= mc2) , length contraction (moving objects shorten) , and time dilation (moving clocks run more slowly) . The factor ? by which lengths contract and times dilate is known as the Lorentz factor and is given by ? =
(1 ? v2 / c2) ? 1 / 2 , where v is the speed of the object . The difference of ? from 1 is negligible for speeds much slower than c , such as most everyday speeds ? in which case special relativity is closely approximated by Galilean relativity ? but it increases at relativistic speeds and diverges to infinity as v approaches c .
The results of special relativity can be summarized by treating space and time as a unified structure known as spacetime (with c relating the units of space and time) , and requiring that physical theories satisfy a special symmetry called Lorentz invariance , whose mathematical formulation contains the parameter c . Lorentz invariance is an almost universal assumption for modern physical theories , such as quantum electrodynamics , quantum chromodynamics , the Standard Model of particle physics , and general relativity . As such , the parameter c is ubiquitous in modern physics , appearing in many contexts that are unrelated to light . For example , general relativity predicts that c is also the speed of gravity and of gravitational waves . In non @-@ inertial frames of reference (gravitationally curved spacetime or accelerated reference frames) , the local speed of light is constant and equal to c , but the speed of light along a trajectory of finite length can differ from c , depending on how distances and times are defined .
It is generally assumed that fundamental constants such as c have the same value throughout spacetime , meaning that they do not depend on location and do not vary with time . However , it has been suggested in various theories that the speed of light may have changed over time . No conclusive evidence for such changes has been found , but they remain the subject of ongoing research .
It also is generally assumed that the speed of light is isotropic , meaning that it has the same value regardless of the direction in which it is measured . Observations of the emissions from nuclear energy levels as a function of the orientation of the emitting nuclei in a magnetic field (see Hughes ? Drever experiment) , and of rotating optical resonators (see Resonator experiments) have put stringent limits on the possible two @-@ way anisotropy .

= = = Upper limit on speeds = = =

According to special relativity , the energy of an object with rest mass m and speed v is given by ?mc2 , where ? is the Lorentz factor defined above . When v is zero , ? is equal to one , giving rise to the famous E = mc2 formula for mass ? energy equivalence . The ? factor approaches infinity as v approaches c , and it would take an infinite amount of energy to accelerate an object with mass to the speed of light . The speed of light is the upper limit for the speeds of objects with positive rest mass , and individual photons cannot travel faster than the speed of light . This is experimentally established in many tests of relativistic energy and momentum .
More generally , it is normally impossible for information or energy to travel faster than c . One argument for this follows from the counter @-@ intuitive implication of special relativity known as the relativity of simultaneity . If the spatial distance between two events A and B is greater than the time interval between them multiplied by c then there are frames of reference in which A precedes B , others in which B precedes A , and others in which they are simultaneous . As a result , if something were travelling faster than c relative to an inertial frame of reference , it would be travelling backwards in time relative to another frame , and causality would be violated . In such a frame of reference , an " effect " could be observed before its " cause " . Such a violation of causality has never been recorded , and would lead to paradoxes such as the tachyonic antitelephone .

= = Faster @-@ than @-@ light observations and experiments = =

There are situations in which it may seem that matter , energy , or information travels at speeds greater than c , but they do not . For example , as is discussed in the propagation of light in a medium section below , many wave velocities can exceed c . For example , the phase velocity of X

@-@ rays through most glasses can routinely exceed c , but phase velocity does not determine the velocity at which waves convey information .
If a laser beam is swept quickly across a distant object , the spot of light can move faster than c , although the initial movement of the spot is delayed because of the time it takes light to get to the distant object at the speed c . However , the only physical entities that are moving are the laser and its emitted light , which travels at the speed c from the laser to the various positions of the spot . Similarly , a shadow projected onto a distant object can be made to move faster than c , after a delay in time . In neither case does any matter , energy , or information travel faster than light .
The rate of change in the distance between two objects in a frame of reference with respect to which both are moving (their closing speed) may have a value in excess of c . However , this does not represent the speed of any single object as measured in a single inertial frame .
Certain quantum effects appear to be transmitted instantaneously and therefore faster than c , as in the EPR paradox . An example involves the quantum states of two particles that can be entangled . Until either of the particles is observed , they exist in a superposition of two quantum states . If the particles are separated and one particle 's quantum state is observed , the other particle 's quantum state is determined instantaneously (i.e. , faster than light could travel from one particle to the other) . However , it is impossible to control which quantum state the first particle will take on when it is observed , so information cannot be transmitted in this manner .
Another quantum effect that predicts the occurrence of faster @-@ than @-@ light speeds is called the Hartman effect ; under certain conditions the time needed for a virtual particle to tunnel through a barrier is constant , regardless of the thickness of the barrier . This could result in a virtual particle crossing a large gap faster @-@ than @-@ light . However , no information can be sent using this effect .
So @-@ called superluminal motion is seen in certain astronomical objects , such as the relativistic jets of radio galaxies and quasars . However , these jets are not moving at speeds in excess of the speed of light : the apparent superluminal motion is a projection effect caused by objects moving near the speed of light and approaching Earth at a small angle to the line of sight : since the light which was emitted when the jet was farther away took longer to reach the Earth , the time between two successive observations corresponds to a longer time between the instants at which the light rays were emitted .
In models of the expanding universe , the farther galaxies are from each other , the faster they drift apart . This receding is not due to motion through space , but rather to the expansion of space itself . For example , galaxies far away from Earth appear to be moving away from the Earth with a speed proportional to their distances . Beyond a boundary called the Hubble sphere , the rate at which their distance from Earth increases becomes greater than the speed of light .

