

Force

Philosophers in antiquity used the concept of force in the study of stationary and moving objects and simple machines, but thinkers such as Aristotle and Archimedes retained fundamental errors in understanding force. In part this was due to an incomplete understanding of the sometimes non-obvious force of friction, and a consequently inadequate view of the nature of natural motion. A fundamental error was the belief that a force is required to maintain motion, even at a constant velocity. Most of the previous misunderstandings about motion and force were eventually corrected by Galileo Galilei and Sir Isaac Newton. With his mathematical insight, Sir Isaac Newton formulated laws of motion that were not improved-on for nearly three hundred years. By the early 20th century, Einstein developed a theory of relativity that correctly predicted the action of forces on objects with increasing momenta near the speed of light, and also provided insight into the forces produced by gravitation and inertia.

With modern insights into quantum mechanics and technology that can accelerate particles close to the speed of light, particle physics has devised a Standard Model to describe forces between particles smaller than atoms. The Standard Model predicts that exchanged particles called gauge bosons are the fundamental means by which forces are emitted and absorbed. Only four main interactions are known: in order of decreasing strength, they are: strong, electromagnetic, weak, and gravitational. 2–10:79 High-energy particle physics observations made during the 1970s and 1980s confirmed that the weak and electromagnetic forces are expressions of a more fundamental electroweak interaction.

Aristotle provided a philosophical discussion of the concept of a force as an integral part of Aristotelian cosmology. In Aristotle's view, the terrestrial sphere contained four elements that come to rest at different "natural places" therein. Aristotle believed that motionless objects on Earth, those composed mostly of the elements earth and water, to be in their natural place on the ground and that they will stay that way if left alone. He distinguished between the innate tendency of objects to find their "natural place" (e.g., for heavy bodies to fall), which led to "natural motion", and unnatural or forced motion, which required continued application of a force. This theory, based on the everyday experience of how objects move, such as the constant application of a force needed to keep a cart moving, had conceptual trouble accounting for the behavior of projectiles, such as the flight of arrows. The place where the archer moves the projectile was at the start of the flight, and while the projectile sailed through the air, no discernible efficient cause acts on it. Aristotle was aware of this problem and proposed that the air displaced through the projectile's path carries the projectile to its target. This explanation demands a continuum like air for change of place in general.

The shortcomings of Aristotelian physics would not be fully corrected until the 17th century work of Galileo Galilei, who was influenced by the late Medieval idea that objects in forced motion carried an innate force of impetus. Galileo constructed an experiment in which stones and cannonballs were both rolled down an incline to disprove the Aristotelian theory of motion early in the 17th century. He showed that the bodies were accelerated by gravity to an extent that was independent of their mass and argued that objects retain their velocity unless acted on by a force, for example friction.

Newton's First Law of Motion states that objects continue to move in a state of constant velocity unless acted upon by an external net force or resultant force. This law is an extension of Galileo's insight that constant velocity was associated with a lack of net force (see a more detailed description of this below). Newton proposed that every object with mass has an innate inertia that functions as the fundamental equilibrium "natural state" in place of the Aristotelian idea of the "natural state of rest". That is, the first law contradicts the intuitive Aristotelian belief that a net force is required to keep an object moving with constant velocity. By making rest physically indistinguishable from non-zero constant velocity, Newton's First Law directly connects inertia with the concept of relative velocities. Specifically, in systems where objects are moving with different velocities, it is impossible to determine which object is "in motion" and which object is "at rest". In other words, to phrase matters more technically, the laws of physics are the same in every inertial frame of reference, that is, in all frames related by a Galilean transformation.

For instance, while traveling in a moving vehicle at a constant velocity, the laws of physics do not change from being at rest. A person can throw a ball straight up in the air and catch it as it falls down without worrying about applying a force in the direction the vehicle is moving. This is true even though another person who is observing the moving vehicle pass by also observes the ball follow a curving parabolic path in the same direction as the motion of the vehicle. It is the inertia of the ball associated with its constant velocity in the direction of the vehicle's motion that ensures the ball continues to move forward even as it is thrown up and falls back down. From the perspective of the person in the car, the vehicle and everything inside of it is at rest: It is the outside world that is moving with a constant speed in the opposite direction. Since there is no experiment that can distinguish whether it is the vehicle that is at rest or the outside world that is at rest, the two situations are considered to be physically indistinguishable. Inertia therefore applies equally well to constant velocity motion as it does to rest.

The concept of inertia can be further generalized to explain the tendency of objects to continue in many different forms of constant motion, even those that are not strictly constant velocity. The rotational inertia of planet Earth is what fixes the constancy of the length of a day and the length of a year. Albert Einstein extended the principle of inertia further when he explained that reference frames subject to constant acceleration, such as those free-falling toward a gravitating object, were physically equivalent to inertial reference frames. This is why, for example, astronauts experience weightlessness when in free-fall orbit around the Earth, and why Newton's Laws of Motion are more easily discernible in such environments. If an astronaut places an object with mass in mid-air next to himself, it will remain stationary with respect to the astronaut due to its inertia. This is the same thing that would occur if the astronaut and the object were in intergalactic space with no net force of gravity acting on their shared reference frame. This principle of equivalence was one of the foundational underpinnings for the development of the general theory of relativity.

