Continue

Welcome to the Physics Library. This Living Library is a principal hub of the LibreTexts project, which is a multi-institutional collaborative venture to develop the next generation of open-access texts to improve postsecondary education at all levels of higher learning. The LibreTexts approach is highly collaborative where an Open Access textbook environment is under constant revision by students, faculty, and outside experts to supplant conventional paper-based books. Campus BookshelvesBookshelvesLearning Objects Home is shared under a not declared license and was authored, remixed, and/or curated by LibreTexts. Newton's Laws of Motion, formulated by the renowned English physicist Sir Isaac Newton, are fundamental principles that form the core of classical mechanics. These three laws explain how objects move and interact with forces, shaping our view of everything from everyday movement to the dynamics of complex systems. Whether it's how a car accelerates or predicting the trajectory of a satellite, Newton's Laws are essential in analysing the behaviour of moving objects.Newton's Laws of Motion in physics are the fundamental laws that describe the relationship between the motion of an object and the forces acting on it. There are three laws under Newton's Law of Motion:First Law of MotionSecond Law of MotionThird Law of MotionNewton's Laws of MotionFirst Law of Motion (Law of Inertia) An object at rest will remain at rest, and an object in motion will continue in a straight line at constant speed, unless acted upon by an external unbalanced force. This is also known as the law of inertia.This law introduces the concept of inertia, the resistance of an object to changes in its motion.An objects mass determines its inertia, with heavier objects requiring more force to change their motion.In the absence of external forces, such as friction or gravity, an object in motion will continue indefinitely.Objects at rest will remain stationary unless a force is applied to move them.The law is foundational to other laws of motion and is crucial in explaining real-world scenarios like the motion of vehicles or the trajectory of space objects.For Example , A car parked on a level surface will remain stationary until an external force, such as a push, is applied, In this picture a person applied a force on car but the car didnt move.A rolling football eventually stops due to the friction force on the ground. (Change in State: Motion to rest , Force Applied: Friction) Newton's Second Law of MotionThe rate of change of an objects momentum is directly proportional to the applied unbalanced force and occurs in the direction of the force.Newton's Second Law of Motion defines the relationship between force, mass, and acceleration.It can be mathematically expressed as F = ma, where "F" is the force applied, "m" is the mass of the object, and "a" is the acceleration produced.The law implies that the acceleration of an object depends on the net force acting upon it and its mass.The larger the mass of an object, the smaller its acceleration for a given force.This law is crucial for calculating the force required to move objects, from everyday activities like pushing a cart to complex calculations in engineering and space missions.For Example,Catching a ball on the cricket field by a fielder is the best example of Newton's second law of motion. When the fielder catches the ball it moves its hands backward to increase the time of the catch resulting in lowering the force by the ball on the hands of the catcher.Imagine youre pushing a shopping cart. The harder you push (more force), the faster it rolls (accelerates), right? Thats the basic idea behind Newtons Second Law of Motion!Formula for Newtons Second Law of MotionNewton's Second Law of Motion explains how a force affects a body's motion by changing its velocity and acceleration.Mathematically it is shown as,Force (Change in Momentum) / (Time Taken)F d(mv)/dtF = kd(mv)/dtF = k\{v.dm/dt + m.dv/dt\}As mass is always constant, \{dm/dt = 0\}F = km.dv/dtExperimentally, k = 1F = m.dv/dtwe \ know \ that, \ dv/dt = aF= mawhere,F is the Force Appliedm is the Mass of Objecta is the Acceleration of ObjectTry it now!Imagine you're pushing a sled on a smooth surface. If you apply a constant force, how does the acceleration of the sled change if you increase its mass? What happens to the sled's acceleration if you increase the force applied while keeping the mass constant? Conduct an experiment to verify how force and mass affect the sled's acceleration, and record your observations."Newtons Third Law of MotionNewton's third law states that for every action, there is an equal and opposite reaction. Forces described by Newton's Third Law always come in pairs, meaning two objects interact through forces that are equal in magnitude but opposite in direction.The law helps explain the conservation of momentum in systems where objects collide. The momentum lost by one object is gained by the other, keeping the total momentum constant.For Example,Recoil of the gun when a bullet is fired is an example of Newton's Third Law of Motion. This means that whenever one object exerts a force on a second object, the second object exerts a force of equal magnitude but in the opposite direction on the first object.This law is also explained as, when an object "A" applies a force of "F1" on object "B" then "B" applies a force of "F2" on the object such that,F1 = -F2Third Law of Motion by Newton is also called the Law of Action and Reaction. When you push off the boat to jump onto the dock, the force you apply to the boat causes a reaction where the boat pushes back on you with an equal and opposite force. This mutual interaction causes the boat to move backward as you move forward.Solved Examples on Newton's Laws of MotionQuestion 1. Find out how much net force will be needed to accelerate a 2500 kg truck at 5.50 m/s2.Given,Acceleration (a) = 5.50 m/s2Mass of the Truck (m)= 2500 kgHence,Force = Mass AccelerationF = 2500 5.5F = 13750 NNet force will be needed to accelerate a 2500 kg truck at 5.50 m/s2 is 13750 N.Question 2. What will happen If a net force of 6 N is applied on 0.5 kg object. Calculate the acceleration of the material.Given,Force (F) = 6 NMass (m) = 0.5 kgAcceleration (a) = ?Force = Mass AccelerationF = m aa =F/ma =6/0.5a = 12 m/s2The acceleration of the object is 12 m/s2Question 3. If a racing car driver is on the race track in order to overtake accelerates his racing car first at the rate of 8 m/s2 and then at the rate of 16 m/s2. Find the ratio of the forces exerted by the engine for the acceleration change.Given,We have to find the ratio ofF1/F2F1/F2 = ma1/ma2Mass of the racing car is same in both the cases,F1/F2 = a1/a2F1/F2 = 8/16F1/F2 = 1/2 = 1:2Question 4: When a bullet of mass 20 gm is shot from a gun that has an initial velocity of 40 m/s the mass of the gun is 5 kg. What is the initial recoil velocity of the gun?Given,Mass of Bullet (m1) = 20 gm or 0.02 kgMass of Gun (m2) = 5 kgInitial velocity = 40 m/sLet final velocity is v m/sBy Law of Conservation of Momentum,0 = 0.02 40 + 5 v5 v = -0.8v = -0.8 / 5v = -0.16 m/sPractice Questions on Newton's Laws of MotionProblem 1: A book is placed on a table. Describe what happens to the book when:a) No force is applied to it.b) A gentle horizontal force is applied to the book.c) A vertical force is applied to the book.Problem 2: What will happen to a stationary soccer ball if no external forces are applied to it?Problem 3: A bicycle is moving on a flat road. What force causes it to eventually stop if no one keeps pedaling? How does this relate to the first law?Problem 5: A force of 10 N is applied to a 2 kg object. What is the objects acceleration?(Hint: Use the formula F=ma)Problem 6: If a force of 15 N causes an object to accelerate at 3 m/s, what is the mass of the object?Problem 8: When a rocket launches, it expels gas downwards, yet it moves upwards. How does this demonstrate Newton's third law?Problem 9: Two ice skaters, one with a mass of 60 kg and the other with a mass of 80 kg, push off each other on an ice rink. If the 60 kg skater exerts a force of 200 N on the 80 kg skater, what force does the 80 kg skater exert on the 60 kg skater?ConclusionNewton's laws of motion explain how forces affect the movement of objects. These principles are essential to classical mechanics and offer a foundation for understanding the behavior and interactions of objects. They help us predict how objects will move in response to various forces and are crucial for fields like engineering and physics. By applying these laws, we can analyze everything from the motion of everyday objects to complex systems in space. Newtons laws of motion are a set of three laws that govern the motion of an object. They describe a relationship between the motion and the forces acting on the object. Newtons laws are important because they set up the foundations of classical physics and revolutionized our understanding of the motion of objects.The laws have been named after English mathematician and physicist Sir Isaac Newton. He published them in 1687. There are three laws of motion due to Newton. They are known as First, Second, and Third Laws. Newtons Laws of Motion Statement:An object at rest remains at rest, and object in motion remains at a constant speed and in a straight line unless acted upon by an unbalanced force. According to the first law, an object cannot start, stop, or change direction all by itself. In order to cause an action, it will require force. Consider the case where the object is at rest. It is because either no forces act on it or all the external forces cancel each other. It will remain at rest unless an unbalanced force displaces it. Example: A book lying on a table. Consider the case where the object is moving at a constant speed in a straight line. It will continue to move with the same speed and remain in a straight line as long as no external force acts on it. If there is an external force, the object will either change its direction, accelerate or decelerate, or come to a stop. Example 1: A car moving on a road at a constant speed comes to a stop when the brakes are applied. Here, the action of applying brakes is the force responsible for stopping the car. Example 2: A balloon moving in a straight line will continue to move in the same direction unless the wind sweeps it and changes its direction. Here, the wind is the force responsible for changing the direction of the balloon. The balloon can come to a stop if it is stuck in a tree. In this case, the tree applies force responsible for ceasing the motion of the balloon. The first law is also known as the law of inertia. Statement: When an object is in motion, its acceleration depends upon its mass and the applied force. The second law defines a force on an object given by the product of its mass and acceleration. Consider two objects of different masses one heavy and another light. If the same force is applied to both the objects, the lighter one will move faster than the heavier one. Example 1: A rock rolling down a hill due to gravity. It will roll down with a constant acceleration, whose value will depend upon the mass of the rock and the angle of inclination of the hill. Example 2: A ball falling through the air with acceleration g due to Earths gravity. The Earth pulls the ball with a force given by the product of the balls mass and acceleration due to gravity. This force is equal to the balls weight. A heavier ball will experience more force. Equation: Mathematically, the second law is written as follows. Force (F) = mass (m) x acceleration (a) Or, F = ma Statement: If one object exerts a force on another object, then the other object exerts an equal and opposite force on the first object. According to the third law, for every action, there is an equal and opposite reaction. Consider two objects A and B colliding with one another. A strikes B with force, which is the action. B reacts by exerting a force on A, which is the reaction. According to the third law, action and reaction forces are equal and opposite. Therefore, this law is also known as action-reaction law. Example 1: The thrust of a rocket produces the force required to lift the rocket from Earth. Here, the thrust is the action, and the lift of the rocket is the reaction. Example 2: When a person stands on Earths surface, they experience a force due to gravity. The persons weight is the action, and the force exerted by Earth on them is the reaction. Article was last reviewed on Monday, December 20, 2021 Laws in physics about force and motion"Newton's laws" redirects here. For other uses, see Newton's law. "F=ma" redirects here. For the physics competition, see F=ma exam.Part of a series onClassical mechanics F = d p d t {\displaystyle {\textbf {F}}={\frac {d\mathbf {p} }{dt}}} Second law of motionHistoryTimelineTextbooksBranchesAppliedCelestialContinuumDynamicsField theoryKinematicsKineticsStaticsStatistical mechanicsFundamentalsAccelerationAngular momentumCoupleD'Alembert's principleEnergykineticpotentialForceFrame of referenceInertial frame of referenceImpulseInertia/ Moment of inertiaMassMechanical powerMechanical workMomentMomentumSpaceSpeedTimeTorqueVelocityVirtual workFormulationsNewton's laws of motionAnalytical mechanics Lagrangian mechanicsHamiltonian mechanicsRouthian mechanicsHamiltonJacobi equationAppell's equation of motionKoopmanvon Neumann mechanicsCore topicsDampingDisplacementEquations of motionEuler's laws of motionFictitious forceFrictionHarmonic oscillatorInertial/ Non-inertial reference frameMotion(linear)Newton's law of universal gravitationNewton's laws of motionRelative velocityRigid bodydynamicsEuler's equationsSimple harmonic motionVibrationRotationCircular motionRotating reference frameCentripetal forceCentrifugal forcereactiveCoriolis forcePendulumTangential speedRotational frequencyAngular acceleration/ displacement/ frequency/ velocityScientistsKeplerGalileoHuygensNewtonHorrocksHalleyMaupertuisDaniel BernoulliJohann BernoulliEulerd'AlembertClairautLagrangeLaplacePoissonHamiltonJacobiCauchyRouthLiouvilleAppellGibbsKoopmanvon Neumann Physics portalCategoryvteNewton's laws of motion are three physical laws that describe the relationship between the motion of an object and the forces acting on it. These laws, which provide the basis for Newtonian mechanics, can be paraphrased as follows:A body remains at rest, or in motion at a constant speed in a straight line, unless it is acted upon by a force.At any instant of time, the net force on a body is equal to the body's acceleration multiplied by its mass or, equivalently, the rate at which the body's momentum is changing with time.If two bodies exert forces on each other, these forces have the same magnitude but opposite directions.[1][2]The three laws of motion were first stated by Isaac Newton in his Philosophi Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy), originally published in 1687.[3] Newton used them to investigate and explain the motion of many physical objects and systems. In the time since Newton, new insights, especially around the concept of energy, built the field of classical mechanics on his foundations. Limitations to Newton's laws have also been discovered; new theories are necessary when objects move at very high speeds (special relativity), are very massive (general relativity), or are very small (quantum mechanics).Newton's laws are often stated in terms of point or particle masses, that is, bodies whose volume is negligible. This is a reasonable approximation for real bodies when the motion of internal parts can be neglected, and when the separation between bodies is much larger than the size of each. For instance, the Earth and the Sun can both be approximated as pointlike when considering the orbit of the former around the latter, but the Earth is not pointlike when considering activities on its surface.