Gravity: The Law of Attraction

Lecture 1, Oct. 1

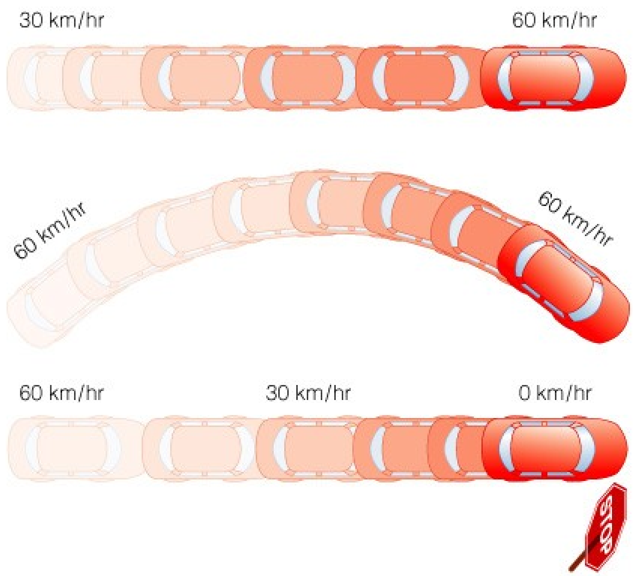
Astronomy 102, Autumn 2009

Questions of the day:

- How are **Force, acceleration,** and **mass** related?
- Why is gravity the most important force for astronomy?
- How does the strength of the gravitational force change with increasing mass? How does it change with increasing distance?
- Why does gravity cause orbital motion?

I. How do we define acceleration?

To understand acceleration, we first need to look at an object's motion:



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

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

example: speed of 10 m/s

- **Direction** of motion

- **Velocity**: Speed plus direction
  example: 10 m/s, due east

- **Acceleration**: Any change in velocity (either speed ***or*** direction)

Acceleration, sweet acceleration

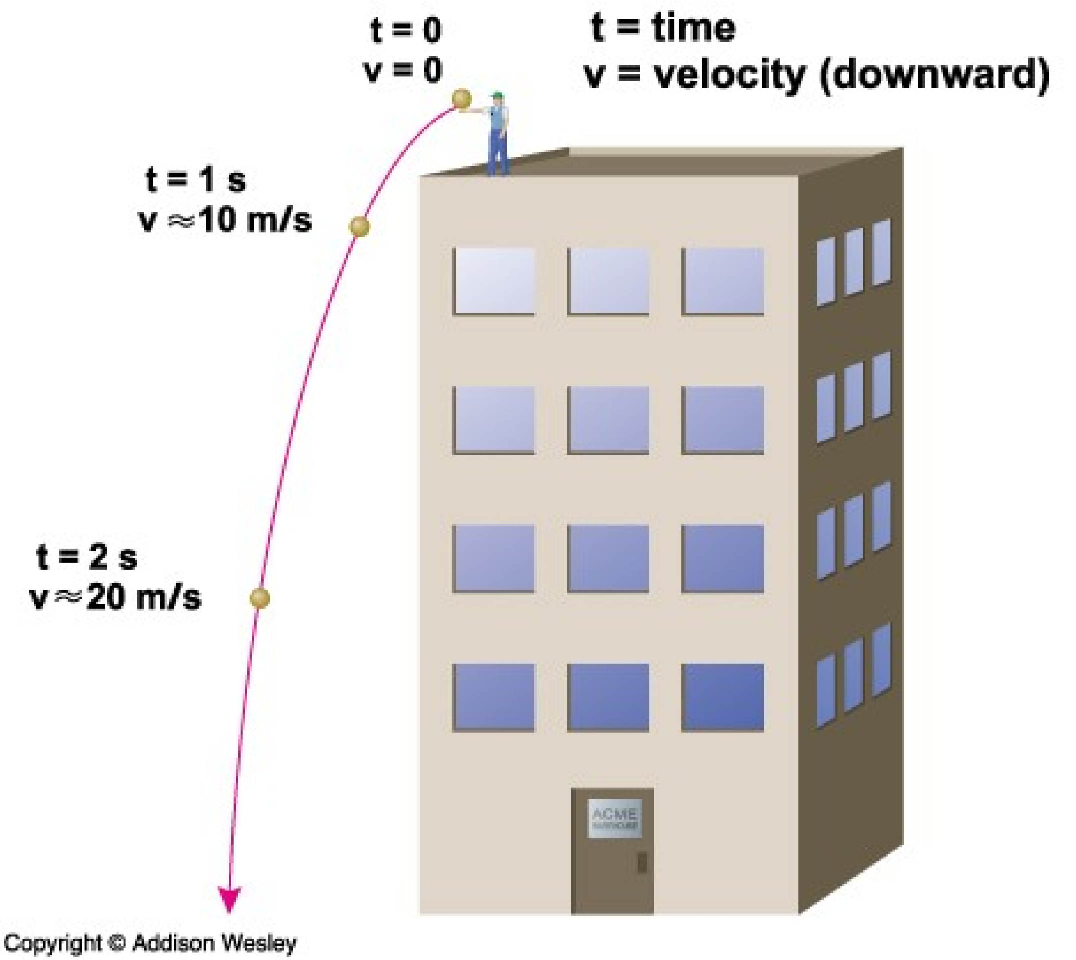
Tesla Roadster
Zero To Sixty < 4 sec!
Top Speed - 125 mph
220 mile range

