ChatGPT

Force and Motion

A **force** is an influence that can cause an object to change its velocity (accelerate) en.wikipedia.org . In physics a force is a **vector** (having both magnitude and direction) and its SI unit is the newton (N) en.wikipedia.org . In everyday terms forces manifest as pushes or pulls on objects. Forces are broadly classified into **contact forces** (acting through physical contact between objects) and **non-contact forces** (acting at a distance). Contact forces include, for example, friction, tension, normal, spring, applied (push/pull), and air-resistance forces physicsclassroom.com . Non-contact ("action-at-a-distance") forces include gravity, electrical, and magnetic forces physicsclassroom.com . (In modern physics there are also the strong and weak nuclear forces, but at the macroscopic level gravity and electromagnetism dominate.)

- **Contact Forces:** These arise when two objects touch. For example, the **normal force** is the perpendicular contact force from a surface; the **frictional force** acts parallel to a surface and opposes relative motion; **tension** is the pull transmitted along a string or rope; an **elastic (spring) force** acts in a stretched or compressed spring; an **applied force** is any push/pull by an agent. Each contact force is a vector and can be resolved into components. For instance, on an incline a block's weight decomposes into a component along the plane (opposed by friction) and a component perpendicular to the plane (balanced by the normal force) 【89†】. Quantitatively, the **spring force** obeys Hooke's law $F_s = -kx$ (force is proportional to displacement) en.wikipedia.org , while **friction** is often modeled as $f = \mu N$ up to a maximum (static friction) or $f = \mu_k N$ (kinetic friction), where N is the normal force. The **weight** of an object near Earth's surface is $W = mg$, where $g \approx 9.8\ \mathrm{m/s}^2$ physicsclassroom.com britannica.com . Real-life examples: pushing a block on a table (applied force and friction), a hanging mass on a string (tension), a compressing spring toy (spring force), or air drag on a falling leaf.

- **Non-Contact Forces:** These act across a distance. **Gravitational force** attracts two masses m_1 and m_2 with magnitude $F = G\, m_1 m_2 / r^2$ en.wikipedia.org . Near Earth's surface this leads to the familiar constant acceleration $g = GM_\oplus / R_\oplus^2 \approx 9.8\ \mathrm{m/s}^2$ britannica.com . **Electric forces** between point charges q_1, q_2 obey Coulomb's law $F = k_e\, q_1 q_2 / r^2$ (attracting or repelling). **Magnetic forces** act on moving charges or magnetic dipoles (e.g. Lorentz force $F = qv \times B$). (At the atomic level, normal and frictional forces ultimately arise from electromagnetic repulsion between atoms.) All forces, contact or not, **add vectorially** to produce a net force $F_{\text{net}} = \sum F_i$, and an object will accelerate in the direction of the net force according to Newton's laws (below).

In summary, forces are either **fundamental** (gravity, electromagnetism, strong/weak nuclear) or **derived** effects (like tension or friction due to molecular forces). They always come in equal-and-opposite pairs (Newton's 3rd law), are vectors, and can cause changes in motion. The net effect of multiple forces is found by vector addition (e.g. by decomposing into F_x and F_y components).

Galileo's Law of Inertia

Long before Newton, Galileo Galilei (1564–1642) clarified the concept of motion: an object will **continue in its state of rest or uniform straight-line motion unless acted upon by an unbalanced force**. This is the **Law of Inertia**, a cornerstone of classical mechanics britannica.com . Galileo deduced this by rolling balls down inclined planes: he observed that a ball on a frictionless level would never stop but continue rolling indefinitely, contrary to the then-common (Aristotelian) belief that motion requires a continual push britannica.com . In effect, Galileo showed that **no force is needed to maintain constant motion** (only to change it) and that a force is only required to overcome friction or to change velocity. He phrased it such that "if a body is at rest or moving at constant speed in a straight line, it will remain so unless a force acts on it" britannica.com . This was a radical departure from ancient ideas and laid the groundwork for Newton's First Law.

Historical implication: Galileo's insight eliminated "natural rest" or "natural speed" for an object – instead, motion is relative and persists without force. It introduced the idea of **inertial reference frames**: from Galileo's perspective, a smoothly moving ship has the same physics as a stationary one (no experiment inside can detect motion). Real-life illustration: a hockey puck gliding on an almost frictionless ice would keep moving straight unless a force (friction, a stick) changes its motion.

