Motion, Energy & Gravity

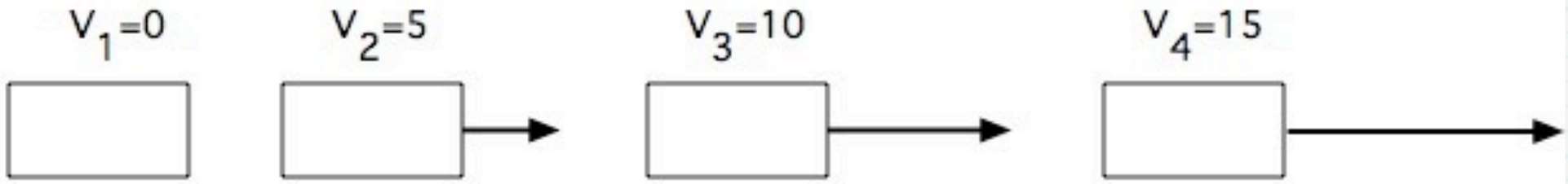
Chapter 4


energy
circular orbit
field
light
opposite
planet
force
time
orbit
Gravity
Entropy
Escape Velocity
motion
Motion
Conservation of Energy
orbital
Thermal Energy
hyperbolae
elliptical
Moon
Conservation of Angular Momentum
distance
object
parabolic orbit
Temperature
attraction
matter
Mass
period
Tides
objects
Change
reaction
gain
Potential
radiative
parabolae
rotating
Energy
elliptic orbit
weight
Momentum
orbit
transfer
mc2
Kinetic Energy
kinetic
mass
freefall
bodies
Laws
inertia
space
Force
ellipses
hyperbolic orbit
disorder
Orbital Energy
spacetime
circular
direction
masses
Earth
velocity
paths
gravity
speed
Sun
gravitational
acceleration
orbiting
exchange
proportional
Newton
momentum
Kepler's
Astronomy
hyperbolic
potential
Energy
orbits
strength
Gravitational
Conservation
laws
Einstein

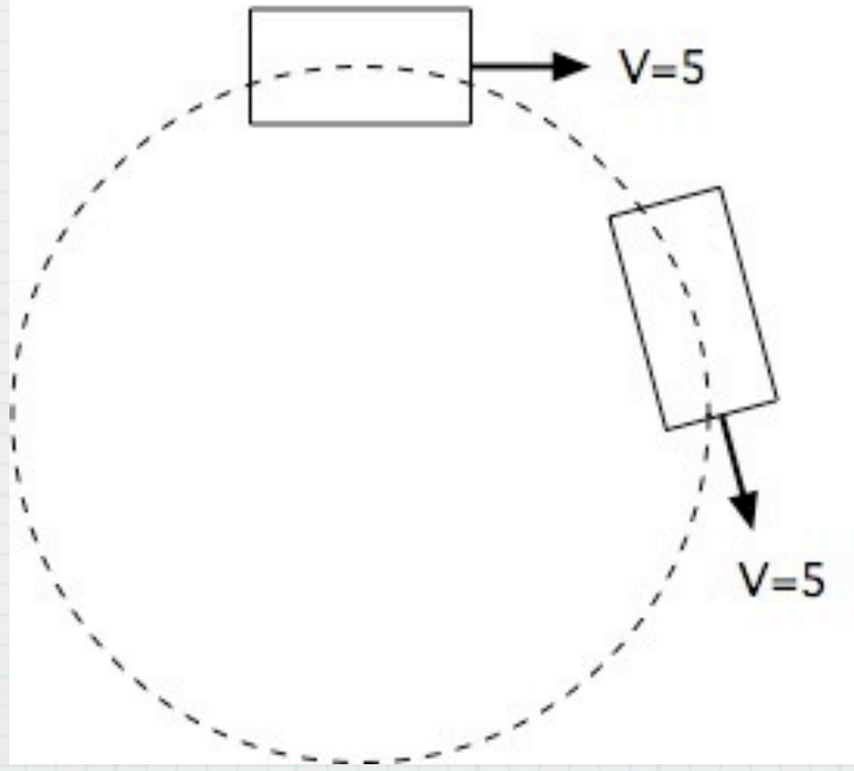
Understanding Motion

* What is motion?
  * something moving!
  * it moves with a velocity
  * it may also have an acceleration
* Velocity describes both speed and direction (it is a 2-dimensional quantity)
* An acceleration is a change in either speed or direction or both

All velocities are in meters per second



The box is accelerating with a rate of 5 meters per second per second



While this box is going around in a circle with exactly the same speed, it is nevertheless accelerating(!) because it is changing direction.

Gravity

* Gravity is a special kind of acceleration
* On Earth, it makes things fall
* In space, objects get attracted toward one another
* These two are the same thing, but it took millennia to understand that

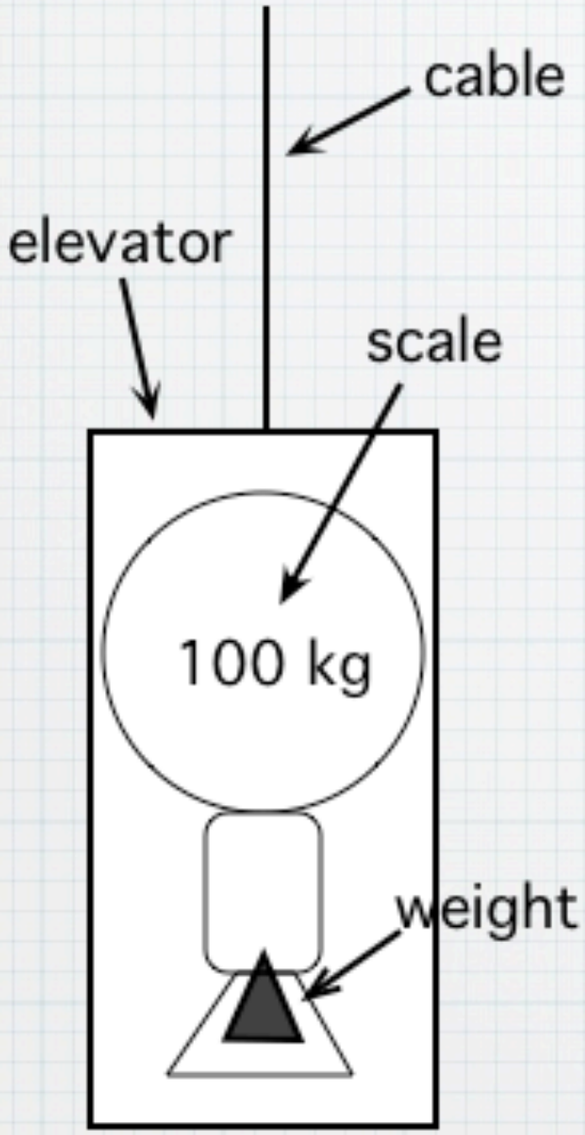
Old Concepts

* Some concepts you may have forgotten:
  * Mass = amount of matter in an object
  * Momentum = mass x velocity
  * Mass ≠ weight
  * Weight = mass x acceleration = a force

New Concepts

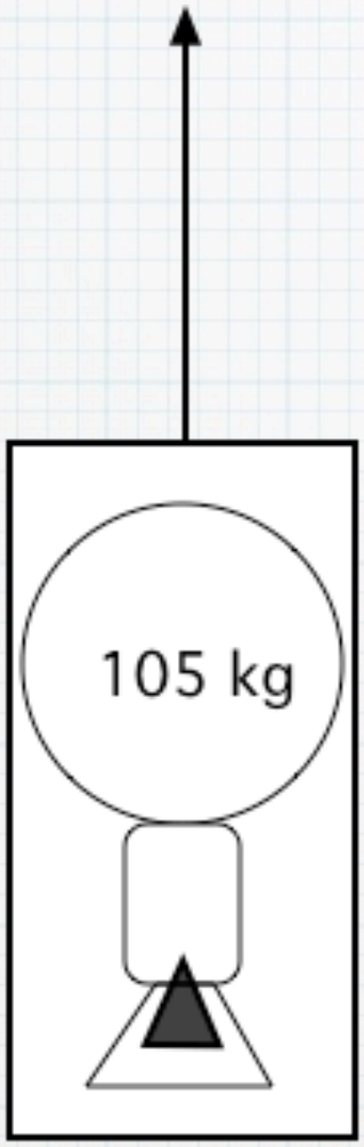
* And brand new ones:
  * space-time is the fabric of our Universe
  * everything (matter & energy) is embedded in this fabric
  * mass can be interpreted as a friction with the fabric of space-time

A weight is a mass in an acceleration field



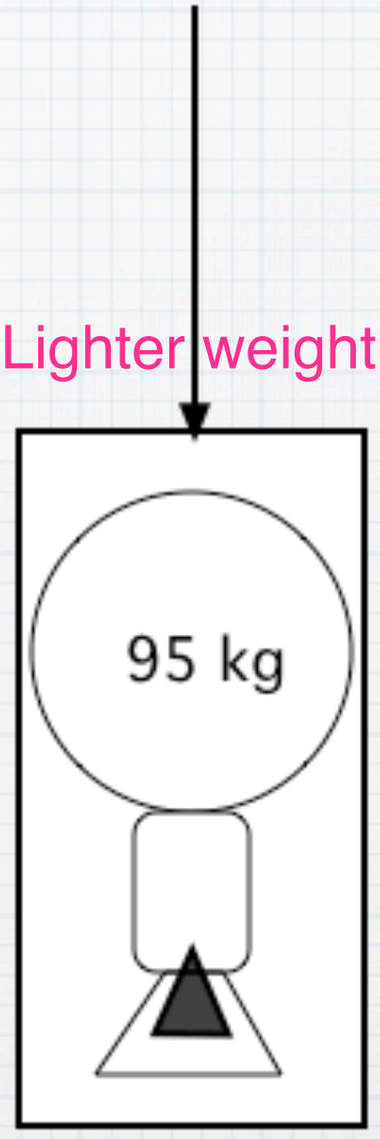
At rest, or at constant velocity

Normal weight

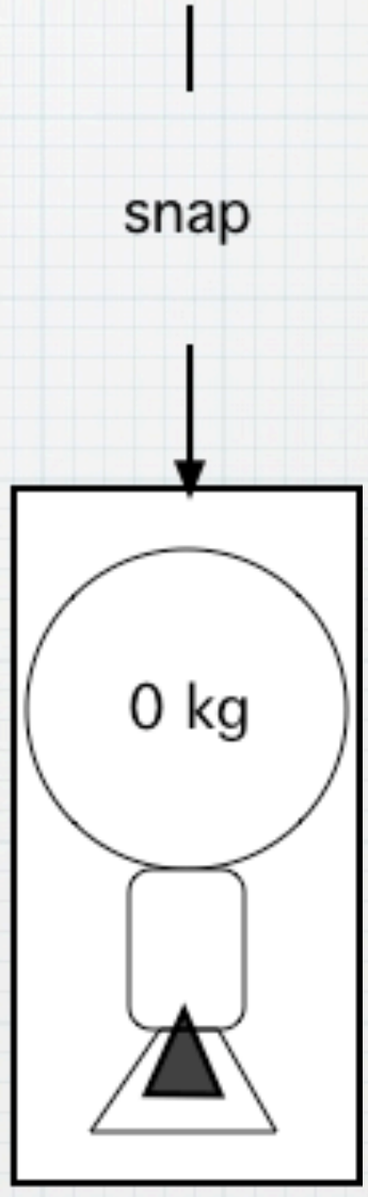


While the elevator starts moving up

Heavier weight



While the elevators starts moving down



Freefall

Weightless

Mass & Weight

* How is mass different from weight?
* Mass is a quantity of matter
* Weight is due to a force acting on a mass
* Weightlessness is achieved when a mass is in freefall (or when there is no local acceleration)
* "freefall" is a motion due to no acceleration beside that provided by gravity

Question

On the Moon, the force of gravity is 1/6th that of Earth. If you were now on the Moon, what statement applies?

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

Question

On the Moon, the force of gravity is 1/6th that of Earth. If you were now on the Moon, what statement applies?

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

Snapshot

* How do we describe motion?
* speed = distance / time
* velocity is speed and direction
* acceleration is a velocity change
* momentum = mass x velocity
* force is a momentum change (usually due to an acceleration)

Snapshot

* How is mass different from weight?
* Mass is a quantity of matter
* Weight is a force acting on mass
* Weightlessness is achieved when a mass is in freefall (or when there is no local acceleration)
* "freefall" is a motion due to no acceleration beside that provided by gravity

Newton
(1642 - 1727)

* English
* Realized what gravity was:
  * what made an apple fall from a tree also made the Moon orbit the Earth!
* Gravity operated on Earth and in the heavens in the exact same way

More on Newton

* Formulated the laws of motion & gravity
* Father of modern calculus
* Lots of work in the field of Optics
  * Demonstrated that white light can be decomposed in a spectrum
  * Invented the reflecting telescope
  * ...

Newton's Three Laws of Motion

I. Law of Inertia, momentum = m · v is conserved in an isolated system

II. Law of Resultant Force , force = sum of all forces acting on one object = change of momentum over time

III. Law of Reciprocal Actions: for any force, there is always an equal and opposite reaction force

* Note: Newton does not say WHY they work

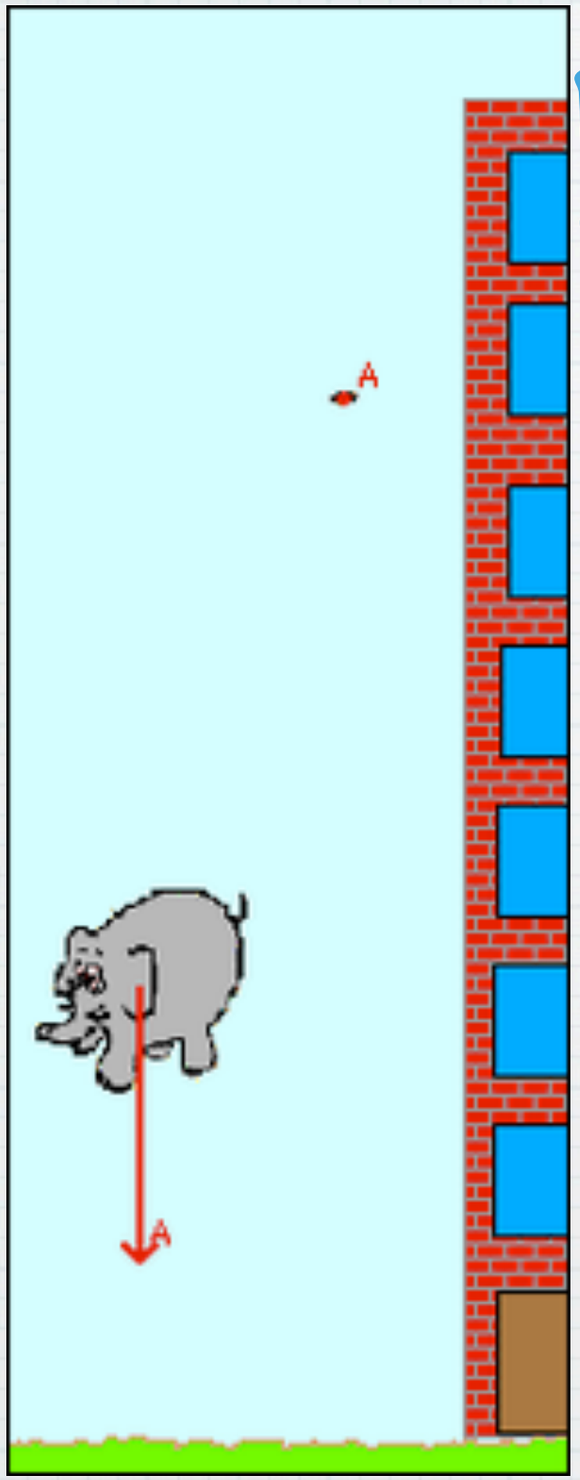
Law 1: Law of Inertia

a. An object that is not moving will not move until a net force acts upon it (obvious...)