Price $\$10^5$ (0.1 M$)

$$acceleration = \frac{velocity}{time} = \frac{60 mi/hr}{3.8 \sec} = \frac{26.8 m/s}{3.8 \sec} = 7.0 \frac{m}{s^2}$$

Gravity causes acceleration

- All falling objects accelerate at the same rate regardless of their weight
- Air resistance can affect the acceleration of an object as well
- On Earth, $g \approx 10$ m/s^2: speed increases 10 m/s with each second of falling.



II. What is a Force?

- **In Astronomy a Force is a pull (attraction) or a push (repulsion).**
- **Forces cause the direction and/or speed of motion to change.**

BUT

- **Forces can cancel each other out (meaning no change in direction or speed)**
- **Acceleration requires a “net force” - not all forces on an object are cancelled**

Forces…

If speed changes or direction changes

Then there must be a net force acting on it!

If both speed and direction are constant (or an object remains at rest)

Then no force acts OR else the forces balance each other out.

Which of these do NOT have a net force (i.e. no acceleration)?

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

III. What is mass?

- Not **weight**: your weight is different on the Moon!
- The amount of matter in an object: your mass is the same everywhere

IV. What are Newton's Laws & why are they important?

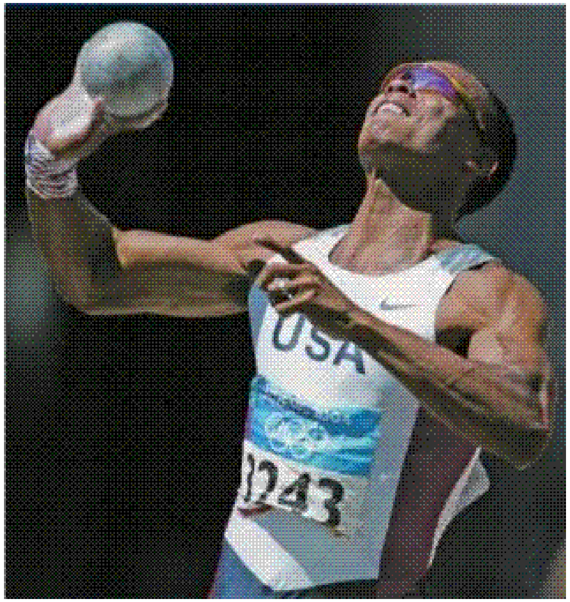
Sir Isaac Newton
(1642-1727)

