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Time and Metrology

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ABSTRACT
The recourse to Quantum Mechanics for the definition of the International System of Units has been the trigger of significant progress. In the first part of the paper, we briefly recall the definitions of units now in use for the basic quantities. We summarize the levels of precision available today within the framework of these definitions.

Time, whether we are aware of it or not, is a very special physical quantity. We therefore expose the extended use that could be made of the expression of physical quantities by means of time, like what is already practiced for the masses, expressed by means of energies. We detail a little more the case of the electrical quantities voltage and resistance which, without being basic quantities, benefit from new approaches thanks to two quantum phenomena: the Josephson effect, and the Quantum Hall Effect.

But time is not an absolute. The next part of the paper exposes the corresponding teachings brought by Special Relativity on the one hand, and General Relativity on the other hand.

Finally, the perspectives of the field are approached under the aspect of the metrological repercussions. Indeed, the technologies applicable to the measurement of time lead to performances that can be considered extraordinary in absolute terms, and in any case superior in relative to anything that can be achieved for other physical quantities.

In conclusion, we examine the challenge that may represent the achievement of ever-increasing metrological performance for all physical quantities, and for time in particular, and the perspectives opened up for research in the domain by fields of knowledge not yet covered.

Section: RESEARCH PAPER

Keywords: International Unit System; Josephson effect; Quantum Hall effect; relativity; time measurement

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1. INTRODUCTION

Whether we are aware of it or not, quantum mechanics exerts a profound influence on our lives today. Through the rules it lays down, to describe the world of the infinitely small, it troubles us, it disturbs us. At the same time, we do not deprive ourselves, sometimes to excess, of making use of the technological applications it has enabled. Just think of all the developments in electronics, computing, and means of communication.

Its repercussions are now also visible in a somewhat particular world, that of metrology, with the recent reform of the International System of Units (2018).

International metrology bodies usually act very carefully. Indeed, it is important to ensure the historical continuity of the references used in the field of measurement, and in the same time, to take full advantage of the progress made possible by the evolution of theoretical knowledge and that of technologies.

The step was thus recently taken to replace all the material references at the base of the system of units, by the attribution of exact values to a set of natural physical constants. This point will be described in more detail below.

Let us note now that this step was made possible by the great degree of confidence that exists today in the ability of quantum models to account for physical reality.

For the particular field of electromagnetism, two major advances have made it possible to move forward in the desired direction; these are the Josephson Effect, applicable to the measurement of voltages, and the Quantum Hall Effect, applicable to the measurement of electrical resistance.

2. OVERVIEW OF THE INTERNATIONAL UNIT SYSTEM: THE SI

The system of units includes a priori the minimum number of quantities necessary for the quantification of all the physical quantities encountered in nature.

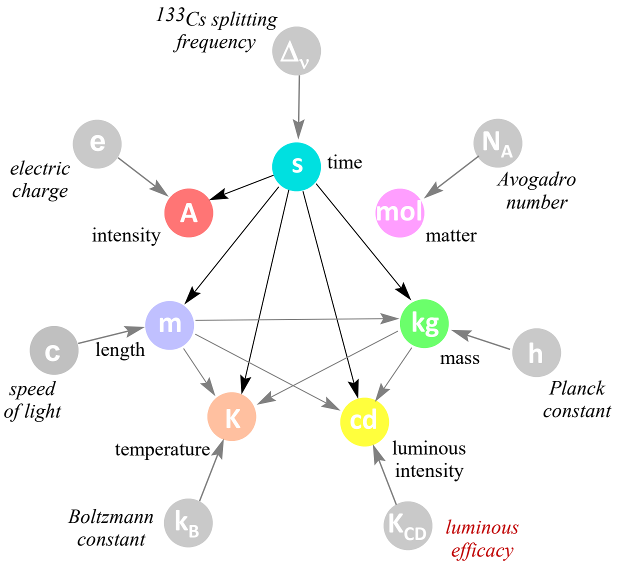

Figure 1. Structure of SI.

To date, the system comprises 7 so-called basic units, and units derived from them. The base units are according to Table 1.

2.1. Present definitions of basic units

The definitions instituted by the new system of units call on 7 natural constants whose values are defined as exact, and from which the seven base units now derive [1].

These constants are according to Table 2.

This principle of founding a system on natural constants makes the traditional notion of derived units (22 units to date) loses some of its value, because derived units can be directly defined from natural constants.

Table 1. Base units of SI.

Physical quantity	Name	Symbol
time	second	s
length	metre	m
mass	kilogram	kg
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
quantity of substance	mole	mol
electrical intensity	ampere	A

Table 2. Natural constants used by SI.

Symbol	Nature	Associated parameter	Value	Unit
$\Delta\nu_{Cs}$	caesium hyperfine frequency	time	9.192 631 770	GHz
c	speed of light in vacuum	length	299 792 458	m/s
h	PLANCK constant	mass	$6.626\,070\,15 \times\cdot 10^{-34}$	J·s
k_B	BOLTZMANN constant	thermodynamic temperature	$1.380\,649 \times\cdot 10^{-23}$	$J\cdot K^{-1}$
k_{CD}	luminous efficiency constant	luminous intensity	683	$cd\cdot sr\cdot W^{-1}$
N_A	AVOGADRO constant	quantity of matter	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
e	elementary electric charge	electrical intensity	$1.602\,176\,634 \times\cdot 10^{-19}$	C

The definitions of the base units are partly interdependent. This is explained by the diagram in Figure 1.

Examination of the diagram shows that with one exception – the mole – all the base units refer to time, in the sense that we need the reference to time to establish their definition.

The BIPM brochure on the SI [1] is the authoritative source for the definitions that follow.

Although these are very well known, they are briefly recalled in order to allow the developments of the following chapter.

