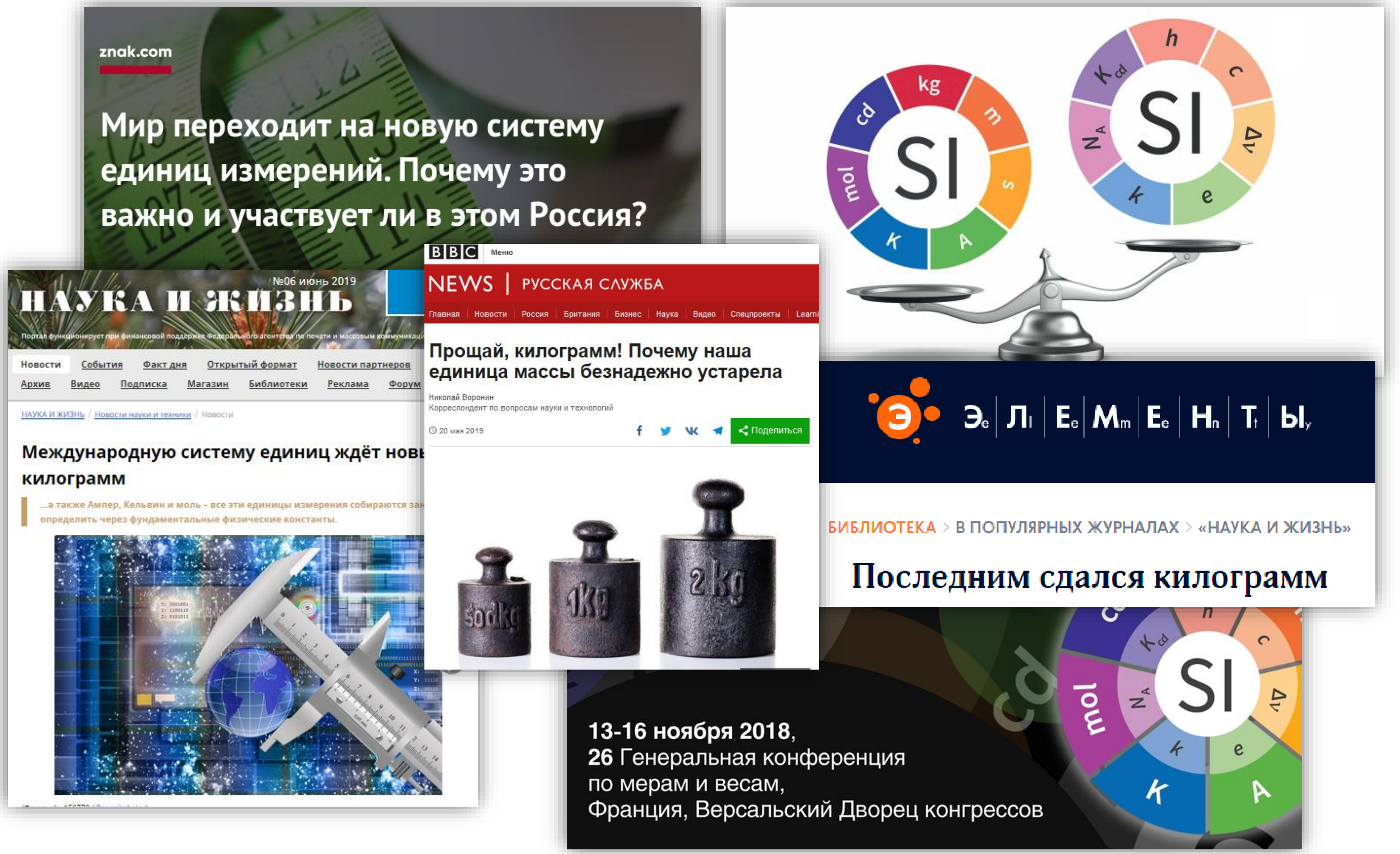
Килограмм уже не тот

Переопределение международной системы единиц СИ

Андрей Суржиков

Technische Universität Braunschweig /
Physikalisch-Technische Bundesanstalt (PTB)

New system of units SI



What it is all about? What is the system of units and why it requires revision?

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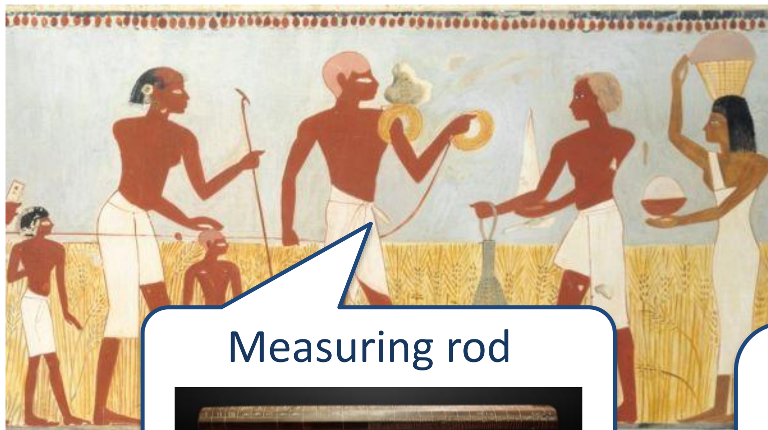
Standards of measurements

The measurements have been known and strongly demanded from the earliest days of human history: in religion, in farming, in trade.

Anubis weighing the souls of the dead.



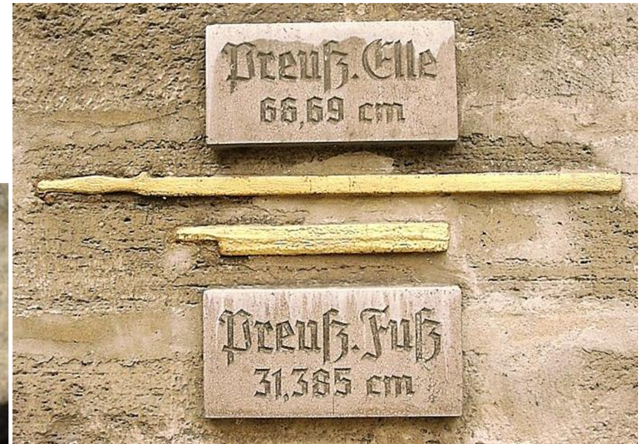
Land surveying (1400 B.C.)

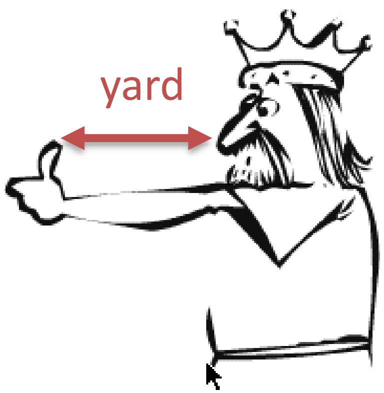
merchandise (500 BC)

In order to make measurements and compare their results one needs to define the **standard of measurement**.

Obsolete length measures

In ancient and medieval Europe, there were no common standard length measures: each region could have its own.





The yard was introduced by King Edgar the Peaceful and defined as the distance from the tip of His Majesty's nose to the tip of the finger stretched out towards the hand. But kings change... And the yard, respectively, also changed.

The **unification** of the standards was required!

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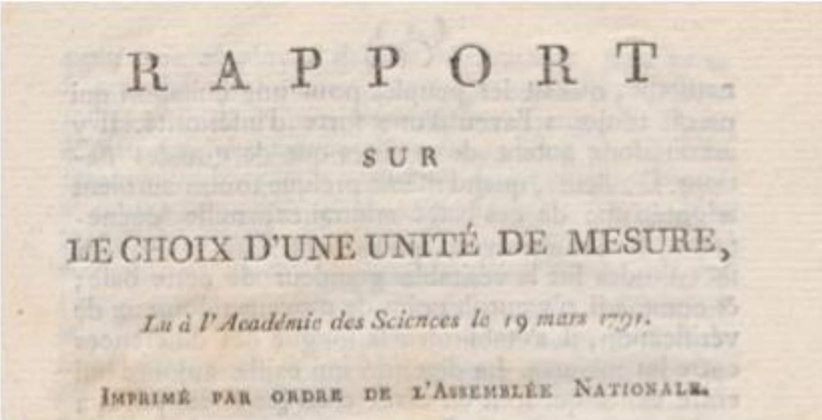
Universal length measure



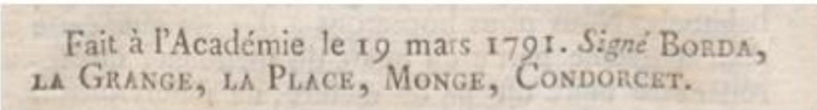
RAPPORT

SUR

LE CHOIX D'UNE UNITÉ DE MESURE,

Lu à l'Académie des Sciences le 19 mars 1791.

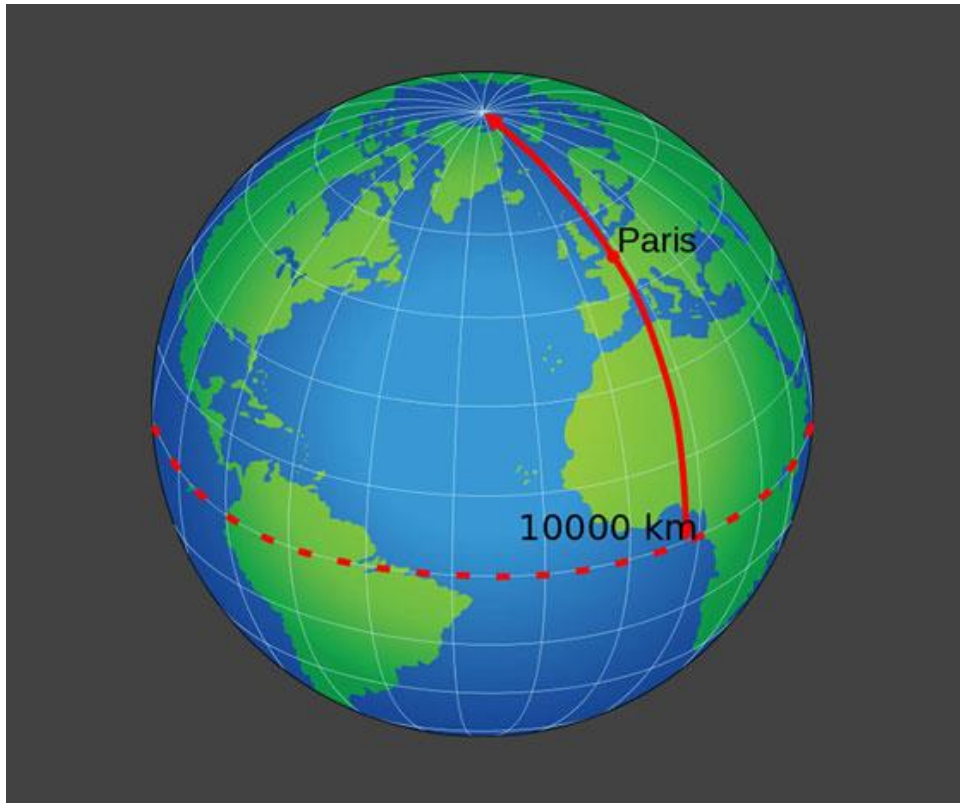
IMPRIMÉ PAR ORDRE DE L'ASSEMBLÉE NATIONALE.



Fait à l'Académie le 19 mars 1791. *Signé* BORDA, LA GRANGE, LA PLACE, MONGE, CONDORCET.

"…The idea of **referring all measurements to a unit of length taken from Nature** was seized upon by mathematicians as soon as the existence of such a unit and the possibility of determining it became known…"

The French revolution has led to the idea of a universal measure of length – **meter** as one forty-millionth part of the Paris meridian .



Terry Quinn's translation of the original French text of the report made to the Académie Royale des Sciences "on the choice of a unit of measurement"

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Parisian meridian: Length measurement

BASE

DU SYSTÈME MÉTRIQUE DÉCIMAL,

OU

MESURE DE L'ARC DU MÉRIDIEN

COMPRIS ENTRE LES PARALLÈLES

DE DUNKERQUE ET BARCELONE,

EXÉCUTÉE EN 1792 ET ANNÉES SUIVANTES,

PAR MM. MÉCHAIN ET DELAMBRE.

Rédigée par M. Delambre, [illegible]

SUITE DES MÉMOIRES DE L'INSTITUT.

TOME PREMIER.

