Units of Speed and Time

Luz Craddock

First Edition, 2012

ISBN 978-81-323-4051-5

Published by:
White Word Publications
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter-1

Orders of Magnitude

To help compare different orders of magnitude, the following list describes various speed levels between 1.3×10^{-11} m/s and 3×10^{8} m/s.

List of orders of magnitude for speed

List of orders of magnitude for speed

Factor	Value (m/s)	Value (km/h)	Item
10^{-11}	9.5×10^{-11}	3.4×10^{-10}	Rate of global sea level rise in 1993–2003 (approx. 3 mm/year).
	1.3×10^{-9}	4.68×10^{-9}	Average rate of the Moon receding from the Earth (approx. 38 mm/year).
10^{-9}	0.3×10^{-9} to 3×10^{-9}	1×10^{-9} to 1×10^{-8}	Typical relative speed of continental drift.
	1.7×10^{-8}	6.12×10^{-8}	Hair growth.
10^{-6}	1.52×10^{-6}	5.4×10^{-6}	Speed of a cellular vesicle propelled by a motor protein.
10^{-5}	1.4×10^{-5}	5.0×10^{-5}	Growth rate of bamboo, the fastest-growing woody plant, over 24 hours.
10^{-4}	4.0×10^{-4}	1.4×10^{-3}	Speed of Jakobshavn Isbræ, one of the fastest glaciers, in 2003.
	6×10^{-4}	2.2×10^{-3}	Typical speed of *Thiovulum majus*, the fastest-swimming bacterium.
10^{-2}	0.013	0.0468	Speed of a Garden snail .
	0.0476	0.171	Compact cassette tape speed.
10^{-1}	0.28	1	1 km/hour.
	0.447	1.6093	1 mph.
10^{0}	1.2	4.32	Typical scanning speed of an audio compact disc.
	1–1.5	3.6–5.4	Average walking speed.
	2.39	8.53	World record time 50m freestyle

			swim (20.94 seconds)
	5.72	20.42	World record time marathon (2h03m59s)
	11.80	42.48	Top speed of Donovan Bailey and Maurice Greene 1997 World Championship 100 meter sprint (Top speed ~42.5 km/h).
	11.1	40	Typical speed of car (city road).
	14	50	Typical speed of road-race cyclist.
	16.7	60	Typical speed of thoroughbred racehorse.
	16.7	60	Typical speed of racing greyhound.
	5–25	18–90	Speed of propagation for unmyelinated sensory neurons.
10^1	30	108	Typical speed of car (major road), Cheetah—fastest of all terrestrial animals, Sailfish—fastest Fish. Speed of go-fast boat.
	36	130	Land speed record for a human powered vehicle.
	40	144	Typical peak speed of a local service train (or intercity on lower standard tracks).
	90	320	Typical speed of a modern high-speed train (e.g. latest generation of production TGV), a diving Peregrine Falcon—fastest bird.
	98.6	355	Maximum speed of the Enzo Ferrari.
	103	370	Speed of super torpedo VA-111 Shkval.
	105.5	379.8	Maximum speed of a Ferrari F50 GT1.
	119.742	431.072	Maximum speed of the Bugatti Veyron Super Sport (currently the fastest production car in the world).
10^2	120	432	Speed of propagation for mammalian motor neurons.
	130	468	Wind speed of a powerful tornado.
	150.6	539	Top speed of an internal combustion powered NHRA Top Fuel Dragster.
	152.7	550	Speed of Transrapid.
	157	575	Speed of experimental test TGV in

			2007.
	161	580	Speed of JR-Maglev in 2003.
	250	900	Typical cruising speed of a modern jet airliner, e.g. an Airbus A380.
	331.5	1,193.4	Speed of sound in dry air at 0 °C.
	344.66	1,240.77	Max speed reached by the jet-propelled car ThrustSSC in 1997—Land speed record.
	428	1,540.8	Max speed of Bell X-1.
	464	1,670	Speed of Earth's rotation at the equator.
	603	2,170.8	Speed of the Concorde airliner.
	975	3,510	Muzzle velocity of M16 rifle.
	981	3,532	SR-71 Blackbird, the fastest aircraft driven by a mechanical jet engine.
	1,500	5,400	Speed of sound in water.
	1 789	6,443	Speed of BrahMos II hypersonic cruise missile
	2,000	7,200	Estimated speed of a thermal neutron.
10^3	2,019	7,268.4	Speed of the North American X-15 rocket plane.
	7,111	25,599.6	Speed of the X-43 rocket/scramjet plane.
	7,700	27,700	Speed of International Space Station and typical speed of a satellite and the space Shuttle in low Earth orbit.
	7,777	28,000	Speed of propagation of the explosion in a detonating cord.
	11,082	39,895	Speed of Apollo 10—High speed record for manned vehicle.
	11,200	40,320	Escape velocity from Earth.
10^4	16,210	58,356	Escape speed from Earth by NASA *New Horizons* spacecraft—Fastest escape velocity.
	29,800	107,280	Speed of the Earth in orbit around the Sun.
	47,800	172,100	Atmospheric entry speed of the Galileo atmospheric probe—Fastest controlled atmospheric entry for a man-made object.

	70,220	252,792	Speed of the Helios 2 solar probe—Fastest man-made object.
	200,000	700,000	Orbital speed of the solar system in the Milky Way galaxy.
10^5	450,000	1,600,000	Typical speed of a particle of the solar wind, relative to the Sun.
	552,000	1,990,000	Speed of the Milky Way, relative to the cosmic microwave background.
	617,700	2,224,000	Escape velocity from the surface of the Sun.
	1,000,000	3,600,000	Typical speed of a Moreton wave across the surface of the Sun.
10^6	1,610,000	5,800,000	Speed of hypervelocity star PSR B2224+65, which currently seems to be leaving the Milky Way.
	36,000,000	129,600,000	Typical speed of a fast neutron.
10^7	30,000,000	100,000,000	Typical speed of an electron in a cathode ray tube.
	124,000,000	447,000,000	Speed of light in a diamond (Refractive index 2.417).
10^8	200,000,000	720,000,000	Speed of a signal in a cable.
	299,792,458	1,079,252,848.8	Speed of light (or electromagnetic radiation) in vacuum. Also, Planck speed

Comparison of speeds in mph and km/h

Comparison of speeds in mph and km/h

Value (mph)	Value (km/h)	Item
3 mph	5 km/h	Walking speed
12– 15 mph	20– 25 km/h	Comfortable bicycling speed.
18–31 mph	30– 50 km/h	Typical residential speed limit. Top speed of a running cat, or dog.
45–62 mph	72–100 km/h	Speed limit on a major road. Top speed of an antelope.

55– 81 mph	88–130 km/h	Highway or motorway speed.
103 mph	166 km/h	Top speed (as of 2006) of a baseball pitcher's fastball.
128 mph	206 km/h	The normal launch speed of the world's fastest roller coaster, Kingda Ka.
190 mph	300 km/h	Typical top running speed of High-speed train.
267.856 mph	431.072 km/h	Top speed of the world's fastest production car (Bugatti Veyron Super Sport).
560 mph	900 km/h	Jet airliner cruising speed.
761 mph	1,225 km/h	The speed of sound on sea level in standard atmosphere (15 °C & 1 atm).
763 mph	1,228 km/h	Current world land speed record.
6,000 mph	9,600 km/h	Speed of wind on exoplanet HD 189733b.
16,250 mph	26,000 km/h	Re-entry speed of a space shuttle.
24,759 mph	40,320 km/h	Earth's escape velocity at the equator.
670,616,628.6 mph	1,079,252,848.8 km/h	Speed of light.

Example speeds in m/s

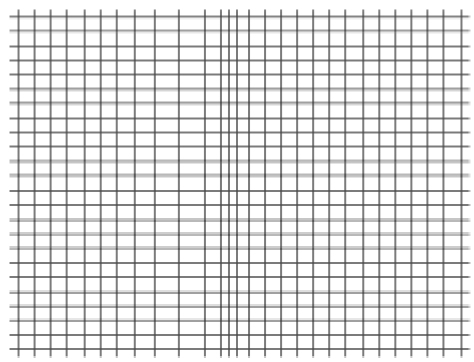
Some examples of speeds in m/s

Value (m/s)	Item
0.00275 m/s	World record speed of the fastest snail in the Congham, UK .
0.080 m/s	The top speed of a sloth (= 8.0 cm/s).
1.2 m/s	A typical human walking speed (2.7 mph or 4.3 km/h); below a speed of about 2 m/s, it is more efficient to walk than to run, but above that speed, it is more efficient to run. The speed of signals (action potentials) traveling along axons in the human cortex.
2 m/s	Maximum allowed wind speed in track and field competition for meet records to be set. Common in the sprints, jumping, and some of the throwing events.

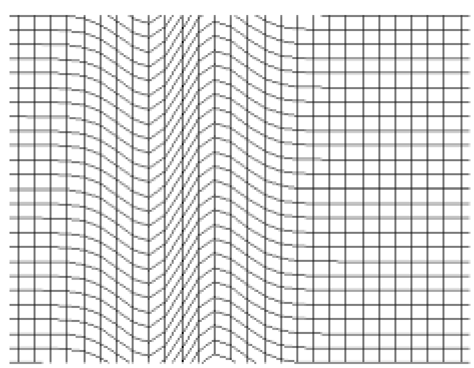
10.44 m/s	Average speed of Jamacian athlete Usain Bolt whilst setting the 100m world record in Berlin, 2009.
32 m/s	Oft-quoted top speed of cheetah, the fastest land mammal (~110–120 km/h).
89 m/s	Speed of Peregrine falcon in a dive. Also the 320 km/h or 200 mph *Supercar limit*: A parameter sometimes used in defining a supercar .
120 m/s	The maximum speed of signals (action potentials) traveling along myelinated axons in the spinal cord.
320 m/s	The speed of a typical .22 LR bullet.
336 m/s	The speed of sound in the Black Rock Desert when the land speed record was set in 1997.
341 m/s	The current land speed record, which was set by ThrustSSC in 1997. This was supersonic (Mach 1.016) in the Black Rock Desert at the time but might not have been supersonic in other places.
343 m/s	The approximate speed of sound under standard conditions, which varies according to air temperature.
559 m/s	The average speed of the Concorde's Atlantic crossing (1996, based on 1250 mph).
1,000 m/s	The average top speed of a sub-orbital spacecraft.
1,400 m/s	The speed of the Space Shuttle when the solid rocket boosters separate.
4,500 m/s	A typical value for the specific impulse of current rockets is 4.5 km/s.
8,000 m/s	The speed of the Space Shuttle at main engine shutdown just before it enters orbit.
17,000 m/s	The approximate speed of the Voyager 1 probe relative to the sun, when it exited the Solar System.
10,000 to 1,000,000 m/s	Specific impulse of the proposed Project Orion atomic powered spaceship
100,000,000 m/s	The escape velocity of a neutron star.
299,792,458 m/s	The speed of light (exact value by definition of the metre).

Chapter-2

Speed of Sound



Pressure-pulse or compression-type wave (longitudinal wave) confined to a plane. This is the only type of sound wave that travels in fluids (gases and liquids)



Transverse wave affecting atoms initially confined to a plane. This additional type of sound wave (additional type of elastic wave) travels only in solids, and the sideways shearing motion may take place in **any** direction at right angles to the direction of wave-travel (only one shear direction is shown here, at right angles to the plane). Furthermore, the right-angle shear direction may change over time and distance, resulting in different types of polarization of shear-waves

The **speed of sound** is the distance travelled during a unit of time by a sound wave propagating through an elastic medium. In dry air at 20 °C (68 °F), the speed of sound is 343.2 metres per second (1,126 ft/s). This is 1,236 kilometres per hour (768 mph), or about one kilometer in three seconds or approximately one mile in five seconds.

In fluid dynamics, the speed of sound in a fluid medium (gas or liquid) is used as a relative measure of speed itself. The speed (in distance per time) divided by the speed of sound in the fluid is called the Mach number. Objects moving at speeds greater than *Mach1* are traveling at supersonic speeds.

The speed of sound in an ideal gas is independent of frequency, but it weakly depends on frequency for all real physical situations. It is a function of the square root of temperature, but is nearly independent of pressure or density for a given gas. For different gases, the speed of sound is inversely dependent on square root of the mean molecular weight of the gas, and affected to a lesser extent by the number of ways in which the molecules of the gas can store heat from compression, since sound in gases is a type of compression. Although, in the case of gases only, the speed of sound *may* be expressed in terms of a ratio of *both* density and pressure, these quantities are not fully independent of each other, and canceling their common contributions from physical conditions, leads to a velocity expression using the independent variables of temperature, composition, and heat capacity noted above.

In common everyday speech, *speed of sound* refers to the speed of sound waves in air. However, the speed of sound varies from substance to substance. Sound travels faster in liquids and non-porous solids than it does in air. It travels about 4.3 times faster in water (1,484 m/s), and nearly 15 times as fast in iron (5,120 m/s), than in air at 20 degrees Celsius.

In solids, sound waves propagate as two different types. A longitudinal wave is associated with compression and decompression in the direction of travel, which is the same process as all sound waves in gases and liquids. A transverse wave, often called shear wave, is due to elastic deformation of the medium perpendicular to the direction of wave travel; the direction of shear-deformation is called the "polarization" of this type of wave. In general, transverse waves occur as a pair of orthogonal polarizations. These different waves (compression waves and the different polarizations of shear waves) may have different speeds at the same frequency. Therefore, they arrive at an observer at different times, an extreme example being an earthquake, where sharp compression waves arrive first, and rocking transverse waves seconds later.

The speed of an elastic wave in any medium is determined by the medium's compressibility and density. The speed of shear waves, which can occur only in solids, is determined by the solid material's stiffness, compressibility and density.

Basic concept

The transmission of sound can be illustrated by using a toy model consisting of an array of balls interconnected by springs. For real material the balls represent molecules and the springs represent the bonds between them. Sound passes through the model by compressing and expanding the springs, transmitting energy to neighboring balls, which transmit energy to *their* springs, and so on. The speed of sound through the model depends on the stiffness of the springs (stiffer springs transmit energy more quickly). Effects like dispersion and reflection can also be understood using this model.

In a real material, the stiffness of the springs is called the elastic modulus, and the mass corresponds to the density. All other things being equal, sound will travel more slowly in spongy materials, and faster in stiffer ones. For instance, sound will travel much faster in steel than soft iron, due to the greater stiffness of steel at about the same density. Similarly, sound travels about $\sqrt{2}$= about 1.41 times faster in light hydrogen (protium) gas than in heavy hydrogen (deuterium) gas, since deuterium has similar properties but twice the density. At the same time, "compression-type" sound will travel faster in solids than in liquids, and faster in liquids than in gases, because the solids are more difficult to compress than liquids, while liquids in turn are more difficult to compress than gases.

Some textbooks mistakenly state that the speed of sound increases with increasing density. This is usually illustrated by presenting data for three materials, such as air, water and steel, which also have vastly different compressibilities which more than make up for the density differences. An illustrative example of the two effects is that sound travels only 4.3 times faster in water than air, despite enormous differences in compressibility of the two media. The reason is that the larger density of water, which works to *slow* sound in water relative to air, nearly makes up for the compressibility differences in the two media.

Basic formula

In general, the speed of sound *c* is given by the Newton-Laplace equation:

$$c = \sqrt{\frac{C}{\rho}}$$

where

> *C* is a coefficient of stiffness, the bulk modulus (or the modulus of bulk elasticity for gas mediums),
> ρ is the density

Thus the speed of sound increases with the stiffness (the resistance of an elastic body to deformation by an applied force) of the material, and decreases with the density. For general equations of state, if classical mechanics is used, the speed of sound *c* is given by

$$c^2 = \frac{\partial p}{\partial \rho}$$

where differentiation is taken with respect to adiabatic change.

where *p* is the pressure and ρ is the density

If relativistic effects are important, the speed of sound may be calculated from the relativistic Euler equations.

In a **non-dispersive medium** sound speed is independent of sound frequency, so the speeds of energy transport and sound propagation are the same. For audible sounds air is a non-dispersive medium. But air does contain a small amount of CO_2 which *is* a dispersive medium, and it introduces dispersion to air at ultrasonic frequencies (> 28 kHz).

In a **dispersive medium** sound speed is a function of sound frequency, through the dispersion relation. The spatial and temporal distribution of a propagating disturbance will continually change. Each frequency component propagates at its own phase velocity, while the energy of the disturbance propagates at the group velocity.

Dependence on the properties of the medium

The speed of sound is variable and depends on the properties of the substance through of which the wave is travelling. In solids, the speed of longitudinal waves depend on the stiffness to tensile stress, and the density of the medium. In fluids, the medium's compressibility and density are the important factors.

In gases, compressibility and density are related, making other compositional effects and properties important, such as temperature and molecular composition. In low molecular weight gases, such as helium, sound propagates faster compared to heavier gases, such as xenon (for monatomic gases the speed of sound is about 75% of the mean speed that molecules move in the gas). For a given ideal gas the sound speed depends only on its temperature. At a constant temperature, the ideal gas pressure has no effect on the speed of sound, because pressure and density (also proportional to pressure) have equal but opposite effects on the speed of sound, and the two contributions cancel out exactly. In a similar way, compression waves in solids depend both on compressibility and density—just as in liquids—but in gases the density contributes to the compressibility in such a way that some part of each attribute factors out, leaving only a dependence on temperature, molecular weight, and heat capacity. Thus, for a single given gas (where molecular weight does not change) and over a small temperature range (where heat capacity is relatively constant), the speed of sound becomes dependent on only the temperature of the gas.

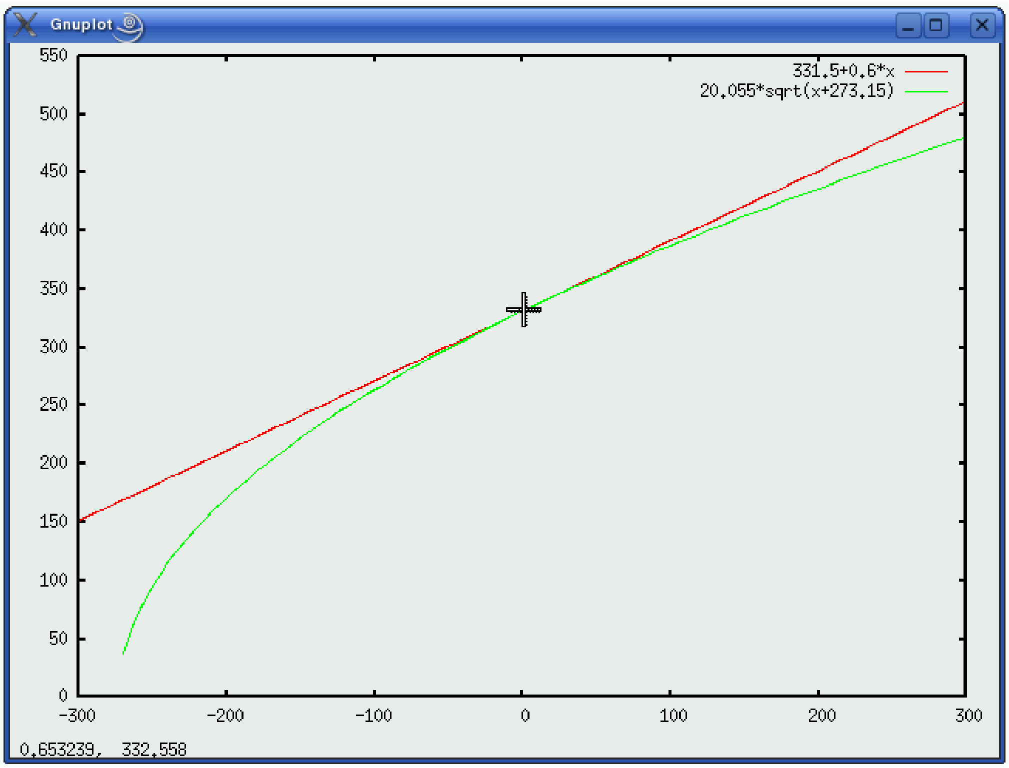
In non-ideal gases, such as a van der Waals gas, the proportionality is not exact, and there is a slight dependence of sound velocity on the gas pressure.

Humidity has a small but measurable effect on sound speed (causing it to increase by about 0.1%-0.6%), because oxygen and nitrogen molecules of the air are replaced by lighter molecules of water. This is a simple mixing effect.

Implications for atmospheric acoustics

In the Earth's atmosphere, the most important factor affecting the speed of sound is the temperature. Since temperature and thus the speed of sound normally decrease with increasing altitude, sound is refracted upward, away from listeners on the ground, creating an acoustic shadow at some distance from the source. The decrease of the sound speed with height is referred to as a negative sound speed gradient. However, in the stratosphere, the speed of sound increases with height due to heating within the ozone layer, producing a positive sound speed gradient.

Practical formula for dry air



Speed of sound graph of (red) truncated Taylor series (331.5+0.6*x) vs. the (green) more accurate equation (20.055*sqrt(x+273.15) in m/s. The x axis is the temperature in °C. Note that the slightly different value of 331.5 m/s (rather than 331.3 m/s) at °C, has been used in both equations in the graph.

The approximate speed of sound in dry (0% humidity) air, in meters per second (**m·s**$^{-1}$), at temperatures near 0 °C, can be calculated from:

$$c_{\text{air}} = (331.3 + (0.606^{\circ}\text{C}^{-1} \cdot \vartheta))\ \text{m} \cdot \text{s}^{-1}$$

where ϑ is the temperature in degrees Celsius (°C).

This equation is derived from the first two terms of the Taylor expansion of the following more accurate equation:

$$c_{\text{air}} = 331.3\text{m} \cdot \text{s}^{-1}\sqrt{1 + \frac{\vartheta}{273.15\ ^\circ\text{C}}}$$

Dividing the first part, and multiplying the second part, on the right hand side, by $\sqrt{273.15}$ gives the exactly equivalent form:

$$c_{\text{air}} = 20.0457\text{m} \cdot \text{s}^{-1}\sqrt{\vartheta + 273.15}$$

The value of 331.3 m/s, which represents the 0 °C speed, is based on theoretical (and some measured) values of the heat capacity ratio, γ, as well as on the fact that at 1 atm real air is very well described by the ideal gas approximation. Commonly found values for the speed of sound at 0 °C may vary from 331.2 to 331.6 due to the assumptions made when it is calculated. If ideal gas γ is assumed to be 7/5 = 1.4 exactly, the 0 °C speed is calculated to be 331.3 m/s, the coefficient used above.

This equation is correct to a much wider temperature range, but still depends on the approximation of heat capacity ratio being independent of temperature, and for this reason will fail, particularly at higher temperatures. It gives good predictions in relatively dry, cold, low pressure conditions, such as the Earth's stratosphere. The equation fails at extremely low pressures and short wavelengths, due to dependence on the assumption that the wavelength of the sound in the gas is much longer than the average mean free path between gas molecule collisions. A derivation of these equations will be given in the following section.