Newton's Second Law asserts the direct proportionality of acceleration to force and the inverse proportionality of acceleration to mass. Accelerations can be defined through kinematic measurements. However, while kinematics are well-described through reference frame analysis in advanced physics, there are still deep questions that remain as to what is the proper definition of mass. General relativity offers an equivalence between space-time and mass, but lacking a coherent theory of quantum gravity, it is unclear as to how or whether this connection is relevant on microscale. With some justification, Newton's second law can be taken as a quantitative definition of mass by writing the law as an equality; the relative units of force and mass then are fixed.

Newton's Third Law is a result of applying symmetry to situations where forces can be attributed to the presence of different objects. The third law means that all forces are interactions between different bodies,[Note 3] and thus that there is no such thing as a unidirectional force or a force that acts on only one body. Whenever a first body exerts a force F on a second body, the second body exerts a force $-F$ on the first body. F and $-F$ are equal in magnitude and opposite in direction. This law is sometimes referred to as the action-reaction law, with F called the "action" and $-F$ the "reaction". The action and the reaction are simultaneous:

This means that in a closed system of particles, there are no internal forces that are unbalanced. That is, the action-reaction force shared between any two objects in a closed system will not cause the center of mass of the system to accelerate. The constituent objects only accelerate with respect to each other, the system itself remains unaccelerated. Alternatively, if an external force acts on the system, then the center of mass will experience an acceleration proportional to the magnitude of the external force divided by the mass of the system.:19-1

Since forces are perceived as pushes or pulls, this can provide an intuitive understanding for describing forces. As with other physical concepts (e.g. temperature), the intuitive understanding of forces is quantified using precise operational definitions that are consistent with direct observations and compared to a standard measurement scale. Through experimentation, it is determined that laboratory measurements of forces are fully consistent with the conceptual definition of force offered by Newtonian mechanics.

Forces act in a particular direction and have sizes dependent upon how strong the push or pull is. Because of these characteristics, forces are classified as "vector quantities". This means that forces follow a different set of mathematical rules than physical quantities that do not have direction (denoted scalar quantities). For example, when determining what happens when two forces act on the same object, it is necessary to know both the magnitude and the direction of both forces to calculate the result. If both of these pieces of information are not known for each force, the situation is ambiguous. For example, if you know that two people are pulling on the same rope with known magnitudes of force but you do not know which direction either person is pulling, it is impossible to determine what the acceleration of the rope will be. The two people could be pulling against each other as in tug of war or the two people could be pulling in the same direction. In this simple one-dimensional example, without knowing the direction of the forces it is impossible to decide whether the net force is the result of adding the two force magnitudes or subtracting one from the other. Associating forces with vectors avoids such problems.

Historically, forces were first quantitatively investigated in conditions of static equilibrium where several forces canceled each other out. Such experiments demonstrate the crucial properties that forces are additive vector quantities: they have magnitude and direction. When two forces act on a point particle, the resulting force, the resultant (also called the net force), can be determined by following the parallelogram rule of vector addition: the addition of two vectors represented by sides of a parallelogram, gives an equivalent resultant vector that is equal in magnitude and direction to the transversal of the parallelogram. The magnitude of the resultant varies from the difference of the magnitudes of the two forces to their sum, depending on the angle between their lines of action. However, if the forces are acting on an extended body, their respective lines of application must also be specified in order to account for their effects on the motion of the body.

As well as being added, forces can also be resolved into independent components at right angles to each other. A horizontal force pointing northeast can therefore be split into two forces, one pointing north, and one pointing east. Summing these component forces using vector addition yields the original force. Resolving force vectors into components of a set of basis vectors is often a more mathematically clean way to describe forces than using magnitudes and directions. This is because, for orthogonal components, the components of the vector sum are uniquely determined by the scalar addition of the components of the individual vectors. Orthogonal components are independent of each other because forces acting at ninety degrees to each other have no effect on the magnitude or direction of the other. Choosing a set of orthogonal basis vectors is often done by considering what set of basis vectors will make the mathematics most convenient. Choosing a basis vector that is in the same direction as one of the forces is desirable, since that force would then have only one non-zero component. Orthogonal force vectors can be three-dimensional with the third component being at right-angles to the other two.

Pushing against an object on a frictional surface can result in a situation where the object does not move because the applied force is opposed by static friction, generated between the object and the table surface. For a situation with no movement, the static friction force exactly balances the applied force resulting in no acceleration. The static friction increases or decreases in response to the applied force up to an upper limit determined by the characteristics of the contact between the surface and the object.

A static equilibrium between two forces is the most usual way of measuring forces, using simple devices such as weighing scales and spring balances. For example, an object suspended on a vertical spring scale experiences the force of gravity acting on the object balanced by a force applied by the "spring reaction force", which equals the object's weight. Using such tools, some quantitative force laws were discovered: that the force of gravity is proportional to volume for objects of constant density (widely exploited for millennia to define standard weights); Archimedes' principle for buoyancy; Archimedes' analysis of the lever; Boyle's law for gas pressure; and Hooke's law for springs. These were all formulated and experimentally verified before Isaac Newton expounded his Three Laws of Motion.