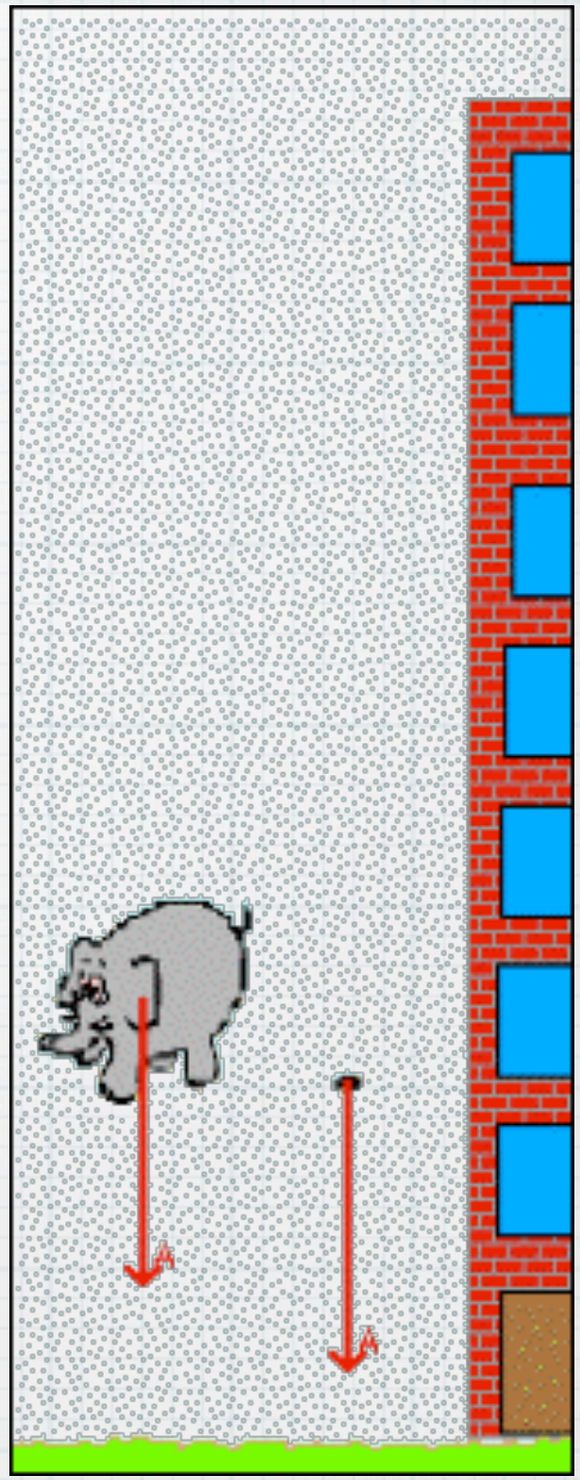
b. An object that is in motion will not change velocity (accelerate) until a net force acts upon it (non-obvious except for celestial bodies)

Law 2: Law of Resultant Force

The resultant force acting on a body is the sum of all forces acting on that body



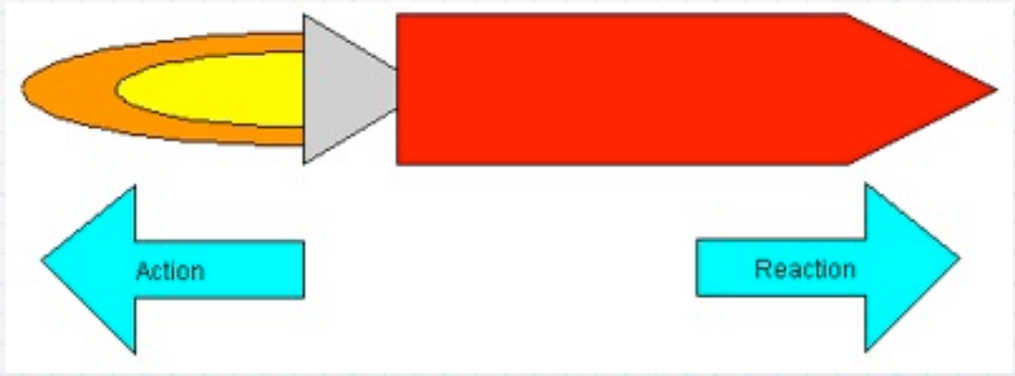
air



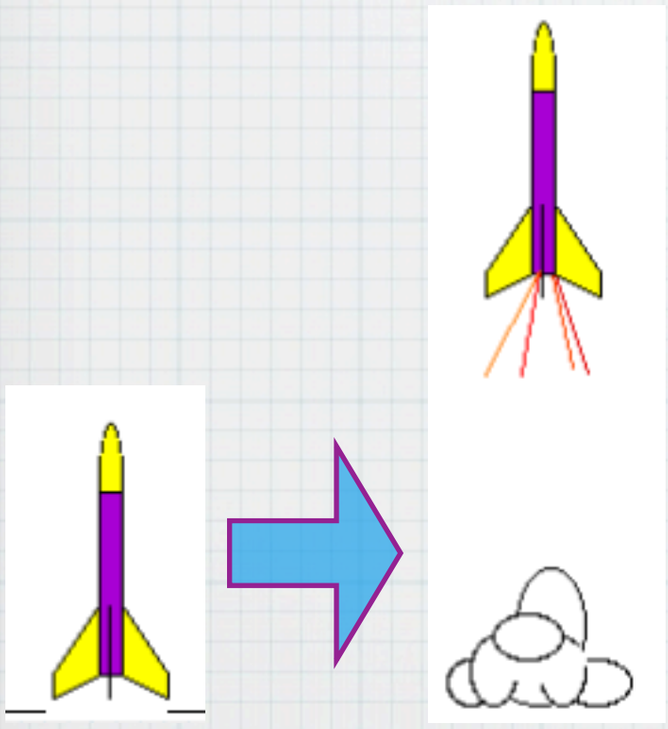
vacuum

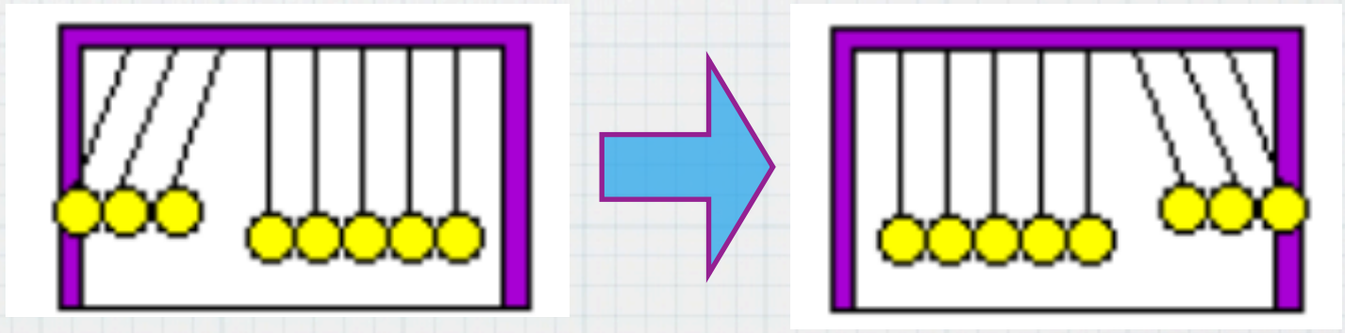
no elephants were harmed in the making of this slide

Law 3: Law of Reciprocal Actions



For every action, there is an equal and opposite reaction





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

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

Questions

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 or F]

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 or F]

3) The change of velocity of the car is the same as the change of velocity of the truck [T or F]

Questions

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 [True]

2) The momentum transferred from the truck to the car is equal and opposite to the momentum transferred from the car to the truck [True]

3) The change of velocity of the car is the same as the change of velocity of the truck [False]

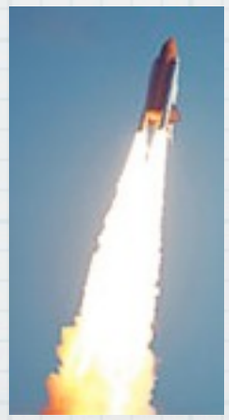
Snapshot

What are Newton's Three Laws of Motion?

1) Objects move at constant velocity if no net force is acting

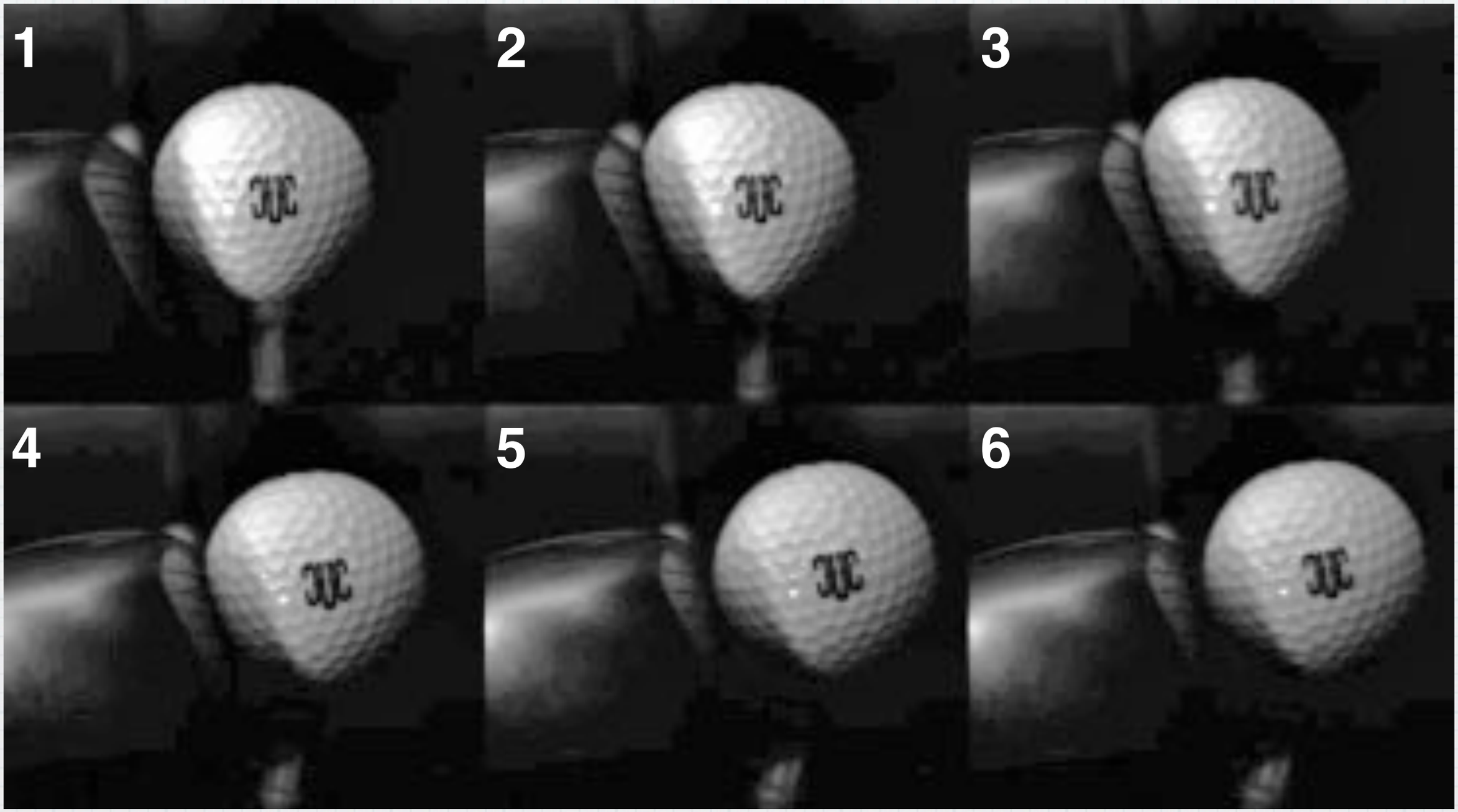
2) Force = change of (mass x velocity)

3) For every force there is an equal and opposite reaction force

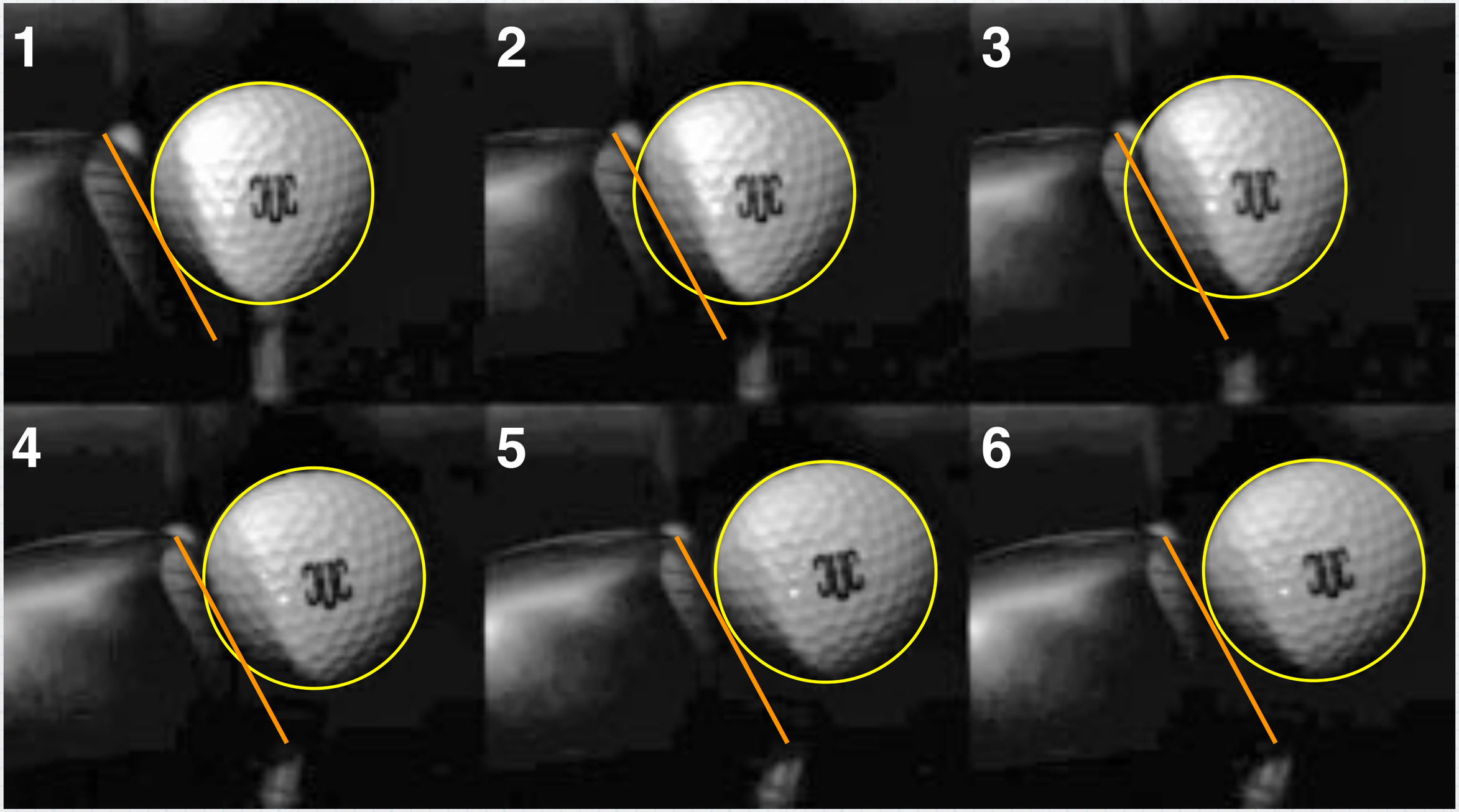


Why does a golf ball move away after being hit?

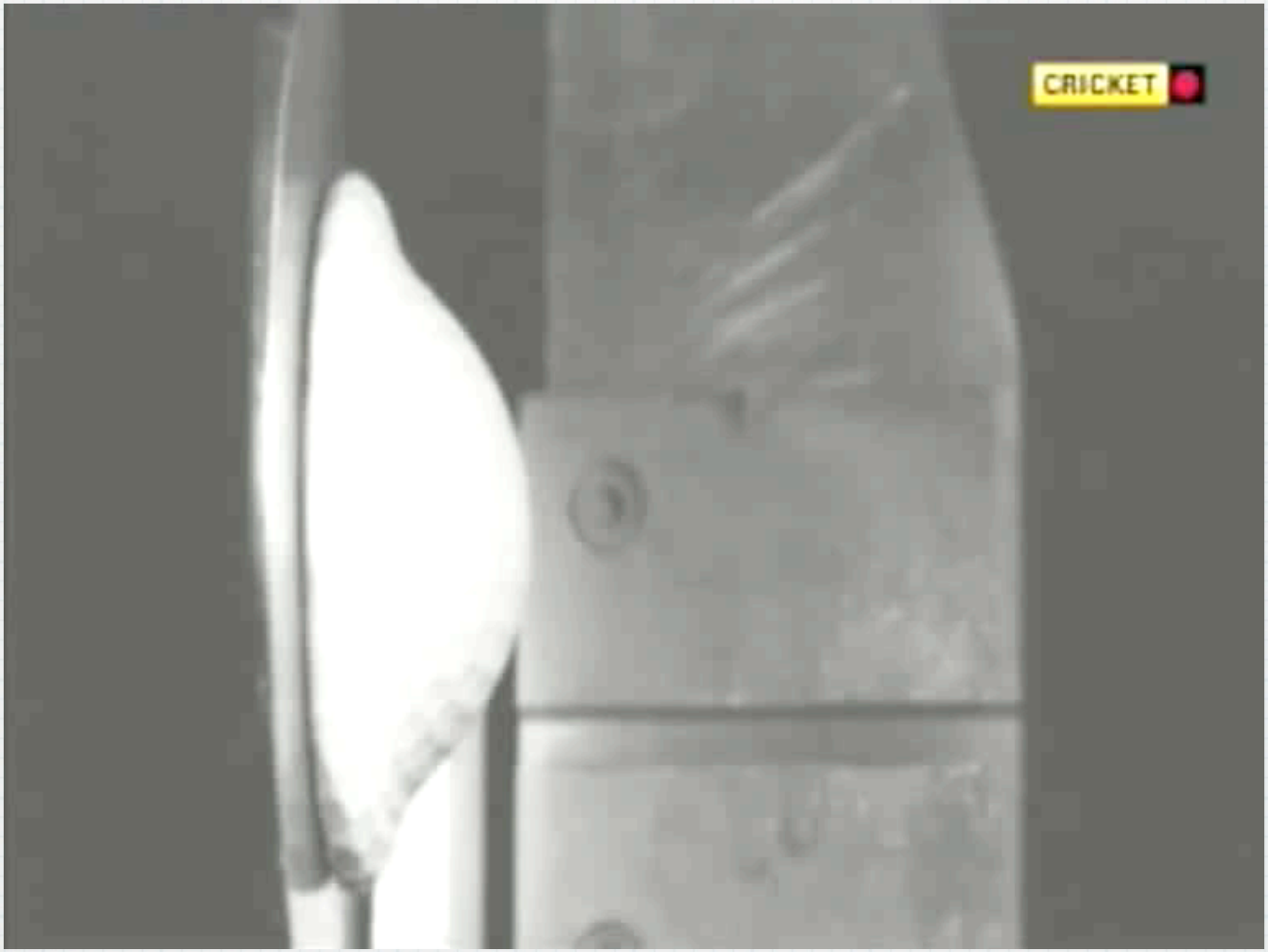
Hint: it is not being pushed...



Why does a golf ball move away after being hit?
Hint: it is not being pushed...



150 mph golf ball hitting a wall - 70,000 fps



solid or fluid?