= = Propagation of light = =

In classical physics , light is described as a type of electromagnetic wave . The classical behaviour of the electromagnetic field is described by Maxwell 's equations , which predict that the speed c with which electromagnetic waves (such as light) propagate through the vacuum is related to the electric constant ?0 and the magnetic constant ?0 by the equation
<formula>
In modern quantum physics , the electromagnetic field is described by the theory of quantum electrodynamics (QED) . In this theory , light is described by the fundamental excitations (or quanta) of the electromagnetic field , called photons . In QED , photons are massless particles and thus , according to special relativity , they travel at the speed of light in vacuum .
Extensions of QED in which the photon has a mass have been considered . In such a theory , its speed would depend on its frequency , and the invariant speed c of special relativity would then be the upper limit of the speed of light in vacuum . No variation of the speed of light with frequency has been observed in rigorous testing , putting stringent limits on the mass of the photon . The limit obtained depends on the model used : if the massive photon is described by Proca theory , the experimental upper bound for its mass is about 10 ? 57 grams ; if photon mass is generated by a

Higgs mechanism , the experimental upper limit is less sharp , m ? 10 ? 14 eV / c2 (roughly 2 × 10 ? 47 g) .
Another reason for the speed of light to vary with its frequency would be the failure of special relativity to apply to arbitrarily small scales , as predicted by some proposed theories of quantum gravity . In 2009 , the observation of the spectrum of gamma @-@ ray burst GRB 090510 did not find any difference in the speeds of photons of different energies , confirming that Lorentz invariance is verified at least down to the scale of the Planck length (lP = ? ?G / c3 ? 1 @.@ 6163 × 10 ? 35 m) divided by 1 @.@ 2 .

= = = In a medium = = =

In a medium , light usually does not propagate at a speed equal to c ; further , different types of light wave will travel at different speeds . The speed at which the individual crests and troughs of a plane wave (a wave filling the whole space , with only one frequency) propagate is called the phase velocity vp . An actual physical signal with a finite extent (a pulse of light) travels at a different speed . The largest part of the pulse travels at the group velocity vg , and its earliest part travels at the front velocity vf .
The phase velocity is important in determining how a light wave travels through a material or from one material to another . It is often represented in terms of a refractive index . The refractive index of a material is defined as the ratio of c to the phase velocity vp in the material : larger indices of refraction indicate lower speeds . The refractive index of a material may depend on the light 's frequency , intensity , polarization , or direction of propagation ; in many cases , though , it can be treated as a material @-@ dependent constant . The refractive index of air is approximately 1 @.@ 0003 . Denser media , such as water , glass , and diamond , have refractive indexes of around 1 @.@ 3 , 1 @.@ 5 and 2 @.@ 4 , respectively , for visible light . In exotic materials like Bose ? Einstein condensates near absolute zero , the effective speed of light may be only a few metres per second . However , this represents absorption and re @-@ radiation delay between atoms , as do all slower @-@ than @-@ c speeds in material substances . As an extreme example of light " slowing " in matter , two independent teams of physicists claimed to bring light to a " complete standstill " by passing it through a Bose ? Einstein condensate of the element rubidium , one team at Harvard University and the Rowland Institute for Science in Cambridge , Mass . , and the other at the Harvard ? Smithsonian Center for Astrophysics , also in Cambridge . However , the popular description of light being " stopped " in these experiments refers only to light being stored in the excited states of atoms , then re @-@ emitted at an arbitrarily later time , as stimulated by a second laser pulse . During the time it had " stopped , " it had ceased to be light . This type of behaviour is generally microscopically true of all transparent media which " slow " the speed of light .
In transparent materials , the refractive index generally is greater than 1 , meaning that the phase velocity is less than c . In other materials , it is possible for the refractive index to become smaller than 1 for some frequencies ; in some exotic materials it is even possible for the index of refraction to become negative . The requirement that causality is not violated implies that the real and imaginary parts of the dielectric constant of any material , corresponding respectively to the index of refraction and to the attenuation coefficient , are linked by the Kramers ? Kronig relations . In practical terms , this means that in a material with refractive index less than 1 , the absorption of the wave is so quick that no signal can be sent faster than c .
A pulse with different group and phase velocities (which occurs if the phase velocity is not the same for all the frequencies of the pulse) smears out over time , a process known as dispersion . Certain materials have an exceptionally low (or even zero) group velocity for light waves , a phenomenon called slow light , which has been confirmed in various experiments . The opposite , group velocities exceeding c , has also been shown in experiment . It should even be possible for the group velocity to become infinite or negative , with pulses travelling instantaneously or backwards in time .
None of these options , however , allow information to be transmitted faster than c . It is impossible to transmit information with a light pulse any faster than the speed of the earliest part of the pulse (