A graph comparing results of the two equations is at right, using the slightly different value of 331.5 m/s for the speed of sound °C.

Details

Speed in ideal gases and in air

For a gas, *K* (the bulk modulus in equations above, equivalent to C, the coefficient of stiffness in solids) is approximately given by

$$K = \gamma \cdot p$$

thus

$$c = \sqrt{\gamma \cdot \frac{p}{\rho}}$$

Where:

γ is the adiabatic index also known as the *isentropic expansion factor*. It is the ratio of specific heats of a gas at a constant-pressure to a gas at a constant-volume(C_p / C_v), and arises because a classical sound wave induces an adiabatic compression, in which the heat of the compression does not have enough time to escape the pressure pulse, and thus contributes to the pressure induced by the compression.
p is the pressure.
ρ is the density

Using the ideal gas law to replace *p* with *nRT*/*V*, and replacing *ρ* with *nM*/*V*, the equation for an ideal gas becomes:

$$c_{\mathrm{ideal}} = \sqrt{\gamma \cdot \frac{p}{\rho}} = \sqrt{\frac{\gamma \cdot R \cdot T}{M}} = \sqrt{\frac{\gamma \cdot k \cdot T}{m}}$$

where

- c_{ideal} is the speed of sound in an ideal gas.
- *R* (approximately 8.3145 $\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$) is the molar gas constant.
- *k* is the Boltzmann constant
- γ (gamma) is the adiabatic index (sometimes assumed 7/5 = 1.400 for diatomic molecules from kinetic theory, assuming from quantum theory a temperature range at which thermal energy is fully partitioned into rotation (rotations are fully excited), but none into vibrational modes. Gamma is actually experimentally measured over a range from 1.3991 to 1.403 at 0 degrees Celsius, for air. Gamma is assumed from kinetic theory to be exactly 5/3 = 1.6667 for monoatomic molecules such as noble gases).
- *T* is the absolute temperature in kelvins.
- *M* is the molar mass in kilograms per mole. The mean molar mass for dry air is about 0.0289645 kg/mol.
- *m* is the mass of a single molecule in kilograms.

This equation applies only when the sound wave is a small perturbation on the ambient condition, and the certain other noted conditions are fulfilled, as noted below. Calculated values for c_{air} have been found to vary slightly from experimentally determined values.

Newton famously considered the speed of sound before most of the development of thermodynamics and so incorrectly used isothermal calculations instead of adiabatic. His result was missing the factor of γ but was otherwise correct.

Numerical substitution of the above values gives the ideal gas approximation of sound velocity for gases, which is accurate at relatively low gas pressures and densities (for air, this includes standard Earth sea-level conditions). Also, for diatomic gases the use of $\gamma = 1.4000$ requires that the gas exist in a temperature range high enough that rotational heat capacity is fully excited (i.e., molecular rotation is fully used as a heat energy "partition" or reservoir); but at the same time the temperature must be low enough that molecular vibrational modes contribute no heat capacity (i.e., insigificant heat goes into vibration, as all vibrational quantum modes above the minimum-energy-mode, have energies too high to be populated by a significant number of molecules at this temperature). For air, these conditions are fulfilled at room temperature, and also temperatures considerably below room temperature.

For air, we use a simplified symbol $R_* = R/M_{\mathrm{air}}$.

Additionally, if temperatures in degrees Celsius(°C) are to be used to calculate air speed in the region near 273 kelvins, then Celsius temperature $\vartheta = T - 273.15$ may be used. Then:

$$c_{\mathrm{ideal}} = \sqrt{\gamma \cdot R_* \cdot T} = \sqrt{\gamma \cdot R_* \cdot (\vartheta + 273.15\ ^\circ\mathrm{C})}$$
$$c_{\mathrm{ideal}} = \sqrt{\gamma \cdot R_* \cdot 273.15} \cdot \sqrt{1 + \frac{\vartheta}{273.15\ ^\circ\mathrm{C}}}$$

For dry air, where ϑ(theta) is the temperature in degrees Celsius(°C).

Making the following numerical substitutions:

$$R = 8.314510 \cdot \mathrm{J} \cdot \mathrm{mol}^{-1} \cdot K^{-1}$$

is the molar gas constant in J/mole/Kelvin;

$$M_{\mathrm{air}} = 0.0289645 \cdot \mathrm{kg} \cdot \mathrm{mol}^{-1}$$

is the mean molar mass of air, in kg; and using the ideal diatomic gas value of $\gamma = 1.4000$

Then:

$$c_{\mathrm{air}} = 331.3\ \mathrm{m} \cdot \mathrm{s}^{-1} \sqrt{1 + \frac{\vartheta ^\circ\mathrm{C}}{273.15\ ^\circ\mathrm{C}}}$$

Using the first two terms of the Taylor expansion:

$$c_{\mathrm{air}} = 331.3\ \mathrm{m} \cdot \mathrm{s}^{-1} (1 + \frac{\vartheta ^\circ\mathrm{C}}{2 \cdot 273.15\ ^\circ\mathrm{C}})$$

$$c_{\mathrm{air}} = (331.3 + 0.606\ {}^\circ\mathrm{C}^{-1} \cdot \vartheta)\ \mathrm{m \cdot s^{-1}}$$

The derivation includes the first two equations given in the *Practical formula for dry* air section above.

Effects due to wind shear

The speed of sound varies with temperature. Since temperature and sound velocity normally decrease with increasing altitude, sound is refracted upward, away from listeners on the ground, creating an acoustic shadow at some distance from the source. Wind shear of 4 $\mathrm{m \cdot s^{-1} \cdot km^{-1}}$ can produce refraction equal to a typical temperature lapse rate of 7.5 °C/km. Higher values of wind gradient will refract sound downward toward the surface in the downwind direction, eliminating the acoustic shadow on the downwind side. This will increase the audibility of sounds downwind. This downwind refraction effect occurs because there is a wind gradient; the sound is not being carried along by the wind.

For sound propagation, the exponential variation of wind speed with height can be defined as follows:

$$U(h) = U(0)h^{\zeta}$$
$$\frac{dU}{dH} = \zeta \frac{U(h)}{h}$$

where:

$U(h)$ = speed of the wind at height h, and $U(0)$ is a constant
ζ = exponential coefficient based on ground surface roughness, typically between 0.08 and 0.52
$\frac{dU}{dH}$ = expected wind gradient at height h

In the 1862 American Civil War Battle of Iuka, an acoustic shadow, believed to have been enhanced by a northeast wind, kept two divisions of Union soldiers out of the battle, because they could not hear the sounds of battle only six miles downwind.

Tables

In the standard atmosphere:

- T_0 is 273.15 K (= 0 °C = 32 °F), giving a theoretical value of 331.3 $\mathrm{m \cdot s^{-1}}$ (= 1086.9 ft/s = 1193 $\mathrm{km \cdot h^{-1}}$ = 741.1 mph = 644.0 knots). Values ranging from 331.3-331.6 may be found in reference literature, however.

- T_{20} is 293.15 K (= 20 °C = 68 °F), giving a value of 343.2 m·s^{-1} (= 1126.0 ft/s = 1236 km·h^{-1} = 767.8 mph = 667.2 knots).
- T_{25} is 298.15 K (= 25 °C = 77 °F), giving a value of 346.1 m·s^{-1} (= 1135.6 ft/s = 1246 km·h^{-1} = 774.3 mph = 672.8 knots).

In fact, assuming an ideal gas, the speed of sound *c* depends on temperature only, **not on the pressure** or **density** (since these change in lockstep for a given temperature and cancel out). Air is almost an ideal gas. The temperature of the air varies with altitude, giving the following variations in the speed of sound using the standard atmosphere - *actual conditions may vary*.

Effect of temperature

Temperature	**Speed of sound**	**Density of air**	**Acoustic impedance**
ϑ in °C	**c in m·s^{-1}**	**ρ in kg·m^{-3}**	**Z in N·s·m^{-3}**
+35	351.96	1.1455	403.2
+30	349.08	1.1644	406.5
+25	346.18	1.1839	409.4
+20	343.26	1.2041	413.3
+15	340.31	1.2250	416.9
+10	337.33	1.2466	420.5
+5	334.33	1.2690	424.3
±0	331.30	1.2920	428.0
-5	328.24	1.3163	432.1
-10	325.16	1.3413	436.1
-15	322.04	1.3673	440.3
-20	318.89	1.3943	444.6
-25	315.72	1.4224	449.1

Given normal atmospheric conditions, the temperature, and thus speed of sound, varies with altitude:

Altitude	**Temperature**	**m·s^{-1}**	**km·h^{-1}**	**mph**	**knots**
Sea level	15 °C (59 °F)	340	1225	761	661
11 000 m−20 000 m (Cruising altitude of commercial jets, and first supersonic flight)	−57 °C (−70 °F)	295	1062	660	573
29 000 m (Flight of X-43A)	−48 °C (−53 °F)	301	1083	673	585

Effect of frequency and gas composition

The medium in which a sound wave is travelling does not always respond adiabatically, and as a result the speed of sound can vary with frequency.

The limitations of the concept of speed of sound due to extreme attenuation are also of concern. The attenuation which exists at sea level for high frequencies applies to successively lower frequencies as atmospheric pressure decreases, or as the mean free path increases. For this reason, the concept of speed of sound (except for frequencies approaching zero) progressively loses its range of applicability at high altitudes.: The standard equations for the speed of sound apply with reasonable accuracy only to situations in which the wavelength of the soundwave is considerably longer than the mean free path of molecules in a gas.

The molecular composition of the gas contributes both as the mass (M) of the molecules, and their heat capacities, and so both have an influence on speed of sound. In general, at the same molecular mass, monatomic gases have slightly higher sound speeds (over 9% higher) because they have a higher γ (5/3 = 1.66...) than diatomics do (7/5 = 1.4). Thus, at the same molecular mass, the sound speed of a monatomic gas goes up by a factor of

$$\frac{c_{\mathrm{gas:monatomic}}}{c_{\mathrm{gas:diatomic}}} = \sqrt{\frac{5/3}{7/5}} = \sqrt{\frac{25}{21}} = 1.091\ldots$$

This gives the 9 % difference, and would be a typical ratio for sound speeds at room temperature in helium vs. deuterium, each with a molecular weight of 4. Sound travels faster in helium than deuterium because adiabatic compression heats helium more, since the helium molecules can store heat energy from compression only in translation, but not rotation. Thus helium molecules (monatomic molecules) travel faster in a sound wave and transmit sound faster. (Sound generally travels at about 70% of the mean molecular speed in gases).

Note that in this example we have assumed that temperature is low enough that heat capacities are not influenced by molecular vibration. However, vibrational modes simply cause gammas which decrease toward 1, since vibration modes in a polyatomic gas gives the gas additional ways to store heat which do not affect temperature, and thus do not affect molecular velocity and sound velocity. Thus, the effect of higher temperatures and vibrational heat capacity acts to increase the difference between sound speed in monatomic vs. polyatomic molecules, with the speed remaining greater in monatomics.

Mach number

U.S. Navy F/A-18 breaking the sound barrier. The white halo consists of condensed water droplets formed by the sudden drop in air pressure behind the shock cone around the aircraft.

Mach number, a useful quantity in aerodynamics, is the ratio of air speed to the local speed of sound. At altitude, for reasons explained, Mach number is a function of temperature. Aircraft flight instruments, however, operate using pressure differential to compute Mach number, not temperature. The assumption is that a particular pressure represents a particular altitude and, therefore, a standard temperature. Aircraft flight instruments need to operate this way because the stagnation pressure sensed by a Pitot tube is dependent on altitude as well as speed.

Assuming air to be an ideal gas, the formula to compute Mach number in a subsonic compressible flow is derived from Bernoulli's equation for $M<1$:

$$M = \sqrt{5\left[\left(\frac{q_c}{P}+1\right)^{\frac{2}{7}}-1\right]}$$

where

M is Mach number
q_c is dynamic pressure and
P is static pressure.

The formula to compute Mach number in a supersonic compressible flow is derived from the Rayleigh Supersonic Pitot equation:

$$M = 0.88128485\sqrt{\left(\frac{q_c}{P}+1\right)\left(1-\frac{1}{7M^2}\right)^{2.5}}$$

where

M is Mach number
q_c is dynamic pressure measured behind a normal shock
P is static pressure.

As can be seen, M appears on both sides of the equation. The easiest method to solve the supersonic M calculation is to enter both the subsonic and supersonic equations into a computer spreadsheet such as Microsoft Excel, OpenOffice.org Calc, or some equivalent program. First determine if M is indeed greater than 1.0 by calculating M from the subsonic equation. If M is greater than 1.0 at that point, then use the value of M from the subsonic equation as the initial condition in the supersonic equation. Then perform a simple iteration of the supersonic equation, each time using the last computed value of M, until M converges to a value—usually in just a few iterations.

Experimental methods

A range of different methods exist for the measurement of sound in air.

The earliest reasonably accurate estimate of the speed of sound in air was made by William Derham, and acknowledged by Isaac Newton. Derham had a telescope at the top of the tower of the Church of St Laurence in Upminster, England. On a calm day, a synchronized pocket watch would be given to an assistant who would fire a shotgun at a pre-determined time from a conspicuous point some miles away, across the countryside. This could be confirmed by telescope. He then measured the interval between seeing gunsmoke and arrival of the noise using a half-second pendulum. The distance from where the gun was fired was found by triangulation, and simple division (time / distance) provided velocity. Lastly, by making many observations, using a range of different distances, the inaccuracy of the half-second pendulum could be averaged out, giving his final estimate of the speed of sound. Modern stopwatches enable this method to be used today over distances as short as 200–400 meters, and not needing something as loud as a shotgun.

Single-shot timing methods

The simplest concept is the measurement made using two microphones and a fast recording device such as a digital storage scope. This method uses the following idea.

If a sound source and two microphones are arranged in a straight line, with the sound source at one end, then the following can be measured:

1. The distance between the microphones (x), called microphone basis. 2. The time of arrival between the signals (delay) reaching the different microphones (t)

Then $v = x / t$

Other methods

In these methods the time measurement has been replaced by a measurement of the inverse of time (frequency).

Kundt's tube is an example of an experiment which can be used to measure the speed of sound in a small volume. It has the advantage of being able to measure the speed of sound in any gas. This method uses a powder to make the nodes and antinodes visible to the human eye. This is an example of a compact experimental setup.

A tuning fork can be held near the mouth of a long pipe which is dipping into a barrel of water. In this system it is the case that the pipe can be brought to resonance if the length of the air column in the pipe is equal to *({1+2n}λ/4)* where n is an integer. As the antinodal point for the pipe at the open end is slightly outside the mouth of the pipe it is best to find two or more points of resonance and then measure half a wavelength between these.

Here it is the case that $v = f\lambda$

Non-gaseous media

Speed of sound in solids

In a solid, there is a non-zero stiffness both for volumetric and shear deformations. Hence, it is possible to generate sound waves with different velocities dependent on the deformation mode. Sound waves generating volumetric deformations (compressions) and shear deformations are called longitudinal waves and shear waves, respectively. In earthquakes, the corresponding seismic waves are called P-waves and S-waves, respectively. The sound velocities of these two type waves are respectively given by:

$$c_l = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

$$c_s = \sqrt{\frac{G}{\rho}},$$

where *K* and *G* are the bulk modulus and shear modulus of the elastic materials, respectively. Note that the speed of longitudinal/compression waves depends both on the compression and shear resistance properties of the material, while the speed of shear waves depends on the shear properties only.

Typically, compression or P-waves travel faster in materials than do shear waves, and in earthquakes this is the reason that onset of an earthquake is often preceded by a quick upward-downward shock, before arrival of waves that produce a side-to-side motion. *E* is the Young's modulus, and ν is Poisson's ratio.
For example, for a typical steel alloy, K = 170 GPa, G = 80 GPa and ρ = 7700 kg/m^3, yielding a longitudinal velocity c_l of 6000 m/s. This is in reasonable agreement with c_l=5930 m/s measured experimentally for a (possibly different) type of steel.

The shear velocity c_s is estimated at 3200 m/s using the same numbers.

Speed of sound in liquids

In a fluid the only non-zero stiffness is to volumetric deformation (a fluid does not sustain shear forces).

Hence the speed of sound in a fluid is given by

$$c_{\text{fluid}} = \sqrt{\frac{K}{\rho}}$$

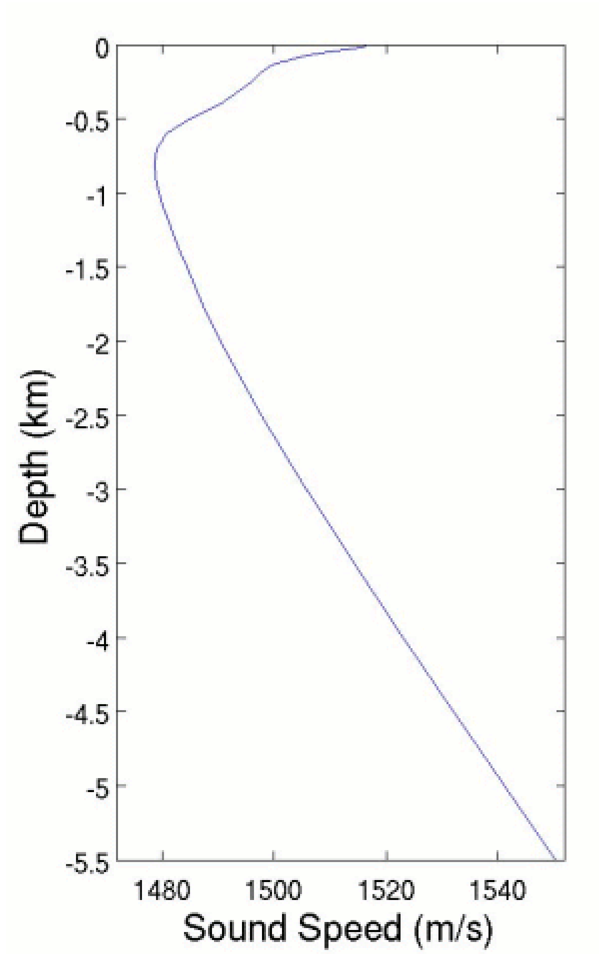
where

K is the bulk modulus of the fluid

Water

The speed of sound in water is of interest to anyone using underwater sound as a tool, whether in a laboratory, a lake or the ocean. Examples are sonar, acoustic communication and acoustical oceanography.

Seawater



Sound speed as a function of depth at a position north of Hawaii in the Pacific Ocean derived from the 2005 World Ocean Atlas. The SOFAR channel is centered on the minimum in sound speed at ca. 750-m depth.

In salt water that is free of air bubbles or suspended sediment, sound travels at about 1560 m/s. The speed of sound in seawater depends on pressure (hence depth), temperature (a change of 1 °C ~ 4 m/s), and salinity (a change of 1‰ ~ 1 m/s), and empirical equations have been derived to accurately calculate sound speed from these variables. Other factors affecting sound speed are minor. Since temperature decreases with depth while pressure and generally salinity increase, the profile of sound speed with depth generally shows a characteristic curve which decreases to a minimum at a depth of several hundred meters, then increases again with increasing depth (right).

A simple empirical equation for the speed of sound in sea water with reasonable accuracy for the world's oceans is due to Mackenzie:

$$c(T, S, z) = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5(S - 35) + a_6z + a_7z^2 + a_8T(S - 35) + a_9Tz^3$$

where T, S, and z are temperature in degrees Celsius, salinity in parts per thousand and depth in meters, respectively. The constants a_1, a_2, ..., a_9 are:

$$a_1 = 1448.96,\ a_2 = 4.591,\ a_3 = -5.304\times10^{-2},\ a_4 = 2.374\times10^{-4},\ a_5 = 1.340,$$
$$a_6 = 1.630\times10^{-2},\ a_7 = 1.675\times10^{-7},\ a_8 = -1.025\times10^{-2},\ a_9 = -7.139\times10^{-13}$$

with check value 1550.744 m/s for T=25 °C, S=35‰, z=1000 m. This equation has a standard error of 0.070 m/s for salinity between 25 and 40 ppt.

Other equations for sound speed in sea water are accurate over a wide range of conditions, but are far more complicated, e.g., that by V. A. Del Grosso and the Chen-Millero-Li Equation.

Speed in plasma

The speed of sound in a plasma for the common case that the electrons are hotter than the ions (but not too much hotter) is given by the formula

$$c_s = (\gamma Z k T_e/m_i)^{1/2} = 9.79 \times 10^3 (\gamma Z T_e/\mu)^{1/2}\,\mathrm{m/s}$$

In contrast to a gas, the pressure and the density are provided by separate species, the pressure by the electrons and the density by the ions. The two are coupled through a fluctuating electric field.

Gradients

When sound spreads out evenly in all directions in three dimensions, the intensity drops in proportion to the inverse square of the distance. However, in the ocean there is a layer called the 'deep sound channel' or SOFAR channel which can confine sound waves at a particular depth.

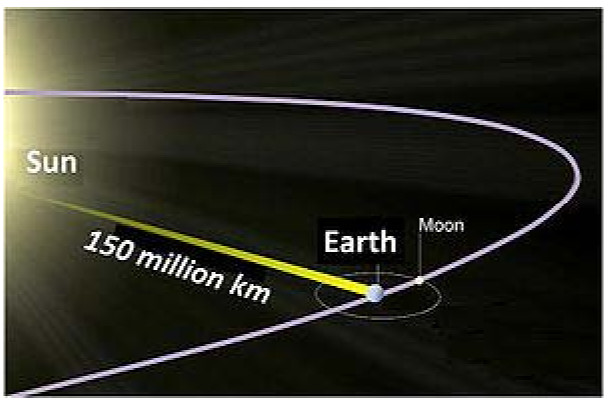
In the SOFAR channel, the speed of sound is lower than that in the layers above and below. Just as light waves will refract towards a region of higher index, sound waves will refract towards a region where their speed is reduced. The result is that sound gets confined in the layer, much the way light can be confined in a sheet of glass or optical fiber. Thus, the sound is confined in essentially two dimensions. In two dimensions the intensity drops in proportion to only the inverse of the distance. This allows waves to travel much further before being undetectably faint.

A similar effect occurs in the atmosphere. Project Mogul successfully used this effect to detect a nuclear explosion at a considerable distance.

Chapter-3

Speed of Light

Speed of light



Sunlight takes about 8 minutes, 19 seconds to reach Earth

Exact values	
metres per second	299,792,458
miles per second	186,282.39
Approximate values	
kilometres per second	300,000
kilometres per hour	1,079 million
miles per hour	671 million
astronomical units per day	173
Approximate light signal travel times	
Distance	**Time**
one foot	1.0 ns
one metre	3.3 ns
one kilometre	3.3 μs
one statute mile	5.4 μs

from geostationary orbit to Earth	119 ms
the length of Earth's equator	134 ms
from Moon to Earth	1.3 s
from Sun to Earth (1 AU)	8.3 min
one parsec	3.26 years
from Proxima Centauri to Earth	4.24 years
from Alpha Centauri to Earth	4.37 years
from the nearest galaxy (the Canis Major Dwarf Galaxy) to Earth	25,000 years
across the Milky Way	100,000 years
from the Andromeda Galaxy to Earth	2.5 million years
from the furthest observed galaxy to Earth	13 billion years

The **speed of light**, usually denoted by ***c***, is a physical constant important in many areas of physics. Light and all other forms of electromagnetic radiation always travel at this speed in empty space (vacuum), regardless of the motion of the source or the inertial frame of reference of the observer. Its value is exactly 299,792,458 metres per second (approximately 186,282 miles per second). In the theory of relativity, c interrelates space and time, and appears in the famous equation of mass–energy equivalence $E = mc^2$. It is the speed of all massless particles and associated fields in vacuo, and it is predicted by the current theory to be the speed of gravity (that is, gravitational waves) and an upper bound on the speed at which energy, matter, and information can travel.