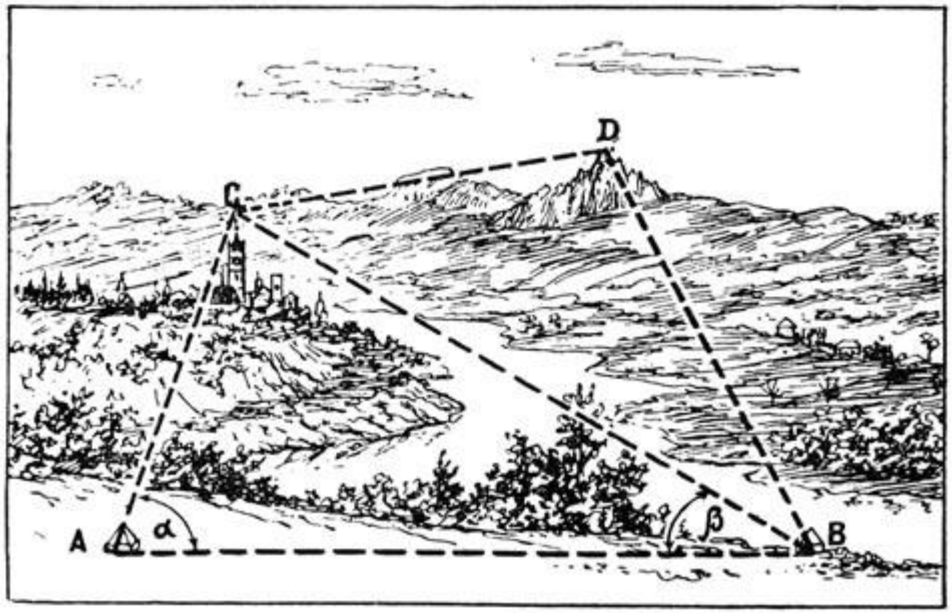
PARIS,

BAUDOUIN, IMPRIMEUR DE L'INSTITUT NATIONAL.

[illegible]

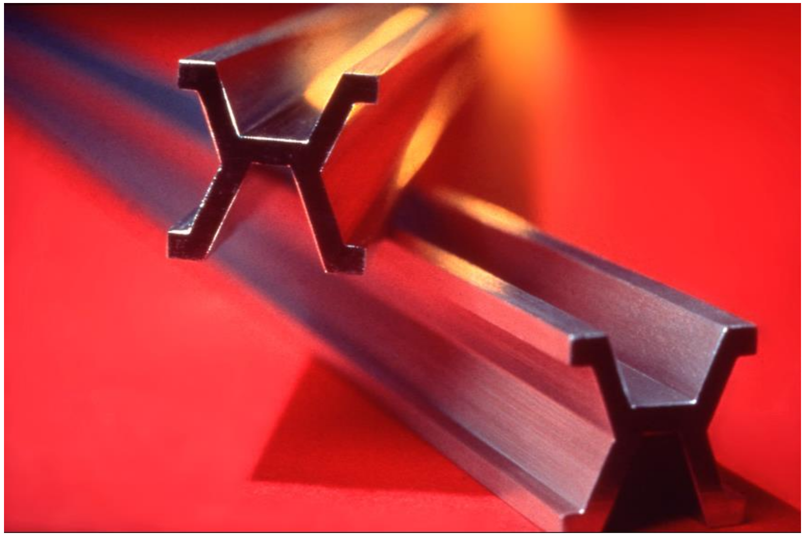
JANVIER [illegible]

In 1792-1797, Delambre and Mechain measured the arc of the Parisian meridian length of 9° 40' from Dunkirk to Barcelona, laying a chain of 115 triangles across all of France and part of Spain.



Standard meter

There is no need to measure the meridian length every time we need to determine what a meter is. You can create a **standard** for a meter.



On December 10, 1799, the introduction of a new **metric system** was announced. That year, the first ever standard meter was created. Thousand copies of the new unit of measurement were made and sent to the entire country, and then to the world.

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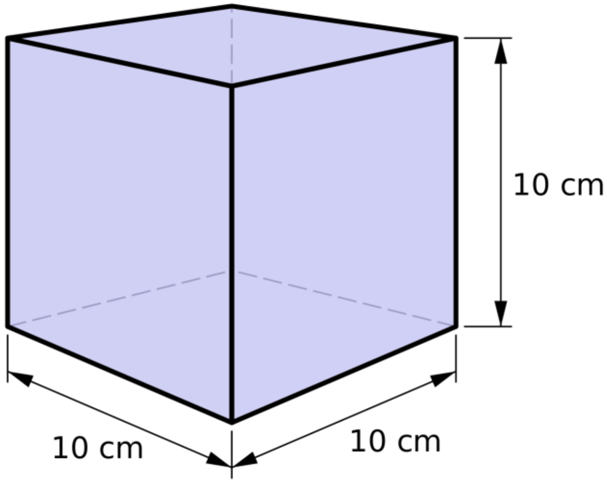
From meter to kilogram

We can now define a kilogram as the mass of one cubic decimeter of distilled water at the temperature of melting ice.

Please note: we determine kilogram based on the meter!



Again, it is not very convenient to measure the mass of one liter of water each time.

The "main" standard is made of platinum-iridium alloy and is stored in the International Bureau of Weights and Measures.

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For all times, for all people

In 1875 in Paris was signed an international treaty "Metric Convention", which serves to ensure the unity of metrological standards in different countries.

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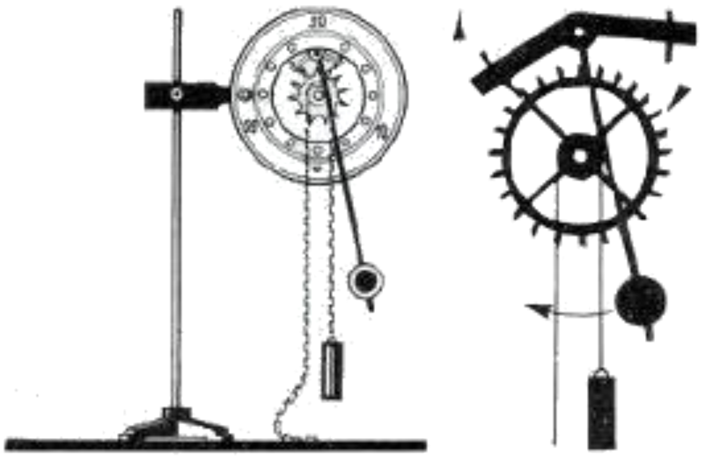
For all times, for all people

Time measurements

So far, we haven't touched the time units. It is clear that we need some kind of **cyclic process** to measure time. Since ancient times, people observed such processes: the alternation of night and day, seasons...



In the Age of Discovery, more and more precise mechanical watches have been developed. But the period of oscillation of the pendulum depends on the geographical latitude. And, much more seriously, it is impossible to create several the same mechanisms.

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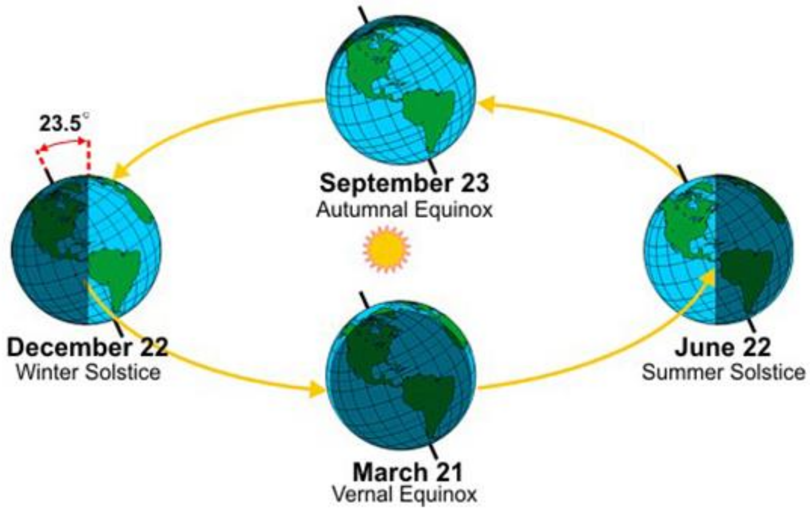
Day, year and... second

Over many centuries of astronomical observations, very accurate data on the movement of the Sun have been accumulated. It seemed natural to define a second as a certain proportion of the year.



For example, in 1960, the second was defined as

„the fraction 1⁄31,556,925.9747 of the tropical year for
1900 January 0 at 12 hours ephemeris time “

Why is that such a strange definition? What does 1900 have to do with this? The reason is that the Earth's speed of rotation is not constant, but changes over time.

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International System of Units

The extension of the metric system is the international system of units (SI), which we all know since our school physics classes.

International System of Units (SI)

SI Base Units

Base Quantity	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

SI Derived Units

Derived Quantity	Name	Symbol	Equivalent SI units
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$m \cdot kg \cdot s^{-2}$
Pressure	pascal	Pa	N/m^2
Energy	joule	J	$N \cdot m$
Power	watt	W	J/s
Electric charge	coulomb	C	$s \cdot A$
Electric potential	volt	V	W/A
Electric resistance	ohm	Ω	V/A
Celsius temperature	degree Celsius	°C	K*

*Unit degree Celcius is equal in magnitude to unit kelvin.

SI Prefixes

Factor	Name	Symbol	Numerical Value
10^{12}	tera	T	1 000 000 000 000
10^{9}	giga	G	1 000 000 000
10^{6}	mega	M	1 000 000
10^{3}	kilo	k	1 000
10^{2}	hecto	h	100
10^{1}	deka	da	10
10^{-1}	deci	d	0.1
10^{-2}	centi	c	0.01
10^{-3}	milli	m	0.001
10^{-6}	micro	µ	0.000 001
10^{-9}	nano	n	0.000 000 001
10^{-12}	pico	p	0.000 000 000 001

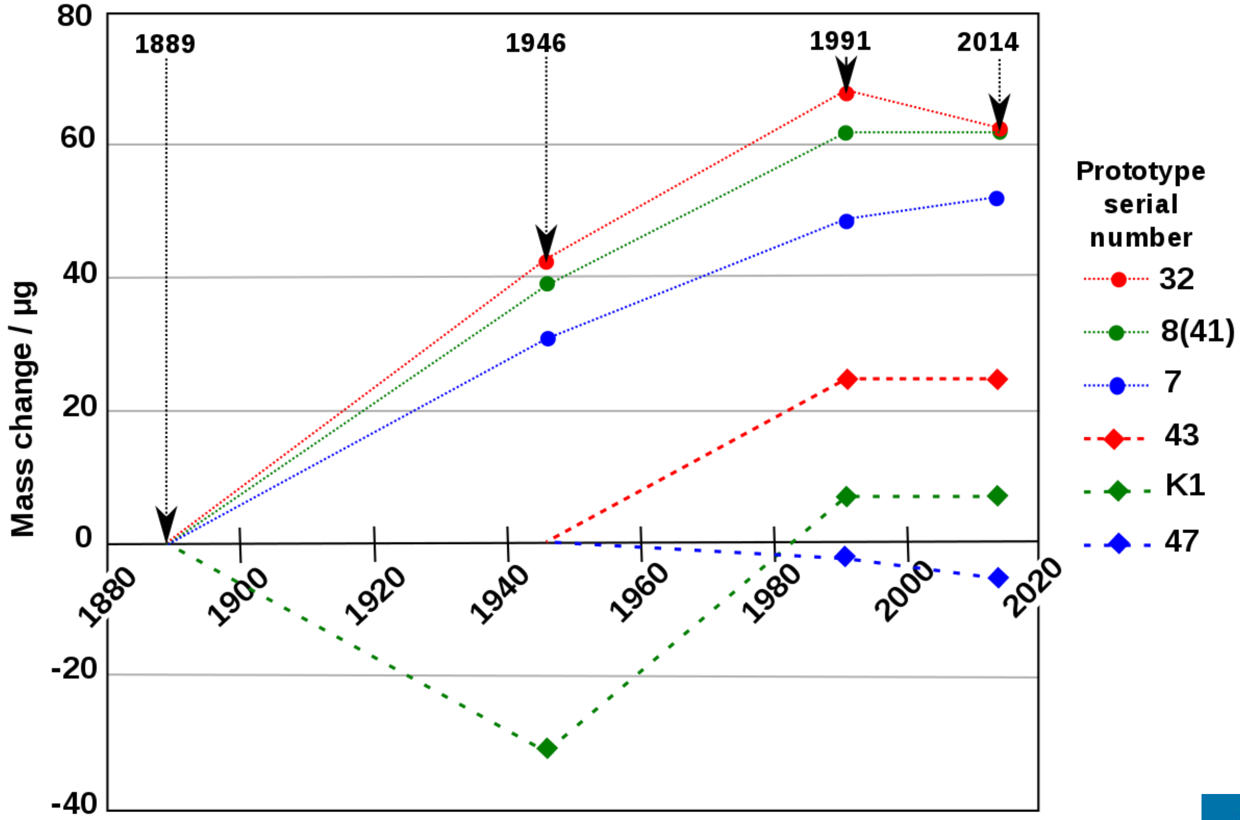
- Adapted from NIST Special Publication 811
- SI rules and style conventions recommend using spaces rather than commas to separate groups of three digits.

Is that all? Is this the end of our history? Not at all!

Problems with artifacts

Old standards are physical objects (artifacts) whose properties can change over time.