It should be noted that if a given constant is defined as exact, with a finite number of digits, it cannot be the same for its inverse, a number belonging to the body of rational numbers, and which cannot be written in an exhaustive manner. Hence the following formulas.

2.1.1. Time unit (second, s)

The second is 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 caesium133 atom, of frequency $\Delta\nu_{Cs}$

$$1\ \mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu_{\mathrm{Cs}}}\,. \tag{1}$$

2.1.2. Length unit (metre, m)

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 second

$$1\ \mathrm{m} = \frac{c}{299\,972\,458}\,\mathrm{s}\,. \tag{2}$$

2.1.3. Mass unit (kilogram, kg)

The definition of the kilogram is based on PLANCK's constant h, of exact value. It requires the prior definition of the meter and the second,

$$1\ \mathrm{kg} = \frac{h}{6.62607015 \cdot 10^{-34}}\,\mathrm{m}^{-2}\mathrm{s}\,. \tag{3}$$

The kilogram can be produced using a KIBBLE balance (WATT balance), the principle of which is to seek a balance between a gravitational force (weight) and an electro-dynamic force. This balance is derived in principle from the Ampere balance, with an inverse objective (kilogram from the ampere, and not ampere from the NEWTON).

The realization of the kilogram still requires the definition of the PLANCK mass m_P, whose equation is

$$m_{\mathrm{P}} = \sqrt{\frac{\hbar c}{G}} = 2.176\,434\,(24) \cdot 10^{-8}\ \mathrm{kg}\,, \tag{4}$$

where: $\hbar$ is the reduced PLANCK constant, G is the gravitational constant, c the speed of light in vacuum.

2.1.4. Thermodynamic temperature unit (kelvin, K)

The kelvin is the thermodynamic temperature unit of SI. It is defined by taking the fixed numerical value of the BOLTZMANN constant k_B

$$1\ \mathrm{K} = \frac{1.380\,649 \cdot 10^{-23}}{k_{\mathrm{B}}}\,\mathrm{kg\,m^2s^{-2}}\,. \tag{5}$$

2.1.5. Luminous intensity unit (candela, cd)

The candela is the luminous intensity, in a given direction, of a source emitting monochromatic radiation of frequency $f = 540 \cdot 10^{12}$ Hz, and having a radiation intensity in this direction of 1/683 watt per steradian. The frequency f corresponds to the visible wavelength $\lambda = 555$ nm.

This definition, linking a human sensitivity, statistically approximated, to an energy, has been unchanged since 1979

$$1\ \mathrm{cd} = \frac{K_{\mathrm{cd}}}{683}\ \mathrm{kg\ m^2\ s^{-3}\ sr^{-1}}\ . \qquad (6)$$

2.1.6. Substance quantity unit (mole, mol)

AVOGADRO's number (strictly speaking: AVOGADRO's constant), denoted N_A, reflects the fact that the number of elements (atoms, molecules, ions, etc.) contained in a quantity equal, in grams, to the number of nuclear particles present in this element is a constant, whatever the chemical nature of the element considered.

In fact, the respective masses of the neutron and the proton are very close, and the mass of the electron is very small compared to them. The reference volume for one mole of gas at the reference conditions of temperature and pressure $v = 22.4$ dm^3 is the same for all bodies given that the volume of vacuum /volume of matter ratio is very high.

Avogadro's constant has been assigned the exact value

$$N_{\mathrm{A}} = 6.022\,140\,76\ \cdot\ 10^{23}\ \mathrm{mol^{-1}}\ . \qquad (7)$$

2.1.7. Electrical intensity unit (ampere, A)

The ampere is defined as the current allowing the transfer of $1/(1.602\,176\,634 \cdot 10^{-19})$ elementary electric charges during the unit of time [1]

$$1\ \mathrm{A} = \frac{e}{1.602\,176\,634 \cdot 10^{-19}}\ \mathrm{s^{-1}}\ . \qquad (8)$$

2.2. Previous references and evolutions

As a reminder, the main changes are:

- the kilogram (unit of mass) was equal to the mass of the International Prototype Kilogram (IPK).
  It was the last basic unit of the SI defined by a material artefact; the instability of its mass is estimated at 50 µg per century; and its source of traceability was unique: the BIPM.
- the kelvin, unit of thermodynamic temperature, was the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
- the mole was the amount of substance in a system containing as many elementary entities as there are atoms in 0.012 kilograms of carbon 12 (this material was therefore the reference).

The ampere, the unit of electrical intensity, was previously defined since 1948, at the same time than the constant μ_0

"*The ampere is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2 × 10^{-7} Newton per meter length*".

We can see that this principle did not adapt well to a practical realization.

The logo in Figure 2 summarizes the changes made by the new version of the unit system: appearance of the 7 natural constants defining the base units, abandonment of the prototype kilogram IPK, end of the use of the triple point of water, reference material carbon 12, and "downgrading" of the vacuum magnetic permeability constant μ_0.

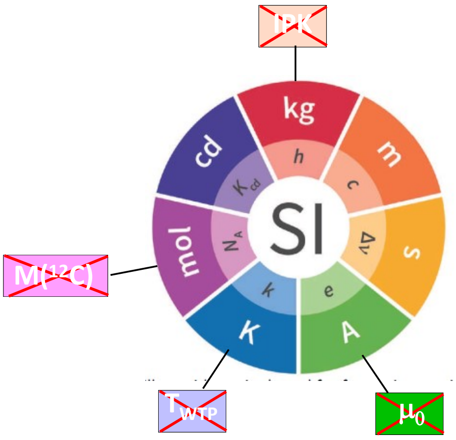

Figure 2. Evolution of SI.