The Force of Gravity

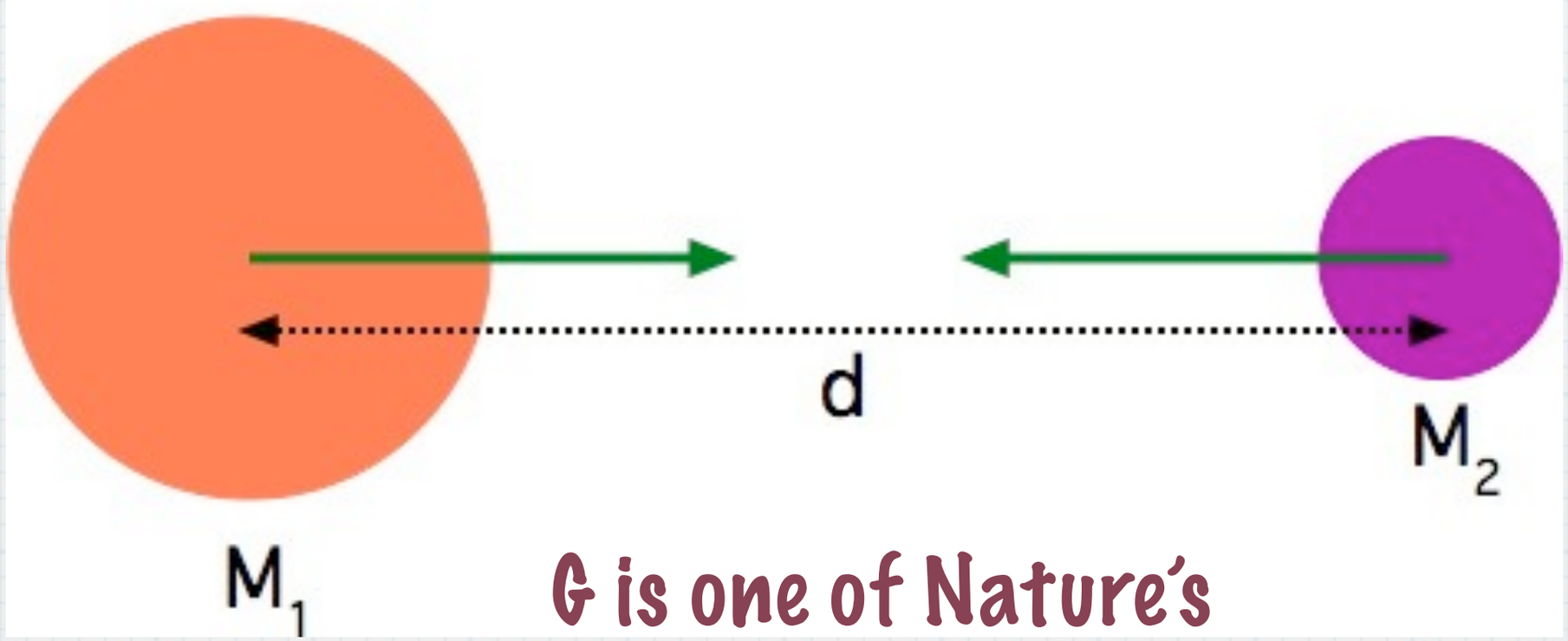
* The most important force in Astronomy
* Every mass attracts every other mass
* Its range is infinite

* The strength of attraction between two objects is directly proportional to the product of the two masses
* The strength of attraction between two objects is inversely proportional to the square of their distance

Force of Gravity between two bodies

$$F = G \frac{M_1 M_2}{d^2}$$

G = universal gravitational constant



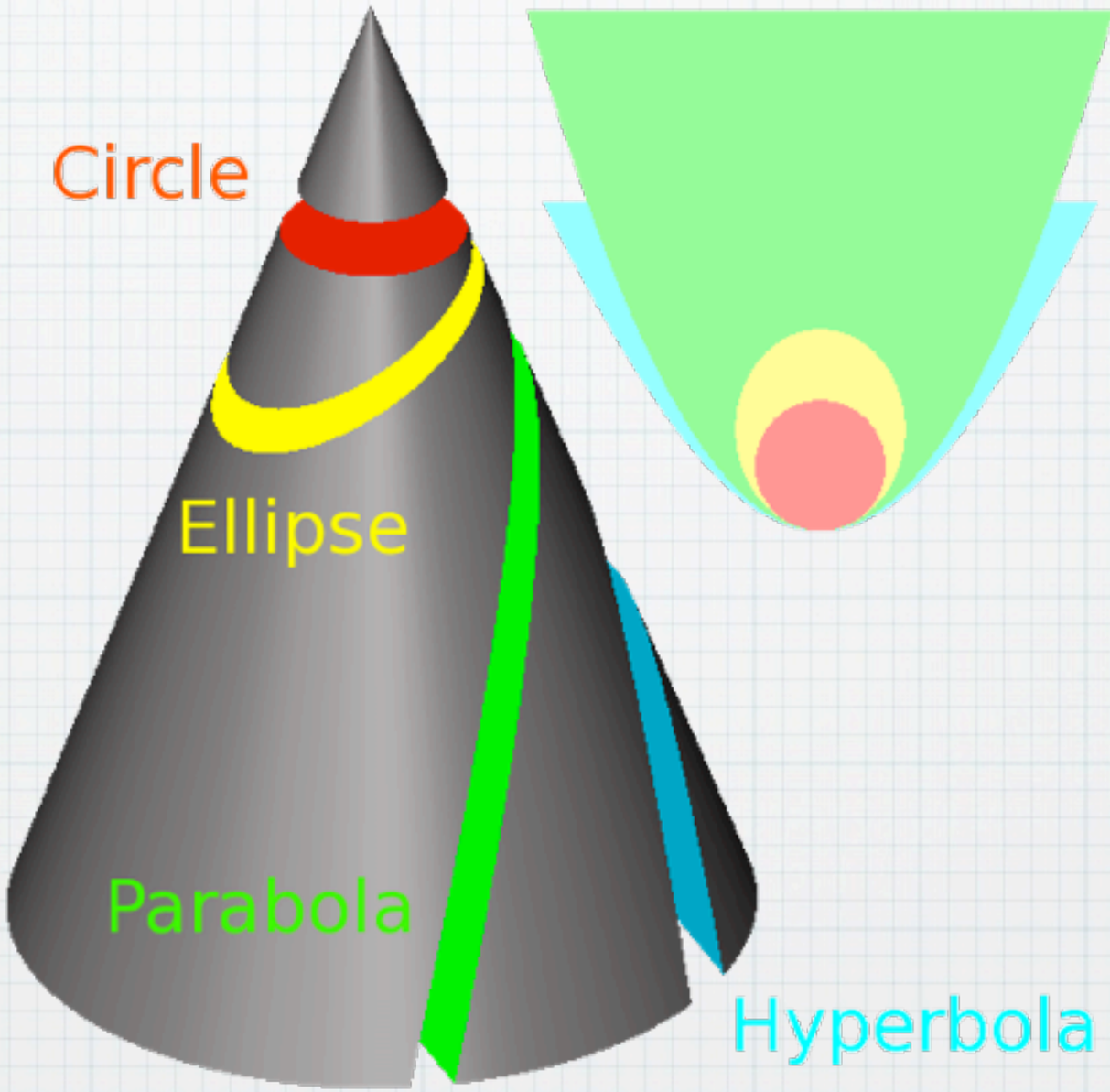
G is one of Nature's fundamental constants
(there are 26 that we know of)

Kepler, Newton & Einstein

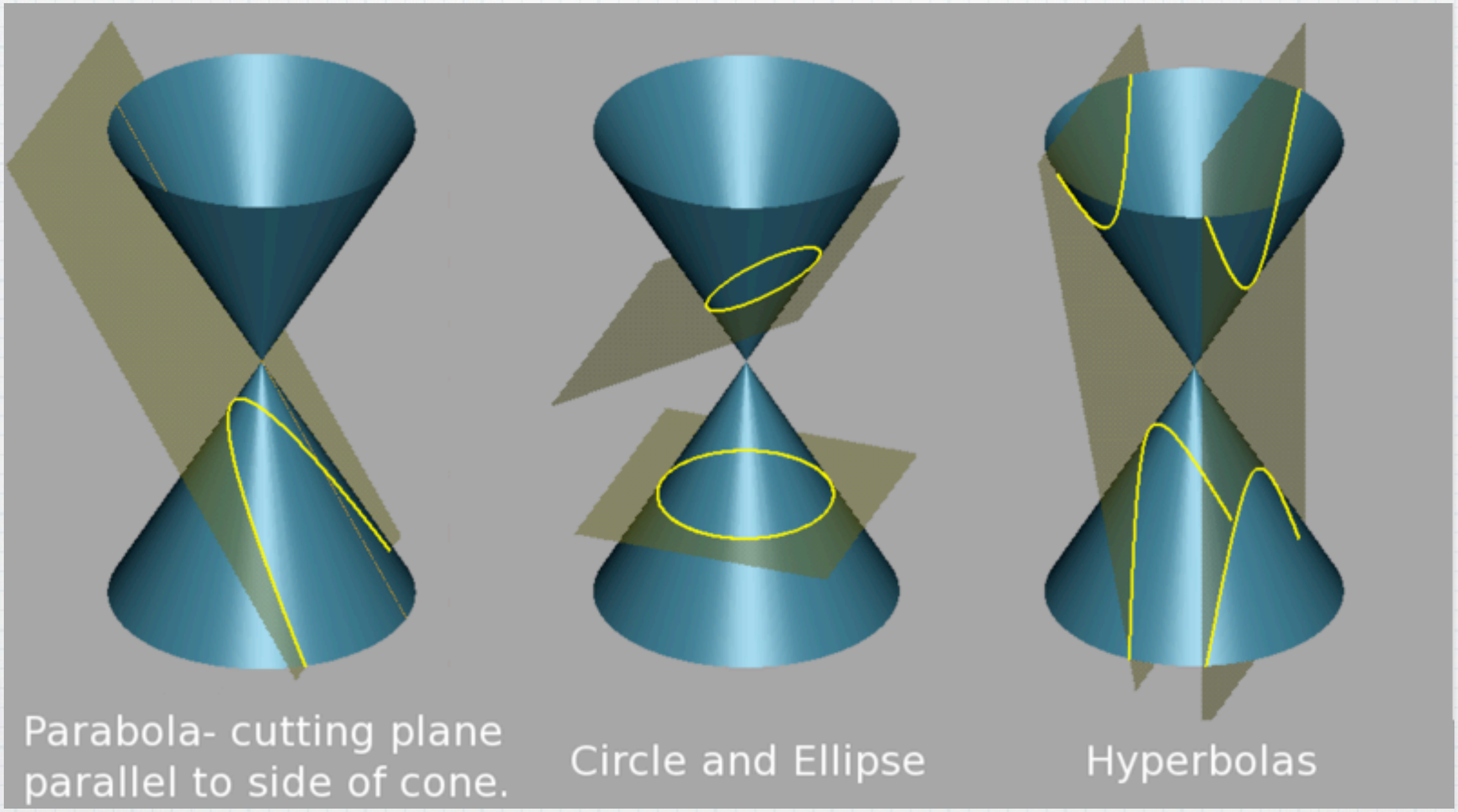
* People knew Kepler's laws were correct but they did not why (empirical laws)
* Newton solved this with his three laws of motion (expressed as equations)
* Kepler's first two laws were generalized by Newton to apply to all orbiting objects, not just planets orbiting the Sun
* However, Newton did not explain how Gravity works. Einstein did that later

* Newton found that there are more orbital paths than just ellipses: introducing: parabolae and hyperbolae
* Bound (closed) orbital paths are ellipses
* Unbound (open) orbital paths are hyperbolae and parabolae
* a parabola is a "special" orbit located between an elliptical orbit and a hyperbolic orbit
* All these orbital paths are said to be conical

Conical Paths

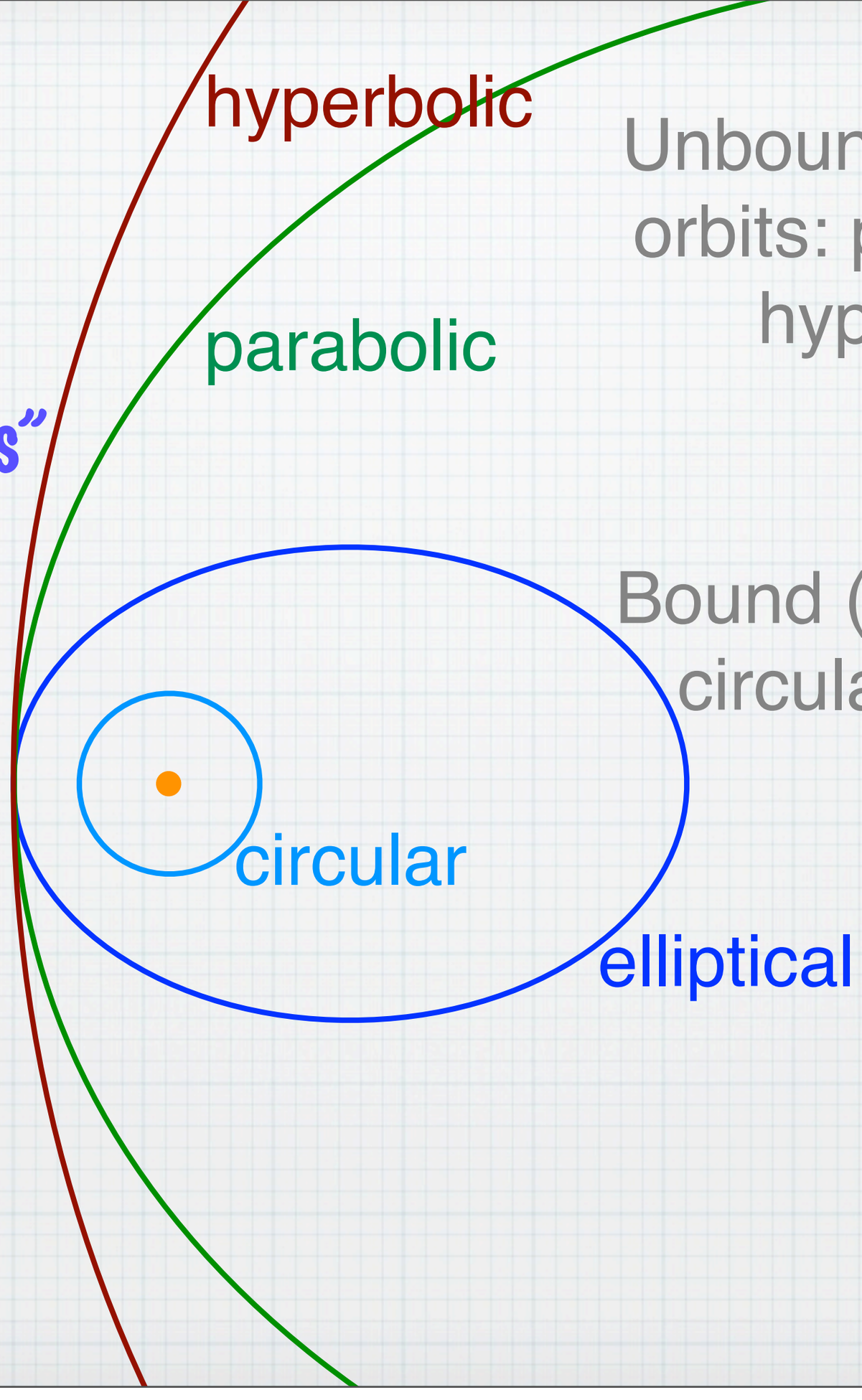


More on conical paths



The different orbital paths

Newton and "classical physics"

