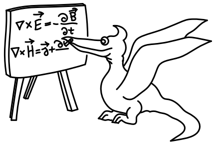

Serial: Time

This year's series will explore measurement, standardization, and the now widely used system of SI units. We will look at the historical development of the definitions of the base units, which will be closely related to the procedures and the precision of measurements of physical quantities, as well as their current forms and methods of measurement on different scales and in different situations.

Standardization

Humankind probably started measuring in prehistoric times. However, this "measuring" was very simple, such as counting the number of days elapsed or dividing the found booty. Advances in measurement came in Mesopotamia with the development of trade, brewing, and the judiciary system, by introducing various measures of volume, length, and weight. The situation did not change much until the end of the Middle Ages – each kingdom usually had its own currency as well as length, volume, and weight measures, which were usually derived from the currently reigning ruler (coins bearing his image or inches and feet given by his physical dimensions). Thus, in addition to being a tool of trade and craftsmanship, measures also became political tools. Moreover, in each country, the base units were divided into smaller/larger subunits, derived as different fractions of the base units, as can still be seen, for example, with the imperial units. This situation made international trade more difficult and, with the advent of the Industrial Revolution, when the design of machines began to require precise measurements, it became unbearable.

The standardization of the decimal-based units we use today began at the time of the French Revolution with the creation of the platinum prototypes of kilogram and meter, which were placed in the National Archives in Paris in 1799. Later, in 1832, C. F. Gauss proposed these units, along with the astronomically defined second, to become the base units of physical measurements. The CGS system based on centimeter, gram, and second was developed in 1874. With the discovery of electrical and magnetic properties of materials, it was necessary to standardize the electromagnetic quantities. However, the units of electromagnetic quantities derived from the CGS system had inconvenient dimensions for practical use. In the 1880s, the International Electrical Congress adopted a new system of electromagnetic units whose names are in use nowadays – ampere, volt, ohm, farad, siemens, etc.

On the 20th May 1875, with the signing of the Metric Convention, the International Bureau of Weights and Measures was established (Bureau International des Poids et Mesures),[1] which at its first congress adopted the standard units of mechanical quantities that we know today (kilogram, meter, and second), and to this day oversees the standardization of measurements. in 1901, Giovanni Giorgi showed that by adopting a single electrical unit, it was possible to include electromagnetism in the mechanical system, which led to the adoption of ampere as a base unit of physics in 1946. More units were added to the system in 1954. Kelvin became the unit of thermodynamic temperature, candela the unit of luminous intensity, and in 1971, mole

[1] The webpage of the Bureau `https://www.bipm.org/en/home` has a lot of interesting pieces of information, both historical and technical

became the unit for the amount of substance – the system of SI units was born (Système International). In addition to the base units, this system also introduced derived units of quantities, prefixes for the characterization of the decadic order of the measured values, and typographical rules for the handling of the measured values of quantities. It also provides a methodology for the calibration of instruments based on these definitions.

Over time, there has been a transition from using physical standards to define units, towards relying on natural constants. That has resulted in a gradual improvement in the precision of base units. The transition was finalized with a new definition for kilogram approved at a congress in 2019. As of today, we define physical units by fixed values of the following constants:

- the hyperfine transition frequency of cesium $\Delta\nu_{\mathrm{Cs}}$,
- the speed of light in vacuum c,
- the Planck constant h,
- the elementary charge e,
- the Boltzmann constant k_{B},
- the Avogadro constant N_{A},
- the luminous efficacy K_{cd} of monochromatic radiation of a given wavelength.

The metric system was adopted in the Czech territory at the time of the Austro-Hungarian monarchy in 1871 and entered use in 1876. Since then, the units and standards in the Czech Republic have been given by international development. Nowadays, the Czech Metrology Institute based in Brno is responsible for the standardization of units and calibration of instruments.

