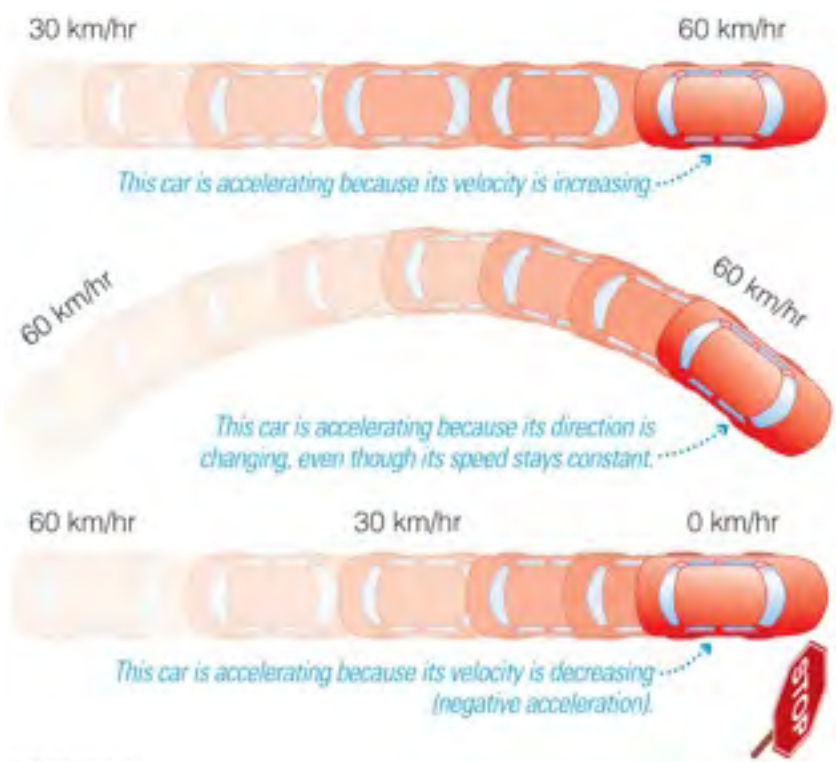
Making Sense of the Universe: Understanding Motion, Energy, and Gravity

How do we describe motion?



Precise definitions to describe motion:

- **Speed**: Rate at which object moves

$$\text{speed} = \frac{\text{distance}}{\text{time}} \quad \left(\text{units of } \frac{\text{m}}{\text{s}}\right)$$

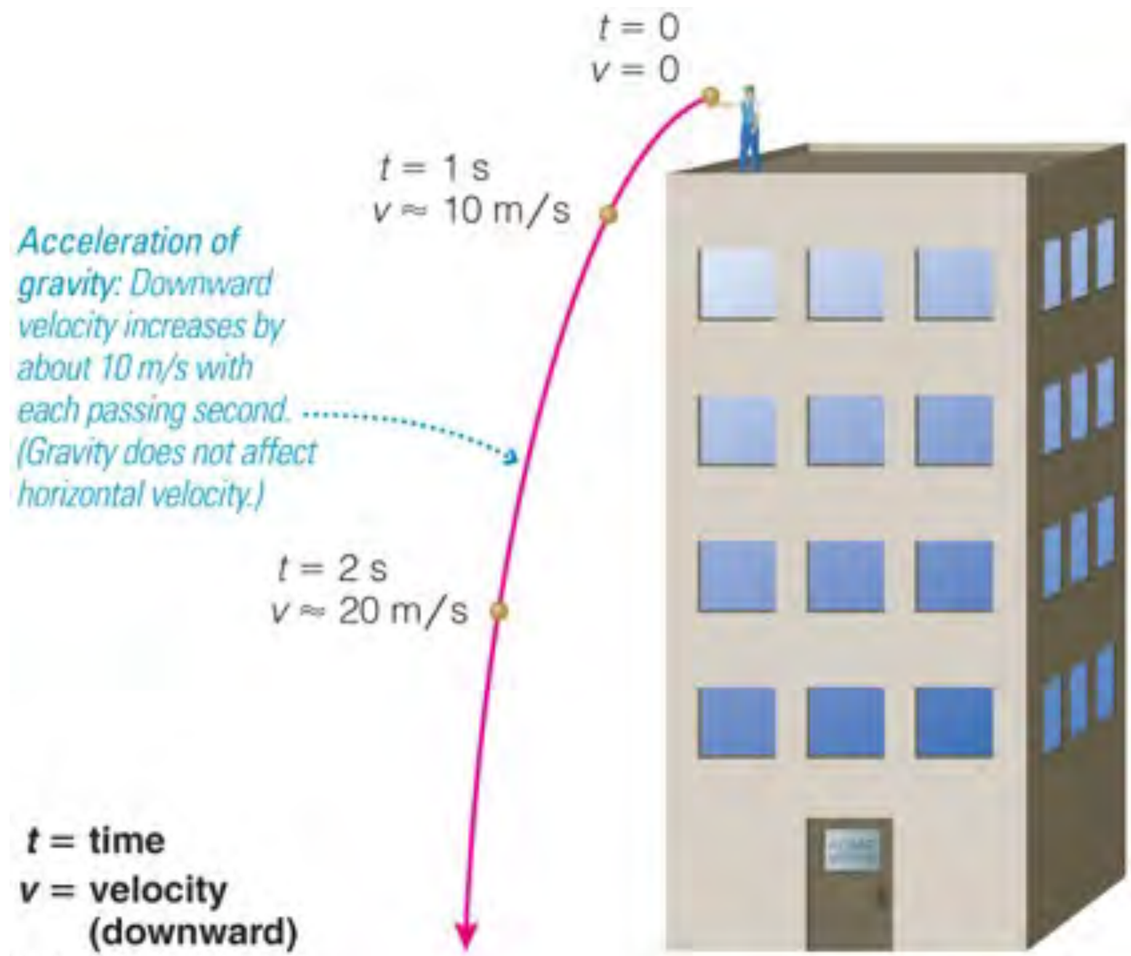
Example: 10 m/s

- **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.

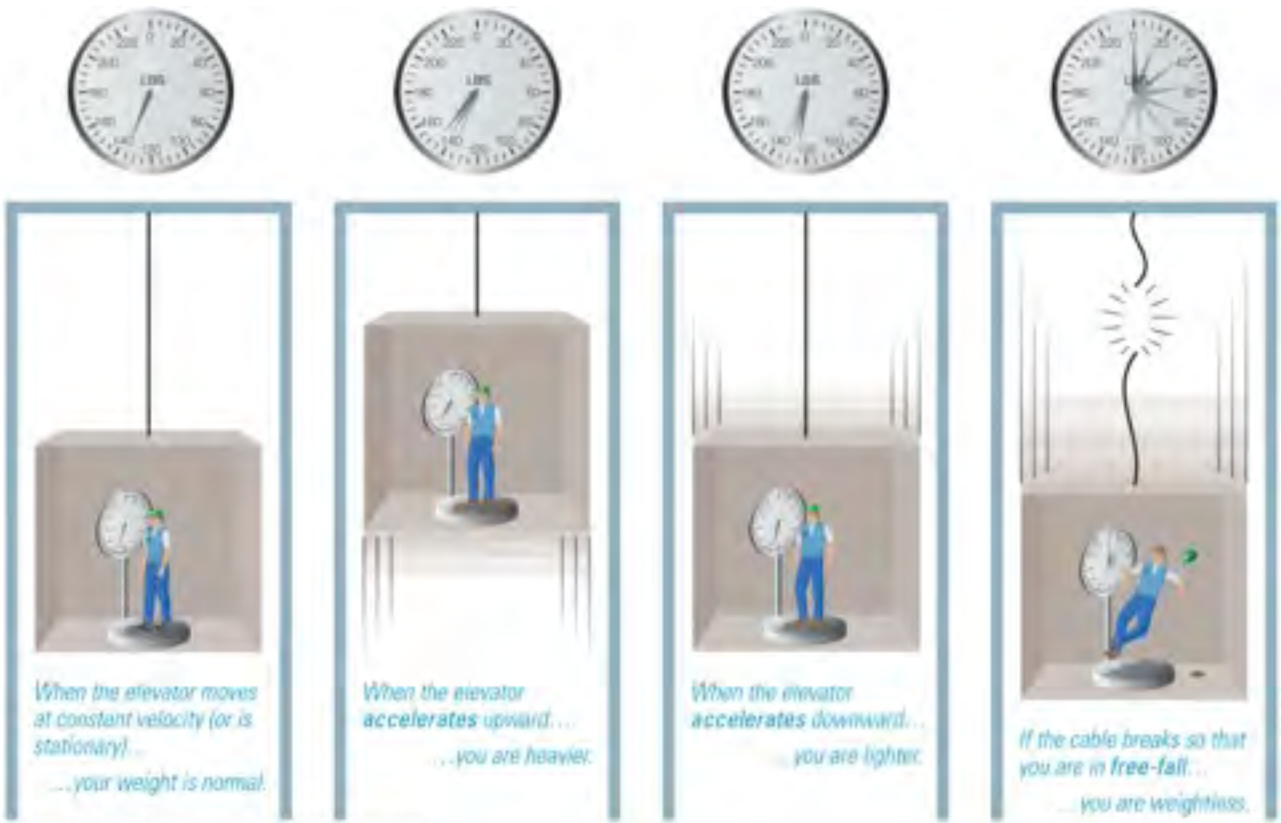
Apollo 15 demonstration
http://www.youtube.com/watch?v=03SPBXALJZI

Momentum and Force

- Momentum = mass × velocity ($p = mv$)
- A **net force** changes momentum, which generally means an acceleration (change in velocity).
- Rotational momentum of a spinning or orbiting object is known as **angular momentum**.

