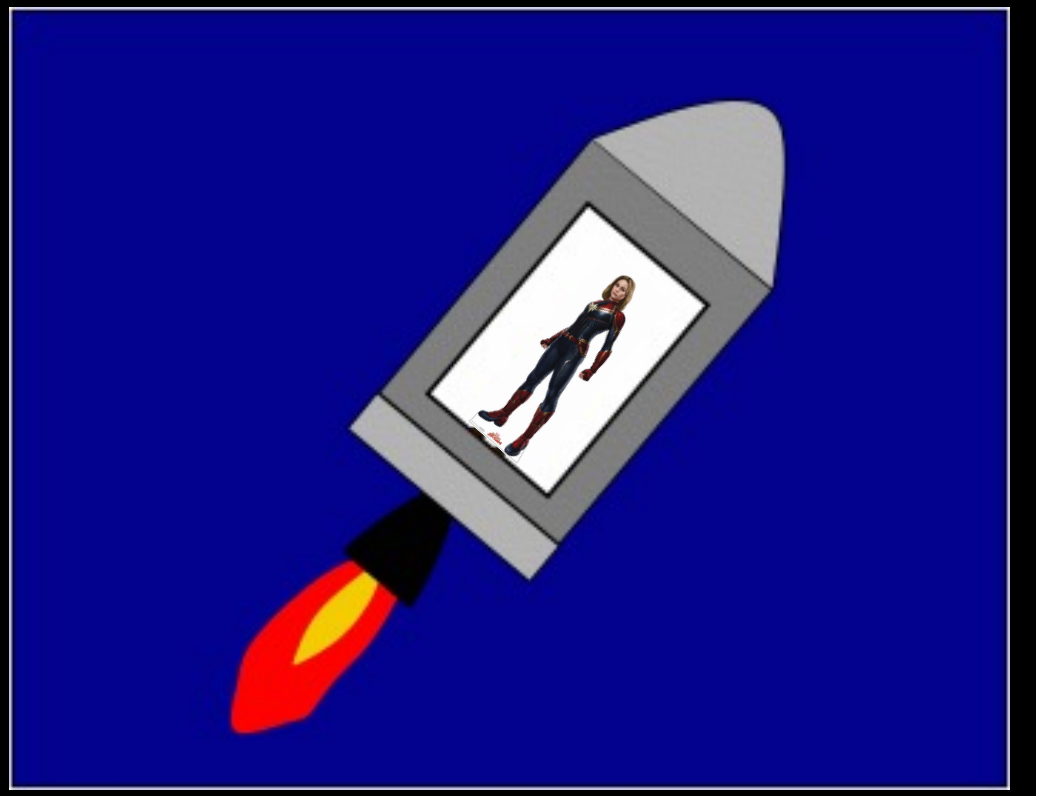
Special relativity

The speed of light in vacuum is the same in all inertial frames and is independent of the motion of the source.