Dynamic equilibrium was first described by Galileo who noticed that certain assumptions of Aristotelian physics were contradicted by observations and logic. Galileo realized that simple velocity addition demands that the concept of an "absolute rest frame" did not exist. Galileo concluded that motion in a

constant velocity was completely equivalent to rest. This was contrary to Aristotle's notion of a "natural state" of rest that objects with mass naturally approached. Simple experiments showed that Galileo's understanding of the equivalence of constant velocity and rest were correct. For example, if a mariner dropped a cannonball from the crow's nest of a ship moving at a constant velocity, Aristotelian physics would have the cannonball fall straight down while the ship moved beneath it. Thus, in an Aristotelian universe, the falling cannonball would land behind the foot of the mast of a moving ship. However, when this experiment is actually conducted, the cannonball always falls at the foot of the mast, as if the cannonball knows to travel with the ship despite being separated from it. Since there is no forward horizontal force being applied on the cannonball as it falls, the only conclusion left is that the cannonball continues to move with the same velocity as the boat as it falls. Thus, no force is required to keep the cannonball moving at the constant forward velocity.

A simple case of dynamic equilibrium occurs in constant velocity motion across a surface with kinetic friction. In such a situation, a force is applied in the direction of motion while the kinetic friction force exactly opposes the applied force. This results in zero net force, but since the object started with a non-zero velocity, it continues to move with a non-zero velocity. Aristotle misinterpreted this motion as being caused by the applied force. However, when kinetic friction is taken into consideration it is clear that there is no net force causing constant velocity motion.

The notion "force" keeps its meaning in quantum mechanics, though one is now dealing with operators instead of classical variables and though the physics is now described by the Schrödinger equation instead of Newtonian equations. This has the consequence that the results of a measurement are now sometimes "quantized", i.e. they appear in discrete portions. This is, of course, difficult to imagine in the context of "forces". However, the potentials $V(x,y,z)$ or fields, from which the forces generally can be derived, are treated similar to classical position variables, i.e., .

However, already in quantum mechanics there is one "caveat", namely the particles acting onto each other do not only possess the spatial variable, but also a discrete intrinsic angular momentum-like variable called the "spin", and there is the Pauli principle relating the space and the spin variables. Depending on the value of the spin, identical particles split into two different classes, fermions and bosons. If two identical fermions (e.g. electrons) have a symmetric spin function (e.g. parallel spins) the spatial variables must be antisymmetric (i.e. they exclude each other from their places much as if there was a repulsive force), and vice versa, i.e. for antiparallel spins the position variables must be symmetric (i.e. the apparent force must be attractive). Thus in the case of two fermions there is a strictly negative correlation between spatial and spin variables, whereas for two bosons (e.g. quanta of electromagnetic waves, photons) the correlation is strictly positive.

In modern particle physics, forces and the acceleration of particles are explained as a mathematical by-product of exchange of momentum-carrying gauge bosons. With the development of quantum field theory and general relativity, it was realized that force is a redundant concept arising from conservation of momentum (4-momentum in relativity and momentum of virtual particles in quantum electrodynamics). The conservation of momentum can be directly derived from the homogeneity or symmetry of space and so is usually considered more fundamental than the concept of a force. Thus the currently known fundamental forces are considered more accurately to be "fundamental interactions".:199–128 When particle A emits (creates) or absorbs (annihilates) virtual particle B, a momentum conservation results in recoil of particle A making impression of repulsion or attraction between particles A A' exchanging by B. This description applies to all forces arising from fundamental interactions. While sophisticated mathematical descriptions are needed to predict, in full detail, the accurate result of such interactions, there is a conceptually simple way to describe such interactions through the use of Feynman diagrams. In a Feynman diagram, each matter particle is represented as a straight line (see world line) traveling through time, which normally increases up or to the right in the diagram. Matter and anti-matter particles are identical except for their direction of propagation through the Feynman diagram. World lines of particles intersect at interaction vertices, and the Feynman diagram represents any force arising from an interaction as occurring at the vertex with an associated instantaneous change in the direction of the particle world lines. Gauge bosons are emitted away from the vertex as wavy lines and, in the case of virtual particle

exchange, are absorbed at an adjacent vertex.