[note 1]The mathematical description of motion, or kinematics, is based on the idea of specifying positions using numerical coordinates. Movement is represented by these numbers changing over time: a body's trajectory is represented by a function that assigns to each value of a time variable the values of all the position coordinates. The simplest case is one-dimensional, that is, when a body is constrained to move only along a straight line. Its position can then be given by a single number, indicating where it is relative to some chosen reference point. For example, a body might be free to slide along a track that runs left to right, and so its location can be specified by its distance from a convenient zero point, or origin, with negative numbers indicating positions to the left and positive numbers indicating positions to the right. If the body's location as a function of time is s (t) {\displaystyle s(t)} , then its average velocity over the time interval from t 0 {\displaystyle t_{0}} to t 1 {\displaystyle t_{1}} is[6] s t = s (t 1) s (t 0) t 1 t 0 . {\displaystyle {\frac {\Delta s}{\Delta t}}={\frac {s(t_{1})-s(t_{0})}{t_{1}-t_{0}}}.} Here, the Greek letter {\displaystyle \Delta } (delta) is used, per tradition, to mean "change in". A positive average velocity means that the position coordinate s {\displaystyle s} increases over the interval in question, a negative average velocity indicates a net decrease over that interval, and an average velocity of zero means that the body ends the time interval in the same place as it began. Calculus gives the means to define an instantaneous velocity, a measure of a body's speed and direction of movement at a single moment of time, rather than over an interval. One notation for the instantaneous velocity is to replace {\displaystyle \Delta } with the symbol d {\displaystyle d} , for example, v = d s d t . {\displaystyle v={\frac {ds}{dt}}.} This denotes that the instantaneous velocity is the derivative of the position with respect to time. It can roughly be thought of as the ratio between an infinitesimally small change in position d s {\displaystyle ds} to the infinitesimally small time interval d t {\displaystyle dt} over which it occurs.[7] More carefully, the velocity and all other derivatives can be defined using the concept of a limit.[6] A function f (t) {\displaystyle f(t)} has a limit of L {\displaystyle L} at a given input value t 0 {\displaystyle t_{0}} if the difference between f {\displaystyle f} and L {\displaystyle L} can be made arbitrarily small by choosing an input sufficiently close to t 0 {\displaystyle t_{0}} . One writes, lim t t 0 f (t) = L . {\displaystyle \lim _{t\to t_{0}}f(t)=L.} Instantaneous velocity can be defined as the limit of the average velocity as the time interval shrinks to zero: d s d t = lim t 0 s (t + t) s (t) t . {\displaystyle {\frac {ds}{dt}}=\lim _{\Delta t\to 0}{\frac {s(t+\Delta t)-s(t)}{\Delta t}}.} Acceleration is to velocity as velocity is to position: it is the derivative of the velocity with respect to time.[note 2] Acceleration can likewise be defined as a limit: a = d v d t = lim t 0 v (t + t) v (t) t . {\displaystyle a={\frac {dv}{dt}}=\lim _{\Delta t\to 0}{\frac {v(t+\Delta t)-v(t)}{\Delta t}}.} Consequently, the acceleration is the second derivative of position,[7] often written d 2 s d t 2 {\displaystyle {\frac {d^{2}s}{dt^{2}}}} .Position, when thought of as a displacement from an origin point, is a vector: a quantity with both magnitude and direction.[9]:1 Velocity and acceleration are vector quantities as well. The mathematical tools of vector algebra provide the means to describe motion in two, three or more dimensions. Vectors are often denoted with an arrow, as in s {\displaystyle {\vec {s}}} , or in bold typeface, such as s {\displaystyle {\bf {s}}} . Often, vectors are represented visually as arrows, with the direction of the vector being the direction of the arrow, and the magnitude of the vector indicated by the length of the arrow. Numerically, a vector can be represented as a list; for example, a body's velocity vector might be v = (3 m / s , 4 m / s) {\displaystyle \mathbf {v} =(\mathrm {3~m/s} ,\mathrm {4~m/s})} , indicating that it is moving at 3 metres per second along the horizontal axis and 4 metres per second along the vertical axis. The same motion described in a different coordinate system will be represented by different numbers, and vector algebra can be used to translate between these alternatives.[9]:4 The study of mechanics is complicated by the fact that household words like energy are used with a technical meaning.[10][11] Moreover, words which are synonymous in everyday speech are not so in physics: force is not the same as power or pressure, for example, and mass has a different meaning than weight.[12][13]:150 The physics concept of force makes quantitative the everyday idea of a push or a pull. Forces in Newtonian mechanics are often due to strings and ropes, friction, muscle effort, gravity, and so forth. Like displacement, velocity, and acceleration, force is a vector quantity.Artificial satellites move along curved orbits, rather than in straight lines, because of the Earth's gravity.Translated from Latin, Newton's first law reads,Every object perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.[note 3]Newton's first law expresses the principle of inertia: the natural behavior of a body is to move in a straight line at constant speed. A body's motion preserves the status quo, but external forces can perturb this.The modern understanding of Newton's first law is that no inertial observer is privileged over any other. The concept of an inertial observer makes quantitative the everyday idea of feeling no effects of motion. For example, a person standing on the ground watching a train go past is an inertial observer. If the observer on the ground sees the train moving smoothly in a straight line at a constant speed, then a passenger sitting on the train will also be an inertial observer: the train passenger feels no motion. The principle expressed by Newton's first law is that there is no way to say which inertial observer is "really" moving and which is "really" standing still. One observer's state of rest is another observer's state of uniform motion in a straight line, and no experiment can deem either point of view to be correct or incorrect. There is no absolute standard of rest.[18][15]:6263[19]:79 Newton himself believed that absolute space and time existed, but that the only measures of space or time accessible to experiment are relative.[20]The change of motion of an object is proportional to the force impressed; and is made in the direction of the straight line in which the force is impressed.[15]:114By "motion", Newton meant the quantity now called momentum, which depends upon the amount of matter contained in a body, the speed at which that body is moving, and the direction in which it is moving.[21] In modern notation, the momentum of a body is the product of its mass and its velocity: p = m v , {\displaystyle \mathbf {p} =m\mathbf {v} \,,} where all three quantities can change over time.In common cases the mass m {\displaystyle m} does not change with time and the derivative acts only upon the velocity. Then force equals the product of the mass and the time derivative of the velocity, which is the acceleration:[22] F = m d v d t = m a . {\displaystyle \mathbf {F} =m{\frac {d\mathbf {v} }{dt}}=m\mathbf {a} \,.} As the acceleration is the second derivative of position with respect to time, this can also be written F = m d 2 s d t 2 . {\displaystyle \mathbf {F} =m{\frac {d^{2}\mathbf {s} }{dt^{2}}}.} Newton's second law, in modern form, states that the time derivative of the momentum is the force:[23]:4.1 F = d p d t . {\displaystyle \mathbf {F} ={\frac {d\mathbf {p} }{dt}}\,.} When applied to systems of variable mass, the equation above is only valid only for a fixed set of particles. Applying the derivative as in F = m d v d t + v d m d t (i n c o r r e c t) {\displaystyle \mathbf {F} =m{\frac {\mathrm {d} \mathbf {v} }{\mathrm {d} t}}+\mathbf {v} {\frac {\mathrm {d} m}{\mathrm {d} t}}\ \ \mathrm {(incorrect)} } can lead to incorrect results.[24] For example, the momentum of a water jet system must include the momentum of the ejected water:[25] F e x t = d p d t v e j e c t d m d t . {\displaystyle \mathbf {F} _{\mathrm {ext} }={\mathrm {d} \mathbf {p} \over \mathrm {d} t}-\mathbf {v} _{\mathrm {eject} }{\frac {\mathrm {d} m}{\mathrm {d} t}}.} A free body diagram for a block on an inclined plane, illustrating the normal force perpendicular to the plane (N), the downward force of gravity (mg), and a force f along the direction of the plane that could be applied, for example, by friction or a string The forces acting on a body add as vectors, and so the total force on a body depends upon both the magnitudes and the directions of the individual forces.[23]:58 When the net force on a body is equal to zero, then by Newton's second law, the body does not accelerate, and it is said to be in mechanical equilibrium. A state of mechanical equilibrium is stable if, when the position of the body is changed slightly, the body remains near that equilibrium. Otherwise, the equilibrium is unstable.[15]:121[23]:174A common visual representation of forces acting in concert is the free body diagram, which schematically portrays a body of interest and the forces applied to it by outside influences.[26] For example, a free body diagram of a block sitting upon an inclined plane can illustrate the combination of gravitational force, "normal" force, friction, and string tension.[note 4]Newton's second law is sometimes presented as a definition of force, i.e., a force is that which exists when an inertial observer sees a body accelerating. This is sometimes regarded as a potential tautology acceleration implies force, force implies acceleration. However, Newton's second law not only merely defines the force by the acceleration: forces exist as separate from the acceleration produced by the force in a particular system. The same force that is identified as producing acceleration to an object can then be applied to any other object, and the resulting accelerations (coming from that same force) will always be inversely proportional to the mass of the object. What Newton's Second Law states is that all the effect of a force onto a system can be reduced to two pieces of information: the magnitude of the force, and it's direction, and then goes on to specify what the effect is.Beyond that, an equation detailing the force might also be specified, like Newton's law of universal gravitation. By inserting such an expression for F {\displaystyle \mathbf {F} } into Newton's second law, an equation with predictive power can be written.[note 5] Newton's second law has also been regarded as setting out a research program for physics, establishing that important goals of the subject are to identify the forces present in nature and to catalogue the constituents of matter.[15]:134[28]:12-2However, forces can often be measured directly with no acceleration being involved, such as through weighing scales. By postulating a physical object that can be directly measured independently from acceleration, Newton made a objective physical statement with the second law alone, the predictions of which can be verified even if no force law is given.To every action, there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.[15]:116Rockets work by creating unbalanced high pressure that pushes the rocket upwards while exhaust gas exits through an open nozzle.[30]In other words, if one body exerts a force on a second body, the second body is also exerting a force on the first body, of equal magnitude in the opposite direction. Overly brief paraphrases of the third law, like "action equals reaction" might have caused confusion among generations of students: the "action" and "reaction" apply to different bodies. For example, consider a book at rest on a table. The Earth's gravity pulls down upon the book. The "reaction" to that "action" is not the support force from the table holding up the book, but the gravitational pull of the book acting on the Earth.[note 6]Newton's third law relates to a more fundamental principle, the conservation of momentum. The latter remains true even in cases where Newton's statement does not, for instance when force fields as well as material bodies carry momentum, and when momentum is defined properly, in quantum mechanics as well.[note 7] In Newtonian mechanics, if two bodies have momenta p 1 {\displaystyle \mathbf {p} _{1}} and p 2 {\displaystyle \mathbf {p} _{2}} respectively, then the total momentum of the pair is p = p 1 + p 2 {\displaystyle \mathbf {p} =\mathbf {p} _{1}+\mathbf {p} _{2}} , and the rate of change of p {\displaystyle \mathbf {p} } is d p d t = d p 1 d t + d p 2 d t . {\displaystyle {\frac {d\mathbf {p} }{dt}}={\frac {d\mathbf {p} _{1}}{dt}}+{\frac {d\mathbf {p} _{2}}{dt}}.} By Newton's second law, the first term is the total force upon the first body, and the second term is the total force upon the second body. If the two bodies are isolated from outside influences, the only force upon the first body can be that from the second, and vice versa. By Newton's third law, these forces have equal magnitude but opposite direction, so they cancel when added, and p {\displaystyle \mathbf {p} } is constant. Alternatively, if p {\displaystyle \mathbf {p} } is known to be constant, it follows that the forces have equal magnitude and opposite direction.Various sources have proposed elevating other ideas used in classical mechanics to the status of Newton's laws. For example, in Newtonian mechanics, the total mass of a body made by bringing together two smaller bodies is the sum of their individual masses. Frank Wilczek has suggested calling attention to this assumption by designating it "Newton's Zeroth Law".[37] Another candidate for a "zeroth law" is the fact that at any instant, a body reacts to the forces applied to it at that instant.[38] Likewise, the idea that forces add like vectors (or in other words obey the superposition principle), and the idea that forces change the energy of a body, have both been described as a "fourth law".[note 8]Moreover, some texts organize the basic ideas of Newtonian mechanics into different postulates, other than the three laws as commonly phrased, with the goal of being more clear about what is empirically observed and what is true by definition.[19]:9[27]The study of the behavior of massive bodies using Newton's laws is known as Newtonian mechanics. Some example problems in Newtonian mechanics are particularly noteworthy for conceptual or historical reasons.Main articles: Free fall and Projectile motionA bouncing ball photographed at 25 frames per second using a stroboscopic flash. In between bounces, the ball's height as a function of time is close to being a parabola, deviating from a parabolic arc because of air resistance, spin, and deformation into a non-spherical shape upon impact.If a body falls from rest near the surface of the Earth, then in the absence of air resistance, it will accelerate at a constant rate. This is known as free fall. The speed attained during free fall is proportional to the elapsed time, and the distance traveled is proportional to the square of the elapsed time.