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

Newton's second law of motion

$$\boxed{acceleration = \frac{Force}{mass}}$$

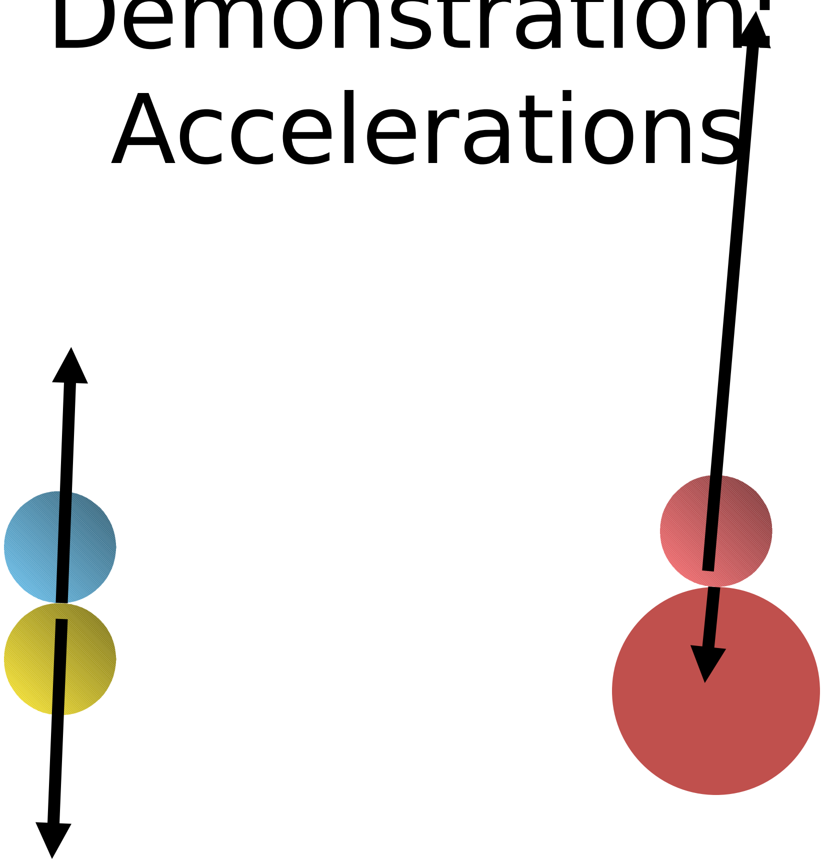
Accelerations are responses to forces, and the acceleration is BIGGER for smaller masses (per pound of force)



Demonstration: Forces

Equal and Opposite

Demonstration: Accelerations



$$acceleration = \frac{Force}{MASS}$$

Nature has **FOUR** fundamental forces…

- Gravitational force - attractive, long-range, weak, depends on mass
- Electromagnetic force - repulsive or attractive, depends on electric charge
- Strong nuclear force - “glue” of atomic nuclei
- Weak nuclear force - causes heavy atoms to break apart creating radioactivity

Gravity is the primary force that matters for astronomy!

- Strong and Weak Nuclear forces have very short distance of influence ($<10^{-12}$ cm).
- Electromagnetic force has a large distance of influence, but astronomical objects are not charged.

BUT IN CONTRAST

- Gravity operates over *any* distance, and affects *anything* with mass.