Calibration

Before we get into the core of the series, let's review the definitions of a couple of terms. A physical quantity is a property of a material, object, system, or process that can be quantified – expressed as a value consisting of a numerical value and a physical unit. The determination of this value typically involves employing a specific measurement technique with a measuring instrument – usually by reading the value from a digital display of an electronic measuring device or the position of a needle on a dial in the case of a mechanical instrument.

Each measurement involves determining the accuracy of the result, i.e., estimating the deviation of the measured value from the actual one. The deviation usually comprises a random component that fluctuates from one measurement to another. We can determine this component by repeating the measurement and suppressing it by averaging the measured values. However, more problematic is the systematic error, which stays the same in every measurement – typically due to inaccurate calibration of the instrument or the method itself. The accuracy of the apparatus is usually indicated directly on the device (in the case of mechanical devices, the accuracy of the measured value is the product of the accuracy class in percentage and the scale range) or in the documentation (in the case of electronic instruments, it usually contains a constant and a linear component given by the magnitude of the measurand). If this information is not provided, assuming that accuracy is half of the smallest division on the instrument's scale is common practice The values measured by the apparatus may change over time or due to external conditions (e.g., temperature), which impact the stability of the device.

The calibration of measuring instruments and evaluation of their accuracy is usually carried out by repeatedly measuring the same object on the device that is being calibrated, and a reference instrument (also called secondary standard) at different conditions and comparing the measured values. The reference instrument has a higher accuracy and was itself calibrated using the highest precision primary standards. Primary standards usually implement the unit definition of a given physical quantity using a standardized international practice (mise en pratique). This way, we obtain a chain of calibration relationships between the definition of the units of the quantities and the instruments we use with progressively decreasing precision.

Time

Time is one of the most fundamental quantities describing natural processes, from nuclear (nuclear decay) and biological processes (aging) to geological and astronomical ones (the age of the universe). In physics, we often study temporal changes in physical quantities, and therefore, the description of the exact time is necessary.

Calendars

Historically, agriculture was the first area where the description of time, as the first-ever physical quantity, proved necessary Even the first human societies needed to determine when to sow and when to harvest before the approaching winter. Our ancestors, therefore, looked up to the sky and eventually created calendars based on the movement of the moon and the sun – the lunisolar calendar. It is not known when was the first ever calendar made, but it was before the invention of writing. A new month usually began a few days after the new moon with the sighting of the crescent moon. Since the length of the year is not exactly divisible by the lunation period, two 12-month years were often followed by a 13-month year. Remnants of this calendar can be seen in the dates of several religious festivals such as Easter, Hanukkah, and Ramadan.

A substantial change came with the reform of the Roman calendar by Julius Caesar in 44 BC. The Julian calendar is based only on the movements of the Earth and the Sun – the year consists of 365 days, with an extra day inserted every four years.[2] Besides changing the duration of the individual months, the beginning of a new year was moved to the beginning of January, and this modification necessitated the previous year to span up to 445 days.

However, the Julian calendar was not accurate enough. The moment of the vernal equinox, which was essential for determining the time of Easter, was gradually shifting, i.e., in 1582 it was ten days later than at the time of the Council of Nicaea. Thus, a new calendar, designed by the Neapolitan physicist Aloysius Lilius, was adopted by Pope Gregory XIII in 1582. This Gregorian calendar introduced a leap February into all years divisible by four, as had been the custom up to that time, but with an exception in the first years of every century not divisible by four. That makes the Gregorian calendar three days shorter than the Julian calendar over a thousand years. In addition, the accumulated time was also corrected – the 4th of October was directly followed by the 15th of October in 1582. The adoption of this calendar around the world was a gradual process. The Kingdom of Bohemia adopted it in 1584. Afghanistan, Iran, Ethiopia, Eritrea, and Nepal still use different calendar systems.

