GRAVITY

IT'S UNIVERSAL

GRAVITY CONCEPTS

1   Gravity is the universal force of attraction between all matter

2   Weight is a measure of the gravitational force pulling objects toward Earth

3   Objects seem "weightless" when there is nothing holding them up

4   An orbit results from a combination of the forward motion of an object and the force of gravity

5   Astronomers use the law of gravity to analyze distant phenomena

Take a look at a few key concepts that are important to astronomy and astrophysics: gravity, orbits, weight, and weightlessness. Explore these concepts further using the recommended resources mentioned in this reading selection.

Gravity and astronomy

Why is understanding gravity important for astronomers? For one thing, gravity determines the structure and motion of every object in the universe. Without gravity, there would be no stars or planets—including Earth. All stars and planets are born inside giant clouds of gas and dust called nebulae. Stars and planets form when particles in these clouds are pulled toward each other by gravity.

Gravity also supplies the forces that keep Earth in orbit around the Sun, and the Moon in orbit around Earth. Without an orbit keeping Earth just the right distance from the Sun, we would not receive the Sun's life-giving light and warmth. Gravity also holds the atmosphere to Earth, and keeps us all from floating off into space. We owe our very lives to gravity.

On a practical level, no spacecraft could reach its destination, or achieve a successful orbit, without precise predictions of how gravitational forces will shape its journey through space. Fortunately, astronomers can predict how objects will move in space because gravitational forces work according to precise mathematical laws. Perhaps the most important application of these laws, however, is that astronomers can learn a great deal about objects billions of miles away by observing how they are affected by gravitational forces.

1 Gravity is the universal force of attraction between all matter

Gravity is more than just a force that pulls objects toward Earth. It is a universal force of attraction between all matter. The strength of this attraction depends on only two quantities: the mass of each object and the distance between the objects.

Gravity and Mass: The strength of the gravitational force between two objects depends on their mass, or how much matter they contain. The more mass, the stronger the gravitational force. For example, if you double the mass of one of two objects, you double the force of gravity between them. If you double both of the masses, then the force of gravity between them would be four times as strong. Thus, the strength of the force of gravity is directly proportional to the mass of the first object times the mass of the second.
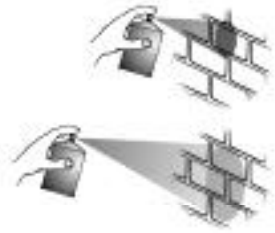
! Mathematically the inverse square law is expressed as an equation; however, it can be described with the following simple analogy. Imagine using a can of spray paint. If you stand one foot in front of a wall and spray the paint, it will make a small circle of thick paint. If you step back another foot and spray the paint again, you will get a much larger, and thinner, circle of paint. In this analogy, as you move farther away from an object, its gravitational attraction weakens in much the same way as the spray paint thins out the farther the can is moved away from the wall.

Gravity and Distance: The farther apart two objects are, the weaker the attraction between them. This relationship can be defined using an equation called the **inverse square law**:

$$F_1 \text{ (force)} = \frac{Gm_1m_2}{d^2}$$

G = Gravitational constant, m_1 = mass 1, m_2 = mass 2, d = distance between m_1 and m_2

This equation states that the gravitational force between two objects decreases with the square of the distance. For example, if the distance between the objects doubles, the gravitational force decreases by two squared, or four.

$$F_2 \text{ (force at twice the distance)} = \frac{Gm_1m_2}{(2d)^2} = \frac{Gm_1m_2}{4d^2} = \frac{1}{4}F_1$$

Increasing the distance by ten times would decrease the gravitational attraction by one hundred times.

$$F_{10} \text{ (force at ten times the distance)} = \frac{Gm_1m_2}{(10d)^2} = \frac{Gm_1m_2}{100d^2} = \frac{1}{100}F_1$$

Distance Must Be Measured from the Center

For an object as big as a planet, the distance considered in the inverse square law must be measured from the center of the object. The force of gravity between you and the Earth always pulls you toward the center of the Earth. This is because every piece of Earth attracts every piece of you. Some of these pieces are very close to you, but some are on the far side of Earth. Added together, all these forces of attraction add up to one big force pulling you toward the center of the Earth.

If you wanted to double the distance between you and the Earth, according to the inverse square law, you would have to double your distance from the center of Earth. Because Earth has a radius of 4,000 miles, you would need to travel to a point 4,000 miles above the surface of Earth. That is much, much higher than the astronauts in the Space Shuttle!