All of the forces in the universe are based on four fundamental interactions. The strong and weak forces are nuclear forces that act only at very short distances, and are responsible for the interactions between subatomic particles, including nucleons and compound nuclei. The electromagnetic force acts between electric charges, and the gravitational force acts between masses. All other forces in nature derive from these four fundamental interactions. For example, friction is a manifestation of the electromagnetic force acting between the atoms of two surfaces, and the Pauli exclusion principle, which does not permit atoms to pass through each other. Similarly, the forces in springs, modeled by Hooke's law, are the result of electromagnetic forces and the Exclusion Principle acting together to return an object to its equilibrium position. Centrifugal forces are acceleration forces that arise simply from the acceleration of rotating frames of reference.:12-11:359

The development of fundamental theories for forces proceeded along the lines of unification of disparate ideas. For example, Isaac Newton unified the force responsible for objects falling at the surface of the Earth with the force responsible for the orbits of celestial mechanics in his universal theory of gravitation. Michael Faraday and James Clerk Maxwell demonstrated that electric and magnetic forces were unified through one consistent theory of electromagnetism. In the 20th century, the development of quantum mechanics led to a modern understanding that the first three fundamental forces (all except gravity) are manifestations of matter (fermions) interacting by exchanging virtual particles called gauge bosons. This standard model of particle physics posits a similarity between the forces and led scientists to predict the unification of the weak and electromagnetic forces in electroweak theory subsequently confirmed by observation. The complete formulation of the standard model predicts an as yet unobserved Higgs mechanism, but observations such as neutrino oscillations indicate that the standard model is incomplete. A Grand Unified Theory allowing for the combination of the electroweak interaction with the strong force is held out as a possibility with candidate theories such as supersymmetry proposed to accommodate some of the outstanding unsolved problems in physics. Physicists are still attempting to develop self-consistent unification models that would combine all four fundamental interactions into a theory of everything. Einstein tried and failed at this endeavor, but currently the most popular approach to answering this question is string theory.:212-219

What we now call gravity was not identified as a universal force until the work of Isaac Newton. Before Newton, the tendency for objects to fall towards the Earth was not understood to be related to the motions of celestial objects. Galileo was instrumental in describing the characteristics of falling objects by determining that the acceleration of every object in free-fall was constant and independent of the mass of the object. Today, this acceleration due to gravity towards the surface of the Earth is usually designated as g and has a magnitude of about 9.81 meters per second squared (this measurement is taken from sea level and may vary depending on location), and points toward the center of the Earth. This observation means that the force of gravity on an object at the Earth's surface is directly proportional to the object's mass. Thus an object that has a mass of m will experience a force:

Newton came to realize that the effects of gravity might be observed in different ways at larger distances. In particular, Newton determined that the acceleration of the Moon around the Earth could be ascribed to the same force of gravity if the acceleration due to gravity decreased as an inverse square law. Further, Newton realized that the acceleration due to gravity is proportional to the mass of the attracting body. Combining these ideas gives a formula that relates the mass (M) and the radius (R) of the Earth to the gravitational acceleration:

In this equation, a dimensional constant is used to describe the relative strength of gravity. This constant has come to be known as Newton's Universal Gravitation Constant, though its value was unknown in Newton's lifetime. Not until 1798 was Henry Cavendish able to make the first measurement of using a torsion balance; this was widely reported in the press as a measurement of the mass of the Earth since knowing G could allow one to solve for the Earth's mass given the above equation. Newton, however, realized that since all celestial bodies followed the same laws of motion, his law of gravity had to be universal. Succinctly stated, Newton's Law of Gravitation states that the force on a spherical object of

mass due to the gravitational pull of mass is

It was only the orbit of the planet Mercury that Newton's Law of Gravitation seemed not to fully explain. Some astrophysicists predicted the existence of another planet (Vulcan) that would explain the discrepancies; however, despite some early indications, no such planet could be found. When Albert Einstein formulated his theory of general relativity (GR) he turned his attention to the problem of Mercury's orbit and found that his theory added a correction, which could account for the discrepancy. This was the first time that Newton's Theory of Gravity had been shown to be less correct than an alternative.

Since then, and so far, general relativity has been acknowledged as the theory that best explains gravity. In GR, gravitation is not viewed as a force, but rather, objects moving freely in gravitational fields travel under their own inertia in straight lines through curved space-time – defined as the shortest space-time path between two space-time events. From the perspective of the object, all motion occurs as if there were no gravitation whatsoever. It is only when observing the motion in a global sense that the curvature of space-time can be observed and the force is inferred from the object's curved path. Thus, the straight line path in space-time is seen as a curved line in space, and it is called the ballistic trajectory of the object. For example, a basketball thrown from the ground moves in a parabola, as it is in a uniform gravitational field. Its space-time trajectory (when the extra ct dimension is added) is almost a straight line, slightly curved (with the radius of curvature of the order of few light-years). The time derivative of the changing momentum of the object is what we label as "gravitational force".

Through combining the definition of electric current as the time rate of change of electric charge, a rule of vector multiplication called Lorentz's Law describes the force on a charge moving in a magnetic field. The connection between electricity and magnetism allows for the description of a unified electromagnetic force that acts on a charge. This force can be written as a sum of the electrostatic force (due to the electric field) and the magnetic force (due to the magnetic field). Fully stated, this is the law:

The origin of electric and magnetic fields would not be fully explained until 1864 when James Clerk Maxwell unified a number of earlier theories into a set of 20 scalar equations, which were later reformulated into 4 vector equations by Oliver Heaviside and Josiah Willard Gibbs. These "Maxwell Equations" fully described the sources of the fields as being stationary and moving charges, and the interactions of the fields themselves. This led Maxwell to discover that electric and magnetic fields could be "self-generating" through a wave that traveled at a speed that he calculated to be the speed of light. This insight united the nascent fields of electromagnetic theory with optics and led directly to a complete description of the electromagnetic spectrum.