How is mass different from weight?

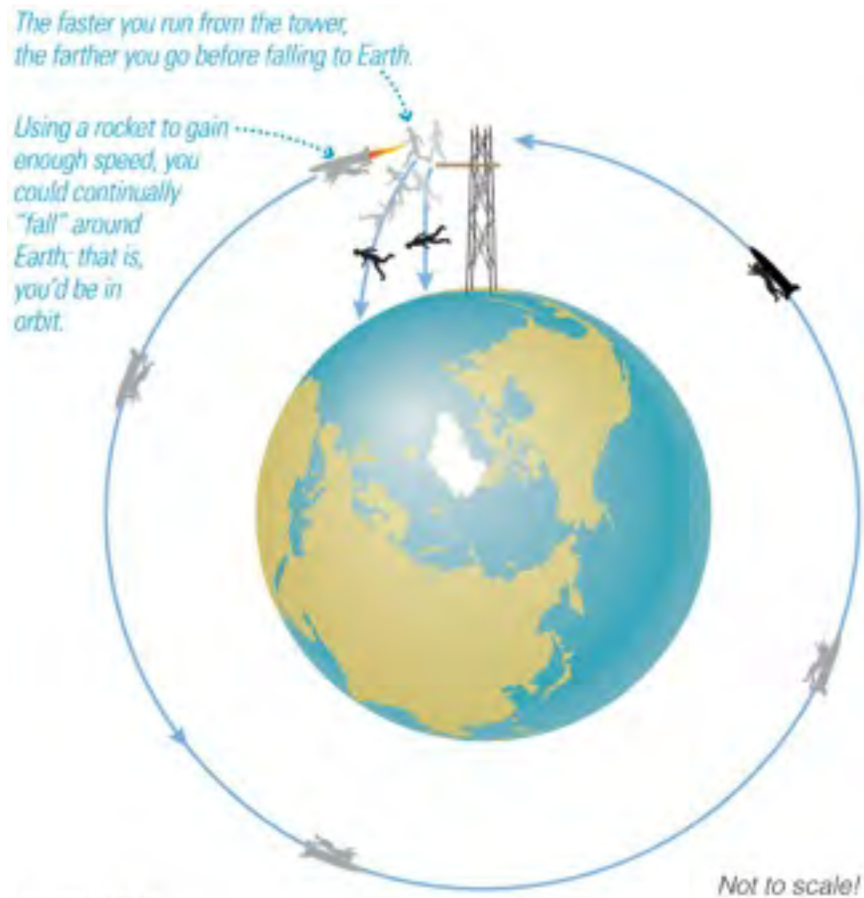
- **Mass** – the amount of matter in an object
- **Weight** – the *force* that acts upon an object



You are weightless in free-fall!

Why are astronauts weightless in space?

- There *is* gravity in space.
- Weightlessness is due to a constant state of free-fall.



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

  ⇒ 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.

Newton's second law of motion:

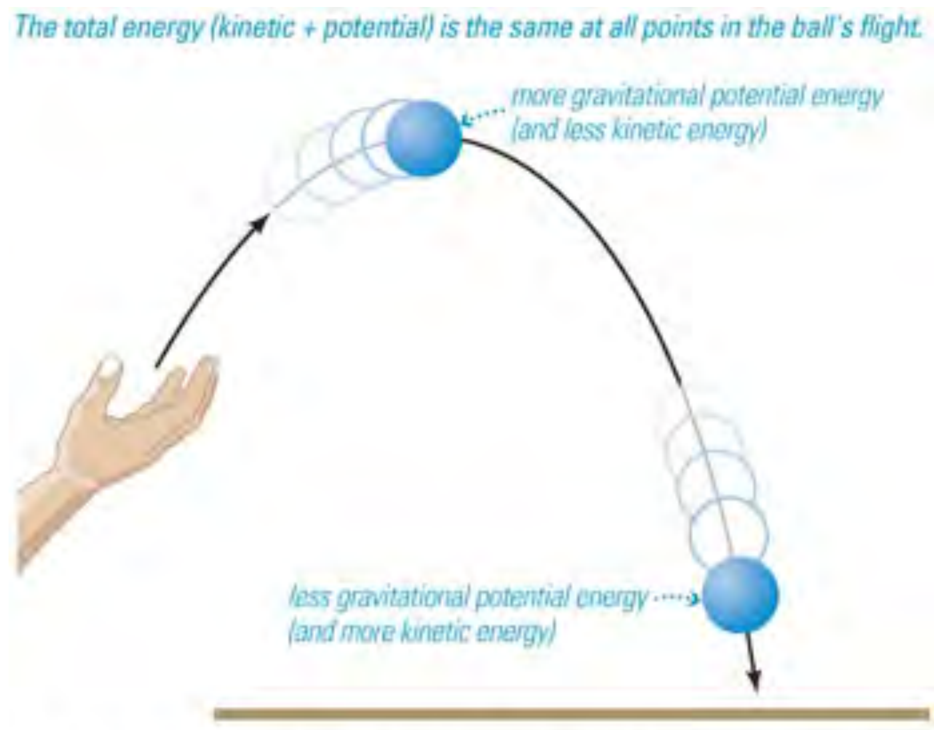
Force = mass × acceleration ($F=ma$)

Newton's third law of motion:

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

Gravitational Potential Energy

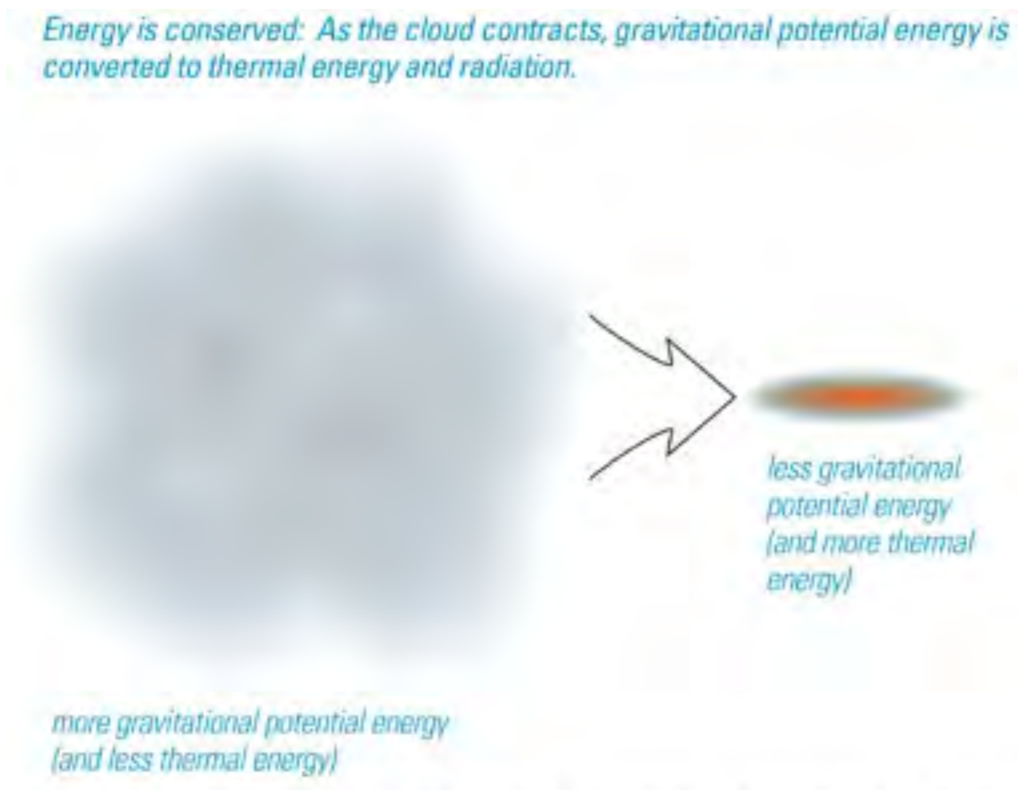
- On Earth, depends on:
  - object's mass (m)
  - strength of gravity (g)
  - distance object could potentially fall