The speed at which light propagates through transparent materials, such as glass or air, is less than c. The ratio between c and the speed v at which light travels in a material is called the refractive index n of the material ($n = c / v$). For example, for visible light the refractive index of glass is typically around 1.5, meaning that light in glass travels at c / 1.5 ≈ 200,000 km/s; the refractive index of air for visible light is about 1.0003, so the speed of light in air is about 90 km/s slower than c.

In most practical cases, light can be thought of as moving instantaneously, but for long distances and very sensitive measurements the finite speed of light has noticeable effects. In communicating with distant space probes, it can take minutes to hours for the message to get from Earth to the satellite and back. The light we see from stars left them many years ago, allowing us to study the history of the universe by looking at distant objects. The finite speed of light also limits the theoretical maximum speed of computers, since information must be sent within the computer chips and from chip to chip. Finally, the speed of light can be used with time of flight measurements to measure large distances to high precision.

Ole Rømer first demonstrated in 1676 that light travelled at a finite speed (as opposed to instantaneously) by studying the apparent motion of Jupiter's moon Io. In 1905, Albert Einstein postulated that the speed of light in vacuum was independent of the source or inertial frame of reference, and explored the consequences of that postulate by deriving the theory of special relativity and showing that the parameter *c* had relevance outside of the context of light and electromagnetism. After centuries of increasingly precise measurements, in 1975 the speed of light was known to be 299,792,458 m/s with a relative measurement uncertainty of 4 parts per billion. In 1983, the metre was redefined in the International System of Units (SI) as the distance travelled by light in vacuum in $^1\!/_{299,792,458}$ of a second. As a result, the numerical value of *c* in metres per second is now fixed exactly by the definition of the metre.

Numerical value, notation, and units

The speed of light in vacuum is usually denoted by *c*, for "constant" or the Latin *celeritas* (meaning "swiftness"). Originally, the symbol *V* was used, introduced by James Clerk Maxwell in 1865. In 1856, Wilhelm Eduard Weber and Rudolf Kohlrausch used *c* for a constant later shown to equal $\sqrt{2}$ times the speed of light in vacuum. In 1894, Paul Drude redefined *c* with its modern meaning. Einstein used *V* in his original German-language papers on special relativity in 1905, but in 1907 he switched to *c*, which by then had become the standard symbol.

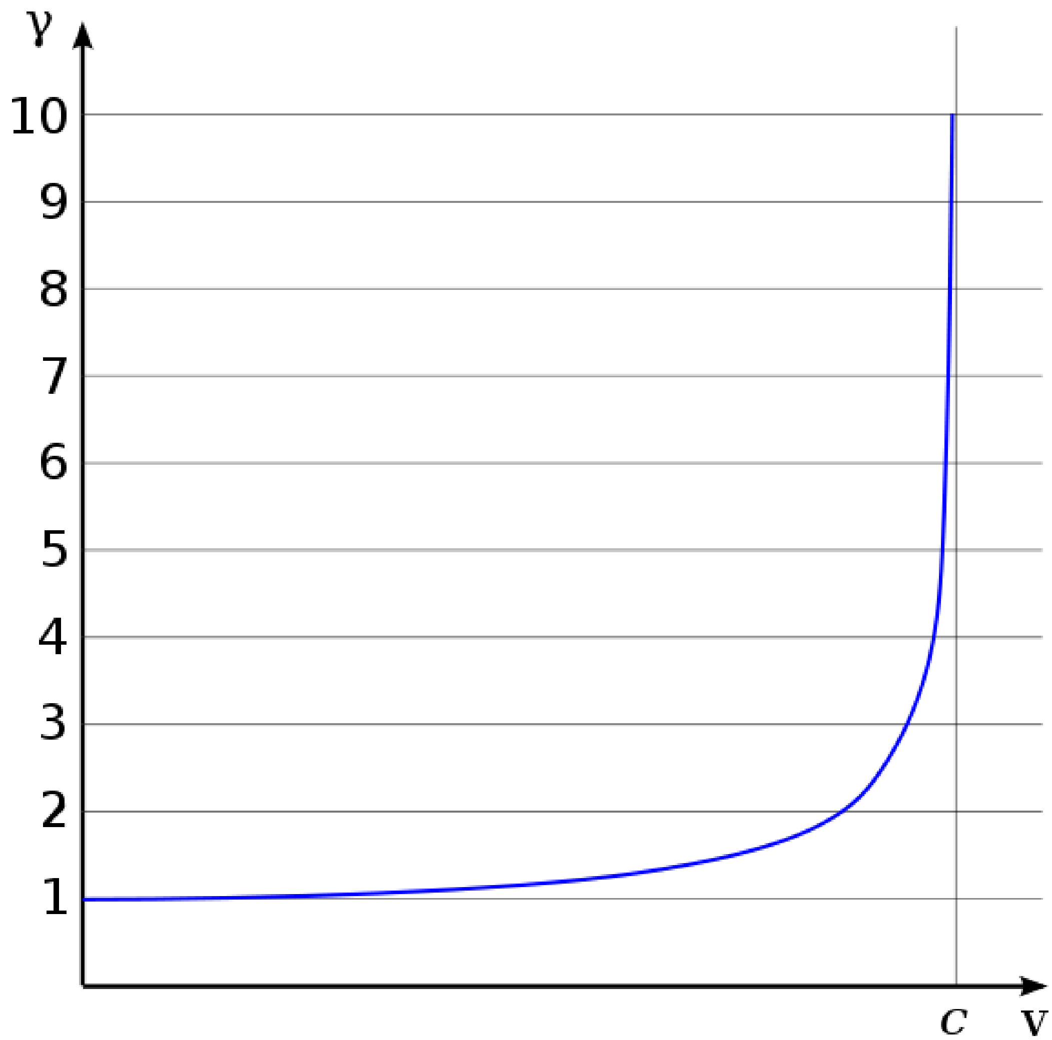
Sometimes *c* is used for the speed of waves in *any* material medium, and c_0 for the speed of light in vacuum. This subscripted notation, which is endorsed in official SI literature, has the same form as other related constants: namely, μ_0 for the vacuum permeability or magnetic constant, ε_0 for the vacuum permittivity or electric constant, and Z_0 for the impedance of free space. Here we, uses *c* exclusively for the speed of light in vacuum.

In the International System of Units (SI), the metre is defined as the distance light travels in vacuum in $^1\!/_{299,792,458}$ of a second. This definition fixes the speed of light in vacuum at exactly 299,792,458 m/s. As a dimensional physical constant, the numerical value of *c* is different for different unit systems.

In branches of physics in which *c* appears often, such as in relativity, it is common to use systems of natural units of measurement in which $c = 1$. Using these units, *c* does not appear explicitly because multiplication or division by 1 does not affect the result.

Fundamental role in physics

The speed at which light propagates in vacuum is independent both of the motion of the light source and of the inertial frame of reference of the observer. This invariance of the speed of light was postulated by Einstein in 1905, after being motivated by Maxwell's theory of electromagnetism and the lack of evidence for the luminiferous ether; it has since been consistently confirmed by many experiments. The theory of special relativity explores the consequences of this invariance of *c* with the assumption that the laws of physics are the same in all inertial frames of reference. One consequence is that c is the speed at which all massless particles and waves, including light, must travel.



The Lorentz factor γ as a function of velocity. It starts at 1 and approaches infinity as v approaches c.

Special relativity has many counter-intuitive and experimentally verified implications. These include the equivalence of mass and energy ($E = mc^2$), length contraction (moving objects shorten), and time dilation (moving clocks run slower). The factor γ by which lengths contract and times dilate, is known as the Lorentz factor and is given by $\gamma = (1 - v^2/c^2)^{-1/2}$, where v is the speed of the object. The difference of γ 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.

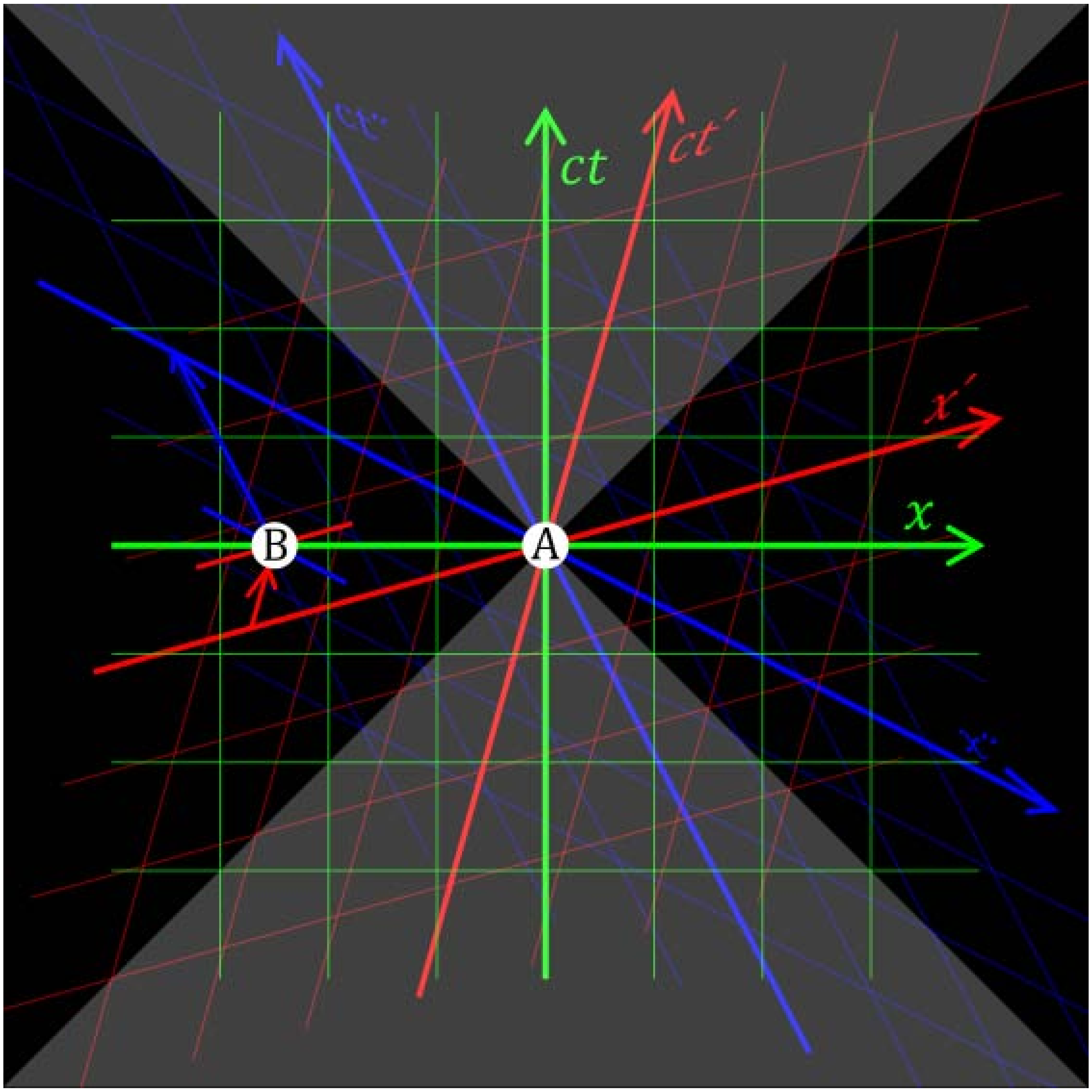
The results of special relativity can be summarized by treating space and time as a unified structure known as spacetime (with c relating the units of space and time), and requiring that physical theories satisfy a special symmetry called Lorentz invariance, whose mathematical formulation contains the 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 space 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 and of rotating optical resonators have put stringent limits on the possible anisotropy.

Upper limit on speeds

According to special relativity, the energy of an object with rest mass m and speed v is given by γmc^2, where γ is the Lorentz factor defined above. When v is zero, γ is equal to one, giving rise to the famous $E = mc^2$ formula for mass-energy equivalence. Since the γ factor approaches infinity as v approaches c, 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.



Event A precedes B in the red frame, is simultaneous with B in the green frame, and follows B in the blue frame.

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 such waves do not convey any 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

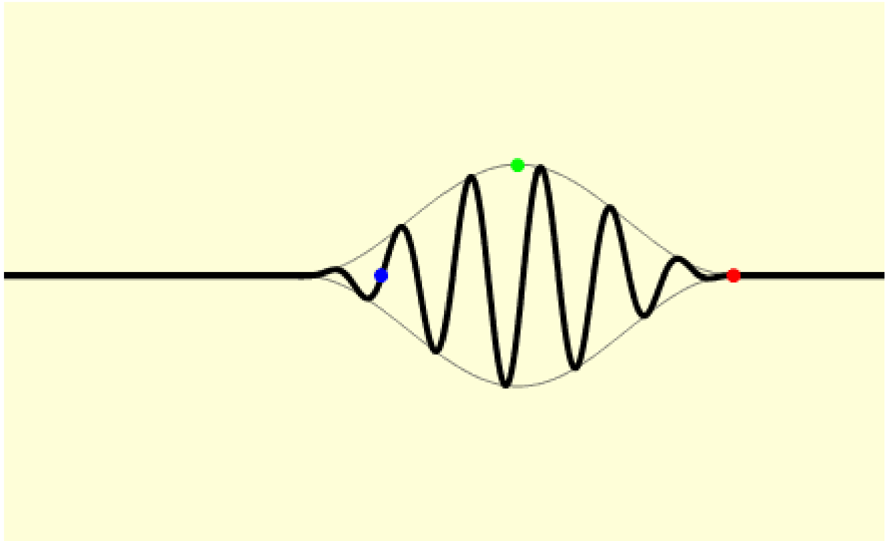
In classical physics, light is described as a type of electromagnetic wave. The classical behaviour of the electromagnetic field is described by Maxwell's equations, which predict that the speed c with which electromagnetic waves (such as light) propagate through the vacuum is related to the electric constant ε_0 and the magnetic constant μ_0 by the equation $c = 1/\sqrt{\varepsilon_0\mu_0}$. 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, $m \leq 10^{-14}$ eV/c^2 (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 ($l_P = \sqrt{\hbar G/c^3} \approx 1.6163\times10^{-35}$ 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) propagates is called the phase velocity v_p. 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 v_g, and its earliest part travels at the front velocity v_f.



The blue dot moves at the speed of the ripples, the phase velocity; the green dot moves with the speed of the envelope, the group velocity; and the red dot moves with the speed of the foremost part of the pulse, the front velocity

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 v_p 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 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 an electrical insulator, the electromagnetic equivalent of a shock wave, known as Cherenkov radiation, is emitted.

Practical effects of finiteness

The finiteness of the speed of light has implications for various sciences and technologies. In some cases, it is a hindrance: for example, *c*, being the upper limit of the speed with which signals can be sent, provides a theoretical upper limit for the operating speed of microprocessors. On the other hand, some techniques depend on it, for example in distance measurements.

The speed of light is of relevance to communications. For example, given the equatorial circumference of the Earth is about 40,075 km and *c* about 300,000 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.

A beam of light is depicted travelling between the Earth and the Moon in the time it takes a light pulse to move between them: 1.255 seconds at their mean orbital (surface-to-surface) distance. The relative sizes and separation of the Earth–Moon system are shown to scale.

Another consequence of the finite speed of light is that 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, 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.

The speed of light can also be of concern over very short distances. 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.

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 300,000 kilometres (186,000 miles) 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.

Astronomy

The finite speed of light is important in astronomy. Due to the vast distances involved, it can take a very long time for light to travel from its source to Earth. For example, it has taken 13 billion (13×10^9) 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. Proxima Centauri, the closest star to Earth after the Sun, is around 4.2 light-years away.

Measurement

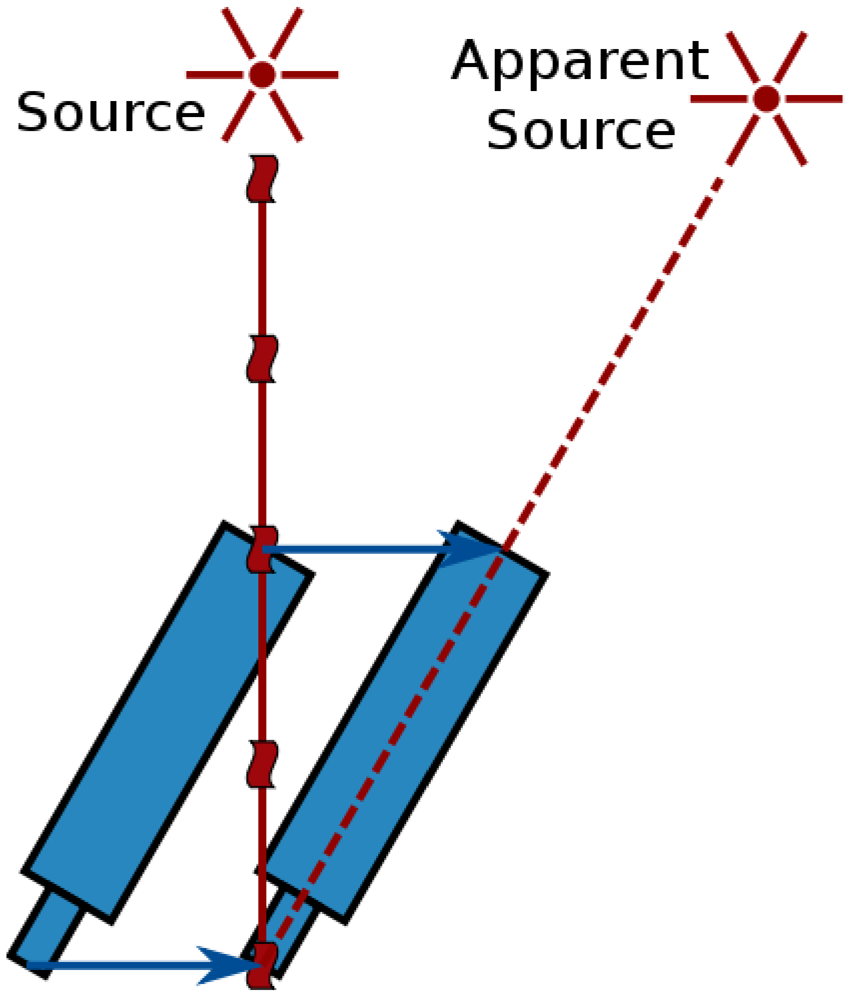
There are different ways to determine the value of *c*. One way is to measure the actual speed at which light waves propagate, which can be done in various astronomical and earth-based setups. However, it is also possible to determine *c* from other physical laws where it appears, for example, by determining the values of the electromagnetic constants ε_0 and μ_0 and using their relation to *c*. Historically, the most precise results have been obtained by separately determining the frequency and wavelength of a lightwave, with their product equaling *c*.

In 1983 the metre was defined as "the length of the path travelled by light in vacuum during a time interval of 1⁄299,792,458 of a second", fixing the value of the speed of light at 299,792,458 m/s by definition, as described below. Consequently, precision measurements of the speed of light yield a precise realization of the metre rather than a precise value of *c*.

Astronomical measurements

Outer space is a natural 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. An astronomical unit is approximately the average distance between the Earth and Sun; it is not based on the International System of Units. Because the AU determines an actual length, and is not based upon time-of-flight like the SI units, modern measurements of the speed of light in astronomical units per day can be compared with the defined value of *c* in the International System of Units.

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 actually 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.



Aberration of light: light from a distant source appears to be from a different location for a moving telescope due to the finite speed of light.

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. 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 easily 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.

Nowadays, the "light time for unit distance"—the inverse of *c*, expressed in seconds per astronomical unit—is 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 is obtained. As of 2009, the best estimate, as approved by the International Astronomical Union (IAU), is:

light time for unit distance: 499.004783836(10) s
c = 0.00200398880410(4) AU/s = 173.144632674(3) AU/day.

The relative uncertainty in these measurements is 0.02 parts per billion (2×10^{-11}), equivalent to the uncertainty in Earth-based measurements of length by interferometry. Since the metre is defined to be the length travelled by light in a certain time interval, the measurement of the light time for unit distance can also be interpreted as measuring the length of an AU in metres.

Time of flight techniques

A method of measuring the speed of light is to measure the time needed for light to travel to a mirror at a known distance and back. This is the working principle behind the Fizeau–Foucault apparatus developed by Hippolyte Fizeau and Léon Foucault.

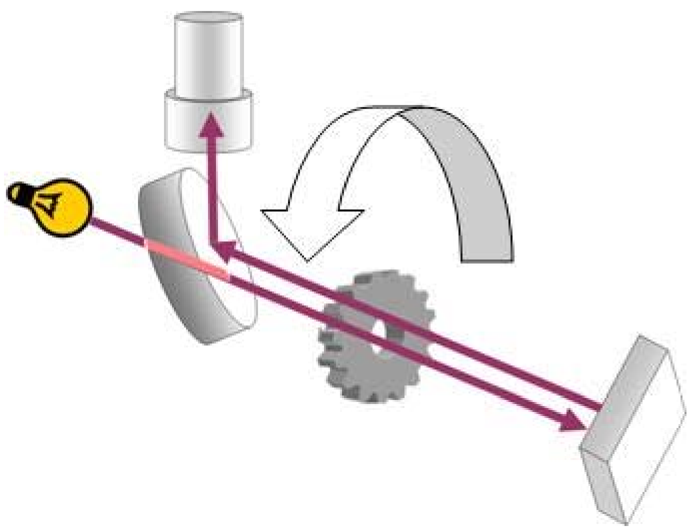


Diagram of the Fizeau apparatus

The setup as used by Fizeau consists of a beam of light directed at a mirror 8 kilometres (5 mi) away. On the way from the source to the mirror, the beam passes through a rotating cogwheel. At a certain rate of rotation, the beam passes through one gap on the way out and another on the way back, but at slightly higher or lower rates, the beam strikes a tooth and does not pass through the wheel. Knowing the distance between the wheel and the mirror, the number of teeth on the wheel, and the rate of rotation, the speed of light can be calculated.