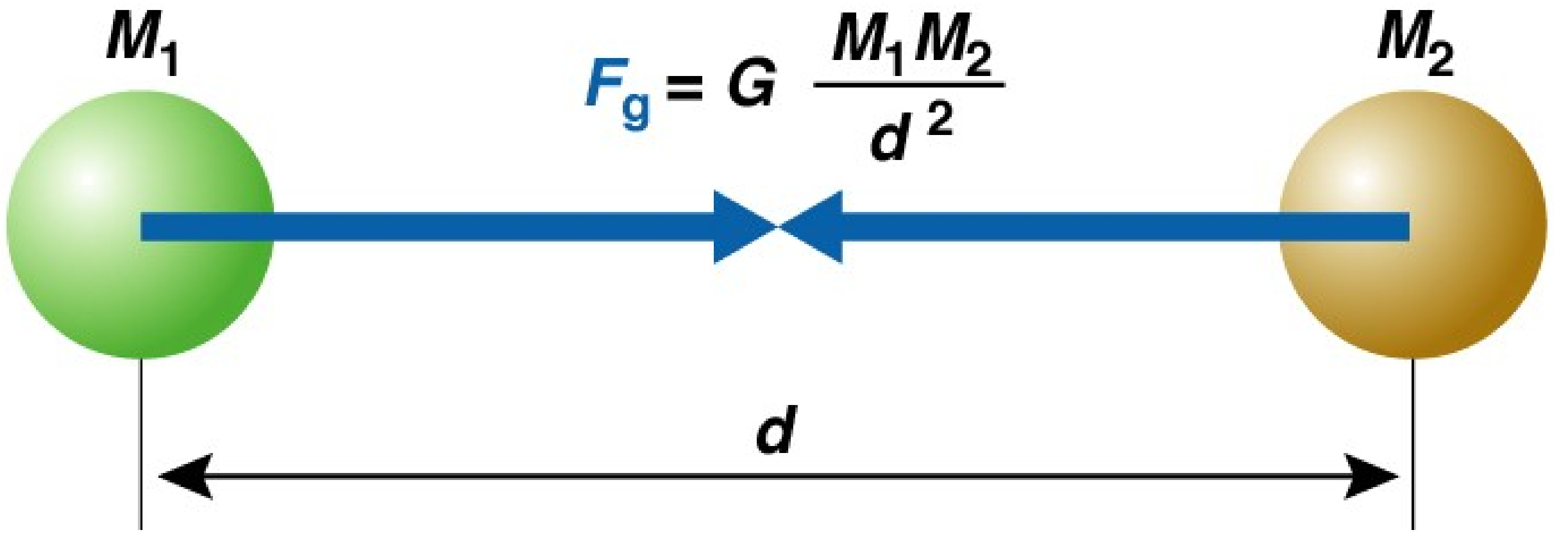
Getting to know Gravity

- Gravitational force is stronger between larger masses.
- The gravitational force gets weaker over larger distances.
- When a planet/star/galaxy is spherical, you can pretend that all the mass is in a single point at the center of the sphere, rather than an extended distribution

V. How does the strength of gravity vary with mass and distance?

The **Universal Law of Gravitation:**

- Every mass attracts every other mass.
- The gravitational force between two objects increases when either mass increases.
- The gravitational force between two objects decreases as the *square* of the distance between their *centers* increases.



Dissecting the gravitational force equation…

These represent the mass of both objects.