Newton's Laws of Motion

Isaac Newton (1642–1727) synthesized these ideas into three precise laws. In **Newton's First Law** (essentially Galileo's Law of Inertia) he stated that *"a body remains at rest, or in motion at constant speed in a straight line, unless acted upon by a net force"* britannica.com . In other words, if all forces on an object balance to zero, its acceleration is zero britannica.com . Conversely, any **unbalanced force** produces acceleration. For example, a book resting on a table is not accelerating because the upward normal force balances the downward weight; apply a sideways push (unbalanced), and the book starts moving. In formula form, a state of zero acceleration means $\sum F = 0$ (equilibrium) britannica.com . Newton's First Law highlights the concept of inertia: objects "resist" changes in motion proportional to their mass.

Newton's Second Law

Newton's Second Law quantifies how a net force produces acceleration. It can be stated as "**the time rate of change of momentum of a body is equal to the net force acting on it**" britannica.com . Since momentum $p = mv$ (mass times velocity) is a vector, this means $\frac{dp}{dt} = F_{\text{net}}$ britannica.com . For a constant mass m, this reduces to the familiar formula:

$$F_{\text{net}} = ma,$$

where a is the acceleration (a vector) britannica.com . Thus, the acceleration an object experiences is directly proportional to the net force and inversely proportional to its mass. (Equivalently, ma *defines* the net force.) In words: **more force means more acceleration; more mass means less acceleration for the same force.** Since force and acceleration are vectors, we write in component form $\sum F_x = ma_x$, $\sum F_y = ma_y$, etc. If no net force acts ($\sum F = 0$), then $a = 0$ and the object moves with constant velocity (First Law).

Real-world examples: pushing a 1000 kg car with 2000 N of force produces $a = 2000/1000 = 2\ \text{m/s}^2$ forward. In ballistic missiles or rockets, the thrust force and resulting mass change (as fuel burns) lead to complex acceleration, but still obeys $F_{\text{net}} = ma$. Experimental confirmation of Newton's Second Law comes from many sources: e.g. weighing a cart's acceleration under known force using a spring scale, or dropping masses in Atwood's machine and measuring acceleration vs. force and mass. All agree that $a = F_{\text{net}}/m$ physicsclassroom.com britannica.com .

Impulse–Momentum Theorem: A useful corollary is the impulse-momentum theorem. Since $F_{\text{net}} = dp/dt$, integrating over a time interval Δt gives

$$F_{\text{net}}\,\Delta t = \Delta p \ = \ m\,\Delta v.$$

This equation is called **impulse**: $J = F\,\Delta t$ equals the change in momentum physicsclassroom.com . For a constant average force, a longer application time gives a greater change in velocity. **In words:** applying a force for some time imparts an impulse that changes the object's momentum. For example, when a car crashes, the braking force times the braking time reduces the car's momentum; if the stopping distance is longer (airbags, crumple zones), the deceleration and forces are smaller. The impulse theorem is often written $J = \Delta p$ physicsclassroom.com , and is directly derived from $F = ma$ and $a = \Delta v/\Delta t$ physicsclassroom.com .

Example (Impulse Calculation):

A 0.15 kg baseball moving at 40 m/s is caught by a glove, coming to rest in 0.02 s. The average force magnitude on the ball is
$F = m\,\Delta v/\Delta t = 0.15\,\frac{(0-40)}{0.02} = -300\,\mathrm{N}.$
The negative sign indicates the force direction opposite the ball's motion. Thus the glove exerts about 300 N on the ball to stop it in that time.

Newton's Third Law

Newton's Third Law states: *For every action there is an equal and opposite reaction*. More precisely, **when two bodies interact, the force exerted by body A on body B is equal in magnitude and opposite in direction to the force exerted by B on A** britannica.com . In notation: if A exerts $F_{A\to B}$ on B, then B exerts $F_{B\to A} = -F_{A\to B}$ on A. These forces act on **different objects**. Common examples: when you push against a wall, the wall pushes back on you with equal force. A swimmer pushes water backwards, and the water pushes the swimmer forward. A rocket's engines expel gas downward, and the gas pushes the rocket upward. Even the Earth and Moon pull on each other with equal and opposite gravitational forces eng.libretexts.org .

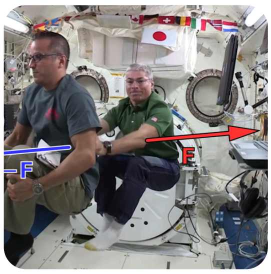

Figure: Two astronauts on the International Space Station demonstrate Newton's third law. When the right astronaut pushes the left astronaut (red arrow, force F), an equal and opposite force (blue arrow, $-F$) accelerates the left astronaut backwards britannica.com . Notice the forces act on different bodies (action on one, reaction on the other). This illustrates that forces always come in pairs of equal magnitude and opposite direction britannica.com .