2.3. The contribution of Quantum Mechanics

By taking physical constants present immutably in nature as a reference, quantum mechanics gives to the system of units greater durability and stability [2]-[4].

In addition, it restores the overall coherence of the system, by facilitating the reintegration of the volt and ohm units, normally derived from the ampere, which was no longer the case between 1990 and 2018.

During this transitory period indeed, volt and ohm were already defined starting from the natural constants h and e, but without possibility of attachment to the ampere.

2.4. The measurement accuracies accessible today

A current state of the art for different physical quantities can be established as in Table 3.

Note the "advance" of the second, and the "delay" of the candela, in terms of precision.

2.5. Unit systems and scales

The systems of units are designed to accompany in the most convenient way possible the different fields of activity:

1) everyday life, industrial and commercial activities: the SI
2) particle physics: in this field, the base units are
    - the atomic mass unit for mass, the AMU
    - the electron-volt for energies, or rather its multiple, the GeV
      1 eV = $1.602 \cdot 10^{-19}$ J 1 J = $0.6242 \cdot 10^{7}$ GeV.
3) cosmology

Table 3. Uncertainties accessible for basic physical quantities.

Quantity	Unit	Accessible uncertainty
time/frequency	second/hertz	10^{-15}
length	metre	$3 \cdot 10^{-11}$
mass	kilogram	$5 \cdot 10^{-9}$
voltage	volt	10^{-10}
resistance	ohm	$5 \cdot 10^{-10}$
intensity	ampere	10^{-7}
capacity	farad	10^{-6}
inductance	henry	$2 \cdot 10^{-6}$
temperature	kelvin	10^{-6}
luminosity	candela	$1{,}5 \cdot 10^{-2}$

- the astronomical unit of length (au) is defined as exactly 1.49 597 870 700 · 10^{11} m (approximate distance from the Earth to the Sun).

We can deduce :
- the light-year 63 241 ua
- the parsec 648 000/π ua.

Natural systems of units

As early as 1899, physicist Max PLANCK had proposed a system of units based on natural constants.

PLANCK had considered units based on the physical constants G, $\hbar$, c, and k_B, which lead to natural units for mass, length, time, and temperature [5].

However, this system did not include electromagnetism, whose formalization by MAXWELL was too recent. The electrical charge was later added to it.

The peculiarity of a system of natural units is to make disappear, in appearance, the dimensional aspect of the relations between the physical sizes.

Thus, if we take $G = \hbar = c = k_B = 1$,

we have the following physical equations:

mass-energy formula of EINSTEIN

$E = m$ instead of $E = m\,c^2$,

for gravitation

$F = -\frac{m_1 \cdot m_2}{r^2}$ instead of $F = -G\frac{m_1 \cdot m_2}{r^2}$

etc.

The values of the measurements of the different quantities can thus be identical in PLANCK units.

The use of PLANCK's system of natural units or derived systems is still topical in physics today, especially for the study of black holes, insofar as it greatly simplifies the equations used.

The historical units systems

The primary concern of the creators of French Revolutionary unit systems was not to promote scientific progress, but to facilitate everyday life. In fact, under the *Ancien Régime*, the quantitative value associated with units was only valid within a limited geographical area. Hence, the idea of also including in the system of units a monetary unit (the pound). This unity, unrelated to physics, did not last [6].

Units from the media

Among these are:
- the football field, a very approximate surface unit, approximately 10^{-2} km², a unit no doubt linked to the popularity of this sport
- the barrel, unit of volume associated with an obsolete means of transport because replaced by oil pipelines and ore ships, but in fact still used to characterize, from the financial aspect, transactions relating to hydrocarbons.

These units, unrelated to the SI, have the raison d'être of wanting to be "speaking".

3. ALMOST ANYTHING CAN BE MEASURED WITH TIME

One can ask the question whether all base units are really necessary.

In the past, we have seen the use of certain units, such as the calorie, disappear because of the recognized equivalence of heat and work (first principle of thermodynamics).

In fact, we observe that there frequently exist between the different basic quantities simple relations, such as proportionalities [7]. It can be proportionality to time, or proportionality to its inverse, the frequency.

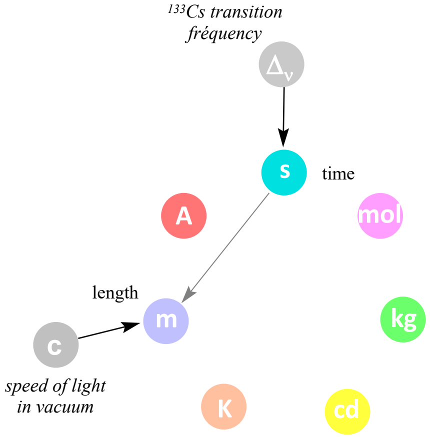

Figure 3. The metre.

3.1. The case of length

c being a speed of definite value, it connects the time τ and the length ℓ,

$\ell = c\,\tau$

"The meter is the distance travelled by light in vacuum for a time equal to $\frac{1}{299\,792\,458}$ *second"* .

We have the equivalence

1 metre ⇔ 3.335 640 95 nanoseconds, see Figure 3.

3.2. Mass/energy relationship

Special Relativity shows us the close relationship between the energy E and the mass m,

$E = m\,c^2$.

In nuclear physics, we commonly see the masses expressed in eV/c^2 (electron-volt per c^2), that is to say by an energy, for questions of better handling of the data in this unit. We often omit in passing the factor $1/c^2$, and we use a convenient reference, of intermediate size, which is the GeV (= 10^9 eV):

- the mass of the proton is 0.931 GeV c^{-2}
- the mass of the Higgs boson is 125 GeV c^{-2}

etc.

1 kilogram ⇔ $E_{kg} = c^2$ joules = 8.987 552 · 10^{16} joules.