However, attempting to reconcile electromagnetic theory with two observations, the photoelectric effect, and the nonexistence of the ultraviolet catastrophe, proved troublesome. Through the work of leading theoretical physicists, a new theory of electromagnetism was developed using quantum mechanics. This final modification to electromagnetic theory ultimately led to quantum electrodynamics (or QED), which fully describes all electromagnetic phenomena as being mediated by wave-particles known as photons. In QED, photons are the fundamental exchange particle, which described all interactions relating to electromagnetism including the electromagnetic force.[Note 4]

It is a common misconception to ascribe the stiffness and rigidity of solid matter to the repulsion of like charges under the influence of the electromagnetic force. However, these characteristics actually result from the Pauli exclusion principle.[citation needed] Since electrons are fermions, they cannot occupy the same quantum mechanical state as other electrons. When the electrons in a material are densely packed together, there are not enough lower energy quantum mechanical states for them all, so some of them must be in higher energy states. This means that it takes energy to pack them together. While this effect is manifested macroscopically as a structural force, it is technically only the result of the existence of a finite set of electron states.

The strong force only acts directly upon elementary particles. However, a residual of the force is observed between hadrons (the best known example being the force that acts between nucleons in atomic nuclei) as

the nuclear force. Here the strong force acts indirectly, transmitted as gluons, which form part of the virtual pi and rho mesons, which classically transmit the nuclear force (see this topic for more). The failure of many searches for free quarks has shown that the elementary particles affected are not directly observable. This phenomenon is called color confinement.

The weak force is due to the exchange of the heavy W and Z bosons. Its most familiar effect is beta decay (of neutrons in atomic nuclei) and the associated radioactivity. The word "weak" derives from the fact that the field strength is some 10^{13} times less than that of the strong force. Still, it is stronger than gravity over short distances. A consistent electroweak theory has also been developed, which shows that electromagnetic forces and the weak force are indistinguishable at a temperatures in excess of approximately 1015 kelvins. Such temperatures have been probed in modern particle accelerators and show the conditions of the universe in the early moments of the Big Bang.

The normal force is due to repulsive forces of interaction between atoms at close contact. When their electron clouds overlap, Pauli repulsion (due to fermionic nature of electrons) follows resulting in the force that acts in a direction normal to the surface interface between two objects.:⁹³ The normal force, for example, is responsible for the structural integrity of tables and floors as well as being the force that responds whenever an external force pushes on a solid object. An example of the normal force in action is the impact force on an object crashing into an immobile surface.

Tension forces can be modeled using ideal strings that are massless, frictionless, unbreakable, and unstretchable. They can be combined with ideal pulleys, which allow ideal strings to switch physical direction. Ideal strings transmit tension forces instantaneously in action-reaction pairs so that if two objects are connected by an ideal string, any force directed along the string by the first object is accompanied by a force directed along the string in the opposite direction by the second object. By connecting the same string multiple times to the same object through the use of a set-up that uses movable pulleys, the tension force on a load can be multiplied. For every string that acts on a load, another factor of the tension force in the string acts on the load. However, even though such machines allow for an increase in force, there is a corresponding increase in the length of string that must be displaced in order to move the load. These tandem effects result ultimately in the conservation of mechanical energy since the work done on the load is the same no matter how complicated the machine.

Newton's laws and Newtonian mechanics in general were first developed to describe how forces affect idealized point particles rather than three-dimensional objects. However, in real life, matter has extended structure and forces that act on one part of an object might affect other parts of an object. For situations where lattice holding together the atoms in an object is able to flow, contract, expand, or otherwise change shape, the theories of continuum mechanics describe the way forces affect the material. For example, in extended fluids, differences in pressure result in forces being directed along the pressure gradients as follows:

where A is the relevant cross-sectional area for the volume for which the stress-tensor is being calculated. This formalism includes pressure terms associated with forces that act normal to the cross-sectional area (the matrix diagonals of the tensor) as well as shear terms associated with forces that act parallel to the cross-sectional area (the off-diagonal elements). The stress tensor accounts for forces that cause all strains (deformations) including also tensile stresses and compressions.:^{133–134:38–1–38–11}

Torque is the rotation equivalent of force in the same way that angle is the rotational equivalent for position, angular velocity for velocity, and angular momentum for momentum. As a consequence of Newton's First Law of Motion, there exists rotational inertia that ensures that all bodies maintain their angular momentum unless acted upon by an unbalanced torque. Likewise, Newton's Second Law of Motion can be used to derive an analogous equation for the instantaneous angular acceleration of the rigid body:

where m is the mass of the object, v is the velocity of the object and r is the distance to the center of the circular path and \hat{r} is the unit vector pointing in the radial direction outwards from the center. This means that the unbalanced centripetal force felt by any object is always directed toward the center of the curving path.