In static situations, third-law pairs ensure equilibrium: e.g. a book on a table pushes down on the table with its weight, and the table pushes up on the book with an equal normal force britannica.com . In dynamics, these pairs underlie conservation laws. For instance, in an elastic collision two balls exchange equal and opposite forces; as a result total momentum is conserved. An iconic demonstration is **Newton's cradle** (series of swinging spheres): when one sphere strikes, the impulse is transmitted through to the opposite end sphere, which swings off with equal momentum, illustrating action-reaction and momentum conservation simultaneously.

In summary, Newton's three laws cover inertia, dynamics, and interactions:

- **First law:** no net force means no acceleration (motion persists) britannica.com .
- **Second law:** $F_{\text{net}} = ma$, or $\Delta p = F_{\text{net}}\Delta t$ britannica.com physicsclassroom.com .

- **Third law:** forces always occur in equal/opposite pairs britannica.com .

Newton’s Law of Universal Gravitation

Building on his laws of motion, Newton formulated the law of gravity: **every pair of point masses attracts each other** with a force given by

$$F = G\frac{m_1 m_2}{r^2},$$

where m_1 and m_2 are the masses, r is the distance between their centers, and G is the gravitational constant (approximately 6.674×10^{-11} N·m^2/kg^2) en.wikipedia.org . This inverse-square law unified celestial and terrestrial gravity: the same force that causes apples to fall also keeps the Moon in orbit en.wikipedia.org . Newton deduced the $1/r^2$ dependence by comparing the Moon’s orbit with an apple’s acceleration (Galileo’s falling bodies) en.wikipedia.org animations.physics.unsw.edu.au . In fact, equating the Earth’s gravitational pull on the Moon to the centripetal force required for circular motion gives $a_{\text{moon}} = GM_{\oplus}/r^2$, the same law that yields $g \approx 9.8$ m/s^2 at the surface (since $M_{\oplus}/R_{\oplus}^2 \approx 1/g$).

Figure: “**Earthrise**”: A view of Earth as seen from the Moon (Apollo 8 mission). This dramatic image emphasizes that Earth and Moon mutually attract by gravity. Newton’s law says the force between them is $F = Gm_{\text{Earth}}m_{\text{Moon}}/r^2$ en.wikipedia.org . Equivalently, the **acceleration** of the Moon toward Earth is $a = GM_{\oplus}/r^2$, which at the Moon’s distance (~384,000 km) yields an orbital speed consistent with the Moon’s 27.3-day period. Near Earth’s surface ($r \approx R_{\oplus}$), this gives the familiar $g = GM_{\oplus}/R_{\oplus}^2 \approx 9.8\ \mathrm{m/s}^2$ britannica.com , so $W = mg$.

Because of gravity's inverse-square nature, **orbital motion** can be analyzed by equating gravitational and centripetal forces. For a circular orbit of radius r, $GMm/r^2 = mv^2/r$, giving orbital speed $v = \sqrt{GM/r}$ astronomynotes.com . (The small mass m cancels out, reflecting that all bodies fall at the same rate in a given gravitational field.) For example, low Earth orbit (r ≈ 6.78×10^6 m) yields $v \approx 7.8$ km/s (about 28,000 km/h). The orbital period follows Kepler's Third Law: $T = 2\pi r/v \propto r^{3/2}$. Using Newton's law one can derive Kepler's laws: the planets move in ellipses with the Sun at one focus, and $T^2 \propto r^3$ for circular orbits.

Other applications: calculating satellite orbits, space missions, and even the mass of celestial bodies. For instance, using the Moon's orbit one can solve $M_\oplus = v^2 r/G$ astronomynotes.com (setting m the satellite and M the central mass). The **Cavendish experiment** (1798) used a torsion balance to measure G by observing tiny gravitational forces between lead spheres en.wikipedia.org , thereby determining Earth's mass.

Free Fall and Weight

In a uniform gravitational field (like near Earth's surface), all objects accelerate at the same rate $g \approx 9.8\ \mathrm{m/s}^2$ (neglecting air resistance). This Galileo–Newton result means a hammer and feather would fall together in a vacuum. In practice, air resistance often matters: a parachute greatly increases drag, reducing net force and terminal speed. But in vacuum, **free-fall acceleration** is $a = F/m = GM_\oplus/r^2$, independent of the object's mass.

Weight is the gravitational force on an object: $W = mg$ on Earth's surface physicsclassroom.com . Because g decreases with altitude ($g = GM/(R+h)^2$), a person's weight is slightly less in high mountains than at sea level. In orbit (e.g. ISS), both astronaut and spacecraft accelerate together under gravity; this creates a sensation of weightlessness, even though gravity still acts.

Applications in Everyday and Astronomy

- **Satellites:** Artificial satellites orbit by balancing gravity and centripetal acceleration. Geostationary satellites are placed at $r \approx 4.2 \times 10^7$ m so that $T = 24$ hours. Weather and communication satellites, GPS satellites, and the ISS rely on Newton's laws for trajectory design.