Sundial

When dividing the day into smaller parts, the movement of the sky is most useful. Determining the time during the night was possible from the position of the stars and during the day from the position of the sun. The main instrument thus became a sundial consisting of a gnomon – a rod parallel to the axis of Earth casting a shadow – and a shade with a scale. These clocks show the true local solar time determined by the position of the Sun in the sky. However, the Earth orbits

[2] The original Roman year began with March, which is why this day is inserted at the end of February

the Sun in an elliptical orbit at a non-uniform velocity, so the length of the solar day varies throughout the year. Compared to the mean solar time, which runs uniformly, the true solar time can be up to a quarter of an hour behind/forward – this difference varies throughout the year, and we describe it by the so-called equation of time. Based on the rotation of the Earth around its axis, we arrive at the typical definition of second as a unit of time measurement:

> A second is 1/86 400 of the mean solar day.

However, it is worth reminding that minutes and seconds were not yet feasible. Hence, these units could not be used until the advent of mechanical clocks in the late 17th century. The smallest fractions of time used in this period were 1/12 of an hour.

From the position of the stars, it is possible to derive the sidereal time using the stars on the meridian, which is the junction of south, the zenith, and north on the celestial sphere. As the Earth orbits the Sun, the sidereal day is shorter than the solar day by a factor of one day/year, which corresponds to 23 hours, 56 minutes, and 4 seconds.

Various other instruments were used to measure shorter periods or when it was cloudy, such as the hourglass, a burning candle, or the outflow of water from a container. These methods tended to have a significantly lower accuracy on long-time scales. For example, for a water clock with a long spout, a change in water temperature of as little as one degree Celsius will cause a time measurement error of half an hour per day due to a change in viscosity and, subsequently, in the flow rate.

Fig. 1: Sundial[3]

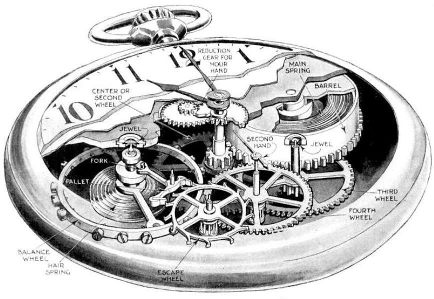

Fig. 2: Diagram of mechanical watches[4]

Mechanical clock

A significant advance in time-measuring accuracy came with the invention of the pendulum clock. Following Galileo Galilei's discovery in the early seventeenth century about the period of a pendulum being independent of its deflection, Christian Huygens constructed the first pendulum clock in 1656. The accuracy of time measurement was improved from 15 minutes per

[3] `https://pixabay.com/photos/sun-dial-sun-dial-clock-sundial-1759241/`
[4] `https://commons.wikimedia.org/wiki/File:Pocketwatch_cutaway_drawing.jpg`

day to 15 seconds per day. The period of the small oscillations of a (mathematical) pendulum is given as

$$T = 2\pi\sqrt{\frac{l}{g}}\,,$$

where g is the acceleration due to gravity and l is the length of the hinge. In the case of a real – physical pendulum with a moment of inertia I with respect to the axis of rotation, mass m, and distance of the center of gravity from the point of the hinge a – the relation is a little more complicated.

$$T = 2\pi\sqrt{\frac{I}{mga}}$$

For a pendulum with a swing time of 1 s, we need a hinge of length $l = 0.994\,\mathrm{m}$. Regulating the swing time is possible by changing the effective length of the hinge.

Each mechanical clock consists of several parts. The periodic oscillations of the *oscillator* (in our first case, the oscillations of the pendulum) are converted using a *balance wheel* into pulses of the clock *gear*, moving them in one direction. Simultaneously, using the balance wheel, the lost energy of the oscillator is replaced by an external *energy supply*, typically a weight or spring, which needs to be lifted/stretched from time to time. A gear train consisting of about five gears converts the motion of the *balance wheel* into that of the watch hands. The time is read from the *dial*.

The gradual refinement of the balance wheel made it possible to reduce the amplitude of the oscillations from the original 90° to just a few degrees, which led to the introduction of the minute hand around 1700. Later, it was found that pendulum clocks ran slower in summer due to the thermal expansion of the pendulum hinge material. Around 1726, John Harrison proposed a design, which is still in use today, where a pair of metals with different thermal expansion coefficients form the hinge. In addition to temperature, the moving pendulum is subject to time-varying air resistance due to atmospheric pressure changes, humidity, and temperature. The duration of the oscillation, and therefore the accuracy of the moving clock, is also affected by the value of the gravitational acceleration, which varies from place to place. Furthermore, the running clock must be always kept upright.