[43] Importantly, the acceleration is the same for all bodies, independently of their mass. This follows from combining Newton's second law of motion with his law of universal gravitation. The latter states that the magnitude of the gravitational force from the Earth upon the body is F = G M m r 2 , {\displaystyle F={\frac {GMm}{r^{2}}},} where m {\displaystyle m} is the mass of the falling body, M {\displaystyle M} is the mass of the Earth, G {\displaystyle G} is Newton's constant, and r {\displaystyle r} is the distance from the center of the Earth to the body's location, which is very nearly the radius of the Earth. Setting this equal to m a {\displaystyle ma} , the body's mass m {\displaystyle m} cancels from both sides of the equation, leaving an acceleration that depends upon G {\displaystyle G} , M {\displaystyle M} , and r {\displaystyle r} , and r {\displaystyle r} can be taken to be constant. This particular value of acceleration is typically denoted g {\displaystyle g} : g = G M r 2 9.8 m / s 2 . {\displaystyle g={\frac {GM}{r^{2}}}\approx \mathrm {9.8~m/s^{2}} .} If the body is not released from rest but instead launched upwards and/or horizontally with nonzero velocity, then free fall becomes projectile motion.[44] When air resistance can be neglected, projectiles follow parabola-shaped trajectories, because gravity affects the body's vertical motion and not its horizontal. At the peak of the projectile's trajectory, its vertical velocity is zero, but its acceleration is g {\displaystyle g} downwards, as it is at all times. Setting the wrong vector equal to zero is a common confusion among physics students.[45]Main article: Circular motionTwo objects in uniform circular motion, orbiting around the barycenter (center of mass of both objects)When a body is in uniform circular motion, the force on it changes the direction of its motion but not its speed. For a body moving in a circle of radius r {\displaystyle r} at a constant speed v {\displaystyle v} , its acceleration has a magnitude a = v 2 r {\displaystyle a={\frac {v^{2}}{r}}} and is directed toward the center of the circle.[note 9] The force required to sustain this acceleration, called the centripetal force, is therefore also directed toward the center of the circle and has magnitude m v 2 / r {\displaystyle mv^{2}/r} . Many orbits, such as that of the Moon around the Earth, can be approximated by uniform circular motion. In such cases, the centripetal force is gravity, and by Newton's law of universal gravitation has magnitude G M m / r 2 {\displaystyle GMm/r^{2}} , where M {\displaystyle M} is the mass of the larger body being orbited. Therefore, the mass of a body can be calculated from observations of another body orbiting around it.[47]:130Newton's cannonball is a thought experiment that interpolates between projectile motion and uniform circular motion. A cannonball that is lobbed weakly off the edge of a tall cliff will hit the ground in the same amount of time as if it were dropped from rest, because the force of gravity only affects the cannonball's momentum in the downward direction, and its effect is not diminished by horizontal movement. If the cannonball is launched with a greater initial horizontal velocity, then it will travel farther before it hits the ground, but it will still hit the ground in the same amount of time. However, if the cannonball is launched with an even larger initial velocity, then the curvature of the Earth becomes significant: the ground itself will curve away from the falling cannonball. A very fast cannonball will fall away from the inertial straight-line trajectory at the same rate that the Earth curves away beneath it; in other words, it will be in orbit (imagining that it is not slowed by air resistance or obstacles).[48]Main article: Harmonic oscillatorAn undamped springmass system undergoes simple harmonic motion.Consider a body of mass m {\displaystyle m} able to move along the x {\displaystyle x} axis, and suppose an equilibrium point exists at the position x = 0 {\displaystyle x=0} . That is, at x = 0 {\displaystyle x=0} , the net force upon the body is the zero vector, and by Newton's second law, the body will not accelerate. If the force upon the body is proportional to the displacement from the equilibrium point, and directed to the equilibrium point, then the body will perform simple harmonic motion. Writing the force as F = k x {\displaystyle F=-kx} , Newton's second law becomes m d 2 x d t 2 = k x . {\displaystyle m{\frac {d^{2}x}{dt^{2}}}=-kx\,.} This differential equation has the solution x (t) = A cos t + B sin t {\displaystyle x(t)=A\cos \omega t+B\sin \omega t\,} where the frequency {\displaystyle \omega } is equal to k / m {\displaystyle {\sqrt {k/m}}} , and the constants A {\displaystyle A} and B {\displaystyle B} can be calculated knowing, for example, the position and velocity the body has at a given time, like t = 0 {\displaystyle t=0} .One reason that the harmonic oscillator is a conceptually important example is that it is good approximation for many systems near a stable mechanical equilibrium.[note 10] For example, a pendulum has a stable equilibrium in the vertical position: if motionless there, it will remain there, and if pushed slightly, it will swing back and forth. Neglecting air resistance and friction in the pivot, the force upon the pendulum is gravity, and Newton's second law becomes d 2 d t 2 = g L sin , {\displaystyle {\frac {d^{2}\theta }{dt^{2}}}=-{\frac {g}{L}}\sin \theta ,} where L {\displaystyle L} is the length of the pendulum and {\displaystyle \theta } is its angle from the vertical. When the angle {\displaystyle \theta } is small, the sine of {\displaystyle \theta } is nearly equal to {\displaystyle \theta } (see small-angle approximation), and so this expression simplifies to the equation for a simple harmonic oscillator with frequency = g / L {\displaystyle \omega ={\sqrt {g/L}}} .A harmonic oscillator can be damped, often by friction or viscous drag, in which case energy bleeds out of the oscillator and the amplitude of the oscillations decreases over time. Also, a harmonic oscillator can be driven by an applied force, which can lead to the phenomenon of resonance.[50]Main article: Variable-mass systemRockets, like the Space Shuttle Atlantis, expel mass during operation. This means that the mass being pushed, the rocket and its remaining onboard fuel supply, is constantly changing.Newtonian physics treats matter as being neither created nor destroyed, though it may be rearranged. It can be the case that an object of interest gains or loses mass because matter is added to or removed from it. In such a situation, Newton's laws can be applied to the individual pieces of matter, keeping track of which pieces belong to the object of interest over time. For instance, if a rocket of mass M (t) {\displaystyle M(t)} , moving at velocity v (t) {\displaystyle \mathbf {v} (t)} , ejects matter at a velocity u {\displaystyle \mathbf {u} } relative to the rocket, then[24] F = M d v d t u d M d t {\displaystyle \mathbf {F} =M{\frac {d\mathbf {v} }{dt}}-\mathbf {u} {\frac {dM}{dt}}\,} where F {\displaystyle \mathbf {F} } is the net external force (e.g., a planet's gravitational pull).[23]:139A boat equipped with a fan and a sailThe fan and sail example is a situation studied in discussions of Newton's third law.[51] In the situation, a fan is attached to a cart or a sailboat and blows on its sail. From the third law, one would reason that the force of the air pushing in one direction would cancel out the force done by the fan on the sail, leaving the entire apparatus stationary. However, because the system is not entirely enclosed, there are conditions in which the vessel will move; for example, if the sail is built in a manner that redirects the majority of the airflow back towards the fan, the net force will result in the vessel moving forward.[34][52]The concept of energy was developed after Newton's time, but it has become an inseparable part of what is considered "Newtonian" physics. Energy can broadly be classified into kinetic, due to a body's motion, and potential, due to a body's position relative to others. Thermal energy, the energy carried by heat flow, is a type of kinetic energy not associated with the macroscopic motion of objects but instead with the movements of the atoms and molecules of which they are made. According to the work-energy theorem, when a force acts upon a body while that body moves along the line of the force, the force does work upon the body, and the amount of work done is equal to the change in the body's kinetic energy.[note 11] In many cases of interest, the net work done by a force when a body moves in a closed loop starting at a point, moving along some trajectory, and returning to the initial point is zero. If this is the case, then the force can be written in terms of the gradient of a function called a scalar potential:[46]:303 F = U . {\displaystyle \mathbf {F} =-\mathbf {abla } U\,.} This is true for many forces including that of gravity, but not for friction; indeed, almost any problem in a mechanics textbook that does not involve friction can be expressed in this way.[49]:19 The fact that the force can be written in this way can be understood from the conservation of energy. Without friction to dissipate a body's energy into heat, the body's energy will trade between potential and (non-thermal) kinetic forms while the total amount remains constant. Any gain of kinetic energy, which occurs when the net force on the body accelerates it to a higher speed, must be accompanied by a loss of potential energy. So, the net force upon the body is determined by the manner in which the potential energy decreases.Main article: Rigid-body motionA rigid body is an object whose size is too large to neglect and which maintains the same shape over time. In Newtonian mechanics, the motion of a rigid body is often understood by separating it into movement of the body's center of mass and movement around the center of mass.Main article: Center of massThe total center of mass of the forks, cork, and toothpick is on top of the pen's tip.Significant aspects of the motion of an extended body can be understood by imagining the mass of that body concentrated to a single point, known as the center of mass. The location of a body's center of mass depends upon how that body's material is distributed. For a collection of pointlike objects with masses m 1 , , m N {\displaystyle m_{1},\ldots ,m_{N}} at positions r 1 , , r N {\displaystyle \mathbf {r} _{1},\ldots ,\mathbf {r} _{N}} , the center of mass is located at R = i = 1 N m i r i M , {\displaystyle \mathbf {R} =\sum _{i=1}^{N}{\frac {m_{i}\mathbf {r} _{i}}{M}},} where M {\displaystyle M} is the total mass of the collection. In the absence of a net external force, the center of mass moves at a constant speed in a straight line. This applies, for example, to a collision between two bodies.[55] If the total external force is not zero, then the center of mass changes velocity as though it were a point body of mass M {\displaystyle M} . This follows from the fact that the internal forces within the collection, the forces that the objects exert upon each other, occur in balanced pairs by Newton's third law. In a system of two bodies with one much more massive than the other, the center of mass will approximately coincide with the location of the more massive body.[19]:2224When Newton's laws are applied to rotating extended bodies, they lead to new quantities that are analogous to those invoked in the original laws. The analogue of mass is the moment of inertia, the counterpart of momentum is angular momentum, and the counterpart of force is torque.Angular momentum is calculated with respect to a reference point.[56] If the displacement vector from a reference point to a body is r {\displaystyle \mathbf {r} } and the body has momentum p {\displaystyle \mathbf {p} } , then the body's angular momentum with respect to that point is, using the vector cross product, L = r p . {\displaystyle \mathbf {L} =\mathbf {r} \times \mathbf {p} .} Taking the time derivative of the angular momentum gives d L d t = (d r d t) p + r d p d t = v m v + r F . {\displaystyle {\frac {d\mathbf {L} }{dt}}=\left({\frac {d\mathbf {r} }{dt}}\right)\times \mathbf {p} +\mathbf {r} \times {\frac {d\mathbf {p} }{dt}}=\mathbf {v} \times m\mathbf {v} +\mathbf {r} \times \mathbf {F} .} The first term vanishes because v {\displaystyle \mathbf {v} } and m v {\displaystyle m\mathbf {v} } point in the same direction. The remaining term is the torque, = r F . {\displaystyle \mathbf {\tau } =\mathbf {r} \times \mathbf {F} .} When the torque is zero, the angular momentum is constant, just as when the force is zero, the momentum is constant.[19]:1415 The torque can vanish even when the force is non-zero, if the body is located at the reference point (r = 0 {\displaystyle \mathbf {r} =0}) or if the force F {\displaystyle \mathbf {F} } and the displacement vector r {\displaystyle \mathbf {r} } are directed along the same line.The angular momentum of a collection of point masses, and thus of an extended body, is found by adding the contributions from each of the points. This provides a means to characterize a body's rotation about an axis, by adding up the angular momenta of its individual pieces. The result depends on the chosen axis, the shape of the body, and the rate of rotation.[19]:28Main articles: Two-body problem and Three-body problemAnimation of three points or bodies attracting to each otherNewton's law of universal gravitation states that any body attracts any other body along the straight line connecting them. The size of the attracting force is proportional to the product of their masses, and inversely proportional to the square of the distance between them. Finding the shape of the orbits that an inverse-square force law will produce is known as the Kepler problem. The Kepler problem can be solved in multiple ways, including by demonstrating that the LaplaceRungeLenz vector is constant,[57] or by applying a duality transformation to a 2-dimensional harmonic oscillator.[58] However it is solved, the result is that orbits will be conic sections, that is, ellipses (including circles), parabolas, or hyperbolas. The eccentricity of the orbit, and thus the type of conic section, is determined by the energy and the angular momentum of the orbiting body. Planets do not have sufficient energy to escape the Sun, and so their orbits are ellipses, to a good approximation; because the planets pull on one another, actual orbits are not exactly conic sections.If a third mass is added, the Kepler problem becomes the three-body problem, which in general has no exact solution in closed form. That is, there is no way to start from the differential equations implied by Newton's laws and, after a finite sequence of standard mathematical operations, obtain equations that express the three bodies' motions over time.[59][60] Numerical methods can be applied to obtain useful, albeit approximate, results for the three-body problem.[61] The positions and velocities of the bodies can be stored in variables within a computer's memory; Newton's laws are used to calculate how the velocities will change over a short interval of time, and knowing the velocities, the changes of position over that time interval can be computed. This process is looped to calculate, approximately, the bodies' trajectories. Generally speaking, the shorter the time interval, the more accurate the approximation.[62]Main article: Chaos theoryThree double pendulums, initialized with almost exactly the same initial conditions, diverge over time.Newton's laws of motion allow the possibility of chaos.[63][64] That is, qualitatively speaking, physical systems obeying Newton's laws can exhibit sensitive dependence upon their initial conditions: a slight change of the position or velocity of one part of a system can lead to the whole system behaving in a radically different way within a short time. Noteworthy examples include the three-body problem, the double pendulum, dynamical billiards, and the FermiPastaUlamTsingou problem.Newton's laws can be applied to fluids by considering a fluid as composed of infinitesimal pieces, each exerting forces upon neighboring pieces. The Euler momentum equation is an expression of Newton's second law adapted to fluid dynamics.