Physics in the XXIst century

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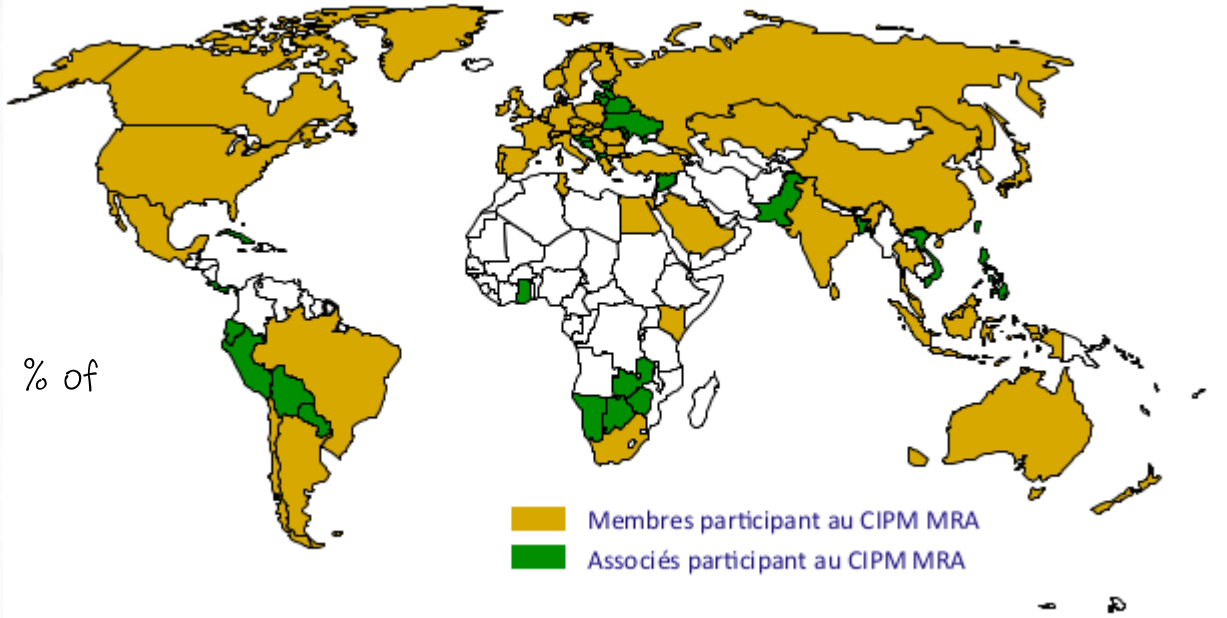
The International System of Units (SI)

Units are one of the major differences between maths and physics !
One can check the unit homogeneity of a formula in physics.

International Committee for Weights and Measures (CIPM)

Units System for 97.6 % of the world economy



The earth has been measured as a basis for permanent standard of length, and every property of metals has been investigated to guard against any alteration of the material standards when made. To weigh or measure any thing with modern accuracy, requires a course of experiment and calculation in which almost every branch of physics and mathematics is brought into requisition.

Yet after all, the dimensions of our earth and its time of rotation, though, relatively to our present means of comparison, very permanent, are not so by any physical necessity. The earth might contract by cooling, or it might be enlarged by a layer of meteorites falling on it, or its rate of revolution might slowly slacken, and yet it would continue to be as much a planet as before.

But a molecule, say of hydrogen, if either its mass or its time of vibration were to be altered in the least, would no longer be a molecule of hydrogen.

James C. Maxwell, British Association for the Advancement of Sciences, Liverpool 1870

20 May 2019 : biggest revolution in measurement units since the French revolution

The new adopted system is based on fundamental natural constants appearing in fundamental physical laws.

Its a system based on geometry, action and entropy.

Geometry, action and entropy

We could also say relativity, quantum mechanics and statistical mechanics.

$$c^2 d^2\tau = c^2 d^2 t - d^2 \vec{r}$$

proper time

time coordinate

space coordinates

$$E = h\nu$$

$$\Delta E \Delta t \geqslant \hbar/2 = \frac{h}{4\pi}$$

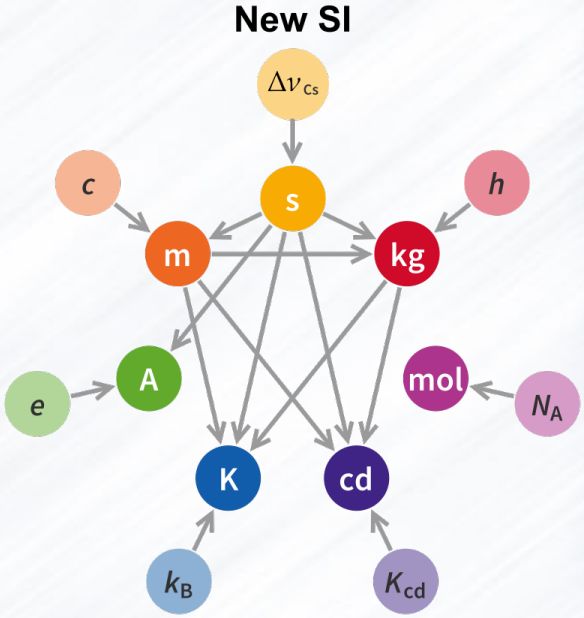
$$\Delta p_x \Delta x \geqslant \hbar/2 = \frac{h}{4\pi}$$

$$S = k_B \ln \Omega$$

International system of units

SI is built on seven base (fundamental) units :

- meter , m
- second , s
- Kilogram , Kg
- ampere , A
- Kelvin , K
- mole , mol
- candela , cd