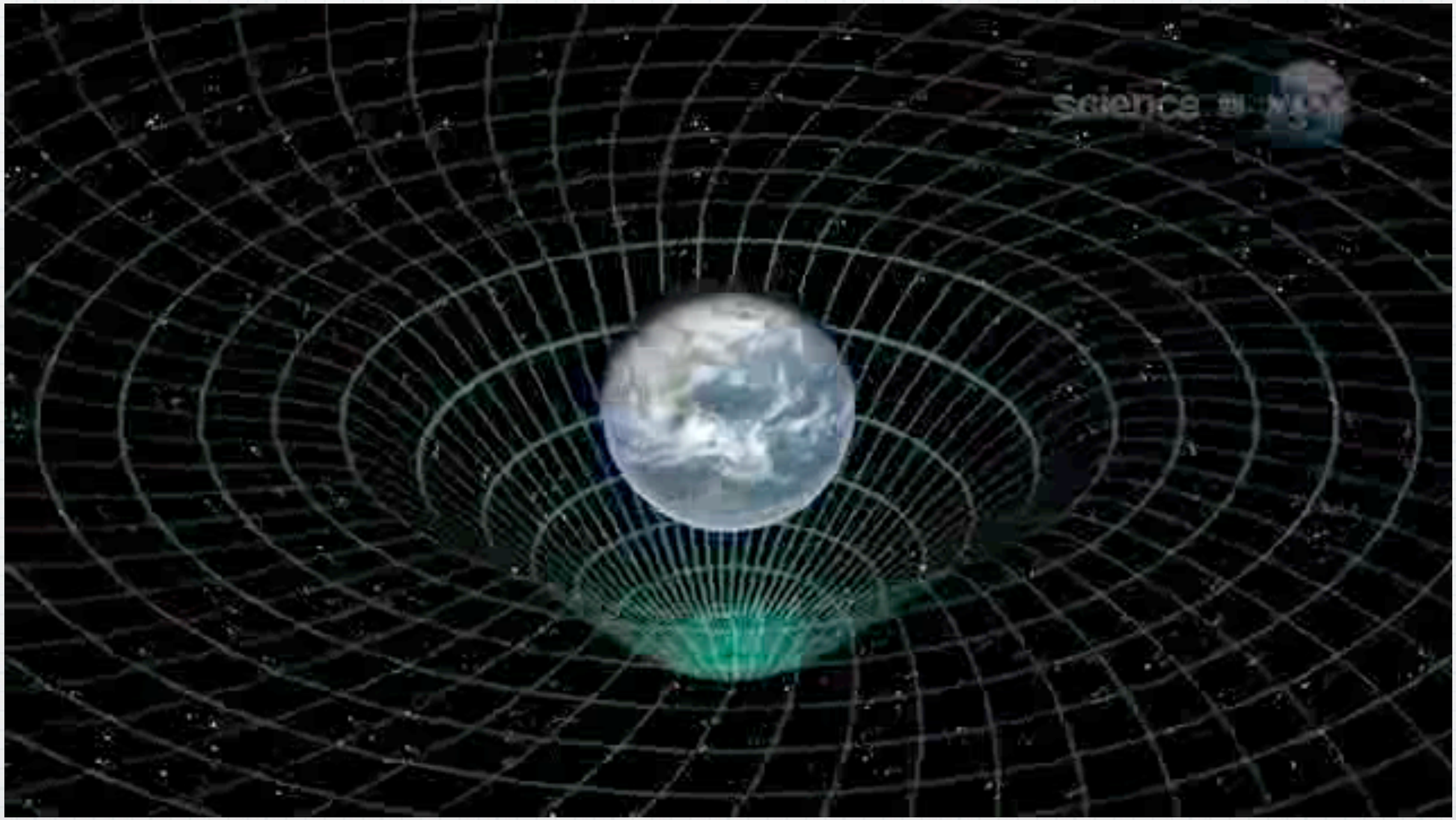


Unbound (opened) orbits: parabolic & hyperbolic

Bound (closed) orbits: circular & elliptical

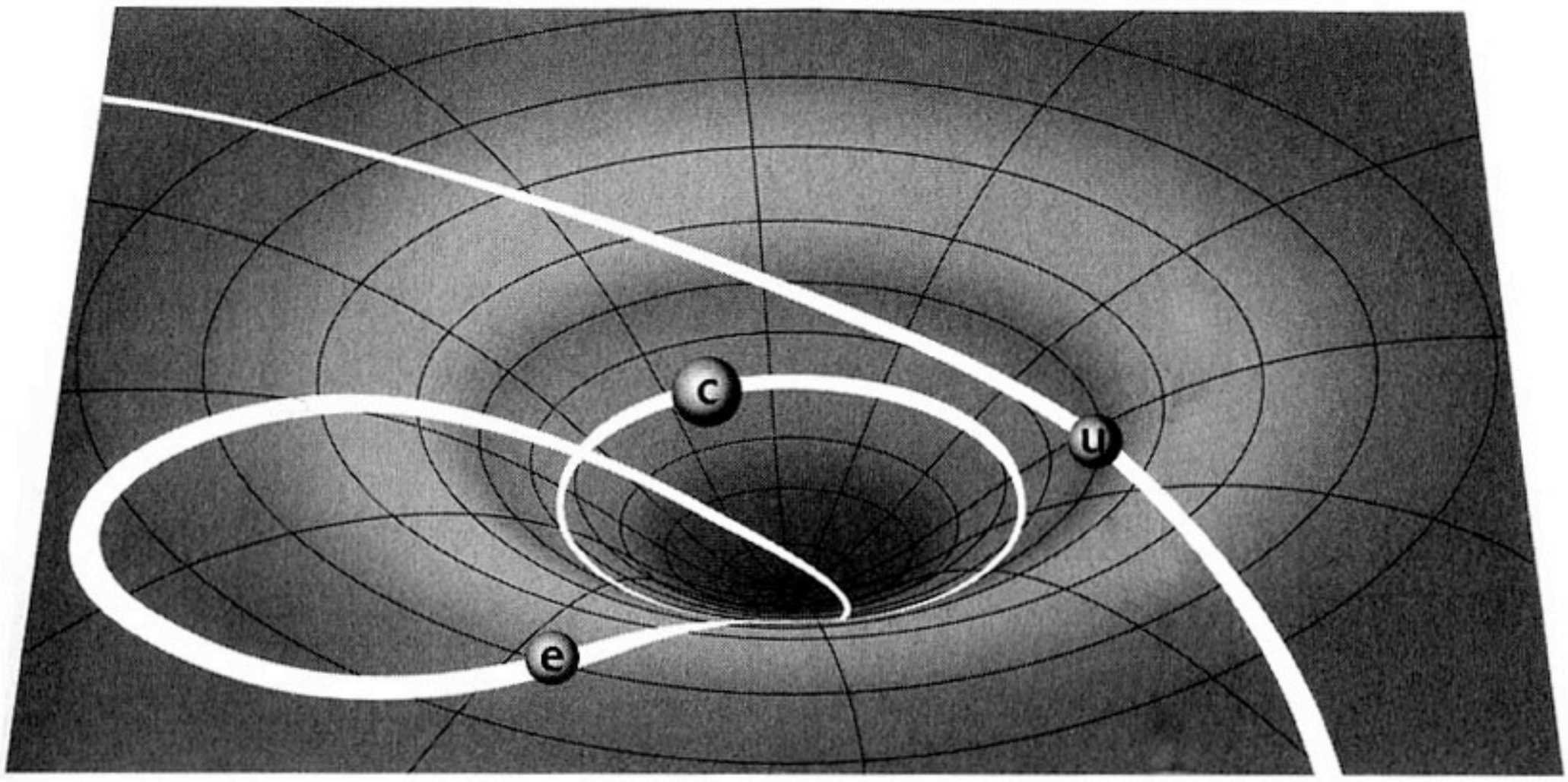
Einstein

What gravity really is: The fabric of space-time is distorted by the presence of mass & energy



The different orbital paths

Einstein and "relativistic physics"



Instead of action at a distance, general relativity explains gravity as curvature of spacetime. By the trampoline analogy, masses respond to gravity much as marbles respond to a depression in the trampoline. If there were no friction between the marble and the trampoline, a marble "orbiting" about the bottom of the depression would never stop, just as planets never stop orbiting the Sun.

Warped space-time near the Sun

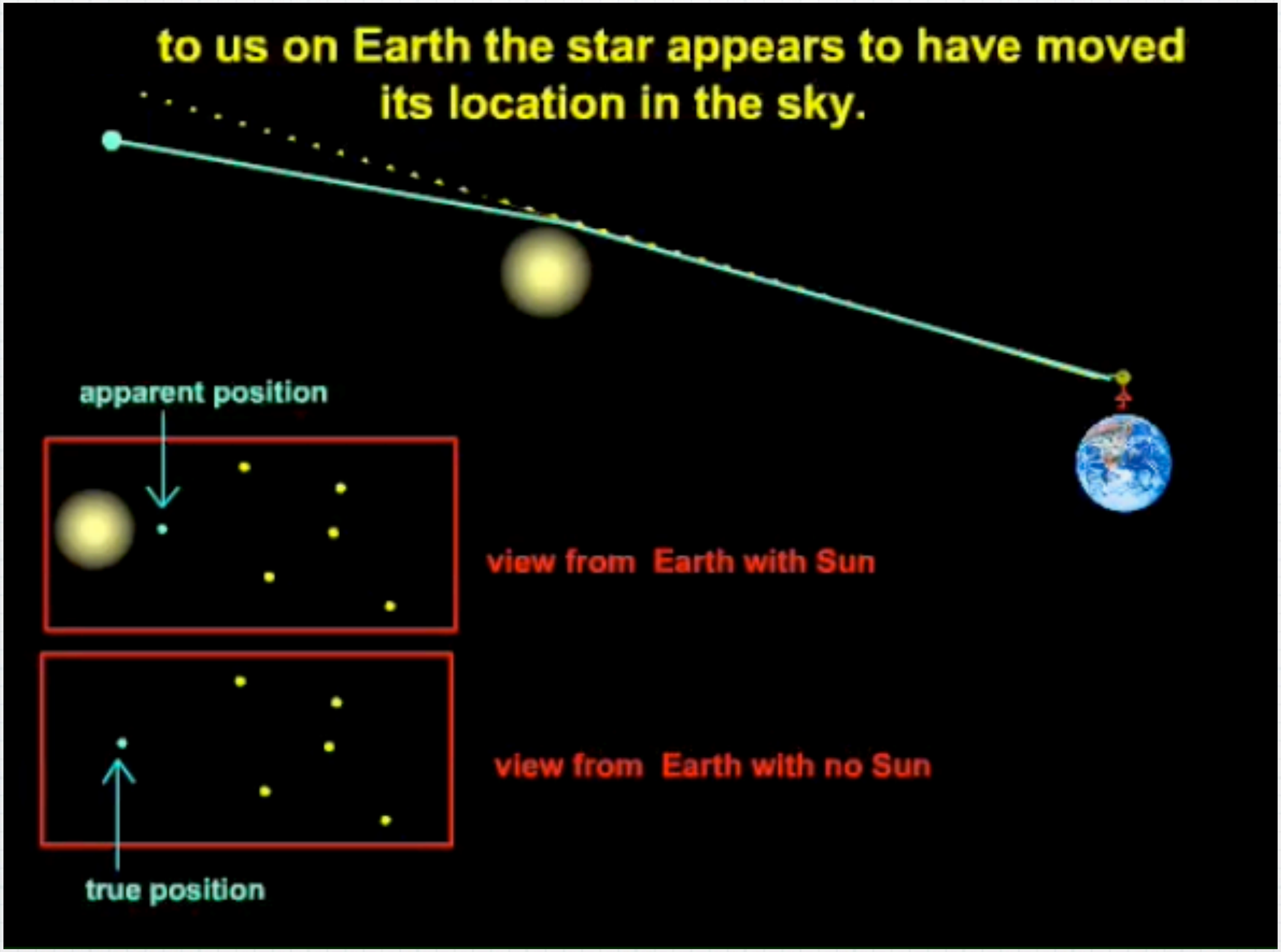
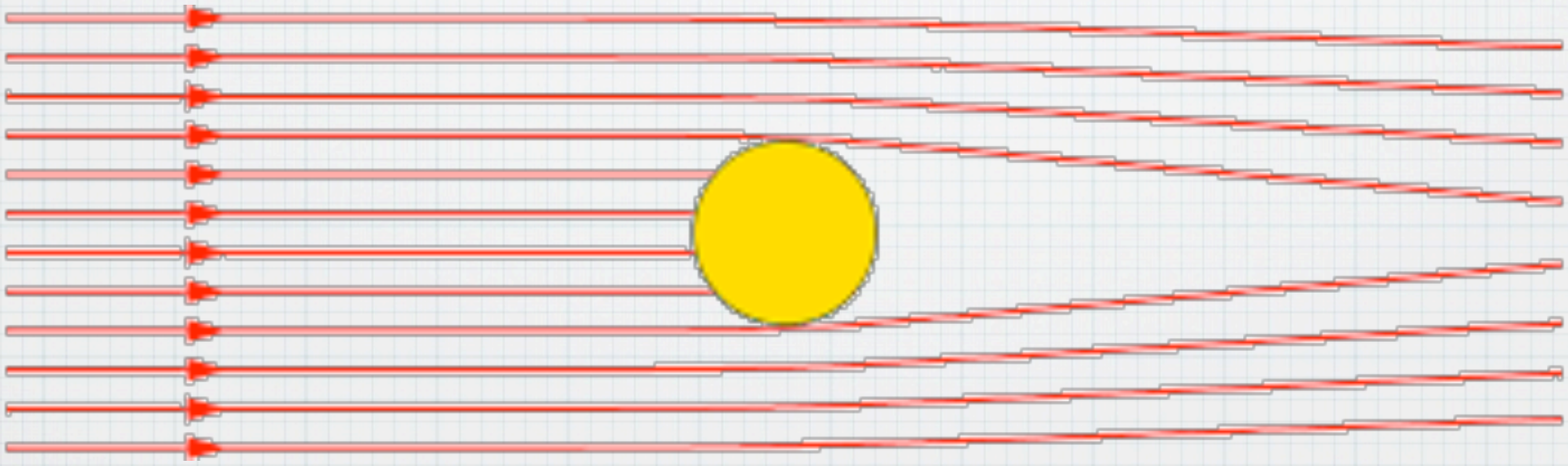


Image from Dr. Cecilia Barnbaum

The Light Side of Gravity

Light is deflected by gravity

The deflection is due to warped space-time



General Relativity explained simply

(by John Wheeler)

1. Matter/energy tells spacetime how to curve while

2. spacetime tells matter/energy how to move

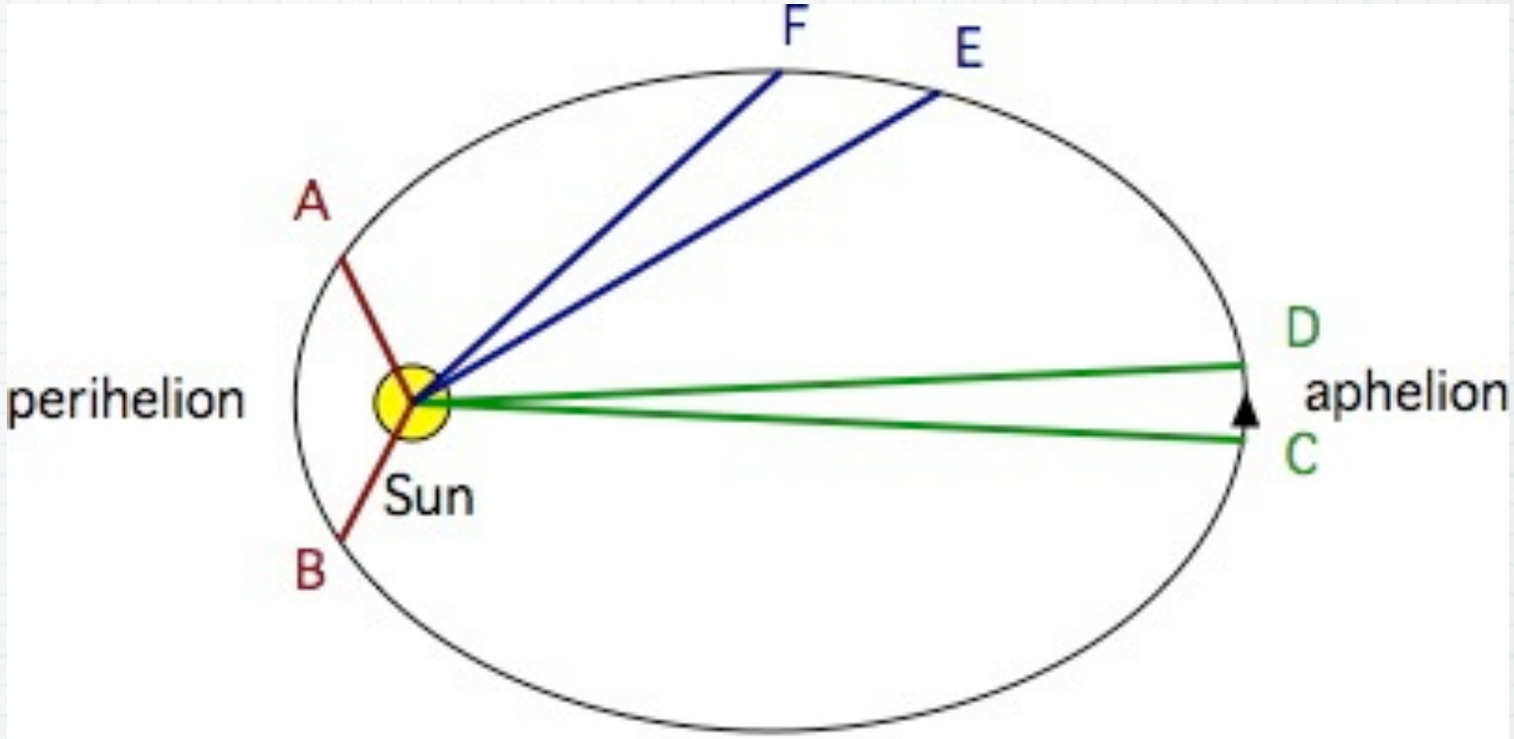
However, Einstein's equations **do not** explain **why** the presence of matter and energy curves spacetime. No one knows this yet as we do not know what makes spacetime

Conservation Laws in Astronomy

Newton's Laws of Motion can be expressed in terms of Conservation Laws

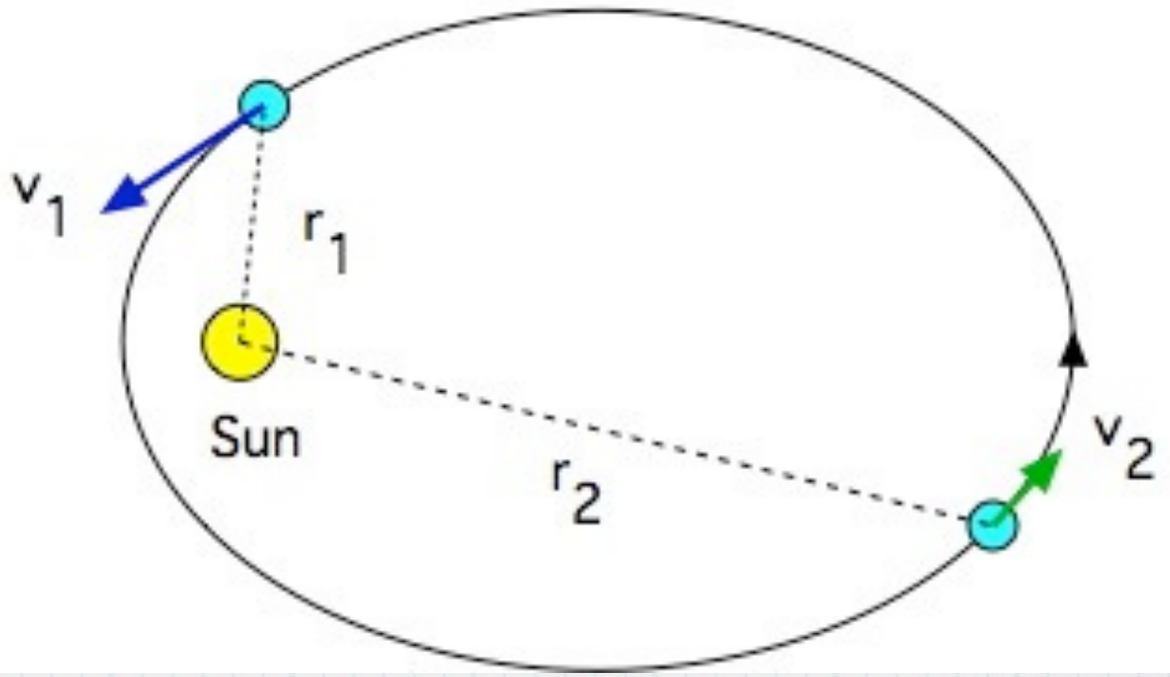
1. The Conservation of Momentum (m • v)
2. The Conservation of Angular Momentum (m • v • r)
3. The Conservation of Energy

Kepler's second law: a planet sweeps out equal areas in equal times



Conservation of angular momentum

m x v x r



Greater distance (r) means smaller velocity (v)

The Conservation of Angular Momentum explains why

* The Earth will keep on rotating on itself at the same rate
  * (although there is a Earth-Moon tidal exchange)
* The Earth will keep on revolving around the Sun with the same period
* This, of course, applies to all orbital bodies

Snapshot

* What keeps a planet rotating and orbiting its star?
* The law of conservation of angular momentum

Energy

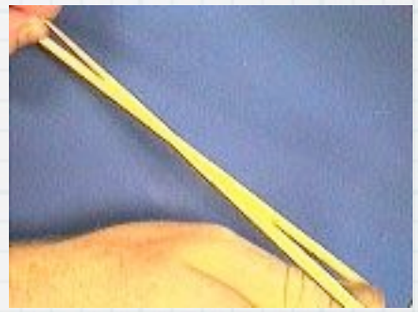
* Energy can take many different forms and representations
* Three basic categories of Energy

1. motion (kinetic)
2. stored (potential)
3. light (radiative)

+ many subcategories: gravity, radiation, thermal, chemical, electrical, nuclear, ...

