Teacher Tune-up

Quick Content Refresher for Busy Professionals

What is gravity?

One of the first things that children notice as they become aware of the world is that things fall toward the ground if they are not supported by something. We feel the effect of gravity on our own bodies and see it operating throughout the world around us, so we quickly come to take it for granted. This intuitive understanding of gravity works in day-to-day life, but it is very limited. For one thing, until Galileo's experiments on falling objects, people didn't understand that (leaving aside air resistance) all falling objects accelerate at the same rate regardless of their weight (falling 9.8 meters per second faster each passing second, or 9.8 m/s^2). And until Newton, it was far from obvious that the same gravitational force that pulls us to earth also governs the motion of the moon and planets. This wide-reaching explanatory power puts the "universal" in Newton's Law of Universal Gravitation.

Gravity is a force

In 1686, Isaac Newton showed that both local gravity on Earth and the orbits of planets could be explained if every piece of matter slightly attracts every other piece of matter according to a simple equation. Gravity is the force that attracts any pair of objects with mass to one another: the earth and the sun, the moon and the earth, an apple and the earth, and even one apple and another. Gravity always goes both ways: the earth attracts the apple and the apple also attracts the earth.

Newton formulated this insight in the Law of Universal Gravitation: the force of gravitational attraction between two objects is proportional to the product of their masses divided by the square of the distance between them.

$$F_{grav} \propto \frac{m_1 m_2}{d^2}$$

Here m_1 and m_2 are the masses of two objects, and d is the distance between them. This proportionality becomes a full-fledged equation when you include the universal constant of gravitation, G, which makes the units come out right.

$$F_{grav} = \frac{G m_1 m_2}{d^2}$$

Sidebar on *G*:

A quick look at G underscores an important point. The universal gravitational constant G has been experimentally determined to be 6.67×10^{-11} $N{\cdot}m^2/kg^2$. The N stands for newton, a unit of force equal to about 0.225 pounds, or roughly the weight of an apple. Those clunky squared meters and kilograms at the end just make things cancel out so we can get our answer in newtons. The thing to notice here is that sneaky little exponent, -11. That little guy is whispering to us that gravity is an *extremely* weak force.

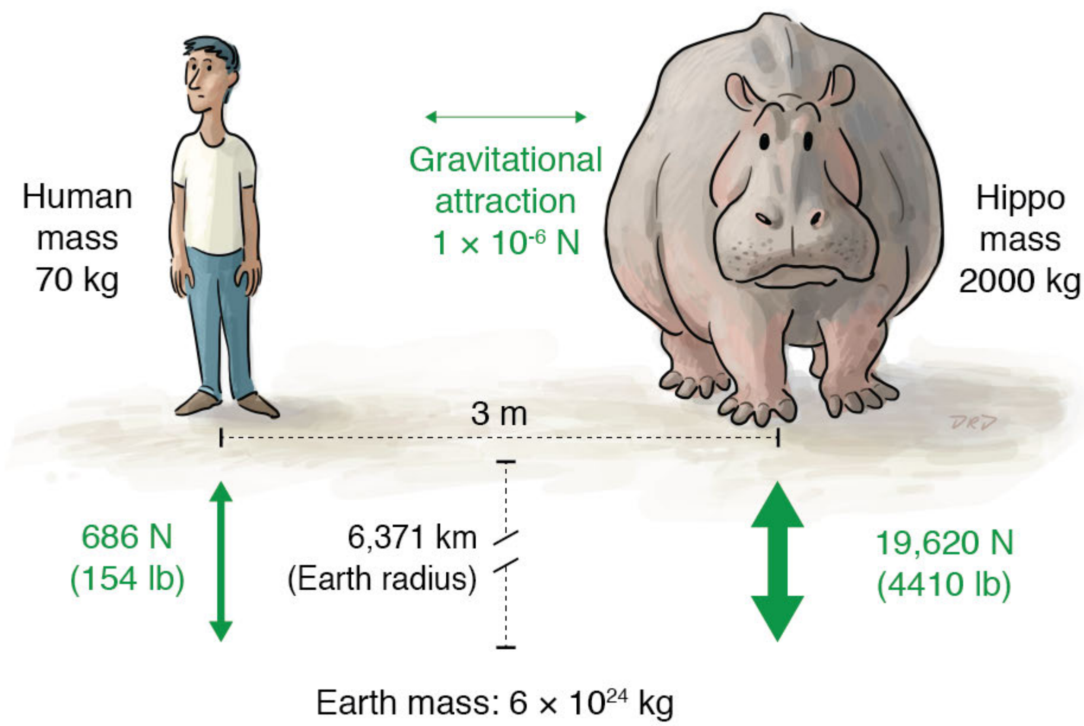
To see how weak, take the simplest possible case for this equation: two masses of 1 kilogram each, placed 1 meter apart (so that $m_1 m_2/d^2$ is simply equal to 1) have a gravitational attraction for each other of 6.67×10^{-11} N, or about 0.0000000000667 times the weight of an apple. To call that imperceptible would be an understatement!