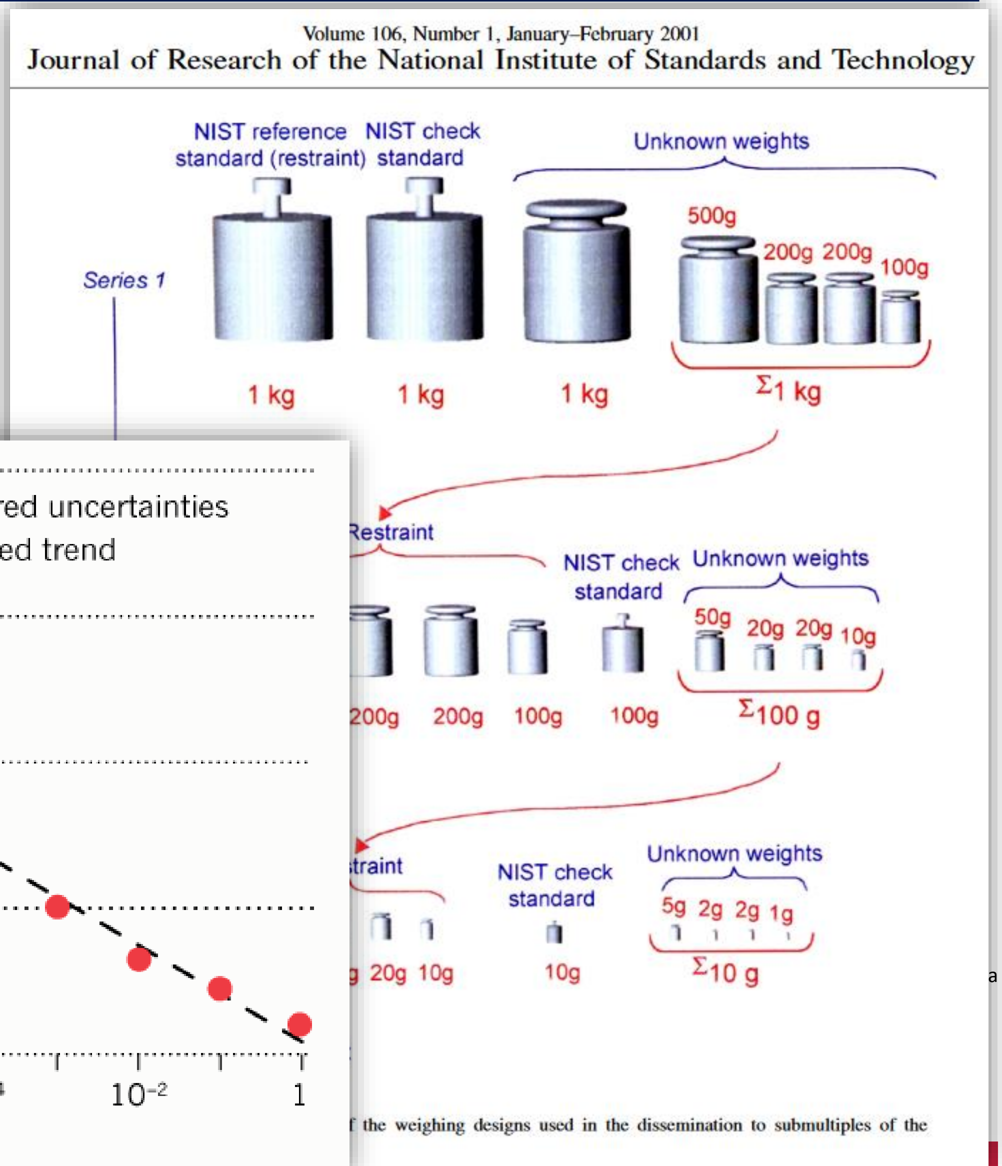
For example, the Parisian (main) standard of the kilogram has "become lighter" in a hundred years.

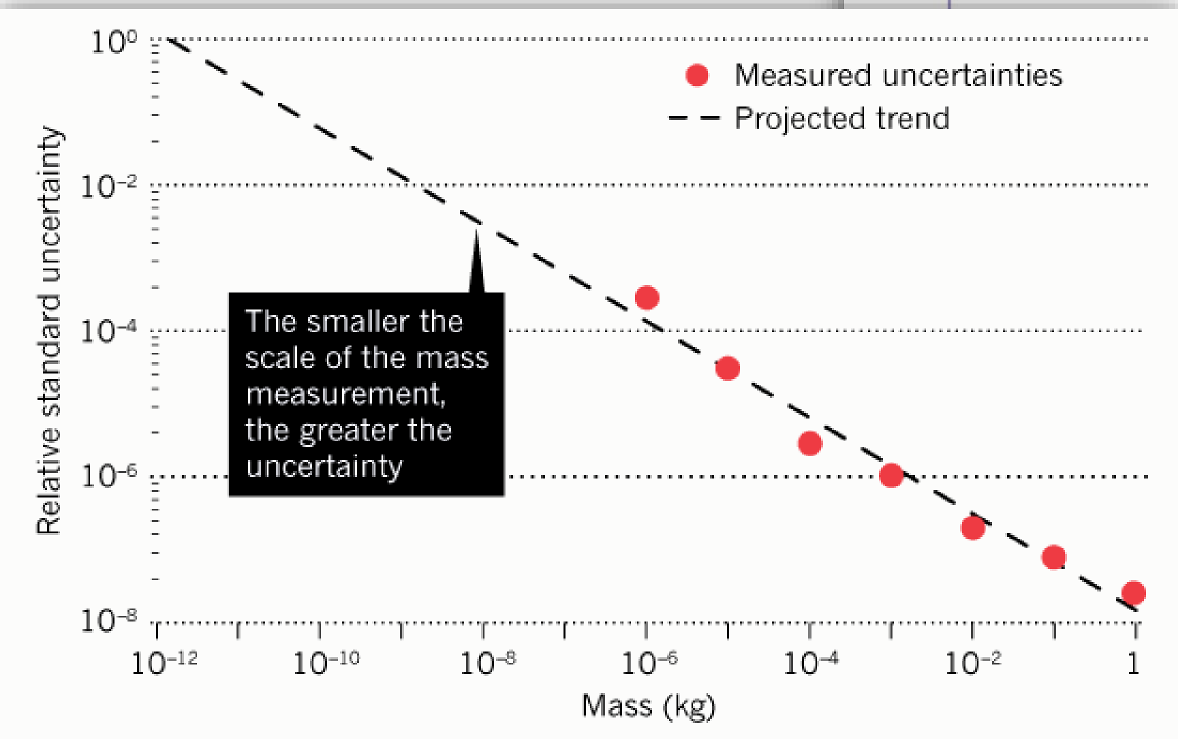


Changes in mass between working prototype kilograms and the IPK

Problems with scalability of measurements

Yet another problem with artifacts as standards: how to measure very small/very large (comparing to an artifact) quantities?

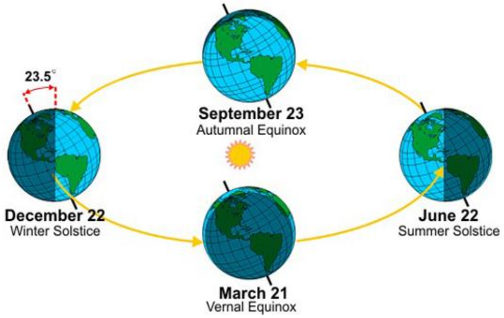




New system of units

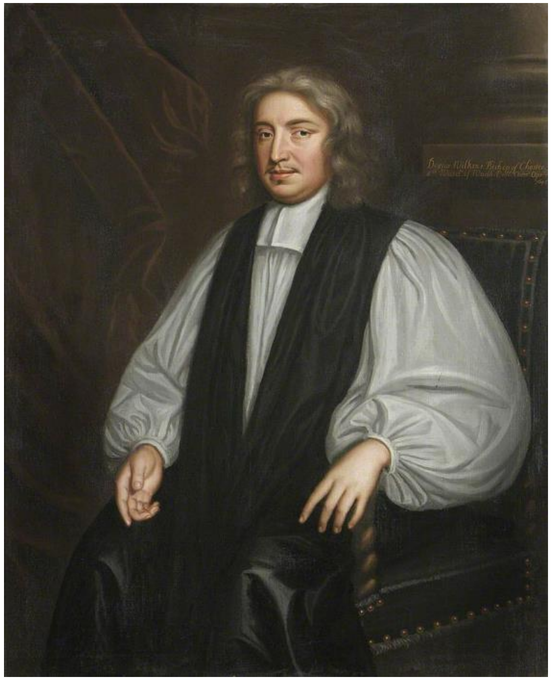
Over the last hundred years, the system of SI units has been modified step by step. In May 2019, this modification was completed. What is its main meaning of this modification?

From the artifacts



To physical phenomena

Measures based on natural phenomena



John Wilkins (1614-1672)

John Wilkins offered to choose for the unit length the pendulum with a half-period of oscillations equal to 1 s.

Just at that time, Christian Huygens perfected the pendulum clock.

The idea didn't work: the oscillation period depends on the geographical latitude.

But the ides was right!

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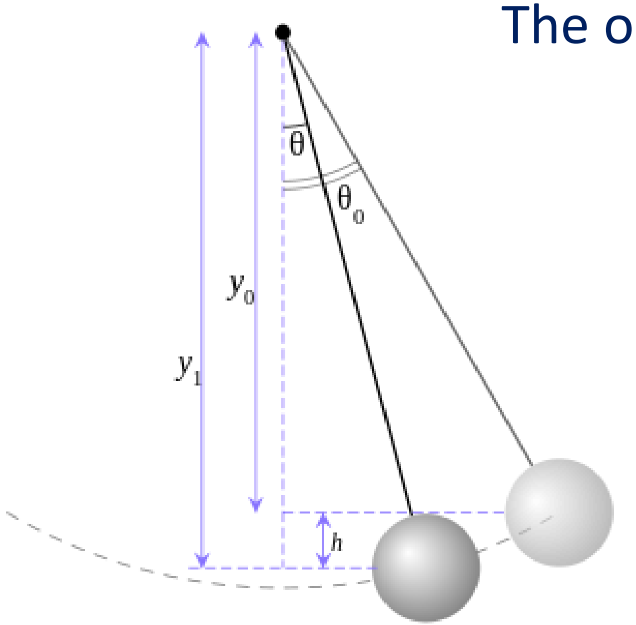
Simple model: Mathematical pendulum



The oscillation period of the mathematical pendulum:

$$T = 2\pi\sqrt{l/g}$$

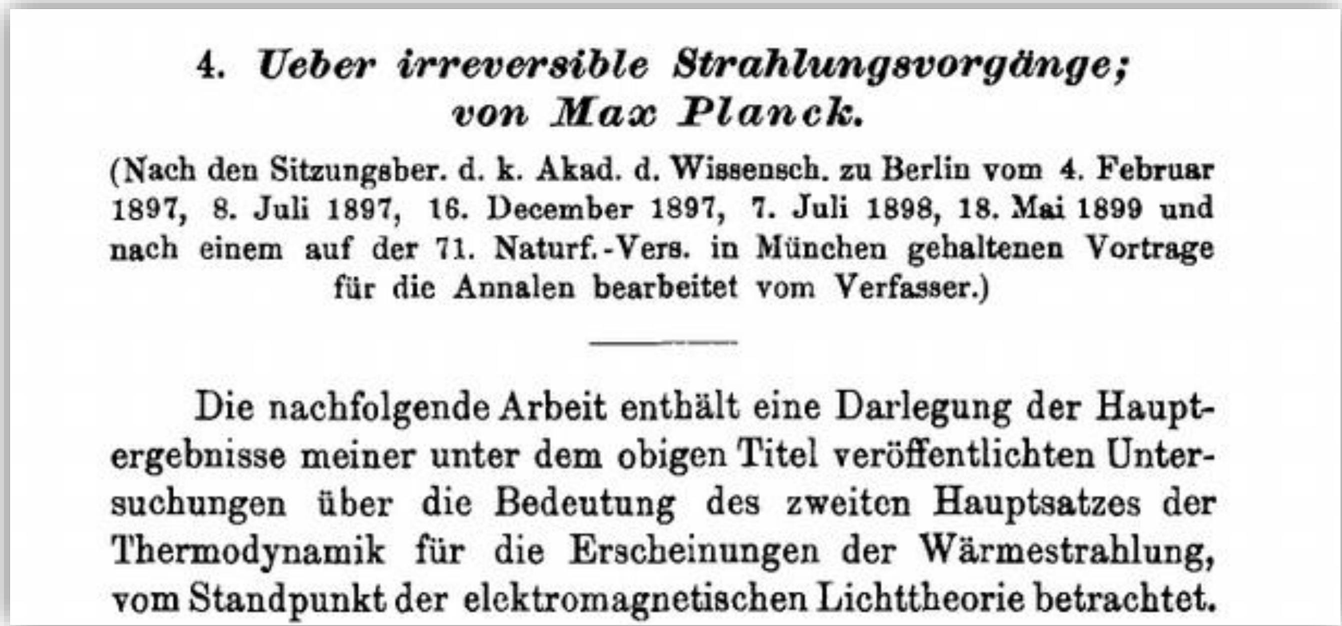
If we could accurately measure the oscillation time, we determine the length unit through the length of the pendulum l.