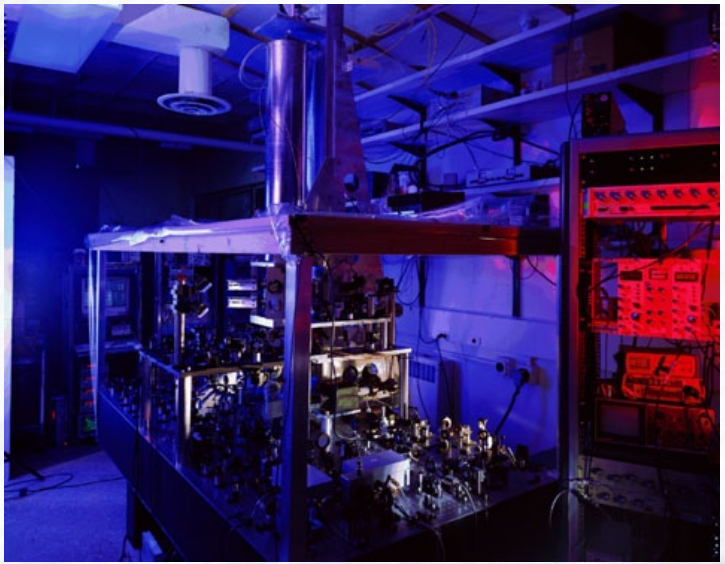
Interdependency of SI base units

The very first principle is in fact to set the velocity of light in vacuum to $c = 299\,792\,458\ m\ s^{-1}$.

According to relativity, c is a constant when considered in an inertial frame (free-falling frame).

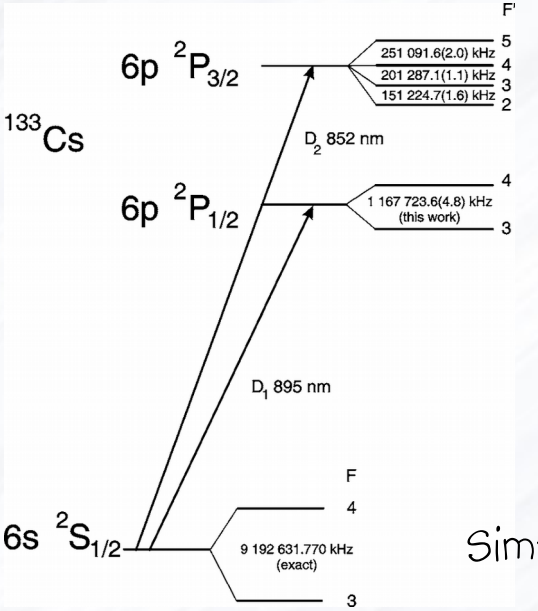
Second

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



NIST-F1 in NIST (US)
Cs fountain atomic clock
stability = $5\ 10^{-16}$
1 second of drift over 60 million years.

Why ^{133}Cs ?



Electronic structure [Xe] $6s^1$, Z = 55

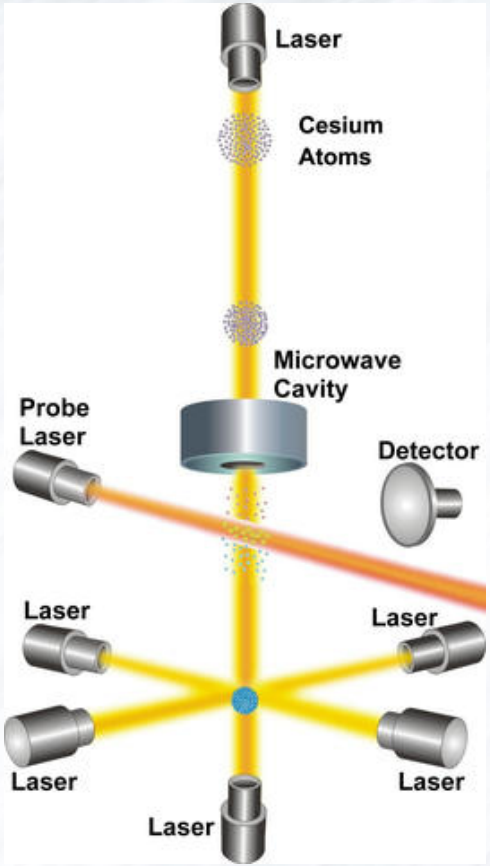
then L = 0 , S = 1/2 , J = 1/2 ($^{2S+1}L_J = {}^2S_{1/2}$)

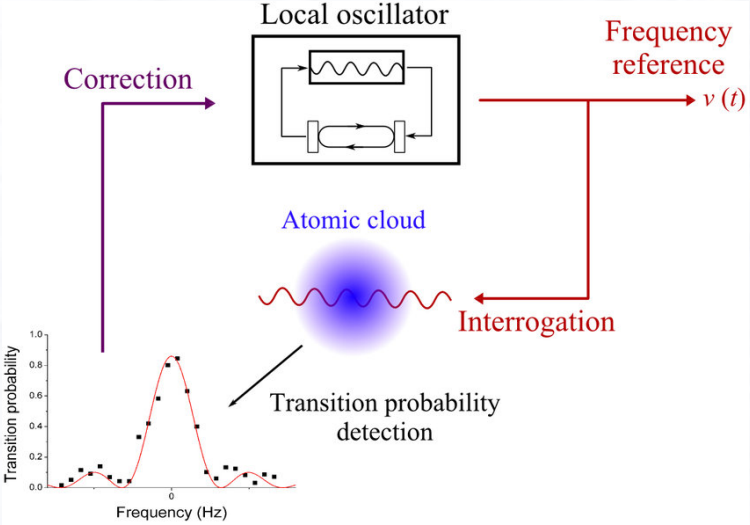
Cs is a mono-nucleide element : only one stable isotope (^{133}Cs) naturally exists

