Universal Gravitation

Gravity is the reason behind books being dropped and suitcases feeling heavy. It's also the reason our atmosphere sticks around and oceans staying put on the surface of the earth. Gravity is what pulls it all together, and we're going to look deeper into what this one-way attractive force is all about.

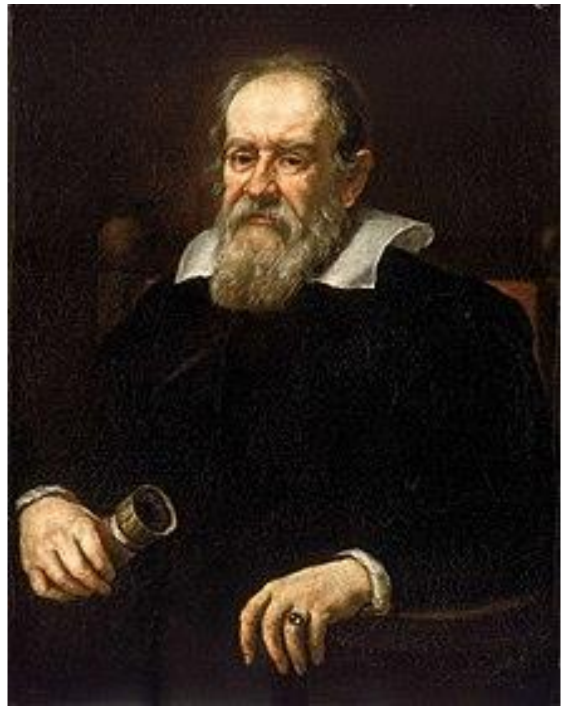
Galileo was actually one of the first people to do science experiment on gravity. Galileo soon figured out that objects could be the same shape and different weights (think of a golf ball and a ping pong ball), and they will still fall the same. It was only how they interacted with the air that caused the fall rate to change. By studying ramps (and not just dropping things), he could measure how long things took to drop using not a stopwatch but a water clock (imagine having a sink that regularly dripped once per second).

Whenever I teach a class about gravity, I'll drop something (usually something large). After the heads whip around, I ask the hard question: "Why did it fall?"

You already know the answer – *gravity*.

But why? Why does gravity pull things down, not up? And when did people first start noticing that we stick to the surface of the planet and not float up into the sky? No one can tell you why gravity is – that's just the way the universe is wired. **Gravitation is a natural thing that happens when you have mass.**

Would it sound strange to you if I said that **gravity propagates at the speed of light**? If we suddenly made the sun disappear, the Earth's orbit wouldn't be instantaneously affected… it would take time for that information to travel to the earth. What does that mean? By the end of these labs, you'll be able to tell me about it!



So far, saying the force of gravity is pretty comfortable. When you throw a ball high in the air, the force of gravity slows it down and as it falls back to the earth the force of gravity speeds the ball up. The force of gravity causes an acceleration during this flight, and is called the acceleration of gravity.

The acceleration of gravity g is the acceleration experienced by an object when the only force acting on it is the force of gravity. This value of g is the same no matter how massive the object is. It's always 9.81 m/s^2.

Johannes Kepler, a German mathematician and astronomer in the 1600s, was one of the key players of his time in astronomy. Among his best discoveries was the development of three laws of planetary orbits. He worked for Tycho Brahe, who had logged huge volumes of astronomical data, which was later passed onto to Kepler.

Kepler took this information to design and develop his ideas about the movements of the planets around the Sun. We explored Kepler's

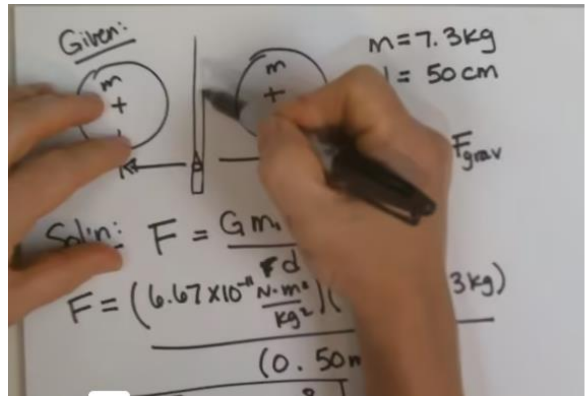
Laws last week in detail, but here they are in a nutshell:

1. The Law of Orbits: All planets move in elliptical orbits, with the sun at one focus.
2. The Law of Areas: A line joining the planet to the sun sweeps out equal areas in equal times.
3. The Law of Periods: The square of the period of any planet is proportional tot he cube of the semi-major axis of its orbit.