But! In addition to the formula linking T and l, we need to know the value of the physical constant g - acceleration of gravity.

Very important moment. The introduction of a system of units based on natural phenomena requires us to know:

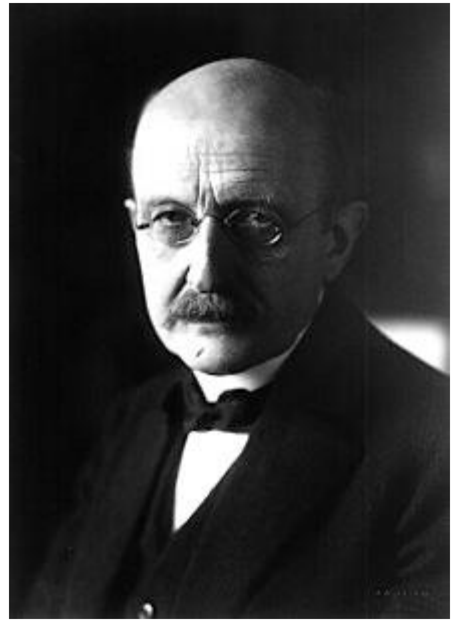
The laws of physics (formulas) + **The physical constants** that enter these formulas

Units based on natural phenomena


4. *Ueber irreversible Strahlungsvorgänge;*
von Max Planck.

(Nach den Sitzungsber. d. k. Akad. d. Wissensch. zu Berlin vom 4. Februar 1897, 8. Juli 1897, 16. December 1897, 7. Juli 1898, 18. Mai 1899 und nach einem auf der 71. Naturf.-Vers. in München gehaltenen Vortrage für die Annalen bearbeitet vom Verfasser.)

Die nachfolgende Arbeit enthält eine Darlegung der Hauptergebnisse meiner unter dem obigen Titel veröffentlichten Untersuchungen über die Bedeutung des zweiten Hauptsatzes der Thermodynamik für die Erscheinungen der Wärmestrahlung, vom Standpunkt der elektromagnetischen Lichttheorie betrachtet.



Max Planck (1858-1947)

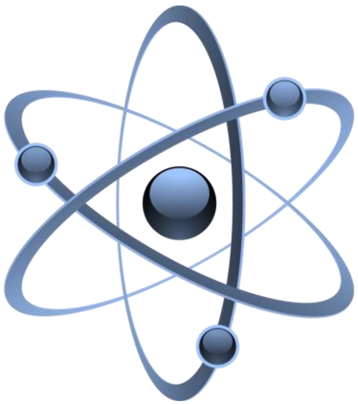
"…On the other hand, it should be of interest to remark that **with the help of the two constants *a* and *b*, we have the possibility of establishing units for length, mass, time, and temperature** which—independent of special bodies and substances—necessarily maintain their validity for all time and for all cultures, even extra-terrestrial and nonhuman…"

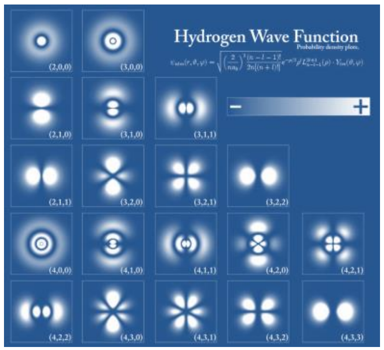
Physics theory ➜ Physics constants ➜ Units of measurements

Quantum physics and relativity

Two theories define the modern physics: quantum theory and relativity.

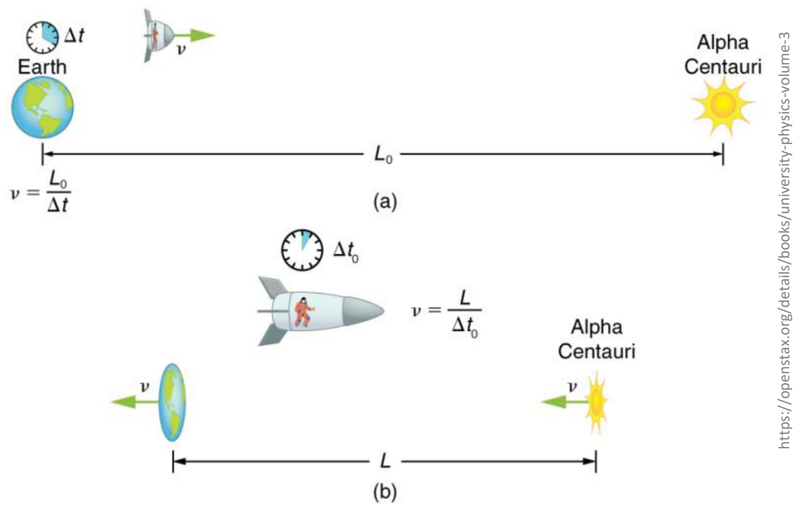
Quantum theory





Going deeper and deeper into the microscopic world.

Theory of relativity



Going faster and faster.

Which constants of Nature were “originated” from these two theories? And which role do they play in metrology?

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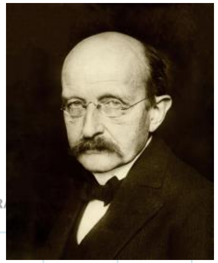
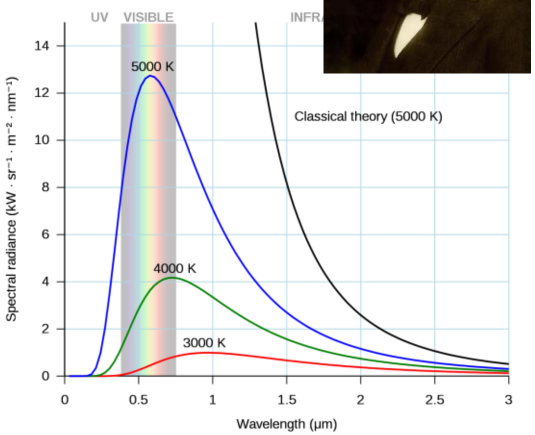
Quantum physics and Planck constant

Planck's law

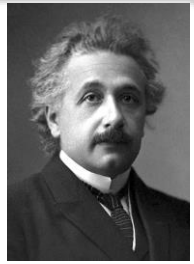


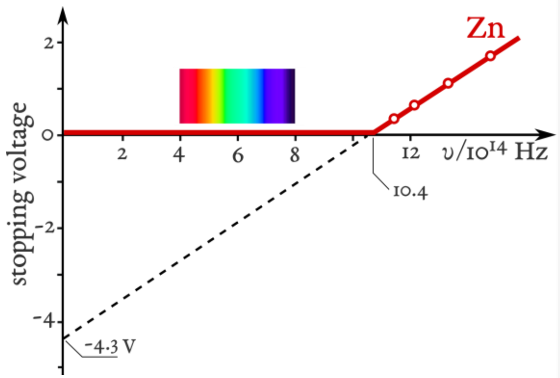


h as fitting parameter

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

Photoelectric effect

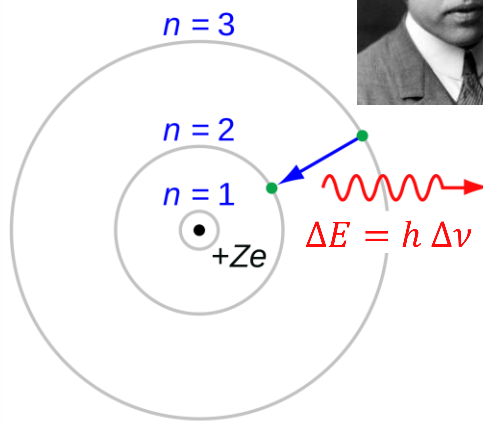




Idea of light quanta

$$E_{kin} = h\nu - E_b$$

Atomic spectra



Atomic transition energies are quantized

$$E_a - E_b = h\, \Delta\nu_{ab}$$

Concept of quantization of atomic levels and, hence, transition energies (frequencies) allowed modern definition of the **second**:

$$\Delta\nu_{Cs} = 9\ 192\ 631\ 770\ 1/s$$

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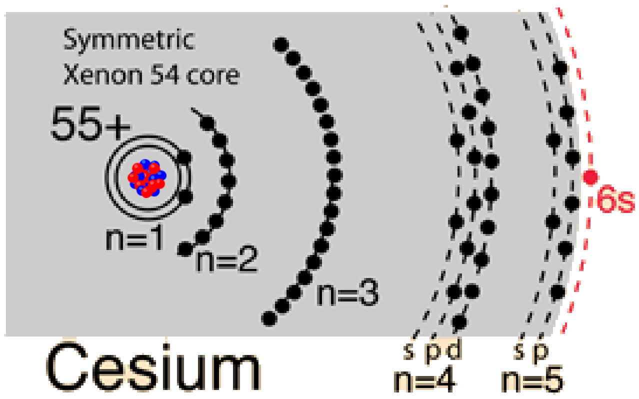
Cesium atomic clocks

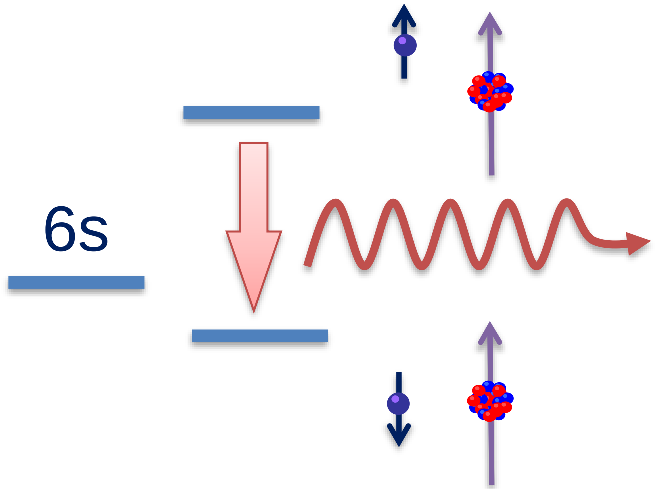
A second is defined as the duration of 9192631770 cycles of microwave radiation absorbed or emitted during the hyperfine transition in cesium-133 atom undisturbed by external fields:

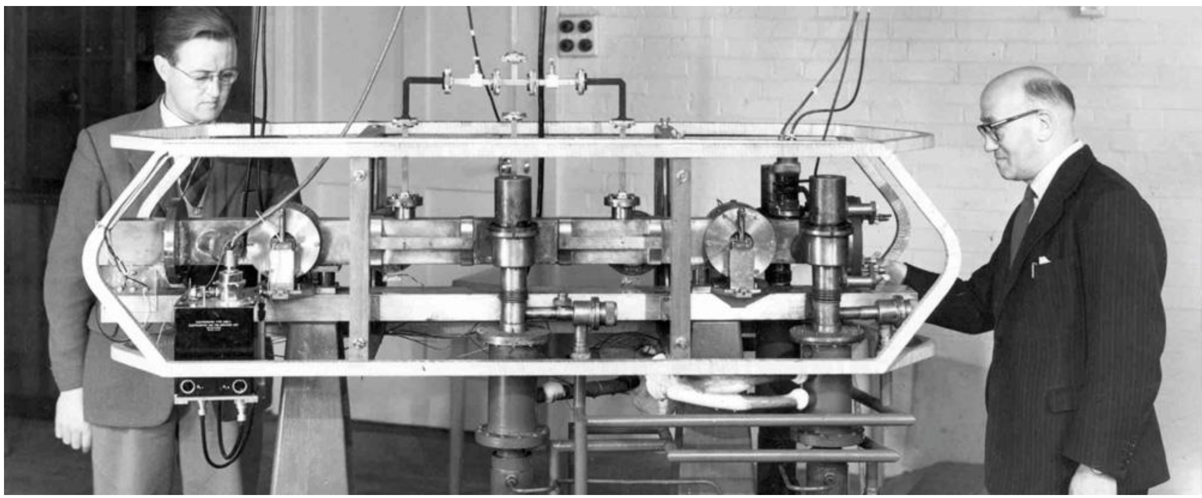
$$\Delta\nu_{Cs} = 9192631770 \text{ Hz}$$

The relative standard uncertainty of the Cs clocks is about 10^{-16}.



Quelle des Bildes: hyperphysics.phy-astr.gsu.edu





First cesium clock built in 1953 at the NPL by Louis Essen and Jack Parry.