E_{kg} is the energy that would be released by a nuclear mass conversion reaction, by fission or nuclear fusion, bearing on 1 kg of mass, see Figure 4.

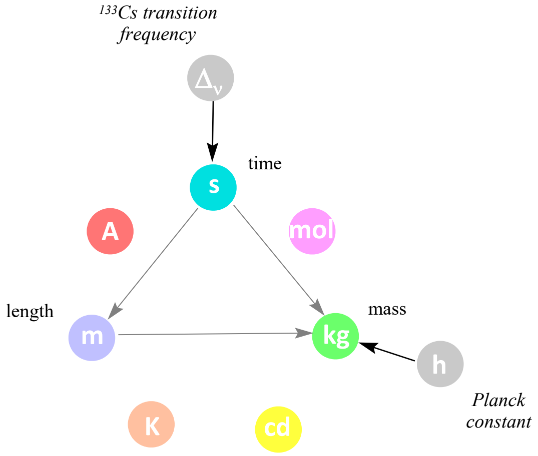

Figure 4. Mass-energy relationship.

As a reminder, 1 EPR reactor produces 14.4 terawatt-hours (TWh) annually, i.e. $5.20 \cdot 10^{16}$ joules.

It transforms 1 kg of substance into energy in about 2 years.

The correspondence between Joule and GeV is written

1 joule = $6.242\,197\,25 \cdot 10^{9}$ GeV

One also has:

1 joule ⇔ $1.113 \cdot 10^{-17}$ kg c^{-2}.

3.3. Time/energy and mass/time relationships

The link between energy E, time τ, and length ℓ has a deep physical meaning: if we consider a particle of energy E under the wave aspect, it has a frequency $\nu = E/h$; hence a period τ and a wavelength $\lambda = \frac{c\,h}{e}$.

The energy E is proportional to a time parameter which is the frequency (via PLANCK's constant h).

We have for 1 joule

$\nu_{1J} = 0.150919018 \cdot 10^{34}$ Hz, $\tau_{1J} = 6.62607015 \cdot 10^{-34}$ s.

If we take an energy $E = 1$ GeV as a reference, we have

$\nu_{1Gev} = 2.41781481 \cdot 10^{23}$ Hz, $\tau_{1GeV} = 4.135966770 \cdot 10^{-24}$ s.

For more consistent and more usual energies:

1 kWh = $3.6 \cdot 10^{6}$ J ⇔ $\nu_{1kWh} = 5.433\,084\,65 \cdot 10^{39}$ Hz.

The correspondence between energy and frequency being established (see above), we can therefore associate a frequency with the kilogram

1 kilogram ⇔ $8.998\,347\,46 \cdot 10^{16} * \nu_{1J} = 1.356\,392\,49 \cdot 10^{50}$ Hz

This value being very high, remains out of reach of the directory of prefixes of the International System, in spite of its envisaged extension (1 quettahertz = 10^{30} hertz).

3.4. The case of temperature

The kelvin is based on the microscopic definition of temperature.

The thermal agitation of the atoms of a body, independent of the chemical nature of its constituents, constitutes its internal energy E_{th}.

E_{th} is linked to the thermodynamic temperature T via the BOLTZMANN constant k_B, which is therefore now used to define the kelvin, see Figure 5.

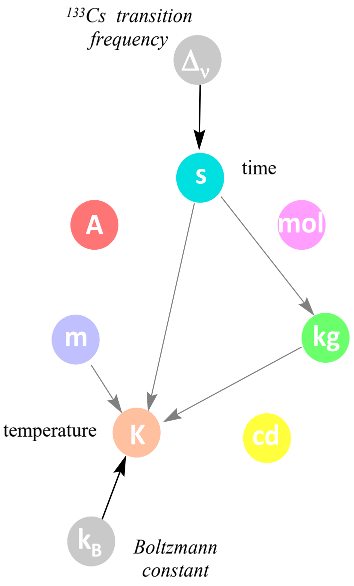

Figure 5. The kelvin.

k_B is an entropy, with value $k_B = 1.380\,649 \cdot 10^{-23}$ J·K^{-1}

the absolute entropy of a system being

$S = k_B \log \Omega$ (for Ω micro-states).

For a system with 1 Degree Of Freedom (DOF), which can be for example an electric resistor, we thus have $E_{th} = ½\, k_B\, T$, or for a monatomic gas (3 DOF) $E_{th} = 3/2\, k_B\, T$.

It makes real physical sense to express temperatures in joules, temperature being the image of the average energy of particles in a body.

Current language already makes use, unwittingly, of this permutation of units. When we use the expression "*what a heat today!*", we are in fact talking about temperature, and not about energy.

It results from the definition that one kelvin is equal to the change in thermodynamic temperature $\Delta T = 1$ resulting from a change in thermal energy $k_B\, \Delta T$

1 kelvin ⇔ $k_B \cdot$ J = $1.380\,649 \cdot 10^{-23}$ J.

In addition, we have seen that the energy could be related to the frequency

1 kelvin ⇔ $k_B \cdot 1$ J = $2.083\,7 \cdot 10^{10}$ hertz.

An ambient temperature of 296 K (23 °C) thus corresponds to 6.167 6 THz.

We can therefore express a temperature in joules, but also in hertz.

In practice, many physicists of low temperatures express these in frequency (Hz) or in energy (eV).

3.5. Electrical parameters

The particularity of the electromagnetic field is that two of the fundamental quantities, voltage U and resistance R, can now be measured with reference to very precise phenomena; whereas the basic quantity registered in the system of units is a third quantity, the intensity I.

The definition of the volt, like that of the ohm, calls upon the exact constants e and h.

The concrete implementation of the volt and the ohm requires cryogenic means.