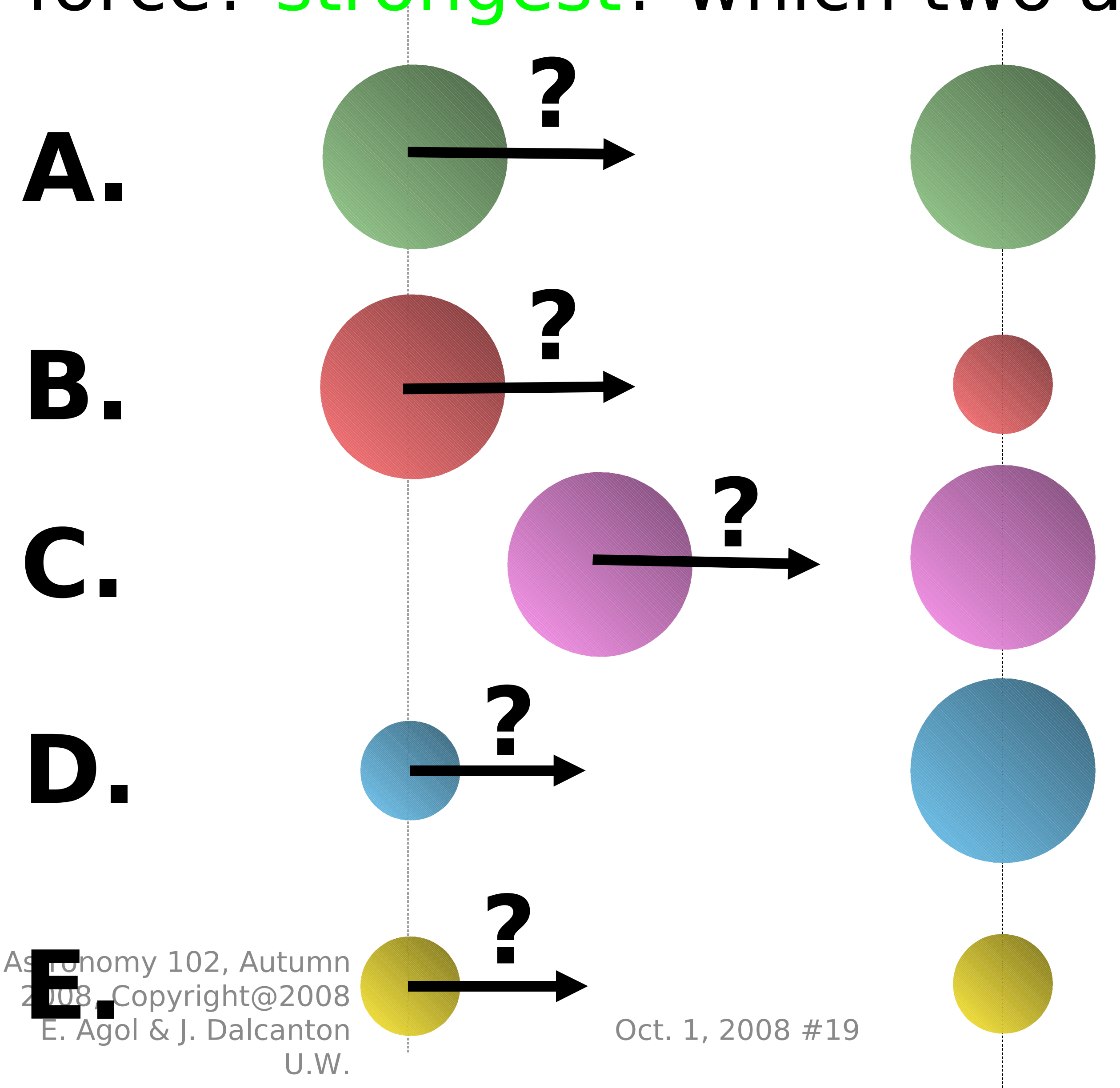
Amount of force

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

G is a universal constant we call “Newton’s Constant” (G=6.67x10^{-11} $m^3/kg/s^2$).

d = distance between the objects. Because we’re dividing by d^2, the force gets weaker as the distance increases.

Which of the following is the weakest force? strongest? which two are equal?



<u>Question:</u>

If gravity depends on mass, why is the gravitational acceleration the same for objects of any mass?

$$a_1 = \frac{F_g}{\cancel{M_1}}$$

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

$$a_1 = G\frac{M_2}{d^2}$$

So....

$$a_1 = G\frac{M_2}{d^2}$$

Since M_1 has cancelled, the gravitational acceleration of an object *doesn't* depend on that object's mass.

Your change in motion depends on every *other* mass in the universe, but *not your own mass*!

Many things in the universe travel in (nearly) circular motion:

- Moons around planets
- Planets around stars
- Stars around the center of galaxies
- UFOs that get lost & don't ask for directions

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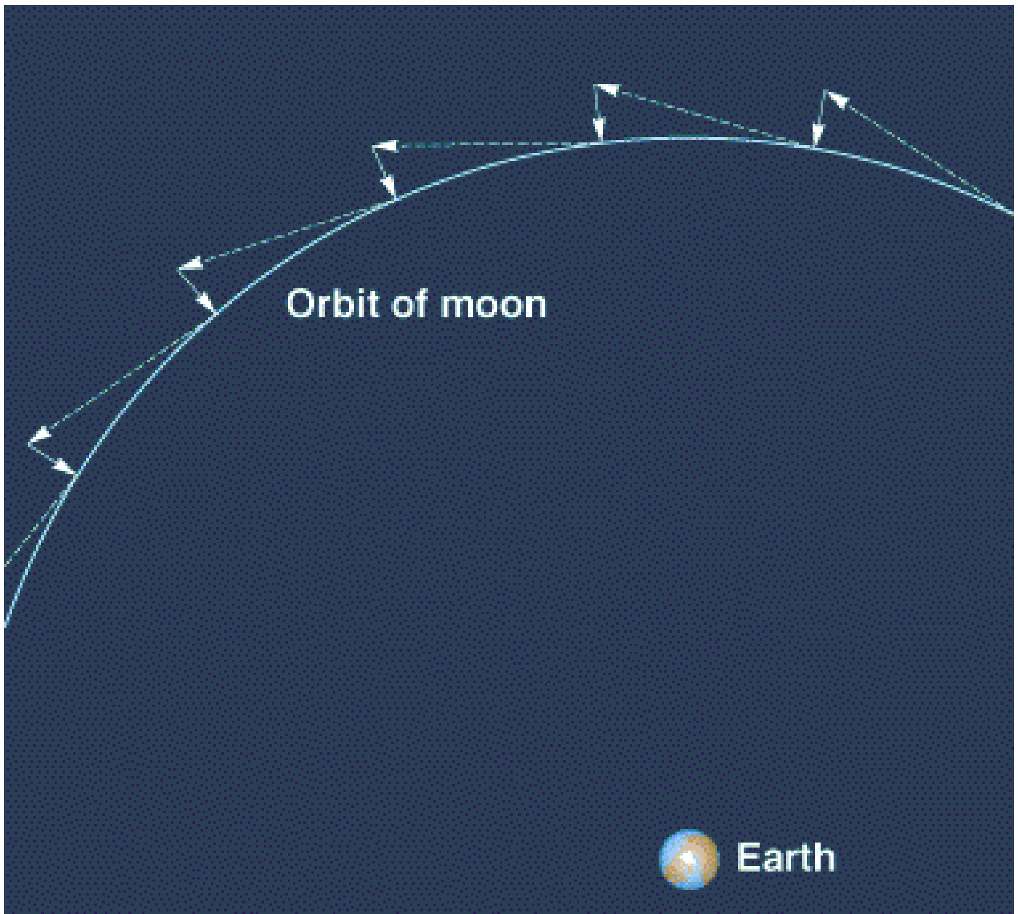
VI. Why does gravity cause orbital motion?