The second option is to generate a periodic signal by oscillating a spring as in the case of a pocket watch. Spring-wound clocks were built around 1660 by Christian Huygens, using an idea by Robert Hooke, improving the accuracy of pocket watches from a few hours per day to about ten minutes. In this design, a spiral torsion spring called a mainspring, causes rotational oscillations of the balance wheel. A well-constructed pocket watch spring follows Hooke's law – the force it exerts is directly proportional to the deflection from the equilibrium position, which is achievable by winding the spring so that its center of gravity lies on the axis of the balance wheel. The gradual refinement was achieved by changing the spring material (the original untempered steel springs lost strength through fatigue) and changes in the shape of the spring itself. Nowadays, mainsprings are mainly made from hardened and tempered steel and use the Breguet winding. The period of oscillation is usually regulated by changing the length of the working part of the spring (and the stiffness of the whole spring) – a shorter spring is stiffer and oscillates faster.

For a spring of stiffness κ and a balance wheel of a moment of inertia I, we have the equation of motion for the deflection angle θ and the angular acceleration α

$$M = -\kappa\theta = I\ \alpha = I\ \frac{\mathrm{d}^2\theta}{\mathrm{d}t^2}\,.$$

Such a spring behaves as a harmonic oscillator with an oscillation period dependent on the deflection

$$T = 2\pi\sqrt{\frac{I}{\kappa}}\,.$$

The operation of such clocks is influenced mainly by the temperature, which causes changes in the dimensions of the components and the modulus of elasticity, as well as the stiffness of the spring, and the change in friction caused by the aging of the oil that lubricates the mechanism.

The longitude problem

After the beginning of transoceanic crossings in the sixteenth century, accurate timekeeping in complicated conditions – changing temperature, humidity, different accelerations of gravity, or the movement of the ship itself on the open ocean – proved essential. On a ship, we can easily determine latitude from the height of the celestial pole above the horizon. Determining the longitude is more complicated, as we need to know the reference time besides measuring the position of stars. The Earth makes one revolution every 24 hours, so to determine longitude to within one degree (111 km at the equator), we need to know the time with an accuracy of a few minutes. Moreover, we need to maintain this accuracy for at least one month. The problem was so urgent that the rulers of countries such as Spain, the Netherlands, and Great Britain proposed large financial rewards. The latter, in 1713, issued a prize of 10 000 pounds[5] after achieving an accuracy of one degree after a six-week voyage to India.

The most successful solver was John Harrison with his marine chronometers. After a lifetime of work, he built the H4 chronometer, which lost only five seconds during an 81-day voyage to the Caribbean. This significant advance was achieved through a low-friction design incorporating oscillating gears excited by a spring – they were thus independent of the Earth's gravitational field and resistant to external forces, such as centrifugal force during a change of course, which affects conventional pendulum clock. High precision was also achieved thanks to temperature stabilization using a bimetallic strip, the invention of a better stepping gear, and a special roller bearing.[6] Advances in British watchmaking were one of the reasons for the dominance of the British Navy and the main reason why the Greenwich Observatory is today's standard of time and longitude.

The second way of determining the time was by using astronomical observations. On land, the exact time was determined by observing the predicted eclipses of Jupiter's moons with a telescope – but at sea, these observations were infeasible. Another huge advance was made with Tobias Mayer's tables describing the motion of the moon in the sky – at that time a very challenging celestial mechanics problem due to the mutual gravitational interaction of the Earth, the Sun, and the Moon.