the front velocity) . It can be shown that this is (under certain assumptions) always equal to c .
It is possible for a particle to travel through a medium faster than the phase velocity of light in that medium (but still slower than c) . When a charged particle does that in a dielectric material , the electromagnetic equivalent of a shock wave , known as Cherenkov radiation , is emitted .

= = Practical effects of finiteness = =

The speed of light is of relevance to communications : the one @-@ way and round @-@ trip delay time are greater than zero . This applies from small to astronomical scales . On the other hand , some techniques depend on the finite speed of light , for example in distance measurements .

= = = Small scales = = =

In supercomputers , the speed of light imposes a limit on how quickly data can be sent between processors . If a processor operates at 1 gigahertz , a signal can only travel a maximum of about 30 centimetres (1 ft) in a single cycle . Processors must therefore be placed close to each other to minimize communication latencies ; this can cause difficulty with cooling . If clock frequencies continue to increase , the speed of light will eventually become a limiting factor for the internal design of single chips .

= = = Large distances on Earth = = =

For example , given the equatorial circumference of the Earth is about 40075 km and c about 300000 km / s , the theoretical shortest time for a piece of information to travel half the globe along the surface is about 67 milliseconds . When light is travelling around the globe in an optical fibre , the actual transit time is longer , in part because the speed of light is slower by about 35 % in an optical fibre , depending on its refractive index n . Furthermore , straight lines rarely occur in global communications situations , and delays are created when the signal passes through an electronic switch or signal regenerator .

= = = Spaceflights and astronomy = = =

Similarly , communications between the Earth and spacecraft are not instantaneous . There is a brief delay from the source to the receiver , which becomes more noticeable as distances increase . This delay was significant for communications between ground control and Apollo 8 when it became the first manned spacecraft to orbit the Moon : for every question , the ground control station had to wait at least three seconds for the answer to arrive . The communications delay between Earth and Mars can vary between five and twenty minutes depending upon the relative positions of the two planets . As a consequence of this , if a robot on the surface of Mars were to encounter a problem , its human controllers would not be aware of it until at least five minutes later , and possibly up to twenty minutes later ; it would then take a further five to twenty minutes for instructions to travel from Earth to Mars .
NASA must wait several hours for information from a probe orbiting Jupiter , and if it needs to correct a navigation error , the fix will not arrive at the spacecraft for an equal amount of time , creating a risk of the correction not arriving in time .
Receiving light and other signals from distant astronomical sources can even take much longer . For example , it has taken 13 billion (13 × 109) years for light to travel to Earth from the faraway galaxies viewed in the Hubble Ultra Deep Field images . Those photographs , taken today , capture images of the galaxies as they appeared 13 billion years ago , when the universe was less than a billion years old . The fact that more distant objects appear to be younger , due to the finite speed of light , allows astronomers to infer the evolution of stars , of galaxies , and of the universe itself .
Astronomical distances are sometimes expressed in light @-@ years , especially in popular science publications and media . A light @-@ year is the distance light travels in one year , around 9461

billion kilometres , 5879 billion miles , or 0 @.@ 3066 parsecs . In round figures , a light year is nearly 10 trillion kilometres or nearly 6 trillion miles . Proxima Centauri , the closest star to Earth after the Sun , is around 4 @.@ 2 light @-@ years away .