- Why doesn't the moon fall into the Earth?
- How fast does an object have to be going to orbit another object?

Gravity leads to circular orbits because IT PULLS.



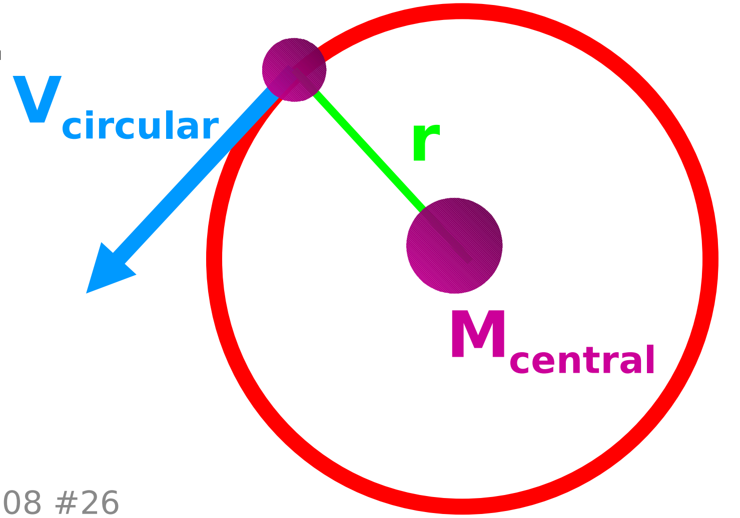
The Moon tries to travel in a straight path, but the gravitational pull of the Earth keeps tugging it back onto a circular path.

It's the same for the Earth around the Sun, or the Sun around the center of the Galaxy.