Mass affects force strength

The more mass either of two objects has, the stronger the force of gravity between them (so there is a stronger force between the Earth and a car than between the Earth and a person). This relationship is directly proportional: double the mass of either object, for example, and the strength of the force of gravity also doubles. Since the force of gravity depends on the mass of both objects, a change in either one will affect the force strength.

Gravity is so weak that we do not notice the gravitational attraction between the relatively small objects around us. Gravity only becomes noticeable when one or both objects have a great deal of mass and are relatively near.

For example, if a 70-kilogram person stands 3 meters from the center of a 2000-kg hippopotamus (don't try this at home), the attraction between them is about one millionth of a newton. (One newton [1 N] is the force required to accelerate a one-kilogram object by one meter per second squared, or about 0.225 pounds.) The same person easily feels their own 686-newton weight, because Earth's huge 6-septillion-kilogram mass is more than enough to balance the larger distance of 6,371 km to its center.



Distance affects force strength

The closer the two objects are, the stronger the gravitational force (so there is a stronger force between the Moon and Earth than between the Moon and the Sun). This relationship is inversely proportional, and depends on the distance *squared*: if the distance is greater, the force is *much* weaker. For example, if the distance is doubled, the force is one-fourth of its original strength, because $1/2^2 = 1/4$. (So does an object 2 meters above the ground weigh 1/4 what it weighs when it's only 1 meter above the ground? Of course not—remember, we're measuring distance from the *center* of the earth!)

We do not personally notice the Moon's attraction on our bodies (about 0.0007 newtons for a 70-kilogram person) because the Moon is 384,400 km away and has 1.2% of Earth's mass (although this weak attraction is enough to cause ocean tides).

The force of gravity due to Earth is also called weight

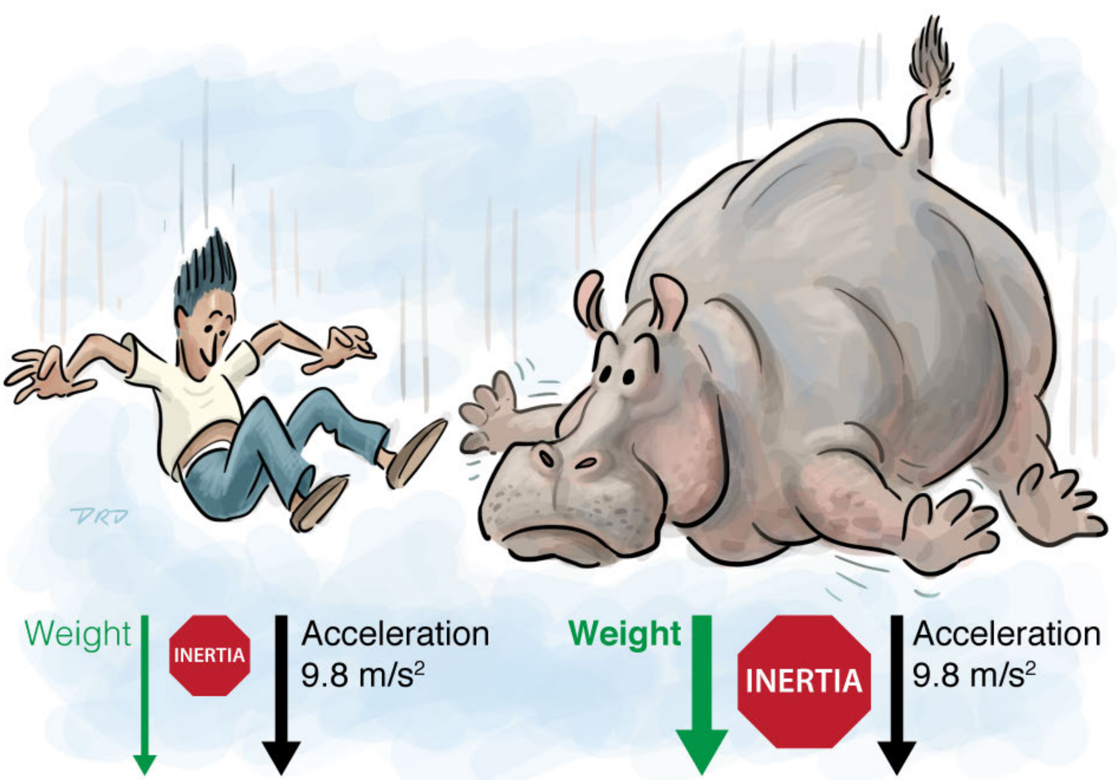
All objects in the universe are gravitationally attracted to each other. But because of small masses and/or vast distances, we can ignore many of these attractions. During our everyday lives, the force of gravity due to the earth is the dominant gravitational force on an object, and that's what we call the *weight* of the object.