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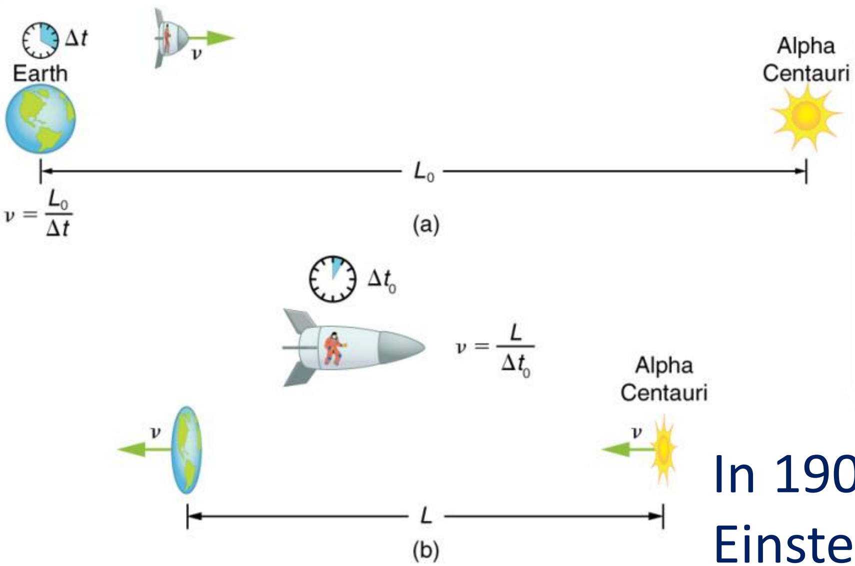
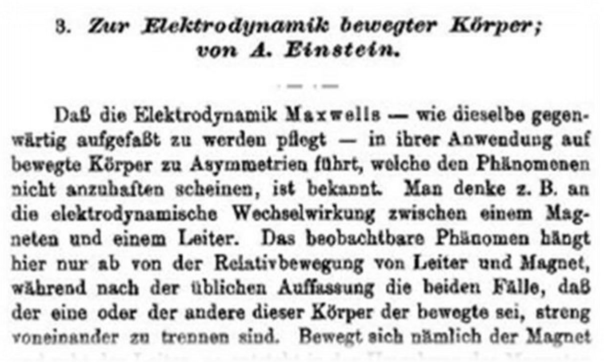
Theory of relativity and speed of light

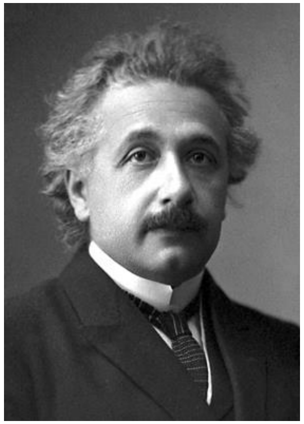


https://openstax.org/details/books/university-physics-volume-3



3. ***Zur Elektrodynamik bewegter Körper;***
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet



In 1905, in two of his *Annus Mirabilis* papers, Einstein has postulated the invariance of **speed of light** c on observer's system and derived mass-energy equivalence: $E = mc^2$

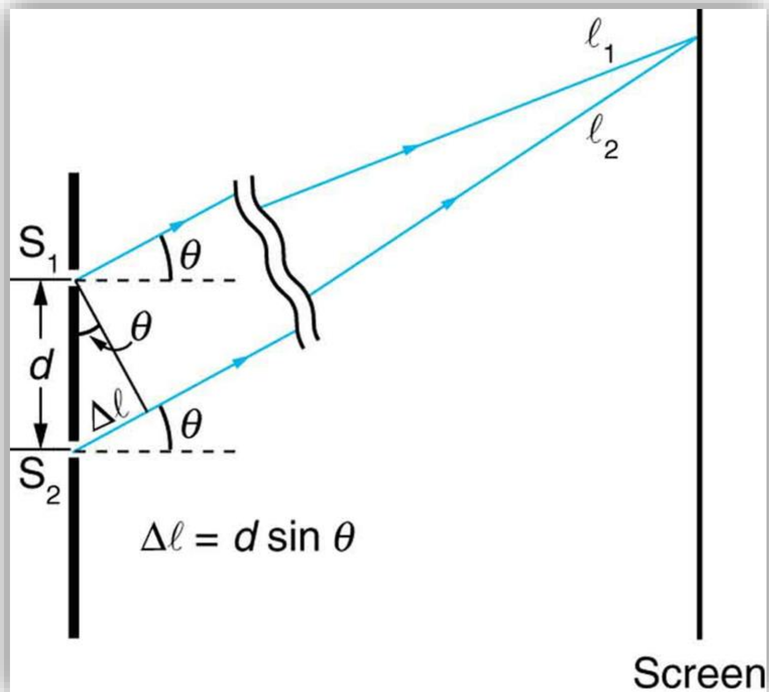
The concept of speed c of light as fundamental constant, that defines the upper limit, allows definition of the **meter**:

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

Implementation of the meter: Interference

We remember Young's double slit experiment, which demonstrates the interference of light.

What determines the alternation of light and dark stripes on the screen?



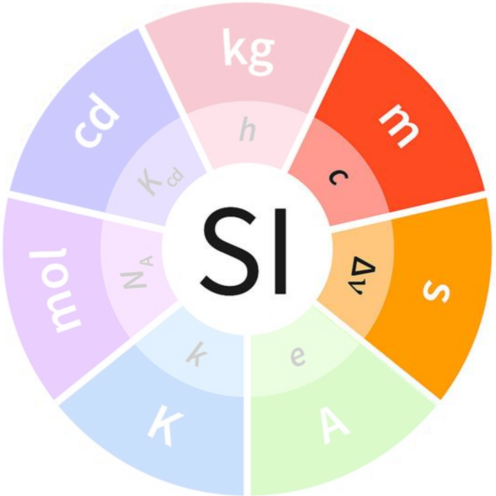
Travelled path difference:

$$\Delta l = d \sin\theta$$

leads to the relative phase difference:

$$\delta\varphi = \frac{2\pi}{\lambda}\,\Delta l = \frac{2\pi}{c}\,\nu\,\Delta l$$

What is with kilogram?



Two main physics theories of 20th century, quantum theory and relativity, “gave birth” to the concepts of quantization of frequency $\Delta\nu$ and of the upper limit of speed c…

…and allowed to define the second and the meter.

What is with kilogram? Do we need one more theory?

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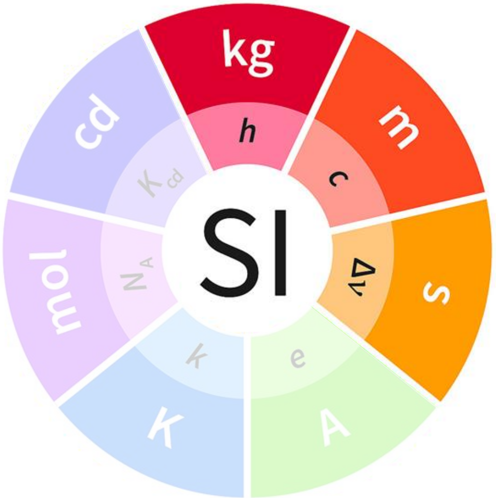
What is with kilogram?



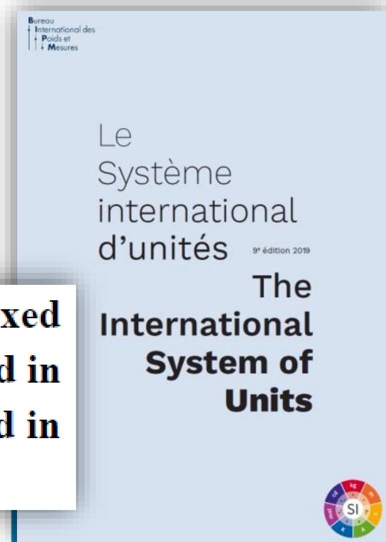
We can realize kilogram by connecting (relativistic) energy of a particle or object to a frequency!

Quantum theory		Theory of relativity
$E = h\,\Delta\nu$	+	$E = mc^2$

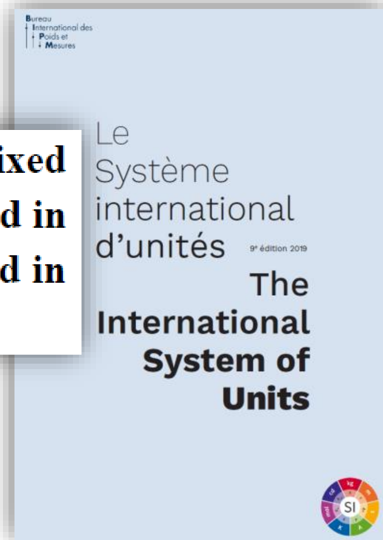
$$m = \frac{\Delta\nu\, h}{c^2}$$

Note that Planck constant h comes into play!

The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant, h, to be 6.626 070 15 × 10^{-34} when expressed in the unit J s, which is equal to kg m^2 s^{-1}, where the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$.



Redefinition of the kilogram



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Before we go further, let us note:

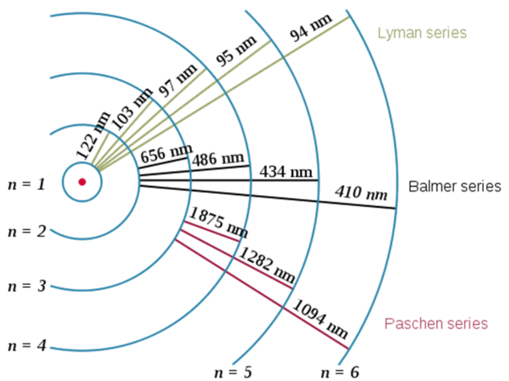
- The definition fixes exact value of the Planck constatnt.
- The definition relies on definitions of the meter and second.
- The definition does **not** suggest the realization of the unit!

From atoms to kilogram: Avogadro project

Idea is simple: mass of a body = number of atoms **x** mass of atom

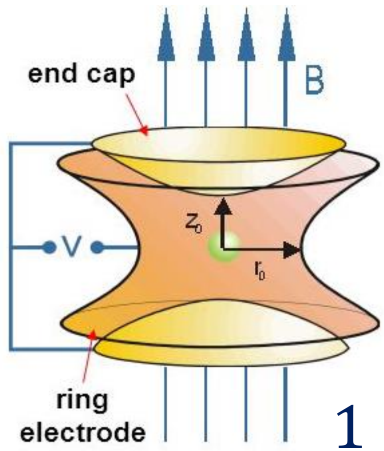
Electron mass from atomic spectroscopy

$$hcR_\infty = \frac{1}{2}\, m_e\, (\alpha Z)^2$$



Rydberg constant can be measured with a precision of 10^{-12}

Atom mass from electron mass



$$f_c = \frac{1}{2\pi}\frac{q}{m} B$$

Measuring of cyclotron **frequencies** in Penning trap (for e^- and ions)

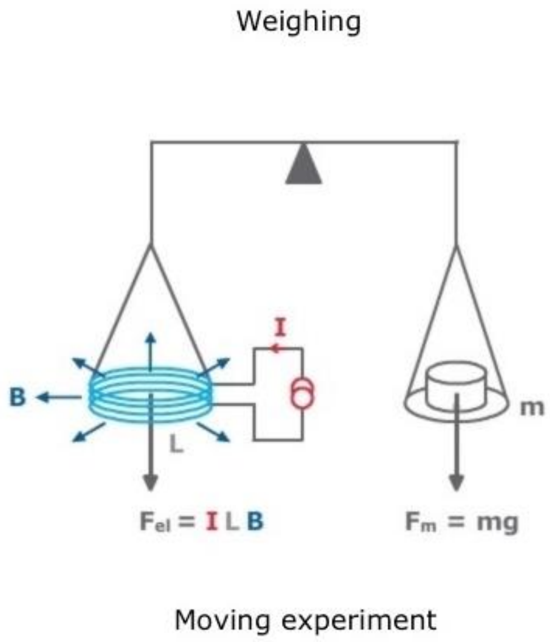
Mass of object from atom mass

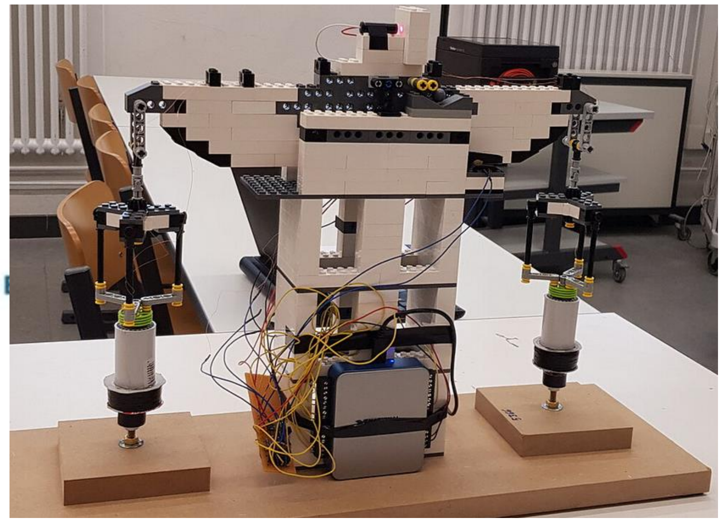
$$M = m_e \frac{M_{Si}}{m_e} \frac{8V}{a^3}$$

Number of Si atoms in sphere with volume V

➡ Avogadro project

Kibble balance: Very basic ideas





By running the Kibble balance in weighing and velocity modes we can find the relation between (virtual) electrical power and a mechanical power:

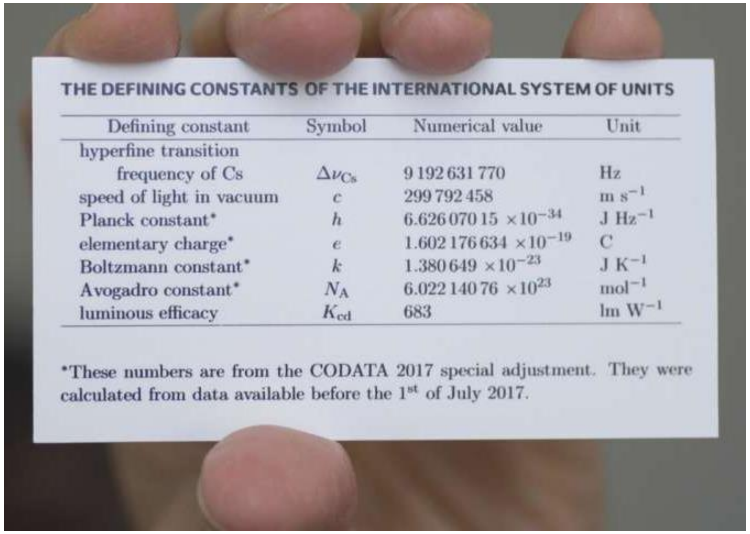
$$IU = mgv$$

The voltage and current are measured by using two macroscopic quantum phenomena, the Josephson effect and the quantum Hall effect.

$$m = \frac{1}{gv}\frac{n_1 f_1\, n_2 f_2}{r'}\frac{h}{4}$$

Quantities related to the measurement of the voltage and current

For all times and all cultures ?



THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	$m\ s^{-1}$
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	$J\ Hz^{-1}$
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	$J\ K^{-1}$
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	$lm\ W^{-1}$

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

With revised SI we made one more step towards the Planck's vision of units, based on fundamental constants, that "will certainly retain their relevance for all times and for all cultures".

But… the way is not over! We have many open questions.

- Are defining constants of SI fundamental?
- Are defining/fundamental constants constant?
- Do we understand well related constants?
- Do we go beyond Cesium standard?

These and many other questions are related to our understanding of fundamental physics

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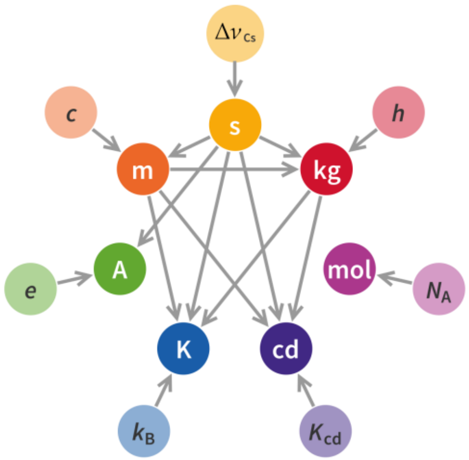
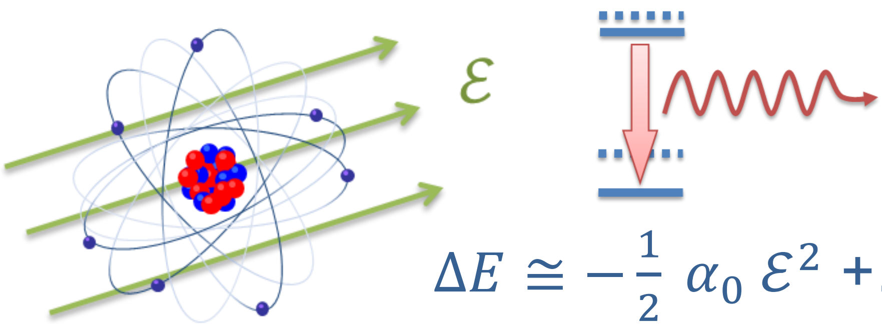
"Future of time": Going beyond Cesium



The second, as defined based on the Cs standard, is the key base unit of the new SI.

The relative standard uncertainty of the Cs clocks is about 10^{-16}. Can the accuracy of atomic clocks be further improved and why do we need it?

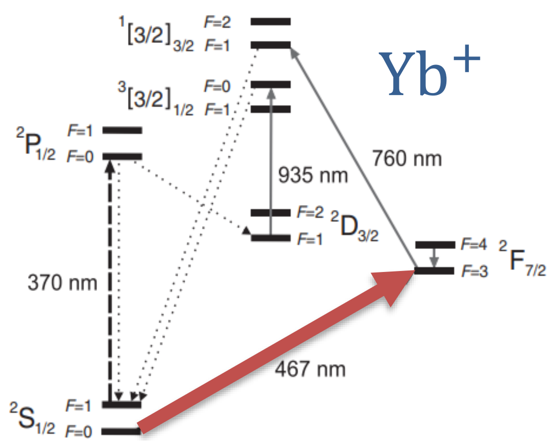
External fields lead to the shift of the energy levels and, hence, of frequencies.



$$\Delta E \cong -\frac{1}{2}\,\alpha_0\,\mathcal{E}^2 + \dots$$

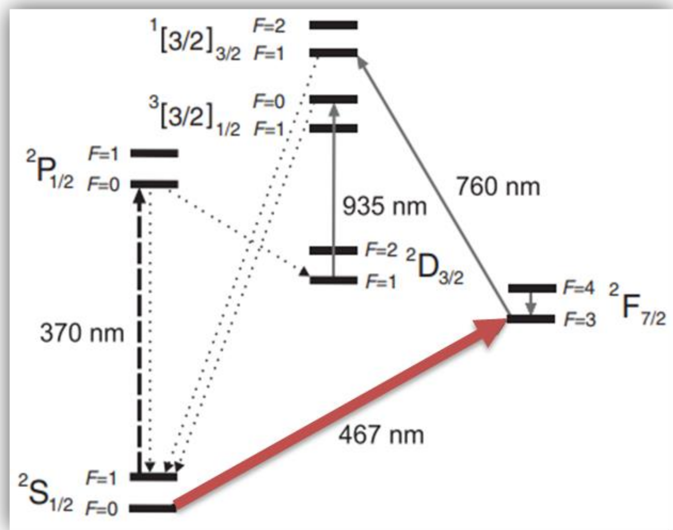
We need atomic systems that are **less "coupled" to external fields**.

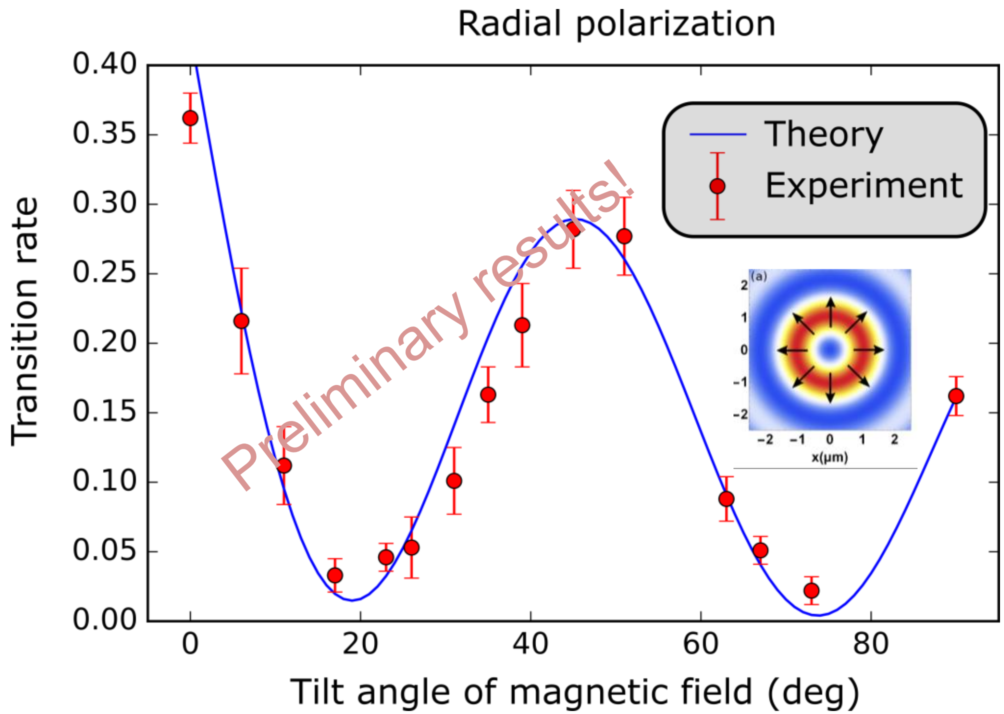
We need narrow transitions in **optical domain** (higher frequency = higher accuracy!)

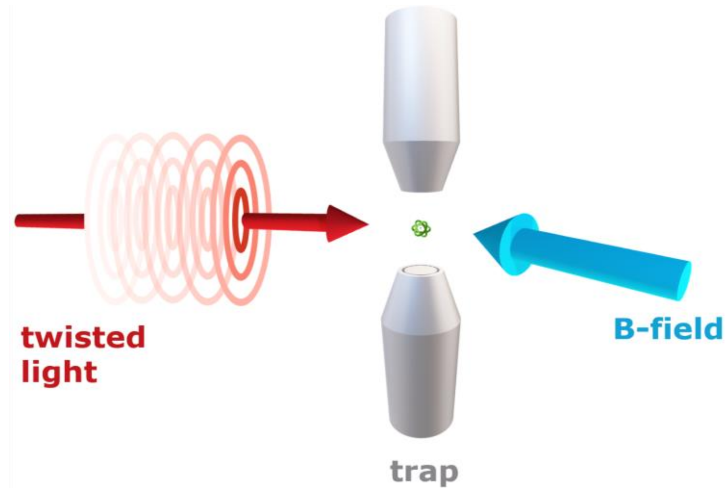


Inducing atomic-clock transitions by twisted light

The electric octupole (E3) transition in Yb^+ has attracted much attention as a candidate for a novel frequency standard, and the use of the twisted light may supress the AC-Stark shift of its frequency.







S. A.-L. Schulz, A. A. Peshkov, R. A. Müller, R. Lange, N. Huntemann, Chr. Tamm, E. Peik, and A. Surzhykov, Phys. Rev. A **102**, 012812 (2020)
R. Lange, E. Peik, A. Surzhykov, A. A. Peshkov *et al*, in preparation (2021)

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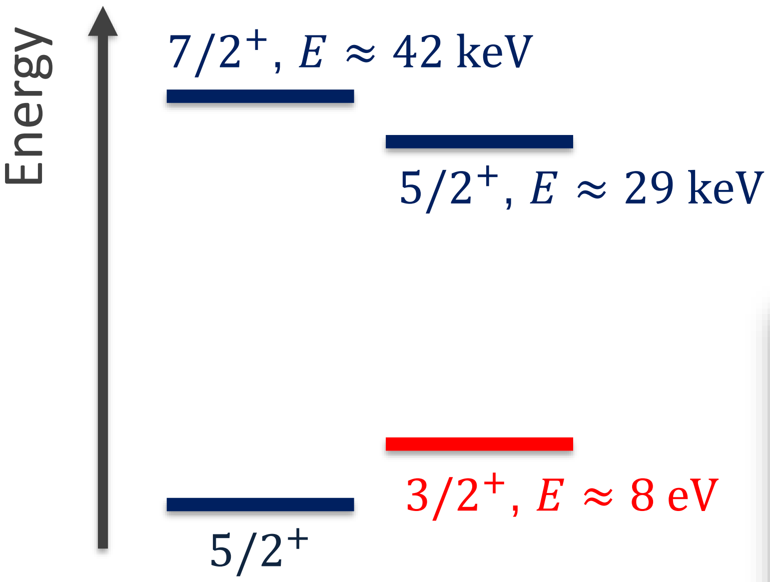
Thorium-229 nuclear clocks



Since 1990's the ^{229}Th isotope attracts considerable attention as a promising candidate for the development of nuclear clocks.

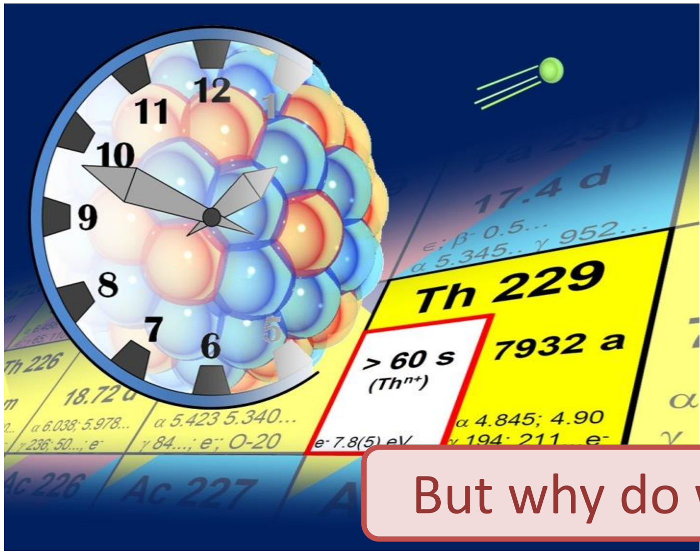
Physica Scripta. Vol. 53, 296–299, 1996

Processes of the Nuclear Isomer ^{229m}Th($3/2^+$, 3.5 ± 1.0 eV) Resonant Excitation by Optical Photons

E. V. Tkalya[1] and V. O. Varlamov
Laboratory of Theory of Radiation Processes, Nuclear Safety Institute of Russian Academy of Sciences, Bolshaya Tulskaya – 52, Moscow, 113191, Russia
and
V. V. Lomonosov and S. A. Nikulin
Institute of General Nucl

Received June 29, 1995; a

properties of solids by means of measuring the half-life time of isomeric levels and energies of emitted photons; development of a high stability nuclear source of light for metrology; creation of γ-laser in the optical range, and so on.