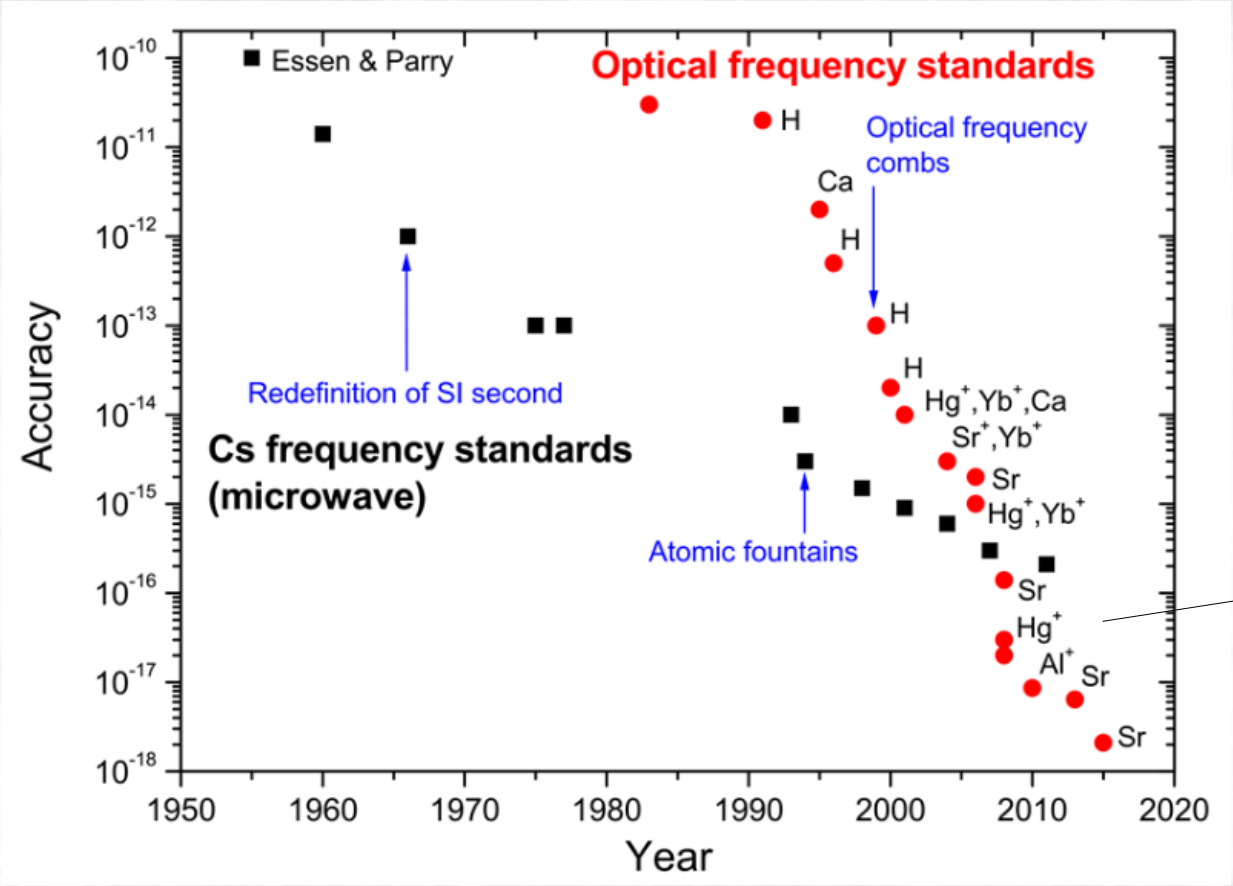
I (nuclear spin) = 7/2 then F (I+J) = 3 and 4

Simple hyperfine splitting of ground state !

^{133}Cs atomic fountain clock







towards a new definition !

Meter

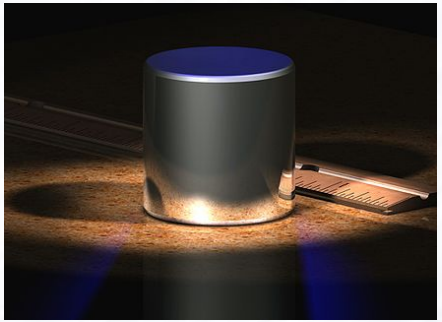
The meter is the length of the path traveled by light in vacuum during a time interval of 1/299792458 of a second.

Originally, it was first set as :

10^{-7} of the distance from the Earth's equator to the North Pole measured on the circumference through Paris.

Kilogram

The kilogram was equal to the mass of the international prototype of the kilogram (IPK), a platinum-iridium alloy cylinder (~47 cm^3) stored in a vault near Paris.

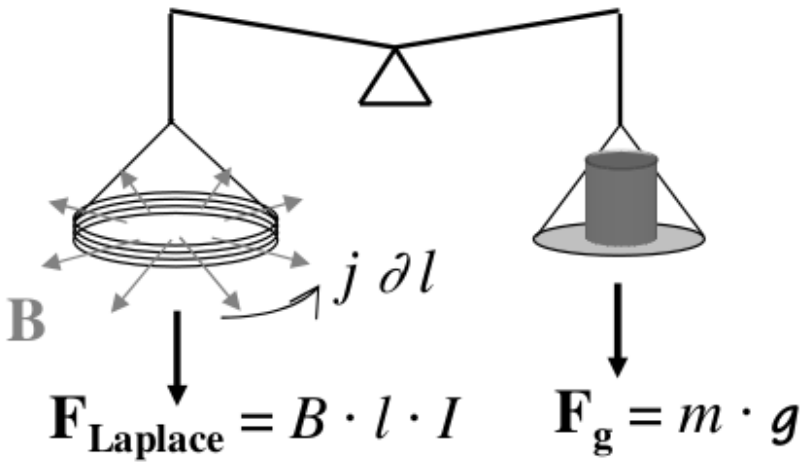


A new definition took effect in 2019 :