Equivalence Principle

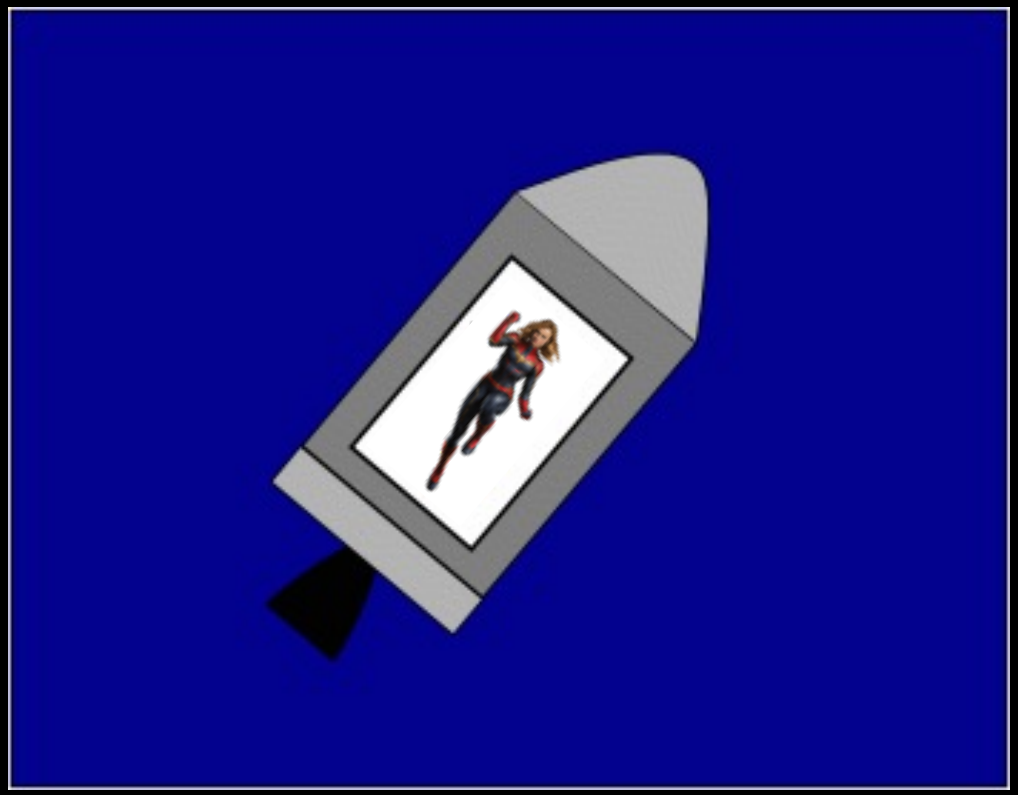
Can you tell the difference between being in a windowless room on Earth and in the same room hurtling through space with an acceleration of 9.8 m/s^2?





Equivalence Principle

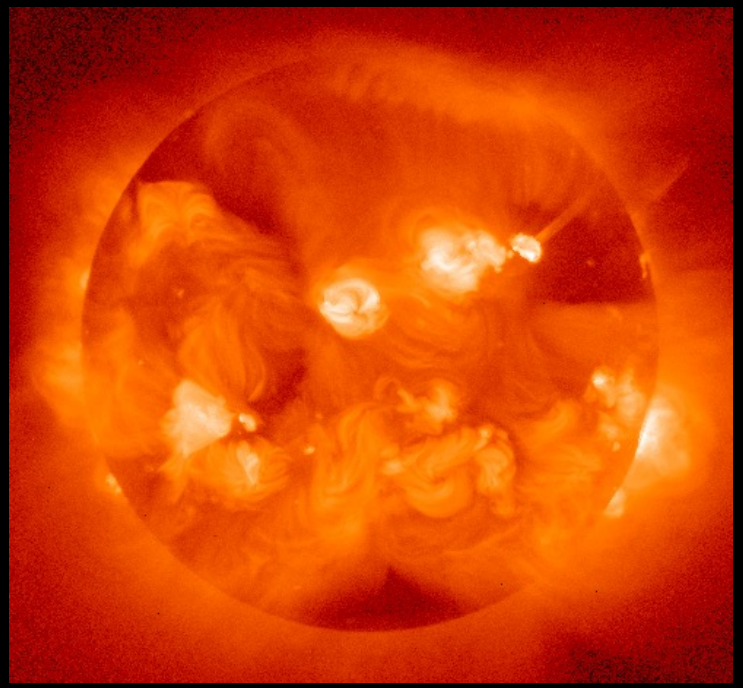
- Can you tell the difference between being in an elevator in freefall and being weightless in space?
- Equivalence Principle: The effects of gravity and the effects of acceleration are exactly equivalent!!!