Gravitational Potential Energy

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

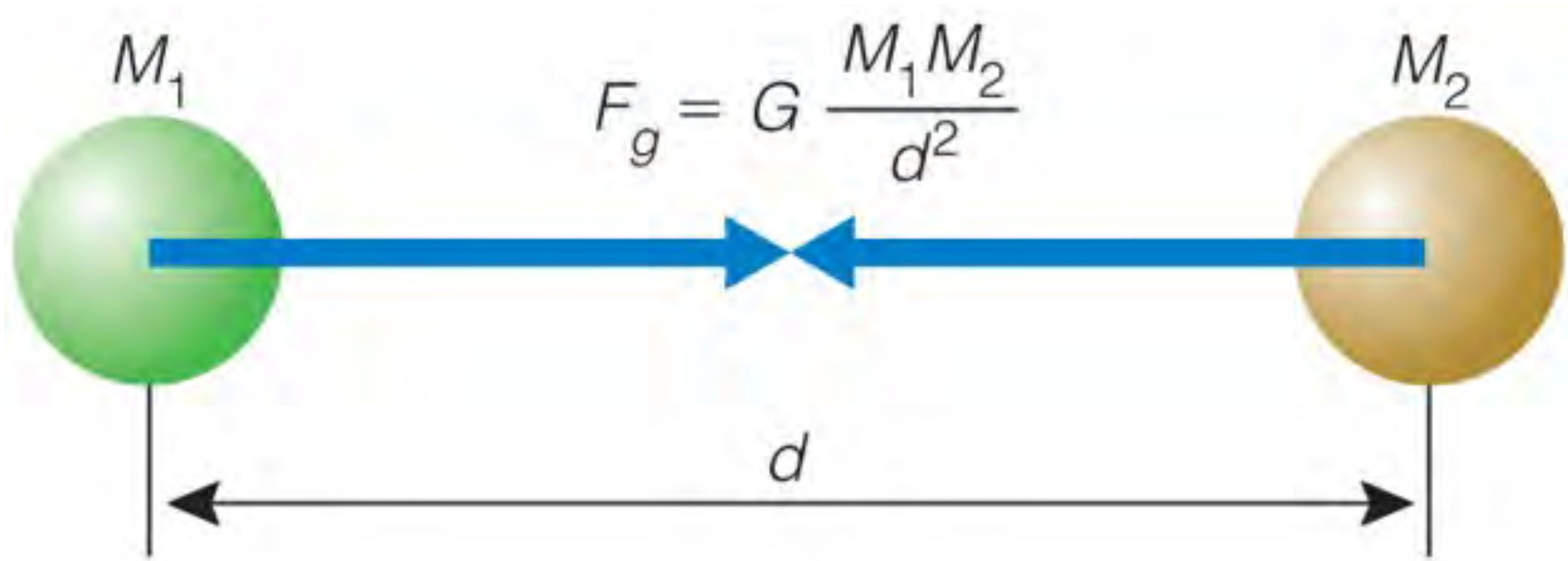
⇒ A contracting cloud converts gravitational potential energy to thermal energy.



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.



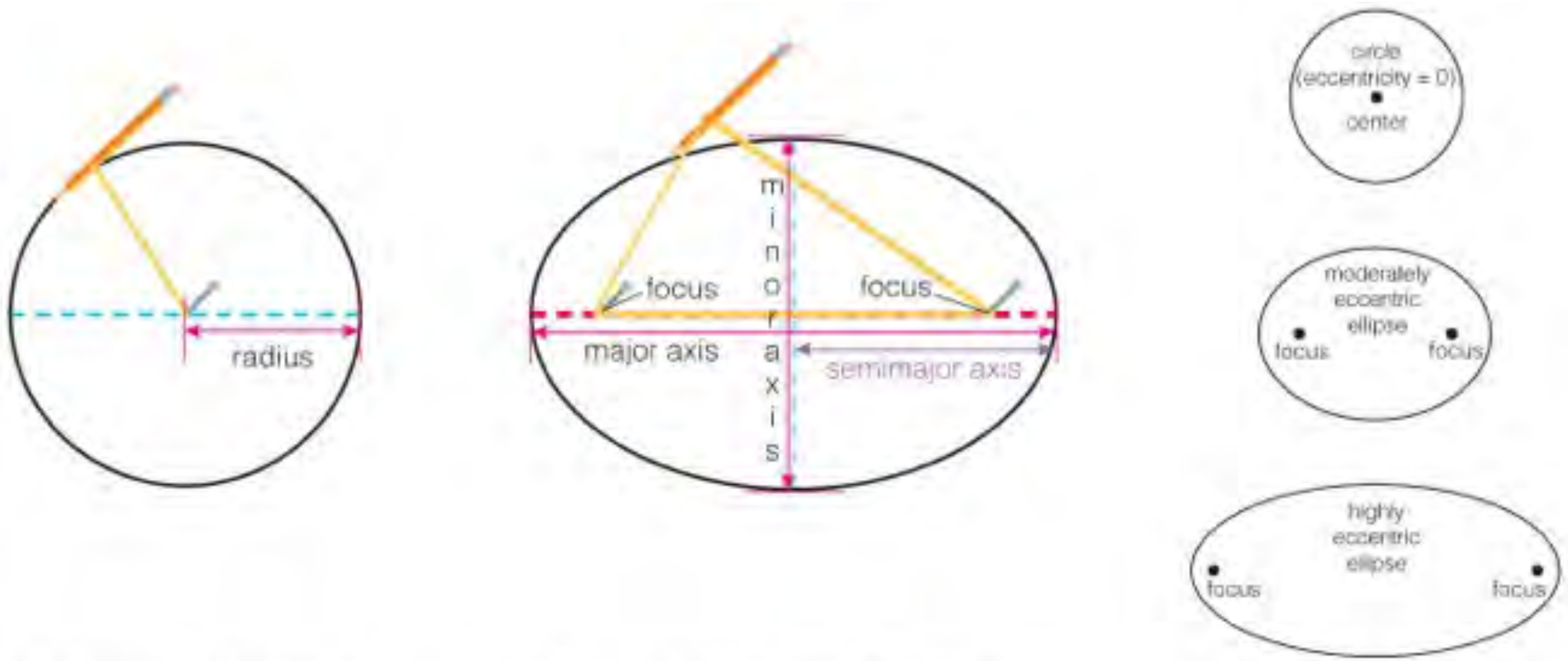
Kepler and the Laws of Planetary Motion

Johannes Kepler
(1571-1630)

- Kepler first tried to match Tycho's observations with circular orbits
- But an 8-arcminute discrepancy led him eventually to ellipses.

"If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy."