But… still many open questions about energy of isomeric state and its excitation by laser or atomic processes.

But why do we need more accurate clocks?

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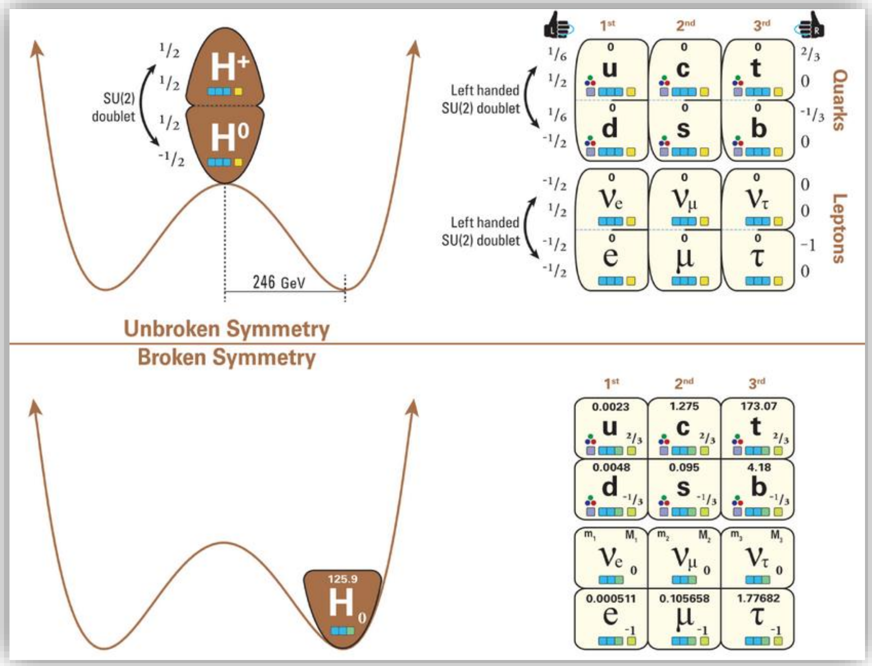
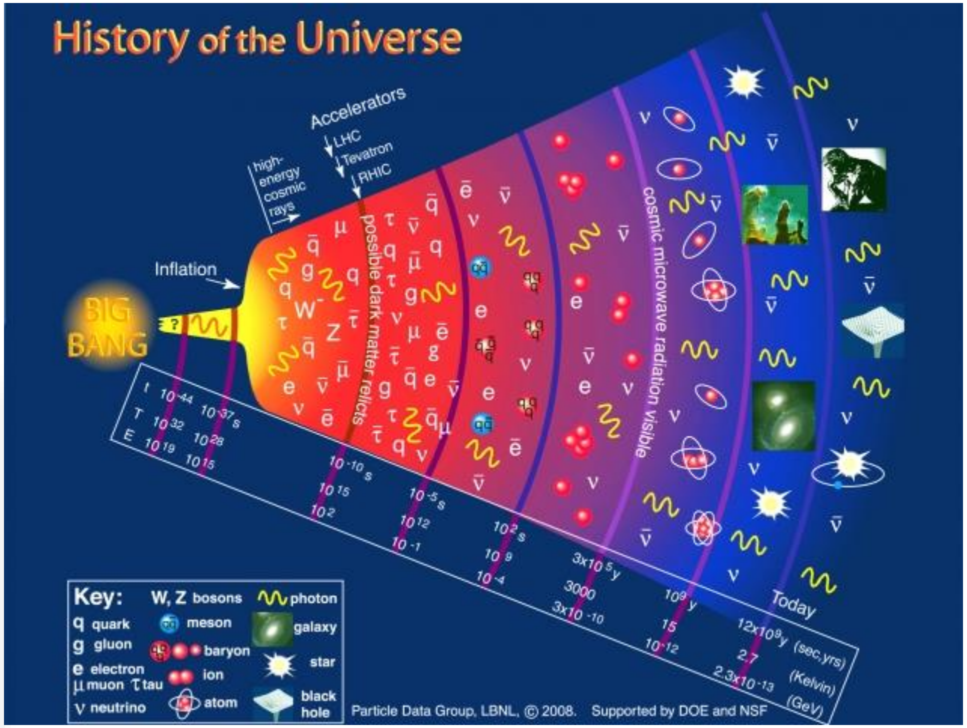
Are constants of Nature constant?

From the viewpoint of Standard Model the answer is clear:

Constants are **not** constant!





In early hot Universe masses of leptons and coupling constants are the same.

Physically correct question would be: how strong is **present variation** of constants?

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One more time about constants

There are two kinds of constants of Nature:

- dimensionless (coupling constants)
- dimensionful (for example $c, \hbar, G$)

For new SI the latter constants are of importance. However, discussion of variation of dimensionful constants has usually no meaning.

TABLE I An abbreviated list of the CODATA recommended values of the fundamental constants of physics and chemistry based on the 2014 adjustment.

Quantity	Symbol	Numerical value	Unit	Relative std. uncert. u_r
speed of light in vacuum	c, c_0	299 792 458	$m\ s^{-1}$	exact
magnetic constant	μ_0	$4\pi \times 10^{-7}$	$N\ A^{-2}$	
		$= 12.566\,370\,614... \times 10^{-7}$	$N\ A^{-2}$	exact
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	$F\ m^{-1}$	exact
Newtonian constant of gravitation	G	$6.674\,08(31) \times 10^{-11}$	$m^3\ kg^{-1}\ s^{-2}$	4.7×10^{-5}
Planck constant	h	$6.626\,070\,040(81) \times 10^{-34}$	J s	1.2×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,800(13) \times 10^{-34}$	J s	1.2×10^{-8}
elementary charge	e	$1.602\,176\,6208(98) \times 10^{-19}$	C	6.1×10^{-9}
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,831(13) \times 10^{-15}$	Wb	6.1×10^{-9}
conductance quantum $2e^2/h$	G_0	$7.748\,091\,7310(18) \times 10^{-5}$	S	2.3×10^{-10}
electron mass	m_e	$9.109\,383\,56(11) \times 10^{-31}$	kg	1.2×10^{-8}
proton mass	m_p	$1.672\,621\,898(21) \times 10^{-27}$	kg	1.2×10^{-8}
proton-electron mass ratio	m_p/m_e	1836.152 673 89(17)		9.5×10^{-11}
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5664(17) \times 10^{-3}$		2.3×10^{-10}
inverse fine-structure constant	α^{-1}	137.035 999 139(31)		2.3×10^{-10}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	10 973 731.568 508(65)	m^{-1}	5.9×10^{-12}
Avogadro constant	N_A, L	$6.022\,140\,857(74) \times 10^{23}$	mol^{-1}	1.2×10^{-8}
Faraday constant $N_A e$	F	96 485.332 89(59)	$C\ mol^{-1}$	6.2×10^{-9}
molar gas constant	R	8.314 4598(48)	$J\ mol^{-1}\ K^{-1}$	5.7×10^{-7}
Boltzmann constant R/N_A	k	$1.380\,648\,52(79) \times 10^{-23}$	$J\ K^{-1}$	5.7×10^{-7}
Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3 c^2$	σ	$5.670\,367(13) \times 10^{-8}$	$W\ m^{-2}\ K^{-4}$	2.3×10^{-6}
Non-SI units accepted for use with the SI				
electron volt (e/C) J	eV	$1.602\,176\,6208(98) \times 10^{-19}$	J	6.1×10^{-9}
(unified) atomic mass unit $\frac{1}{12}m(^{12}C)$	u	$1.660\,539\,040(20) \times 10^{-27}$	kg	1.2×10^{-8}

We focus on variation of the fine-structure constant α and on the electron to proton mass ratio m_e/m_p.

But why these variations are important?

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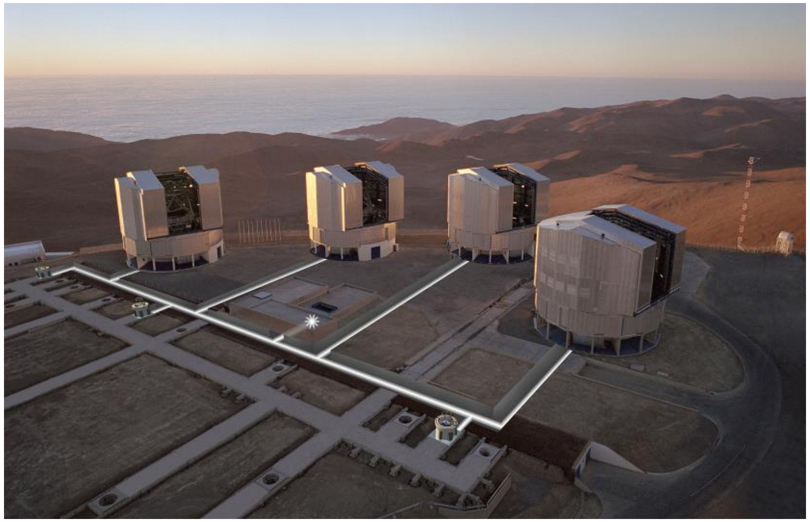
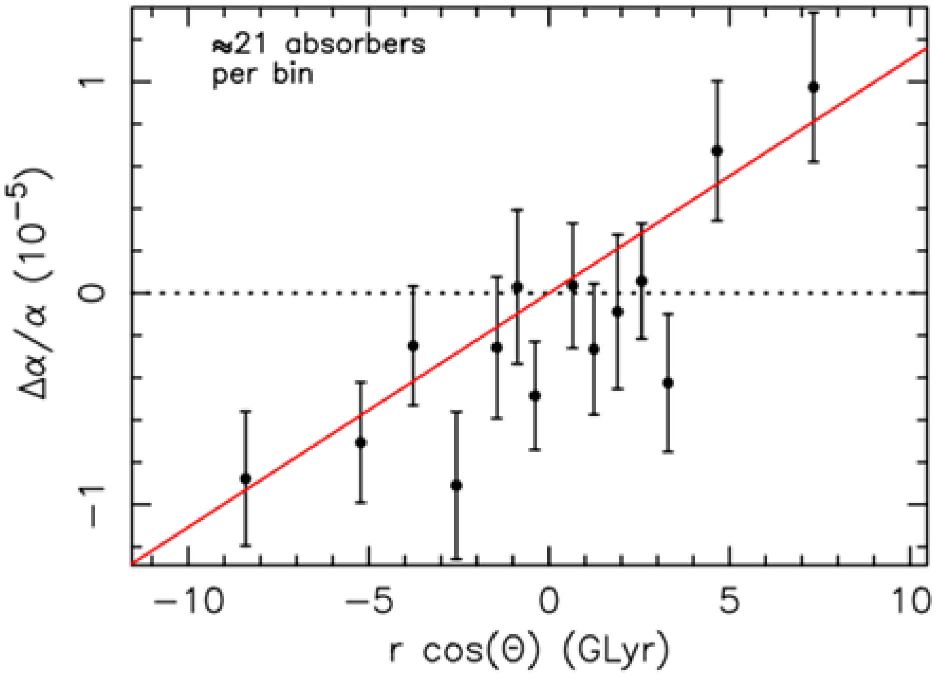
Variation of fine-structure constant

Based on the data on quasars obtained by the Very Large Telescope a dipole-like structure in the variation of the fine-structure constant across the observable universe was reported in 2010.