[65][66] A fluid is described by a velocity field, i.e., a function v (x , t) {\displaystyle \mathbf {v} (\mathbf {x} ,t)} that assigns a velocity vector to each point in space and time. A small object being carried along by the fluid flow can change velocity for two reasons: first, because the velocity field at its position is changing over time, and second, because it moves to a new location where the velocity field has a different value. Consequently, when Newton's second law is applied to an infinitesimal portion of fluid, the acceleration a {\displaystyle \mathbf {a} } has two terms, a combination known as a total or material derivative. The mass of an infinitesimal portion depends upon the fluid density, and there is a net force upon it if the fluid pressure varies from one side of it to another. Accordingly, a = F / m {\displaystyle \mathbf {a} =\mathbf {F} /m} becomes v t + (v) v = 1 P + f , {\displaystyle {\frac {\partial v}{\partial t}}+(\mathbf {abla } \cdot \mathbf {v})\mathbf {v} =-{\frac {1}{\rho }}\mathbf {abla } P+\mathbf {f} ,} where {\displaystyle \rho } is the density, P {\displaystyle P} is the pressure, and f {\displaystyle \mathbf {f} } stands for an external influence like a gravitational pull. Incorporating the effect of viscosity turns the Euler equation into a NavierStokes equation: v t + (v) v = 1 P + 2 v + f , {\displaystyle {\frac {\partial v}{\partial t}}+(\mathbf {abla } \cdot \mathbf {v})\mathbf {v} =-{\frac {1}{\rho }}\mathbf {abla } P+u abla ^{2}\mathbf {v} +\mathbf {f} ,} where {\displaystyle u } is the kinematic viscosity.[65]It is mathematically possible for a collection of point masses, moving in accord with Newton's laws, to launch some of themselves away so forcefully that they fly off to infinity in a finite time.[67] This unphysical behavior, known as a "noncollision singularity",[60] depends upon the masses being pointlike and able to approach one another arbitrarily closely, as well as the lack of a relativistic speed limit in Newtonian physics.[68]It is not yet known whether or not the Euler and NavierStokes equations exhibit the analogous behavior of initially smooth solutions "blowing up" in finite time. The question of existence and smoothness of NavierStokes solutions is one of the Millennium Prize Problems.[69]Classical mechanics can be mathematically formulated in multiple different ways, other than the "Newtonian" description (which itself, of course, incorporates contributions from others both before and after Newton). The physical content of these different formulations is the same as the Newtonian, but they provide different insights and facilitate different types of calculations. For example, Lagrangian mechanics helps make apparent the connection between symmetries and conservation laws, and it is useful when calculating the motion of constrained bodies, like a mass restricted to move along a curving track or on the surface of a sphere.[19]:48 Hamiltonian mechanics is convenient for statistical physics,[70][71]:57 leads to further insight about symmetry,[19]:251 and can be developed into sophisticated techniques for perturbation theory.[19]:284 Due to the breadth of these topics, the discussion here will be confined to concise treatments of how they reformulate Newton's laws of motion.Lagrangian mechanics differs from the Newtonian formulation by considering entire trajectories at once rather than predicting a body's motion at a single instant.[19]:109 It is traditional in Lagrangian mechanics to denote position with q {\displaystyle q} and velocity with q {\displaystyle {\dot {q}}} . The simplest example is a massive point particle, the Lagrangian for which can be written as the difference between its kinetic and potential energies: L (q , q) = T V , {\displaystyle L(q,{\dot {q}})=T-V,} where the kinetic energy is T = 1 2 m q 2 {\displaystyle T={\frac {1}{2}}m{\dot {q}}^{2}} and the potential energy is some function of the position, V (q) {\displaystyle V(q)} . The physical path that the particle will take between an initial point q i {\displaystyle q_{i}} and a final point q f {\displaystyle q_{f}} is the path for which the integral of the Lagrangian is "stationary". That is, the physical path has the property that small perturbations of it will, to a first approximation, not change the integral of the Lagrangian. Calculus of variations provides the mathematical tools for finding this path.[46]:485 Applying the calculus of variations to the task of finding the path yields the EulerLagrange equation for the particle, d d t (L q) = L q . {\displaystyle {\frac {d}{dt}}\left({\frac {\partial L}{\partial {\dot {q}}}}\right)={\frac {\partial L}{\partial q}}.} Evaluating the partial derivatives of the Lagrangian gives d d t (m q) = d V d q , {\displaystyle {\frac {d}{dt}}(m{\dot {q}})=-{\frac {dV}{dq}},} which is a restatement of Newton's second law. The left-hand side is the time derivative of the momentum, and the right-hand side is the force, represented in terms of the potential energy.[9]:737Landau and Lifshitz argue that the Lagrangian formulation makes the conceptual content of classical mechanics more clear than starting with Newton's laws.[29] Lagrangian mechanics provides a convenient framework in which to prove Noether's theorem, which relates symmetries and conservation laws.[72] The conservation of momentum can be derived by applying Noether's theorem to a Lagrangian for a multi-particle system, and so, Newton's third law is a theorem rather than an assumption.[19]:124Emmy Noether, whose 1915 proof of a celebrated theorem that relates symmetries and conservation laws was a key development in modern physics and can be conveniently stated in the language of Lagrangian or Hamiltonian mechanicsIn Hamiltonian mechanics, the dynamics of a system are represented by a function called the Hamiltonian, which in many cases of interest is equal to the total energy of the system.[9]:742 The Hamiltonian is a function of the positions and the momenta of all the bodies making up the system, and it may also depend explicitly upon time. The time derivatives of the position and momentum variables are given by partial derivatives of the Hamiltonian, via Hamilton's equations.[19]:203 The simplest example is a point mass m {\displaystyle m} constrained to move in a straight line, under the effect of a potential. Writing q {\displaystyle q} for the position coordinate and p {\displaystyle p} for the body's momentum, the Hamiltonian is H (p , q) = p 2 2 m + V (q) . {\displaystyle {\mathcal {H}}(p,q)={\frac {p^{2}}{2m}}+V(q).} In this example, Hamilton's equations are d q d t = H p {\displaystyle {\frac {dq}{dt}}={\frac {\partial {\mathcal {H}}}{\partial p}}} and d p d t = H q . {\displaystyle {\frac {dp}{dt}}=-{\frac {\partial {\mathcal {H}}}{\partial q}}.} Evaluating these partial derivatives, the former equation becomes d q d t = p m , {\displaystyle {\frac {dq}{dt}}={\frac {p}{m}},} which reproduces the familiar statement that a body's momentum is the product of its mass and velocity. The time derivative of the momentum is d p d t = d V d q , {\displaystyle {\frac {dp}{dt}}=-{\frac {dV}{dq}},} which, upon identifying the negative derivative of the potential with the force, is just Newton's second law once again.[63][9]:742As in the Lagrangian formulation, in Hamiltonian mechanics the conservation of momentum can be derived using Noether's theorem, making Newton's third law an idea that is deduced rather than assumed.[19]:251Among the proposals to reform the standard introductory-physics curriculum is one that teaches the concept of energy before that of force, essentially "introductory Hamiltonian mechanics".[73][74]The HamiltonJacobi equation provides yet another formulation of classical mechanics, one which makes it mathematically analogous to wave optics.[19]:284[75] This formulation also uses Hamiltonian functions, but in a different way than the formulation described above. The paths taken by bodies or collections of bodies are deduced from a function S (q 1 , q 2 , , t) {\displaystyle S(\mathbf {q} _{1},\mathbf {q} _{2},\ldots ,t)} of positions q i {\displaystyle \mathbf {q} _{i}} and time t {\displaystyle t} . The Hamiltonian is incorporated into the HamiltonJacobi equation, a differential equation for S {\displaystyle S} . Bodies move over time in such a way that their trajectories are perpendicular to the surfaces of constant S {\displaystyle S} , analogously to how a light ray propagates in the direction perpendicular to its wavefront. This is simplest to express for the case of a single point mass, in which S {\displaystyle S} is a function S (q , t) {\displaystyle S(\mathbf {q} ,t)} , and the point mass moves in the direction along which S {\displaystyle S} changes most steeply. In other words, the momentum of the point mass is the gradient of S {\displaystyle S} : v = 1 m S . {\displaystyle \mathbf {v} ={\frac {1}{m}}\mathbf {abla } S.} The HamiltonJacobi equation for a point mass is S t = H (q , S , t) . {\displaystyle -{\frac {\partial S}{\partial t}}=H\left(\mathbf {q} ,\mathbf {abla } S,t\right).} The relation to Newton's laws can be seen by considering a point mass moving in a time-independent potential V (q) {\displaystyle V(\mathbf {q})} , in which case the HamiltonJacobi equation becomes S t = 1 2 m (S) 2 + V (q) . {\displaystyle -{\frac {\partial S}{\partial t}}={\frac {1}{2m}}\left(\mathbf {abla } S\right)^{2}+V(\mathbf {q}).} Taking the gradient of both sides, this becomes S t = 1 2 m (S) 2 + V . {\displaystyle -\mathbf {abla } {\frac {\partial S}{\partial t}}={\frac {1}{2m}}\mathbf {abla } \left(\mathbf {abla } S\right)^{2}+\mathbf {abla } V.} Interchanging the order of the partial derivatives on the left-hand side, and using the power and chain rules on the first term on the right-hand side, t S = 1 m (S) S + V . {\displaystyle -{\frac {\partial }{\partial t}}\mathbf {abla } S={\frac {1}{m}}\left(\mathbf {abla } S\cdot \mathbf {abla } \right)\mathbf {abla } S+\mathbf {abla } V.} Gathering together the terms that depend upon the gradient of S {\displaystyle S} , [t + 1 m (S)] S = V . {\displaystyle \left[{\frac {\partial }{\partial t}}+{\frac {1}{m}}\left(\mathbf {abla } S\cdot \mathbf {abla } \right)\right]\mathbf {abla } S=-\mathbf {abla } V.} This is another re-expression of Newton's second law.[76] The expression in brackets is a total or material derivative as mentioned above,[77] in which the first term indicates how the function being differentiated changes over time at a fixed location, and the second term captures how a moving particle will see different values of that function as it travels from place to place: [t + 1 m (S)] = [t + v] = d d t . {\displaystyle \left[{\frac {\partial }{\partial t}}+{\frac {1}{m}}\left(\mathbf {abla } S\cdot \mathbf {abla } \right)\right]=\left[{\frac {\partial }{\partial t}}+\mathbf {v} \cdot \mathbf {abla } \right]={\frac {d}{dt}}.} A simulation of a larger, but still microscopic, particle (in yellow) surrounded by a gas of smaller particles, illustrating Brownian motionIn statistical physics, the kinetic theory of gases applies Newton's laws of motion to large numbers (typically on the order of the Avogadro number) of particles. Kinetic theory can explain, for example, the pressure that a gas exerts upon the container holding it as the aggregate of many impacts of atoms, each imparting a tiny amount of momentum.[71]:62The Langevin equation is a special case of Newton's second law, adapted for the case of describing a small object bombarded stochastically by even smaller ones.[78]:235 It can be written m a = v + {\displaystyle m\mathbf {a} =-\gamma \mathbf {v} +\mathbf {\xi } \,} where {\displaystyle \gamma } is a drag coefficient and {\displaystyle \mathbf {\xi } } is a force that varies randomly from instant to instant, representing the net effect of collisions with the surrounding particles. This is used to model Brownian motion.[79]Newton's three laws can be applied to phenomena involving electricity and magnetism, though subtleties and caveats exist.Coulomb's law for the electric force between two stationary, electrically charged bodies has much the same mathematical form as Newton's law of universal gravitation: the force is proportional to the product of the charges, inversely proportional to the square of the distance between them, and directed along the straight line between them. The Coulomb force that a charge q 1 {\displaystyle q_{1}} exerts upon a charge q 2 {\displaystyle q_{2}} is equal in magnitude to the force that q 2 {\displaystyle q_{2}} exerts upon q 1 {\displaystyle q_{1}} , and it points in the exact opposite direction. Coulomb's law is thus consistent with Newton's third law.[80]Electromagnetism treats forces as produced by fields acting upon charges. The Lorentz force law provides an expression for the force upon a charged body that can be plugged into Newton's second law in order to calculate its acceleration.[81]:85 According to the Lorentz force law, a charged body in an electric field experiences a force in the direction of that field, a force proportional to its charge q {\displaystyle q} and to the strength of the electric field. In addition, a moving charged body in a magnetic field experiences a force that is also proportional to its charge, in a direction perpendicular to both the field and the body's direction of motion. Using the vector cross product, F = q E + q v B . {\displaystyle \mathbf {F} =q\mathbf {E} +q\mathbf {v} \times \mathbf {B} .} The Lorentz force law in effect: electrons are bent into a circular trajectory by a magnetic field.If the electric field vanishes (E = 0 {\displaystyle \mathbf {E} =0}), then the force will be perpendicular to the charge's motion, just as in the case of uniform circular motion studied above, and the charge will circle (or more generally move in a helix) around the magnetic field lines at the cyclotron frequency = q B / m {\displaystyle \omega =qB/m} .[78]:222 Mass spectrometry works by applying electric and/or magnetic fields to moving charges and measuring the resulting acceleration, which by the Lorentz force law yields the mass-to-charge ratio.[82]Collections of charged bodies do not always obey Newton's third law: there can be a change of one body's momentum without a compensatory change in the momentum of another. The discrepancy is accounted for by momentum carried by the electromagnetic field itself. The momentum per unit volume of the electromagnetic field is proportional to the Poynting vector.[83]:184[84]There is subtle conceptual conflict between electromagnetism and Newton's first law: Maxwell's theory of electromagnetism predicts that electromagnetic waves will travel through empty space at a constant, definite speed. Thus, some inertial observers seemingly have a privileged status over the others, namely those who measure the speed of light and find it to be the value predicted by the Maxwell equations. In other words, light provides an absolute standard for speed, yet the principle of inertia holds that there should be no such standard. This tension is resolved in the theory of special relativity, which revises the notions of space and time in such a way that all inertial observers will agree upon the speed of light in vacuum.[note 12]Further information: Relativistic mechanics and Acceleration (special relativity)In special relativity, the rule that Wilczek called "Newton's Zeroth Law" breaks down: the mass of a composite object is not merely the sum of the masses of the individual pieces.