When considering the weight of objects near the surface of the earth, we can simplify the earlier formula given for the force of gravity. Here's how: *G* is the same, m_1 is the mass of our object, m_2 is the mass of the earth, and *d*, the distance between the objects, is the radius of the earth (assuming the object is close to its surface.) Since the mass of the earth, the radius of the earth, and G are all constant numbers, we can pull out all those factors, yielding:

$$F_{grav} = m_{obj}\left(\frac{GM_{Earth}}{R^2_{Earth}}\right)$$

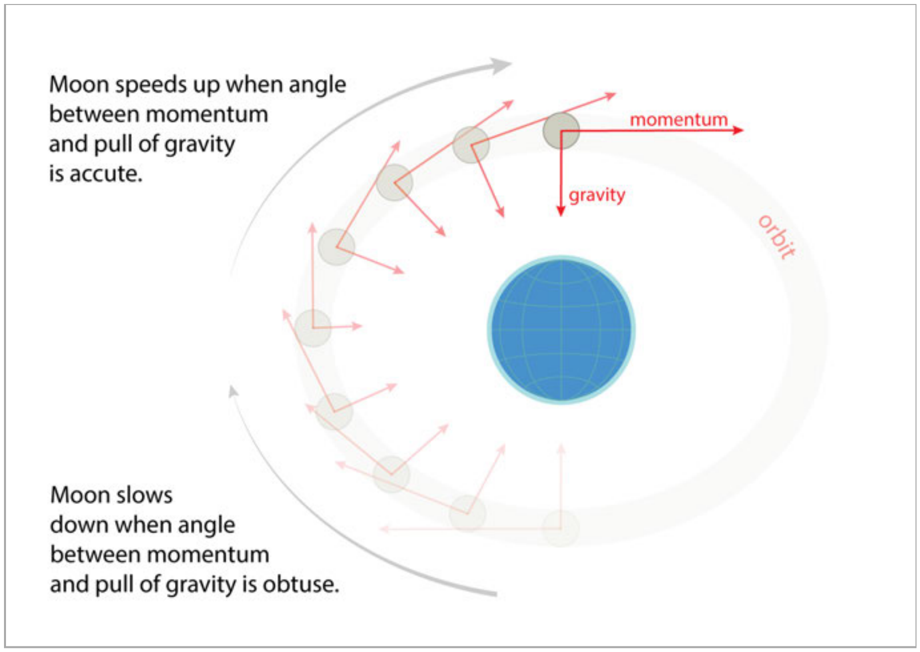
When you calculate the quantity in the parentheses above, you get 9.8 m/s^2: the acceleration due to gravity at the surface of the earth. That's the g in $F_{grav} = mg$. (Where do the seconds in 9.8 m/s^2 come from? Those units were packed inside of G, the universal constant of gravitation.)

That constant acceleration of 9.8 m/s^2 agrees with Galileo's observations. Earth's local gravity accelerates different objects at the same rate (leaving aside air resistance) because as *gravitational mass* increases, so does *inertial mass*. Drop a 1 kg object and a 2 kg object from the same height, and (leaving aside air resistance) twice the gravitational force working against twice the inertia yields the same acceleration.



And while we are puzzling over non-intuitive motion, how is it that the same gravitational force that pulls an apple straight down facilitates the orbit of the moon around the earth? Well, the gravitational attraction of the moon and Earth *does* pull the moon straight toward the earth. But at the same time, the moon has a lot of momentum pulling it sideways. If there were no gravity, the moon would make a beeline for deep space (in accordance with Newton's

First Law of Motion). But at every instant, the moon falls from its would-be straight-line path. This continuous tug-of-war between straight-line momentum and earthward pull results in a smoothly curving orbit around the earth.



While free-fall acceleration is 9.8 m/s² near the surface of the earth, it is 5.4 ft/sec² on the moon. A person who weighs 150 pounds on Earth would weigh about 25 pounds on the Moon. The smaller Moon mass reduces its gravity proportionally; gravity would be even weaker than it is on the moon's surface, but it's radius is 4 times shorter than that of Earth.

What about relativity, curved space-time, and all that jazz?

Newton's law of universal gravitation is a very reliable law when you're thinking about the weight of objects on Earth, building bridges, or launching satellites into orbit.

Newtonian thinking cannot explain certain phenomena, however. Light, for instance, has no mass, and yet gravity bends light rays. Another example: while Newtonian physics describes most planetary motions well, there's a small anomaly in the orbit of Mercury, the planet closest to the sun. (Mercury's orbit precesses about a hundredth of a degree more per century than it "should"; that may not sound like much, but it's enough to keep an astronomer up at night.)

This brings us to Albert Einstein's general theory of relativity. Newton described gravity as a force. Einstein reimagined gravity not as a force, but as a consequence of the fact that mass bends space-time. Objects traveling in straight lines (including light) follow the curvature of space-time caused by mass. General relativity also accounts for the anomaly in Mercury's orbital precession, and for other things that classical Newtonian physics doesn't get quite right.

Einsteinian relativity plays havoc with both Euclidian geometry and Newtonian physics where gravity is extremely powerful (as it is on Mercury's nearest approach to the sun) or when objects are moving at a significant fraction of light speed. But for life's daily little jobs like making a free throw in basketball or planning a trip to the moon, Newton's law of universal gravitation remains a remarkably precise approximation.