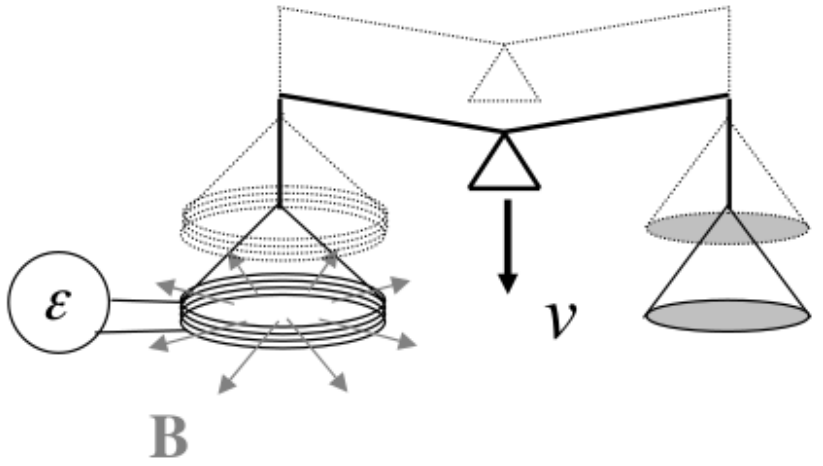
It is now defined by fixing the numerical value of the Planck constant h to be $6.62607015 \times 10^{-34}$ when expressed in the unit J·s, which is equal to kg m^2 s^{-1}.

Since the meter and the second were already defined, kg is now fixed as a function of those.

Kibble balance



$$F_z = mg = Bli$$



$$\epsilon = -Blv$$

$$mgv = \epsilon i = \epsilon V/R$$

Using the Josephson effect, the Quantum Hall effect and measuring local gravity (g), it measures : $\frac{m}{h}$

X-Ray Crystal Density

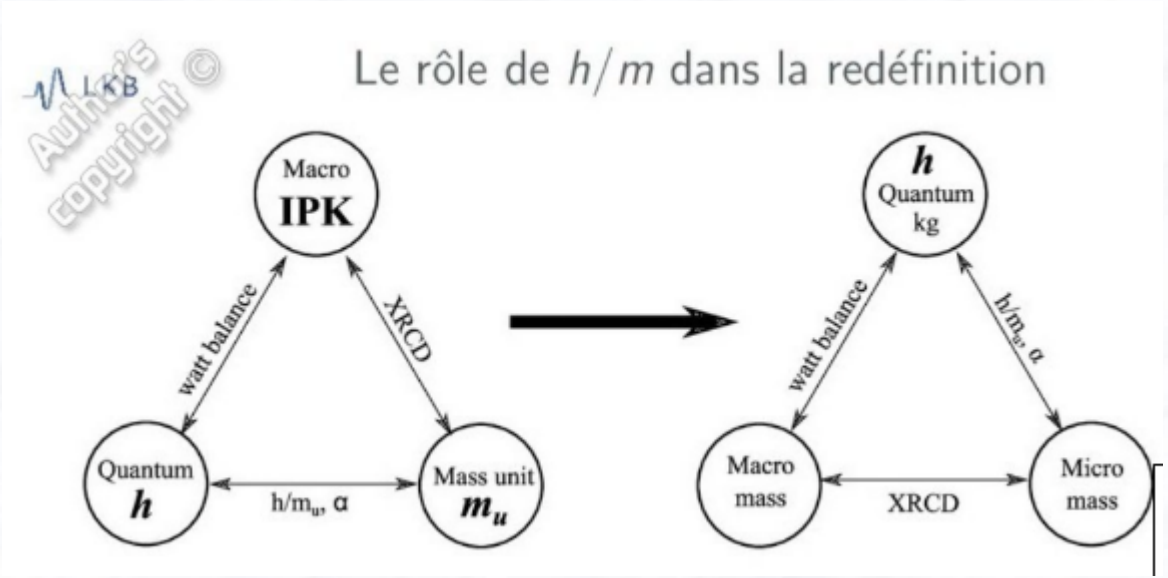
1 kg of ^{28}Si

Measure its volume.

By X-ray diffraction, determine the unit cell volume of the lattice.

Obtain the number of ^{28}Si atoms per Kilogram and set the atomic mass unit (m_u).

Transition to new Kg definition



Ampere

The ampere, is defined by taking the fixed numerical value of the elementary charge e to be 1.602 176 634 $\times 10^{-19}$ when expressed in the unit C, which is equal to A s.

The second being defined, A is defined.