Did you notice that while Kepler's Laws describe the motion of the planets around the sun, they don't say *why* these paths are there? Kepler only hinted at an interaction between the sun and the planets to drive their motion, but not between the planets themselves, and it really was only a teensy hint.

Sir Isaac Newton wasn't satisfied with this explanation. He was determined to figure out the cause for the elliptical motion, especially since it wasn't a circle or a straight line (remember *Newton's First Law: Objects in motion tend to stay in motion unless acted upon by an unbalanced force*) And circular motion needs centripetal force to keep the object following a curved path (we'll cover this soon in our math labs). So what force was keeping the planets in an ellipse around the sun? That's what our Math Labs are going to explore and discover!

All objects are attracted to each other with a gravitational force. You need objects the size of planets in order to detect this force, but everything, everywhere has a gravitational field and force associated with it. If you have mass, you have a gravitational attractive force. Newton's Universal Law of Gravitation is amazing not because he figured out the relationship between mass, distance, and gravitational force (which is pretty incredible in its own right), but the fact that it's universal, meaning that this applies to every object, everywhere.



One of Newton's biggest contributions was figuring out how to show that gravity was the same force that caused both objects like an apple to fall to the earth at a rate of 9.81 m/s^2 AND the moon being accelerated toward the earth but at a different rate of 0.00272 m/s^2.

If these are both due to the same force of gravity, why are they different numbers then? Why is the acceleration of the moon 1/3600th the acceleration of objects near the surface of the earth?

It has to do with the fact that gravity decreases the further you are from an object. The moon is in orbit about 60 times further from the earth's center than an object on the surface of the earth, which indicates that gravity is proportional to the inverse of the square of the distance (also called the inverse square law).

The force of gravity acts between any two objects and is inversely proportional to the square of the distance between the two centers. The further apart the objects are, the less they force of gravity is between the two of them. If you separate the objects by twice the distance, the gravitational force goes down by a factor of 4.

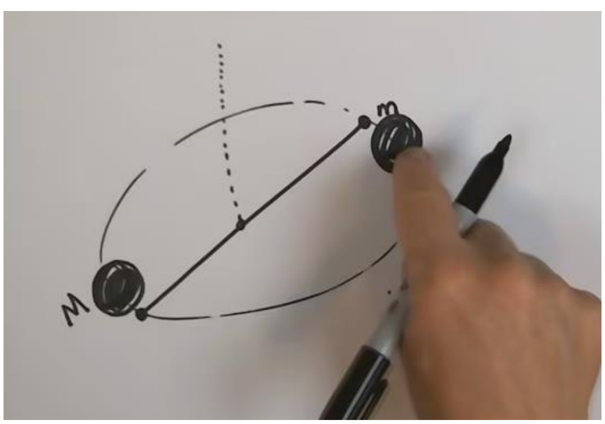
Universal Law of Gravitation:

Newton suggested that every particle everywhere attracts every other particle with a force given by the following equation. If you have mass, then this force applies to you. Newton's Universal Law of Gravitation is:

$$F = G\frac{m_1 m_2}{r^2} \qquad \text{where } G = 6.673 \times 10^{-11}\ \frac{N\,m^2}{kg^2}$$

That G is called the universal gravitation constant and is determined by doing experiments.

Lord Henry Cavendish in 1798 (about a century after Newton) performed experiments with a torsion balance to figure out the value of G. It's a very small number, so Cavendish had to carefully calibrate his experiment! The reason the number is so small is because we don't see the effects of gravity until objects are very massive, like a moon or a planet in size.



Cavendish used an experiment where two small lead spheres were fastened to the ends of a rod which had a very fine string (actually a quartz fiber) attached to the middle so it could be lifted off the ground. This is called a torsion balance, meaning that you can carefully measure the twist in the string by measuring how much the rod spins around. (Torsion balances can be made from other materials that have a stiffer spring constant value, like metal rods.)

Back to his experiment: Cavendish placed two large lead spheres next to the smaller spheres, which moved the larger spheres and exerted a torque on the rod, and Cavendish was able to calculate the value of G.

The value of G is always the same, everywhere you go and any situation you apply it to. Once you know the masses and distances between objects, you can always calculate the force due to gravity with this one equation.

Although Newton's Law of Gravitation applies only to particles, you can apply it to real objects as long as the sizes of the objects is small when you compare it to the distances between them.

LABS: For the labs, please get out your math journal and watch the videos, and write down everything as I am demonstrating it to you. I'll explain each of the problems in detail as well as working out the solution. Due to the complexity of these problems, we're going to everything on the videos together.