Potential Energy

* Potential energy is "stored" energy
* Examples:
  * a stretched elastic band has potential energy which will eventually be released as kinetic energy

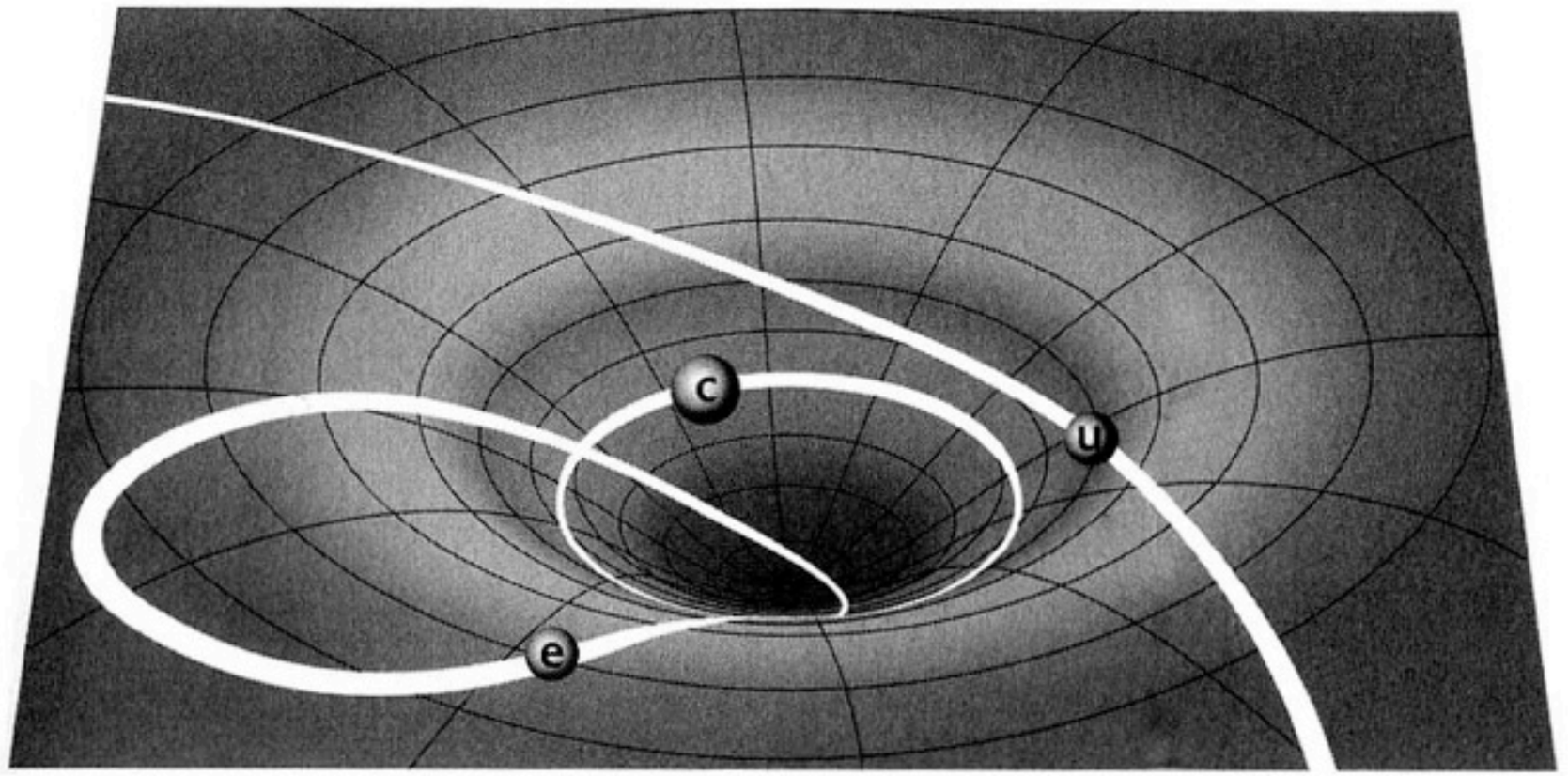


  * a yoyo constantly transfers its energy from potential to kinetic and back

Potential Energy

* Two are important in Astronomy
* Gravitational Potential Energy is the energy an object possesses because of its position in a gravitational field
* Mass-Energy Potential Energy is defined as $E = mc^2$, as discovered by Einstein, is the energy an object of a certain mass, and at rest, always possesses

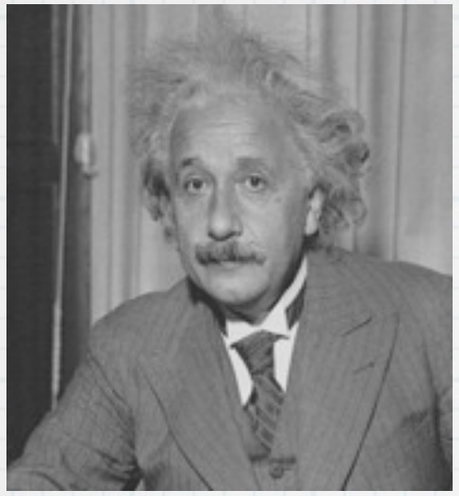
Gravitational Potential Energy



G.P.E. is easier to visualize with a gravitational field being represented as the curvature of spacetime (Einstein's theory)

Mass-Energy Potential Energy

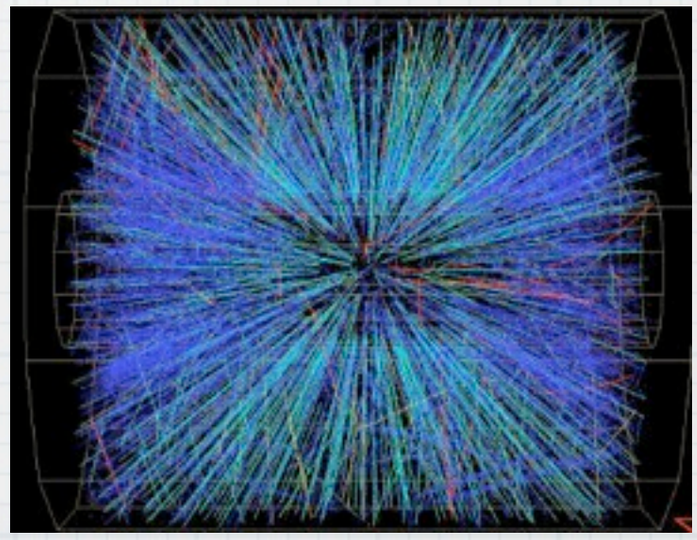
$E = m c^2$



Mass - Energy

$$m = \frac{E}{c^2}$$

* Mass itself is a form of potential energy
* It is a two-way street:
* Highly concentrated energy can spontaneously turn into matter too



Energy Laws
1) Conservation of Energy

* First Law: Conservation of Energy
  * We cannot create nor destroy energy
  * Energy gets transformed from one type to another (photosynthesis: light to chemical, muscles: chemical to mechanical, nervous system: chemical to electrical, ...)

Conservation Energy Principle

* Energy does not appear from and does not disappear out of nowhere
* Objects can only gain or lose energy because they interact with others
* Interaction means: exchange or convert

Energy Laws
2) Entropy

* **Second Law**: is an expression of the universal principle of energy decay observable in Nature
* It is measured and expressed in terms of a property called entropy
* An engine, for instance, converts chemical energy into mechanical energy. The decay is heat. The less decay, the more efficient the engine is, as the heat is considered a loss since it is not used into the work of the engine

Energy Laws
2) Entropy...

* The second law says that in a closed (isolated) system, concentrated energy disperses over time, and consequently less and less concentrated energy is available to do useful work

* Low entropy system -> highly ordered system

* High entropy system -> low order, chaotic system

Energy Laws
2) Entropy...

* Entropy can be visualized with these concepts:
  * Drop an unbound 20-page document onto the floor. What are your chances of picking up all the sheets in the right order without looking at them?
  * The fact that a cooked meal can never be uncooked demonstrates that entropy is a one-way street

The two energy laws put together

1. According to the first energy law, we will never run out of energy

2. According to the second energy law, we can run out of "useful" (high-grade) energy

➡ This means that energy gets converted into a lower potential type of energy which gets harder and harder to tap from (related to the expansion of the Universe and the direction of time)

Entropy Summary

* As time goes by, the Universe moves from a low entropy state to a higher one (entropy increase)
* Which is the same as stating that it evolves from an ordered, high energy density system to an unordered, low energy density one

More on Entropy

* Via Internet
  * http://www.ted.com/talks/sean_carroll_on_the_arrow_of_time_part_1.html
  * http://www.ted.com/talks/sean_carroll_on_the_arrow_of_time_part_2.html
* Book
  * From Eternity to Here - The Quest for the Ultimate Theory of Time, by Sean Carroll

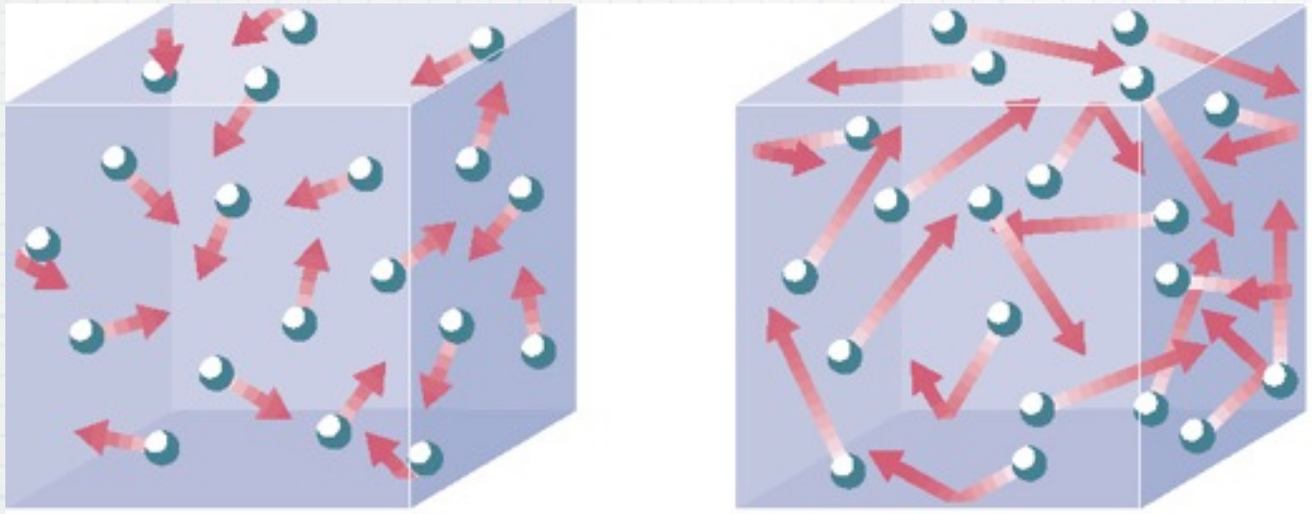
Thermal Energy

* Thermal energy is the collective kinetic energy of the many particles in a substance

* Temperature is the average kinetic energy of the many particles in a substance

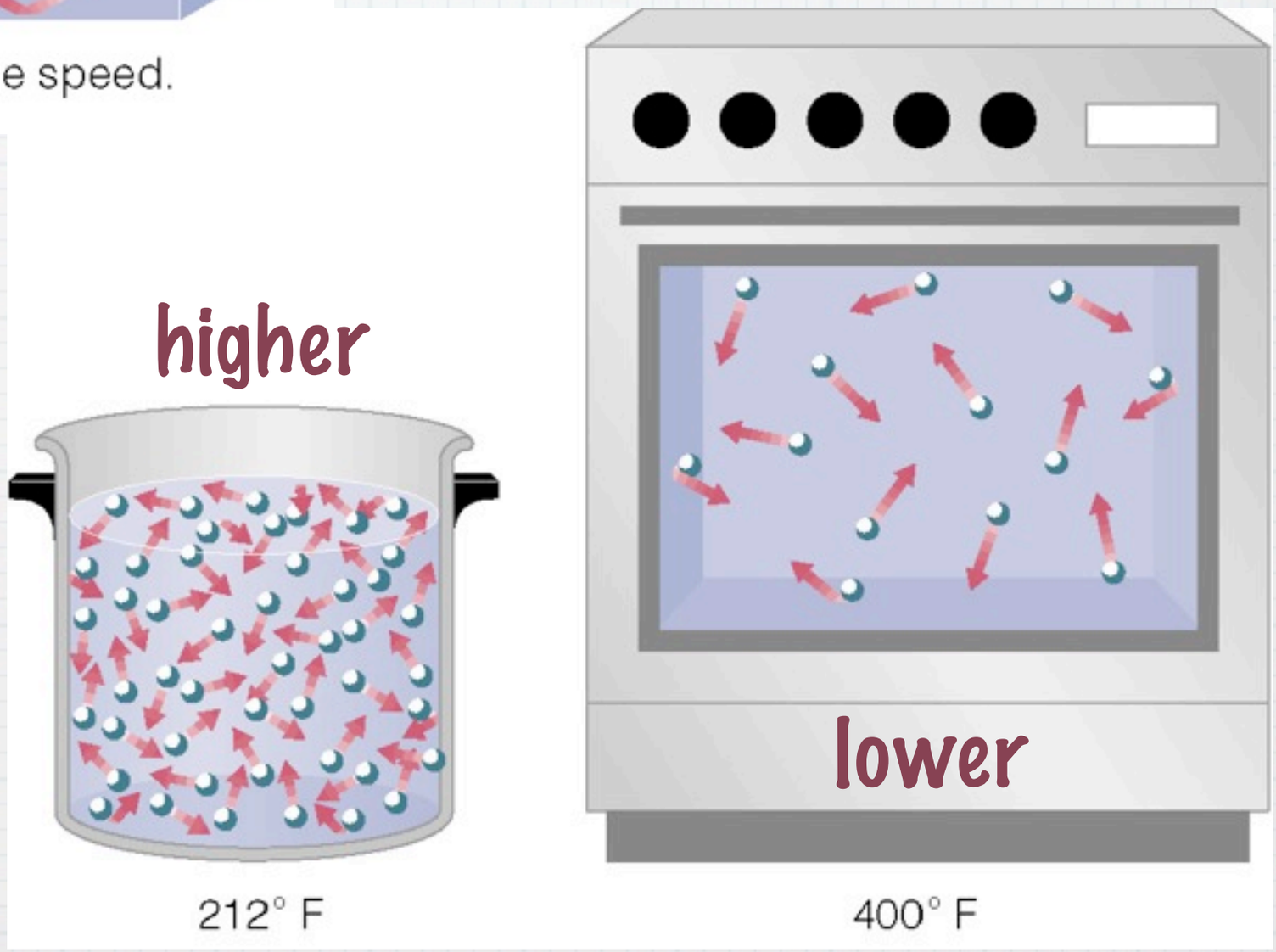
* Thermal energy is related to temperature just as momentum is related to velocity

Thermal Energy vs. Temperature



Longer arrows mean higher average speed.

Thermal energy depends both on temperature and density



Kepler's Third Law

$P^2 = a^3$

* Kepler's third empirical law links how long a planet (satellite) takes to make a full orbit and how far it is from its star (planet)
* Newton, deriving the law mathematically, obtained a more general result:
* This result links the masses of both objects

$$P^2 = \frac{4\pi^2}{G(M+m)} a^3$$

Newton deriving Kepler's Third Law

* This law can be generalized in such a way that it can be used to find the mass of distant objects

* e.g.: by knowing the Earth's orbital period and its average distance from the Sun, we can calculate the mass of the Sun!