Mass is equivalent to energy

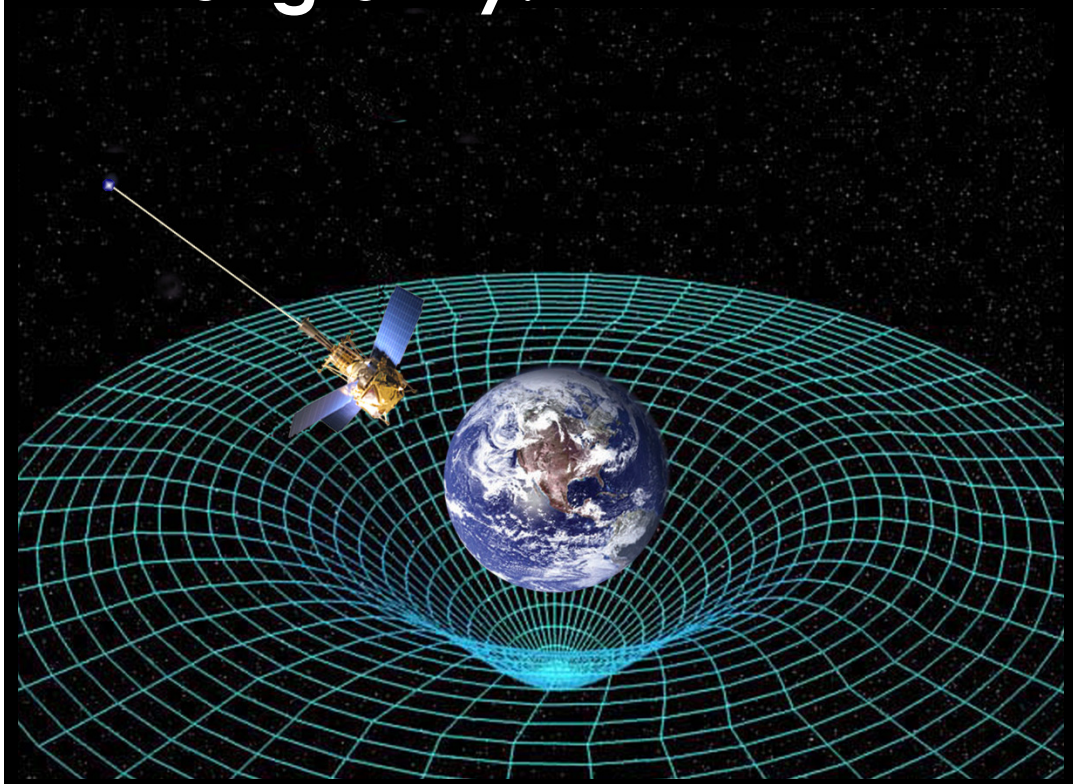
$$E = mc^2$$

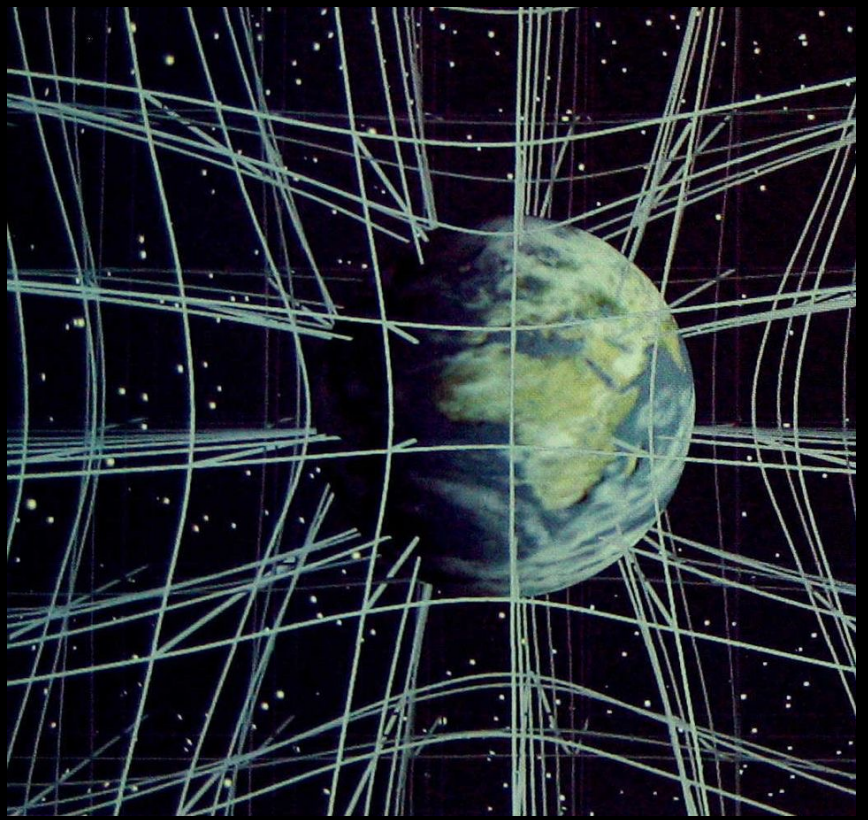
Our sun converts 600 million tons of hydrogen to 596 million tons of helium every second. The "missing" 4 million tons is converted to radiative energy, producing 10^{26} Watts of power.