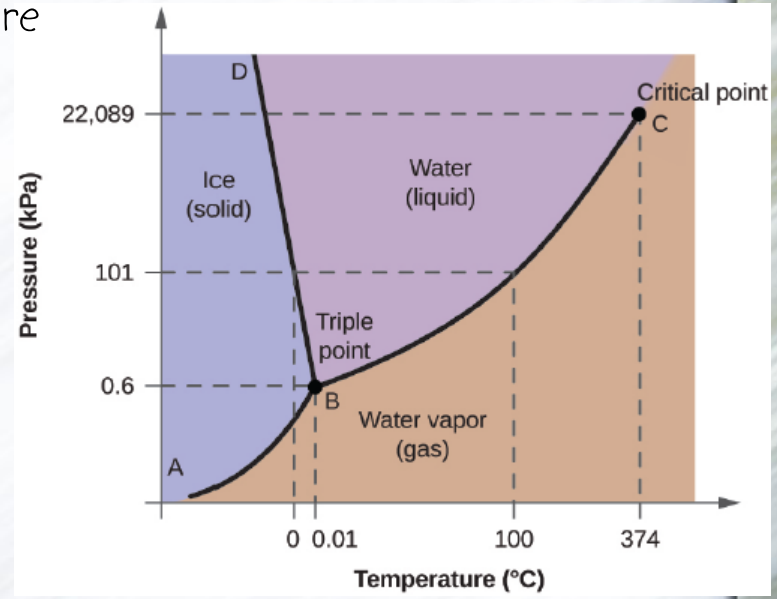
Kelvin

1 K was originally defined as 1/273.16 of the thermodynamic temperature of the triple point of water.

0 K is set to the absolute thermodynamic temperature (no remaining internal motion)

The Kelvin is now defined by taking the fixed numerical value of the Boltzmann constant K_b to be $1.380\ 649 \times 10^{-23}$ when expressed in the unit $J\ K^{-1}$, which is equal to $kg\ m^2\ s^{-2}\ K^{-1}$.

The kilogram, meter and second being defined, K is defined.



Mole

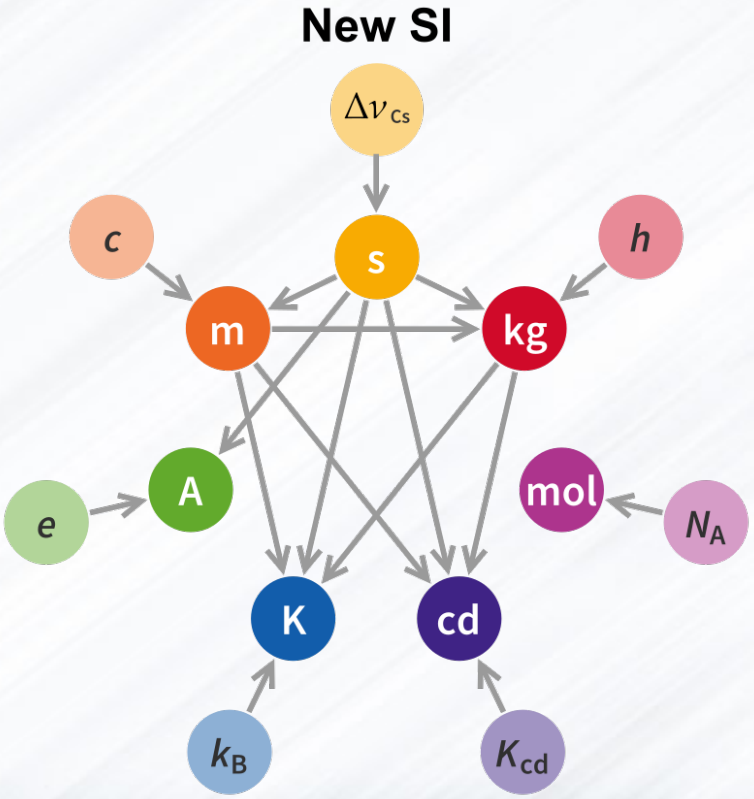
The mole, symbol mol, is the unit of amount of substance. One mole contains exactly 6.022 140 76 x 10^{23} elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A , when expressed in the unit mol^{-1} and is called the Avogadro number.

Candela

The candela, symbol cd, is the unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 x10^{12} Hz, K_{cd} , to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1} , or cd sr kg^{-1} m^{-2} s^3. (sr = steradiant)

Used in photometry and takes into account the effect of the standard human eye sensitivity to visible light.

Inter-dependency of new SI units



Epilogue

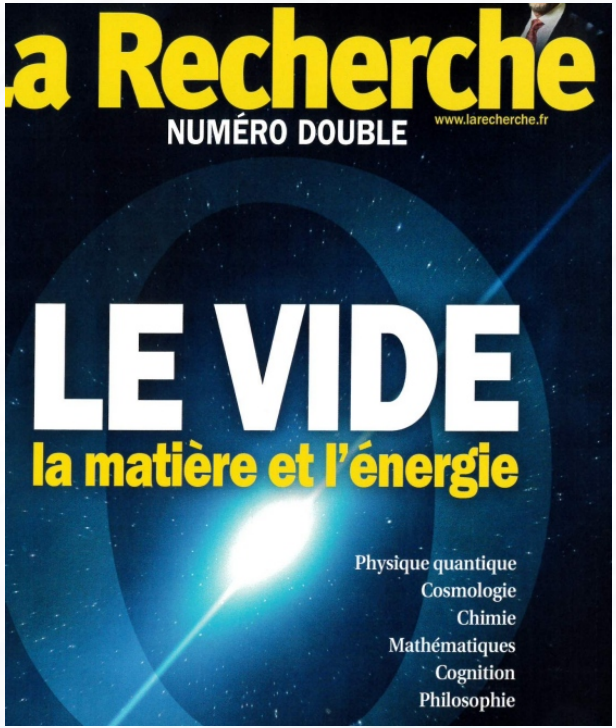
18 hours of lectures and 350 slides later

Summary/lessons for the future

- Stop believing/teaching that Christopher Columbus discovered America
- Science is made/tested by many more than what the history books let us believe
- Be careful of paradigms ! Powerful but they always impose conceptual limits that are hard to overpass
- Pillars of physics and of modern science in general : relativity, quantum mechanics and statistical mechanics, atomic paradigm, in other words modern mechanics, since everything is in motion, nothing is at rest ...