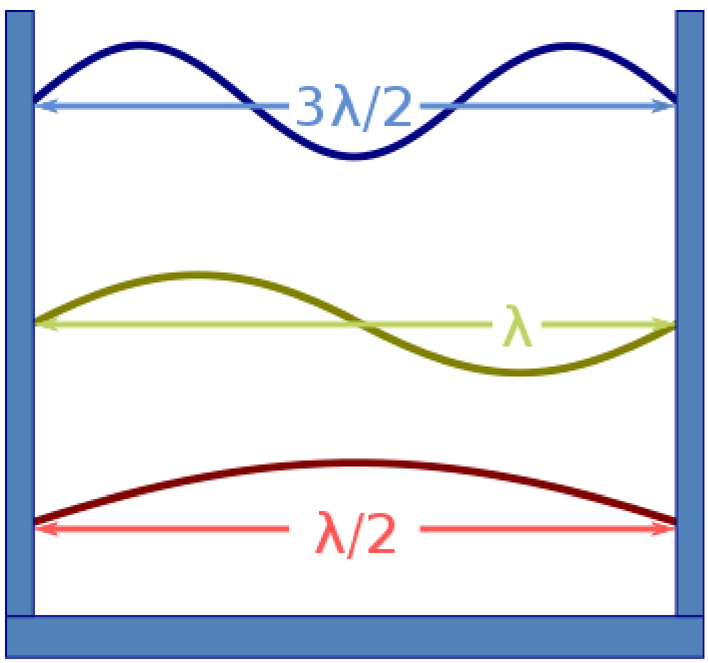
The method of Foucault replaces the cogwheel by a rotating mirror. Because the mirror keeps rotating while the light travels to the distant mirror and back, the light is reflected from the rotating mirror at a different angle on its way out than it is on its way back. From this difference in angle, the known speed of rotation and the distance to the distant mirror the speed of light may be calculated.

Nowadays, using oscilloscopes with time resolutions of less than one nanosecond, the speed of light can be directly measured by timing the delay of a light pulse from a laser or an LED reflected from a mirror. This method is less precise (with errors of the order of 1%) than other modern techniques, but it is sometimes used as a laboratory experiment in college physics classes.

Electromagnetic constants

An option for measuring c that does not directly depend on the propagation of electromagnetic waves is to use relation between c and the vacuum permittivity ε_0 vacuum permeability μ_0 established by Maxwell theory: $c^2 = 1/(\varepsilon_0\mu_0)$. The vacuum permittivity may be determined by measuring the capacitance and dimensions of a capacitor, whereas the value of the vacuum permeability is fixed at exactly 4π×10–7 H·m^{-1} through the definition of the ampere. Rosa and Dorsey used this method in 1907 to find a value of 299,710±22 km/s.

Cavity resonance



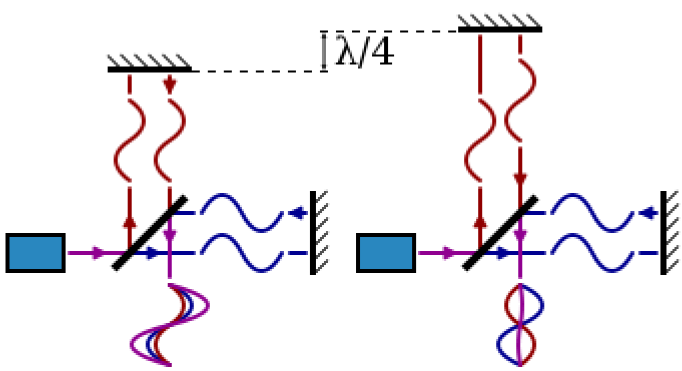
Electromagnetic standing waves in a cavity.

Another way to measure the speed of light is to independently measure the frequency f and wavelength λ of an electromagnetic wave in vacuum. The value of c can then be found by using the relation $c = f\lambda$. One option is to measure the resonance frequency of a cavity resonator. If the dimensions of the resonance cavity are also known, these can be used determine the wavelength of the wave. In 1946, Louis Essen and A.C. Gordon-Smith establish the frequency for a variety of normal modes of microwaves of a microwave cavity of precisely known dimensions. The dimensions were established to an accuracy of about ±0.8 μm using gauges calibrated by interferometry. As the wavelength of the modes was known from the geometry of the cavity and from electromagnetic theory, knowledge of the associated frequencies enabled a calculation of the speed of light.

The Essen–Gordon-Smith result, 299,792±9 km/s, was substantially more precise than those found by optical techniques. By 1950, repeated measurements by Essen established a result of 299,792.5±3.0 km/s.

A household demonstration of this technique is possible, using a microwave oven and food such as marshmallows or margarine: if the turntable is removed so that the food does not move, it will cook the fastest at the antinodes (the points at which the wave amplitude is the greatest), where it will begin to melt. The distance between two such spots is half the wavelength of the microwaves; by measuring this distance and multiplying the wavelength by the microwave frequency (usually displayed on the back of the oven, typically 2450 MHz), the value of c can be calculated, "often with less than 5% error".

Interferometry



An interferometric determination of length. Left: constructive interference; Right: destructive interference.

Interferometry is another method to find the wavelength of electromagnetic radiation for determining the speed of light. A coherent beam of light (e.g. from a laser), with a known frequency (f), is split to follow two paths and then recombined. By adjusting the path length while observing the interference pattern and carefully measuring the change in path length, the wavelength of the light (λ) can be determined. The speed of light is then calculated using the equation $c = \lambda f$.

Before the advent of laser technology, coherent radio sources were used for interferometry measurements of the speed of light. However interferometric determination of wavelength becomes less precise with wavelength and the experiments were thus limited in precision by the long wavelength (~0.4 cm) of the radiowaves. The precision can be improved by using light with a shorter wavelength, but then it becomes difficult to directly measure the frequency of the light. One way around this problem is to start with a low frequency signal of which the frequency can be precisely measured, and from this signal progressively synthesize higher frequency signals whose frequency can then be linked to the original signal. A laser can then be locked to the frequency, and its wavelength can be determined using interferometry. This technique was due to a group at the National Bureau of Standards (NBS) (which later became NIST). They used it in 1972 to measure the speed of light in vacuum with a fractional uncertainty of 3.5×10^{-9}.

History

History of measurements of *c* (in km/s)

1675	Rømer and Huygens, moons of Jupiter	220,000
1729	James Bradley, aberration of light	301,000
1849	Hippolyte Fizeau, toothed wheel	315,000
1862	Léon Foucault, rotating mirror	298,000±500
1907	Rosa and Dorsey, EM constants	299,710±30
1926	Albert Michelson, rotating mirror	299,796±4
1950	Essen and Gordon-Smith, cavity resonator	299,792.5±3.0
1958	K.D. Froome, radio interferometry	299,792.50±0.10
1972	Evenson *et al.*, laser interferometry	299,792.4562±0.0011
1983	17th CGPM, definition of the metre	299,792.458 (exact)

Until the early modern period, it was not known whether light travelled instantaneously or at a very fast finite speed. The first extant recorded examination of this subject was in ancient Greece. Empedocles was the first to claim that the light has a finite speed. He maintained that light was something in motion, and therefore must take some time to travel. Aristotle argued, to the contrary, that "light is due to the presence of something, but it is not a movement". Euclid and Ptolemy advanced the emission theory of vision, where light is emitted from the eye, thus enabling sight. Based on that theory, Heron of Alexandria argued that the speed of light must be infinite because distant objects such as stars appear immediately upon opening the eyes.

Early Islamic philosophers initially agreed with the Aristotelian view that light had no speed of travel. In 1021, Alhazen (Ibn al-Haytham) published the *Book of Optics*, in which he presented a series of arguments dismissing the emission theory in favour of the now accepted intromission theory of vision, in which light moves from an object into the eye. This led Alhazen to propose that light must have a finite speed, and that the speed of light is variable, decreasing in denser bodies. He argued that light is substantial matter, the propagation of which requires time, even if this is hidden from our senses.

Also in the 11th century, Abū Rayhān al-Bīrūnī agreed that light has a finite speed, and observed that the speed of light is much faster than the speed of sound. Roger Bacon argued that the speed of light in air was not infinite, using philosophical arguments backed by the writing of Alhazen and Aristotle. In the 1270s, Witelo considered the possibility of light travelling at infinite speed in vacuum, but slowing down in denser bodies.

In the early 17th century, Johannes Kepler believed that the speed of light was infinite, since empty space presents no obstacle to it. René Descartes argued that if the speed of light were finite, the Sun, Earth, and Moon would be noticeably out of alignment during a lunar eclipse. Since such misalignment had not been observed, Descartes concluded the speed of light was infinite. Descartes speculated that if the speed of light were found to be finite, his whole system of philosophy might be demolished.

First measurement attempts

In 1629, Isaac Beeckman proposed an experiment in which a person observes the flash of a cannon reflecting off a mirror about one mile (1.6 km) away. In 1638, Galileo Galilei proposed an experiment, with an apparent claim to having performed it some years earlier, to measure the speed of light by observing the delay between uncovering a lantern and its perception some distance away. He was unable to distinguish whether light travel was instantaneous or not, but concluded that if it were not, it must nevertheless be extraordinarily rapid. Galileo's experiment was carried out by the Accademia del Cimento of Florence, Italy, in 1667, with the lanterns separated by about one mile, but no delay was observed. Based on the modern value of the speed of light, the actual delay in this experiment is about 11 microseconds.

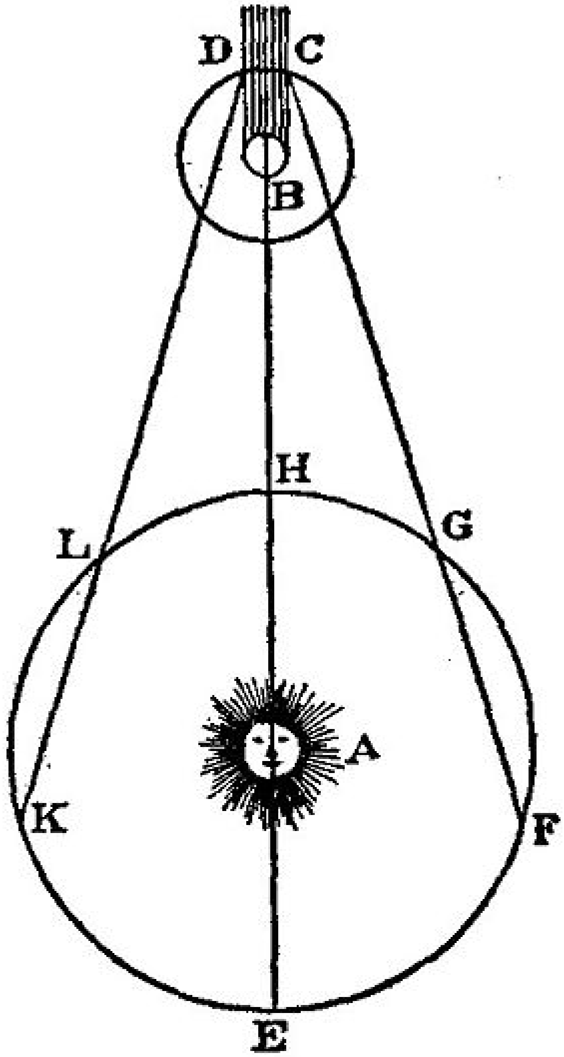


Fig. 70.

Rømer's observations of the occultations of Io from Earth

The first quantitative estimate of the speed of light was made in 1676 by Rømer. From the observation that the periods of Jupiter's innermost moon Io appeared to be shorter when the Earth was approaching Jupiter than when receding from it, he concluded that light travels at a finite speed, and estimated that it takes light 22 minutes to cross the diameter of Earth's orbit. Christiaan Huygens combined this estimate with an estimate for the diameter of the Earth's orbit to obtain an estimate of speed of light of 220,000 km/s, 26% lower than the actual value.

In his 1704 book *Opticks*, Isaac Newton reported Rømer's calculations of the finite speed of light and gave a value of "seven or eight minutes" for the time taken for light to travel from the Sun to the Earth (the modern value is 8 minutes 19 seconds). Newton queried whether Rømer's eclipse shadows were coloured; hearing that they were not, he concluded the different colours travelled at the same speed. In 1729, James Bradley discovered the aberration of light. From this effect he determined that light must travel 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.

19th and early 20th century

In the 19th century Hippolyte Fizeau developed a method to determine the speed of light based on time-of-flight measurements on Earth and reported a value of 315,000 km/s. His method was improved upon by Léon Foucault who obtained a value of 298,000 km/s in 1862. In the year 1856, Wilhelm Eduard Weber and Rudolf Kohlrausch measured the ratio of the electromagnetic and electrostatic units of charge, $1/\sqrt{\varepsilon_0\mu_0}$, by discharging a Leyden jar, and found that its numerical value was very close to the speed of light as measured directly by Fizeau. The following year Gustav Kirchhoff calculated that an electric signal in a resistanceless wire travels along the wire at this speed. In the early 1860s, Maxwell showed that according to the theory of electromagnetism which he was working on, that electromagnetic waves propagate in empty space at a speed equal to the above Weber/Kohrausch ratio, and drawing attention to the numerical proximity of this value to the speed of light as measured by Fizeau, he proposed that light is in fact an electromagnetic wave.

It was thought at the time that empty space was filled with a background medium called the luminiferous aether in which the electromagnetic field existed. Some physicists thought that this aether acted as an absolute reference frame for all physics and therefore it should be possible to measure the motion of the Earth with respect to this medium. Beginning in the 1880s several experiments were performed to try to detect this motion, the most famous of which is the experiment performed by Albert Michelson and Edward Morley in 1887. The detected motion was always less than the observational error. Modern experiments indicate that the two-way speed of light is isotropic (the same in every direction) to within 6 nanometres per second. Because of this experiment Hendrik Lorentz proposed that the motion of the apparatus through the aether may cause the apparatus to contract along its length in the direction of motion, by a factor such as to ensure that there is no interference fringes detected by the interferometer. Based on Lorentz's theory, Poincare concluded in 1904 that the speed of light is a limiting factor in dynamics. In 1905 Einstein proposed that the speed of light in vacuum, measured by a non-accelerating observer, is independent of the motion of the source or observer. Using this and the principle of relativity as a basis he derived the special theory of relativity, in which the speed of light in vacuum c featured as a fundamental parameter, also appearing in contexts unrelated to light.

Increased accuracy of *c* and redefinition of the metre

In the second half of the 20th century much progress was made in increasing the accuracy of measurements of the speed of light, first by cavity resonance techniques and later by laser interferometer techniques. In 1972, using the latter method, a group at NBS in Boulder, Colorado determined the speed of light in vacuum to be $c = 299{,}792{,}456.2 \pm 1.1$ m/s. This was 100 times less uncertain than the previously accepted value. The remaining uncertainty was mainly related to the definition of the metre. Since similar experiments found comparable results for c, the 15th Conférence Générale des Poids et Mesures (CGPM) in 1975 recommended using the value 299,792,458 m/s for the speed of light.

Because the previous definition was deemed inadequate for the needs of various experiments, the 17th CGPM in 1983 decided to redefine the metre. The new (and current) definition reads: "The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second." As a result of this definition, the value of the speed of light in vacuum is exactly 299,792,458 m/s and has become a defined constant in the SI system of units. Improved experimental techniques do not affect the value of the speed of light in SI units, but do result in a more precise realization of the metre.

Chapter-4

Variable Speed of Light

The **variable speed of light** (VSL) concept states that the speed of light in a vacuum, usually denoted by *c*, may not be constant in some cases. In most situations in condensed matter physics when light is traveling through a medium, it effectively has a slower speed. Virtual photons in some calculations in quantum field theory may also travel at a different speed for short distances; however, this doesn't imply that anything can travel faster than light. While it is usually thought that no meaning can be ascribed to a dimensional quantity such as the speed of light varying in time (as opposed to a dimensionless number such as the fine structure constant), in some controversial theories in cosmology, the speed of light also varies by changing the postulates of special relativity. This though would require a rewrite of much of modern physics, to replace the current system which depends on a constant *c*.

Varying c *in classical physics*

The photon, the particle of light which mediates the electromagnetic force is believed to be massless. The so-called Proca action describes a theory of a massive photon. Classically, it is possible to have a photon which is extremely light but nonetheless has a tiny mass, like the neutrino. These photons would propagate at less than the speed of light defined by special relativity and have three directions of polarization. However, in quantum field theory, the photon mass is not consistent with gauge invariance or renormalizability and so is usually ignored. However, a quantum theory of the massive photon can be considered in the Wilsonian effective field theory approach to quantum field theory, where, depending on whether the photon mass is generated by a Higgs mechanism or is inserted in an ad hoc way in the Proca Lagrangian, the limits implied by various observations/experiments may be different.

Varying c *in quantum theory*

In quantum field theory the Heisenberg uncertainty relations indicate that photons can travel at any speed for short periods. In the Feynman diagram interpretation of the theory, these are known as "virtual photons", and are distinguished by propagating off the mass shell. These photons may have any velocity, including velocities greater than the speed of light. To quote Richard Feynman "...there is also an amplitude for light to go faster (or slower) than the conventional speed of light. You found out in the last lecture that light doesn't go only in straight lines; now, you find out that it doesn't go only at the speed of light! It may surprise you that there is an amplitude for a photon to go at speeds faster or slower than the conventional speed, *c*." These virtual photons, however, do not violate causality or special relativity, as they are not directly observable and information cannot be transmitted acausally in the theory. Feynman diagrams and virtual photons are interpreted not as a physical picture of what is actually taking place, but rather as a convenient calculation tool (which, in some cases, happen to involve faster-than-light velocity vectors).

Varying c *in time*

In 1937, Paul Dirac and others began investigating the consequences of natural constants changing with time. For example, Dirac proposed a change of only 5 parts in 10^{11} per year of Newton's constant G to explain the relative weakness of the gravitational force compared to other fundamental forces. This has become known as the Dirac large numbers hypothesis. However, Richard Feynman showed in his famous lectures that the gravitational constant most likely could not have changed this much in the past 4 billion years based on geological and solar system observations (although this may depend on assumptions about the constant not changing other constants).

It is not clear what a variation in a dimensionful quantity actually means, since any such quantity can be changed merely by changing one's choice of units. John Barrow wrote:

"[An] important lesson we learn from the way that pure numbers like α define the world is what it really means for worlds to be different. The pure number we call the fine structure constant and denote by α is a combination of the electron charge, *e*, the speed of light, *c*, and Planck's constant, *h*. At first we might be tempted to think that a world in which the speed of light was slower would be a different world. But this would be a mistake. If *c*, *h*, and *e* were all changed so that the values they have in metric (or any other) units were different when we looked them up in our tables of physical constants, but the value of α remained the same, this new world would be *observationally indistinguishable* from our world. The only thing that counts in the definition of worlds are the values of the dimensionless constants of Nature. If all masses were doubled in value [including the Planck mass m_P] you cannot tell because all the pure numbers defined by the ratios of any pair of masses are unchanged."

Any equation of physical law can be expressed in such a manner to have all dimensional quantities normalized against like dimensioned quantities (called *nondimensionalization*) resulting in only dimensionless quantities remaining. In fact, physicists often *choose* their units so that the physical constants *c*, *G*, *h*/(2π), and $4\pi\varepsilon_0$ take the value one, resulting in every physical quantity being normalized against its corresponding Planck unit. As such, many physicists think that specifying the evolution of a dimensionful quantity is at best meaningless and at worst inconsistent. When Planck units are used and such equations of physical law are expressed in this nondimensionalized form, **no** dimensional physical constants such as *c*, *G*, or *h* remain, only dimensionless quantities. Shorn of their anthropometric unit dependence, there simply is no speed of light, gravitational constant, or Planck's constant, remaining in mathematical expressions of physical reality to be subject to such hypothetical variation. For example, in the case of the gravitational constant, *G*, the relevant dimensionless quantities that were assumed to vary ultimately became the ratios of the Planck mass to the masses of the fundamental particles. Some key dimensionless quantities (thought to be constant) depend on the speed of light, notably the fine-structure constant, would have meaningful variance and their possible variation continues to be studied.

In relativity, space-time is 4 dimensions of the same physical property of either space or time, depending on which perspective is chosen. The conversion factor of length=i*c*time is described in Appendix 2 of Einstein's *Relativity*. A changing c in relativity would mean the imaginary dimension of time is changing compared to the other three real-valued spacial dimensions of space-time.

Specifically regarding VSL, if the SI meter definition was reverted to its pre-1960 definition as a length on a prototype bar (making it possible for the measure of *c* to change), then a conceivable change in *c* (the reciprocal of the amount of time taken for light to travel this prototype length) could be more fundamentally interpreted as a change in the dimensionless ratio of the meter prototype to the Planck length or as the dimensionless ratio of the SI second to the Planck time or a change in both. If the number of atoms making up the meter prototype remains unchanged (as it should for a stable prototype), then a perceived change in the value of *c* would be the consequence of the more fundamental change in the dimensionless ratio of the Planck length to the sizes of atoms or to the Bohr radius or, alternatively, as the dimensionless ratio of the Planck time to the period of a particular caesium-133 radiation or both.

One group, studying distant quasars, has claimed to detect a variation of the fine structure constant at the level in one part in 10^5. Other authors dispute these results. Other groups studying quasars claim no detectable variation at much higher sensitivities. Moreover, even more stringent constraints, placed by study of certain isotopic abundances in the Oklo natural nuclear fission reactor, seem to indicate no variation is present.

Paul Davies and collaborators have suggested that it is in principle possible to disentangle which of the dimensionful constants (the elementary charge, Planck's constant, and the speed of light) of which the fine-structure constant is composed is responsible for the variation. However, this has been disputed by others and is not generally accepted.

The varying speed of light cosmology

The varying speed of light cosmology has been proposed independently by Jean-Pierre Petit in 1988, John Moffat in 1992, and the two-man team of Andreas Albrecht and João Magueijo in 1998 to explain the horizon problem of cosmology and propose an alternative to cosmic inflation. An alternative VSL model has also been proposed.

In Petit's VSL model, the variation of *c* accompanies the joint variations of all physical constants combined to space and time scale factors changes, so that all equations and measurements of these constants remain unchanged through the evolution of the universe. The Einstein field equations remain invariant through convenient joint variations of *c* and *G* in Einstein's constant. Late-model restricts the variation of constants to the higher energy density of the early universe, at the very beginning of the Radiation-Dominated Era where spacetime is identified to space-entropy with a metric conformally flat. However it should be noted that while this was the first VSL model to be published, and the sole to date where an evolution law is given relating the joint variations of constants through time while leaving the physics unchanged, these papers received few citations in the later VSL literature.

The idea from Moffat and the team Albrecht-Magueijo is that light propagated as much as 60 orders of magnitude faster in the early universe, thus distant regions of the expanding universe have had time to interact at the beginning of the universe. There is no known way to solve the horizon problem with variation of the fine-structure constant, because its variation does not change the causal structure of spacetime. To do so would require modifying gravity by varying Newton's constant or redefining special relativity . Classically, varying speed of light cosmologies propose to circumvent this by varying the dimensionful quantity *c* by breaking the Lorentz invariance of Einstein's theories of general and special relativity in a particular way. More modern formulations preserve local Lorentz invariance.