Curvature of spacetime

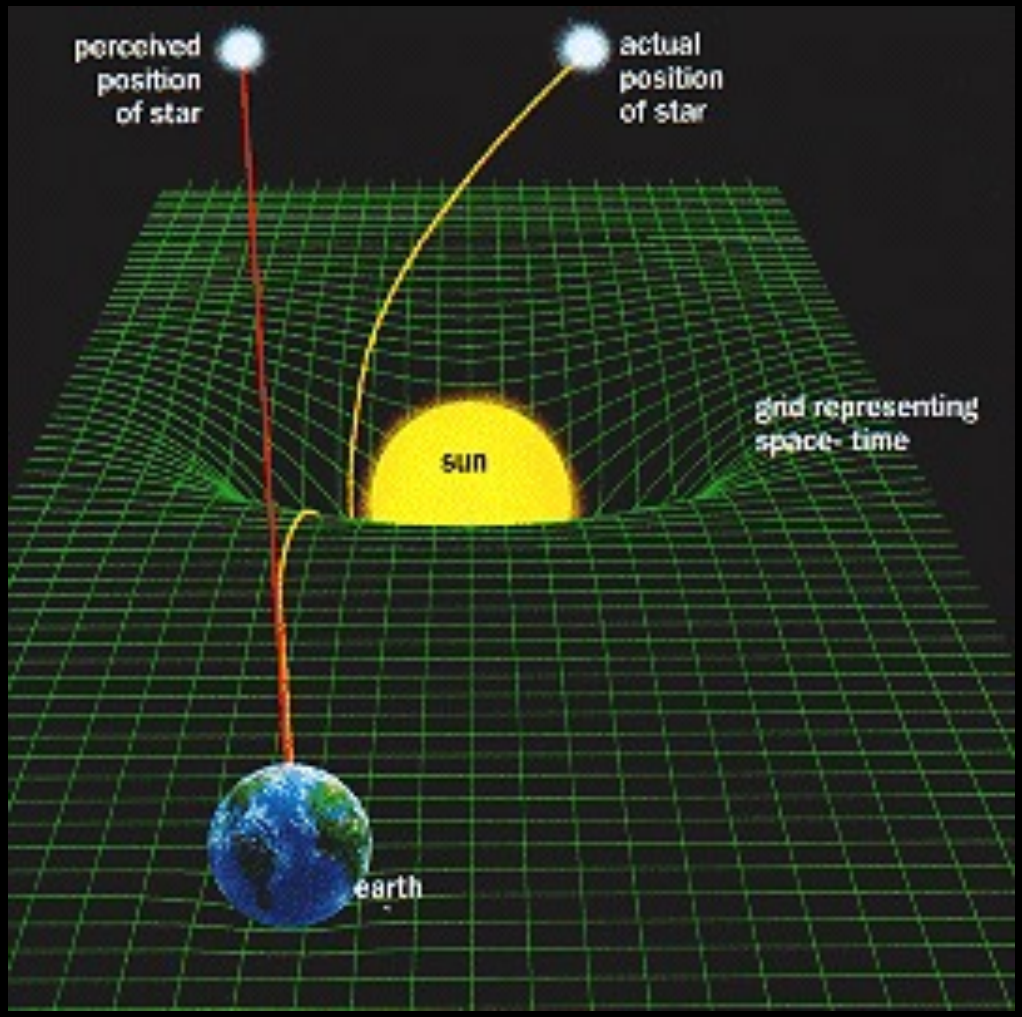
Three-dimensional space and time combine into spacetime, and **spacetime is curved by the force of gravity**.