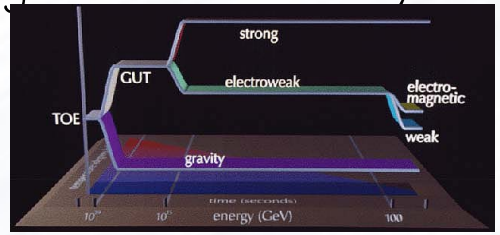
Vacuum : the never ending topics

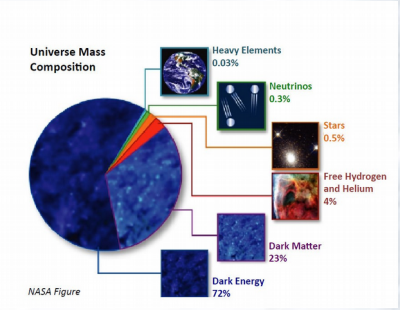
August 2020 issue of
La Recherche !



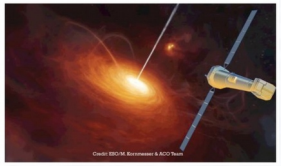
Physical enigmas (not an exhaustive list ...)

- Energy/matter budget of the Universe (dark matter , dark energy)
- Matter predominance over antimatter
- Grand Unification of forces (strong and electroweak)





- Masses of elementary particles
- Quantum gravity / Geometry
- Formation of super massive black holes



- Theory of high-temperature superconductors

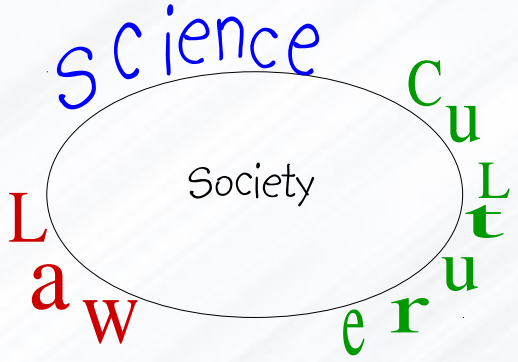
Challenges for the XXIst century (not an exhaustive list...)

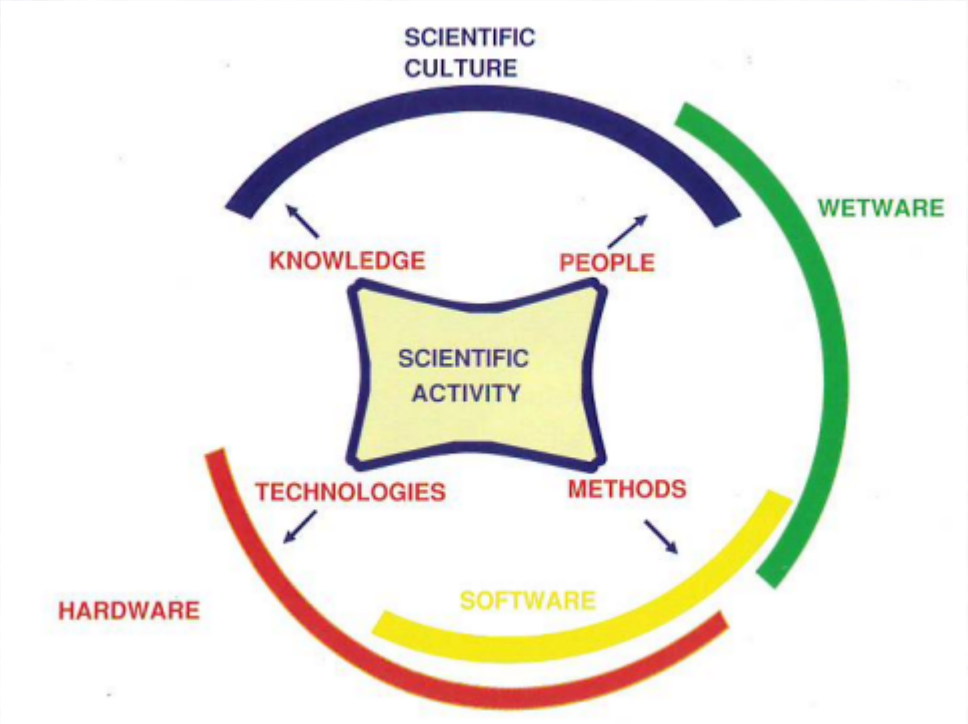
- Revise history of science with a much wider view and more open attitude with respect to all civilizations
- Laser Interferometer Space Antenna : LISA
- Next high-energy particle collider beyond LHC
- Quantum computing
- Complex and biological systems
- Greener world energy supply in the climate warming era

"Why do we devise theories at all ? The answer is simply because we enjoy comprehending ... There exists a passion for comprehending, just as there exists a passion for music "

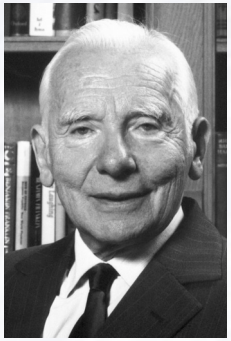
Albert Einstein

Society triptych




SCIENTIFIC
CULTURE
WETWARE
KNOWLEDGE
PEOPLE
SCIENTIFIC
ACTIVITY
TECHNOLOGIES
METHODS
HARDWARE
SOFTWARE

Ethics and science



Josef Rotblat 1908 - 2005

Pugwash

Pugwash Conferences
on Science and World Affairs

Nobel Peace Prize 1995

1995 Nobel Prize for peace

Pugwash pledge :