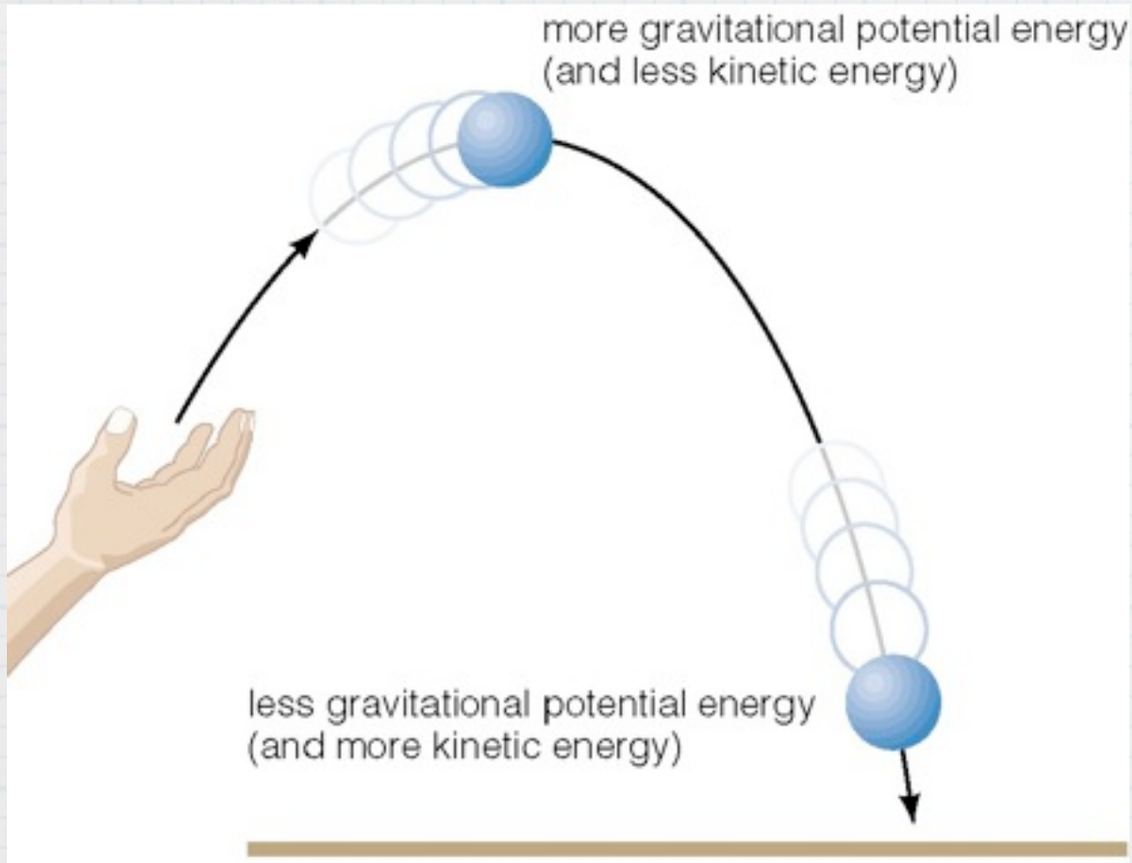
* or by measuring the orbital period of one of Jupiter's moon and its average distance from that planet, we can obtain the mass of Jupiter! $M \approx \frac{4\pi^2}{G P^2} a^3$

Orbital Energy

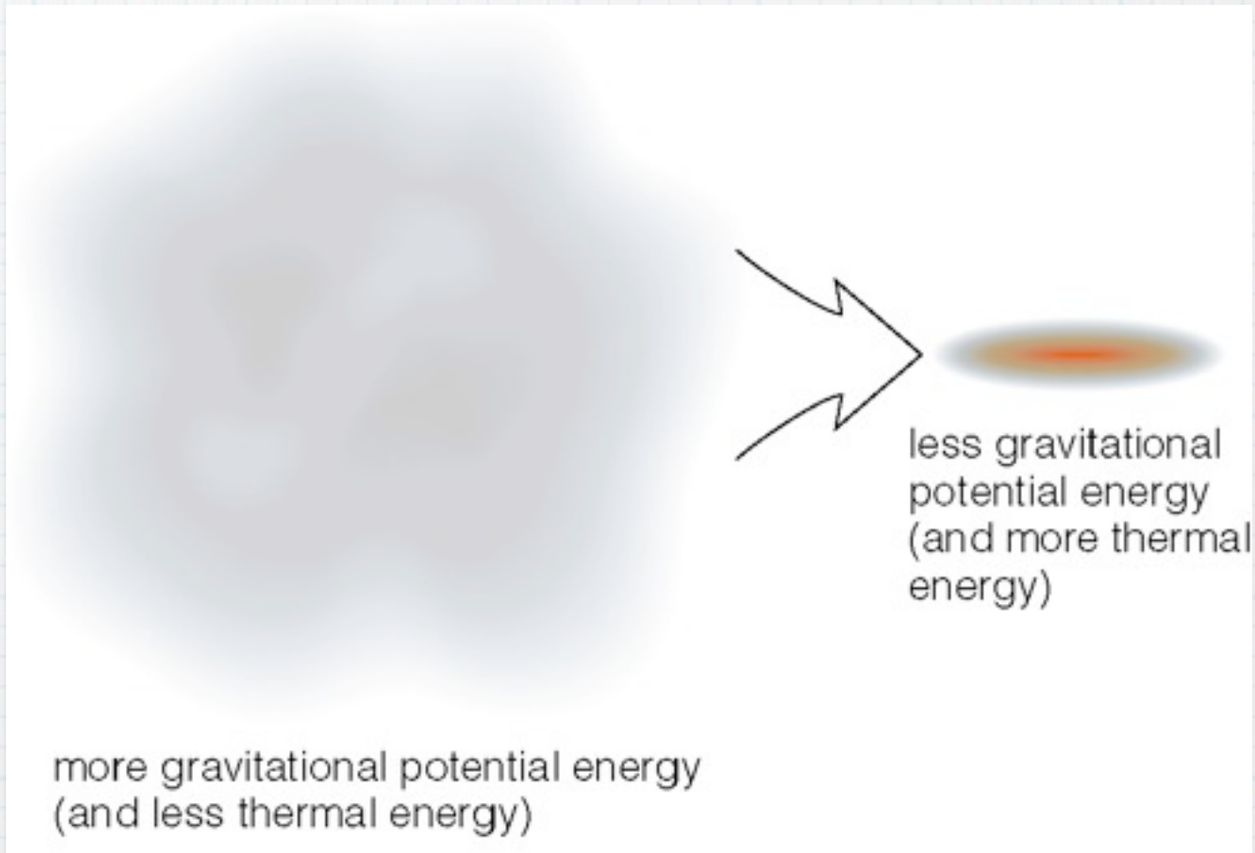
* The orbital energy of a body is a constant
* It is the sum of
  * its kinetic energy
  * its (gravitational) potential energy
* Both change equally in the orbit
* The orbit is stable due to conservation of energy

Gravitational Potential and Kinetic Energies

On Earth

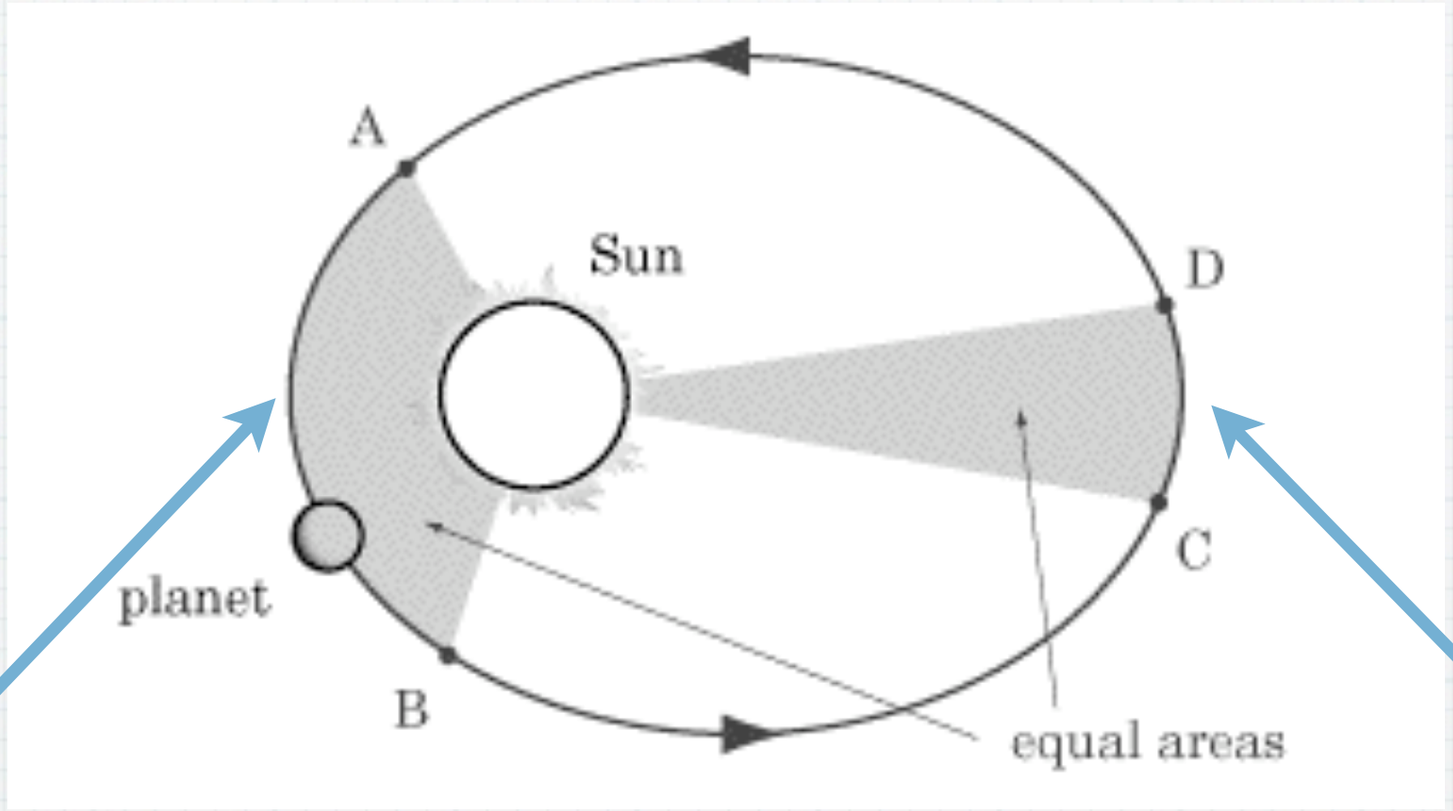


In Space



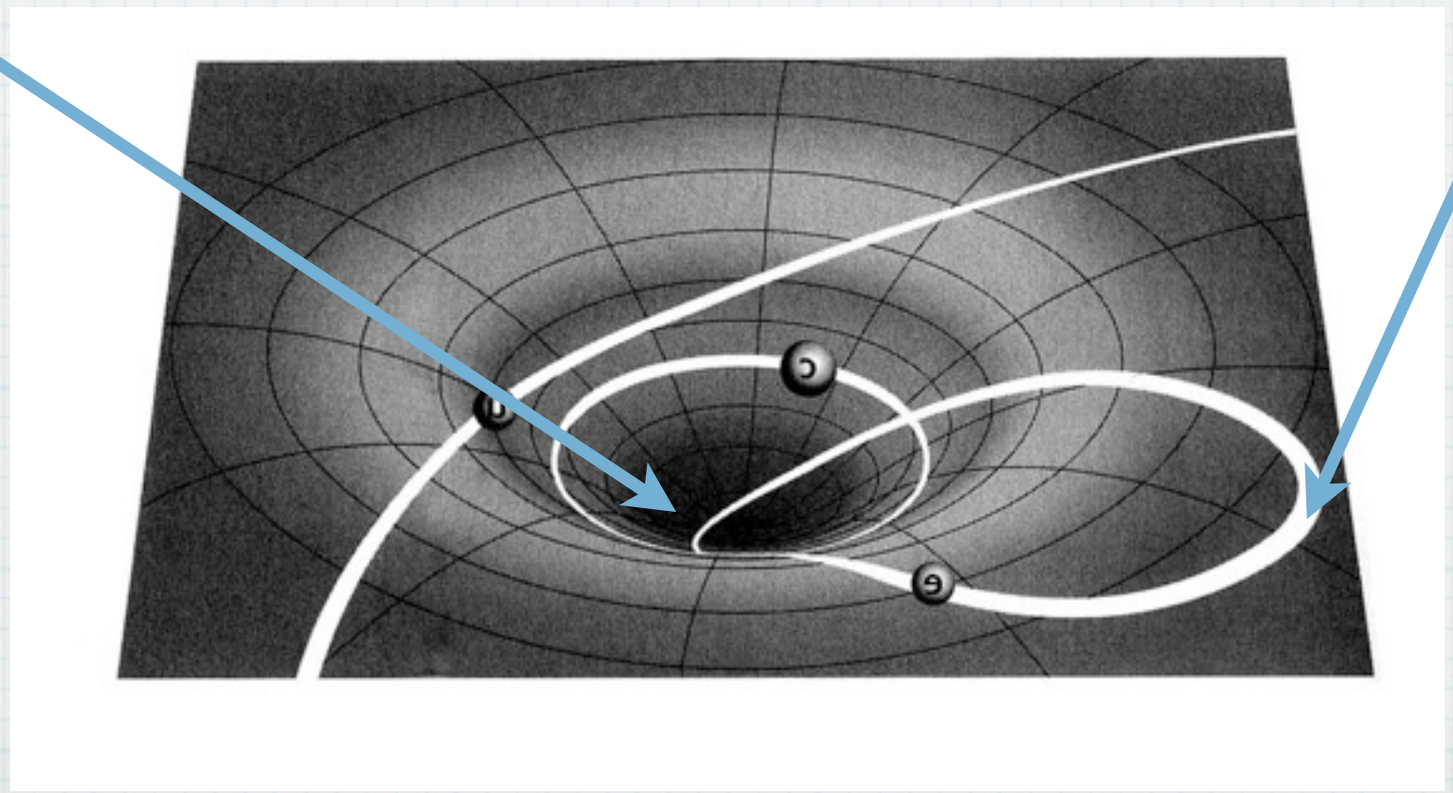
Orbital Energy = Gravitational Potential Energy + Kinetic Energy

Newtonian Spacetime



low GPE
high KE

High GPE
low KE



Curved Spacetime

Snapshot

* 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, gravitational potential energy, mass-energy ($E = mc^2$)

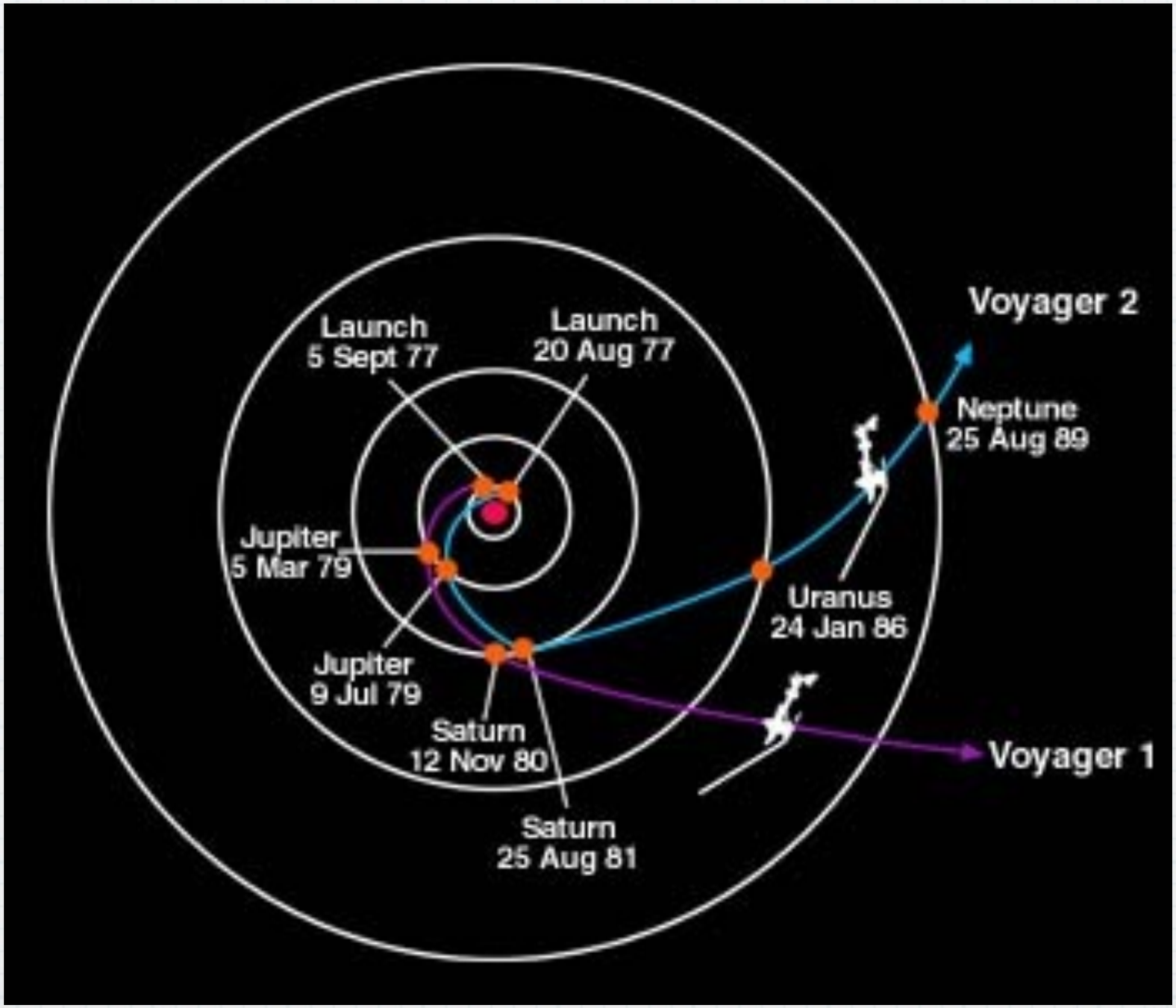
Snapshot

* What is entropy?
* Entropy
  * is a measure of the state of disorder of Nature
  * increases with the arrow of time
  * explains why hot water cools off and why a cooked meal can never be uncooked