3.5.1. The volt: the Josephson Effect and the measurement of voltages

The Josephson Effect is itself based on the tunnel effect.

The tunnel effect is a quantum effect; it exploits the fact that electrical charges present at the junction of two semiconductor materials can statistically, in small proportions, cross a normally impassable potential barrier. It can exist at room temperature.

The materials used for a Josephson junction are Niobium or Gallium Arsenide (AsGa), under superconducting conditions. The thickness of the intermediate insulating medium, consisting of alumina (Al_2O_3) must be sufficiently small (1 nanometer - as a reminder: the aluminium atom has a diameter of 0.3 nm and its nucleus has a diameter of $0.3 \cdot 10^{-6}$ nm).

A direct current can flow through the junction in the absence of applied voltage, due to superconductivity combined with tunnelling, up to a critical current value I_0. see Figure 6.

If a DC voltage U is applied to the terminals of the junction, the current of the pairs of coupled electrons, called Cooper pairs, crossing the junction oscillates at a frequency f_0 which depends only on the applied voltage:

$$U = f_0\,\frac{h}{2\,e}\,. \tag{9}$$

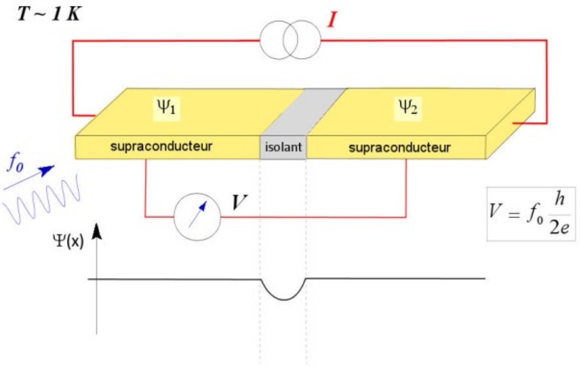

Figure 6. Josephson Effect - principle.

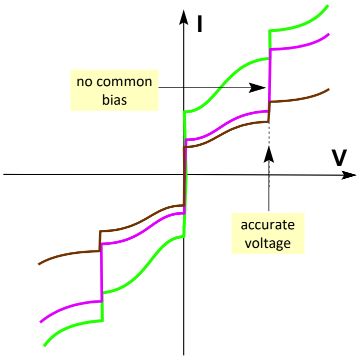

Figure 7. Association of Josephson junction cells.

The configuration of the device presented here corresponds to the case where, conversely, the Josephson junction is irradiated by means of an electromagnetic wave of frequency f_0.

The Josephson Effect therefore makes it possible to very precisely link the frequency to the voltage, or the reverse.

The constant $h/2e$ is the quantum of magnetic flux Φ_0 (in webers).

Since the voltage of a single junction is low, for example 40 µV for a control frequency of 20 GHz, networks of junctions connected in series are necessary to obtain the usual calibration voltages, see Figure 7.

The volt corresponds to the voltage associated with the Josephson frequency, noted f_J

U = 1 volt ⇔ $f_0 = f_J = h/2e$ = 483.597 9 THz

("optical" frequencies : 400 to 800 THz).

In addition, two phenomena make it possible to link the electrical voltage to the temperature:

1) the thermal voltage V_T related to a semiconductor junction (equation of the diode in the model of SHOCKLEY) given by

$$\frac{V_T}{T} = \frac{k_B}{e} = 8.617\,330\,34 \cdot 10^{-5}\,\frac{\mathrm{V}}{\mathrm{K}}, \tag{10}$$

i.e., $V_T \sim 25$ mV at room temperature. The voltage/temperature relationship can be written as 1 volt ⇔ 11604.518 K.

Moreover, the BOLTZMANN constant k_B relates the temperature T to a wavelength λ:

$$\frac{h \cdot c}{k_\mathrm{B}} = \lambda \cdot T . \tag{11}$$

However, this relationship is not a proportionality, but an inverse proportionality.

2) the thermal noise produced by a resistor R

$$V_\mathrm{T}^2 = 4\,k_\mathrm{B}\,T\,R\,\Delta f . \tag{12}$$

3.5.2. The ohm: the Quantum Hall Effect and the measurement of resistance

The Hall effect is the production of a potential difference (the Hall voltage) appearing transversely in an electric conductor traversed by a current, when a magnetic field is applied perpendicular to the current, see Figure 8.

The integer Quantum Hall Effect is a quantum version of the Hall effect, observed in two-dimensional electronic systems, subjected to very low temperatures and strong magnetic fields.

In the latter, the Hall conductance σ_{xy} undergoes quantum Hall transitions, to take quantized values.

Several forms of the Quantum Hall Effect (EHQ or QHE) have been highlighted: integer QHE (VON KLITZING, 1980), fractional QHE according to the value of a "filling factor" n, and spin QHE. The application to resistance metrology uses the entire QHE.

This application takes advantage of the exceptionally stable and accurate value of the QHE conductance σ_{xy}. Indeed the quantification of the Hall conductance has the property of being extremely precise. Recent measurements of this conductance have turned out to be whole or fractional multiples of e^2/h, to within one unit in 10^9, see Figure 9.

This phenomenon has made it possible to define a new practical standard for electrical resistance, based on the quantum

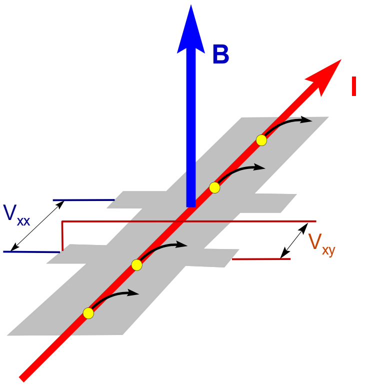

Figure 8. Classical Hall effect.