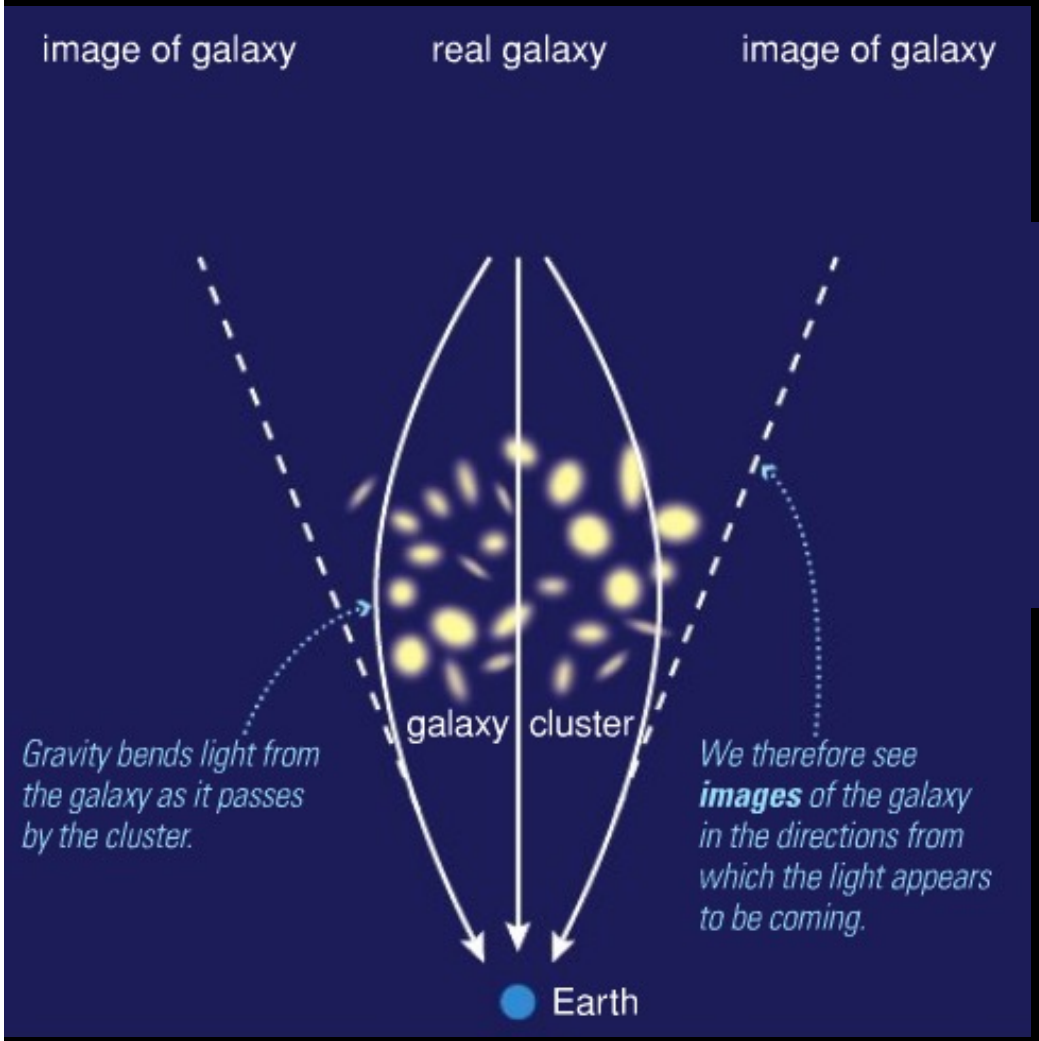


Curvature of spacetime

Spacetime curvature observed during the 1919 eclipse: light of stars is bent by the Sun.