[87]:33 Newton's first law, inertial motion, remains true. A form of Newton's second law, that force is the rate of change of momentum, also holds, as does the conservation of momentum. However, the definition of momentum is modified. Among the consequences of this is the fact that the more quickly a body moves, the harder it is to accelerate, and so, no matter how much force is applied, a body cannot be accelerated to the speed of light. Depending on the problem at hand, momentum in special relativity can be represented as a three-dimensional vector, p = m v {\displaystyle \mathbf {p} =m\gamma \mathbf {v} } , where m {\displaystyle m} is the body's rest mass and {\displaystyle \gamma } is the Lorentz factor, which depends upon the body's speed. Alternatively, momentum and force can be represented as four-vectors.[88]:107Newton's third law must be modified in special relativity. The third law refers to the forces between two bodies at the same moment in time, and a key feature of special relativity is that simultaneity is relative. Events that happen at the same time relative to one observer can happen at different times relative to another. So, in a given observer's frame of reference, action and reaction may not be exactly opposite, and the total momentum of interacting bodies may not be conserved. The conservation of momentum is restored by including the momentum stored in the field that describes the bodies' interaction.[89][90]Newtonian mechanics is a good approximation to special relativity when the speeds involved are small compared to that of light.[91]:131General relativity is a theory of gravity that advances beyond that of Newton. In general relativity, the gravitational force of Newtonian mechanics is reimagined as curvature of spacetime. A curved path like an orbit, attributed to a gravitational force in Newtonian mechanics, is not the result of a force deflecting a body from an ideal straight-line path, but rather the body's attempt to fall freely through a background that is itself curved by the presence of other masses. A remark by John Archibald Wheeler that has become proverbial among physicists summarizes the theory: "Spacetime tells matter how to move; matter tells spacetime how to curve."[92][93] Wheeler himself thought of this reciprocal relationship as a modern, generalized form of Newton's third law.[92] The relation between matter distribution and spacetime curvature is given by the Einstein field equations, which require tensor calculus to express.[87]:43[94]The Newtonian theory of gravity is a good approximation to the predictions of general relativity when gravitational effects are weak and objects are moving slowly compared to the speed of light.[85]:327[95]Quantum mechanics is a theory of physics originally developed in order to understand microscopic phenomena: behavior at the scale of molecules, atoms or subatomic particles. Generally and loosely speaking, the smaller a system is, the more an adequate mathematical model will require understanding quantum effects. The conceptual underpinning of quantum physics is very different from that of classical physics. Instead of thinking about quantities like position, momentum, and energy as properties that an object has, one considers what result might appear when a measurement of a chosen type is performed. Quantum mechanics allows the physicist to calculate the probability that a chosen measurement will elicit a particular result.[96][97] The expectation value for a measurement is the average of the possible results it might yield, weighted by their probabilities of occurrence.[98]The Ehrenfest theorem provides a connection between quantum expectation values and Newton's second law, a connection that is necessarily inexact, as quantum physics is fundamentally different from classical. In quantum physics, position and momentum are represented by mathematical entities known as Hermitian operators, and the Born rule is used to calculate the expectation values of a position measurement or a momentum measurement. These expectation values will generally change over time; that is, depending on the time at which (for example) a position measurement is performed, the probabilities for its different possible outcomes will vary. The Ehrenfest theorem says, roughly speaking, that the equations describing how these expectation values change over time have a form reminiscent of Newton's second law. However, the more pronounced quantum effects are in a given situation, the more difficult it is to derive meaningful conclusions from this resemblance.[note 13]Isaac Newton (16431727), in a 1689 portrait by Godfrey KnellerNewton's own copy of his Principia, with hand-written corrections for the second edition, in the Wren Library at Trinity College, CambridgeNewton's first and second laws, in Latin, from the original 1687 Principia MathematicaThe concepts invoked in Newton's laws of motion mass, velocity, momentum, force have predecessors in earlier work, and the content of Newtonian physics was further developed after Newton's time. Newton combined knowledge of celestial motions with the study of events on Earth and showed that one theory of mechanics could encompass both.[note 14]As noted by scholar I. Bernard Cohen, Newton's work was more than a mere synthesis of previous results, as he selected certain ideas and further transformed them, with each in a new form that was useful to him, while at the same time proving false of certain basic or fundamental principles of scientists such as Galileo Galilei, Johannes Kepler, Ren Descartes, and Nicolaus Copernicus.[103] He approached natural philosophy with mathematics in a completely novel way, in that instead of a preconceived natural philosophy, his style was to begin with a mathematical construct, and build on from there, comparing it to the real world to show that his system accurately accounted for it.[104]Aristotle (384322 BCE)The subject of physics is often traced back to Aristotle, but the history of the concepts involved is obscured by multiple factors. An exact correspondence between Aristotelian and modern concepts is not simple to establish: Aristotle did not clearly distinguish what we would call speed and force, used the same term for density and viscosity, and conceived of motion as always through a medium, rather than through space. In addition, some concepts often termed "Aristotelian" might better be attributed to his followers and commentators upon him.[105] These commentators found that Aristotelian physics had difficulty explaining projectile motion.[note 15] Aristotle divided motion into two types: "natural" and "violent". The "natural" motion of terrestrial solid matter was to fall downwards, whereas a "violent" motion could push a body sideways. Moreover, in Aristotelian physics, a "violent" motion requires an immediate cause; separated from the cause of its "violent" motion, a body would revert to its "natural" behavior. Yet, a javelin continues moving after it leaves the thrower's hand. Aristotle concluded that the air around the javelin must be imparted with the ability to move the javelin forward. John Philoponus, a Byzantine Greek thinker active during the sixth century, found this absurd: the same medium, air, was somehow responsible both for sustaining motion and for impeding it. If Aristotle's idea were true, Philoponus said, armies would launch weapons by blowing upon them with bellows. Philoponus argued that setting a body into motion imparted a quality, impetus, that would be contained within the body itself. As long as its impetus was sustained, the body would continue to move.[107]:47 In the following centuries, versions of impetus theory were advanced by individuals including Nur ad-Din al-Bitruji, Avicenna, Abu'l-Barakt al-Baghdd, John Buridan, and Albert of Saxony. In retrospect, the idea of impetus can be seen as a forerunner of the modern concept of momentum.[note 16] The intuition that objects move according to some kind of impetus persists in many students of introductory physics.[109]See also: Galileo Galilei InertiaThe French philosopher Ren Descartes introduced the concept of inertia by way of his "laws of nature" in The World (Trait du monde et de la lumire) written 162933. However, The World purported a heliocentric worldview, and in 1633 this view had given rise a great conflict between Galileo Galilei and the Roman Catholic Inquisition. Descartes knew about this controversy and did not wish to get involved. The World was not published until 1664, ten years after his death.[110]Galileo Galilei (15641642)The modern concept of inertia is credited to Galileo. Based on his experiments, Galileo concluded that the "natural" behavior of a moving body was to keep moving, until something else interfered with it. In Two New Sciences (1638) Galileo wrote:[111][112]Imagine any particle projected along a horizontal plane without friction; then we know, from what has been more fully explained in the preceding pages, that this particle will move along this same plane with a motion which is uniform and perpetual, provided the plane has no limits.Ren Descartes (15961650)Galileo recognized that in projectile motion, the Earth's gravity affects vertical but not horizontal motion.[113] However, Galileo's idea of inertia was not exactly the one that would be codified into Newton's first law. Galileo thought that a body moving a long distance inertially would follow the curve of the Earth. This idea was corrected by Isaac Beeckman, Descartes, and Pierre Gassendi, who recognized that inertial motion should be motion in a straight line.[114] Descartes published his laws of nature (laws of motion) with this correction in Principles of Philosophy (Principia Philosophiae) in 1644, with the heliocentric part toned down.[115][110]Ball in circular motion has string cut and flies off tangentially.First Law of Nature: Each thing when left to itself continues in the same state; so any moving body goes on moving until stopped by something.Second Law of Nature: Each moving thing if left to itself moves in a straight line; so any body moving in a circle always tends to move away from the centre of the circle.According to American philosopher Richard J. Blackwell, Dutch scientist Christiaan Huygens had worked out his own, concise version of the law in 1656.[116] It was not published until 1703, eight years after his death, in the opening paragraph of De Motu Corporum ex Percussione.Hypothesis I: Any body already in motion will continue to move perpetually with the same speed and in a straight line unless it is impeded.According to Huygens, this law was already known by Galileo and Descartes among others.[116]Christiaan Huygens (16291695)Christiaan Huygens, in his Horologium Oscillatorium (1673), put forth the hypothesis that "By the action of gravity, whatever its sources, it happens that bodies are moved by a motion composed both of a uniform motion in one direction or another and of a motion downward due to gravity." Newton's second law generalized this hypothesis from gravity to all forces.[117]One important characteristic of Newtonian physics is that forces can act at a distance without requiring physical contact.[note 17] For example, the Sun and the Earth pull on each other gravitationally, despite being separated by millions of kilometres. This contrasts with the idea, championed by Descartes among others, that the Sun's gravity held planets in orbit by swirling them in a vortex of transparent matter, aether.[124] Newton considered aetherial explanations of force but ultimately rejected them.[122] The study of magnetism by William Gilbert and others created a precedent for thinking of immaterial forces,[122] and unable to find a quantitatively satisfactory explanation of his law of gravity in terms of an aetherial model, Newton eventually declared, "I feign no hypotheses": whether or not a model like Descartes's vortices could be found to underlie the Principia's theories of motion and gravity, the first grounds for judging them must be the successful predictions they made.[125] And indeed, since Newton's time every attempt at such a model has failed.Johannes Kepler (15711630)Johannes Kepler suggested that gravitational attractions were reciprocal that, for example, the Moon pulls on the Earth while the Earth pulls on the Moon but he did not argue that such pairs are equal and opposite.[126] In his Principles of Philosophy (1644), Descartes introduced the idea that during a collision between bodies, a "quantity of motion" remains unchanged. Descartes defined this quantity somewhat imprecisely by adding up the products of the speed and "size" of each body, where "size" for him incorporated both volume and surface area.[127] Moreover, Descartes thought of the universe as a plenum, that is, filled with matter, so all motion required a body to displace a medium as it moved. During the 1650s, Huygens studied collisions between hard spheres and deduced a principle that is now identified as the conservation of momentum.[128][129] Christopher Wren would later deduce the same rules for elastic collisions that Huygens had, and John Wallis would apply momentum conservation to study inelastic collisions. Newton cited the work of Huygens, Wren, and Wallis to support the validity of his third law.[130]Newton arrived at his set of three laws incrementally. In a 1684 manuscript written to Huygens, he listed four laws: the principle of inertia, the change of motion by force, a statement about relative motion that would today be called Galilean invariance, and the rule that interactions between bodies do not change the motion of their center of mass. In a later manuscript, Newton added a law of action and reaction, while saying that this law and the law regarding the center of mass implied one another. Newton probably settled on the presentation in the Principia, with three primary laws and then other statements reduced to corollaries, during 1685.[131]Page 157 from Mechanism of the Heavens (1831), Mary Somerville's expanded version of the first two volumes of Laplace's Trait de mcanique cleste.[132] Here, Somerville deduces the inverse-square law of gravity from Kepler's laws of planetary motion.Newton expressed his second law by saying that the force on a body is proportional to its change of motion, or momentum. By the time he wrote the Principia, he had already developed calculus (which he called "the science of fluxions"), but in the Principia he made no explicit use of it, perhaps because he believed geometrical arguments in the tradition of Euclid to be more rigorous.[133]:15[134] Consequently, the Principia does not express acceleration as the second derivative of position, and so it does not give the second law as F = ma {\displaystyle F=ma} . This form of the second law was written (for the special case of constant force) at least as early as 1716, by Jakob Hermann; Leonhard Euler would employ it as a basic premise in the 1740s.[135] Euler pioneered the study of rigid bodies[136] and established the basic theory of fluid dynamics.[137] Pierre-Simon Laplace's five-volume Trait de mcanique cleste (17981825) forsook geometry and developed mechanics purely through algebraic expressions, while resolving questions that the Principia had left open, like a full theory of the tides.[138]The concept of energy became a key part of Newtonian mechanics in the post-Newton period. Huygens' solution of the collision of hard spheres showed that in that case, not only is momentum conserved, but kinetic energy is as well (or, rather, a quantity that in retrospect we can identify as one-half the total kinetic energy). The question of what is conserved during all other processes, like inelastic collisions and motion slowed by friction, was not resolved until the 19th century. Debates on this topic overlapped with philosophical disputes between the metaphysical views of Newton and Leibniz, and variants of the term "force" were sometimes used to denote what we would call types of energy. For example, in 1742, milie du Chtelet wrote, "Dead force consists of a simple tendency to motion: such is that of a spring ready to relax; living force is that which a body has when it is in actual motion." In modern terminology, "dead force" and "living force" correspond to potential energy and kinetic energy respectively.