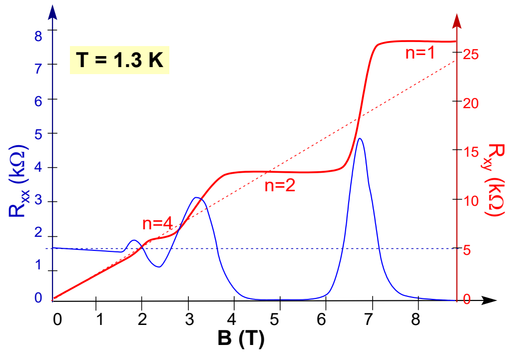

Figure 9. Quantum Hall Effect.

of conductance G_0 of exact value $2 \cdot e^2/h$, deduced from the Von Klitzing constant $R_K = h/e^2 = 25\ 812.807\ 46\ \Omega$.

Dimensionally, we have

$$[\Omega] = \frac{[V]}{[I]} = \frac{[\Phi] \cdot [T^{-1}]}{[Q] \cdot [T^{-1}]} = \frac{[\Phi]}{[Q]} = \frac{f_J \cdot \frac{h}{2 \cdot e}}{f_J \cdot e} = \frac{h}{e^2}. \qquad (13)$$

In other words 1 ohm = 1 weber per coulomb; this relationship does not involve time.

3.5.3. The ampere

The former definition

The previous definition of the ampere is recalled above in § 2.2. It was already appealing to time, although one might think at first sight that AMPÈRE's balance is a static device. In fact, this balance compares forces, and not masses: LAPLACE's force of electromagnetic origin, and gravitational force. The definition of a force involves acceleration, therefore time.

The new definition

The new definition of the ampere still calls on time, combined with the elementary charge of the electron, an exact constant. The ampere is the current which makes a charge of 1 coulomb flow during the unit of time. The number of electrons needed is $n_e = 1\ \mathrm{C}\ / e = 6.241\ 509\ 074\ 5 \cdot 10^{18}$.

The ampere is linked to time quantities by $I\ (= 1\ \mathrm{A}) = e \cdot f_J$, f_J being the Josephson frequency.

The fundamental quantities of electricity: voltage U, current I, and resistance R, are linked by OHM's law, an experimental law expressing a proportionality $U = R\ I$.

It can be seen that, admittedly indirectly, the current I can be the subject of a metrological determination from the voltage U and the resistance R, knowing that U and R can be obtained with high precision by using the two quantum phenomena of Josephson Effect and Quantum Hall Effect.

The realization of the ampere is a research subject of great topicality [8].

3.5.4. the number of moles is a pure number

With the exception of the cases previously mentioned, the quantity of substance is expressed by a pure number, and cannot be related to time.

3.5.5. The case of candela

The definition of the candela is based on power, energy per unit of time, so it makes use of time.

We will not go into more detail here for this quantity.

4. TIME IS NOT AN ABSOLUTE

So we see that everything, or almost, can be expressed by means of a time (or a frequency).

We can imagine new uses for units of measurement, and in particular a more general reference to time.

But is time an absolute?

4.1. The lessons of special relativity

Special relativity teaches us that no, each observer in space has his own measure of time.

MAXWELL's equations had established the identity of the speed of light in vacuum c for all spatial reference frames. Special relativity has drawn the consequences, expressed in terms of the slowing down of clocks and the contraction of lengths. The difference between the times measured by different observers is determined by their relative speed.

Remember that these effects are expressed by the LORENTZ-EINSTEIN transformation, which is written for a relative velocity v colinear with an axis Ox (Ox')

$$x' = \frac{x - v\,t}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}, t' = \frac{t - \frac{v\,x}{c^2}}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}, \qquad (14)$$

with t and t' being the times, and x and x' the abscissas in the two reference frames.

Time is only one of the dimensions of a global entity which is space-time.

This relativity of time is illustrated by the well-known paradox of Paul LANGEVIN, twins, one of which moves at high speed while the other is motionless. This effect is actually detectable by the occupants of the international space station who, each time they return to earth, make a "jump into the future" of a few milliseconds, in a way a resetting to our terrestrial time (the average speed of the station is only 7 km/s).

The high value of the speed of light, the significant energies that must be mobilized to approach this speed, in general, "protect" us from relativistic effects.

4.2. The lessons of general relativity

General relativity goes even further, specifying the role that gravitation plays. The presence of high masses leads to a local deformation of space-time.

In its simplest form, EINSTEIN's equation of general relativity is written:

$$G_{\mu\nu} = \chi\, T_{\mu\nu}\,, \qquad (15)$$

where $G_{\mu\nu}$ is the Einstein tensor, which represents the curvature of space-time at a point, $T_{\mu\nu}$ is the energy-momentum tensor representing the contribution of all matter (and energy) to the density of energy at this point, χ is an appropriate dimensional coefficient.

In the case of a strong deformation of space-time, shortcuts between very distant points in space-time could appear. This creates (weak) hope for time travel, taking advantage of spatio-temporal singularities such as "wormholes" (or EINSTEIN-ROSEN bridges). Hypothetical passages between points of time of very different dates would be possible.

To date, and unlike black holes, wormholes remain a very largely speculative concept (just like multiverses), and are not confirmed by any experimental observation. The conditions of

Figure 10. Symbolic representation of a wormhole; source Polytechnique insight.

their existence and their crossing seem insurmountable (colossal energies, intervention of "exotic" matter with negative mass, etc.), see Figure 10.

We may possibly regret it.