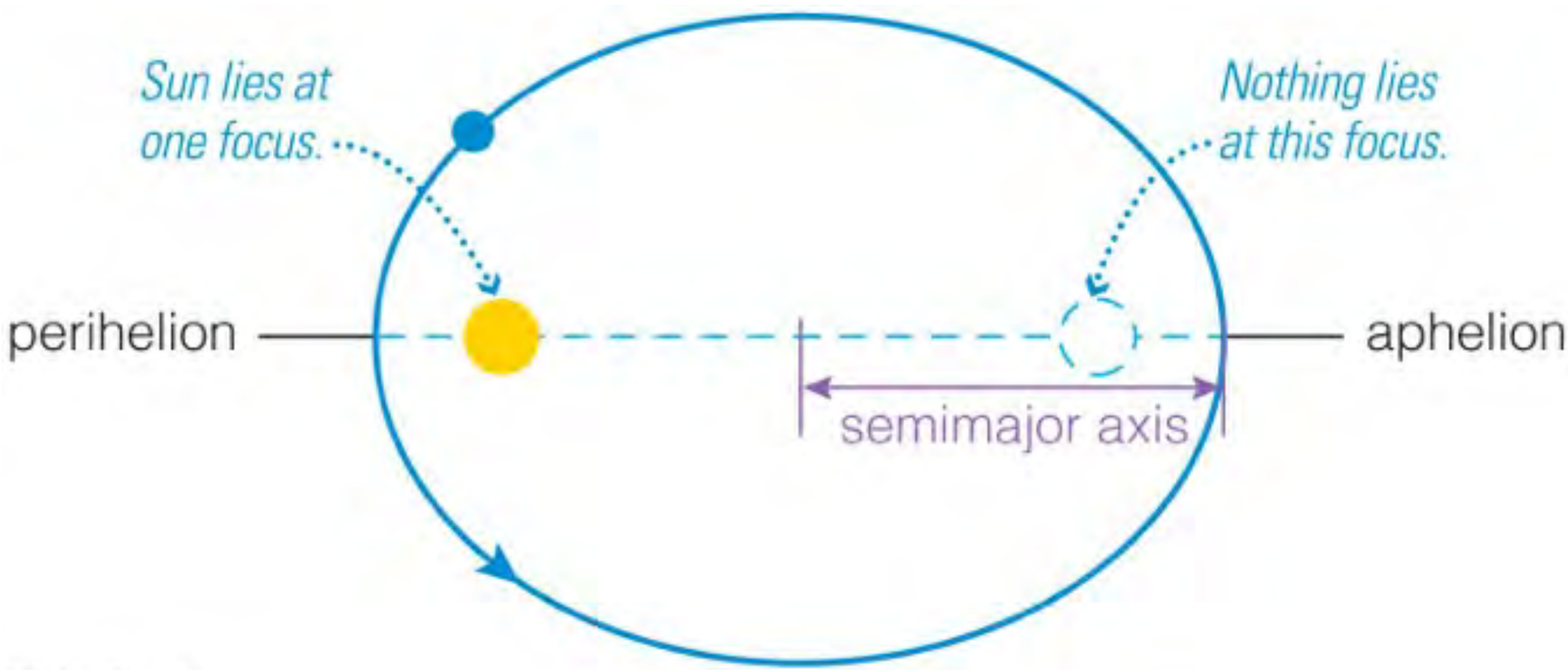
What is an ellipse?



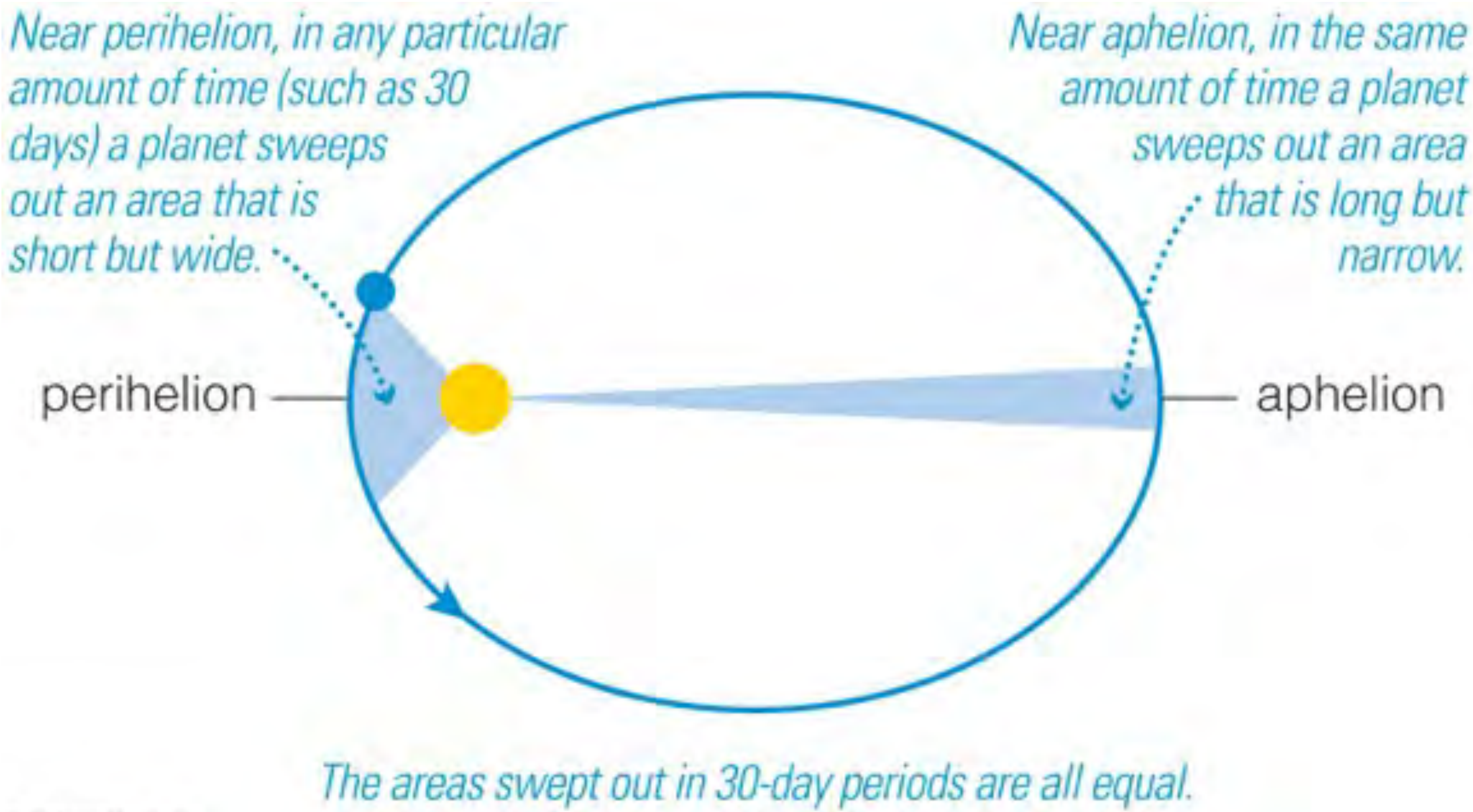
An ellipse looks like an elongated circle.

What are Kepler's three laws of planetary motion?

Kepler's First Law: The orbit of each planet around the Sun is an *ellipse* with the Sun at one focus.



Kepler's Second Law: As a planet moves around its orbit, it sweeps out equal areas in equal times.



This means that a planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

Kepler's Third Law

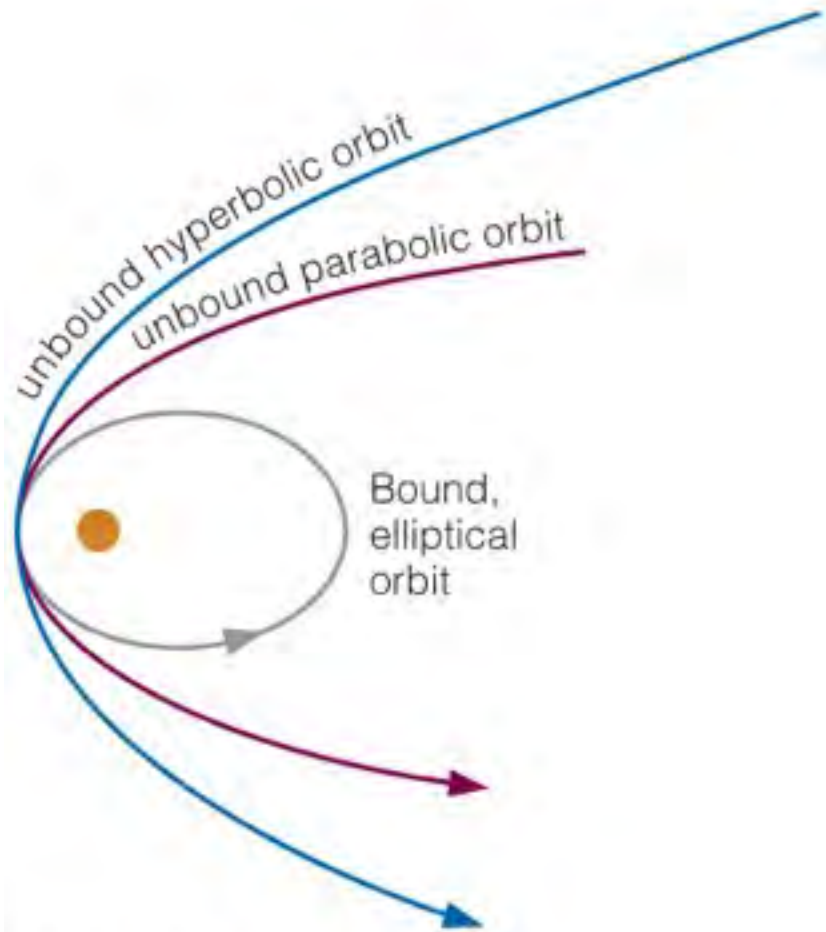
More distant planets orbit the Sun at slower average speeds, obeying the relationship

