Newtonian Gravity: Crash Course Physics #8

Crash Course: Physics
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When people say that Isaac Newton completely transformed the field of physics, they really aren't kidding. Now, we've already talked about his three laws of motion, which we use to describe how things move. But another of Newton's famous contributions to physics was his understanding of gravity.

When Newton was first starting out, scientists' concept of gravity was pretty much nonexistent. I mean, they knew that when you dropped something, it fell to the ground, and from careful observation, they knew that planets and moons orbited in a particular way. What they didn't know was that those two concepts were connected.

Of course, just like with motion, we now know that there's a lot more to gravity than what Newton was able to observe. Even so, when it comes to describing the effects of gravity on the scale of, say, our solar system, Newton's law of universal gravitation is incredibly useful. And it all started with an apple... Probably. [Theme Music] Odds are, you've been told the story of Newton's apple at some point. The story goes that one day, he was sitting under an apple tree in his mother's garden, when an apple fell out of the tree. That's when Newton had his grand realization that something was pulling that apple down to Earth. And that led to another idea: What if the apple was pulling on Earth, too, but you just couldn't tell, because the effect of the apple's force on Earth was less obvious?

A few years later, Newton was sitting in the same garden when he had another stroke of inspiration: What if the same force that pulled the apple to the ground could affect things much farther from Earth's surface -- like the Moon? It was kind of counterintuitive, because the Moon orbits Earth, instead of crashing straight into the ground like an apple that falls off a tree. But Newton realized that the Moon was still being pulled toward Earth -- it was just moving sideways so quickly that it kept missing. That's what was keeping it in orbit.

If gravity was keeping the Moon in orbit, what if it affected the behavior of any two objects -- like a planet orbiting the Sun? That's the official version of the story -- the one Newton himself used to tell. Most historians think he was embellishing at least a little, but there probably is some truth to it. Whether or not the thing with the apple actually happened, Newton thought his idea seemed promising. The idea that gravity might affect everything, including the orbits of other planets and moons. So he started looking for an equation that would accurately describe the way the gravitational force made objects behave -- whether it was an apple falling on the ground, or the Moon orbiting Earth.

Newton knew that however this gravitational force worked, it would probably behave like any other net force on an object -- it would be equal to that object's mass, times its acceleration. The mass part was easy enough -- it would just be the mass of the apple... or the Moon. It was going to be a little harder to figure out the factors that were affecting the acceleration part of the equation.

The first thing Newton realized he'd have to take into account was distance. When an object is close to the Earth's surface, like an apple in a tree, gravity makes it accelerate at about 10 meters per second squared. But the Moon has an acceleration that's only about a 3,600th of that falling apple. The Moon also happens to be about 60 times as far from the center of Earth as that apple would be -- and 60 squared is 3600. So Newton figured that the gravitational force between two objects must get smaller the farther apart they are. More specifically, it must depend on the distance between the two objects squared.

Then there was mass. Not the mass of the apple or the Moon -- the mass of the other object involved in the gravitational dance: in this case, Earth. Newton realized that the greater the masses of the two objects pulling on each other, the stronger the gravitational force would be between them. Once he'd taken into account the distance between two objects, and their masses, Newton had most of his equation for the way gravity behaved: The gravitational force was proportional to the mass of the two objects multiplied together, divided by the square of the distance between them.

It had to be a lot smaller, or else you'd see a force pulling together most everyday objects. Like, that Rubik's cube is staying right where it is instead of being pulled towards me. So the gravitational force between us must be very small. So Newton added a constant to his equation -- a very small number that would make the gravitational force just a tiny fraction of what you'd calculate otherwise. He called it G. And he called this full equation, $F = GMm/r^2$, the law of universal gravitation. Newton had no idea what number big G would be, though. He just knew it would be a tiny number, and put the letter G into his equation as a placeholder.

About a century later, Henry Cavendish, another British scientist, made careful measurements with some of the most sensitive instruments of the time, and figured out that G was equal to about $6.67 * 10^{-11}$ $N*m^2/kg^2$. So indeed, Newton was right about big G having to be quite small. But even though he didn't know the exact value of big G at the time, Newton had enough to establish his law of universal gravitation. He described gravity as a force between any 2 objects, and published his equation for calculating that force. Then Newton took things a step further -- well, technically three steps further.

