Motion, Force, and Gravity

Understanding the motion of the Universe
Laws of Motion

Stationary objects do not begin moving on their own. In the same way, moving objects don’t change their movement spontaneously.

A force is required to cause a change in motion.

We call this the law of inertia.

The word “inertia” was invented from the Latin term for “laziness”. Objects are lazy, they only change their motion if forced to.
Galileo and Motion

So why do cars and balls roll to a stop? Why do planes need continuous thrust to fly?

Because they are acted on by forces. Generally, the important force is friction. Car tires and balls are in contact with the ground and airplanes push against the air they are traveling through.

In space, there is nothing to push against. So no force is necessary to keep planets or spacecraft moving through space. They are coasting...
Isaac Newton (1643-1727)

Newton is one of the greatest thinkers in human history. He made great leaps forward in our understanding of light and optics, the physics of motion, and the nature of gravity.

He also co-invented the new field of mathematics known as calculus.

Newton’s greatest work included much of the foundation of our understanding of physics. In this book, he published his 3 laws of motion.
First Law: A body continues at rest or in uniform motion in a straight line unless acted upon by some force. (law of inertia)

Object (a) and (b) will remain that way.

Object (c) experiences a force.
Imagine whirling a ball on a string over your head. If the string breaks, what path will the ball follow?

Path A
Path B
Path C
Path D
**Second Law**: A body’s change in motion is in proportion to the force and in inverse proportion to the body’s mass. (force law)

\[
\text{acceleration} = \frac{\text{force}}{\text{mass}}
\]

Larger force produces *larger* acceleration.

Larger mass results in *smaller* acceleration, because the body’s inertia (“laziness”) is larger.
Three rockets begin at rest, then fire their engines. The engines produce equal forces on the rockets.

Which rocket shown below has the largest mass?

Rocket A

Rocket B

Rocket C
Third Law: In every action, there is an equal and opposite reaction. (action-reaction pairs)

Forces *always* come in pairs.

When one object exerts a force on another, the second object exerts a force on the first.

You push on a wall, and the wall pushes back.

If it didn’t, there would be nothing to hold you up!
Which of these statements is correct?

A. Earth’s gravity holds you on the ground, but you are simply too small to produce a gravitational attraction on Earth.

B. Earth’s gravity holds you on the ground and you exert a force on Earth, too. But your gravitational force on Earth is much smaller.

C. Earth’s gravity holds onto you and your gravity also pulls up on Earth with equal force.
Newton’s Laws of Motion

According to the 3rd law, the force of gravity between you and Earth is the same each way.

Force of Earth on you = Force of you on Earth

But remember the 2nd law: the acceleration each body feels depends on their masses:

your acceleration = \frac{\text{force}}{\text{your mass}}

Earth’s acceleration = \frac{\text{force}}{\text{Earth’s mass}}
Newton’s Laws of Motion

The forces are equal, but accelerations are not!

You are exerting a force on Earth. But because of its enormous mass \(6 \times 10^{24}\) kg, Earth only accelerates an infinitesimal amount.

This relationship between force, mass, and acceleration is true for any two bodies in the Universe.
Newton’s Cannonball, the Moon

Newton thought the Moon was held in orbit by gravity. But was there gravity that far away?
Universal Theory of Gravitation

Newton showed that the same force of gravity keeping your feet on the ground also keeps the Moon orbiting Earth.

He called his theory “universal gravitation” because it occurred everywhere:

• The Moon orbits Earth due to gravity.
• The planets orbit the Sun due to gravity.
• Stars orbit each other due to gravity.
• Every object attracts every other object.
Universal Theory of Gravitation

Newton described the force of gravity in an equation that relates the force \( F \) to the masses attracting each other \( (M, m) \) and the distance between their centers \( (r) \):

\[
F = \frac{GMm}{r^2}
\]

Big “\( G \)” is a very small number \( (6.67 \times 10^{-11}) \), so a large mass is needed for gravity to be strong.
Newton began his study of the Moon’s orbit with the following *thought experiment*:

Imagine a cannon placed on an immensely tall mountain. Point the cannon horizontally and fire!
Newton and Orbits

If you increase the speed of the cannonball, it flies farther before striking the ground...
Newton and Orbits

Even faster and the cannonball flies so far that Earth’s curvature begins to be important…
Newton and Orbits

At very high speeds, the cannonball flies so far that it lands on the other side of Earth.

Remember, the cannonball is falling toward Earth’s center at each moment…
Newton and Orbits

Finally, you fire the cannonball very, very fast. About 90 minutes later, the cannonball whizzes past you. It missed the ground entirely!
Newton and Orbits

Newton had an explanation for orbits that Kepler did not have:

An object orbiting Earth is moving fast enough to continuously fall and miss the ground.