$$p^2 = a^3$$

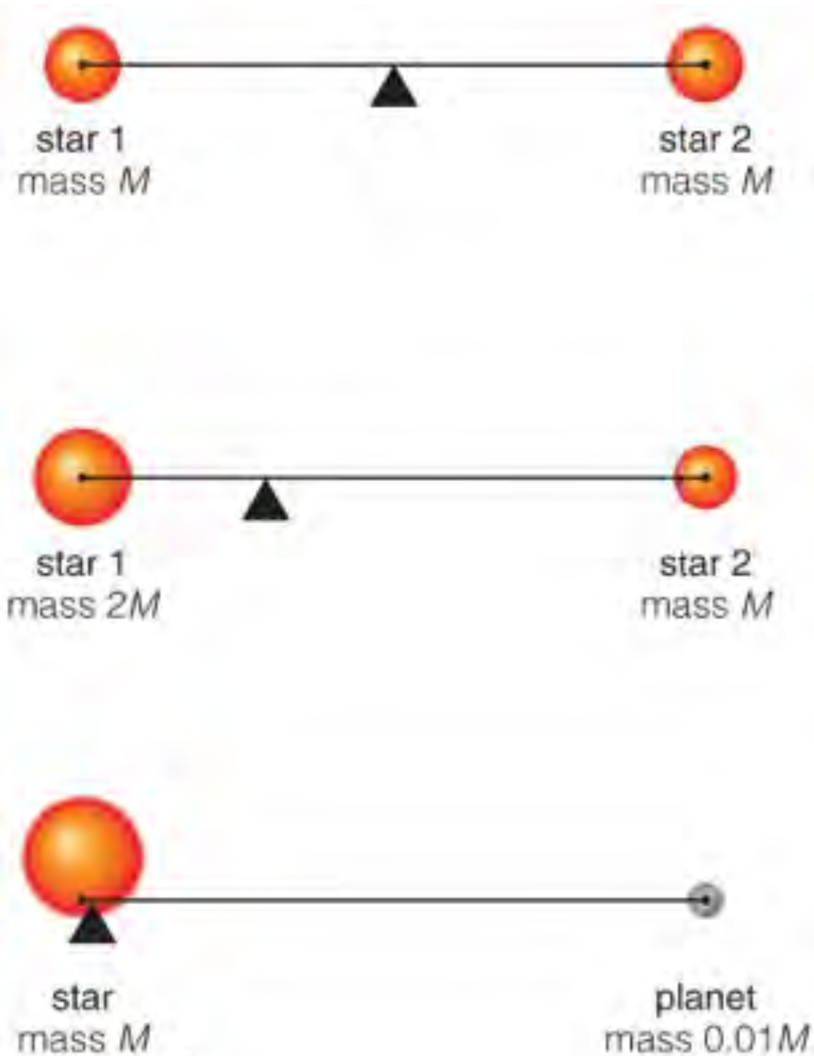
p = orbital period in years
a = avg. distance from Sun in AU

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



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

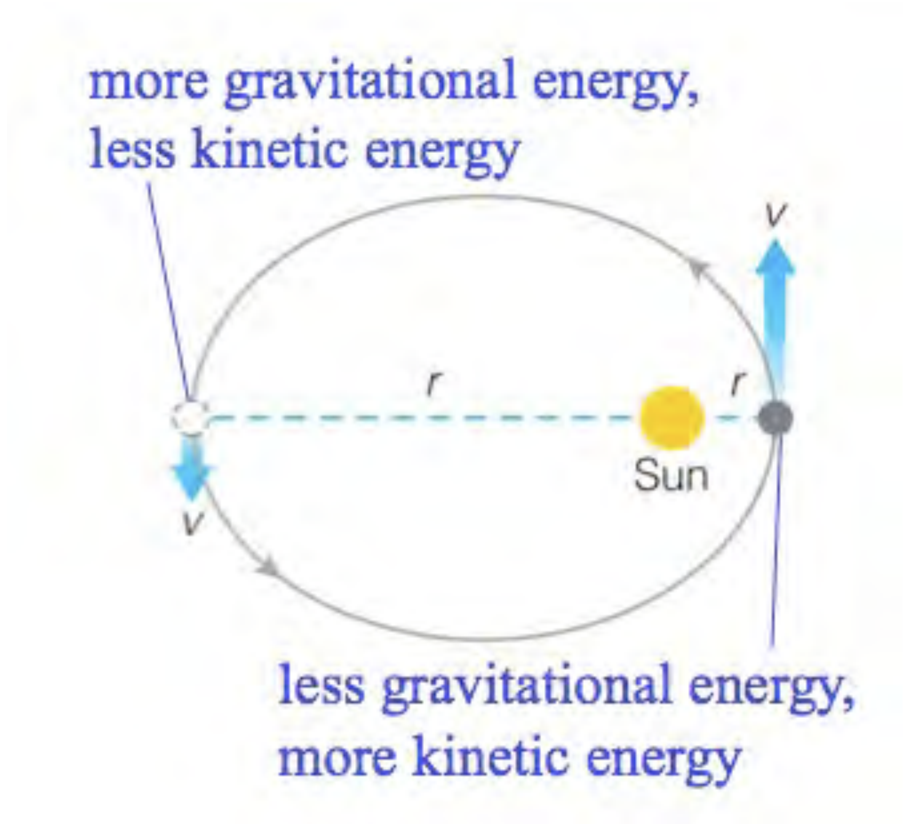
$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \qquad \text{OR} \qquad M_1 + M_2 = \frac{4\pi^2}{G} \frac{a^3}{p^2}$$

p = orbital period

a = average orbital distance (between centers)

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

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



Total orbital energy stays constant.