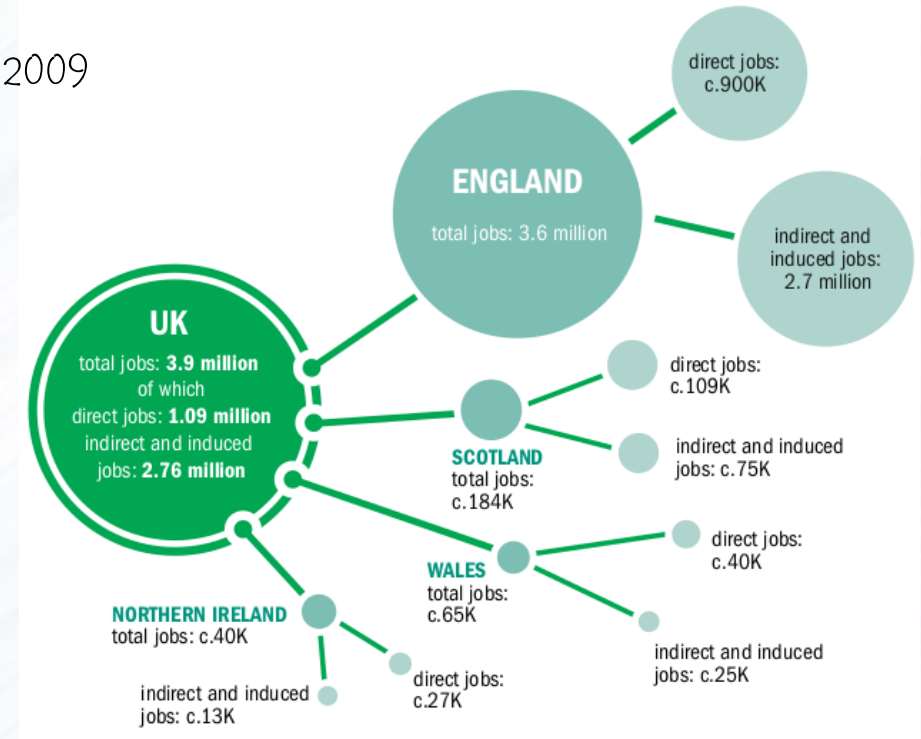
I RESOLVE to always keep ethical thinking foremost in my considerations of my words and actions. I will undertake no projects and support no activities whose harms outweigh their benefits, and I will give full consideration to both throughout my work. I will stay informed about future developments in science, technology, and international security to be a resource to my peers. This I pledge in my career, as a member of my communities, and as a citizen of my nation.

Impact of physics on economy

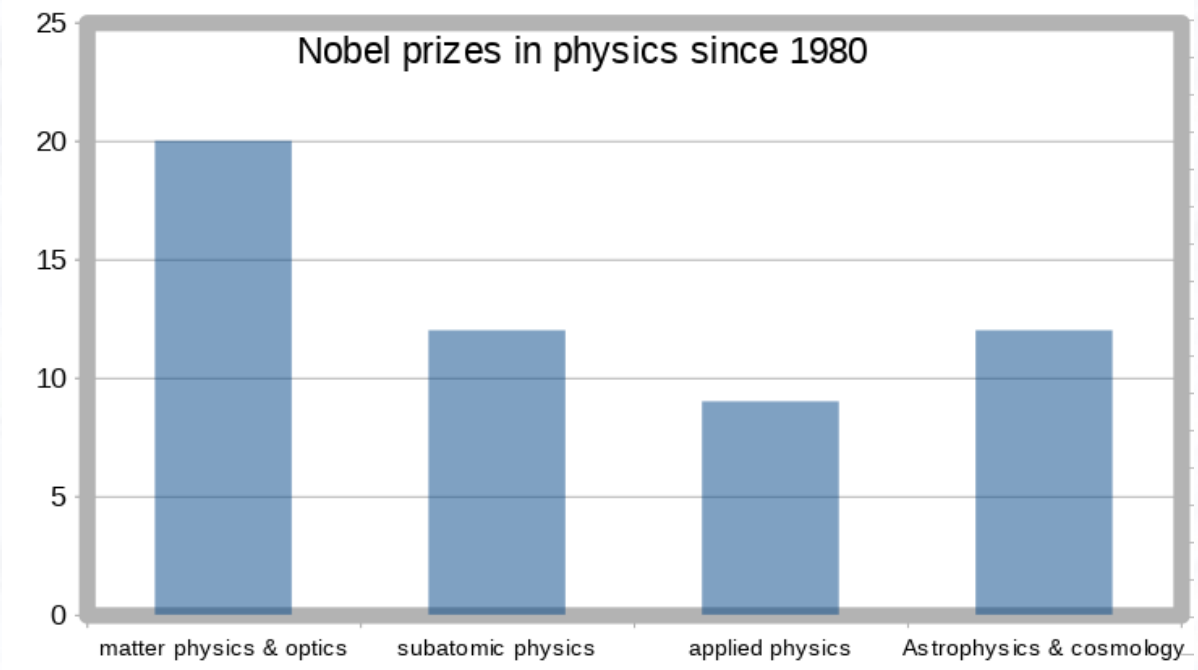
Enquiry performed by IoP in UK in 2009

Physics contribute 8.5% of the UK's economic output.