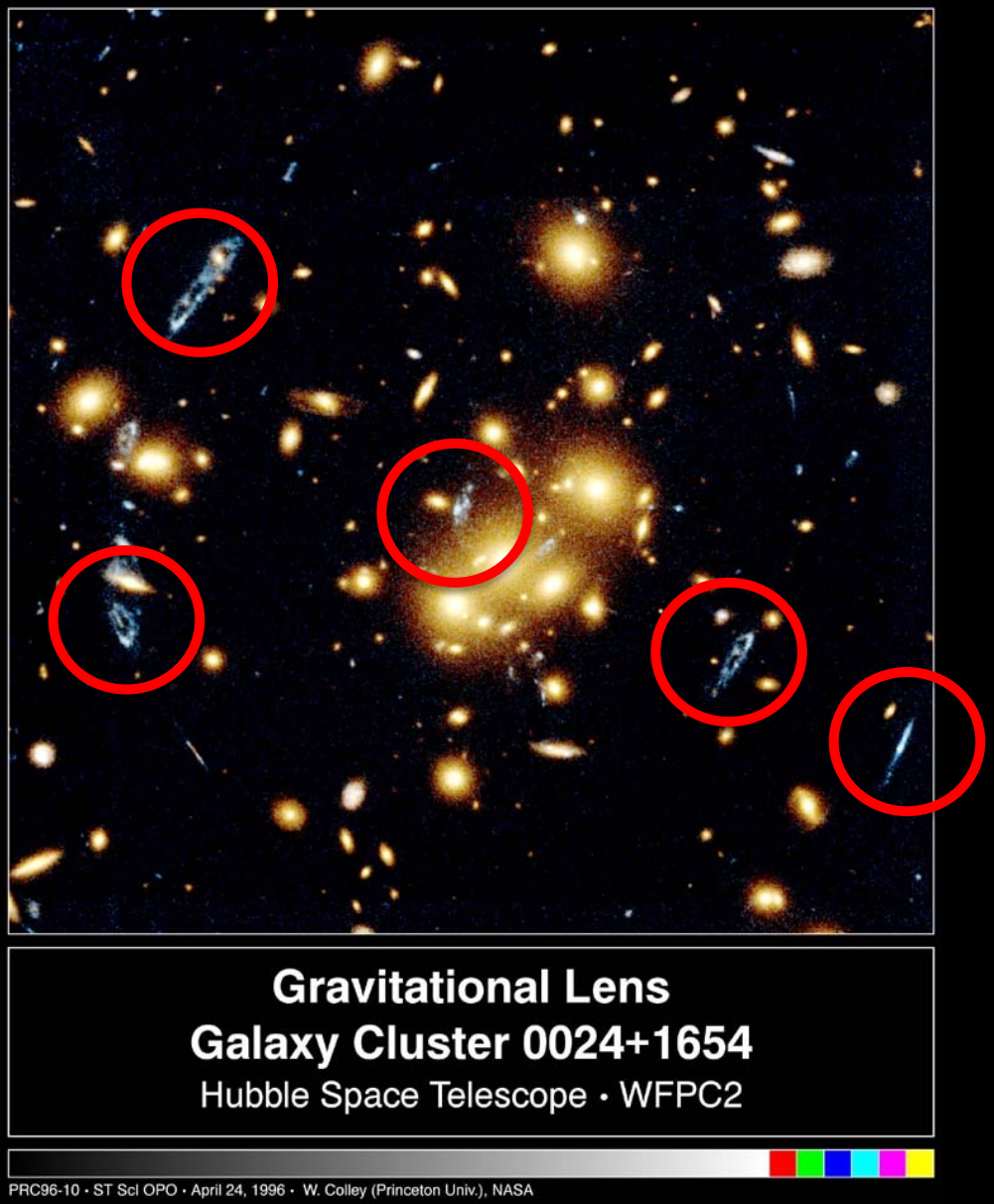


Spacetime: Gravitational Lensing



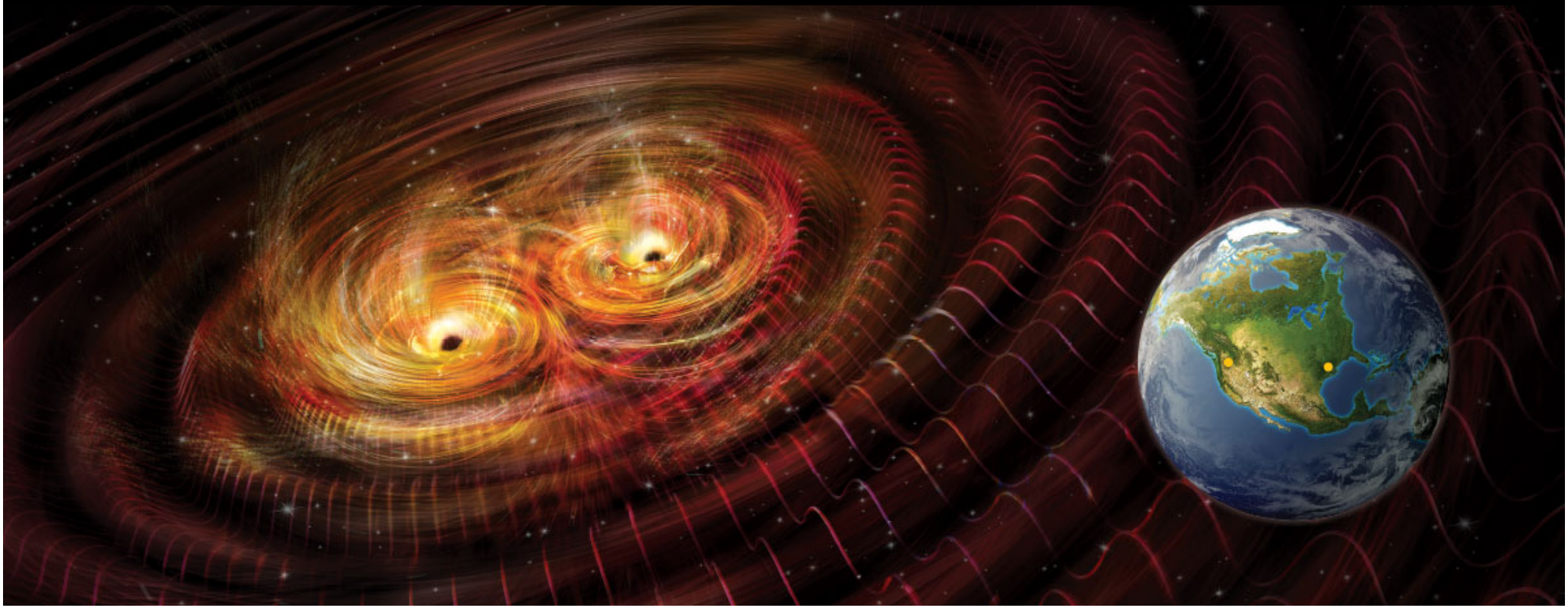
Gravitational Lensing and Einstein's Ring

Spacetime: Gravitational Lensing



Gravitational Waves

- Predicted by Einstein's theory of general relativity.
- Carry gravitational energy away from a system the same way electromagnetic waves carry away energy by radiation.
- First confirmed detection in February 2016.



Gravitational Lensing

question for you

Photons are massless particles... so why do they curve their paths around massive stars?

A. Because photons feel gravitational force.
B. Because they have energy.
C. Because the spacetime around stars is curved.
D. All of the above.
E. I have no idea.

What did we learn in Chapter 5?

- Velocity is speed with a direction.
- Weight is the gravitational force on an object, and depends on the local acceleration of gravity.
- Conservation laws in physics and astronomy:
  - Conservation of energy: energy cannot be created or destroyed, only transformed.
  - Conservation of momentum: momentum of a system is constant unless a force acts on it.
  - Conservation of angular momentum: angular momentum of a system is constant unless a torque acts on it.

What did we learn in Chapter 5?

- Newton's Universal Law of Gravitation showed that planets orbit the Sun because of gravity, and that the laws of physics are the same everywhere in the Universe.
- Newton's three laws of motion:
  - Law of inertia: an object at rest will remain at rest and an object in uniform motion will continue with uniform motion unless acted upon by an external force.
  - Second law: Force = mass times acceleration.
  - Third law: for every action there's an equal and opposite reaction.

What did we learn in Chapter 5?

- Speed of light is constant and independent of reference frames.
- Equivalence principle: the effects of gravity and acceleration are equivalent.
- Massive objects warp spacetime.
- Gravitational lensing occurs when light from a distant object is warped (bent) by a nearby massive object.

What did we learn in Chapter 5?

- Astronomers commonly use the Kelvin temperature scale.
- Types of energy:
  - Kinetic: energy of motion
  - Gravitational Potential: the stored energy due to being at a given height above a large body.
  - Thermal: energy of motion of atoms inside a substance
  - Radiative: energy carried by light
- Escape velocity is speed needed to escape from the gravity of an object.