About 50 years earlier, an astronomer named Johannes Kepler had come up with three laws that described the way orbits worked. And those predictions almost perfectly matched the orbits that astronomers were seeing in the sky. So, Newton knew that his law of universal gravitation had to fit with Kepler's laws, or he'd have to find some way to explain why Kepler was wrong.

Luckily for Newton, his law of gravitation not only fit with Kepler's laws, he was able to use it, in combination with his three laws of motion and calculus, to prove Kepler's laws. According to Kepler, the orbits of the planets were ellipses -- as opposed to circles -- with the Sun at one focus of the ellipse -- one of the two central points used to describe how the ellipse curves. And that's what's known as Kepler's first law, and it actually applies to any elliptical orbit -- not just those of the planets. Our moon's orbit around Earth is also an ellipse, and Earth is at one focus of that ellipse.

Kepler's second law was that if you draw a line from a planet to the sun, it'll always sweep out the same-sized area within a given amount of time. When Earth is at its farthest point from the Sun, for example, over the course of one day we'll have covered an area that looks like a very long, very thin, kinda-lopsided pizza slice. And when we're at our closest point to the Sun, one day's worth of the orbit will sweep out an area that's more like a short, fat pizza slice. Kepler's second law tells us that if we measure them both, those two pizza slices will have the exact same area.

His third law is a little more technical, but it's basically an observation about what happens when you take the longest -- or semimajor -- radius of a planet's orbit and cube it, then divide that by the period of the planet's orbit, squared. According to Kepler, that ratio should be the same for every single planet -- and now we know that it is, almost exactly. For every single planet that orbits our Sun, that ratio is either 3.34 or 3.35.

And! Newton was able to explain why the actual, observed orbits in the night sky sometimes deviated very slightly from Kepler's predictions -- for example, by having those slightly different ratios. What Kepler didn't know, and Newton figured out, was that the

planets and moons were all pulling on each other, and sometimes, that pull was strong enough to change their orbits just a little bit.

There's one more thing we should point out about Newton's law of universal gravitation, which is that it fits what we expect the equation for a net force should look like, according to Newton. From Newton's second law of motion, we know that a net force is equal to mass times acceleration. What the law of universal gravitation is saying, is that when the net force acting on an object comes from gravity, the acceleration is equal to the mass of the bigger object -- like Earth -- divided by the distance between the two objects, times big G.

So, you know how we've been describing the gravitational acceleration at Earth's surface as small g? Well, small g is actually equal to big G, times Earth's mass, divided by Earth's radius, squared...math! And we can use this equation for gravitational acceleration to help NASA out with a challenge they're grappling with right now.

We want to send humans to Mars. But we have to make sure that their spacesuits will work properly in Martian gravity. One way that NASA tests spacesuits is by flying astronauts on special planes -- sometimes called Vomit Comets. They fly in arcs that let the spacesuit-testers experience reduced weight -- or none at all -- for short periods of time. To simulate Martian gravity, the flight plan will need to aim for the gravitational acceleration you'd experience if you started hopping around on the surface of Mars.

So, what would that acceleration be? Well, from Newton's law of universal gravitation, we know that the acceleration of stuff at Mars's surface would be equal to big G, times the mass of Mars, divided by Mars's radius squared. We also happen to know Mars's mass and radius already, which... helps.

So, plugging in the numbers, we can calculate the gravitational acceleration at Mars's surface: it should be about 3.7 meters per second squared. That's the acceleration you'd experience on Mars, and what the Vomit Comet pilots try to attain when they fly -- about 38% of the acceleration that you experience when you jump off the ground here on Earth. So, hundreds of years after Newton's day, NASA is still using his math. Yeah, I'd say he was a pretty big deal.

Today, you learned about how Newton came up with his law of universal gravitation. We also talked about Kepler's three laws, and calculated the gravitational acceleration on the surface of Mars.

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