- **Planetary Motion:** Newton's law explains why the planets orbit the Sun in ellipses (Kepler's first law) and how orbital periods depend on semi-major axis (Kepler's third law). For example, applying $F = ma$ and $F = GmM/r^2$ to Earth orbiting the Sun yields $T^2 = \frac{4\pi^2}{GM_\odot} r^3$, verifying $T^2 \propto r^3$.
- **Projectile Motion:** The downward gravitational force causes all thrown or falling objects to accelerate at g, producing parabolic trajectories. Engineers use $F = ma$ to compute range and height of projectiles (neglecting air resistance).
- **Free-Fall Experiments:** High-speed cameras or modern drop tests confirm that $a \approx g$ for different masses. Galileo's (and later Newton's) insight that heavy and light objects fall alike remains counterintuitive but is experimentally confirmed.
- **Astrophysical Phenomena:** Gravity governs star formation, galaxy rotation, and even the orbits of spacecraft sent to other planets. Newton's law is accurate for most celestial mechanics, with general relativity giving only tiny corrections (e.g. perihelion shift of Mercury).

In conclusion, **force and motion** are governed by Newton's laws and the law of gravitation. We have defined force as a vector, cataloged its types (contact vs non-contact), and explored how forces determine motion through Galileo's inertia and Newton's laws. Newton's **First Law** (inertia) and **Second Law** ($F = ma$) explain why and how motion changes; the **Impulse–Momentum theorem** ($F\Delta t = \Delta p$) quantifies collisions and kicks; **Third Law** (action-reaction) ensures internal force pairs and momentum conservation britannica.com . Universal gravitation provides the force law for weights, orbits, and free-fall en.wikipedia.org .

Sources: Physics textbooks and reputable references were used for definitions, laws, and formulas en.wikipedia.org physicsclassroom.com britannica.com britannica.com physicsclassroom.com en.wikipedia.org britannica.com astronomynotes.com en.wikipedia.org , among others. Each law and key equation is supported by standard physics literature.

Citations

W **Force - Wikipedia**
https://en.wikipedia.org/wiki/Force

Types of Forces
https://www.physicsclassroom.com/class/newtlaws/lesson-2/types-of-forces

W **Hooke's law - Wikipedia**

https://en.wikipedia.org/wiki/Hooke%27s_law

Types of Forces
https://www.physicsclassroom.com/class/newtlaws/lesson-2/types-of-forces

Gravity | Definition, Physics, & Facts | Britannica
https://www.britannica.com/science/gravity-physics

Newton's law of universal gravitation - Wikipedia
https://en.wikipedia.org/wiki/Newton%27s_law_of_universal_gravitation

Law of inertia | Discovery, Facts, & History | Britannica
https://www.britannica.com/science/law-of-inertia

Law of inertia | Discovery, Facts, & History | Britannica
https://www.britannica.com/science/law-of-inertia

Newton’s laws of motion - Force, Mass, Acceleration | Britannica
https://www.britannica.com/science/Newtons-laws-of-motion/Newtons-second-law-F-ma

Newton’s laws of motion - Force, Mass, Acceleration | Britannica
https://www.britannica.com/science/Newtons-laws-of-motion/Newtons-second-law-F-ma

Newton’s laws of motion - Force, Mass, Acceleration | Britannica
https://www.britannica.com/science/Newtons-laws-of-motion/Newtons-second-law-F-ma

Newton's Second Law of Motion
https://www.physicsclassroom.com/class/newtlaws/lesson-3/newton-s-second-law

Momentum Change and Impulse
https://www.physicsclassroom.com/class/momentum/Lesson-1/Momentum-and-Impulse-Connection

Newton’s laws of motion - Force, Mass, Acceleration | Britannica
https://www.britannica.com/science/Newtons-laws-of-motion/Newtons-second-law-F-ma

1.7: Newton's Third Law - Engineering LibreTexts
https://eng.libretexts.org/Bookshelves/Mechanical_Engineering/Mechanics_Map_(Moore_et_al.)/0

Newton's law of universal gravitation - Wikipedia
https://en.wikipedia.org/wiki/Newton%27s_law_of_universal_gravitation

Gravity. From Physclips: Mechanics with animations and film clips.
https://www.animations.physics.unsw.edu.au/jw/gravity.htm

Gravity Applications

https://www.astronomynotes.com/gravappl/s8.htm

Gravity Applications

https://www.astronomynotes.com/gravappl/s8.htm

Newton's law of universal gravitation - Wikipedia

https://en.wikipedia.org/wiki/Newton%27s_law_of_universal_gravitation

All Sources

en.wikipedia　physicsclassroom　britannica　eng.libretexts

animatio....unsw.edu　astronomynotes