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

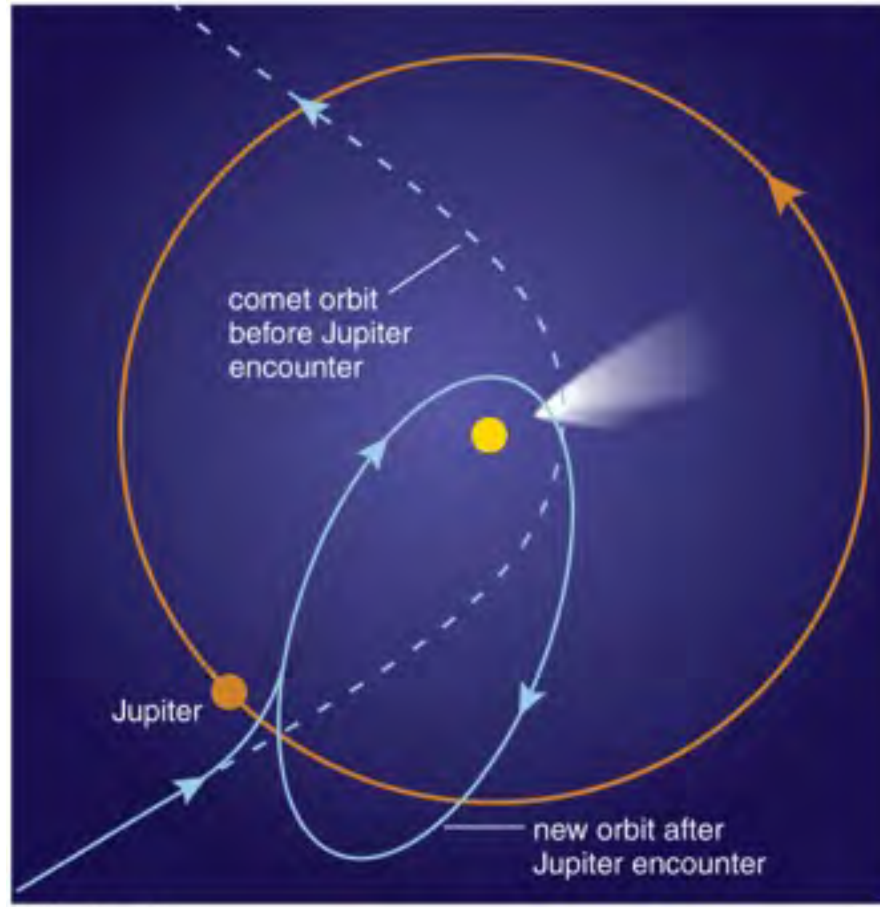
Changing an Orbit

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

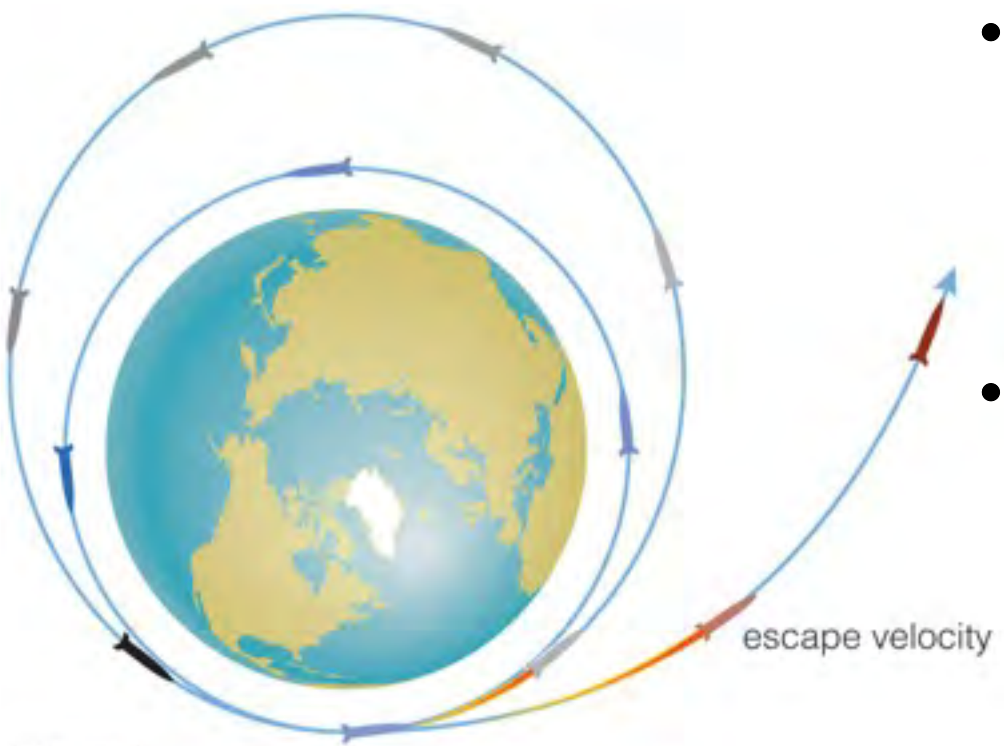
Friction or atmospheric drag

A gravitational encounter

Orbits don't rapidly decay on their own

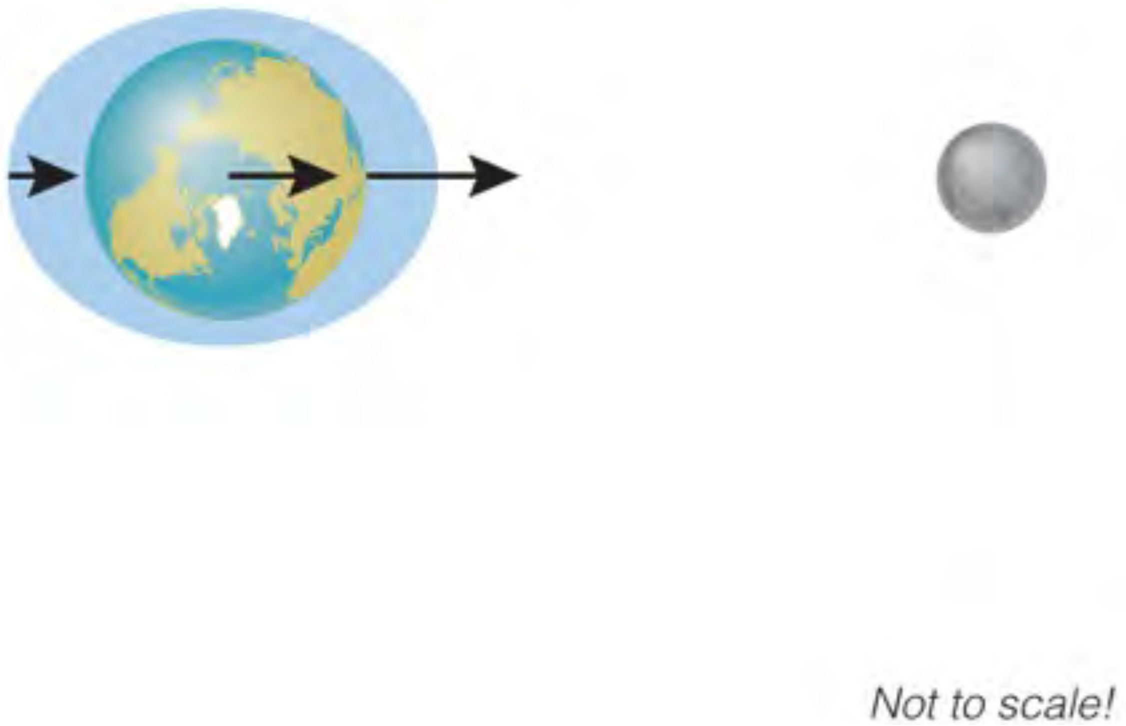


Escape Velocity



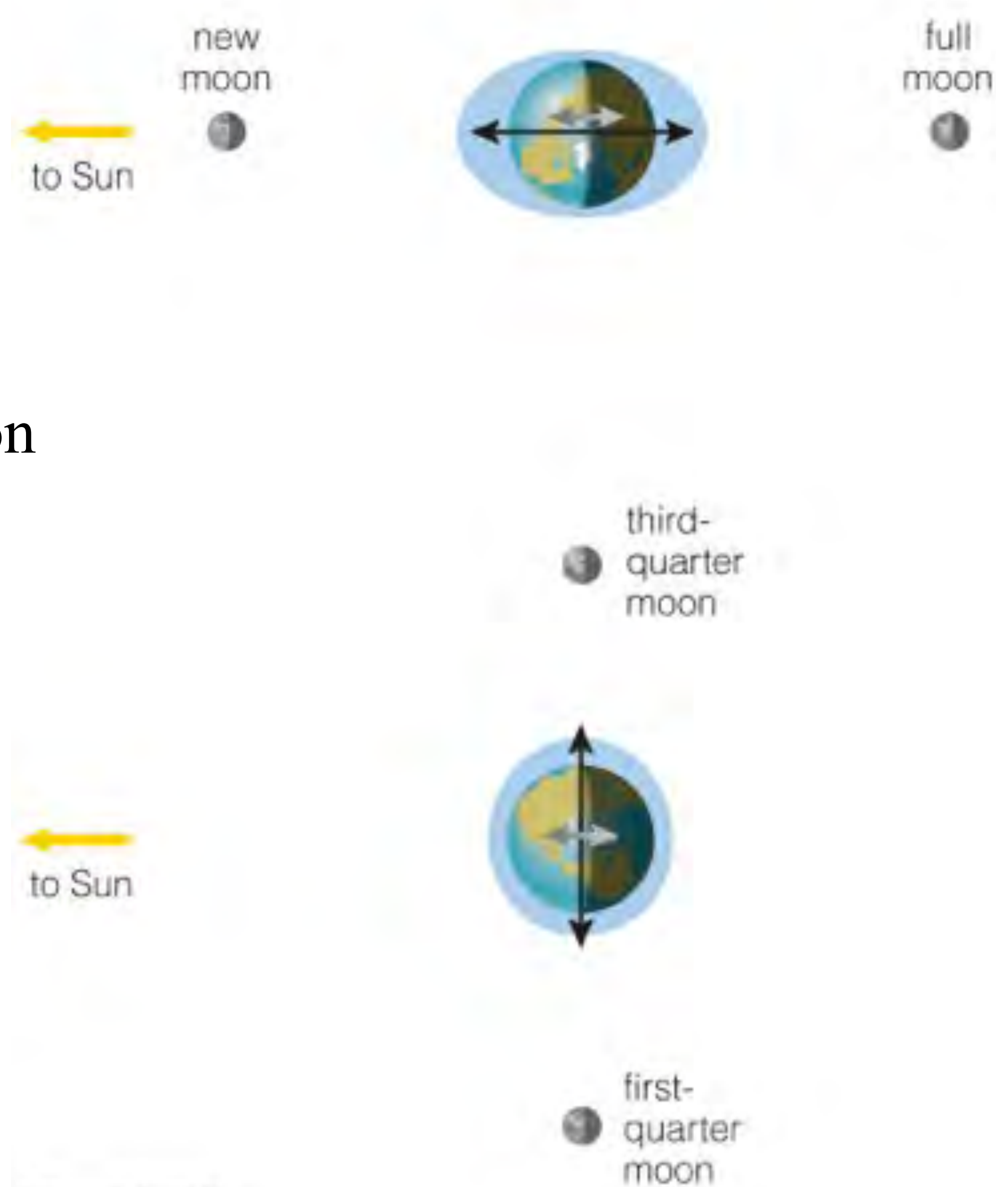
- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit).
- **Escape velocity** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr)

How does gravity cause tides?