Possibility $c \pm V_{receiver} \neq const$

Some scholars consider the **principle of the constancy of the velocity of light** insufficiently substantiated. Simplified for understanding the meaning constant $c = const$, they divide it into two parts: $c \pm V_{source} = c \pm V_{receiver}$. Argue that, although the first part of this equation ($c \pm V_{source} = const$) is proved experimentally *(experiments de Sitter [1913], etc.)*, the second one ($c \pm V_{receiver} = const$) - yet requires experimental confirmation. And physics is mistakenly received experiments, proving the first part of this constant, as a confirmation of a constant, it is the principle of the constancy of the speed of light. The authors note this point as the main flaw of theory of relativity. Accordingly, the authors admit the possibility $c \pm V_{receiver} \neq const$.

Chapter-5

Kilometres, Miles and Metre Per Hour

Kilometres per hour

Automobile speedometer, measuring speed in miles per hour on the outer track, and kilometres per hour on the inner track.

The **kilometre per hour** (American English: **kilometer per hour**) is a unit of speed or velocity, expressing the number of kilometres traveled in one hour. The unit symbol is **km/h** or **km·h**$^{-1}$.

Worldwide, the km/h is the most commonly used speed unit on road signs and car speedometers. Along with the kW·h, km/h is the most commonly used metric unit based on the hour, the latter being a unit for time accepted for use with the International System of Units by the International Bureau of Weights and Measures (BIPM).

In Australian and North American slang and military usage, km/h is commonly pronounced, and sometimes even written, as *klicks* or *kays* (K's), although these may also be used to refer to kilometres.

Use of kph

The colloquial abbreviations "kph" and "kmph" are sometimes also used in English-speaking countries, in analogy to *miles per hour* (mph), even though the official recommendation from the BIPM is to use *km/h*. The symbol (as opposed to abbreviation) is in near-universal use elsewhere, even though the letters "*km*" and "*h*" do not always correspond to "*kilometres*" or "*hours*" in the language concerned.

Irish speed restriction sign showing *km/h*

The following are translations of the text "*kilometres per hour*" where either "*km*" or "*h*" do not appear in the text.

- Italian: *Chilometri all'ora*

- Dutch: *kilometer per uur*
- German: *Kilometer pro Stunde*
- Greek: *χιλιόμετρα ανά ώρα*
- Portuguese: *quilómetros por hora / quilômetro por hora*
- Bulgarian *Километър в час*
- Russian: *Километр в час*

In all cases, EU directives require the use of "km/h" in official documents in these languages.

Conversions

- 3.6 km/h ≡ 1 m/s, the SI unit of speed, metre per second
- 1 km/h ≈ 0.277 78 m/s
- 1 km/h ≈ 0.621 37 mph ≈ 0.911 34 feet per second
- 1 knot ≡ 1.852 km/h (exactly)
- 1 mile per hour ≡ 1.609344 km/h (~1.61 km/h)

Conversions between common units of speed

	m/s	**km/h**	**mph**	**knot**	**ft/s**
1 m/s =	**1**	**3.6**	2.236936	1.943844	3.280840
1 km/h =	0.277778	**1**	0.621371	0.539957	0.911344
1 mph =	**0.44704**	**1.609344**	**1**	0.868976	1.466667
1 knot =	0.514444	**1.852**	1.150779	**1**	1.687810
1 ft/s =	**0.3048**	**1.09728**	0.681818	0.592484	**1**

(Values in **bold face** are exact.)

Miles per hour

Automobile speedometer, measuring speed in miles per hour on the outer track, and kilometres per hour on the inner track.

Miles per hour is an imperial unit of speed expressing the number of statute miles covered in one hour. It is currently the standard unit used for speed limits, and to express speeds generally, on roads in the United Kingdom and the United States. It is also often used to express the speed of delivery of a ball in various sporting events, such as cricket, tennis, and baseball. A common abbreviation is **mph** or **MPH**.

In the International System of Units (SI), the basic unit of speed or velocity is m/s. Road traffic speeds in most countries are quoted in km/h. Occasionally, however, both systems are used: for example, in Ireland, a judge considered a speeding case by examining speeds in both kilometres per hour and miles per hour. The judge was quoted as saying the speed seemed "very excessive" at 180 km/h but did not look "as bad" at 112 mph; a reduced fine was still imposed on the speeding driver.

Nautical and aeronautical applications, however, favour the knot as a common unit of speed: one knot is one nautical mile per hour.

Conversions

1 mph is equal to:

- 0.44704 m/s, the SI derived unit
- 1.609344 km/h
- 1.4667 feet per second (= 22/15 feet per second)
- approx. 0.868976 knots

When converting miles per hour to another unit of measurement, or vice versa, it helps to know exactly how miles and hours are related to other units of distance and time, respectively. For example, 1 mile is equal to 5,280 feet, 1,760 yards, or 1,609.344 metres. Likewise, 1 hour is equal to 60 minutes, or 3,600 seconds.

Conversions between common units of speed

	m/s	**km/h**	**mph**	**knot**	**ft/s**
1 m/s =	**1**	**3.6**	2.236936	1.943844	3.280840
1 km/h =	0.277778	**1**	0.621371	0.539957	0.911344
1 mph =	**0.44704**	**1.609344**	**1**	0.868976	1.466667
1 knot =	0.514444	**1.852**	1.150779	**1**	1.687810
1 ft/s =	**0.3048**	**1.09728**	0.681818	0.592484	**1**

(Values in **bold face** are exact.)

Metre per hour

Metre per hour (American spelling: meter per hour) is a metric unit of both speed (scalar) and velocity (Vector (geometry)). Its symbol is **m/h** or **m·h^{-1}** (not to be confused with the imperial unit symbol mph. By definition, an object travelling at a speed of 1 m/h for an hour would move 1 metre.

The term is rarely used however as the units of metres per second and kilometres per hour are considered sufficient for the majority of circumstances. Metres per hour can however be convenient for documenting extremely slow moving objects. A Garden Snail for instance, typically moves at a speed of up to 47 metres per hour.

Conversions

- 3,600 m/h ≡ 1 $m \cdot s^{-1}$, the SI derived unit of speed, metre per second
- 1 m/h ≈ 0.00027778 m/s
- 1 m/h ≈ 0.00062137 mph ≈ 0.00091134 feet per second

How to convert

- To convert from kilometres per hour to metres per hour, multiply the figure by 1,000 (hence the prefix kilo- from the ancient Greek language word for thousand).
- To convert from metres per second to metres per hour, divide the figure by 3,600 (that is 60 * 60, i.e. 60 seconds for each of the 60 minutes).

Chapter-6

Knot, Inch Per Second and Metre Per Second

Knot (unit)

The **knot** is a unit of speed equal to one nautical mile (which is defined as 1.852 km) per hour, approximately 1.151 mph. The abbreviation **kn** is preferred by the International Hydrographic Organization (IHO), which includes every major sea-faring nation; however, the abbreviations **kt** (singular) and **kts** (plural) are also widely used. The knot is a non-SI unit accepted for use with the International System of Units (SI). Worldwide, the knot is used in meteorology, and in maritime and air navigation—for example, a vessel travelling at 1 knot along a meridian travels one minute of geographic latitude in one hour. Etymologically, the term **knot** derives from counting the number of knots that unspooled from the reel of a chip log in a specific time.

Definitions

1 international knot =

1 nautical mile per hour (by definition),
1.852 kilometres per hour (exactly),
0.514 metres per second,
1.151 miles per hour (approximately).

1,852 m is the length of the internationally-agreed nautical mile. The U.S. adopted the international definition in 1954, having previously used the U.S. nautical mile (1,853.248 m). The U.K. adopted the international nautical mile definition in 1970, having previously used the U.K. Admiralty nautical mile (6,080 ft [1,853.184 m]).

The speeds of vessels relative to the fluids in which they travel (boat speeds and air speeds) are measured in knots. For consistency, the speeds of navigational fluids (tidal streams, river currents and wind speeds) are also measured in knots. Thus, speed over the ground (SOG) (ground speed (GS) in aircraft) and rate of progress towards a distant point ("velocity made good", VMG) are also given in knots.

Conversions between common units of speed

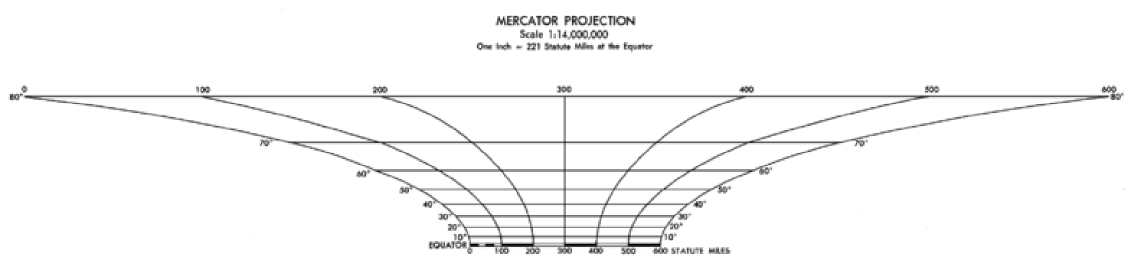
	m/s	km/h	mph	knot	ft/s
1 m/s =	**1**	**3.6**	2.236936	1.943844	3.280840
1 km/h =	0.277778	**1**	0.621371	0.539957	0.911344
1 mph =	**0.44704**	**1.609344**	**1**	0.868976	1.466667
1 knot =	0.514444	**1.852**	1.150779	**1**	1.687810
1 ft/s =	**0.3048**	**1.09728**	0.681818	0.592484	**1**

(Values in **bold face** are exact.)

Origin

Until the mid-19th century vessel speed at sea was measured using a chip log. This consisted of a wooden panel, weighted on one edge to float upright, and thus present substantial resistance to moving with respect to the water around it, attached by line to a reel. The chip log was "cast" over the stern of the moving vessel and the line allowed to pay out. Knots placed at a distance of 47 feet 3 inches (14.4018 m) passed through a sailor's fingers, while another sailor used a 30 second sand-glass (28 second sand-glass is the current accepted timing) to time the operation. The knot count would be reported and used in the sailing master's dead reckoning and navigation. This method gives a value for the knot of 20.25 in/s, or 1.85166 km/h. The difference from the modern definition is less than 0.02%.

Modern use



Graphic scale from a Mercator projection world map, showing the change with latitude.

Although the unit *knot* does not fit within the primary SI system, its retention for nautical and aviation use is important because standard nautical charts are on the Mercator projection and the scale varies with latitude. On a chart of the North Atlantic, the scale varies by a factor of two from Florida to Greenland. A single graphic scale, of the sort on many maps, would, therefore, be useless on such a chart. Since the length of a nautical mile is, for practical purposes, identical to a minute of latitude, a distance in nautical miles on a chart can easily be measured by using dividers and the latitude scales on the sides of the chart.

Speed is sometimes incorrectly expressed as "knots per hour", which would actually be a measure of acceleration, as in "nautical miles per hour per hour".

Aeronautical terms

Prior to 1969, airworthiness standards for civil aircraft in the United States Federal Aviation Regulations specified that distances were to be in statute miles, and speeds in miles per hour. In 1969 these standards were progressively amended to specify that distances were to be in nautical miles, and speeds in knots.

The following abbreviations are used to distinguish between various measurements of airspeed.

- KTAS is "knots true airspeed", the airspeed of an aircraft relative to undisturbed air.
- KIAS is "knots indicated airspeed", the speed shown on an aircraft's pitot-static airspeed indicator.
- KCAS is "knots calibrated airspeed", the indicated airspeed corrected for position error and instrument error.
- KEAS is "knots equivalent airspeed", the calibrated airspeed corrected for adiabatic compressible flow for the particular altitude.

Inch per second

The **inch per second** is a unit of speed or velocity. It expresses the distance in inches (*in*) traveled or displaced, divided by time in seconds (*s*, or *sec*). The equivalent SI unit is the **metre per second**.

Abbreviations include **in/s**, **in/sec** and **ips**, although the representation **in s^{-1}** is not often used.

Conversions

1 inch per second is equivalent to:

= 0.0254 metres per second (exactly)
= 1⁄12 or 0.083 feet per second (exactly)
= 5⁄88 or 0.05681 miles per hour (exactly)
= 0.09144 $km \cdot h^{-1}$ (exactly)

1 metre per second ≈ 39.370079 inches per second (approximately)
1 foot per second = 12 inches per second (exactly)

1 mile per hour = 17.6 inches per second (exactly)
1 kilometre per hour ≈ 10.936133 inches per second (approximately)

Uses

In magnetic tape sound recording, magnetic tape speed is often quoted in inches per second (abbreviated "ips").

Also computer mice sensitivity is also often referred to in inches per second (abbreviated as "ips") along with g force.

In rotorcraft health monitoring, rotor and shaft induced vibration levels are often quoted in inches per second.

Metre per second

Metre per second (U.S. spelling: **meter per second**) is an SI derived unit of both speed (scalar) and velocity (vector quantity which specifies both magnitude and a specific direction), defined by distance in metres divided by time in seconds.

The official SI symbolic abbreviation is $m \cdot s^{-1}$, or equivalently either m/s or $\frac{m}{s}$. Where metres per second are several orders of magnitude too slow to be convenient, such as in astronomical measurements, velocities may be given in kilometres per second, where 1 km/s is equivalent to 10^3 metres per second.

Conversions

1 m/s is equivalent to:

= $3.6\ km \cdot h^{-1}$ (exactly)
≈ 3.2808 feet per second (approximately)
≈ 2.2369 miles per hour (approximately)
≈ 1.9438 knots (approximately)

1 foot per second = $0.3048\ m \cdot s^{-1}$ (exactly)

1 mile per hour = $0.44704\ m \cdot s^{-1}$ (exactly)

$1\ km \cdot h^{-1} \approx 0.2778\ m \cdot s^{-1}$ (approximately)

1 kilometre per second is equivalent to:

≈ 0.6213 miles per second (approximately)
≈ 2237 miles per hour (approximate)

Relation to other measures

Although $m \cdot s^{-1}$ is an SI derived unit, it could be viewed as more fundamental than the metre, since the latter is derived from the speed of light in a vacuum, which is defined as exactly 299 792 458 $m \cdot s^{-1}$ by the BIPM. It follows that one metre is the length of the path travelled by light in a vacuum during a time interval of 1/299 792 458 of one second.

Chapter-7

Week

A **week** is a time unit equal to seven days.

The English word week continues an Old English *wice*, ultimately from a Common Germanic **wikōn-*, from a root **wik-* "turn, move, change". The Germanic word probably had a wider meaning prior to the adoption of the Roman calendar, perhaps "succession series", as suggested by Gothic *wikō* translating *taxis* "order" in Luke 1:8.

The term "week" is sometimes expanded to refer to other time units comprising a few days. Such "weeks" of between 4 and 10 days have been used historically in various places. Intervals longer than 10 days are not usually termed "weeks" as they are closer in length to the fortnight or the month than to the seven-day week.

Seven-day week

Evidence of continuous use of a seven-day week appears with the Jews during the Babylonian Captivity of the 6th century BC. Both Judaism (based on the Creation narrative in the Torah/Bible) and ancient Babylonian religions used a seven day week. Other cultures adopted the seven-day week at different times. Between the 1st and 3rd centuries the Roman Empire gradually replaced the eight day Roman nundinal cycle with the seven-day week. Hindus may have adopted a seven day week as early as the 1st century BC. There is evidence of some Chinese groups using a seven day week as early as 4th century AD.

Systems derived from the seven-day week

Soviet Union

Between 1929 and 1931 USSR changed from the 7-day week to a 5-day week. There were 72 weeks and an additional five national holidays inserted within three of them totaling a year of 365 days.

In 1931 after the Soviet Union's 5-day week they changed to a 6-day week. Every 6th day (6th, 12th, 18th, 24th and 30th) of the Gregorian Calendar was a state rest day. The 5 additional national holidays in the earlier 5-day week remained and did not fall on the state rest day.

But as January, March, May, July, August, October and December have 31 days, the week after the state rest day of the 30th was 7 days long (31st–7th). This extra day was a working day for most or extra holiday for others.

Also as February is only 28 or 29 days depending if a leap year or not, the 1st of March was also made a state rest day, although not every enterprise conformed to this.

To clarify, the week after the state rest day, 24/25 February to 1 March, was only 5 or 6 days long, depending if a leap year or not. The week after that, 2 to 6 March, was only 5 days long.

The calendar was abandoned 26 June 1940 and the 7-day week reintroduced the day after.

Decimal calendar

A 10-day week, called *décade*, was used in France for 9½ years from October 1793 to April 1802; furthermore, the Paris Commune adopted the Revolutionary Calendar for 18 days in 1871.

Christian "eighth day"

For early Christians, Sunday, as well as being the first day of the week, was also the spiritual eighth day, as it symbolised the new world created after Christ's resurrection. The concept of the eighth day was symbolic only and had no effect on the use of the seven-day week for calendar purposes. Justin Martyr wrote: "the first day after the Sabbath, remaining the first of all the days, is called, however, the eighth, according to the number of all the days of the cycle, and [yet] remains the first". This does not set up an 8-day week, since the eighth day is also considered to be the first day of the next cycle (i.e., not the following day).

A period of eight days, starting and ending on a Sunday or starting on a major feast day and finishing on the same day of the week a (7-day) week later, is called an octave. For centuries these were a major feature of the liturgical calendar, particularly of the Catholic Church, and some are still observed, though the number of such octaves has now been radically reduced. Some modern Church uses also preserve the idea of an eight-day period, starting and finishing on the same day of the week, and retain the name "octave" for them; for example, many churches observe an annual "Octave of Prayer for Christian Unity" on 18–25 January or in the week that begins with Pentecost Sunday. Organizations such as 8th Day Center for Justice, based out of Chicago, Illinois, use the concept in terms of social justice as well.

Hermetic lunar week

The Hermetic Lunar Week Calendar is one of many proposed reforms to the Gregorian Calendar. The lunation is divided into the four Moon Phases and has 6, 7, 8, or 9 days depending on the actual time difference between the full moon, First Quarter, new moon and Last Quarter.

"Weeks" in other calendars

Periods termed "weeks" in calendars unrelated to the Judeo-Christian tradition.

Three day

The names of the days of the week (*aste*) in Guipuscoan Basque point to an earlier three-day week.

1. *astelehena* ("week-first", Monday)
2. *asteartea* ("week-between", Tuesday)
3. *asteazkena* ("week-last", Wednesday)

Four-day

The Igbo of Nigeria have a traditional calendar with a 4-day week. This "market week" features prominently in the fiction of Chinua Achebe.

Five-day

The Javanese people of Indonesia have a 5-day week known as the Pasaran cycle. This is still in use today and superimposed with Gregorian calendar and Islamic calendar to become what is known as the Wetonan Cycle.

Six-day

The Akan people of West Africa have 42 day cycle known as *Adaduanan*. The *Adaduanan* cycle appears to be based on an older six-day week, still existant in some northern Guan communities such as the Nchumuru , on which is superimposed a seven-day week which may have been brought south with itinerant traders from the Savannah. The six-day week is referred to as Nanson (literally seven-days) and reflects the lack of zero in the numbering systems; the last day and the first day are both included when counting the days of a week.

Eight-day

Nundinal cycle

The ancient Etruscans developed an 8-day market week known as the nundinal cycle around 8th or 7th century BC. This was passed on to the Romans no later than the 6th century BC. As Rome expanded, it encountered the 7-day week and for a time attempted to include both. The popularity of the 7-day rhythm won and the 8-day week disappeared forever.

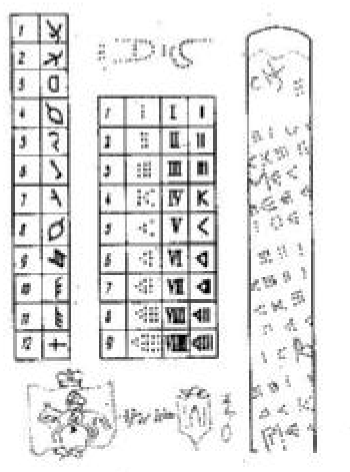
The cycle of seven days, named after the sun, the moon, and the five planets visible to the naked eye, was already customary in the time of Justin Martyr, who wrote of the Christians meeting on the Day of the Sun (Sunday).

Emperor Constantine eventually established the 7-day week in the Roman calendar in AD 321.

Celts

It is believed the Celtic people used a nine-*night* week. The moon was used to measure one day from another so nights were more significant. The 9 nights divided nicely into a Sidereal Month of 27 nights. Each week of 9 nights had 8 days. There was also a half week of 5 nights and 4 days.

Nine-day



The Gediminas Sceptre, a medieval Lithuanian calendar. Showing 12 months and 9 days in a week

Baltic calendars

In the 14th century, the Grand Duchy of Lithuania used a solar-lunar calendar. The structure of this calendar was understood with the help of the so-called Gediminas Sceptre discovered in 1680.

Historical recordsgive evidence that the week of ancient Balts was nine-days long. Thus, the sidereal month must have been divided into three parts.

Ten-day

China

The Chinese 10 day week went as far back as the Shang Dynasty (1200-1045 BC). The law in the Han Dynasty (206 BC – AD 220) required officials of the empire to rest every 5 days, called "mu", while it was changed into 10 days in the Tang Dynasty (AD 618 – 907), called "huan" or xún (旬). Months were almost 3 weeks long (alternating 29 and 30 days to keep in line with the lunation). The weeks were labelled shàng xún (上旬), zhōng xún (中旬), and xià xún (下旬) which mean roughly "upper", "middle" and "lower" week.

Egypt

Ancient Egypt had a 10-day week, 3 weeks per month with 5 extra days at the end of the year.

Other calendar intervals

Aztecs

Restored Aztec sun stone showing the 20 Days

The Aztecs divided a ritual cycle of 260 days, known as Tonalpohualli, into 20 weeks of 13 days known as Trecena.

The Aztecs divided a solar year of 365 days, Xiuhpohualli into 18 periods of 20 days and 5 nameless days known as *Nemontemi*. Although some call this 20-day division or grouping a month, it has no relation to a lunation and therefore the word "week" is more appropriate.

Maya

The Maya divided a 260 ritual cycle known Tzolk'in as into 20 weeks of 13 days known as Trecena.

The Maya also divided the year, Haab', into 18 periods of 20 days, *Uinal*, and 5 nameless days known as *Wayeb'*.

Bali, Indonesia

The Pawukon is a 210-day calendar consisting of 10 different concurrent weeks of 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 days.

Chapter-8

Year

A **year** (from Old English *gēar*) is the orbital period of the Earth moving around the Sun. For an observer on Earth, this corresponds to the period it takes the Sun to complete one course throughout the zodiac along the ecliptic.

In astronomy, the Julian year is a unit of time, defined as 365.25 days of 86,400 SI seconds each.

There is no universally accepted symbol for the year as a unit of time. The International System of Units does not propose one. A common abbreviation in international use is **a** (for Latin *annus*), in English also **y** or **yr**.