Such forces act perpendicular to the velocity vector associated with the motion of an object, and therefore do not change the speed of the object (magnitude of the velocity), but only the direction of the velocity vector. The unbalanced force that accelerates an object can be resolved into a component that is perpendicular to the path, and one that is tangential to the path. This yields both the tangential force, which accelerates the object by either slowing it down or speeding it up, and the radial (centripetal) force, which changes its direction.

A conservative force that acts on a closed system has an associated mechanical work that allows energy to convert only between kinetic or potential forms. This means that for a closed system, the net mechanical energy is conserved whenever a conservative force acts on the system. The force, therefore, is related directly to the difference in potential energy between two different locations in space, and can be considered to be an artifact of the potential field in the same way that the direction and amount of a flow of water can be considered to be an artifact of the contour map of the elevation of an area.

For certain physical scenarios, it is impossible to model forces as being due to gradient of potentials. This is often due to macrophysical considerations that yield forces as arising from a macroscopic statistical average of microstates. For example, friction is caused by the gradients of numerous electrostatic potentials between the atoms, but manifests as a force model that is independent of any macroscale position vector. Nonconservative forces other than friction include other contact forces, tension, compression, and drag. However, for any sufficiently detailed description, all these forces are the results of conservative ones since each of these macroscopic forces are the net results of the gradients of microscopic potentials.

The connection between macroscopic nonconservative forces and microscopic conservative forces is described by detailed treatment with statistical mechanics. In macroscopic closed systems, nonconservative forces act to change the internal energies of the system, and are often associated with the transfer of heat. According to the Second law of thermodynamics, nonconservative forces necessarily result in energy transformations within closed systems from ordered to more random conditions as entropy increases.

The pound-force has a metric counterpart, less commonly used than the newton: the kilogram-force (kgf) (sometimes kilopond), is the force exerted by standard gravity on one kilogram of mass. The kilogram-force leads to an alternate, but rarely used unit of mass: the metric slug (sometimes mug or hyl) is that mass that accelerates at $1 \text{ m} \cdot \text{s}^{-2}$ when subjected to a force of 1 kgf. The kilogram-force is not a part of the modern SI system, and is generally deprecated; however it still sees use for some purposes as expressing aircraft weight, jet thrust, bicycle spoke tension, torque wrench settings and engine output torque. Other arcane units of force include the sthène, which is equivalent to 1000 N, and the kip, which is equivalent to 1000 lbf.

What concept did philosophers in antiquity use to study simple machines

force

What was the belief that maintaining motion required force

fundamental error

Who had mathematical insight

Sir Isaac Newton

How long did it take to improve on Sir Isaac Newton's laws of motion

nearly three hundred years

Who developed the theory of relativity

Einstein

What has particle physics made to describe sub-atomic forces

Standard Model

What are the exchanged particles predicted by the standard Model

gauge bosons

What is the strongest main interaction

strong

What is the weakest main interaction

gravitational

What are weak and electromagnetic forces expressions of

electroweak interaction

Who provided a philosophical discussion of force

Aristotle

What was the concept of force an integral part of

Aristotelian cosmology

How many elements did Aristotle believe the terrestrial sphere to be made up of

four

Where did Aristotle believe the natural place for earth and water elements

on the ground

What did Aristotle refer to forced motion as

unnatural

When were the shortcomings of Aristotle's physics overcome

17th century

Whose work corrected Aristotle's physics in the seventeenth century

Galileo Galilei

What did objects in forced motion contain according to the late Medieval idea that influence Aristotle

impetus

Who experimented by rolling stones and cannonballs down a steep incline

Galileo

What force acted on bodies to retard their velocity

friction

Whose First Law of Motion says that unless acted upon by forces, objects would continue to move at a constant velocity

Newton

What insight of Galileo was associated with constant velocity

lack of net force

Who proposed that innate inertial is the natural state of objects

Newton

What law connects relative velocities with inertia

Newton's First

What are the laws of physics of Galileo, in reference to object in motion and rest

the same

What doesn't change from being at rest to movement at a constant velocity

laws of physics

What path does a ball thrown up and down in a moving vehicle take when seen by an outside observer

parabolic

What state are things inside of a moving vehicle as seen by a person inside the vehicle

at rest

What applies to equally to constant velocity motion as it does to rest.

Inertia

What concept explains why objects continue in constant motion

inertia

What makes day length constant on Earth

rotational inertia of planet

Who explained that inertial reference frames equaled reference frames subject to constant acceleration