[139] Conservation of energy was not established as a universal principle until it was understood that the energy of mechanical work can be dissipated into heat.[140][141] With the concept of energy given a solid grounding, Newton's laws could then be derived within formulations of classical mechanics that put energy first, as in the Lagrangian and Hamiltonian formulations described above.Modern presentations of Newton's laws use the mathematics of vectors, a topic that was not developed until the late 19th and early 20th centuries. Vector algebra, pioneered by Josiah Willard Gibbs and Oliver Heaviside, stemmed from and largely supplanted the earlier system of quaternions invented by William Rowan Hamilton.[142][143]Euler's laws of motionHistory of classical mechanicsList of eponymous lawsList of equations in classical mechanicsList of scientific laws named after peopleList of textbooks on classical mechanics and quantum mechanicsNorton's dome^ See, for example, Zain.[4]:1-2 David Tong observes, "A particle is defined to be an object of insignificant size: e.g. an electron, a tennis ball or a planet. Obviously the validity of this statement depends on the context..."[5]^ Negative acceleration includes both slowing down (when the current velocity is positive) and speeding up (when the current velocity is negative). For this and other points that students have often found difficult, see McDermott et al.[8]^ Per Cohen and Whitman.[2] For other phrasings, see Eddington[14] and Frautschi et al.[15]:114 Andrew Motte's 1729 translation rendered Newton's "nisi quatenus" as unless instead of except insofar, which Hoek argues was erroneous.[16][17]^ One textbook observes that a block sliding down an inclined plane is what "some cynics view as the dullest problem in all of physics".[23]:70 Another quips, "Nobody will ever know how many minds, eager to learn the secrets of the universe, found themselves studying inclined planes and pulleys instead, and decided to switch to some more interesting profession."[15]:173^ For example, José and Saletan (following Mach and Eisenbud[27]) take the conservation of momentum as a fundamental physical principle and treat F = m a {\displaystyle \mathbf {F} =m\mathbf {a} } as a definition of "force".[19]:9 See also Frautschi et al.,[15]:134 as well as Feynman, Leighton and Sands,[28]:12-1 who argue that the second law is incomplete without a specification of a force by another law, like the law of gravity. Kleppner and Kolenkow argue that the second law is incomplete without the third law: an observer who sees one body accelerate without a matching acceleration of some other body to compensate would conclude, not that a force is acting, but that they are not an inertial observer.[23]:60 Landau and Lifshitz bypass the question by starting with the Lagrangian formalism rather than the Newtonian.[29]^ See, for instance, Moebs et al.,[31] Gonick and Huffman,[32] Low and Wilson,[33] Stocklmayer et al.,[34] Hellingman,[35] and Hodanbosi.[36]^ See, for example, Frautschi et al.[15]:356^ For the former, see Greiner,[39] or Wachter and Hoeber.[40] For the latter, see Tait[41] and Heaviside.[42]^ Among the many textbook explanations of this are Frautschi et al.[15]:104 and Boas.[46]:287^ Among the many textbook treatments of this point are Hand and Finch[49]:81 and also Kleppner and Kolenkow.[23]:103^ Treatments can be found in, e.g., Chabay et al.[53] and McCallum et al.[54]:449^ Discussions can be found in, for example, Frautschi et al.,[15]:215 Panofsky and Phillips,[83]:272 Goldstein, Poole and Safko,[85]:277 and Werner.[86]^ Details can be found in the textbooks by, e.g., Cohen-Tannoudji et al.[99]:242 and Peres.[100]:302^ As one physicist writes, "Physical theory is possible because we are immersed and included in the whole process because we can act on objects around us. Our ability to intervene in nature clarifies even the motion of the planets around the sun masses so great and distances so vast that our roles as participants seem insignificant. Newton was able to transform Kepler's kinematical description of the solar system into a far more powerful dynamical theory because he added concepts from Galileo's experimental methods force, mass, momentum, and gravitation. The truly external observer will only get as far as Kepler. Dynamical concepts are formulated on the basis of what we can set up, control, and measure."[101] See, for example, Caspar and Hellman.[102]^ Aristotelian physics also had difficulty explaining buoyancy, a point that Galileo tried to resolve without complete success.[106]^ Anneliese Maier cautions, "Impetus is neither a force, nor a form of energy, nor momentum in the modern sense; it shares something with all these otherconcepts, but it is identical with none of them."[108]:79^ Newton himself was an enthusiastic alchemist. John Maynard Keynes called him "the last of the magicians" to describe his place in the transition between protoscience and modern science.[118][119] The suggestion has been made that alchemy inspired Newton's notion of "action at a distance", i.e., one body exerting a force upon another without being in direct contact.[120] This suggestion enjoyed considerable support among historians of science[121] until a more extensive study of Newton's papers became possible, after which it fell out of favor. However, it does appear that Newton's alchemy influenced his optics, in particular, how he thought about the combination of colors.[122][123]^ Thornton, Stephen T.; Marion, Jerry B. (2004). Classical Dynamics of Particles and Systems (5thed.). Brooke Cole. p.49. ISBN0-534-40896-6.^ a b Newton, I. (1999). The Principia, The Mathematical Principles of Natural Philosophy. Translated by Cohen, I.B.; Whitman, A. Los Angeles: University of California Press.^ Newton, Isaac; Chittenden, N. W.; Motte, Andrew; Hill, Theodore Preston (1846). Newton's Principia: The Mathematical Principles of Natural Philosophy. University of California Libraries. Daniel Adee.^ Zain, Samya (2019). Techniques of Classical Mechanics: from Lagrangian to Newtonian mechanics. Institute of Physics. ISBN978-0-750-32076-4. OCLC1084752471.^ Tong, David (January 2015). "Classical Dynamics: University of Cambridge Part II Mathematical Tripos" (PDF). University of Cambridge. Retrieved 12 February 2022.^ a b Hughes-Hallett, Deborah; McCallum, William G.; Gleason, Andrew M.; etal. (2013). Calculus: Single and Multivariable (6thed.). Hoboken, NJ: Wiley. pp.76-78. ISBN978-0-470-88861-2. OCLC794034942.^ a b Thompson, Silvanus P.; Gardner, Martin (1998). Calculus Made Easy. Macmillan. pp.84-85. ISBN978-0-312-18548-0. OCLC799163595.^ McDermott, Lillian C.; Rosenquist, Mark L.; van Zee, Emily H. (June 1987). "Student difficulties in connecting graphs and physics: Examples from kinematics". American Journal of Physics. 55 (6): 503513. Bibcode:1987AmJPh..55..503M. doi:10.1119/1.15104. ISSN0002-9505.^ a b c d e Gbur, Greg (2011). Mathematical Methods for Optical Physics and Engineering. Cambridge, U.K.: Cambridge University Press. ISBN978-0-511-91510-9. OCLC704518582.^ Driver, Rosalind; Warrington, Lynda (1 July 1985). "Students' use of the principle of energy conservation in problem situations". Physics Education. 20 (4): 171176. Bibcode:1985PhyEd..20..171D. doi:10.1088/0031-9120/20/4/308. S2CID250781921.^ Hart, Christina (May 2002). "If the Sun burns you is that a force? Some definitional prerequisites for understanding Newton's laws". Physics Education. 37 (3): 234238. Bibcode:2002PhyEd..37..234H. doi:10.1088/0031-9120/37/3/307.^ Brookes, David T.; Etkina, Eugenia (25 June 2009). ""Force," ontology, and language". Physical Review Special Topics - Physics Education Research. 5 (1): 010110. Bibcode:2009PRPER...5a0110B. doi:10.1103/PhysRevSTPER.5.010110. ISSN1554-9178.^ Urone, Paul Peter; Hinrichs, Roger; Dirks, Kim; Sharma, Manjula (2021). College Physics. OpenStax. ISBN978-1-947172-01-2. OCLC895896190.^ Eddington, Arthur (1929). The Nature of the Physical World. New York: Macmillan. p.123125.^ a b c d e f g h i j k Frautschi, Steven C.; Olenick, Richard P.; Apostol, Tom M.; Goodstein, David L. (2007). The Mechanical Universe: Mechanics and Heat (Advanced.). Cambridge [Cambridgeshire]: Cambridge University Press. ISBN978-0-521-71590-4. OCLC227002144.^ Hoek, D. (2023). "Forced Changes Only: A New Take on the Law of Inertia". Philosophy of Science. 90 (1): 6073. arXiv:2112.02339. doi:10.1017/psa.2021.38.^ Pappas, Stephanie (5 September 2023). "Mistranslation of Newton's First Law Discovered after Nearly 300 Years". Scientific American.^ Resnick, Robert (1968). Introduction to Special Relativity. Wiley. pp.8-16. OCLC1120819093.^ a b c d e f g h i j k l m n José, Jorge V.; Saletan, Eugene J. (1998). Classical Dynamics: A Contemporary Approach. Cambridge [England]: Cambridge University Press. ISBN978-1-139-64890-5. OCLC857769535.^ Brading, Katherine (August 2019). "A note on rods and clocks in Newton's Principia". Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics. 67: 160166. Bibcode:2019SHPMP..67..160B. doi:10.1016/j.shpsb.2017.07.004. S2CID125131430.^ Feather, Norman (1959). An Introduction to the Physics of Mass, Length, and Time. United Kingdom: University Press. pp.126128.^ Resnick, Robert; Halliday, David (1966). "Section 5-4: Mass; Newton's Second Law". Physics. John Wiley & Sons. LCCN66-11527.^ a b c d e f g Kleppner, Daniel; Kolenkow, Robert J. (2014). An introduction to mechanics (2nded.). Cambridge: Cambridge University Press. ISBN978-0-521-19811-0. OCLC854617117.^ a b Plastino, A.R.; Muzzio, J.C. (1992). "On the use and abuse of Newton's second law for variable mass problems". Celestial Mechanics and Dynamical Astronomy. 53 (3): 227232. Bibcode:1992CeMDA..53..227P. doi:10.1007/BF00052611. ISSN0923-2958.^ Arnold, Sommerfeld (1952). Mechanics. Academic Press. ISBN978-0-12-654668-2. {{cite book}}: ISBN / Date incompatibility (help)^ Rosengrant, David; Van Heuvelen, Alan; Etkina, Eugenia (1 June 2009). "Do students use and understand free-body diagrams?". Physical Review Special Topics - Physics Education Research. 5 (1): 010108. Bibcode:2009PRPER...5a0108R. doi:10.1103/PhysRevSTPER.5.010108. ISSN1554-9178.^ a b Eisenbud, Leonard (1958). "On the Classical Laws of Motion". American Journal of Physics. 26 (3): 144159. Bibcode:1958AmJPh..26..144E. doi:10.1119/1.1934608.^ a b Feynman, Richard P.; Leighton, Robert B.; Sands, Matthew L. (1989) [1965]. The Feynman Lectures on Physics, Volume 1. Reading, Mass.: Addison-Wesley Pub. Co. ISBN0-201-02010-6. OCLC531535.^ a b Landau, Lev D.; Lifshitz, Evgeny M. (1969). Mechanics. Course of Theoretical Physics. Vol.1. Translated by Sykes, J. B.; Bell, J. S. (2nded.). Pergamon Press. p.vii. ISBN978-0-080-06466-6. OCLC898931862. Only with this approach, indeed, can the exposition form a logical whole and avoid tautological definitions of the fundamental mechanical quantities. It is, moreover, essentially simpler, and leads to the most complete and direct means of solving problems in mechanics.^ Warren, J. W. (1979). Understanding force: an account of some aspects of teaching the idea of force in school, college and university courses in engineering, mathematics and science. London: Murray. pp.2829. ISBN978-0-7195-3564-2.^ Moebs, William; etal. (2023). "5.5 Newton's Third Law". University Physics, Volume 1. OpenStax. p.220. ISBN978-1-947172-20-3.^ Gonick, Larry; Huffman, Art (1991). The Cartoon Guide to Physics. HarperPerennial. p.50. ISBN0-06-273100-9.^ Low, David J.; Wilson, Kate F. (January 2017). "The role of competing knowledge structures in undermining learning: Newton's second and third laws". American Journal of Physics. 85 (1): 5465. Bibcode:2017AmJPh..85...54L. doi:10.1119/1.4972041. ISSN0002-9505.^ Stocklmayer, Sue; Rayner, John P.; Gore, Michael M. (October 2012). "Changing the Order of Newton's LawsWhy & How the Third Law Should be First". The Physics Teacher. 50 (7): 406409. Bibcode:2012PhTea..50..406S. doi:10.1119/1.4752043. ISSN0031-921X.^ Hellingman, C. (March 1992). "Newton's third law revisited". Physics Education. 27 (2): 112115. Bibcode:1992PhyEd..27..112H. doi:10.1088/0031-9120/27/2/011. ISSN0031-9120. S2CID250891975.^ Hodanbosi, Carol (August 1996). Fairman, Jonathan G. (ed.). "Third Law of Motion". www.grc.nasa.gov.^ Wilczek, Frank (2003). "The Origin of Mass" (PDF). MIT Physics Annual 2003. Retrieved 13 January 2022.^ Scherr, Rachel E.; Redish, Edward F. (1 January 2005). "Newton's Zeroth Law: Learning from Listening to Our Students". The Physics Teacher. 43 (1): 4145. Bibcode:2005PhTea..43...41S. doi:10.1119/1.1845990. ISSN0031-921X.^ Greiner, Walter (2003). Classical Mechanics: Point Particles and Relativity. New York: Springer. p.135. ISBN978-0-387-21851-9.^ Wachter, Armin; Hoeber, Henning (2006). Compendium of theoretical physics. New York: Springer. p.6. ISBN978-0-387-25799-0.^ Tait, Peter Guthrie (1889). "Mechanics". Encyclopædia Britannica. Vol.15 (9thed.). pp.715716.^ Heaviside, Oliver (August 1905). "The Transverse Momentum of an Electron". Nature. 72 (1870): 429. Bibcode:1905Natur..72Q.429H. doi:10.1038/072429a0. ISSN0028-0836. S2CID4016382.^ Nicodemi, Olympia (1 February 2010). "Galileo and Oresme: Who Is Modern? Who Is Medieval?". Mathematics Magazine. 83 (1): 2432. doi:10.4169/002557010X479965. ISSN0025-570X. S2CID122113958.^ Scholberg, Kate (2020). "Frequently Asked Questions: Projectile Motion". Physics 361. Retrieved 16 January 2022.^ Carli, Marta; Lippiello, Stefania; Pantano, Ornella; Perona, Mario; Tormen, Giuseppe (19 March 2020). "Testing students ability to use derivatives, integrals, and vectors in a purely mathematical context and in a physical context". Physical Review Physics Education Research. 16 (1): 010111. Bibcode:2020PRPER..16a0111C. doi:10.1103/PhysRevPhysEducRes.16.010111. hdl:11577/3340932. ISSN2469-9896. S2CID215832738.^ a b Boas, Mary L. (2006). Mathematical Methods in the Physical Sciences (3rded.). Hoboken, NJ: Wiley. ISBN978-0-471-19826-0. OCLC61332593.^ Brown, Mike (2010). How I Killed Pluto and Why It Had It Coming (1sted.). New York: Spiegel & Grau. ISBN978-0-385-53108-5. OCLC495271396.^ Topper, D.; Vincent, D. E. (1 January 1999). "An analysis of Newton's projectile diagram". European Journal of Physics. 20 (1): 5966. Bibcode:1999EJPh...20...59T. doi:10.1088/0143-0807/20/1/018. ISSN0143-0807. S2CID250883796.^ a b Hand, Louis N.; Finch, Janet D. (1998). Analytical Mechanics. Cambridge: Cambridge University Press. ISBN0-521-57327-0. OCLC37903527.^ Billah, K. Yusuf; Scanlan, Robert H. (1 February 1991). "Resonance, Tacoma Narrows bridge failure, and undergraduate physics textbooks" (PDF). American Journal of Physics. 59 (2): 118124. Bibcode:1991AmJPh..59..118B. doi:10.1119/1.16590. ISSN0002-9505.^ Wilson, Jerry D. (1 September 1972). "LETTERS: Newton's Sailboat". The Physics Teacher. 10 (6): 300. Bibcode:1972PhTea..10..300W. doi:10.1119/1.2352231. ISSN0031-921X.^ Clark, Robert Beck (1 January 1986). "The answer is obvious, Isn't it?". The Physics Teacher. 24 (1): 3839. Bibcode:1986PhTea..24...38C. doi:10.1119/1.2341931. ISSN0031-921X.^ Chabay, Ruth; Sherwood, Bruce; Titus, Aaron (July 2019). "A unified, contemporary approach to teaching energy in introductory physics". American Journal of Physics. 87 (7): 504509. Bibcode:2019AmJPh..87..504C. doi:10.1119/1.5109519. ISSN0002-9505. S2CID197512796.^ Hughes-Hallett, Deborah; McCallum, William G.; Gleason, Andrew M.; etal. (2013). Calculus: Single and Multivariable (6thed.). Hoboken, NJ: Wiley. ISBN978-0-470-88861-2. OCLC794034942.