Due to the Earth's axial tilt, the course of a year sees the passing of the seasons, marked by changes in weather, hours of daylight, and consequently vegetation and fertility. In temperate and subpolar regions, generally four seasons are recognized: *spring*, *summer*, *autumn* and *winter*, astronomically marked by the Sun reaching the points of equinox and solstice, although the climatic seasons lag behind their astronomical markers. In some tropical and subtropical regions it is more common to speak of the rainy (or wet, or monsoon) season versus the dry season.

A calendar year is an approximation of the Earth's orbital period in a given calendar. A calendar year in the Gregorian calendar (as well as in the Julian calendar) has either 365 (common years) or 366 (leap years) days.

The word "year" is also used of periods loosely associated but not strictly identical with either the astronomical or the calendar year, such as the seasonal year, the fiscal year or the academic year, etc. By extension, the term *year* can mean the orbital period of any planet: for example, a "Martian year" is the time in which Mars completes its own orbit. The term is also applied more broadly to any long period or cycle, such as the Platonic "Great Year".

Seasonal year

A **seasonal year** is the time between successive recurrences of a seasonal event such as the flooding of a river, the migration of a species of bird, the flowering of a species of plant, the first frost, or the first scheduled game of a certain sport. All of these events can have wide variations of more than a month from year to year.

Calendar year

A **calendar year** is the time between two dates with the same name in a calendar.

A *half year* (one half of a year) may run from January to June, or July to December.

No astronomical year has an integer number of days or lunar months, so any calendar that follows an astronomical year must have a system of intercalation such as leap years. Financial and scientific calculations often use a 365-day calendar to simplify daily rates.

In the Julian calendar, the average length of a year is 365.25 days. In a non-leap year, there are 365 days, in a leap year there are 366 days. A leap year occurs every 4 years.

The Gregorian calendar attempts to keep the vernal equinox on or soon before March 21, hence it follows the vernal equinox year. The average length of this calendar's year is 365.2425 mean solar days (as 97 out of 400 years are leap years); this is within one ppm of the current length of the mean tropical year (365.24219 days). It is estimated that, by the year 4000, the vernal equinox will fall back by one day in the Gregorian calendar, not because of this difference, but because of the slowing down of the Earth's rotation and the associated lengthening of the sidereal day.

The Persian calendar, in use in Afghanistan and Iran, has its year begin on the day of the vernal equinox as determined by astronomical computation (for the time zone of Tehran), as opposed to using an algorithmic system of leap years.

Numbering calendar years

A calendar era is used to assign a number to individual years, using a reference point in the past as the beginning of the era. In many countries, the most common era is from the estimated date of the birth of Jesus Christ; dates in this era are designated *anno Domini* ("in the year of the Lord", abbreviated *A.D.*) or *C.E.* (common era). Other eras are also used to enumerate the years in different cultural, religious or scientific contexts.

Other annual periods

Fiscal year

A **fiscal year** or financial year is a 12-month period used for calculating annual financial statements in businesses and other organizations. In many jurisdictions, regulations regarding accounting require such reports once per twelve months, but do not require that the twelve months constitute a calendar year.

For example, the federal government of the U.S. has a fiscal year that starts on October 1 instead of January 1. In India the fiscal year is between April 1 and March 31. In the United Kingdom and Canada, the financial year runs from April 6 and April 1 respectively, and in Australia it runs from July 1.

Academic year

An **academic year** refers to the annual period during which a student attends school, college or university.

The school year can be divided up in various ways, two of which are most common in North American educational systems.

- Some schools in the UK and USA divide the academic year into *three* roughly equal-length terms (called trimesters in the USA), more or less coinciding with autumn, winter, and spring. At some, a shortened summer session, sometimes considered part of the regular academic year, is attended by students on a voluntary or elective basis.
- Other schools break the year into *two* main semesters, a first (typically August through December) and a second (January through May). Each of these main semesters may be split in half by mid-term exams, and each of the halves is referred to as a quarter (or term in some countries). There may also be an elective summer session, and/or a short January session.
- Some other schools, including some in the United States, have *four* marking periods. The school year in many countries starts in August or September and ends in May, June or July.
- Some schools in the United States, notably Boston Latin School, may divide the year into *five or more* marking periods. Some state in defense of this that there is perhaps a positive correlation between report frequency and academic achievement.
- There are 180 days of teaching each year in schools in the USA, excluding weekends and breaks, 190 days for pupils in state schools in the United Kingdom, New Zealand and Canada.
- In India the academic year normally starts from June 1 and ends on May 31. Though schools start closing from mid-March, the actual academic closure is on May 31 and in Nepal it starts from July 15.
- Schools and universities in Australia typically have academic years that roughly align with the calendar year (i.e. starting in February or March and ending in October to December), as the southern hemisphere experiences summer from December to February.

Astronomical years

Julian year

The **Julian year**, as used in astronomy and other sciences, is a time unit defined as exactly 365.25 days. This is the normal meaning of the unit "year" (symbol "a" from the Latin *annus*) used in various scientific contexts. The Julian century of 36525 days and the Julian millennium of 365250 days are used in astronomical calculations. Fundamentally, expressing a time interval in Julian years is a way to precisely specify how many days (not how many "real" years), for long time intervals where stating the number of days would be unwieldy and unintuitive. By convention, the Julian year is used in the computation of the distance covered by a light-year.

In the Unified Code for Units of Measure, the symbol **a** (without subscript) always refers to the Julian year $\mathbf{a_j}$ of exactly 31557600 seconds.

365.25 days of 86400 seconds = 1 a = 1 a_j = 31.5576 Ms

The SI multiplier prefixes may be applied to it to form **ka** (kiloannum), **Ma** (megaannum) etc.

Sidereal, tropical, and anomalistic years

Each of these three years can be loosely called an 'astronomical year'.

The **sidereal year** is the time taken for the Earth to complete one revolution of its orbit, as measured against a fixed frame of reference (such as the fixed stars, Latin *sidera*, singular *sidus*). Its duration in SI days of 86,400 SI seconds each is on average:

> 365.256 363 004 days (365 d 6 h 9 min 9.7676 s) (at the epoch J2000.0 = 2000 January 1 12:00:00 TT).

The **tropical year** is "the period of time for the ecliptic longitude of the Sun to increase by 360 degrees. Since the Sun's ecliptic longitude is measured with respect to the equinox, the tropical year comprises a complete cycle of the seasons...The mean tropical year is approximated by 365 days, 5 hours, 48 minutes, 45 seconds." (= 365.24219 days) The tropical year is shorter than the sidereal year because of the precession of the equinoxes.

The **anomalistic year** is the time taken for the Earth to complete one revolution with respect to its apsides. The orbit of the Earth is elliptical; the extreme points, called apsides, are the perihelion, where the Earth is closest to the Sun (January 3 in 2011), and the aphelion, where the Earth is farthest from the Sun (July 4 in 2011). The anomalistic year is usually defined as the time between two successive perihelion passages. Its average duration is:

365.259 636 days (365 d 6 h 13 min 52.6 s) (at the epoch J2011.0).

The anomalistic year is slightly longer than the sidereal year because of the precession of the apsides (also known as anomalistic precession, orbital precession, and, perihelion precession.)

Draconic year

The **draconic year**, **draconitic year**, **eclipse year**, or **ecliptic year** is the time taken for the Sun (as seen from the Earth) to complete one revolution with respect to the same lunar node (a point where the Moon's orbit intersects the ecliptic). This period is associated with eclipses: these occur only when both the Sun and the Moon are near these nodes; so eclipses occur within about a month of every half eclipse year. Hence there are *two eclipse seasons* every eclipse year. The average duration of the eclipse year is:

346.620 075 883 days (346 d 14 h 52 min 54 s) (at the epoch J2000.0).

This term is sometimes erroneously used to designate the draconic or nodal period of lunar precession, that is the time it takes for a complete revolution of the Moon's ascending node around the ecliptic: 18.612 815 932 Julian years (6798.331 019 days; at the epoch J2000.0).

Full moon cycle

The **full moon cycle** is the time for the Sun (as seen from the Earth) to complete one revolution with respect to the perigee of the Moon's orbit. This period is associated with the apparent size of the full moon, and also with the varying duration of the synodic month. The duration of one full moon cycle is:

411.784 430 29 days (411 d 18 h 49 min 34 s) (at the epoch J2000.0).

Lunar year

The **lunar year** comprises twelve full cycles of the phases of the Moon, as seen from Earth. It has a duration of approximately 354.37 days.

Vague year

The **vague year**, from *annus vagus* or wandering year, is an integral approximation to the year equaling 365 days, which wanders in relation to more exact years. Typically the vague year is divided into 12 schematic months of 30 days each plus 5 epagomenal days. The vague year was used in the calendars of Ancient Egypt, Iran, Armenia and in Mesoamerica among the Aztecs and Maya.

Heliacal year

A **heliacal year** is the interval between the heliacal risings of a star. It differs from the sidereal year for stars away from the ecliptic due mainly to the precession of the equinoxes. (To visualise: the constellation Crux, which rose and set as seen from the Mediterranean in ancient Greek times, is never above the horizon in current times.)

Sothic year

The **Sothic year** is the interval between heliacal risings of the star Sirius. It is equal to the sidereal year and its duration is very close to the mean Julian year of 365.25 days.

Gaussian year

The **Gaussian year** is the sidereal year for a planet of negligible mass (relative to the Sun) and unperturbed by other planets that is governed by the Gaussian gravitational constant. Such a planet would be slightly closer to the Sun than Earth's mean distance. Its length is:

365.256 898 3 days (365 d 6 h 9 min 56 s).

Besselian year

The **Besselian year** is a tropical year that starts when the (fictitious) mean Sun reaches an ecliptic longitude of 280°. This is currently on or close to 1 January. It is named after the 19th century German astronomer and mathematician Friedrich Bessel. A formula to compute the current Besselian epoch (in years):

$$B = 1900.0 + (\text{Julian date}_{TT} - 2415020.31352) / 365.242198781$$

The TT subscript indicates for this formula, the Julian date should use the Terrestrial Time scale, or its predecessor, ephemeris time.

Variation in the length of the year and the day

The exact length of an astronomical year changes over time. The main sources of this change are:

- The precession of the equinoxes changes the position of astronomical events with respect to the apsides of Earth's orbit. An event moving toward perihelion recurs with a decreasing period from year to year; an event moving toward aphelion recurs with an increasing period from year to year (though this effect does not change the average value of the length of the year).

- Each planet's movement is perturbed by the gravity of every other planet.

- Tidal drag between the Earth and the Moon and Sun increases the length of the day and of the month (by transferring angular momentum from the rotation of the Earth to the revolution of the Moon); since the apparent mean solar day is the unit with which we measure the length of the year in civil life, the length of the year appears to change. Tidal drag in turn depends on factors such as post-glacial rebound and sea level rise.

- Changes in the effective mass of the Sun, caused by solar wind and radiation of energy generated by nuclear fusion and radiated by its surface, will affect the Earth's orbital period over a long time (approximately an extra 1.25 microsecond per year).

- The Poynting–Robertson effect shortens the year by about 30 nanoseconds per year.

- Gravitational radiation shortens the year by about 165 attoseconds per year.

Summary

- 346.62 days: a draconitic year.
- 353, 354 or 355 days: the lengths of common years in some lunisolar calendars.
- 354.37 days (12 lunar months): the average length of a year in lunar calendars, notably the Muslim calendar.
- 365 days: a vague year and a common year in many solar calendars.
- 365.24219 days: a mean tropical year (rounded to five decimal places) for the epoch 2000.
- 365.2424 days: a vernal equinox year (rounded to four decimal places) for the epoch 2000.
- 365.2425 days: the average length of a year in the Gregorian calendar.
- 365.25 days: the average length of a year in the Julian calendar.
- 365.2564 days: a sidereal year.
- 366 days: a leap year in many solar calendars.
- 383, 384 or 385 days: the lengths of leap years in some lunisolar calendars.
- 383.9 days (13 lunar months): a leap year in some lunisolar calendars.

An average Gregorian year is 365.2425 days = 52.1775 weeks = 8,765.82 hours = 525,949.2 minutes = 31,556,952 seconds (mean solar, not SI).

A common year is 365 days = 8,760 hours = 525,600 minutes = 31,536,000 seconds.

A leap year is 366 days = 8,784 hours = 527,040 minutes = 31,622,400 seconds.

The 400-year cycle of the Gregorian calendar has 146,097 days and hence exactly 20,871 weeks.

Symbol

There is no universally accepted symbol for the year as a unit of time. The International System of Units does not propose one. NIST SP811 and ISO 80000-3:2006 suggest the symbol **a** is taken from the Latin word *annus*. In English, the abbreviations **y** or **yr** are sometimes used, specifically in geology and paleontology, where *kyr, myr, byr* (thousands, millions, and billions of years, respectively) and similar abbreviations are used to denote intervals of time remote from the present.

Symbol a

NIST SP811 and ISO 80000-3:2006 suggest the symbol **a** (in the International System of Units, although **a** is also the symbol for the *are*, the unit of area used to measure land area, but context is usually enough to disambiguate). In English, the abbreviations **y** and **yr** are also used.

The Unified Code for Units of Measure disambiguates the varying symbologies of ISO 1000, ISO 2955 and ANSI X3.50 by using

ar for are (unit), and:
$\mathbf{a_t}$ = a_t = 365.24219 days for the mean tropical year
$\mathbf{a_j}$ = a_j = 365.25 days for the mean Julian year
$\mathbf{a_g}$ = a_g = 365.2425 days for the mean Gregorian year
a = 1 a_j year (without further qualifier)

SI prefix multipliers

- **ka** (for **kiloannum**), is a unit of time equal to one thousand (10^3) years.
- **Ma** (for **megaannum**), is a unit of time equal to one million (10^6) years. It is commonly used in scientific disciplines such as geology, paleontology, and celestial mechanics to signify very long time periods into the past or future. For example, the dinosaur species *Tyrannosaurus rex* was abundant approximately *65 Ma* (65 million years) ago (*ago* may not always be mentioned; if the quantity is specified while not explicitly discussing a duration, one can assume that "ago" is implied; the alternative but deprecated "mya" unit includes "ago" explicitly.). In astronomical applications, the year used is the Julian year of precisely 365.25 days. In geology and paleontology, the year is not so precise and varies depending on the author.
- **Ga** (for **gigaannum**), is a unit of time equal to 10^9 years (one billion on the short scale, one milliard on the long scale). It is commonly used in scientific disciplines such as cosmology and geology to signify extremely long time periods in the past. For example, the formation of the Earth occurred approximately *4.57 Ga* (4.57 billion years) ago.
- **Ta** (for **teraannum**), is a unit of time equal to 10^{12} years (one trillion on the short scale, one billion on the long scale). It is an extremely long unit of time, about 70

times as long as the age of the universe. It is the same order of magnitude as the expected life span of a small red dwarf star.

- **Pa** (for **petaannum**), is a unit of time equal to 10^{15} years (one quadrillion on the short scale, one billiard on the long scale). The half-life of the nuclide cadmium-113 is about 8 Pa. This symbol coincides with that for the pascal without a multiplier prefix, though both are infrequently used and context will normally be sufficient to distinguish time from pressure values.
- **Ea** (for **exaannum**), is a unit of time equal to 10^{18} years (one quintillion on the short scale, one trillion on the long scale). The half-life of tungsten-180 is 1.8 Ea.

Symbols y and yr

In astronomy, geology, and paleontology, the abbreviation *yr* for "years" and *ya* for "years ago" are sometimes used, combined with prefixes for "thousand", "million", or "billion". They are not SI units, using *y* to abbreviate English year, but following ambiguous international recommendations, use either the standard English first letters as prefixes (t,m,and b) and/or the familiar metric multiplier prefixes (k, m, and g). These abbreviations include:

	SI-prefixed equivalent	order of magnitude
kyr	"ka"	* Thousands forms
myr	"Ma"	* Millions forms
byr	"Ga"	* Billions forms
tya or **kya**	"ka ago"	• Appearance of *Homo sapiens, ca. 200 tya* • Out-of-Africa migration, ca. 60 tya • Last Glacial Maximum, ca. 20 tya • Neolithic Revolution, ca. 10 tya

mya	"Ma ago"	• Pliocene 5.3 to 2.6 mya
		  ○ The last geomagnetic reversal was 0.78 mya
		  ○ The (Eemian Stage) Ice Age started 0.13 mya
		• Holocene started 0.01 mya

bya or **gya**	"Ga ago"	• oldest Eukaryotes, 2 bya • age of the Earth, 4.5 bya • Big Bang, 13.7 bya

Use of "mya" and "bya" is deprecated in modern geophysics, the recommended usage being "Ma" and "Ga" for dates Before Present, but "m.y." for the duration of epochs. This *ad hoc* distinction between "absolute" time and time intervals is somewhat controversial amongst members of the Geological Society of America.

Note that on graphs using "ya" units on the horizontal axis time flows from right to left, which may seem counter-intuitive. If the "ya" units are on the vertical axis, time flows from top to bottom which is probably easier to understand than conventional notation.

"Great years"

Equinoctial cycle

The **Great year**, **Platonic year**, or **Equinoctial cycle** corresponds to a complete revolution of the equinoxes around the ecliptic. Its length is about 25,700 years, and cannot be determined precisely as the precession speed is variable.

Galactic year

The **Galactic year** is the time it takes Earth's solar system to revolve once around the galactic center. It comprises roughly 230 million Earth years.

Chapter-9

Month

A **month** is a unit of time, used with calendars, which was first used and invented in Mesopotamia, as a natural period related to the motion of the Moon; *month* and *Moon* are cognates. The traditional concept arose with the cycle of moon phases; such months (lunations) are synodic months and last approximately 29.53 days. From excavated tally sticks, researchers have deduced that people counted days in relation to the Moon's phases as early as the Paleolithic age. Synodic months, based on the Moon's orbital period, are still the basis of many calendars today, and are used to divide the year.

Types of months

The following types of months are mainly of significance in astronomy, most of them (but not the distinction between sidereal and tropical months) first recognized in Babylonian lunar astronomy.

Sidereal month

The period of the Moon's orbit as defined with respect to the celestial sphere (of the fixed stars, nowadays the International Celestial Reference Frame (ICRF)) is known as a *sidereal* month because it is the time it takes the Moon to return to a given position among the stars (Latin: *sidus*): 27.321661 days (27 d 7 h 43 min 11.5 s). This type of month has been observed among cultures in the Middle East, India, and China in the following way: they divided the sky into 27 or 28 lunar mansions, one for each day of the month, identified by the prominent star(s) in them.

Tropical month

It is customary to specify positions of celestial bodies with respect to the vernal equinox. Because of precession, this point moves back slowly along the ecliptic. Therefore it takes the Moon less time to return to an ecliptic longitude of zero than to the same point amidst the fixed stars: 27.321582 days (27 d 7 h 43 min 4.7 s). This slightly shorter period is known as *tropical* month; cf. the analogous tropical year of the Sun.

Anomalistic month

The Moon's orbit approximates an ellipse rather than a circle. However, the orientation (as well as the shape) of this orbit is not fixed. In particular, the position of the extreme points (the line of the apsides: perigee and apogee), makes a full circle (lunar precession) in about nine years. It takes the Moon longer to return to the same apsis because it moved ahead during one revolution. This longer period is called the *anomalistic* month, and has an average length of 27.554551 days (27 d 13 h 18 min 33.2 s). The apparent diameter of the Moon varies with this period, and therefore this type has some relevance for the prediction of eclipses, whose extent, duration, and appearance (whether total or annular) depend on the exact apparent diameter of the Moon. The apparent diameter of the full moon varies with the full moon cycle which is the beat period of the synodic and anomalistic month, and also the period after which the apsides point to the Sun again.

Draconic month

Sometimes written 'draconitic' month, and also called the nodical month. The orbit of the moon lies in a plane that is tilted with respect to the plane of the ecliptic: it has an inclination of about five degrees. The line of intersection of these planes defines two points on the celestial sphere: the ascending node, when the moon's path crosses the ecliptic as the moon moves into the northern hemisphere, and descending node when the moon's path crosses the ecliptic as the moon moves into the southern hemisphere. The draconic or nodical month is the average interval between two successive transits of the moon through its ascending node. Because of the sun's gravitational pull on the moon, the moon's orbit gradually rotates westward on its axis, which means the nodes gradually rotate around the earth. As a result, the time it takes the moon to return to the same node is shorter than a sidereal month. It lasts 27.212220 days (27 d 5 h 5 min 35.8 s). The plane of the moon's orbit precesses over a full circle in about 18.6 years.

Because the moon's orbit is inclined with respect to the ecliptic, the sun, moon, and earth are in line only when the moon is at one of the nodes. Whenever this happens a solar or lunar eclipse is possible. The name "draconic" refers to a mythical dragon, said to live in the nodes and eat the sun or moon during an eclipse.

Synodic month

This is the average period of the Moon's revolution with respect to the Sun. The synodic month is a description of the Moon's phases, because the Moon's appearance depends on the position of the Moon with respect to the Sun as seen from the Earth. While the moon is orbiting the Earth, the Earth is progressing in its orbit around the Sun. This means that after completing a sidereal month the Moon must move a little farther to reach the new position of the Earth with respect to the Sun. This longer period is called the *synodic* month (Greek: σὺν ὁδῴ, *sun hodō*, meaning "with the way [of the Sun]"). Because of perturbations in the orbits of the Earth and Moon, the actual time between lunations may range from about 29.27 to about 29.83 days. The long-term average duration is

29.530589 days (29 d 12 h 44 min 2.9 s). The synodic month is used in the Metonic cycle.

Month lengths

Here is a list of the average length of the various astronomical lunar months. These are not constant, so a first-order (linear) approximation of the secular change is provided:

Valid for the epoch J2000.0 (1 January 2000 12:00 TT):

anomalistic month	27.554549878 − 0.000000010390 × Y days
sidereal month	27.321661547 + 0.000000001857 × Y days
tropical month	27.321582241 + 0.000000001506 × Y days
draconic month	27.212220817 + 0.000000003833 × Y days
synodic month	29.530588853 + 0.000000002162 × Y days

Note: time expressed in Ephemeris Time (more precisely Terrestrial Time) with days of 86,400 SI seconds. **Y** is years since the epoch (2000), expressed in Julian years of 365.25 days. Note that for calendrical calculations, one would probably use days measured in the time scale of Universal Time, which follows the somewhat unpredictable rotation of the Earth, and progressively accumulates a difference with ephemeris time called ΔT.

Calendrical consequences

At the simplest level, all lunar calendars are based on the approximation that 2 lunations last 59 days: a 30 day **full month** followed by a 29 day **hollow month** — but this is only marginally accurate and quickly needs correction by using larger cycles, or the equivalent of leap days.

Second, the synodic month does not fit easily into the year, which makes constructing accurate, rule-based lunisolar calendars difficult. The most common solution to this problem is the Metonic cycle, which takes advantage of the fact that 235 lunations are approximately 19 tropical years (which add up to not quite 6940 days). However, a Metonic calendar (such as the Hebrew calendar) will drift against the seasons by about 1 day every 200 years.