Albert Einstein

What do astronauts experience while in free-fall

weightlessness

What was the basis mentioned for the development of the general theory of relativity

principle of equivalence

What describes the proportionality of acceleration to force and mass

Newton's Second Law

What kind of measurements define accelerations

kinematic

What has an equivalence between mass and space-time

General relativity

What is missing a theory on quantum gravity

General relativity

In Newton's second law, what are the units of mass and force in relation to microscales

fixed

When forces are from the presence of different objects, what law

gives symmetry

Newton's Third

What law states that forces are interactions between bodies

Newton's Third

What kind of force does not exist under Newton's third law

unidirectional

What is the equality of forces between two objects exerting force on each other

magnitude

What experiences acceleration when external force is applied to a system

center of mass

In what kind of system of particles are there no unbalanced internal forces

closed

What is the magnitude of force divided by when external force is added

mass of the system

What does pushing and pulling perceptions provide for describing forces

intuitive understanding

What is used to quantify the intuitive understanding of forces

standard measurement scale

What offers a conceptual definition of force

Newtonian mechanics

How are laboratory measurements of forces determined

experimentation

How are forces classified with regard to push and pull strengt

vector quantities

What physical quantities do not have direction

denoted scalar quantities

How do you avoid problems when determining forces involved on an object from two or more sources

Associating forces with vectors

If you do not know both magnitude and direction of two forces on an object, what would you call that situation

ambiguous

How do you determine the acceleration of a rope when two people are pulling it

Associating forces with vectors

In what conditions were forces first measured historically

static equilibrium

What do forces have with regard to additive quantities

magnitude and direction

What is the resultant force called when two forces act on a particle

net force

When forces are acting on an extended body, what do you need to account for motion effects

respective lines of application

What geometric shape is used in equations to determine net force

parallelogram

When forces are at right angles to each other what can they be broken down to

independent components

If a force is pointing horizontally to the northeast, how many forces can you split the force into

two

What do you get when you figure the sum of forces with vector addition

the original force

What are the independent components of a vector sum that has been determined by scalar addition of individual vectors

orthogonal

What can orthogonal forces be when there are three components with two at right angles to each other

three-dimensional

What can keep an object from moving when it is being pushed on a surface

static friction

What is generated between a surface and an object that is being pushed

static friction

Static friction balances what force when there is no movement of an object on a surface

applied

What makes static friction go up or down in response to contact characteristics between an object and the surface it is on

applied force

What can scales and spring balances measure between two forces by using static equilibrium

forces

What force acts on an object suspended on a spring scale in addition to gravity

spring reaction force

What equals the spring reaction force on an object suspended on a spring reaction scale

gravity

Objects of constant density are proportional to volume by what force to define standard weights.

gravity

Who expounded the Three Laws of Motion

Isaac Newton

Who first described dynamic equilibrium

Galileo

What does motion at a constant velocity equal

rest

Who had the idea of a natural state for objects at rest

Galileo

Where will a canonball dropped from the crow's nest of a ship land according to Aristotle

behind the foot of the mast

Where does a canonball dropped from the crow's nest of a ship actually land

foot of the mast

What occurs when traveling across a surface at a constant velocity with regard to friction

dynamic equilibrium

What directly opposes the force applied to move an object across a surface

kinetic friction force

What has to be accounted for that causes no net force being the cause of constant velocity motion

kinetic friction

Who thought that applied force caused movement of an object regardless of non-zero velocity

Aristotle

What equation currently describes the physics of force.

Schrödinger

What equation described the physics of force before the current Schrodinger equation

Newtonian

How are the forces derived from fields treated similarly to

classical position variables

What type of measurements result under Schrodinger equations when using operators instead of Newtonian variables

quantized

What notion keeps it's meaning through both Newtonian and Schrodinger physics equations

force

What is the intrinsic angular variable called when particles act upon one another

spin

What is the principle about relating spin and space variables

Pauli

What value does the separating into fermions and

bosons depend

spin

If the apparant force of two fermions is attractive, what is the spin function

antiparallel

If the apparant force of two fermions is repulsive, what is the spin function

parallel

How are the particle forces and accelerations explained as by gauge bosons exchange

mathematical by-product

What is the redundant concept coming from momentum conservation

force

What is more fundamental than force in quanton field theory

conservation of momentum

What diagrams are used to simplify particle interactions on a fundamental level

Feynman

Matter particles are shown as what kind of lines in a Feynman diagram

straight

How many interactions are all of the universal forces based on

four

What nuclear forces only act at short distances

strong and weak

What force acts between electric charges

electromagnetic

What do gravitational forces act between

masses

What prohibits atoms from passing through each other

Pauli exclusion principle

Who formed the universal theory of gravitation

Isaac Newton

In what century was quantum mechanics made

20th

What kind of self-consistent models are physicists trying to make that would create a theory of everything

unification

What type of physics model did Einstein fail to make

self-consistent unification

Who identified gravity as a force

Isaac Newton

Who came up with the concept that falling objects

fell at the same speed regardless of weight

Galileo

How fast do objects fall on Earth

about 9.81 meters per second squared

Where was the measurment for the standard gravity on Earth taken

sea level

What is an object's mass proportional to at the surface of the Earth

force of gravity

How might gravity effects be observed differently according to Newton

at larger distances.