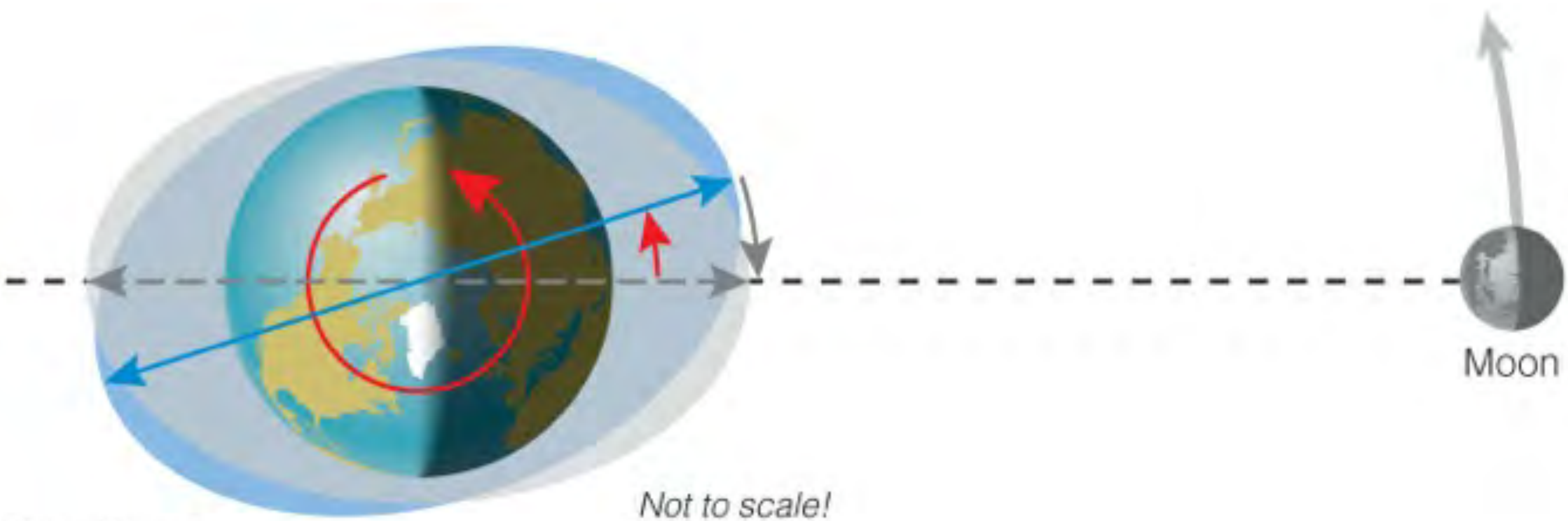
- Moon's gravity pulls harder on near side of Earth than on far side.
- Difference in Moon's gravitational pull stretches Earth.

Tides and Phases



Size of tides depends on phase of Moon.

Tidal Friction



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

Why do all objects fall at the same rate?

$$a_{\text{rock}} = \frac{F_{\text{g}}}{M_{\text{rock}}} \qquad F_{\text{g}} = G\frac{M_{\text{Earth}} M_{\text{rock}}}{R_{\text{Earth}}^2}$$

$$a_{\text{rock}} = G\frac{M_{\text{Earth}} \cancel{M_{\text{rock}}}}{R_{\text{Earth}}^2 \cancel{M_{\text{rock}}}} = G\frac{M_{\text{Earth}}}{R_{\text{Earth}}^2}$$

- The gravitational acceleration of an object like a rock does not depend on its mass because M_{rock} in the equation for acceleration cancels M_{rock} in the equation for gravitational force.
- This "coincidence" was not understood until Einstein's general theory of relativity.