Orbital Change

* For a body in orbit to change its orbit, it must gain or lose orbital energy, such as
  * gravitational encounter: interaction with another body (energy exchange/ transfer)
  * atmospheric drag: friction (energy loss)
  * firing its rocket engine: acceleration (energy gain)

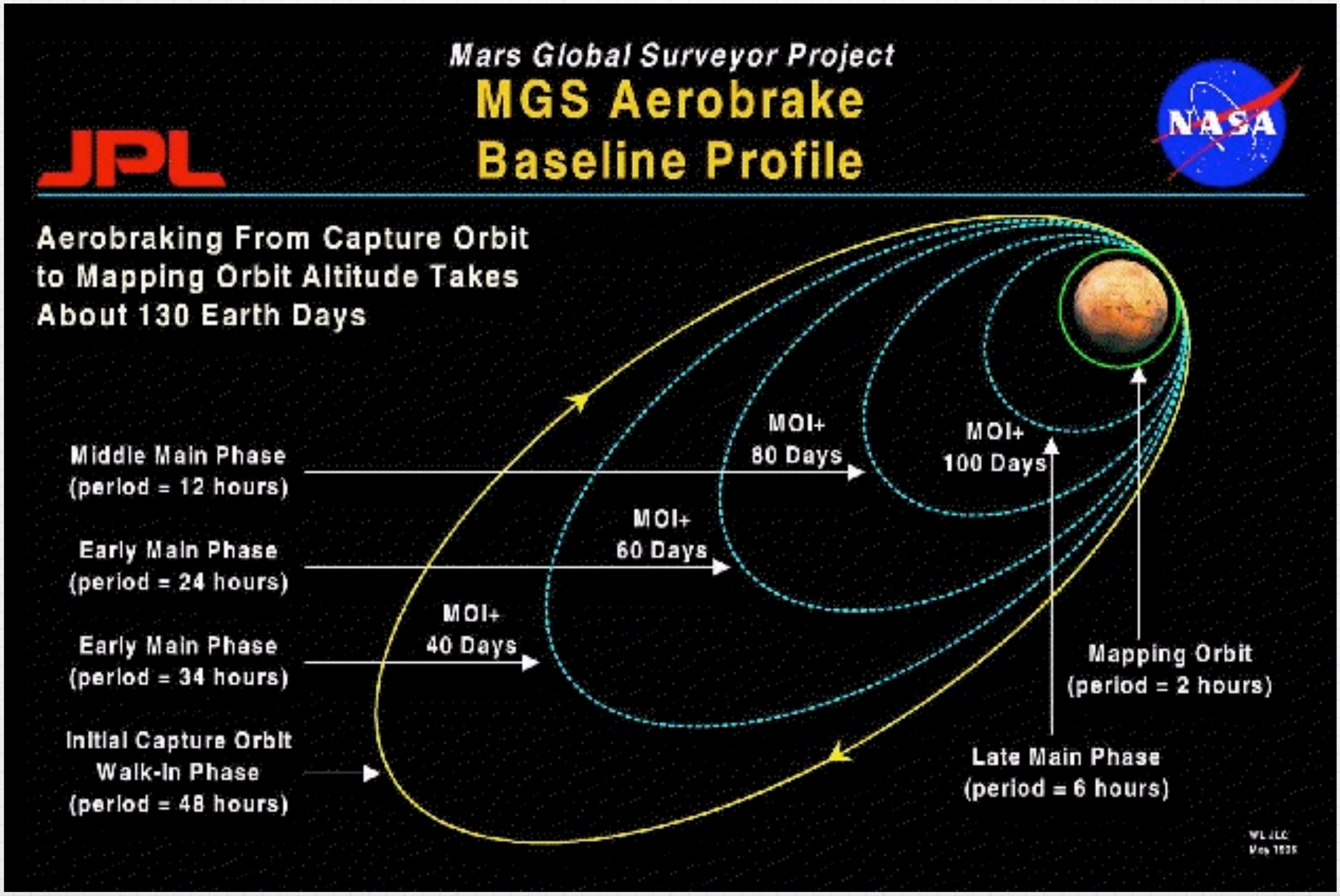
Gravitational Encounter / Assist



Atmospheric Drag

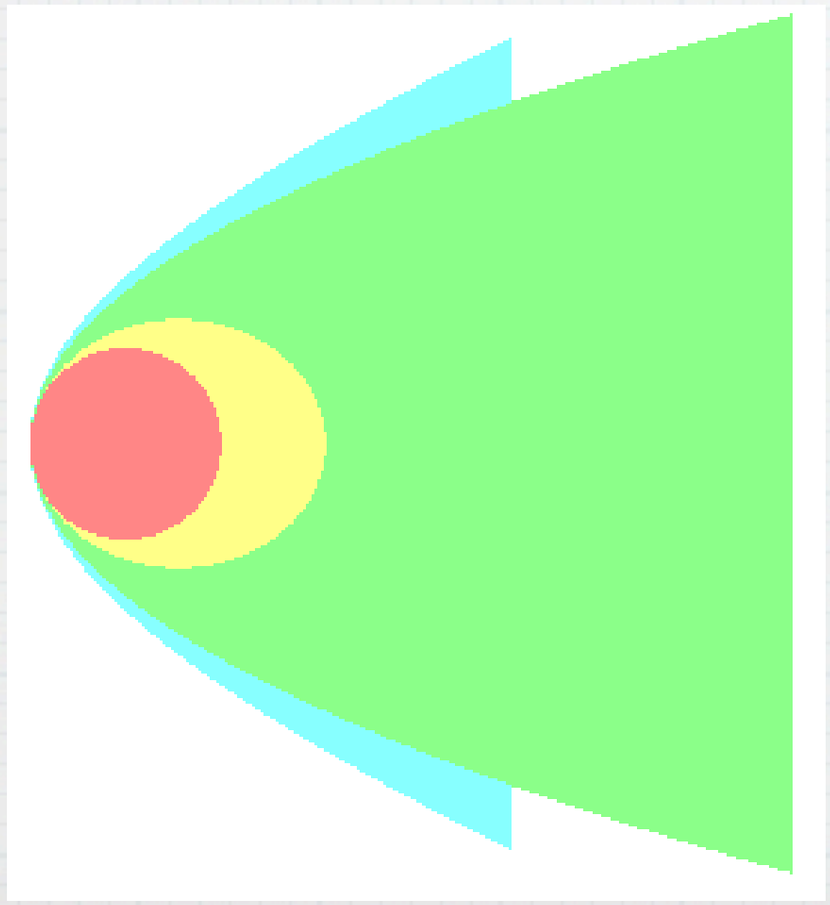
* Earth orbiting satellites do not have constant orbits
* The orbits decay due to the (very tenuous) friction of the satellites with the Earth's atmosphere
* To stay in stable orbits, they need a boost here and there and must carry fuel

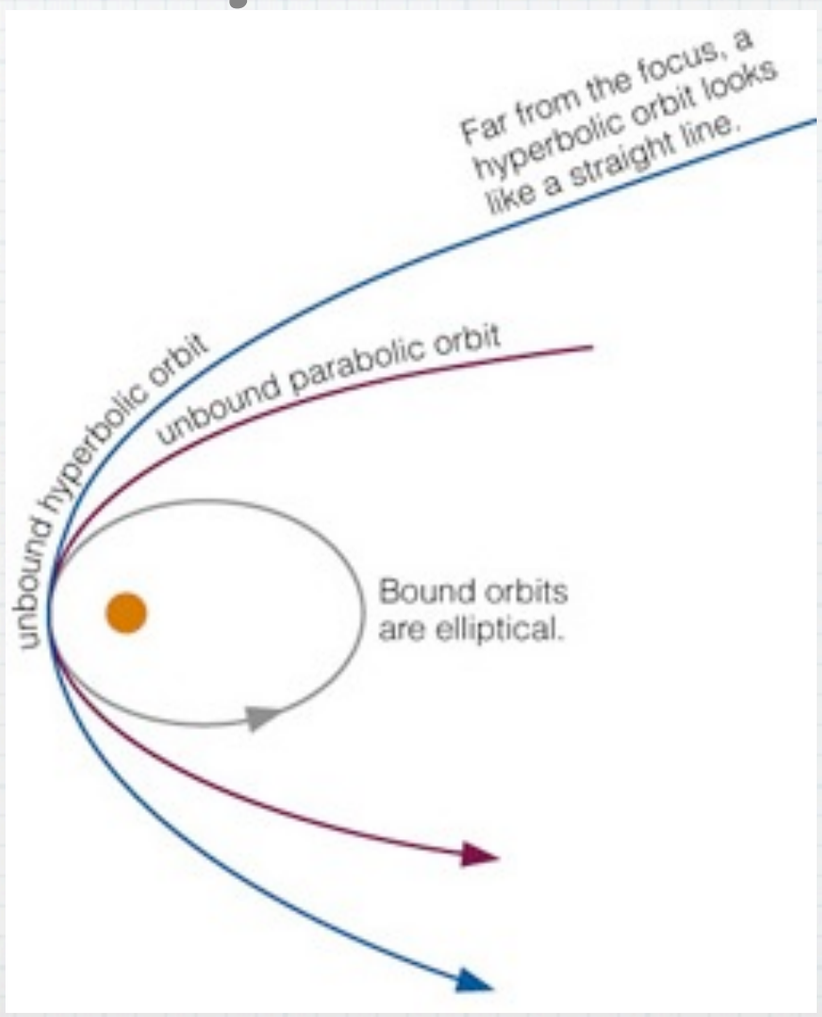
Aerobraking



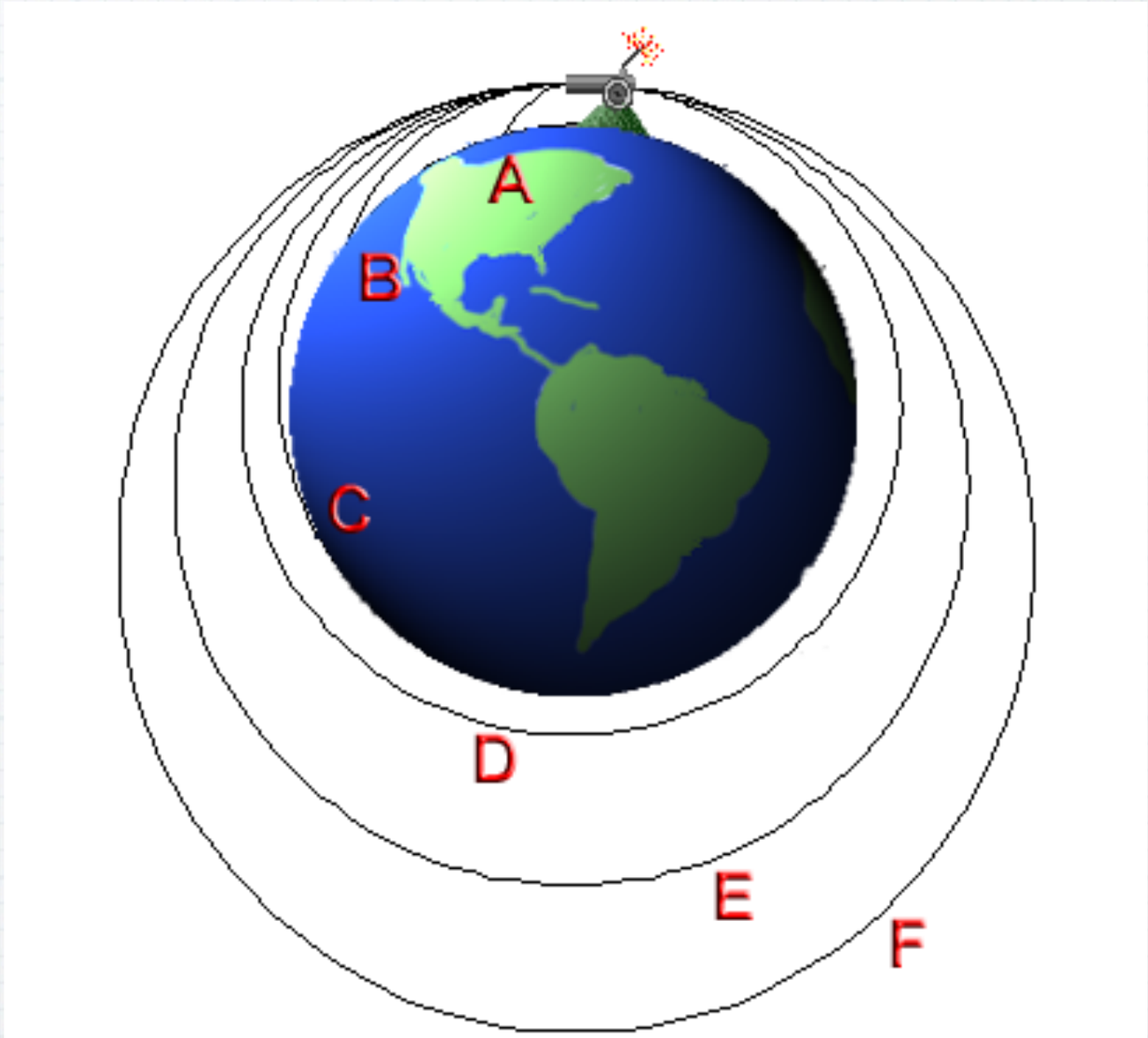
Escape Velocity

* It is the **minimum velocity** an object must have **to break free of the gravitational field** it is located in
* That object path will be a parabolic orbit





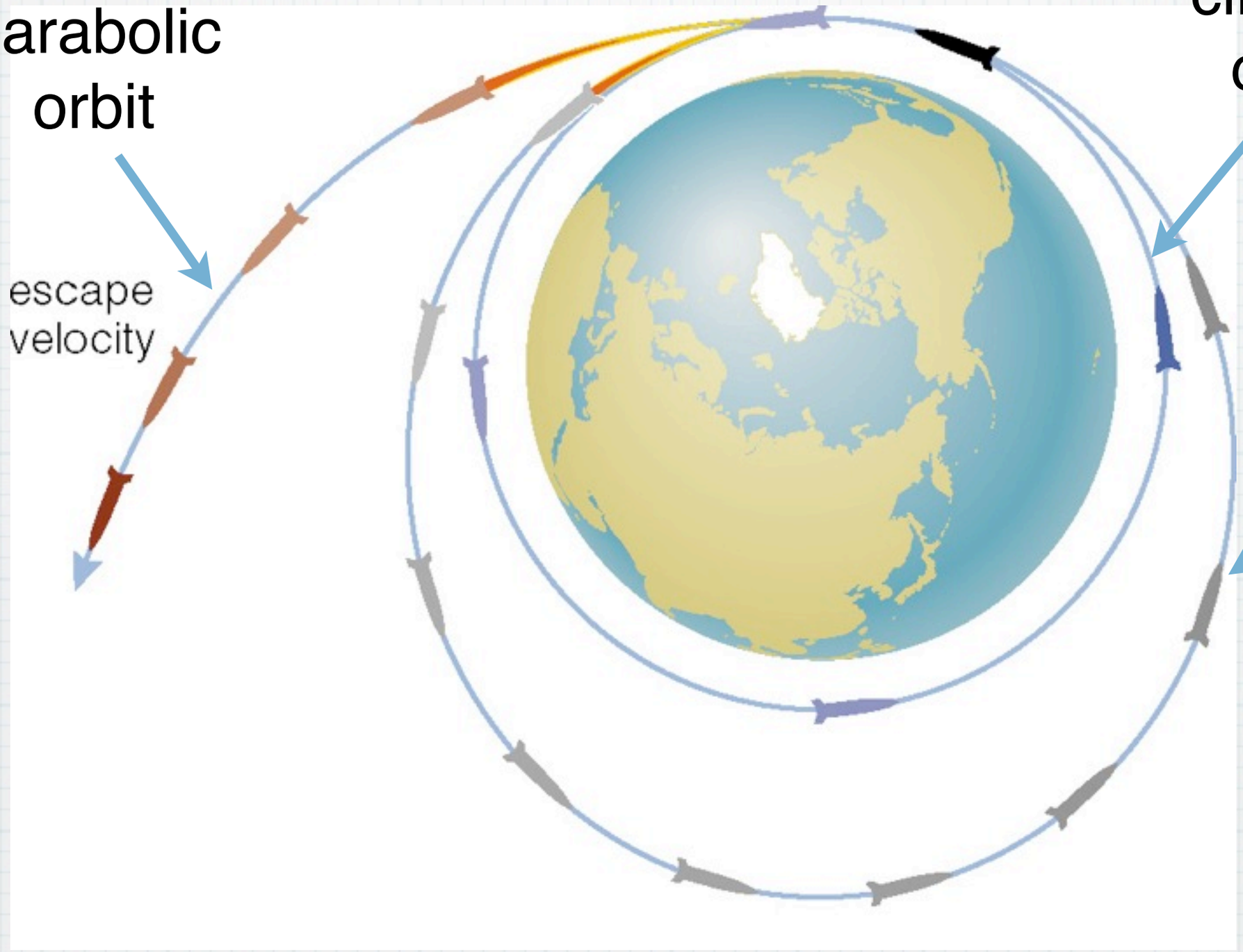
Trajectories of balls shot with increasing velocities



There is gravity in space and weightlessness is due to a constant state of freefall (when the only acceleration is gravity)

A, B, C: cannon ball hits the ground
D: circular path: cannon ball is in constant freefall
E, F: elliptical paths of increasing eccentricities