Ephemeris time

At the turn of the twentieth century, astronomical measurements revealed that the rotation of Earth is not uniform on short timescales and that tidal forces slow it down over long periods. Therefore, astronomers proposed determining accurate time from the positions of bodies in

[5] the value would nowadays correspond to several million

[6] The original article describing the functioning of Harrison's chronometer is available at `https://books.google.cz/books?id=aB8OAAAAQAAJ&printsec=frontcover&redir_esc=y#v=onepage&q&f=false`

the Solar System as a notion of uniform Newtonian time, assuming the validity of Newtonian gravity and mechanics. The definition of second changed in 1956 to:

> A second is a fraction of 1/31 556 925.974 7 of a tropical year[7] on January 0 of the year 1900 at 12 hours of Ephemeris time.

This definition came into existence by observing the positions of the Moon and comparing them to predicted positions – ephemerides – hence the name of this time measure.

Atomic time

The current definition of the second has been implemented in 1967 as follows:

> The second (symbol s) is the SI unit of time defined by taking the fixed numerical value of the cesium frequency, $\Delta\nu_{\mathrm{Cs}}$, the unperturbed ground-state hyperfine transition frequency of the cesium 133 atom, to be $9\,192\,631\,770\,\mathrm{s^{-1}}$.

In the ground state, the only stable isotope of cesium $^{133}\mathrm{Cs}$ has a nucleus with a spin of 7/2 and one unpaired electron with a spin of 1/2. Hence, the ground state of the atom splits into two levels with a total spin of $7/2 \pm 1/2$ depending on whether these spin's orientation is the same or opposite. The transition between these levels is accompanied by the emission of electromagnetic radiation of frequency $\Delta\nu_{\mathrm{Cs}}$, which translates to a wavelength of about three centimeters – hence, it is microwave radiation. The atom in the definition is intact – it is not affected by external electromagnetic fields such as thermal radiation. That corresponds to an atom at a temperature of 0 K. The time defined this way is the proper time in the sense of general relativity in the local reference frame associated with the corresponding atomic clock. In order to build a coordinated time scale for a set of observers, it is therefore necessary to make appropriate relativistic corrections.

The realization of second is possible only in laboratories by generating an electrical signal at a frequency whose relation with $\Delta\nu_{\mathrm{Cs}}$ is precisely known while being adjusted to the effects of the environment or mutual motion of particles. Primary time standards nowadays achieve accuracies of up to $1 : 10^{16}$. In addition to $\Delta\nu_{\mathrm{Cs}}$, some secondary standard frequencies are known to accuracies from $1 : 10^{14}$ to $1 : 10^{16}$.[8]

The International Atomic Time (TAI) is obtained by averaging the time on several hundred atomic clocks around the world. The time obtained in this way has a stability of $3 : 10^{16}$ on the monthly scale. It is usually available retrospectively a few weeks later with the publication of corrections between (TAI) and the individual atomic clocks. For practical use, the transfer of the time signal between the two laboratories is crucial – this is done by calibration using GPS satellites orbiting Earth, using atomic clocks on the satellites themselves, with a usual transfer accuracy of a few nanoseconds.

The atomic time is used to determine Coordinated Universal Time (UTC), which differs from TAI by a whole number of seconds to match the mean solar time at the Greenwich meridian (UT1) with an error of less than 0.9 s. This difference is variable due to the uneven rotation of the Earth, which is why the International Earth Rotation Service sometimes introduces a leap second. Finally, from the UTC time, a correction, usually by whole hours, determines the appropriate zone time. This time is used in everyday life and is commonly propagated via the Internet, radio, and television.

[7] time between two consecutive moments of the vernal equinox

[8] `https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies`

In the Czech Republic, the time standard is called the *State Standard of Time and Frequency*, and it is stored at the Institute of Photonics and Electronics of the Academy of Sciences and produces the UTC(TP) time scale using industrial cesium clocks with a frequency instability of $6 \cdot 10^{-14}$ on the scale of one day.

Atomic clocks

And how does the cesium atomic clock work? Let us look first at the "quantum" part of the clock.