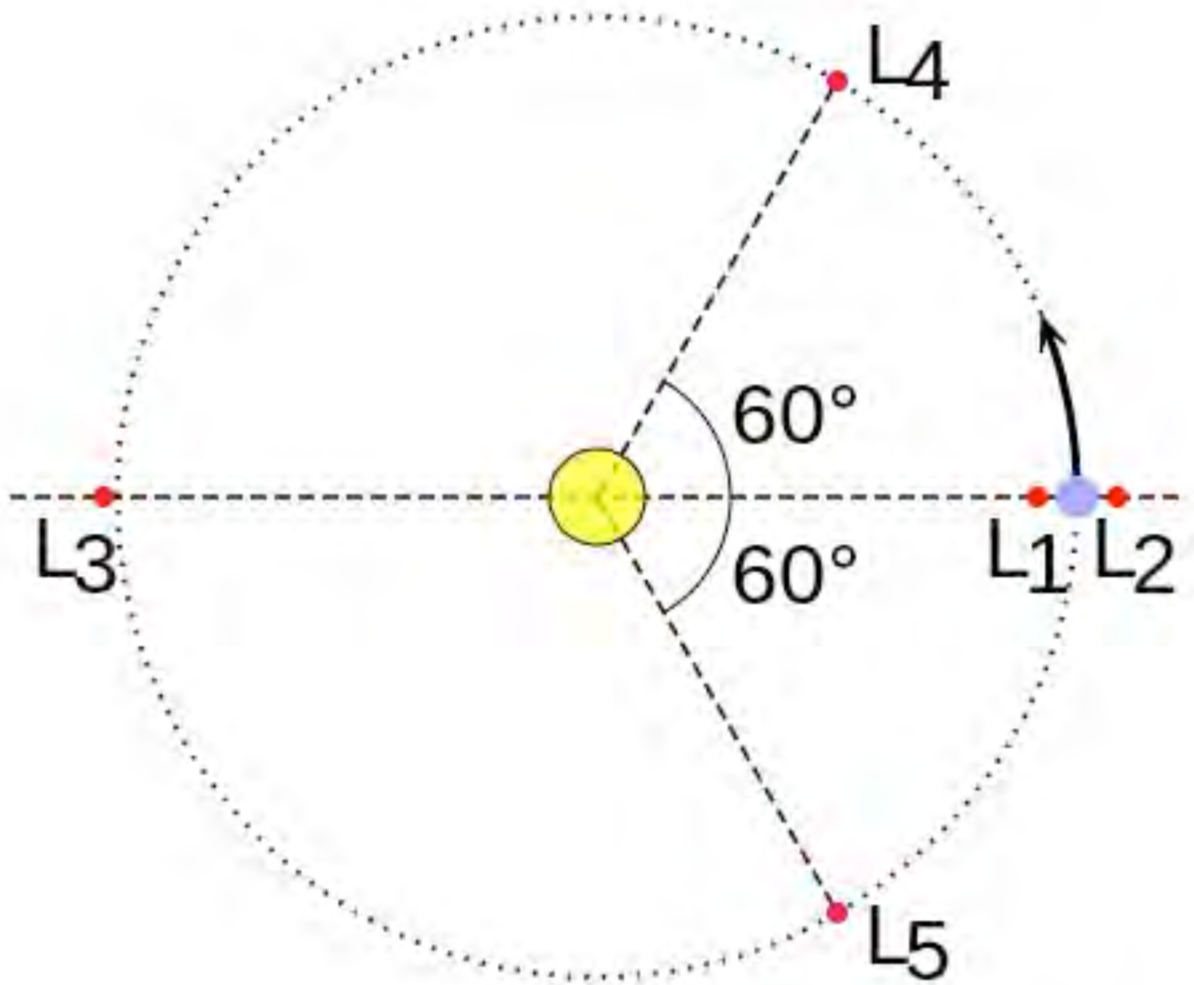
Einstein

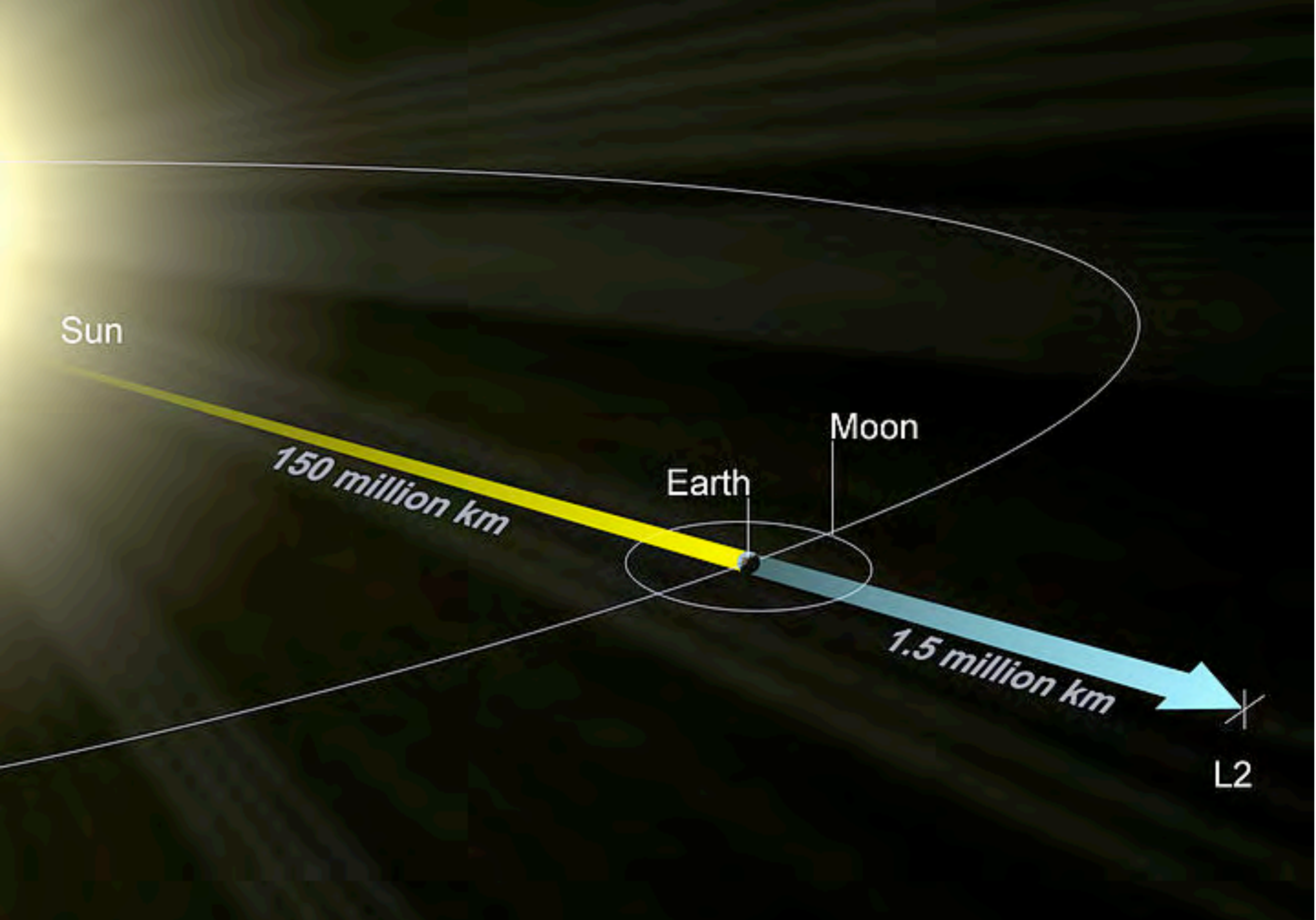
- Modified theory of motion and gravity, only needed in extreme conditions like high velocities or high masses/small sizes
- Depends on speed of light being constant
- Depends on equivalence of gravity and acceleration, leading to…
  - Special/General Relativity
    - Must get it right. Lorentz factor is sometimes enough: $(1-(v^2/c^{2)})^{-1/2}$
  - $E = mc^2$

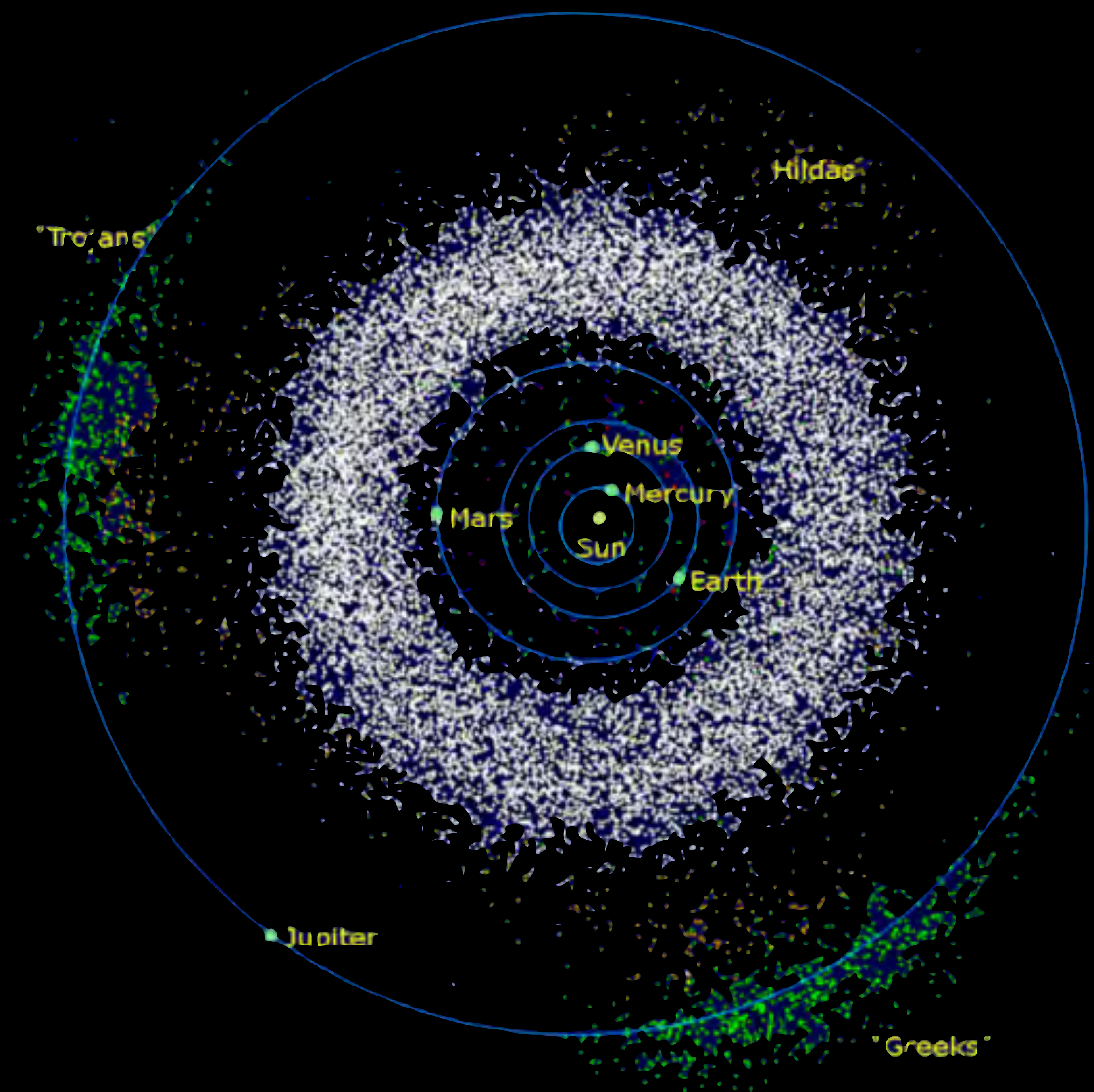
Just the Start!

- Tidal Forces around Condensed Objects
  - "Neutron Star" by Larry Niven
- Orbital Mechanics
  - Hohmann Transfer Orbits, Vis Viva Eqn., etc.
  - Nice website: http://www.mikebrotherton.com/2011/02/10/ten-terrific-resources-for-writing-space-based-hard-science-fiction/ that included a great page on orbital mechanics, as well as other stuff

Lagrangian Points




Sun
150 million km
Earth
Moon
1.5 million km
L2



Hildas
"Trojans"
Venus
Mercury
Mars
Sun
Earth
Jupiter
"Greeks"

Interplanetary Transport Network

http://en.wikipedia.org/wiki/Interplanetary_Transport_Network

Hohmann transfer orbit