2 Weight is a measure of the gravitational force pulling objects toward Earth

Weight is a measure of the gravitational force pulling an object toward Earth's center. The more mass, or matter, that an object contains, the more it weighs. But weight is not the same thing as mass.

An object's weight depends on its mass (the amount of matter it contains), the mass of the Earth, and the distance between their centers. Its mass, on the other hand, is simply a measure of the quantity of matter in an object. The only thing your mass depends on is how many atoms you are composed of and what kind of atoms they are. No matter where you traveled on Earth or in the Universe, your mass would remain the same. But your weight would change, depending on how far away you went from Earth's center.

The only way to change how much you weigh without changing your mass is to move closer to or farther from the center of Earth. But even if you went to the highest point on the surface of the Earth, you would only weigh about a half-pound less. Any small change in weight due to a change in altitude is unnoticeable. Since we spend our entire lives at about the same distance from Earth's center, for all practical purposes, our weight is proportional to our mass.

Changing the Size and Mass of Earth

Your weight depends on your distance from the center of the Earth, your mass, and Earth's mass. If Earth's mass increased, and its diameter stayed the same, your weight would go up. If Earth's diameter increased, and its mass stayed the same, your weight would go down, because you would be farther from Earth's center.

! Measuring Your Weight on the Moon

What would happen if you picked up your bathroom scale and took it to the Moon? Since the Moon is less massive than the Earth, it has a much weaker pull on you. This means your weight would be less on the Moon than on Earth. In fact, you would weigh about one-sixth what you weigh on Earth.

M

If you're visiting the Moveable Museum, you can use a computer simulator to explore what would happen to their weight if they changed the size of Earth, or changed Earth's mass.

3 Objects seem weightless when there is nothing holding them up

To experience a sensation of weight, there must be something to hold you up. Gravity always pulls you down toward the center of the Earth, but the surface of the Earth pushes up against your feet with an equal force, which holds you up. If there were no surface beneath you, you would fall toward the nearest, most massive object (in our case, the Earth). When the only force acting on you is gravity, and there is nothing to resist this force and keep you from falling, you are said to be in a state of "free-fall." It is in this state that you experience "weightlessness."

For astronauts inside the space shuttle, the sensation of weightlessness is constant. The astronauts and the shuttle that contains them are both in a state of free fall, plummeting toward Earth at the same rate, like a rollercoaster that never reaches the bottom. The astronauts have no sensation of weight because no part of the shuttle presses back on them to resist their fall. This experience of weightlessness does not mean that there is no gravity acting upon the astronauts. It simply means that they do not sense gravity's pull because there is nothing resisting the force of gravity on their bodies. The floor of the shuttle does not hold them up because it, too, is falling.

Though people sometimes speak of "zero gravity," scientists prefer the word microgravity, because it is impossible to completely eliminate the force of gravity on an object. If you flew very, very far out into space, the gravitational attraction between you and Earth would become extremely small, because you would have greatly increased your distance from the center of the Earth. You would become very nearly weightless, but a tiny amount of gravitational attraction would always remain.

This is not the situation with astronauts in the Space Shuttle, however. The Space Shuttle orbits at barely 200 miles above the ground. That is only about 5 percent farther from Earth's center than objects on the surface of Earth. This increased distance from the center of Earth is only enough to decrease the weight of the astronauts in the shuttle by about 10 percent! Their experience of weightlessness in the Space Shuttle is not caused by a lack of gravitational forces acting on them. They feel weightless because they are in free-fall, and nothing is holding them up.

▶ **Try this Resource!**

Space Games asks students to imagine how familiar games would change when played in a "weightless" environment, and to determine how the rules of the games could be changed so they could be played in space. This resource is available at http://www.amnh.org/education/resources/rfl/pdf/du_u11_games.pdf

M If you're visiting the Moveable Museum, you can watch a video of astronauts working, eating, sleeping, and playing—all while seemingly "weightless." What do you think would happen to a common Earth toy in the weightlessness of space? After you've determined your answer, you can view an astronaut demonstrating the toy in the weightlessness of the Space Shuttle.

4 An orbit results from a combination of the forward motion of an object and the force of gravity

If Earth's gravity still pulls on the shuttle, why doesn't it fall to the Earth? In fact, the shuttle does get pulled toward Earth. But it is also moving forward at the same time. The combination of a rapid forward speed and falling towards the center of the planet creates a curved path around the Earth called an orbit.