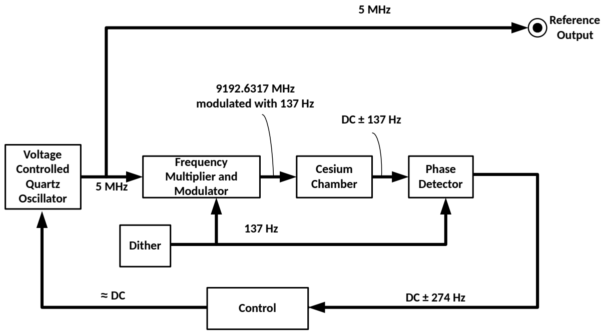

Fig. 3: Block diagram of cesium clock operation[9]

By heating cesium above 100 °C in a furnace, we obtain an evenly distributed stream of atoms (between the upper and lower states of our transition) by gradual evaporation at a temperature between the melting and boiling points. These can be separated when passing through magnets that generate an inhomogeneous magnetic field as in the Stern-Gerlach experiment (SG). Then, we let the bottom filtered transition state pass through a first microwave cavity excited at frequency f. After passing next through a region with a weak magnetic field B, it passes through a second microwave cavity.[10] That allows some of the atoms in the beam to reach the higher state, while the electromagnetic field is quantized as photons with energy $E_f = hf$, where h is Planck's constant. If a cesium atom collides with a photon of just the right energy, it can absorb the energy and jump to a higher energy state. We then filter the excited atoms using SG magnets and ionize them on a hot filament. These ionized particles are analyzed with a mass spectrometer to exclude potentially contaminating atoms and detected with an electron multiplier. The multiplier will have the highest voltage for the highest particle flux at the upper energy state, which happens when we excite the microwave cavity at a resonant frequency $f = \Delta\nu_{\mathrm{Cs}}$.

The electronic part of the instrument is just as important. The core of the instrument is a voltage-controlled crystal oscillator with a frequency of $f_0 = 5\,000\,\mathrm{kHz}$. From this frequency, an alternating electrical signal at a frequency 18 times higher is produced, which, after passing through a highly nonlinear component generating a large number of integer multiples, is then filtered by a microwave cavity, so that only its 102 multiples remain at 9 180 MHz. It remains

[9] `https://commons.wikimedia.org/wiki/File:Caesium_clock_block.svg`

[10] This setup is called the Ramsey method and increases the accuracy of the measurement compared to a single flyby. It is more accurate the further apart the areas of flight through the electromagnetic field are.

to add the locally generated to which is using interference 12.63 MHz from the original f_0 using interference. This resulting frequency is transferred to the microwave cavity through which the cesium atoms fly. The frequency f_0, and hence all the ones derived from it, is adjusted to maximize the voltage on the multiplier using voltage feedback. This whole device is thus a cesium-stabilized crystal oscillator.[11]

For completeness, let's explain how quartz crystal oscillators found in most wristwatches work.[12] A small custom-cut piece of quartz crystal is placed between two electrodes. By applying an external electric field, the crystal lattice is deformed by a piezo-electric effect.[13] If the applied electric field has the same frequency as the natural frequency of the mechanical oscillations of the crystal, resonance will occur. Resonance occurs even at odd multiples of the fundamental frequency, and it does not depend much on the temperature of the quartz crystal. This frequency is adjustable by applying an external voltage of up to some 100 parts per million. The first quartz wristwatches, the ones we see most often today, were made in Japan in 1969 by the now world-renowned company Seiko.

The definition of second will most likely change again to incorporate optical frequencies. So-called optical atomic clocks using forbidden optical transitions of atoms such as strontium or ytterbium achieve accuracies of up to $1 : 10^{20}$. Since these clocks run at high frequencies of several hundred THz, optical circuits must be used instead of electronic circuits, taking advantage of progress in laser technology. To achieve high precision, the atoms must be laser-cooled to microkelvins and kept in optical tweezers to prevent the spectral line from being broadened by thermal motion. The conversion of the optical signal into a usable electronic signal of stable frequency uses the so-called optical Dirac frequency comb, for the development of which Theodor W. Hänsch and John L. Hall were awarded the Nobel Prize in 2005. However, for this clock to become a source of coordinated time, we must resolve the signal transport first. Moreover, an accuracy better than $1 : 10^{18}$ is not achievable for this time – in fact, such little variations are already caused by centimeter shifts in the Earth's gravitational field due to the effects of general relativity.