The problems of creating reliable lunar calendars may explain why solar calendars, having months which no longer relate to the phase of the Moon, and being based only on the motion of the Sun against the sky, have generally replaced lunar calendars for civil use in most societies.

Months in various calendars

Beginning of the lunar month

The Hellenic calendars, the Hebrew Lunisolar calendar and the Islamic Lunar calendar started the month with the first appearance of the thin crescent of the new moon.

However, the motion of the Moon in its orbit is very complicated and its period is not constant. The date and time of this actual observation depends on the exact geographical longitude as well as latitude, atmospheric conditions, the visual acuity of the observers, etc. Therefore the beginning and lengths of months in these calendars can not be accurately predicted.

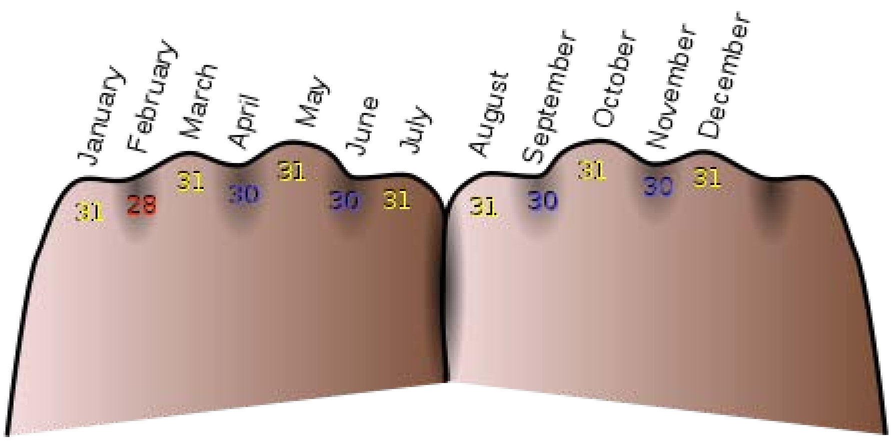
While some like the Karaites Jews still rely on actual moon observations, most people use the Gregorian solar calendar.

Julian and Gregorian calendars

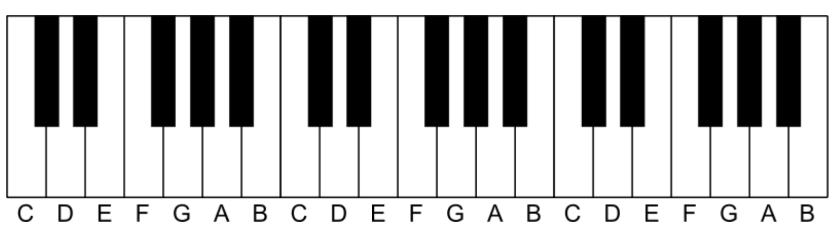
The Gregorian calendar, like the Julian calendar before it, has twelve months:

Chronology	Alphabetic	Days
1	January	31 days
2	February	28 days, 29 in leap years
3	March	31 days
4	April	30 days
5	May	31 days
6	June	30 days

7	July	31 days
8	August	31 days
9	September	30 days
10	October	31 days
11	November	30 days
12	December	31 days



On top of the knuckles (yellow): 31 days Between the knuckles (blue): 30 days February (red) has 28 or 29 days.



The white keys of the musical keyboard correlate to months with 31 days. ('F' correlates to January.)

The average month in the Gregorian calendar has a length of 30.4167 days or 4.345 weeks in a non-leap year and 30.5 days or 4.357 weeks in a leap year, or 30.436875 days in a mean Gregorian month overall (365.2425 ÷ 12).

Months existing in the Roman calendar in the past include:

- Mercedonius, an occasional month after February to realign the calendar.
- Quintilis, renamed to July in honour of Julius Caesar.
- Sextilis, renamed to August in honour of Augustus.

The famous mnemonic *Thirty days hath September* is the most common way of teaching the lengths of the months in the English-speaking world.

Also, note that the latter 10 months of the year form a pair of 31-30-31-30-31-day 5-month cycles.

The knuckles of the four fingers of one's hand and the spaces between them can be used to remember the lengths of the months. By making a fist, each month will be listed as one proceeds across the hand. All months landing on a knuckle are 31 days long and those landing between them are not. When the knuckle of the index finger is reached (July), go back to the first knuckle (or over to the first knuckle on the other fist, held next to the first) and continue with August. This physical mnemonic has been taught to primary school students for many decades.

This cyclical pattern of month lengths matches the musical keyboard alternation of white and black keys (with the note 'F' correlating to the month of January).

Calends, nones, and ides

The **ides** occur on the thirteenth day in eight of the months, but in March, May, July, and October, they occur on the fifteenth. The **nones** always occur 8 days before the ides, i.e., on the fifth or the seventh. The **calends** are always the first day of the month.

Islamic calendar

There are also twelve months in the Islamic calendar. They are named as follows:

1. Muharram ul Haram (or shortened to Muharram) محرّم
2. Safar صفر
3. Rabi`-ul-Awwal (Rabi' I) ربيع الأول
4. Rabi`-ul-Akhir (or Rabi` al-T'haany) (Rabi' II) ربيع الآخر أو ربيع الثاني
5. Jumaada-ul-Awwal (Jumaada I) جمادى الأول
6. Jumaada-ul-Akhir (or Jumaada al-Thaany) (Jumaada II) جمادى الآخر أو جمادى الثاني
7. Rajab رجب
8. Sha'aban شعبان
9. Ramadhan رمضان
10. Shawwal شوّال
11. Dhul Qadah (or Thou al-Qi`dah) ذو القعدة
12. Dhul Hijja (or Thou al-Hijjah) ذو الحجة

Bahá'í calendar

The Bahá'í calendar is the calendar used by the Bahá'í Faith. It is a solar calendar with regular years of 365 days, and leap years of 366 days. Years are composed of 19 months of 19 days each (361 days), plus an extra period of "Intercalary Days" (4 in regular and 5 in leap years). The months are named after the attributes of God. Days of the year begin and end at sundown.

Hebrew Calendar

The Hebrew calendar has 12 or 13 months.

1. Nisan, 30 days ניסן
2. Iyyar, 29 days אייר
3. Sivan, 30 days סיון
4. Tammuz, 29 days תמוז
5. Av, 30 days אב
6. Elul, 29 days אלול
7. Tishri, 30 days תשרי
8. Heshvan, 29/30 days חשון
9. Kislev, 29/30 days כסלו
10. Tevet, 29 days טבת
11. Shevat, 30 days שבט
12. Adar 1, 30 days, intercalary month אדר א
13. Adar 2, 29 days אדר ב

Adar 1 is only added 7 times in 19 years. In ordinary years, Adar 2 is simply called Adar.

French Republican calendar

This calendar was proposed during the French Revolution, and used by the French government for about twelve years from late 1793. There were twelve months of 30 days each, grouped into three ten-day weeks called *décades*. The five or six extra days needed to approximate the tropical year were placed after the months at the end of each year. A period of four years ending on a leap day was to be called a *Franciade*. It began at the autumn equinox:

- Autumn:

1. Vendémiaire
2. Brumaire
3. Frimaire

- Winter:

1. Nivôse

2. Pluviôse
3. Ventôse

- Spring:

1. Germinal
2. Floréal
3. Prairial

- Summer:

1. Messidor
2. Thermidor
3. Fructidor

Iranian/Persian calendar

The Iranian / Persian calendar, currently used in Iran and Afghanistan, also has 12 months. The Persian names are included in the parentheses.

1. Farvardin (فروردین), 31 days
2. Ordibehesht (اردیبهشت), 31 days
3. Khordad (خرداد), 31 days
4. Tir (تیر), 31 days
5. Mordad (مرداد), 31 days
6. Shahrivar (شهریور), 31 days
7. Mehr (مهر), 30 days
8. Aban (آبان), 30 days
9. Azar (آذر), 30 days
10. Dey (دی), 30 days
11. Bahman (بهمن), 30 days
12. Esfand (اسفند), 29 days, 30 in leap years

Reformed Bengali calendar

The Bangla Calendar, used in Bangladesh, follows solar months and it has six seasons. The months and seasons in the calendar are:

Grishho (Summer)

1. Baishakh- 31 days
2. Jyoishtho- 31 days

Borsha (Rainy)

1. Aashar- 31 days

2. Shrabon- 31 days

Sharat (Autumn)

1. Bhadro- 31 days
2. Aashwin- 30 days

Hemanta (Late Autumn)

1. Kartik- 30 days
2. Aghrahayon- 30 days

Sheeth (Winter)

1. Poush- 30 days
2. Magh- 30 days

Bashanta (Spring)

1. Falgoon- 30 days
2. Chaitra- 30 days (31 days in leap year)

Tongan Calendar

The Tongan Calendar are based on the cycles of the moon around the earth in one year.The following months are:

1. Liha Mu'a
2. Liha Mui
3. Vai Mu'a
4. Vai Mui
5. Faka'afu Mo'ui
6. Faka'afu Mate
7. Hilinga Kelekele
8. Hilinga Mea'a
9. 'Ao'ao
10. Fu'ufu'unekinanga
11. 'Uluenga
12. Tanumanga
13. 'O'oamofanongo

Hindu Calendar

The Hindu Calendar has various systems of naming the months. The months in the lunar calendar are:

Sanskrit name	Bengali name	Tamil name
# Chaitra	Chaitra (চৈত্র)	Chitirai
# Vaishaakha	*Baishakha (বৈশাখ)	Vaikasi
# Jyaishtha	Jyaishtha (জ্যৈষ্ঠ)	Aani
# Aashaadha	Ashadha (আষাঢ়)	Aadi
# Shraavana	Shravana (শ্রাবণ)	Aavani
# Bhaadrapada	Bhadra (ভাদ্র)	Purratasi
# Aashvayuja	Ashwina (আশ্বিন)	Aiypasi
# Kaartika	Kartika (কার্তিক)	Kaarthigai
# Maargashiirsha	Agrahayana (অগ্রহায়ণ)	Maargazhi
# Pausha	Pausha (পৌষ)	Thai
# Maagha	Magha (মাঘ)	Maasi
# Phaalguna	Phalguna (ফাল্গুন)	Panguni

In Bengali reckoning, Baishakha is the first month.

These are also the names used in the Indian national calendar for the newly redefined months.

The names in the solar calendar are just the names of the zodiac sign in which the sun travels. They are

1. Mesha
2. Vrishabha
3. Mithuna
4. Kataka
5. Simha
6. Kanyaa
7. Tulaa
8. Vrishcika
9. Dhanus
10. Makara
11. Kumbha
12. Miina

Sinhala calendar

The Sinhala calendar is the Buddhist calendar in Sri Lanka with Sinhala names. Each full moon Poya day marks the start of a Buddhist lunar month. The first month is Bak. The Sinhala and Tamil New Year Day is the start of the Hindu solar calendar (usually 14 April), an event unrelated to the Buddhist calendar.

1. Duruthu
2. Navam
3. Medin
4. Bak
5. Vesak
6. Poson
7. Esala
8. Nikini
9. Binara
10. Vap
11. Il (iL)
12. Unduvap

Icelandic/Old Norse calendar

The old Icelandic calendar is not in official use anymore, but some Icelandic holidays and annual feasts are still calculated from it. It has 12 months, broken down into two groups of six often termed "winter months" and "summer months". The calendar is peculiar in that the months always start on the same weekday rather than on the same date. Hence Þorri always starts on a Friday sometime between January 19 and January 25 *(Old style: January 9 to January 15)*, Góa always starts on a Sunday between February 18 and February 24 *(Old style: February 8 to February 14)*.

- Skammdegi ("Short days")

1. Gormánuður (mid October - mid November, "slaughter month" or "Gór's month")
2. Ýlir (mid November - mid December, "Yule month")
3. Mörsugur (mid December - mid January, "fat sucking month")
4. Þorri (mid January - mid February, "frozen snow month")
5. Góa (mid February - mid March, "Góa's month)
6. Einmánuður (mid March - mid April, "lone" or "single month")

- Náttleysi ("Nightless days")

1. Harpa (mid April - mid May, Harpa is a female name, probably a forgotten goddess, first day of Harpa is celebrated as Sumardagurinn fyrsti - first day of summer)
2. Skerpla (mid May - mid June, another forgotten goddess)
3. Sólmánuður (mid June - mid July, "sun month")

4. Heyannir (mid July - mid August, "hay business month")
5. Tvímánuður (mid August - mid September, "two" or "second month")
6. Haustmánuður (mid September - mid October, "autumn month")

Old English calendar

Like the Old Norse calendar, the Anglo-Saxons had their own calendar before they were Christianized which reflected native traditions and deities. These months were attested by Bede in his work *On Chronology* written in the 8th century. His months are probably those as written in the Northumbrian dialect of Old English which he was familiar with. The months were so named after the moon; the new moon marking the end of an old month and start of a new month; the full moon occurring in the middle of the month, after which the month was named.

1. Æfterra-ġēola mōnaþ (January, 'After-Yule month')
2. Sol-mōnaþ (February, 'Sol month')
3. Hreþ-mōnaþ (March, 'Hreth month')
4. Ēostur-mōnaþ (April, 'Ēostur month')
5. Đrimilce-mōnaþ (May, 'Three-milkings month')
6. Ærra-Liþa (June, 'Ere-Litha')
7. Æftera-Liþa (July, 'After-Litha')
8. Wēod-mōnaþ (August, 'Weed month')
9. Hāliġ-mōnaþ or Hærfest-mōnaþ (September, 'Holy month' or 'Harvest month')
10. Winter-fylleþ (October, 'Winter-filleth')
11. Blōt-mōnaþ (November, 'Blót month')
12. Ærra-ġēola mōnaþ (December, 'Ere-Yule')

Old Hungarian calendar

Historically Hungary used a 12-month calendar that appears to have been zodiacal in nature but eventually came to correspond to the Gregorian months as shown below:

1. Boldogasszony hava (January, 'month of the happy/blessed lady')
2. Böjtelő hava (February, 'month of early fasting/Lent' or 'month before fasting/Lent')
3. Böjtmás hava (March, 'second month of fasting/Lent')
4. Szent György hava (April, 'St. George's month)
5. Pünkösd hava (May, 'Pentecost month')
6. Szent Iván hava (June, 'St. Ivan's month')
7. Szent Jakab hava (July, 'St. James' month')
8. Kisasszony hava (August, 'month of the Virgin')
9. Szent Mihály hava (September, 'St. Michael's month')
10. Mindszent hava (October, 'all saints month')
11. Szent András hava (November, 'St. Andrew's month')
12. Karácsony hava (December, 'month of Yule/Christmas')

Old Egyptian calendar

The ancient civil Egyptian calendar had a year that was 365 days long and was divided into 12 months of 30 days each, plus 5 extra days (epagomenes) at the end of the year. The months were divided into 3 "weeks" of ten days each. Because the ancient Egyptian year was almost a quarter of a day shorter than the solar year and stellar events "wandered" through the calendar, it is referred to as Annus Vagus or "Wandering Year".

1. Thout
2. Paopi
3. Hathor
4. Koiak
5. Tooba
6. Emshir
7. Paremhat
8. Paremoude
9. Pashons
10. Paoni
11. Epip
12. Mesori

Nisga'a calendar

The Nisga'a Calendar coincides with the Gregorian Calendar with each month referring to the type of Harvesting that is done during the month.

1. K'aliiyee = Going North - referring to the Sun returning to its usual place in the sky
2. Buxwlaks = Needles Blowing About - February is usually a very windy month in the Nass River Valley
3. Xsaak = To Eat Oolichans - Oolichans are harvested during this month
4. Mmaal = Canoes - The river has defrosted, hence canoes are used once more
5. Yansa'alt = Leaves are Blooming - Warm weather has arrived and leaves on the trees begin to bloom
6. Miso'o = Sockeye - majority of Sockeye Salmon runs begin this month
7. Maa'y = Berries - berry picking season
8. Wii Hoon = Great Salmon - referring to the abundance of Salmon that are now running
9. Genuugwwikw = Trail of the Marmot - Marmots, Ermines and animals as such are hunted
10. Xlaaxw = To Eat Trout - trout are mostly eaten this time of year
11. Gwilatkw = To Blanket - The earth is "blanketed" with snow
12. Luut'aa = Sit In - the Sun "sits" in one spot for a period of time

Chapter-10

Millennium

A **millennium** (plural **millenniums** or **millennia**) is a period of time equal to ***one thousand years (1,000)*** (from the Latin phrase *mille*, thousand, and *annus*, year), often but not necessarily related numerically to a particular dating system.

For example, a millennium could start at the beginning of the year 289 and finish at the beginning of the year 1289.

Sometimes, it is used specifically for periods of one thousand years that begin at the starting point (initial reference point) of the calendar in consideration (Thus is typically the year "1".), or in later years which are whole number multiples of a thousand years after it. The term can also refer to an interval of time beginning on any date. Frequently in the latter case (and sometimes also in the former) it may have religious or theological implications. Sometimes in religious usages, such an interval called a "millennium" might be interpreted less precisely, i.e., not always being exactly 1000 years long.

Counting years

Ordinal

The original method of counting years was ordinal, whether *1st year A.D.* or regnal *10th year of King Henry VIII*. This ordinal numbering is still present in the *names* of the millennia and centuries, for example *1st Millennium* or the *20th century*, and sometimes in the names of decades, e.g. *1st decade of the 21st century*.

Ranges

A change from ordinals to cardinals is incomplete and might not ever be completed; the main issues arise from the *content* of the various year ranges. Similar issues affect the *contents* of centuries. Decades are usually referred to by their leading numbers and are therefore immune to this controversy: the decade called 1990s would by its naming not include 2000. Similarly the 100 years comprising the 1900s share 99 years in common with the 20th century, but do not include 2000.

Those following ordinal year names naturally choose

- 2001–2100 as the current century
- 2001–3000 as the current millennium

Those following cardinal year names equally naturally choose

- 2000–2099 as the current century
- 2000–2999 as the current millennium

Debate over millennium celebrations

The common Western calendar, i.e. the Gregorian calendar, has been defined with counting origin 1. Thus each period of 1,000 years concludes with a year number with three zeroes, e.g. the first thousand years in the Western calendar included the year 1000. However, there are two viewpoints about how millennia should be thought of in practice, one which relies on the formal operation of the calendar and one which appeals to other notions that attract popular sentiment. A number of countries have legally adopted ISO 8601, also used in other contexts, which uses the astronomical calendar in which year counting starts at 0. Thus, when using this calendar, the millennium starts at x000 and ends at x999. There was a popular debate leading up to the celebrations of the year 2000 as to whether the beginning of that year should be understood (and celebrated) as the beginning of a new millennium. Historically, there has been debate around the turn of previous decades, centuries, and millennia. The issue is tied to the convention of using ordinal numbers to count millennia (as in "the third millennium"), as opposed to using cardinal numbers (as in "the two thousands"), which is unambiguous as it does not depend on which year counting starts. The first convention is common in English speaking countries, but the latter is favored in for example Sweden ("tvåtusentalet").

Arbitrariness of the selection of the Year One

As a side-note to the debate on timing of the "turning of the millennium", the arbitrariness of the era itself can be raised. Mathematically, the choice of the zero point on any timeline is an arbitrary one. (However, once chosen, it must be abided.)

The Gregorian calendar is a secularized, *de facto* standard, based on a significant Christian event, the purported date of the birth of Jesus Christ. Thus, the foundation of the calendar may not be as relevant to non-Christians. The calendar is one among many other calendars that are still in use and have been used, historically. Adjustments and errors in the calendar (such as Dionysius Exiguus's incorrect calculation of the year 1 AD) make the particular dates we use today arbitrary.

However, everyone can utilize the current, very common calendar, referring to its years as either being year of the *"Christian Era"* or the *"Common Era"*, or the years earlier than this one as being either before the *"Christian Era"* or before the *"Common Era"*, abbreviated ***BCE.***.

Viewpoint 1: x001–y000

Those holding that the arrival of new millennium should be celebrated in the transition from 2000 to 2001 (i.e. December 31, 2000), argued that since the Gregorian Calendar has no year zero, the millennia should be counted from 1 AD. Thus the first period of one thousand complete years runs from the beginning of 1 AD to the end of 1000 AD, and the beginning of the second millennium took place at the beginning of 1001. The second millennium thus ends at the end of the year 2000. Then again, those who defend the opposite idea state that the new millennium started with the year 2000 (because of the changes made to the Gregorian calendar in 1582, or because the first millennium started in 1 AD. and ended in 999 AD, being the only millennium (along with the last millennium b.c.) not with 1000 years, but with 999 years).

Arthur C. Clarke gave this analogy (from a statement received by Reuters): "If the scale on your grocer's weighing machine began at 1 instead of 0, would you be happy when he claimed he'd sold you 10 kg of tea?" This statement illustrates the common confusion about the calendar. If one counts from the beginning of AD 1 to the ending of AD 1000, one would have counted 1000 years. The next 1000 years (millennium) would begin on the first day of 1001. So the calendar has not 'cheated' anyone out of a year. In other words, the argument is based on the fact that the last year of the first two thousand years in the Gregorian Calendar was 2000, not 1999.

Viewpoint 2: x000–x999

The "year 2000" has also been a popular phrase referring to an often utopian future, or a year when stories in such a future were set, adding to its cultural significance. There was also media and public interest in the Y2K bug. Thus, the populist argument was that the new millennium should begin when the zeroes "rolled over" to 2000, i.e. the day after December 31, 1999. People felt that the change of hundred digit in the year number, and the zeros rolling over, created a sense that a new century had begun. This is similar to the common demarcation of decades by their most significant digits, e.g. naming the period 1980 to 1989 as the 1980s or "the eighties". Similarly, it would be valid to celebrate the year 2000 as a cultural event in its own right, and name the period 2000 to 2999 as "the 2000s".

Most historians agree that Dionysius nominated Christ's birth as December 25 of the year before AD 1. This corresponded with the belief that the birth year itself was considered too holy to mention. It also corresponds to the notion that AD 1 was "the first year of his life", as distinguished from being the year after his first birthday. Similarly in 1000 AD the church actively discouraged any mention of that year and in modern times it labelled 2000 AD as the "Jubilee Year 2000" marking the 2000th anniversary of the birth of Christ. The *AD system* counts years with origin 1. Some assume a preceding Year 0 for the start of the first Christian millennium in order to start the millennia in year numbers multiple of 1000.

Popular approach

The majority popular approach was to treat the end of 1999 as the end of a millennium, and to hold millennium celebrations at midnight between December 31, 1999 and January 1, 2000, as per viewpoint 2. The cultural and psychological significance of the events listed above combined to cause celebrations to be observed one year earlier than the formal Gregorian date. This does not, of course, establish that insistence on the formal Gregorian date is "incorrect", though some view it as pedantic (as in the comment of Douglas Adams mentioned below). Some event organisers hedged their bets by calling their 1999 celebrations things like "Click" referring to the odometer-like rolling over of the nines to zeros. A second approach was to adopt two different views on the millennium problem and celebrate the new millennium twice.