All orbits are a combination of a forward motion and the pull of gravity. The forward motion must be at just the right speed to produce an orbit. If an orbiting object is moving too slowly, it will spiral inward and fall to Earth. If the object is moving too fast, it will continue on past Earth and sail off into space.

▶ **Try this Resource!**

Space Shuttle Orbiter lets students create an orbit by twirling objects on a string. The string provides an inward force that simulates gravitational attraction toward the Earth. This resource is available at http://www.amnh.org/education/resources/rfl/pdf/du_u12_shuttle.pdf

M If you're visiting the Moveable Museum, you can simulate launching satellites into orbit. A computer animation shows what happens when an orbiting satellite moves too slowly, too fast, or at the correct speed to maintain a stable orbit.
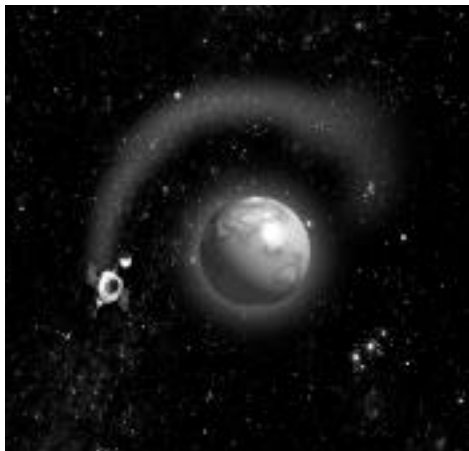
Orbits are a combination of a forward motion and the pull of gravity.

5 Astronomers use the law of gravity to analyze distant phenomena

Gravity behaves according to precise mathematical equations or "laws." These equations make it possible to understand a great deal about objects billions of miles away. For instance, the time it takes one object to orbit another is linked mathematically to the distance between the two objects and the mass of the object being orbited. Mathematical equations let astronomers calculate any of these quantities from the other two. For instance, you can figure out the mass of a planet simply by observing how its moons orbit around it. The mass of Jupiter was calculated this way hundreds of years ago.

Calculating gravitational forces also helps astronomers find planets. In the 1840s, the planet Uranus was observed straying from its predicted orbit. Astronomers reasoned that Uranus was being pulled by the gravitational attraction of another planet that had yet to be discovered. They calculated where the unknown planet would have to be in order to produce the gravitational effects observed on Uranus. Observatories pointed their telescopes in the predicted location —and found Neptune.

All the planets discovered orbiting stars other than the Sun were also found by applying the laws of gravity. Planets exert a gravitational force on the stars they orbit. This causes the stars to move slightly as the planets circle them. When astronomers observe a star "wobbling" back and forth, they can calculate where the planet must be to exert such a force —even when the planet itself is too far away to see.

For many distant objects, gravitational effects are the only thing astronomers can observe. Black holes, for instance, can never be seen directly. Yet many black holes have been located, simply by observing their gravitational effects on the matter around them.

Gravity is not the only force at play in the Universe. The heat inside a star creates pressure, which makes it expand. Gravity, meanwhile, pulls the star's gases back toward the center. The balance between these forces determines the size of the star. Thus, calculating the gravitational forces at work in the Sun, and measuring its size, provides information linked to its pressure and temperature.

Does Gravity Work the Same Everywhere?

Analyzing gravitational forces at work can provide an endless supply of information to astronomers. But in order to interpret distant phenomena by applying the laws of gravity, astronomers must assume that gravity behaves the same way in every part of the Universe. But how do they know that? If gravity were weaker in other galaxies, for instance, the equations used to analyze their motion would be incorrect. Everything ever observed indicates that the laws of physics are indeed universal. But how can anyone know for certain that the same laws apply everywhere?

The answer is, they cannot. There is simply no way to go to every corner of the Universe and perform experiments. To interpret data from distant space, astronomers must rely on what they call the Cosmological Principle: the assumption that the laws of the Universe are the same at all points and times. For instance, when observing light from distant objects, astronomers identify elements in them by the particular wavelengths of light they emit. To do this, they must assume that these elements emit the same wavelengths of light everywhere. There is no way to prove this. But without assumptions like these, all observations would be meaningless.

The Cosmological Principle should not be seen as a weakness of astronomy or physics. Many things simply cannot be proven. Rather, the emphasis placed on the Cosmological Principle should be seen as an example of how careful scientists are to distinguish unproven theories from tested observations.