The BIPM brochure SI edition 9 states that:

> *"The definite second is the unit of time in the sense of the general theory of relativity. To establish a coordinated time scale, signals from different primary clocks around the world are combined, and then corrections are applied to account for the shift frequency relativist between caesium standards.*
>
> *For frequency standards, it is possible to conduct remote comparisons using electromagnetic signals. To interpret the results, it is necessary to use the theory of general relativity since it predicts, among other things, a frequency shift between the standards of about $1 \cdot 10^{-16}$, in relative value, per altitude meter on the Earth's surface. Effects of this order of magnitude must be corrected for when comparing the best frequency standards."*

4.3. Variants of time

4.3.1. Real time

Electronics engineers talk about real time to characterize a data processing system that provides information about a process that is taking place continuously, without falling behind it, i.e. without losing data. This concept is opposed for example to batch processing.

4.3.2. Imaginary time

It is not the imaginary part associated with the previous one. It is a mathematical device used to try to explain certain temporal aspects of the standard model of the Universe (cf. Stephen HAWKING). This time is quantified by a pure imaginary complex number [9].

4.3.3. Universal time

We can consider that the need, mentioned above and identified by the SI, "to establish a coordinated time scale", leads to constructing a universal reference, in other words implicitly amounts to redefining an absolute time.

The current international organization is based on:

- TAI time (International Atomic Time) produced by the BIPM; this time is established by coordination of 450 atomic clocks distributed around the world
- the UT1 time (Time related to the rotation of the Earth) obtained by the IERS (International Service for Earth Rotation and Reference Systems) at the Paris Observatory, from the observation of extra quasars galactic; UT1 is not uniform, because the rotation of the Earth around its axis varies over the long term (mostly slowing down)
- UTC time (Coordinated Universal Time); UTC is periodically adjusted on UT1 by possible addition of whole leap seconds, via administrative decisions.

In a way, we find the concern to facilitate everyday life and exchanges: the web, banking transactions, GSM localization systems, etc.

4.4. Mystery of time

Time retains a mysterious character.

The other fundamental quantities: mass, length, ... have a very concrete aspect, it is easy to visualize the physical data linked to a material object by its weight, its size, ...

Time has less of this concrete aspect. As Etienne KLEIN notes, physicists do not seek to deepen the nature of time.

Physicists, and in particular electricians, have a somewhat privileged view, being familiar with frequency, which is the inverse of time (at least for periodic phenomena, and which allows a somewhat more concrete approach: height (frequency of a sound) and the colour (optical radiation) of an object.

4.4.1. Time and philosophy

Scientists do not have a monopoly on time.

Since Antiquity, many philosophers have wondered about the question of time, Aristotle having been the most striking of them. At this stage, the perception of time is closely linked to the observation of movement.

In close centuries, Emmanuel KANT, then Edmund HUSSERL, Martin HEIDEGGER, and many others, tried to theorize this subject. Hence many works, often arduous, even downright obscure, to the point that certain eminent minds such as Jean-Paul SARTRE did not understand them; and in any case, they are often devoid of practical utility.

Henri BERGSON (Figure 11), for his part, brings a certain clarity to the subject, by basing his analyses on two solid concepts: that of simultaneity, and that of duration.

BERGSON looked at the question of time, not as a physical quantity, but as a human perception. The confrontation between EINSTEIN (Figure 11) and himself, organized in 1922 at the College de France, did not bring, given its brevity, the progress that we wanted to expect. It nevertheless opened the way to renewed exchanges between "exact" sciences and human sciences, which some considered to be without interest or object [10], [11].

BERGSON disputes the spatial approach (of time projected onto space) of psychological realities, and the fact of reducing them to quantity, which is the characteristic of material objects grasped in space, whereas psychological realities come from another dimension. He describes duration as a series of states of consciousness.

Humans have an intuitive approach to time. One feels his own aging. "To live consists in growing old" writes BERGSON again.

An elderly person who uses an anti-wrinkle cream does not reverse the course of time. She is not getting any younger. It just hides marks.

Humans attribute qualitative properties to time. One is having a "good time". Because the French language does not differentiate "time" from "weather", when a person talks about "*mauvais temps*", in fact she is talking of something quite different. These two types of *temps* have in common the fact that they are commonly the subject of endless conversations.

Closer to now, physicist Carlo ROVELLI in [12] deconstructs, from modern physics, our traditional conception of time.

4.4.2. Time and literature

Writers, like philosophers, have been drawn to the subject of time.

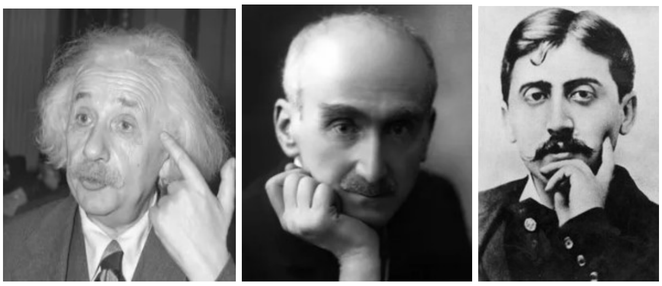

Figure 11. Scientist Albert Einstein, philosopher Henry Bergson, and writer Marcel Proust.

The monumental work of Marcel PROUST (Figure 11) "*In Search of Lost Time*" explores with great detail the psychological perception of time, which leaves the feeling of escaping to man, not so much in his understanding, but in his possession. This work, which dissects the functioning of affective memory, ends with a final volume that evokes time regained. If he was strongly influenced by the ideas of BERGSON, like many writers of his generation, PROUST also distinguished himself by a more freely imaginative vision: while the philosopher remains in a rational and logical approach, the artist is not subject to any such constraint [13].

In addition to PROUST, many writers have taken up this theme, from Paul MORAND ("The hurried man") to René BARJAVEL ("La nuit des temps").

Time is also a potentially limitless theme for science fiction literature.