Commentary on "The Millennium"

- Stephen Jay Gould noted in his essay *Dousing Diminutive Dennis' Debate (or DDDD = 2000)* (*Dinosaur in a Haystack*) that celebrations and media announcements marked the turn into the twentieth century along the boundary of 1900 and 1901, citing, among other examples, the New York Times's headline "Twentieth Century's Triumphant Entry" on January 1, 1901. Gould also included comments on adjustments to the calendar, such as those by Dionysius Exiguus (the eponymous "Diminutive Dennis"), the timing of celebrations over different transitional periods, and the "high" versus "pop" culture interpretation of the transition. Further of his essays on this topic are collected in *Questioning the Millennium: A Rationalist's Guide to a Precisely Arbitrary Countdown*.

- In the editorial to 2002's *Best American Essays* Gould highlights the use of historical events, rather than transitional dates, to delineate periods of history: "Many commentators have stated — quite correctly in my view — that the twentieth century did not truly begin in 1900 or 1901, by any standard of historical continuity, but rather *at the end of World War I*, the great shatterer of illusions about progress and human betterment... I suspect that future chroniclers will date the inception of the third millennium from ***September 11, 2001***."

- Douglas Adams highlighted the sentiment that those in favor of a 2001 celebration were pedantic spoil-sports in his short Internet article *Significant Events of the Millennium*. This sentiment was also demonstrated when, in 1997, the Australian Prime Minister John Howard made a point in favor of the celebration's being in 2001, and he was named "the party pooper of the century" by local newspapers.

- In an episode of the American television series, *Seinfeld*, titled "The Millennium", Jerry Seinfeld states, "Since there was no year zero, the millennium doesn't begin until the year *two-thousand and one*."

- In the TV series, *The X-Files*, there is an episode titled "Millennium", continuing the TV series of the same name. In this episode Dr. Scully mentions that the new Millennium doesn't start until January 1, 2001. She is made fun of, but not suggested to be *incorrect*. Mulder responds, "No one likes a math geek, Scully."

- The action of the book The Headless Bust: A Melancholy Meditation on the False Millennium, by Edward Gorey, takes place on December 31, 1999, and it refers to the next coming year as the start of the new Millennium, despite the fact that the title of the book calls it the "False Millennium."

- The host of the game show *Jeopardy!*, Alex Trebek, proudly welcomed his guests and the contestants to the "first day of the 21st century" on January 1, 2001.

- The science writer Sir Arthur C. Clarke firmly stated in his writings that the beginning of the New Millennium would be on January 1, 2001. Clarke had also very optimistically prophesied that on that date, all telephone calls, worldwide, would become local calls. In other words, there would no longer be any extra charges for long-distance calls, anywhere.

- Linguist Arnold Zwicky suggested an analogy with the adjustment from Julian to Gregorian calendar:

  Let's take a clue from the defective Gregorian year, the one with only 355 days in it. ... If a year can be stipulated to be defective by some days, why can't a decade, century, or millennium be stipulated to be defective by a year? Why don't we just say that the first decade in our western calendar was short by a year? Then as a result the first century was similarly short, and the first millennium too. Thereafter nothing's defective. This stipulation performs a cultural function; it aligns the beginning of every decade, century, and millennium (except the very first of each of these) with an auspiciously numbered year.

Chapter-11

Second

The **second** (SI symbol: **s**), sometimes abbreviated **sec.**, is a unit of time, and is the International System of Units (SI) base unit of time. It may be measured using a clock.

Early definitions of the second were based on the apparent motion of the sun around the earth. The solar day was divided into 24 hours, each of which contained 60 minutes of 60 seconds each, so the second was $^1/_{86\ 400}$ of the mean solar day. However, 19th- and 20th century astronomical observations revealed that this average time is lengthening, and thus the sun/earth motion is no longer considered a suitable basis for definition. With the advent of atomic clocks, it became feasible to define the second based on fundamental properties of nature. Since 1967, the second has been defined to be

the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.

SI prefixes are frequently combined with the word *second* to denote subdivisions of the second, *e.g.*, the millisecond (one thousandth of a second), the microsecond (one millionth of a second), and the nanosecond (one billionth of a second). Though SI prefixes may also be used to form multiples of the second such as kilosecond (one thousand seconds), such units are rarely used in practice. The more common larger non-SI units of time are not formed by powers of ten; instead, the second is multiplied by 60 to form a minute, which is multiplied by 60 to form an hour, which is multiplied by 24 to form a day.

The second is also the base unit of time in the centimetre-gram-second, metre-kilogram-second, metre-tonne-second, and foot-pound-second systems of units.

International second

Under the International System of Units (via the International Committee for Weights and Measures, or CIPM), since 1967 the second has been defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom. In 1997 CIPM added that the periods would be defined for a caesium atom at rest, and approaching the theoretical temperature of absolute zero, and in 1999, it included corrections from ambient radiation.

This definition refers to a caesium atom at rest at a temperature of 0 K (absolute zero). Absolute zero implies no movement, and therefore zero external radiation effects (i.e., zero local electric and magnetic fields). The second thus defined is consistent with the ephemeris second, which was based on astronomical measurements.

The realization of the standard second is described briefly in a special publication from the National Institute of Science and Technology, and in detail by the National Research Council of Canada.

Equivalence to other units of time

1 international second is equal to:

- 1/60 minute
- 1/3,600 hour
- 1/86,400 day (IAU system of units)
- 1/31,557,600 Julian year (IAU system of units)

History

Before mechanical clocks

The Egyptians subdivided daytime and nighttime into twelve hours each since at least 2000 BC, hence the seasonal variation of their hours. The Hellenistic astronomers Hipparchus (*c.* 150 BC) and Ptolemy (*c.* AD 150) subdivided the day sexagesimally and also used a mean hour ($\frac{1}{24}$ day), simple fractions of an hour ($\frac{1}{4}$, $\frac{2}{3}$, etc.) and time-degrees ($\frac{1}{360}$ day or four modern minutes), but not modern minutes or seconds.

The day was subdivided sexagesimally, that is by $\frac{1}{60}$, by $\frac{1}{60}$ of that, by $\frac{1}{60}$ of that, etc., to at least six places after the sexagesimal point (a precision of less than 2 microseconds) by the Babylonians after 300 BC, but they did not sexagesimally subdivide smaller units of time. For example, six fractional sexagesimal places of a day was used in their specification of the length of the year, although they were unable to measure such a small fraction of a day in real time. As another example, they specified that the mean synodic month was 29;31,50,8,20 days (four fractional sexagesimal positions), which was repeated by Hipparchus and Ptolemy sexagesimally, and is currently the mean synodic month of the Hebrew calendar, though restated as 29 days 12 hours 793 halakim (where 1 hour = 1080 halakim). The Babylonians did not use the hour, but did use a double-hour lasting 120 modern minutes, a time-degree lasting four modern minutes, and a barleycorn lasting $3\frac{1}{3}$ modern seconds (the *helek* of the modern Hebrew calendar).

In 1000, the Persian scholar al-Biruni gave the times of the new moons of specific weeks as a number of days, hours, minutes, seconds, thirds, and fourths after noon Sunday. In

1267, the medieval scientist Roger Bacon stated the times of full moons as a number of hours, minutes, seconds, thirds, and fourths (*horae*, *minuta*, *secunda*, *tertia*, and *quarta*) after noon on specified calendar dates. Although a *third* for $^1/_{60}$ of a second remains in some languages, for example Polish (*tercja*) and Turkish (*salise*), the modern second is subdivided decimally.

Seconds measured by mechanical clocks

The earliest clocks to display seconds appeared during the last half of the 16th century. The earliest spring-driven timepiece with a second hand which marked seconds is an unsigned clock depicting Orpheus in the Fremersdorf collection, dated between 1560 and 1570. During the 3rd quarter of the 16th century, Taqi al-Din built a clock with marks every five seconds. In 1579, Jost Bürgi built a clock for William of Hesse that marked seconds. In 1581, Tycho Brahe redesigned clocks that displayed minutes at his observatory so they also displayed seconds. In 1587 he complained that his four clocks disagreed by plus or minus four seconds.

The second first became accurately measurable with the development of pendulum clocks keeping *mean time* (as opposed to the *apparent time* displayed by sundials), specifically in 1670 when William Clement added a seconds pendulum to the original pendulum clock of Christian Huygens. The seconds pendulum has a period of two seconds, one second for a swing forward and one second for a swing back, enabling the longcase clock incorporating it to tick seconds. From this time, a second hand that rotated once per minute in a small subdial began to be added to the clock faces of precision clocks.

Modern measurements

In 1956 the second was defined in terms of the period of revolution of the Earth around the Sun for a particular epoch, because by then it had become recognized that the Earth's rotation on its own axis was not sufficiently uniform as a standard of time. The Earth's motion was described in Newcomb's Tables of the Sun (1895), which provide a formula estimating the motion of the Sun relative to the epoch 1900 based on astronomical observations made between 1750 and 1892. The second thus defined is

the fraction 1/31,556,925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time.

This definition was ratified by the *Eleventh General Conference on Weights and Measures* in 1960. The *tropical year* in the definition was not measured, but calculated from a formula describing a mean tropical year that decreased linearly over time, hence the curious reference to a specific *instantaneous* tropical year. This definition of the second was in conformity with the ephemeris time scale adopted by the IAU in 1952, defined as the measure of time that brings the observed positions of the celestial bodies into accord with the Newtonian dynamical theories of their motion (those accepted for use during most of the 20th century being Newcomb's Tables of the Sun, used from 1900 through 1983, and Brown's Tables of the Moon, used from 1923 through 1983).

With the development of the atomic clock, it was decided to use atomic clocks as the basis of the definition of the second, rather than the revolution of the Earth around the Sun.

Following several years of work, Louis Essen from the National Physical Laboratory (Teddington, England) and William Markowitz from the United States Naval Observatory (USNO) determined the relationship between the hyperfine transition frequency of the caesium atom and the ephemeris second. Using a common-view measurement method based on the received signals from radio station WWV, they determined the orbital motion of the Moon about the Earth, from which the apparent motion of the Sun could be inferred, in terms of time as measured by an atomic clock. They found that the second of ephemeris time (ET) had the duration of 9,192,631,770 ± 20 cycles of the chosen caesium frequency. As a result, in 1967 the Thirteenth General Conference on Weights and Measures defined the second of atomic time in the International System of Units as

FOCS 1, a continuous cold caesium fountain atomic clock in Switzerland, started operating in 2004 at an uncertainty of one second in 30 million years.

the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.

This SI second, referred to atomic time, was later verified to be in agreement, within 1 part in 10^{10}, with the second of ephemeris time as determined from lunar observations. (Nevertheless, this SI second was already, when adopted, a little shorter than the then-current value of the second of mean solar time.)

During the 1970s it was realized that gravitational time dilation caused the second produced by each atomic clock to differ depending on its altitude. A uniform second was produced by correcting the output of each atomic clock to mean sea level (the rotating geoid), lengthening the second by about 1×10^{-10}. This correction was applied at the beginning of 1977 and formalized in 1980. In relativistic terms, the SI second is defined as the proper time on the rotating geoid.

The definition of the second was later refined at the 1997 meeting of the BIPM to include the statement

This definition refers to a caesium atom at rest at a temperature of 0 K.

The revised definition seems to imply that the ideal atomic clock contains a single caesium atom at rest emitting a single frequency. In practice, however, the definition means that high-precision realizations of the second should compensate for the effects of the ambient temperature (black-body radiation) within which atomic clocks operate, and extrapolate accordingly to the value of the second at a temperature of absolute zero.

Today, the atomic clock operating in the microwave region is challenged by atomic clocks operating in the optical region. To quote Ludlow *et al.*, “In recent years, optical atomic clocks have become increasingly competitive in performance with their microwave counterparts. The overall accuracy of single trapped ion based optical standards closely approaches that of the state-of-the-art caesium fountain standards. Large ensembles of ultracold alkaline earth atoms have provided impressive clock stability for short averaging times, surpassing that of single-ion based systems. So far, interrogation of neutral atom based optical standards has been carried out primarily in free space, unavoidably including atomic motional effects that typically limit the overall system accuracy. An alternative approach is to explore the ultranarrow optical transitions of atoms held in an optical lattice. The atoms are tightly localized so that Doppler and photon-recoil related effects on the transition frequency are eliminated.”

The NRC attaches a "relative uncertainty" of 2.5×10^{-11} (limited by day-to-day and device-to-device reproducibility) to their atomic clock based upon the $^{127}I_2$ molecule, and is advocating use of an ^{88}Sr ion trap instead (relative uncertainty due to linewidth of 2.2×10^{-15}).

Such uncertainties rival that of the NIST F-1 caesium atomic clock in the microwave region, estimated as a few parts in 10^{16} averaged over a day.

SI multiples

SI prefixes are commonly used to measure time less than a second, but rarely for multiples of a second. Instead, the non-SI units minutes, hours, days, Julian years, Julian centuries, and Julian millennia are used.

SI multiples for second (s)

Submultiples			Multiples		
Value	**Symbol**	**Name**	**Value**	**Symbol**	**Name**
10^{-1} s	ds	decisecond	10^{1} s	das	decasecond
10^{-2} s	cs	centisecond	10^{2} s	hs	hectosecond
10^{-3} s	**ms**	**millisecond**	10^{3} s	ks	kilosecond
10^{-6} s	**µs**	**microsecond**	10^{6} s	Ms	megasecond
10^{-9} s	**ns**	**nanosecond**	10^{9} s	Gs	gigasecond
10^{-12} s	ps	picosecond	10^{12} s	Ts	terasecond
10^{-15} s	fs	femtosecond	10^{15} s	Ps	petasecond
10^{-18} s	as	attosecond	10^{18} s	Es	exasecond
10^{-21} s	zs	zeptosecond	10^{21} s	Zs	zettasecond
10^{-24} s	ys	yoctosecond	10^{24} s	Ys	yottasecond

Common prefixes are in bold

Other current definitions

For specialized purposes, a second may be used as a unit of time in time scales where the precise length differs slightly from the SI definition. One such time scale is UT1, a form of universal time. McCarthy and Seidelmann refrain from stating that the SI second is the legal standard for timekeeping throughout the world, saying only that "over the years UTC [which ticks SI seconds] has become either the basis for legal time of many countries, or accepted as the *de facto* basis for standard civil time".

Chapter-12

Cenomanian

System	Series	Stage	Age (Ma)
Paleogene	Paleocene	Danian	younger
Cretaceous	Upper	Maastrichtian	65.5–70.6
		Campanian	70.6–83.5
		Santonian	83.5–85.8
		Coniacian	85.8–89.3
		Turonian	89.3–93.5
		Cenomanian	93.5–99.6
	Lower	Albian	99.6–112.0
		Aptian	112.0–125.0
		Barremian	125.0–130.0
		Hauterivian	130.0–136.4
		Valanginian	136.4–140.2
		Berriasian	140.2–145.5
Jurassic	Upper	Tithonian	older

Subdivision of the Cretaceous system according to the IUGS, as of July 2009.

The **Cenomanian** is, in the ICS' geological timescale the oldest or earliest age of the Late Cretaceous epoch or the lowest stage of the Upper Cretaceous series. An age is a unit of geochronology: it is a unit of time; the stage is a unit in the stratigraphic column deposited during the corresponding age. Both age and stage bear the same name.

As a unit of geologic time measure, the Cenomanian age spans the time between 99.6 ± 0.9 **Ma** and 93.5 ± 0.8 **Ma** (million years ago). In the geologic timescale it is preceded by the Albian and is followed by the Turonian.

The Cenomanian is coeval with the Woodbinian of the regional timescale of the Mexican Gulf and the Eaglefordian of the regional timescale of the US eastcoast.

At the end of the Cenomanian an anoxic event took place, called the Cenomanian-Turonian boundary event or the "Bonarelli Event", that is associated with a minor extinction event for marine species.

Stratigraphic definitions

The Cenomanian was introduced in scientific literature by French palaeontologist Alcide d'Orbigny in 1847. Its name comes from the New Latin name of the French city of Le Mans (département Sarthe), *Cenomanum*.

The base of the Cenomanian stage (which is also the base of the Upper Cretaceous series) is placed at the first appearance of foram species *Rotalipora globotruncanoides* in the stratigraphic record. An official reference profile for the base of the Cenomanian (a GSSP) is located in an outcrop at the western flank of Mont Risou, near the village of Rosans in the French Alps (département Hautes-Alpes, coordinates: 44°23'33"N, 5°30'43"E). The base is, in the reference profile, located 36 meters below the top of the Marnes Bleues Formation.

The top of the Cenomanian (the base of the Turonian) is at the first appearance of ammonite species *Watinoceras devonense*.

Important index fossils for the Cenomanian are the ammonites *Calycoceras naviculare*, *Acanthoceras rhotomagense* and *Mantelliceras mantelli*.

Sequence stratigraphy and palaeoclimatology

The late Cenomanian represents the highest mean sea-level observed in the Phanerozoic eon, the past six hundred million years (approximately one hundred and fifty meters above present day sea-levels). A corollary is that the highlands were at all time lows, so the landscape on Earth was one of warm broad shallow seas inundating low lying land areas on the precursors to today's continents. What few lands rose above the waves were made of old mountains and hills, upland plateaus, all much weathered. Tectonic mountain building was minimal and most continents were isolated by large stretches of water. Without highlands to brake winds, the climate would have been windy and waves large, adding to the weathering and fast rate of sediment deposition.

Palaeontology

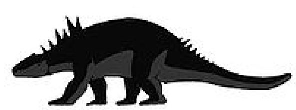
†Belemnites

Belemnites of the Cenomanian

Taxa	Presence	Location	Description	Images
Hibolites				

†Ankylosauria

Ankylosaurs of the Cenomanian

Taxa	Presence	Location	Description	Images
Acanthopholis	Albian or Aptian to Cenomanian	Upper Greensand Group, Cambridgeshire, England	A nodosaurid with an armor of oval plates set almost horizontally into the skin, with spikes protruding from the neck and shoulder area, along the spine. Its size has been estimated to be in the range of 3 to 5.5 meters (10 to 18 ft) long and approximately 380 kilograms (840 lb) in weight.	 *Acanthopholis*
Animantarx	Cenomanian to Turonian	Cedar Mountain Formation, Utah, USA	thought of as a nodosaurid ankylosaur, although its precise relationships within that family are uncertain	
Nodosaurus		Wyoming,	A nodosaurid	

		Kansas, USA	ankylosaur about 4 to 6 meters (13 to 20 feet) long with bony dermal plates covering the top of its body. It may have had spikes along its side as well. It had four short legs, five-toed feet, a short neck, and a long, stiff, clubless tail.
Stegopelta	Late Albian to early Cenomanian	Frontier Formation, Wyoming, USA	A poorly known genus of nodosaurid
Tsagantegia		Baynshiree Svita Formation, Dzun-Bayan, Mongolia	An ankylosaurid known from the remains of its skull
Zhejiangosaurus		Chaochuan Formation, Zhejiang, China	Nodosaurid
Zhongyuansaurus		Ruyang, Henan, China	Nodosaurid

†Ornithopoda

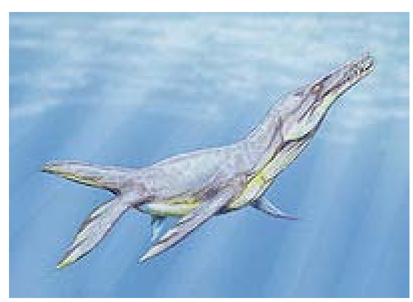
Ornithopods of the Cenomanian

Taxa	Presence	Location	Description	Images
Anabisetia		Cerro Lisandro Formation, Neuquén, Argentina	A small bipedal herbivore, almost seven feet (2 meters) long	
Bihariosaurus		Bihor, Romania	An iguanodont similar to Camptosaurus	
Eolambia	Albian-	Utah, USA	An iguanodont	

Gadolosaurus	Cenomanian	Mongolia	
Notohypsilophodon	Cenomanian-Turonian	Bajo Barreal Formation, Chubut, Argentina	A hypsilophodontid or other basal ornithopod, Notohypsilophodon would have been a bipedal herbivore. Its size has not been estimated
Oryctodromeus		Blackleaf Formation, Montana, and Wayan Formation, Idaho, USA	A burrowing hypsilophodont
Protohadros		Flower Mound, Texas, USA	A primitive hadrosauroid, Protohadros reached 6 m (19.5 ft) in length and had many hadrosaur-like features
Shuangmiaosaurus	Cenomanian-Turonian	China	A poorly known iguanodont

†Plesiosauria

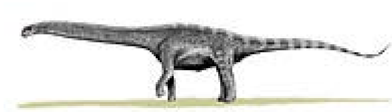
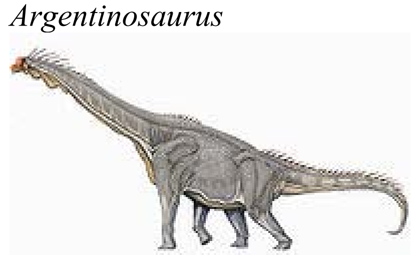
Plesiosaurs of the Cenomanian

Taxa	Presence	Location	Description	Images
Plesiopleurodon		Belle Fourche Shale, Wyoming, USA	A pliosaurid characterized by a moderately long symphysis bearing 8 pairs of teeth, teeth that are nearly circular in cross-section and which are smooth on the outer surface (except near the base), ribs of the	 Plesiopleurodon

			neck vertebrae being singled-headed (double-headed in Jurassic pliosaurs), and a long slender interpectoral bar on the coracoid	

†Sauropoda

Sauropods of the Cenomanian

Taxa	Presence	Location	Description	Images
Argentinosaurus		Río Limay Formation, Neuquén, Argentina		 *Argentinosaurus*
Brachiosaurus	? Brachiosaurus nougaredi	Wargla, Algeria		 *Brachiosaurus*

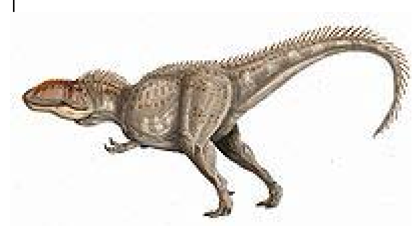
Theropoda

Theropods of the Cenomanian

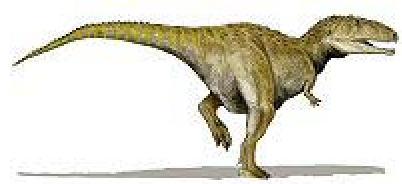
Taxa	Presence	Location	Description	Images
Carcharodontosaurus		Morocco; Niger		

Deltadromeus	Morocco
Giganotosaurus	Rio Limay, Argentina
Mapusaurus	Huincul Formation, Argentina
Siamosaurus	Thailand
Sigilmassasaurus	Tafilalt, Morocco
Spinosaurus	Bahariya Oasis, Egypt; Tunisia; Morocco
Unenlagia	Comahue, Argentina
unnamed enantiornithine bird	Nammoura, Ouadi al Gabour, Lebanon

Deltadromeus



Giganotosaurus



Mapusaurus

Unenlagia