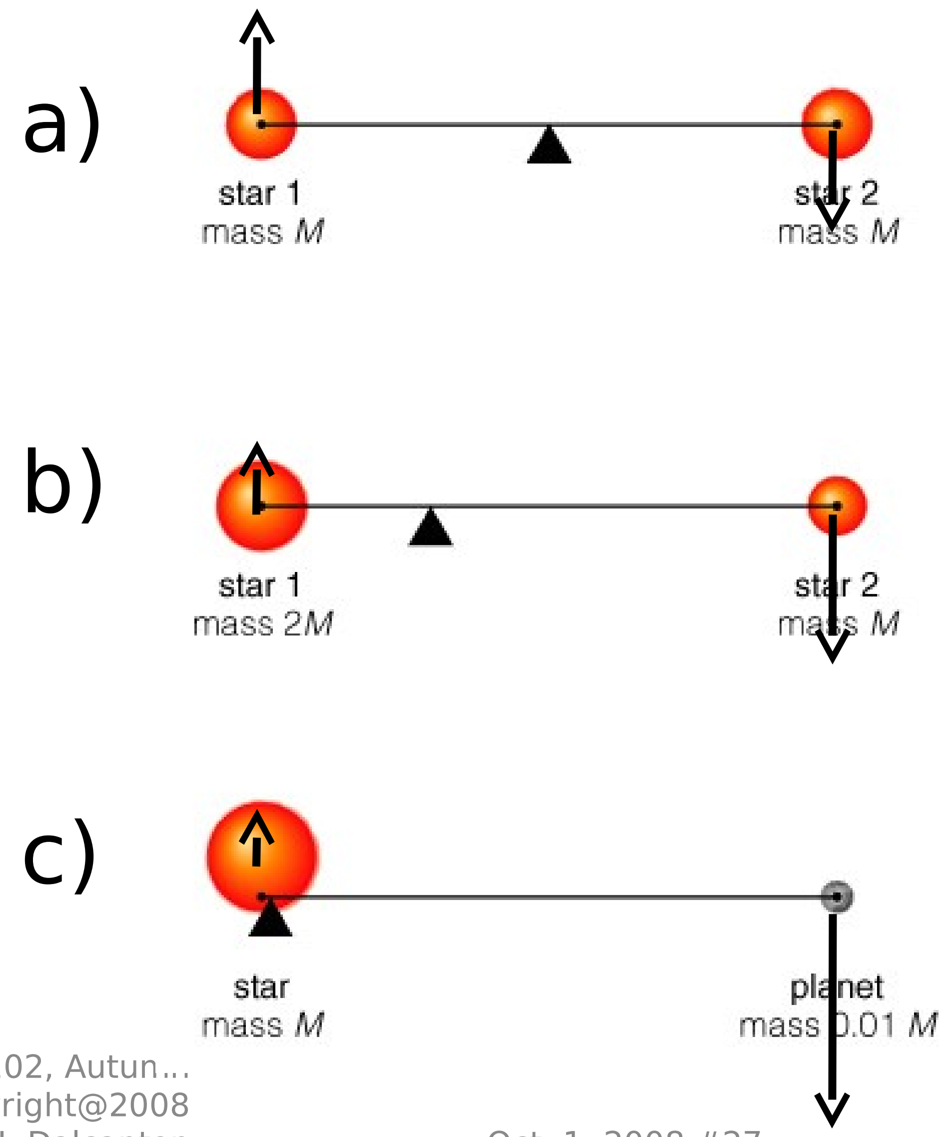
Rules of Orbital Motion

1. The acceleration of an orbiting object only depends on the central mass.
2. If the central mass increases, the velocity of the orbit must increase to stay in orbit.
3. If the separation increases, the velocity decreases.

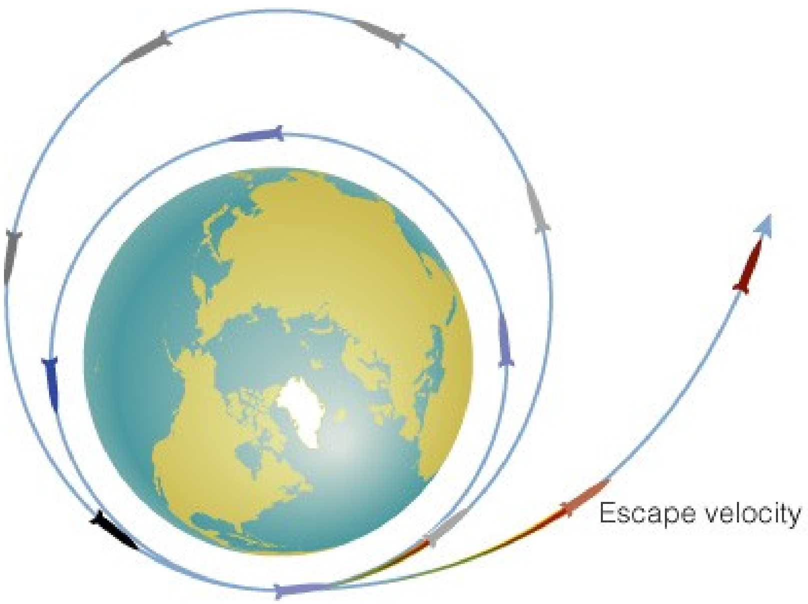
$$V_{circular} = \sqrt{\frac{GM_{central}}{r}}$$



4. Objects orbit around the center of mass



5. Objects can escape orbits



- If an object gains enough velocity, it may escape (change from a bound to unbound orbit)
- **Escape velocity** from Earth ≈ 11.17 km/s from sea level (about 25,000 miles/hr)

Recap:

- Acceleration increases with force and decreases with mass
- Gravity causes attraction between all objects in the universe
- The attraction increases with mass and decreases with distance
- Gravitational acceleration is independent of an object's mass
- Gravitational forces cause objects to orbit in circular motion (or ellipse)
- Objects moving too fast can escape orbit

Next Time

- Atoms & the structure of matter!
- Read Chapter 5.1 and 5.3