Thus, satellites and the Moon are simply falling around Earth.

The same is true of Earth orbiting the Sun.

*An orbit is a path curved by gravity.*
Getting into Orbit

There are no mountains as tall as the one in Newton’s experiment. To launch an object into Earth orbit, you must solve two problems:

• The object must be lifted above the most of the atmosphere to minimize atmospheric drag. This requires an altitude of at least 200 km.

• The object must be moving fast enough to fall all the way around Earth. This requires a velocity of at least 7.8 km/s (or about 4.7 miles/second or about 17,000 mph).
Which statement explains why astronauts in orbit float around inside their spacecraft?

A. There is no gravity once you leave the surface of Earth, so of course they float around.

B. The gravity is so weak that far above Earth’s surface that it is natural they would float for a long time after they’ve pushed away from the floor.

C. Gravity in Earth orbit is nearly as strong as on Earth’s surface. But the astronaut and the spacecraft are falling together around Earth.
Newton’s Cannonball

Let’s return to Newton’s thought experiment:

If we fire so the cannonball falls at exactly the same as Earth’s surface curves, it remains a fixed height above the ground.

This is the special case of a *circular orbit*. The cannonball’s speed is constant through the entire orbit.

*Let’s fire the cannonball faster than the speed needed for a circular orbit. What happens?*
Elliptical Orbits

Now the cannonball moves over the ground so fast it travels away from Earth’s surface.

It climbs and slows down. At maximum height, it is moving slowest.

Then it falls back to Earth, speeding up.
Not Coming Back: Open Orbits

Too much speed and the cannonball moves away from Earth faster than gravity can slow it down.

The cannonball has escaped Earth’s gravity.

These are hyperbolic orbits with eccentricity $> 1$. 
The spacecraft needs to be launched at the right time to arrive at the target orbit when the planet is there.

This time interval is known as the “launch window”.

The window is about 1 week long for Mars and occurs every 2 years as Earth and Mars align.

Half an elliptical orbit takes about 18 months to coast from Earth to Mars orbit.
Today, spacecraft are launched on faster, more direct paths to Mars. These take as little as 7 months, but require far more powerful rockets to send them on their way.

Timing of the launch is still important, otherwise the spacecraft will arrive at Mars orbit without Mars present. Bad news! (Yes, this has happened.)
Planetary Flybys

Some missions have the spacecraft “fly by” the target: that is, the spacecraft swings by so fast it is not captured by the target object’s gravity.

Flybys can be used to get close-up views of a target along the way to another location.

The gravity of the target planet can be used to redirect the spacecraft’s path. *New Horizons* flew past Jupiter on its way to Pluto.
The Grand Tour

The most famous example of planetary flybys occurred with the Voyager missions in the 1980’s. Voyager 1 flew past Jupiter and then Saturn. Voyager 2 visited Jupiter, Saturn, Uranus, and Neptune.

Today, both spacecraft are heading out of the Solar System into interstellar space.
Gravitational Balance Points

One more bit of gravitational trivia: Lagrange points

All points have orbital periods exactly equal to the orbital period of the planet or moon due to the balance of forces.

Lagrange Point 1 or “L1” is a great place for solar observing: SOHO, SDO, TRACE, Genesis

Lagrange Point 2 or “L2” is a great place for space telescopes: WMAP, Planck, Herschel, JWST
Gravitational Balance Points

The balance between the gravity of Jupiter and the Sun causes asteroids to collect at the “leading” and “trailing” Lagrange points along Jupiter’s orbit.

The leading asteroids are known as the “Greek camp” and these bodies have names of Greek warriors in the Trojan War.

Estimated total population equals 50,000 to 500,000 asteroids.

The trailing asteroids are known as the “Trojan camp” and these bodies have names of Trojan warriors in the Trojan War.
Gravitational Balance Points

In the future, Lagrange points in the Earth-Moon system may be used for “building sites” for space stations. The L1 point could be used as a transit station for trips back and forth from Earth to the Moon or on journeys to the other planets.
Ice Skaters and Orbiting Bodies

The conservation of angular momentum relates an object’s rotation rate to its mass distribution.

You’ve seen this effect in action in ice skating and high divers: Arms & legs spread out $\rightarrow$ slow spin

Arms & legs tucked in $\rightarrow$ fast spin
Angular Momentum Examples

The same physics causes a collapsing cloud of gas to spin faster and to flatten into a “disk”.

Along the axis, gas falls directly toward the center. Around the middle, spin slows the collapse of gas.
Planetary Orbits

From the concept of angular momentum, it is small step to explain the “flatness” of the Solar System: the ordered orbital motions we see among the Sun, planets, moons, asteroids, & KBOs.