= = = Distance measurement = = =

Radar systems measure the distance to a target by the time it takes a radio @-@ wave pulse to return to the radar antenna after being reflected by the target : the distance to the target is half the round @-@ trip transit time multiplied by the speed of light . A Global Positioning System (GPS) receiver measures its distance to GPS satellites based on how long it takes for a radio signal to arrive from each satellite , and from these distances calculates the receiver 's position . Because light travels about 300000 kilometres (186000 mi) in one second , these measurements of small fractions of a second must be very precise . The Lunar Laser Ranging Experiment , radar astronomy and the Deep Space Network determine distances to the Moon , planets and spacecraft , respectively , by measuring round @-@ trip transit times .

= = = High @-@ frequency trading = = =

The speed of light has become important in high @-@ frequency trading , where traders seek to gain minute advantages by delivering their trades to exchanges fractions of a second ahead of other traders . For example , traders have been switching to microwave communications between trading hubs , because of the advantage which microwaves travelling at near to the speed of light in air , have over fibre optic signals which travel 30 ? 40 % slower at the speed of light through glass .

= = Measurement = =

There are different ways to determine the value of c . One way is to measure the actual speed at which light waves propagate , which can be done in various astronomical and earth @-@ based setups . However , it is also possible to determine c from other physical laws where it appears , for example , by determining the values of the electromagnetic constants ?0 and ?0 and using their relation to c . Historically , the most accurate results have been obtained by separately determining the frequency and wavelength of a light beam , with their product equalling c .

In 1983 the metre was defined as " the length of the path travelled by light in vacuum during a time interval of 1 ? 299792458 of a second " , fixing the value of the speed of light at 299792458 m / s by definition , as described below . Consequently , accurate measurements of the speed of light yield an accurate realization of the metre rather than an accurate value of c .

= = = Astronomical measurements = = =

Outer space is a convenient setting for measuring the speed of light because of its large scale and nearly perfect vacuum . Typically , one measures the time needed for light to traverse some reference distance in the solar system , such as the radius of the Earth 's orbit . Historically , such measurements could be made fairly accurately , compared to how accurately the length of the reference distance is known in Earth @-@ based units . It is customary to express the results in astronomical units (AU) per day .

Ole Christensen Rømer used an astronomical measurement to make the first quantitative estimate of the speed of light . When measured from Earth , the periods of moons orbiting a distant planet are shorter when the Earth is approaching the planet than when the Earth is receding from it . The distance travelled by light from the planet (or its moon) to Earth is shorter when the Earth is at the point in its orbit that is closest to its planet than when the Earth is at the farthest point in its orbit , the difference in distance being the diameter of the Earth 's orbit around the Sun . The observed change in the moon 's orbital period is caused by the difference in the time it takes light to traverse the shorter or longer distance . Rømer observed this effect for Jupiter 's innermost moon Io and

deduced that light takes 22 minutes to cross the diameter of the Earth 's orbit .
Another method is to use the aberration of light , discovered and explained by James Bradley in the 18th century . This effect results from the vector addition of the velocity of light arriving from a distant source (such as a star) and the velocity of its observer (see diagram on the right) . A moving observer thus sees the light coming from a slightly different direction and consequently sees the source at a position shifted from its original position . Since the direction of the Earth 's velocity changes continuously as the Earth orbits the Sun , this effect causes the apparent position of stars to move around . From the angular difference in the position of stars (maximally 20 @.@ 5 arcseconds) it is possible to express the speed of light in terms of the Earth 's velocity around the Sun , which with the known length of a year can be converted to the time needed to travel from the Sun to the Earth . In 1729 , Bradley used this method to derive that light travelled 10 @,@ 210 times faster than the Earth in its orbit (the modern figure is 10 @,@ 066 times faster) or , equivalently , that it would take light 8 minutes 12 seconds to travel from the Sun to the Earth .

= = = = Astronomical unit = = = =

An astronomical unit (AU) is approximately the average distance between the Earth and Sun . It was redefined in 2012 as exactly 149597870700 m . Previously the AU was not based on the International System of Units but in terms of the gravitational force exerted by the Sun in the framework of classical mechanics . The current definition uses the recommended value in metres for the previous definition of the astronomical unit , which was determined by measurement . This redefinition is analogous to that of the metre , and likewise has the effect of fixing the speed of light to an exact value in astronomical units per second (via the exact speed of light in metres per second) .
Previously , the inverse of c expressed in seconds per astronomical unit was measured by comparing the time for radio signals to reach different spacecraft in the Solar System , with their position calculated from the gravitational effects of the Sun and various planets . By combining many such measurements , a best fit value for the light time per unit distance could be obtained . For example , in 2009 , the best estimate , as approved by the International Astronomical Union (IAU) , was :
light time for unit distance : 499 @.@ 004783836 (10) s