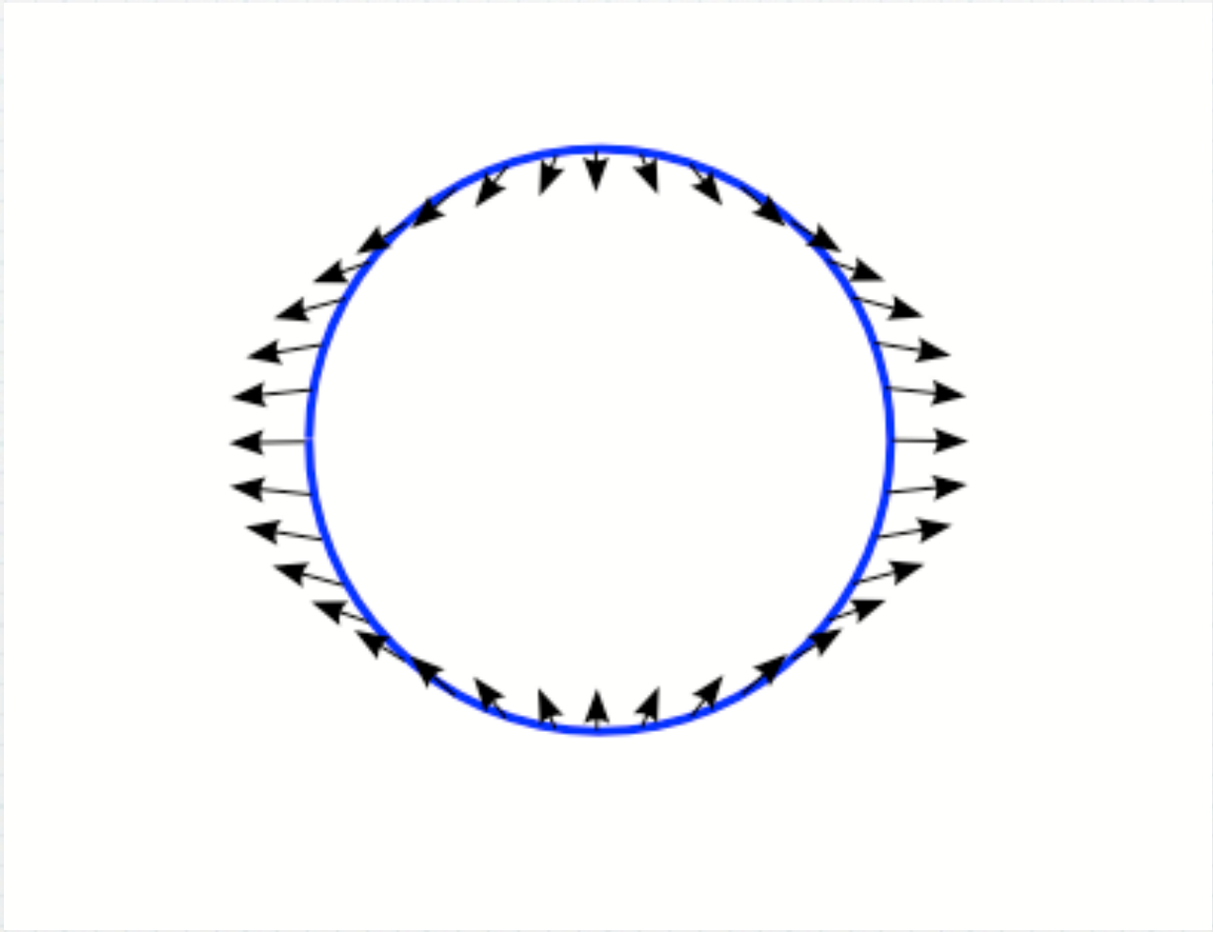
Escape Velocity



On Earth, the escape velocity is about 11 km/s (7 mps)

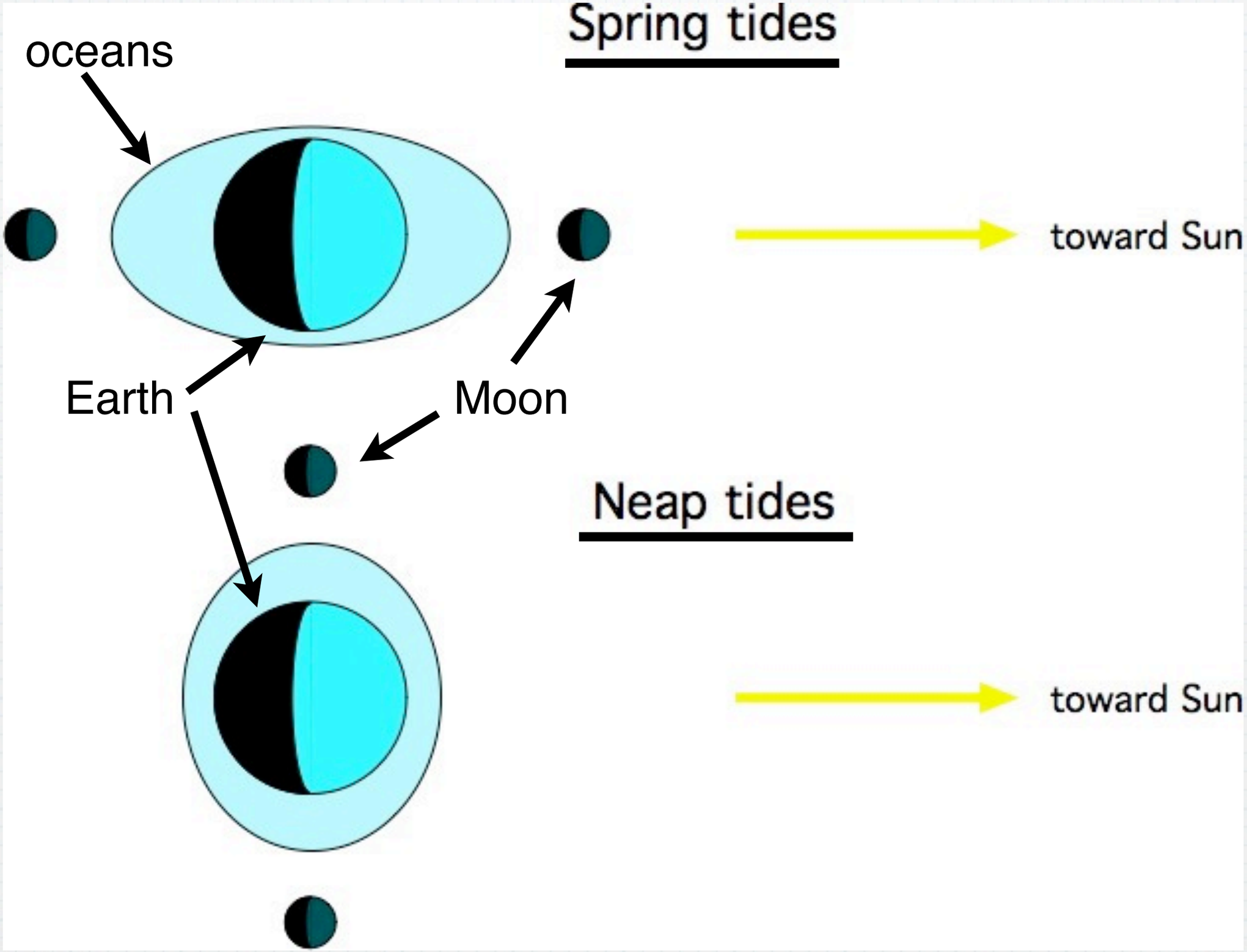
Gravity causes Tides

The Earth is stretched because the gravitational force of the Moon (and the Sun) is felt differently on different sides of the Earth



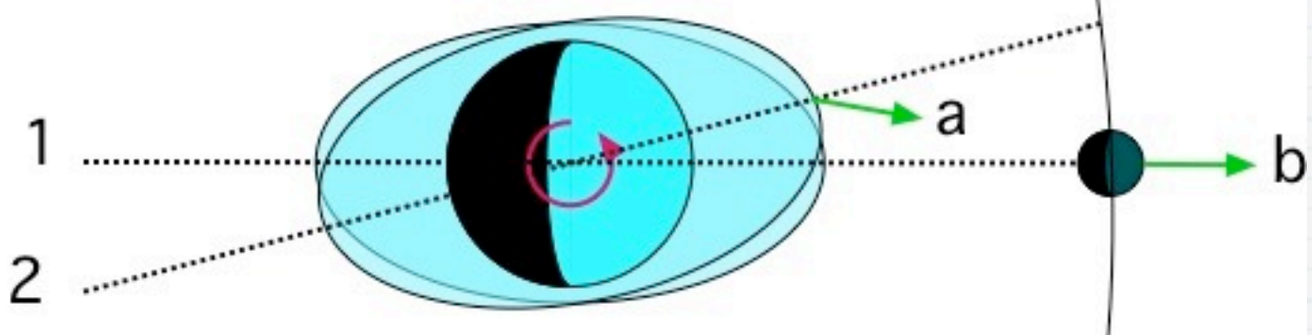
Tides

* Tides affect both oceans and lands!
* Spring tides happen at New Moon and Full Moon (when the Sun and the Moon are aligned)
* Neap tides happen at first and last quarter Moon (when the Sun and the Moon are least aligned)


Spring tides
oceans
toward Sun
Earth
Moon
Neap tides
toward Sun

More tidal effects

1) If the Earth did not spin, the tidal bulges would be lined up with the Moon



2) But the Earth spins, and the oceans have momentum so the tidal bulges are ahead of the Moon (since the Earth spin is faster than the Moon's rotation)

Energy Exchange

a) The Moon tries to pull the bulges back: Earth's spin is slowed

b) The bulges pull the Moon ahead: its velocity is increased, the Moon gets farther away

Synchronous Lock is due to the Tides

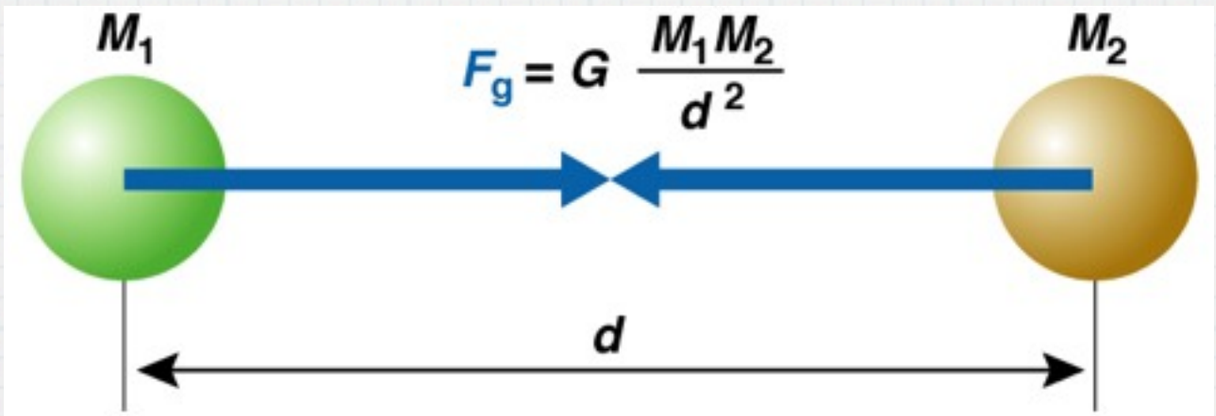
* We always see the same face of the Moon: it spins on its axis, too
* It is locked in a synchronous rotation: it spins one turn in one orbit exactly
* because the Earth is creating a tide on the Moon as well (tidal lock)
* This effect is seen on numerous satellites in the Solar System

The Moon's Synchronous Rotation explained

* Very likely, the Moon rotated much faster in the past. It was closer too
* Tidal frictions with Earth caused the Moon's rotation to slow down, this caused it to move away from Earth
* When the Moon's rotation speed reached the speed of its tidal bulges, there was no further tidal friction and synchronous rotation was achieved

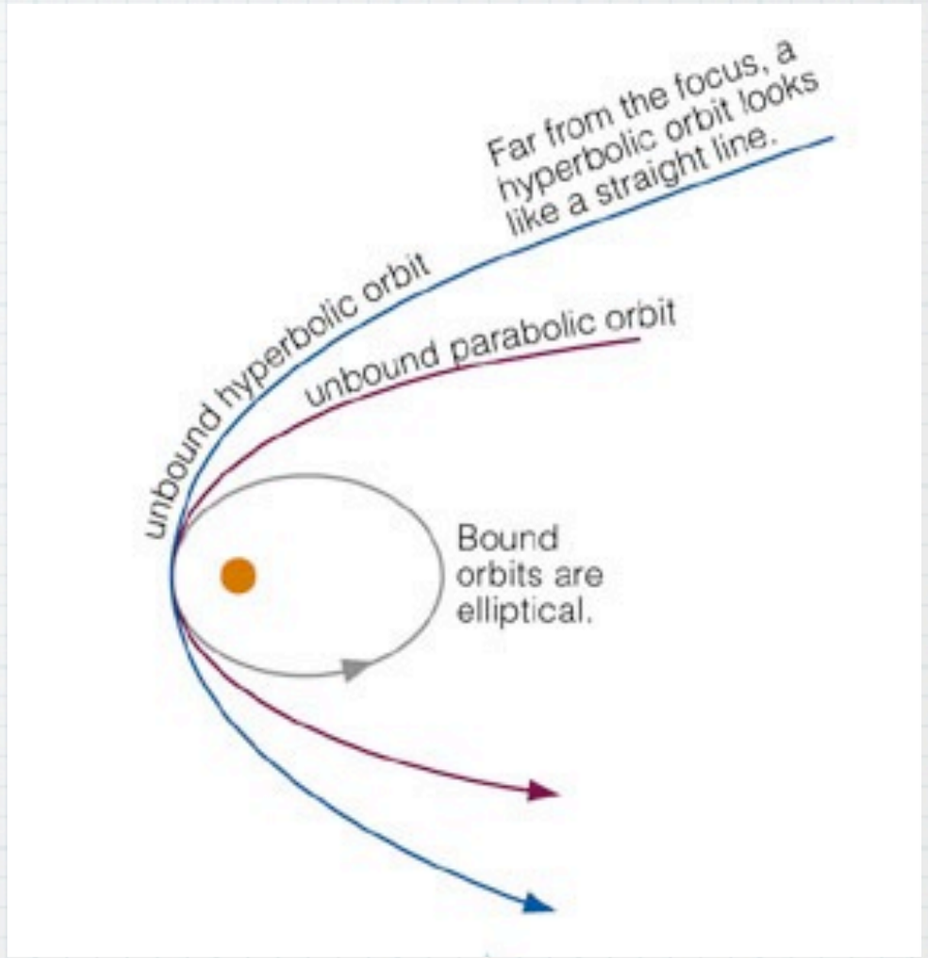
Snapshot

* What determines the strength of gravity?
* Gravity is directly proportional to the product of the masses
* Gravity is inversely proportional to the square of the masses separation

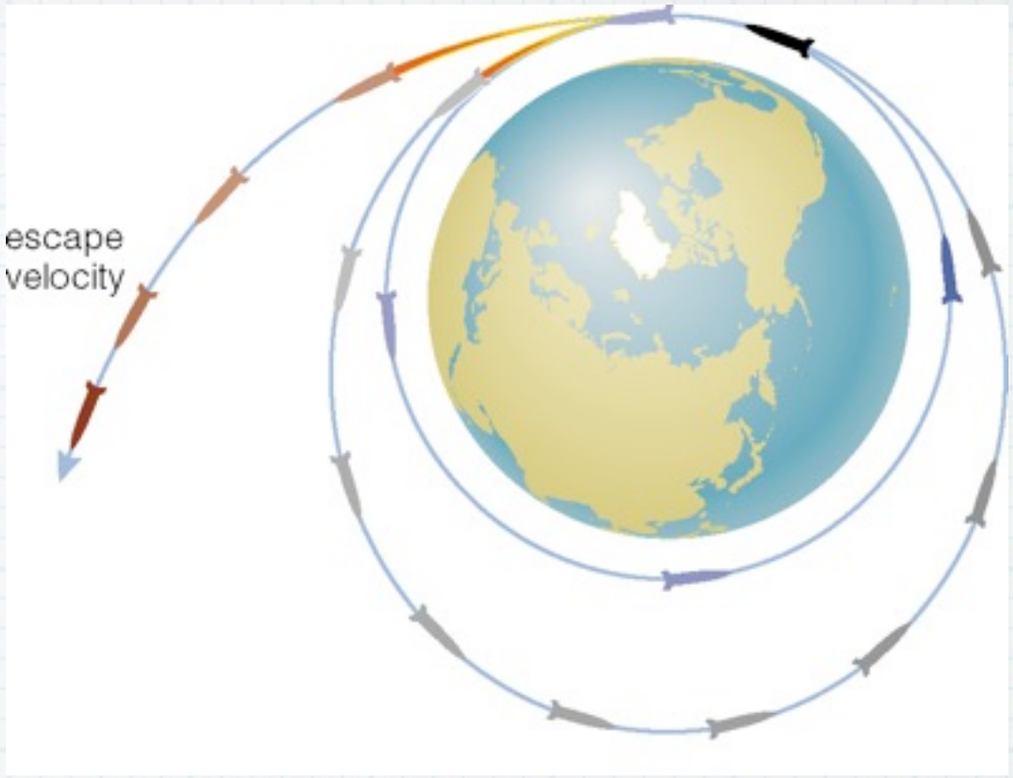


Snapshot

* How does Newton's law of gravity allow us to extend Kepler's laws?
* It applies to all other objects, not just planets
* It includes unbound trajectories: parabolae and hyperbolae



Snapshot



* How does gravity and energy together allow us to understand orbits?
* Gravity determines orbits
* An orbiting object cannot change orbit without an energy transfer

Snapshot

* How does gravity cause tides?
* Gravity stretches Earth along Earth-Moon line because the near side is pulled harder than the far side
* A similar effect is caused by the Sun but its influence is less as it is much further away - even though it is much more massive than the Moon

More Stuff to Access

* http://www.youtube.com/watch?v=XkAPv5s92z0
* http://www.youtube.com/watch?v=DbhuRcmSkMg
* http://www.youtube.com/watch?v=rQbc1HJc5Nw
* http://www.youtube.com/watch?v=rWT-DJNSxtg
* http://www.youtube.com/watch?v=cXsvy2tBJlU
* http://www.youtube.com/watch?v=zsTRxXvQY0s
* http://vimeo.com/41038445