^ Lyublinskaya, Irina E. (January 1998). "Central collisionsThe general case". The Physics Teacher. 36 (1): 1819. Bibcode:1998PhTea..36...18L. doi:10.1119/1.879949. ISSN0031-921X.^ Close, Hunter G.; Heron, Paula R. L. (October 2011). "Student understanding of the angular momentum of classical particles". American Journal of Physics. 79 (10): 10681078. Bibcode:2011AmJPh..79.1068C. doi:10.1119/1.3579141. ISSN0002-9505.^ Mungan, Carl E. (1 March 2005). "Another comment on "Eccentricity as a vector"". European Journal of Physics. 26 (2): L7 L9. doi:10.1088/0143-0807/26/2/L01. ISSN0143-0807. S2CID121740340.^ Saggio, Maria Luisa (1 January 2013). "Bohlin transformation: the hidden symmetry that connects Hooke to Newton". European Journal of Physics. 34 (1): 129137. Bibcode:2013EJPh...34..129S. doi:10.1088/0143-0807/34/1/129. ISSN0143-0807. S2CID119949261.^ Barrow-Green, June (1997). Poincar and the Three Body Problem. American Mathematical Society. pp.812. Bibcode:1997ptbp.book.....B. ISBN978-0-8218-0367-7.^ a b Barrow-Green, June (2008). "The Three-Body Problem". In Gowers, Timothy; Barrow-Green, June; Leader, Imre (eds.). The Princeton Companion to Mathematics. Princeton University Press. pp.726728. ISBN978-0-691-11880-2. OCLC682200048.^ Breen, Barbara J.; Weidert, Christine E.; Lindner, John F.; Walker, Lisa May; Kelly, Kasey; Heidtmann, Evan (April 2008). "Invitation to embarrassingly parallel computing". American Journal of Physics. 76 (4): 347352. Bibcode:2008AmJPh..76..347B. doi:10.1119/1.2834738. ISSN0002-9505.^ McCandlish, David (July 1973). Shirer, Donald L. (ed.). "Solutions to the Three-Body Problem by Computer". American Journal of Physics. 41 (7): 928929. doi:10.1119/1.1987423. ISSN0002-9505.^ a b Masoliver, Jaume; Ros, Ana (1 March 2011). "Integrability and chaos: the classical uncertainty". European Journal of Physics. 32 (2): 431458. arXiv:1012.4384. Bibcode:2011EJPh...32..431M. doi:10.1088/0143-0807/32/2/016. ISSN0143-0807. S2CID58892714.^ Laws, Priscilla W. (April 2004). "A unit on oscillations, determinism and chaos for introductory physics students". American Journal of Physics. 72 (4): 446452. Bibcode:2004AmJPh..72..446L. doi:10.1119/1.1649964. ISSN0002-9505.^ a b Zee, Anthony (2020). Fly by Night Physics. Princeton University Press. pp.363364. ISBN978-0-691-18254-4. OCLC1288147292.^ Han-Kwan, Daniel; Iacobelli, Mikaela (7 April 2021). "From Newton's second law to Euler's equations of perfect fluids". Proceedings of the American Mathematical Society. 149 (7): 30453061. arXiv:2006.14924. doi:10.1090/proc/15349. ISSN0002-9939. S2CID220127889.^ Saari, Donald G.; Xia, Zhihong (May 1995). "Off to infinity in finite time" (PDF). Notices of the American Mathematical Society. 42: 538546.^ Baez, John C. (2021). "Struggles with the Continuum". In Anel, Mathieu; Catren, Gabriel (eds.). New Spaces in Physics: Formal and Conceptual Reflections. Cambridge University Press. pp.281326. arXiv:1609.01421. ISBN978-1-108-49062-7. OCLC1195899886.^ Fefferman, Charles L. (2006). "Existence and smoothness of the NavierStokes equation". In Carlson, James; Jaffe, Arthur; Wiles, Andrew (eds.). The Millennium Prize Problems (PDF). Providence, RI: American Mathematical Society and Clay Mathematics Institute. pp.5767. ISBN978-0-821-83679-8. OCLC466500872.^ Ehrenfest, Paul; Ehrenfest, Tatiana (1990) [1959]. The Conceptual Foundations of the Statistical Approach in Mechanics. New York: Dover Publications. p.18. ISBN0-486-66250-0. OCLC20934820.^ a b Kardar, Mehran (2007). Statistical Physics of Particles. Cambridge University Press. ISBN978-0-521-87342-0. OCLC860391091.^ Byers, Nina (2006). "Emmy Noether". In Byers, Nina; Williams, Gary (eds.). Out of the Shadows: Contributions of 20th Century Women to Physics. Cambridge: Cambridge University Press. pp.8396. ISBN978-0-521-82197-1. OCLC1150964892.^ LeGresley, Sarah E.; Delgado, Jennifer A.; Bruner, Christopher R.; Murray, Michael J.; Fischer, Christopher J. (13 September 2019). "Calculus-enhanced energy-first curriculum for introductory physics improves student performance locally and in downstream courses". Physical Review Physics Education Research. 15 (2): 020126. Bibcode:2019PRPER..15b0126L. doi:10.1103/PhysRevPhysEducRes.15.020126. hdl:1808/29610. ISSN2469-9896. S2CID203484310.^ Ball, Philip (13 September 2019). "Teaching Energy Before Forces". Physics. 12: 100. Bibcode:2019PhyOJ..12..100B. doi:10.1103/Physics.12.100. S2CID204188746.^ Houchmandzadeh, Bahram (May 2020). "The HamiltonJacobi equation: An alternative approach". American Journal of Physics. 88 (5): 353359. arXiv:1910.09414. Bibcode:2020AmJPh..88..353H. doi:10.1119/10.0000781. ISSN0002-9505. S2CID204800598.^ Rosen, Nathan (February 1965). "Mixed States in Classical Mechanics". American Journal of Physics. 33 (2): 146150. Bibcode:1965AmJPh..33..146R. doi:10.1119/1.1971282. ISSN0002-9505.^ Weiner, J. H. (November 1974). "Hydrodynamic Analogy to the HamiltonJacobi Equation". American Journal of Physics. 42 (11): 10261028. Bibcode:1974AmJPh..42.1026W. doi:10.1119/1.1987920. ISSN0002-9505.^ a b Reichl, Linda E. (2016). A Modern Course in Statistical Physics (4thed.). Weinheim, Germany: Wiley-VCH. ISBN978-3-527-69048-0. OCLC966177746.^ Mermin, N. David (August 1961). "Two Models of Brownian Motion". American Journal of Physics. 29 (8): 510517. Bibcode:1961AmJPh..29..510M. doi:10.1119/1.1937823. ISSN0002-9505.^ Kneubil, Fabiana B. (1 November 2016). "Breaking Newton's third law: electromagnetic instances". European Journal of Physics. 37 (6): 065201. Bibcode:2016EJPh...37f5201K. doi:10.1088/0143-0807/37/6/065201. ISSN0143-0807. S2CID126380404.^ Tonnelat, Marie-Antoinette (1966). The principles of electromagnetic theory and of relativity. Dordrecht: D. Reidel. ISBN90-277-0107-5. OCLC844001.^ Chu, Caroline S.; Lebrilla, Carlito B. (2010). "Introduction to Modern Techniques in Mass Spectrometry". In Jue, Thomas (ed.). Biomedical Applications of Biophysics. Totowa, NJ: Humana Press. pp.137154. doi:10.1007/978-1-60327-233-9_6. ISBN978-1-60327-233-9. Retrieved 24 March 2022.^ a b Panofsky, Wolfgang K. H.; Phillips, Melba (2005) [1962]. Classical Electricity and Magnetism (2nded.). Mineola, N.Y.: Dover Publications. ISBN0-486-43924-0. OCLC56526974.^ Bonga, Batrice; Poisson, Eric; Yang, Huan (November 2018). "Self-torque and angular momentum balance for a spinning charged sphere". American Journal of Physics. 86 (11): 839848. arXiv:1805.01372. Bibcode:2018AmJPh..86..839B. doi:10.1119/1.5054590. ISSN0002-9505. S2CID53625857.^ a b Goldstein, Herbert; Poole, Charles P.; Safko, John L. (2002). Classical Mechanics (3rded.). San Francisco: Addison Wesley. ISBN0-201-31611-0. OCLC47056311.^ Werner, Reinhard F. (9 October 2014). "Comment on "What Bell did"". Journal of Physics A: Mathematical and Theoretical. 47 (42): 424011. Bibcode:2014JPhA...47P4011W. doi:10.1088/1751-8113/47/42/424011. ISSN1751-8113. S2CID122180759.^ a b Choquet-Bruhat, Yvonne (2009). General Relativity and the Einstein Equations. Oxford: Oxford University Press. ISBN978-0-19-155226-7. OCLC317496332.^ Ellis, George F. R.; Williams, Ruth M. (2000). Flat and Curved Space-times (2nded.). Oxford: Oxford University Press. ISBN0-19-850657-0. OCLC44694623.^ French, A. P. (1968). Special Relativity. W. W. Norton and Company. p.224. ISBN0-393-09804-4.^ Havas, Peter (1 October 1964). "Four-Dimensional Formulations of Newtonian Mechanics and Their Relation to the Special and the General Theory of Relativity". Reviews of Modern Physics. 36 (4): 938965. Bibcode:1964RvMP...36..938H. doi:10.1103/RevModPhys.36.938. ISSN0034-6861. ...the usual assumption of Newtonian mechanics is that the forces are determined by the simultaneous positions (and possibly their derivatives) of the particles, and that they are related by Newton's third law. No such assumption is possible in special relativity since simultaneity is not an invariant concept in that theory.^ Stavrov, Iva (2020). Curvature of Space and Time, with an Introduction to Geometric Analysis. Providence, Rhode Island: American Mathematical Society. ISBN978-1-4704-6313-7. OCLC1202475208.^ a b Wheeler, John Archibald (18 June 2010). Geons, Black Holes, and Quantum Foam: A Life in Physics. W. W. Norton & Company. ISBN978-0-393-07948-7.^ Kersting, Magdalena (May 2019). "Free fall in curved spacetimehow to visualise gravity in general relativity". Physics Education. 54 (3): 035008. Bibcode:2019PhyEd..54c5008K. doi:10.1088/1361-6552/ab08f5. hdl:10852/74677. ISSN0031-9120. S2CID127471222.^ Prescod-Weinstein, Chanda (2021). The Disordered Cosmos: A Journey into Dark Matter, Spacetime, and Dreams Deferred. New York, NY: Bold Type Books. ISBN978-1-5417-2470-9. OCLC1164503847.^ Goodstein, Judith R. (2018). Einstein's Italian Mathematicians: Ricci, Levi-Civita, and the Birth of General Relativity. Providence, Rhode Island: American Mathematical Society. p.143. ISBN978-1-4704-2846-4. OCLC1020305599.^ Mermin, N. David (1993). "Hidden variables and the two theorems of John Bell". Reviews of Modern Physics. 65 (3): 803815. arXiv:1802.10119. Bibcode:1993RvMP...65..803M. doi:10.1103/RevModPhys.65.803. S2CID119546199. It is a fundamental quantum doctrine that a measurement does not, in general, reveal a pre-existing value of the measured property.^ Schaffer, Kathryn; Barreto Lemos, Gabriela (24 May 2019). "Obliterating Thingness: An Introduction to the "What" and the "So What" of Quantum Physics". Foundations of Science. 26: 726. arXiv:1908.07936. doi:10.1007/s10699-019-09608-5. ISSN1233-1821. S2CID182656563.^ Marshman, Emily; Singh, Chandralekha (1 March 2017). "Investigating and improving student understanding of the probability distributions for measuring physical observables in quantum mechanics". European Journal of Physics. 38 (2): 025705. Bibcode:2017EJPh...38b5705M. doi:10.1088/1361-6404/aa57d1. ISSN0143-0807. S2CID126311599.^ Cohen-Tannoudji, Claude; Diu, Bernard; Lalo, Franck (2005). Quantum Mechanics. Translated by Hemley, Susan Reid; Ostrowsky, Nicole; Ostrowsky, Dan. John Wiley & Sons. ISBN0-471-16433-X.^ Peres, Asher (1993). Quantum Theory: Concepts and Methods. Kluwer. ISBN0-7923-2549-4. OCLC28854083.^ D. Bilodeau, quoted in Fuchs, Christopher A. (6 January 2011). Coming of Age with Quantum Information. Cambridge University Press. pp.310311. ISBN978-0-521-19926-1. OCLC759812415.^ Caspar, Max (2012) [1959]. Kepler. Translated by Hellman, C. Doris. Dover. p.178. ISBN978-0-486-15175-5. OCLC874097920.^ Cohen, I. Bernard (1980). The Newtonian Revolution: With Illustrations of the Transformation of Scientific Ideas. Cambridge University Press. pp.157162. ISBN978-0-521-22964-7.^ Hellyer, Marcus, ed. (2003). The Scientific Revolution: The Essential Readings (Elektronische Ressourceed.). Malden, MA: Blackwell Pub. pp.178193. ISBN978-0-631-23629-0.^ Ugaglia, Monica (2015). "Aristotle's Hydrostatical Physics". Annali della Scuola Normale Superiore di Pisa. Classe di Lettere e Filosofia. 7 (1): 169199. ISSN0392-095X. JSTOR43915795.^ Straulino, S.; Gambi, C. M. C.; Righini, A. (January 2011). "Experiments on buoyancy and surface tension following Galileo Galilei". American Journal of Physics. 79 (1): 3236. Bibcode:2011AmJPh..79...32S. doi:10.1119/1.3492721. hdl:2158/530056. ISSN0002-9505. Aristotle in his Physics affirmed that solid water should have a greater weight than liquid water for the same volume. We know that this statement is incorrect because the density of ice is lower than that of water (hydrogen bonds create an open crystal structure in the solid phase), and for this reason ice can float. [...] The Aristotelian theory of buoyancy affirms that bodies in a fluid are supported by the resistance of the fluid to being divided by the penetrating object, just as a large piece of wood supports an axe striking it or honey supports a spoon. According to this theory, a boat should sink in shallow water more than in high seas, just as an axe can easily penetrate and even break a small piece of wood, but cannot penetrate a large piece.^ Sorabji, Richard (2010). "John Philoponus". Philoponus and the Rejection of Aristotelian Science (2nded.). Institute of Classical Studies, University of London. ISBN978-1-905-67018-5. JSTOR44216227. OCLC878730683.^ Maier, Anneliese (1982). Sargent, Steven D. (ed.). On the Threshold of Exact Science. University of Pennsylvania Press. ISBN978-0-812-27831-6. OCLC495305340.^ See, for example:Eaton, Philip; Vavruska, Kinsey; Willoughby, Shannon (25 April 2019). "Exploring the preinstruction and postinstruction non-Newtonian world views as measured by the Force Concept Inventory". Physical Review Physics Education Research. 15 (1): 010123. Bibcode:2019PRPER..15a0123E. doi:10.1103/PhysRevPhysEducRes.15.010123. ISSN2469-9896. S2CID149482566.Robertson, Amy D.; Goodhew, Lisa M.; Scherr, Rachel E.; Heron, Paula R. L. (March 2021). "Impetus-Like Reasoning as Continuous with Newtonian Physics". The Physics Teacher. 59 (3): 185188. doi:10.1119/10.0003660. ISSN0031-921X. S2CID233803836.Robertson, Amy D.; Goodhew, Lisa M.; Scherr, Rachel E.; Heron, Paula R. L. (30 March 2021). "University student conceptual resources for understanding forces". Physical Review Physics Education Research. 17 (1): 010121. Bibcode:2021PRPER..17a0121R. doi:10.1103/PhysRevPhysEducRes.17.010121. ISSN2469-9896. S2CID243143427.^ a b Blackwell, Richard J. (1966). "Descartes' Laws of Motion". Isis. 57 (2): 220234. doi:10.1086/350115. JSTOR227961. S2CID144278075.^ Galilei, G. (1954) [1638, 1914]. Crew, H.; De Salvio, A. (eds.). Dialogues Concerning Two New Sciences. Dover Publications Inc. p.268.^ Galilei, G. (1974) [1638]. Two new sciences, including centers of gravity & force of percussion. Translated by Drake, S. University of Wisconsin Press. pp.217 [268].^ Hellman, C. Doris (1955). "Science in the Renaissance: A Survey". Renaissance News. 8 (4): 186200. doi:10.2307/2858681. ISSN0277-903X. JSTOR2858681.^ LoLordo, Antonia (2007). Pierre Gassendi and the Birth of Early Modern Philosophy. New York: Cambridge University Press. pp.175180. ISBN978-0-511-34982-9. OCLC182818133.^ Descartes, R. (2008) [1644]. Bennett, J. (ed.). Principles of philosophy (PDF). Part II, 37, 39.^ a b Blackwell, Richard J.; Huygens, Christiaan (1977). "Christiaan Huygens' The Motion of Colliding Bodies". Isis. 68 (4): 574597. doi:10.1086/351876. JSTOR230011. S2CID144406041.^ Pourciau, Bruce (October 2011). "Is Newton's second law really Newton's?". American Journal of Physics. 79 (10): 10151022. Bibcode:2011AmJPh..79.1015P. doi:10.1119/1.3607433. ISSN0002-9505.^ Fara, Patricia (15 August 2003). "Was Newton a Newtonian?". Science. 301 (5635): 920. doi:10.1126/science.1088786. ISSN0036-8075. S2CID170120455.^ Higgitt, Rebekah (2015). Science and Culture in the Nineteenth Century: Recreating Newton. New York: Taylor & Francis. p.147. ISBN978-1-317-31495-0. OCLC934741893.^ Dobbs, Betty Jo Teeter (1975). The Foundations of Newton's Alchemy: Or, "the Hunting of the Greene Lyon". Cambridge University Press. pp.211212. ISBN9780521273817. OCLC1058581988.^ West, Richard (1980). Never at Rest. Cambridge University Press. p.390. ISBN9780521231435. OCLC5677169.^ a b c Newman, William R. (2016). "A preliminary reassessment of Newton's alchemy". The Cambridge Companion to Newton (2nded.). Cambridge University Press. pp.454484. ISBN978-1-107-01546-3. OCLC953450997.^ Nummedal, Tara (1 June 2020). "William R. Newman. Newton the Alchemist: Science, Enigma, and the Quest for Nature's "Secret Fire"". Isis. 111 (2): 395396. doi:10.1086/709344. ISSN0021-1753. S2CID243203703.^ Aldersey-Williams, Hugh (2020). Dutch Light: Christiaan Huygens and the Making of Science in Europe. London: Picador. ISBN978-1-5098-9333-1. OCLC1144105192.^ Cohen, I. Bernard (1962). "The First English Version of Newton's Hypotheses non fingo". Isis. 53 (3): 379388. doi:10.1086/349598. ISSN0021-1753. JSTOR227788. S2CID144575106.