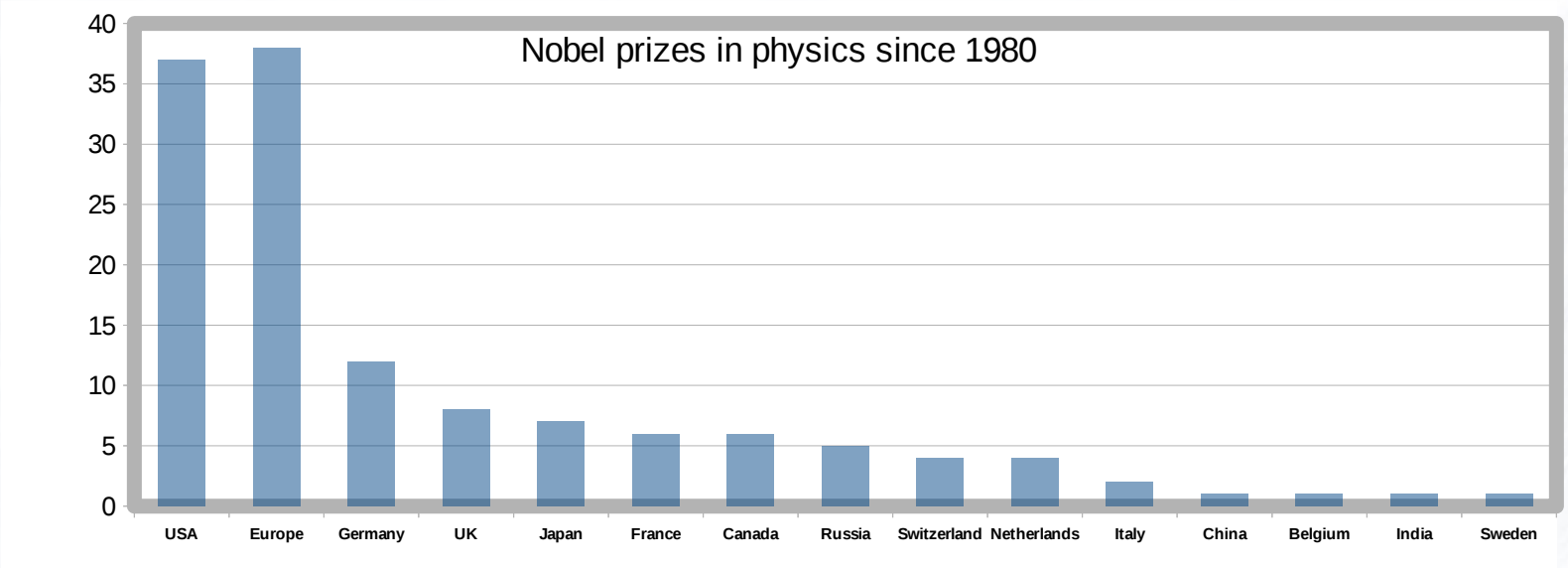
Inducing £220 G of which £100 G in exports.



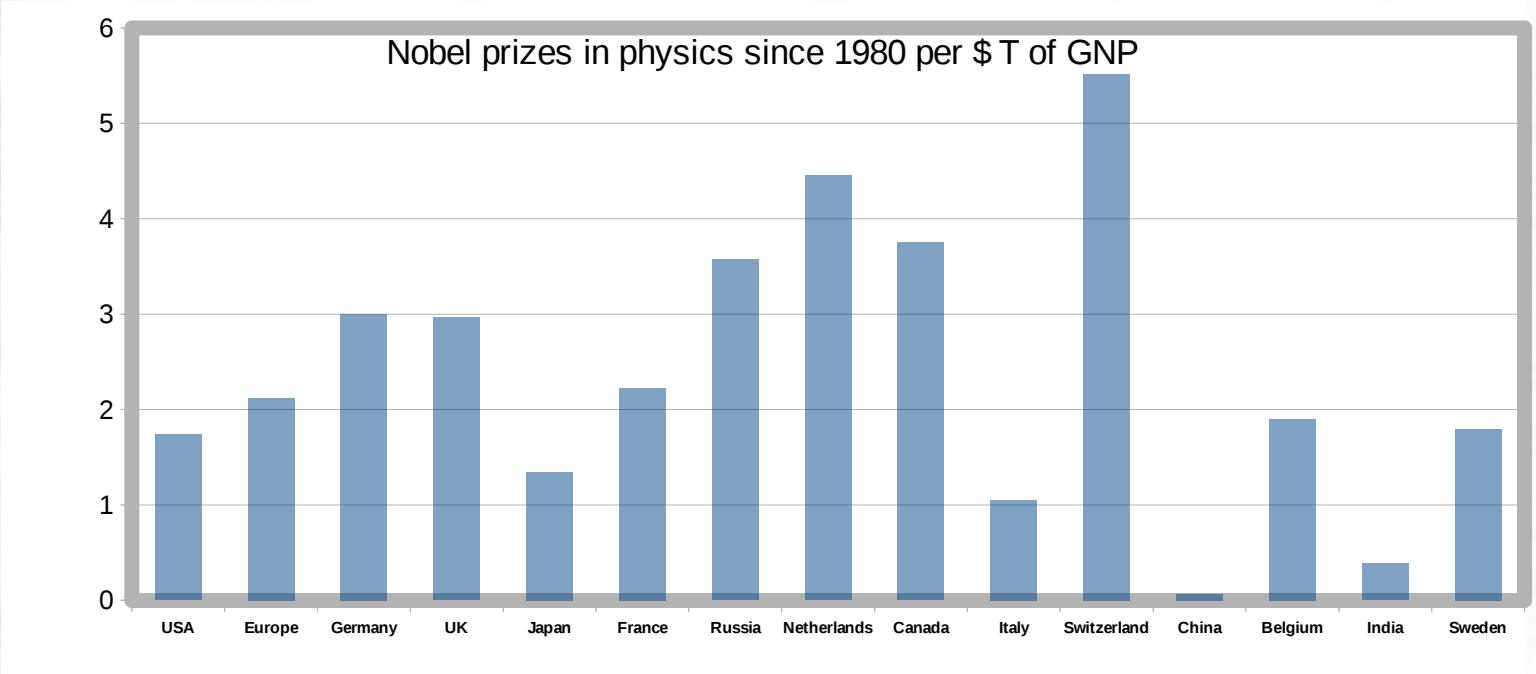
Physics Nobel prizes per main category since 40 years



Physics is part of national pride :
Nobel prizes per country over last 40 years



Nobel prizes per country per $ T of GNP over last 40 years



For further reading :

- https://www.lne.fr/fr/comprendre/systeme-international-unites/introduction-si