What could be attributed to gravity acceleration around the Earth

the Moon

What is gravitational acceleration proportional to

mass

What is included along with gravitational acceration, and mass of the Earth in a formula about rotation about the Earth

radius () of the Earth

What is used to figure the relative strengh of gravity

Newton's Universal Gravitation Constant,

Who made the first to measure value of the Newton Universal Gravitation Constant

Henry Cavendish

When was the first measurement of the value of the Newton Universal Gravitation Constant

1798

Who figured out that his law of gravity had to be universal

Newton

What planet seemed to buck Newton's gravitational laws

Mercury

What planet did astrophysicist predict to explain the problems with Mercury

Vulcan

What theory accounted for the Mercury problem

theory of general relativity

Who came up with the theory of relativity

Albert Einstein

Who first showed that Newton's Theory of Gravity was not as correct as another theory

Albert Einstein

What theory best explains gravity

general relativity

What space-time path is seen as a curved line in space

ballistic trajectory

What is the derivative of an object's changing momentum called

gravitational force

In what sense must you be observing the curvature of space-time

global

What is the law named that defines a charge moving through a magnetic field

Lorentz's Law

What is the time rate of change of electric charge

electric current

What magnetic and electric force acts on a charge

unified electromagnetic

What are the electrostatic and magnetic force written as the sum of

electrostatic force

Who first fully explained the origins of magnetic and electric fields

James Clerk Maxwell

When did the origins of magnetic and electric fields occur

1864

How many scalar equations were formed into a set by James Maxwell

20

How many vector equations did Heaviside and Gibbs reformilate Maxwell's 20 scalar equtions into

4

Who discovered that magnetic and electric could self-generate

Maxwell

What was dificult to reconcile the photoelectric effect and the missing ultraviolet catastrophe

electromagnetic theory

What was used to create a new electromagnetic theory to reconcile the troubles with electromagnetic theory as it used to stand

quantum mechanics

What did electromagnetic theory finally lead to

quantum electrodynamics

What are the wave-particles called that mediate all electromagnetic phenomena

photons

What is QED short for

quantum electrodynamics

What is often misunderstood as the cause of matter rigidity

repulsion of like charges

What actually causes rigidity in matter

the Pauli exclusion principle

What is needed to pack electrons densely together

energy

How is the Pauli exclusion principle manifested in the macro world

as a structural force

What does strong force act upon

elementary particles

What can be seen between hadrons

residual of the force

What is the force between nucleons

nuclear

How are nuclear forces transmitted

as gluons

What is the term for the lack of observable free quarks

color confinement

What does the W and Z boson exchange create

weak force

What is the observable effect of W and Z boson exchange

beta decay

What is the effect of beta decay

radioactivity

How many times less is the strenght of the weak field compared to the strong

1013

At what temperature do weak and electromagnetic forces appear the same

approximately 1015 kelvins

What is the repulsive force of close range atom interaction

normal force

What occurs when electron clouds overlap from different atoms

Pauli repulsion

What causes Pauli repulsion

fermionic nature of electrons

What is the force that causes rigid strength in structures

normal

What can be used to model tension forces

ideal strings

What do you use to let idea strings switch direction

ideal pulleys

In what way do idea strings transmit tesion forces

action-reaction pairs

What is the final effect of adding more and more idea strings to a load

conservation of mechanical energy

What can increase the tension force on a load

movable pulleys

What did Newton's mechanics affect

idealized point particles

What didn't Newton's mechanics affect

three-dimensional objects

In what kind of fluid are pressure differences caused by direction of forces over gradients

extended

What may a force on one part of an object affect

other parts

What does matter actually have that Newtonian mechanics doesn't address

extended structure

What causes strain in structures

stress tensor

What is used to calculate cross section area in the volume of an object

pressure terms

What are associated with normal forces

pressure terms

What includes pressure terms when calculating area in volume

formalism

What is the force equivalent of torque compared to angular momentum

rotational equivalent for position

What would change the rotational inertia of a body under Newton's First Law of Motion

unbalanced torque

To calculate instant angular acceleration of a rigid body what would you use

Newton's Second Law of Motion

Where does centripetal force go

toward the center of the curving path

How do centripetal forces act in relation to vectors of velocity

perpendicular

What force changes an objects direction of travel

centripetal

What is another word for centripetal force

radial

What is responsible for speeding up or slowing down an object

tangential force

What is the only form potential energy can change into

kinetic

What is the only form kinetic energy can change into

potential

What is preserved in a closed system of forces when acted upon

net mechanical energy

What is the force between two locations related to

difference in potential energy

What is the force called regarding a potential field between two locations

artifact

What is sometimes impossible to model

forces

Why are some forces due to that are impossible to model

gradient of potentials

What do electrostatic gradient potentials create

friction

Tension, compression, and drag are what kind of forces

Nonconservative

In what treatment are nonconservative and conservative forces described

statistical mechanics

What changes macroscopic closed system energies

nonconservative forces

What is the exchange of heat associated with

nonconservative forces

What is the law of thermodynamics associated with closed system heat exchange

Second

What makes energy changes in a closed system

nonconservative forces

What is the metric term less used than the Newton

kilogram-force

What is the kilogram-force sometimes referred to as

kilopond

What is a very seldom used unit of mass in the metric system

slug

What seldom used term of a unit of force equal to 1000 pound s of force

kip

What is the seldom used force unit equal to one thousand newtons

sthène