^ Jammer, Max (1999) [1962]. Concepts of Force: A Study in the Foundations of Dynamics. Mineola, N.Y.: Dover Publications. pp.91, 127. ISBN978-0-486-40689-3. OCLC40964671.^ Slowik, Edward (15 October 2021). "Descartes' Physics". Stanford Encyclopedia of Philosophy. Retrieved 6 March 2022.^ Erlichson, Herman (February 1997). "The young Huygens solves the problem of elastic collisions". American Journal of Physics. 65 (2): 149154. Bibcode:1997AmJPh..65..149E. doi:10.1119/1.18659. ISSN0002-9505.^ Smith, George E. (October 2006). "The vis viva dispute: A controversy at the dawn of dynamics". Physics Today. 59 (10): 3136. Bibcode:2006PhT....59j..31S. doi:10.1063/1.2387086. ISSN0031-9228.^ Davies, E. B. (2009). "Some Reflections on Newton's "Principia"". The British Journal for the History of Science. 42 (2): 211224. doi:10.1017/S000708740800188X. ISSN0007-0874. JSTOR25592244. S2CID145120248.^ Smith, George E. (December 2020). "Newton's Laws of Motion". In Schliesser, Eric; Smeenk, Chris (eds.). The Oxford Handbook of Newton. Oxford University Press. Online before print. doi:10.1093/oxfordhb/9780199930418.013.35. ISBN978-0-199-93041-8. OCLC972369868.^ Patterson, Elizabeth C. (December 1969). "Mary Somerville". The British Journal for the History of Science. 4 (4): 311339. doi:10.1017/S0007087400010232. ISSN0007-0874. S2CID246612625. In no sense was it a mere translation of Laplace's work. Instead it endeavoured to explain his method ". . . by which these results were deduced from one general equation of the motion of matter" and to bring the reader's mathematical skill to the point where the exposition of Laplace's mathematics and ideas would be meaningfulthen to give a digest in English of his great work. Diagrams were added when necessary to the original text and proofs of various problems in physical mechanics and astronomy included. ... [F]or almost a hundred years after its appearance the book continued to serve as a textbook for higher mathematics and astronomy in English schools.^ Baron, Margaret E. (1969). The Origins of Infinitesimal Calculus (1sted.). Oxford: Pergamon Press. ISBN978-1-483-28092-9. OCLC892067655.^ Dunlop, Katherine (May 2012). "The mathematical form of measurement and the argument for Proposition I in Newton's Principia". Synthese. 186 (1): 191229. doi:10.1007/s11229-011-9983-8. ISSN0039-7857. S2CID11794836.^ Smith, George (20 December 2007). "Newton's Philosophiae Naturalis Principia Mathematica". Stanford Encyclopedia of Philosophy. Retrieved 6 March 2022.^ Marquina, J. E.; Marquina, M. L.; Marquina, V.; Hernndez-Gmez, J. J. (1 January 2017). "Leonhard Euler and the mechanics of rigid bodies". European Journal of Physics. 38 (1): 015001. Bibcode:2017EJPh...38a5001M. doi:10.1088/0143-0807/38/1/015001. ISSN0143-0807. S2CID125948408.^ Hesse, Mary B. (2005) [1961]. Forces and Fields: The Concept of Action at a Distance in the History of Physics (Dover reprinted.). Mineola, N.Y.: Dover Publications. p.189. ISBN978-0-486-44240-2. OCLC57579169.^ Smith, George (19 December 2007). "Isaac Newton". Stanford Encyclopedia of Philosophy. Retrieved 6 March 2022. These advances in our understanding of planetary motion led Laplace to produce the four principal volumes of his Trait de mcanique cleste from 1799 to 1805, a work collecting in one place all the theoretical and empirical results of the research predicated on Newton's Principia. From that time forward, Newtonian science sprang from Laplace's work, not Newton's.^ Reichenberger, Andrea (June 2018). "milie Du Chtelet's interpretation of the laws of motion in the light of 18th century mechanics". Studies in History and Philosophy of Science Part A. 69: 111. Bibcode:2018SHPSA..69....1R. doi:10.1016/j.shpsa.2018.01.006. PMID29857796. S2CID46923474.^ Frontali, Clara (September 2014). "History of physical terms: "energy"". Physics Education. 49 (5): 564573. Bibcode:2014PhyEd..49..564F. doi:10.1088/0031-9120/49/5/564. ISSN0031-9120. S2CID122097990.^ Gbur, Greg (10 December 2018). "History of the Conservation of Energy: Booms, Blood, and Beer (Part 1)". Skulls in the Stars. Retrieved 7 March 2022. "History of the Conservation of Energy: Booms, Blood, and Beer (Part 2)". 29 December 2018. Retrieved 7 March 2022. "History of the Conservation of Energy: Booms, Blood, and Beer (Part 3)". 25 August 2019. Retrieved 7 March 2022.^ Silva, Cibelle Celestino; de Andrade Martins, Roberto (September 2002). "Polar and axial vectors versus quaternions". American Journal of Physics. 70 (9): 958963. Bibcode:2002AmJPh..70..958S. doi:10.1119/1.1475326. ISSN0002-9505.^ Reich, Karin (1996). "The Emergence of Vector Calculus in Physics: The Early Decades". In Schubring, Gert (ed.). Hermann Gnther Gramann (18091877): Visionary Mathematician, Scientist and Neohumanist Scholar. Boston Studies in the Philosophy of Science. Vol.187. Kluwer. pp.197210. ISBN978-9-048-14758-8. OCLC799299609.Newtons Laws of Dynamics - The Feynman Lectures on PhysicsChakrabarty, Deepto; Dourmashkin, Peter; Tomasik, Michelle; Frebel, Anna; Vuletic, Vladan (2016). "Classical Mechanics". MIT OpenCourseWare. Retrieved 17 January 2022.Portals: Mathematics Physics History of science Astronomy Stars Solar SystemRetrieved from " First Law says objects need a force to start moving or to change their motion.Newton's Second Law shows how force, mass, and acceleration are related through a simple equation.Newton's Third Law tells us that for every action, there is an equal and opposite reaction. Each law of motion Newton developed has significant mathematical and physical interpretations that are needed to understand motionin our universe. The applications of these laws of motion are truly limitless. Essentially, Newton's laws define the means by which motion changes, specifically the way in which those changes in motion are related to force and mass. Sir Isaac Newton (1642-1727) was a British physicist who, in many respects, can be viewed as the greatest physicist of all time. Though there were some predecessors of note, such as Archimedes, Copernicus, and Galileo, it was Newton who truly exemplified the method of scientific inquiry that would be adopted throughout the ages. For nearly a century, Aristotle's description of the physical universe had proven to be inadequate to describe the nature of movement (or the movement of nature, if you will). Newton tackled the problem and came up with three general rules about the movement of objects which have been dubbed as "Newton's three laws of motion." In 1687, Newton introduced the three laws in his book "Philosophiae Naturalis Principia Mathematica" (Mathematical Principles of Natural Philosophy), which is generally referred to as the "Principia." This is where he also introduced his theory of universal gravitation, thus laying the entire foundation of classical mechanics in one volume. Newton's First Law of Motion states that in order for the motion of an object to change, a force must act upon it. This is a concept generally called inertia.Newton's Second Law of Motion defines the relationship between acceleration, force, and mass.Newton's Third Law of Motion states that any time a force acts from one object to another, there is an equal force acting back on the original object. If you pull on a rope, therefore, the rope is pulling back on you as well.Free body diagrams are the means by which you can track the different forces acting on an object and, therefore, determine the final acceleration.Vector mathematics is used to keep track of the directions and magnitudes of the forces and accelerations involved.Variable equations are used in complex physics problems. Every body continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it.- Newton's First Law of Motion, translated from the "Principia" This is sometimes called the Law of Inertia, or just inertia. Essentially, it makes the following two points:An object that is not moving will not move until aforceacts upon it.An object that is in motion will not changevelocity(or stop) until a force acts upon it. The first point seems relatively obvious to most people, but the second may take some thinking through. Everyone knows that things don't keep moving forever. If I slide a hockey puck along a table, it slows and eventually comes to a stop. But according to Newton's laws, this is because a force is acting on the hockey puck and, sure enough, there is a frictional force between the table and the puck. That frictional force is in the direction that is opposite the movement of the puck. It's this force which causes the object to slow to a stop. In the absence (or virtual absence) of such a force, as on an air hockey table or ice rink, the puck's motion isn't as hindered. Here is another way of stating Newton's First Law: A body that is acted on by no net force moves at a constant velocity (which may be zero) and zero acceleration. So with no net force, the object just keeps doing what it is doing. It is important to note the wordsnet force. This means the total forces upon the object must add up to zero. An object sitting on my floor has a gravitational force pulling it downward, but there is also anormal forcepushing upward from the floor, so the net force is zero. Therefore, it doesnt move. To return to the hockey puck example, consider two people hitting the hockey puck onexactlyopposite sides atexactlythe same time and withexactlyidentical force. In this rare case, the puck would not move. Since both velocity and force arevector quantities, the directions are important to this process. If a force (such as gravity) acts downward on an object and there's no upward force, the object will gain a vertical acceleration downward. The horizontal velocity will not change, however. If I throw a ball off my balcony at a horizontal speed of 3 meters per second, it will hit the ground with a horizontal speed of 3 m/s (ignoring the force of air resistance), even though gravity exerted a force (and therefore acceleration) in the vertical direction. If it weren't for gravity, the ball would have kept going in a straight line...at least, until it hit my neighbor's house. The acceleration produced by a particular force acting on a body is directly proportional to the magnitude of the force and inversely proportional to the mass of the body.(Translated from the "Principia") The mathematical formulation of the second law is shown below, withFrepresenting the force,mrepresenting the object's mass andarepresenting the object's acceleration. F = ma This formula is extremely useful in classical mechanics, as it provides a means of translating directly between the acceleration and force acting upon a given mass. A large portion of classical mechanics ultimately breaks down to applying this formula in different contexts. The sigma symbol to the left of the force indicates that it is the net force, or the sum of all the forces. Asvector quantities, the direction of the net force will also be in the same direction as the acceleration. You can also break the equation down intoxandy(and evenz) coordinates, which can make many elaborate problems more manageable, especially if you orient your coordinate system properly. You'll note that when the net forces on an object sum up to zero, we achieve the state defined in Newton's First Law: the net acceleration must be zero. We know this because all objectshave mass (in classical mechanics, at least). If the object is already moving, it will continue to move at a constant velocity, but that velocity will not change until a net force is introduced. Obviously, an object at rest will not move at all without a net force. A box with a mass of 40 kg sits at rest on a frictionless tile floor. With your foot, you apply a 20 N force in a horizontal direction. What is the acceleration of the box? The object is at rest, so there is no net force except for the force your foot is applying. Friction is eliminated. Also, there's only one direction of force to worry about. So this problem is very straightforward. You begin the problem by defining your coordinate system. The mathematics is similarly straightforward: F= m* a F/m=a 20 N / 40 kg =a= 0.5 m / s2 The problems based on this law are literally endless, using the formula to determine any of the three values when you are given the other two. As systems become more complex, you will learn to apply frictional forces, gravity, electromagnetic forces, and other applicable forces to the same basic formulas. To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts. (Translated from the "Principia") We represent the Third Law by looking at two bodies, AandB,that are interacting. We defineFAas the force applied to bodyAby bodyB,andFAas the force applied to bodyBby bodyA. These forces will be equal in magnitude and opposite in direction. In mathematical terms, it is expressed as: FB= -FA or FA+FB= 0 This is not the same thing as having a net force of zero, however. If you apply a force to an empty shoebox sitting on a table, the shoebox applies an equal force back on you. This doesn't sound right at first you're obviously pushing on the box, and it is obviously notpushing on you. Remember that according to the Second Law, force and acceleration are related but they aren't identical! Because your mass is much larger than the mass of the shoebox, the force you exert causes it to accelerate away from you. The force it exerts on you wouldn't cause much acceleration at all. Not only that, but while it's pushing on the tip of your finger, your finger, in turn, pushes back into your body, and the rest of your body pushes back against the finger, and your body pushes on the chair or floor (or both), all of which keeps your body from moving and allows you to keep your finger moving to continue the force. There's nothing pushing back on the shoebox to stop it from moving. If, however, the shoebox is sitting next to a wall and you push it toward the wall, the shoebox will push on the wall and the wall will push back. The shoebox will, at this point, stop moving. You can try to push it harder, but the box will break before it goes through the wall because it isn't strong enough to handle that much force. Most people have played tug of war at some point. A person or group of people grab the ends of a rope and try to pull against the person or group at the other end, usually past some marker (sometimes into a mud pit in really fun versions), thus proving that one of the groups is stronger than the other. All three of Newton's Laws can be seen in a tug of war. There frequently comes a point in a tug of war when neither side is moving. Both sides are pulling with the same force. Therefore, the rope does not accelerate in either direction. This is a classic example of Newton's First Law. Once a net force is applied, such as when one group begins pulling a bit harder than the other, an acceleration begins. This follows the Second Law. The group losing ground must then try to exertmoreforce. When the net force begins going in their direction, the acceleration is in their direction. The movement of the rope slows down until it stops and, if they maintain a higher net force, it begins moving back in their direction. The Third Law is less visible, but it's still present. When you pull on the rope, you can feel that the rope is also pulling on you, trying to move you toward the other end. You plant your feet firmly in the ground, and the ground actually pushes back on you, helping you to resist the pull of the rope. Next time you play or watch a game of tug of war or any sport, for that matter think about all the forces and accelerations at work. It's truly impressive to realize that you can understand the physical laws that are in action during your favorite sport.

Newton's laws simple. What are newton’s 3 laws. Newton's 3 laws of motion explained. What are newton's 3 laws of motion simplified. What were newton's 3 laws.