5. PERSPECTIVES

5.1. Are we moving towards a different use of measurement units?

Undoubtedly not, because we must not underestimate the weight of habits, generator of inertia detrimental to change, even simplifying:

1) the adaptation time, observed during simple changes (change of monetary unit - changeover to the euro) is significant

2) the Anglo-Saxon world still remains attached today to its own system of units, although archaic and above all non-decimal.

It should be remembered that the French Revolution, which is at the origin of the metric system, had tried to include time in it; by establishing, for example, hours of 100 minutes and minutes of 100 seconds, to "decimalize" it. But without achieving it.

It is the original, sexagesimal system that has prevailed. This system goes back to Antiquity, it is of Sumerian origin, and common among others with the angular domain (1 turn = 360°).

5.2. What about metrology?

Metrology progresses.

Time is today the parameter of the system of units which allows the greatest resolution (10^{-15}).

5.2.1. The present reference clocks

They are atomic clocks. These clocks take advantage of the very great stability of the energy levels of the electrons in the electronic shells of the atoms, see Figure 12.

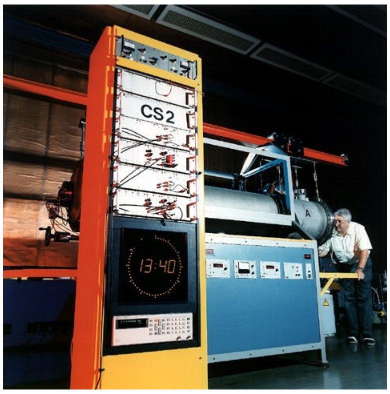

Figure 12. Atomic clock of METAS.

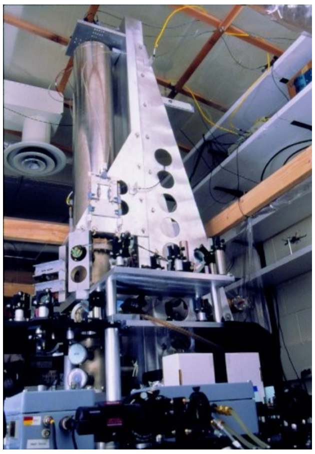

Figure 13. Atomic clock NIST-F1.

The principle of these clocks was acquired in 1955, and the current definition of the second, based on the choice of caesium 133, has remained unchanged since 1967.

The energy level transitions of the electrons, either to a higher energy or to a lower energy, respectively by absorption and by emission of a photon, result in the frequency ν of the associated wave, given by the equation

$$\nu = \frac{E_2 - E_1}{h} . \tag{16}$$

The main spectral line being associated with the main quantum number n, quantum sub-levels can extend this line if necessary, depending on the magnetic environment conditions for certain atoms; we then speak of a fine or hyperfine structure. The official definition of the second specifies that it is the two hyperfine levels of the ground state of the caesium 133 atom.

"Common" atomic clocks, i.e. commercially available, today give a relative measurement uncertainty of 10^{-14} (which corresponds to 1 μs/year)

These clocks are used in particular for the distribution to the public of a reference time: speaking clock, exact Swiss time (https://heure-exacte.net/), etc.

Atomic "fountain" clocks: One of the most advanced realizations of caesium atomic clock is the NIST-F1 caesium atom fountain atomic clock. This clock is the primary time and frequency standard of the United States, with an uncertainty of 5×10^{-16}, Figure 13.

5.2.2. The future reference clocks

The equipment used in the future will be

- atomic clocks, based on other materials, at optical frequencies

  The electronic transition frequency of caesium $\Delta\nu_{\mathrm{Cs}}$ is "only" 9.193 GHz. Some other materials allow higher frequencies (calcium, ytterbium, strontium, mercury, aluminium).

  A factor of 10^5 could be gained compared to caesium. The BIPM has fixed the transition frequency of strontium at 429.228 004 229 873 2 THz.

- nuclear clocks

  These clocks will use transitions at the level of the nucleus of atoms, and no longer at the level of their electronic cloud. Since the size of the nuclei is much smaller than that of the atoms, this type of clock will be much less sensitive to external disturbances, in particular electromagnetic ones. A precision of 10^{-19} can be achieved with ^{229}Th+++ thorium ion nuclei.

5.3. Towards ever greater precision

Is there therefore a stake in increasingly precise references for the basic physical quantities?

We can answer in the affirmative.

Certain sciences in particular, such as astrophysics, need extremely precise experimental data. It is necessary to be able to interpret with certainty any deviations observed from known physical laws, which can reveal phenomena that are still unknown. These differences are getting smaller and smaller. However, when in doubt, the observations cannot be used to conclude. A well-known historical example is the measurements of the deflection of light by gravity, made by EDDINGTON in the 1920s.

Another more recent example is that of the neutrinos observed as part of CERN's Opera experiment in 2011, which seemed to reach superluminal speeds.

5.4. The redefinition of the second

The current definition dates from 1967, half a century ago.

In the framework of the 27th meeting of the GFCM in November 2022, the following recommendation is found: "issue proposals at the 28th CGPM (2026) to choose the favoured species, or set of species, for a redefinition of the second, so that a new definition of the second is adopted by the 29th CGPM in 2030" [14]

This project is based on recent progress on associated measurement uncertainties.

6. CONCLUSION

With the progress of the basic sciences, cosmology and particle physics in particular, our understanding of the physical quantity of time is becoming clearer, within the framework of increasingly well-established theories and models, such as the standard model. At the same time - to use a fashionable phrase - our mastery of the technical aspects of time is improving through increasingly sophisticated and precise metrological instruments.

Time nevertheless retains its mystery. The times we are living in, a notion which is not unrelated to the passage of time, leaves us with immense fields open to new research.

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