Exceptionally short . . .

Finally, let's look at a few extreme cases. Some of the shortest times we can encounter in physics are the mean lifetimes of subatomic particles. For example, for Δ baryons consisting of a triplet of up or down quarks, $\tau = (5.63 \pm 0.14) \cdot 10^{-24}\,\mathrm{s}$, or about five yoctoseconds. These times are measured from the distribution of measured masses of a given particle determined from measurements of the energies and momenta of its decay products. Due to the Heisenberg uncertainty principle, they are not precise, but described by the Breit-Wigner distribution of particle energies

$$f(E) = \frac{\Gamma}{2\pi\left((E - E_0)^2 + \left(\frac{\Gamma}{2}\right)^2\right)}$$

[11] For those extremely interested, a link to the operating and service manual of the atomic clock HP 5061: `http://www.cs.cmu.edu/~dga/time/5061/5061A_ops_and_schematics.pdf`

[12] The first crystal-controlled oscillator was built in 1917 by Alexander M. Nicholson, the first quartz oscillator by Walter G. Cady in 1921, and the first quartz clock in 1927 by Warren Marrison and J.W. Horton at Bell Laboratories.

[13] Jacques and Pierre Curie discovered the piezoelectric properties of quartz in 1880.

where $E_0 = mc^2$ is the rest energy of a particle of mass m, and Γ is the resonance width (energy uncertainty) associated with the mean lifetime as $\tau = \hbar/\Gamma$, where $\hbar$ is the reduced Planck constant.

. . . and extremely long ago

At the other end of the scale are times used in archaeology and geology. But even here, we are using particle decays – long-lived radionuclides. The isotope of carbon ^{14}C is often used for dating in archeology. This isotope is formed in the atmosphere from nitrogen atoms when a proton is knocked out and replaced by a neutron from cosmic rays. It then enters living organisms in the form of carbon dioxide. This isotope decays into the original nitrogen isotope with a half-life of about $T_{1/2} = 5\,700\,\mathrm{years}$.

The age of an organism is determinable by the ratio of carbon isotopes $\left[^{14}\mathrm{C}\right] / \left[^{12}\mathrm{C}\right]$. During life, this ratio is determined by the abundance of isotopes in the environment, which are relatively stable over long-time scales.[14] When the organism dies, the radioactive nuclide begins to decay. The time elapsed since death is determined by the relation

$$\frac{\left[^{14}\mathrm{C}\right]}{\left[^{12}\mathrm{C}\right]}(t) = \frac{\left[^{14}\mathrm{C}\right]}{\left[^{12}\mathrm{C}\right]}(t_0)\left(\frac{1}{2}\right)^{\frac{t-t_0}{T_{1/2}}} .$$

In geology, we use abundances of nuclides of elements with even longer half-lives. The most straightforward situation is in some mineral crystals where the original radioisotopes decay to elements that have no place in the mineral's crystal lattice. One such mineral is zircon, which at the time of crystallization contains uranium and thorium impurities in its crystal structure, but does not contain lead, which is the ending of the respective decay orders – the U-Pb dating method. However, the situation is more complicated when the original isotopic abundance is unknown, such as in meteorites. In this case, several samples are analyzed, and we are interested in the abundances of the parent radionuclide, the daughter stable nuclide, and another stable nuclide of the same element. If our samples had variable chemical compositions, we could use these results to determine the age of the material and the original isotope ratios of the daughter elements.

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[14]Nowadays, we measure so precisely that this ratio is determined from calibration against dendrochronology by determining age using tree rings. Moreover, nuclear tests in the last century have been dominated by atmospheric concentrations of radioactive nuclides.