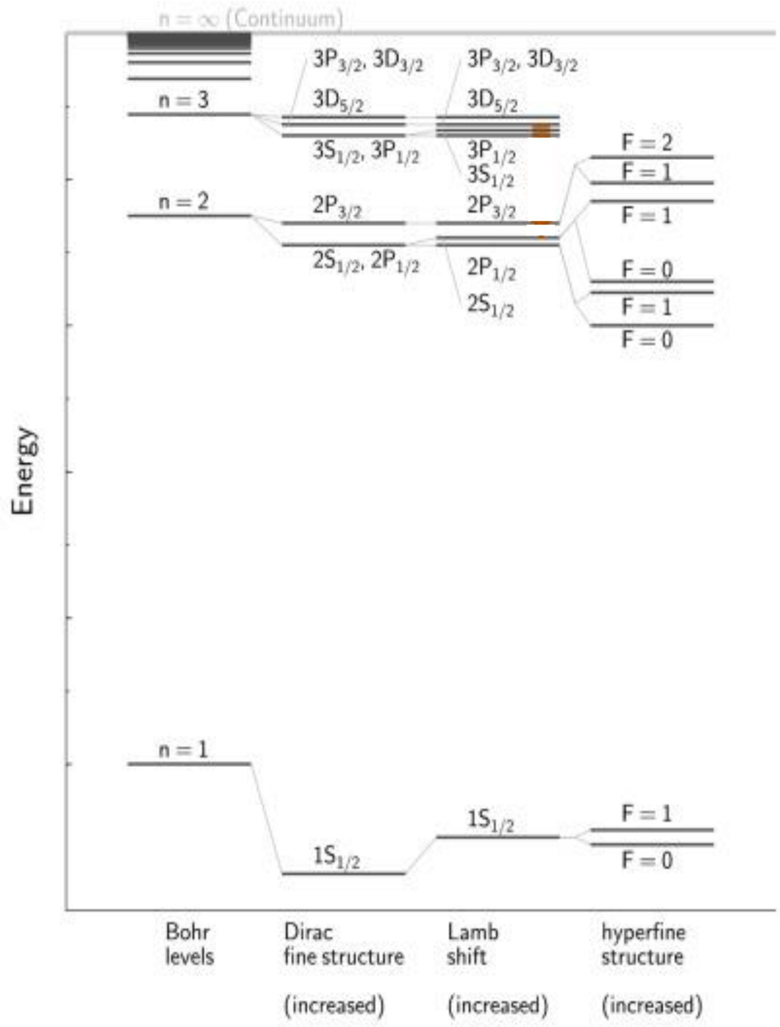


The approaches, made in this work, are under discussion.

We need other methods to search for the variation of constants!

J. K. Webb *et al.*, Phys. Rev. Lett. **107**, 191101 (2011)

Variation of constants: Atomic spectroscopy



We know that even hydrogen atom is more complicated as described in simple Bohr formula:

$$\nu_{ik} = R_\infty \, c \left[\frac{1}{n_i^2} - \frac{1}{n_k^2}\right]$$

We can consider transitions between:

- Fine-structure levels:

$$\nu_{ik} = R_\infty \, c \, F_{fs}(\alpha, r_p, Z \, \dots)$$

- Hyperfine-structure levels:

$$\nu_{ik} = R_\infty \, c \, \alpha^2 \frac{m_e}{m_p} g \, F_{hfs}(\alpha, r_p, Z \, \dots)$$

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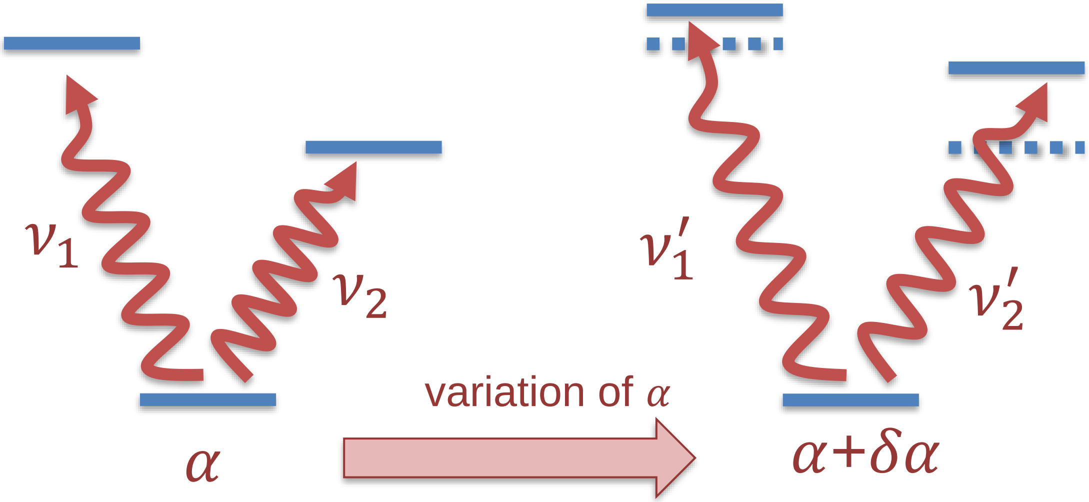
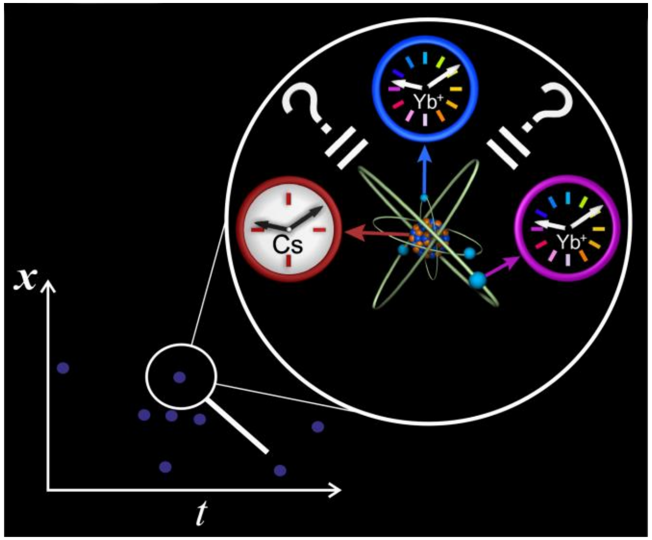
Variation of constants: Atomic spectroscopy



Different atomic levels can be shifted in different ways under the variation of the fine structure constant (as well as other constants).



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Recent experiment with Yb+ atomic clocks have improved the limit on the time variation of α and $\mu = m_e/m_p$:

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = 1.0(1.1) \times 10^{-18}/\text{yr}$$

$$\frac{1}{\mu}\frac{d\mu}{dt} = -8(36) \times 10^{-18}/\text{yr}$$

R. Lange *et al.*, Phys. Rev. Lett. 126, 011102 (2021)

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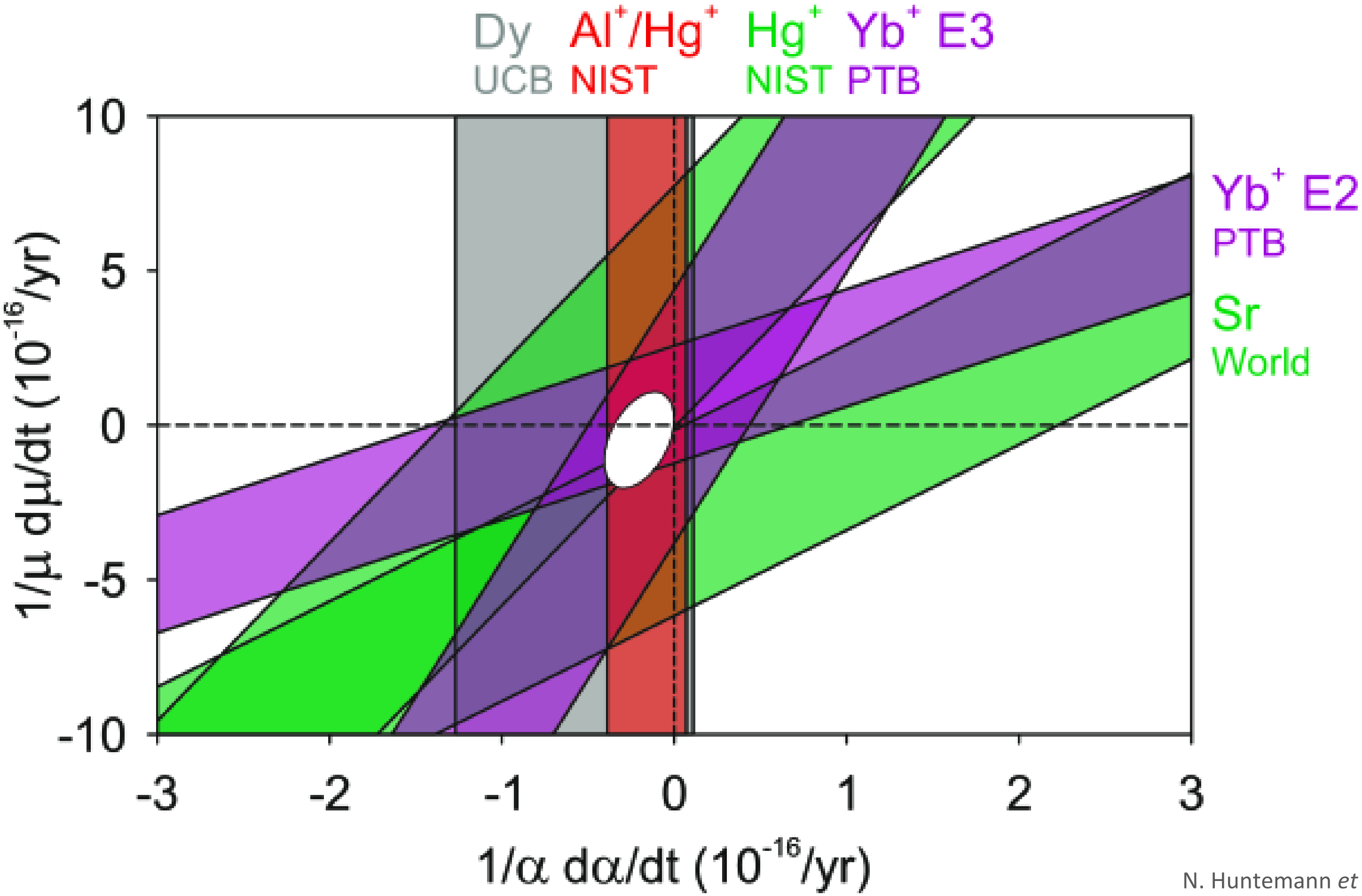
Constraints on temporal variations of constants



N. Huntemann *et al.*,
Phys. Rev. Lett. 113, 210802 (2014)

Constraints on temporal variations of α and $\mu = m_e/m_p$ from comparisons of atomic transition frequencies.

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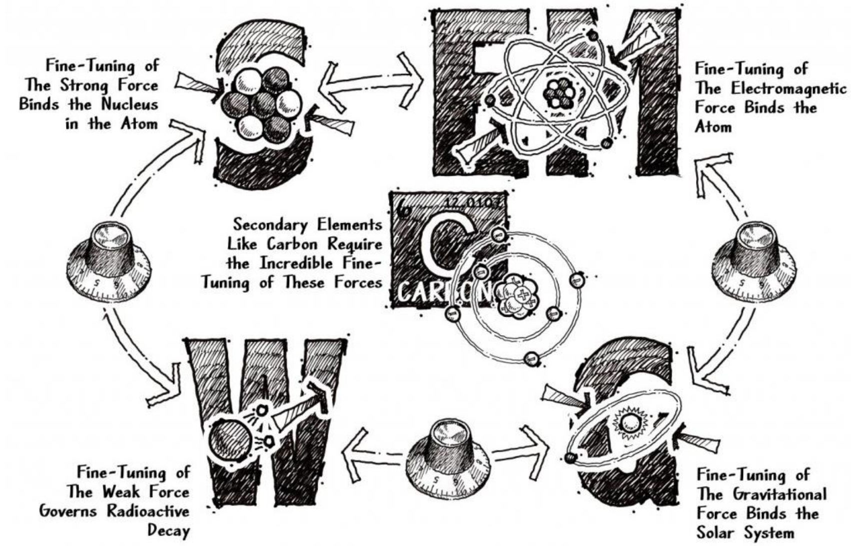
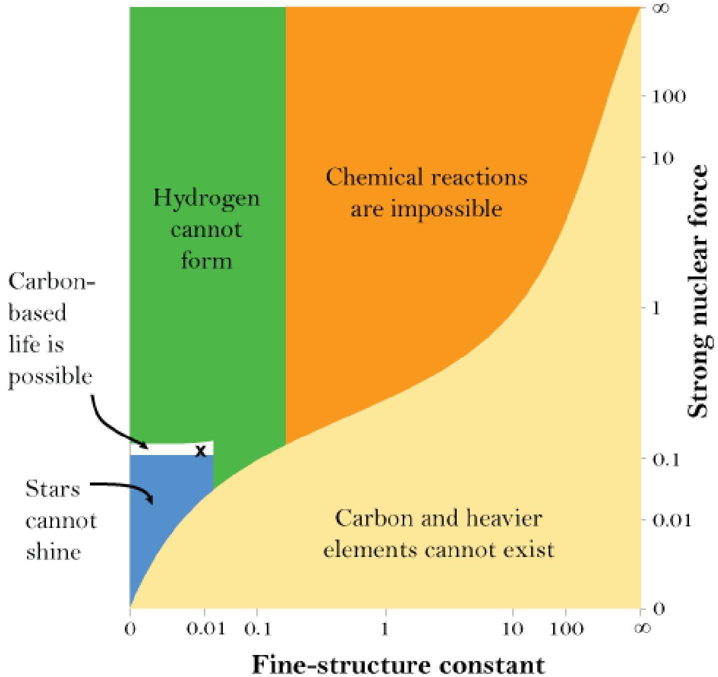
Fine tuning of fundamental constants

Only a very narrow range of fundamental constants are consistent with Universe that contains life.

There are many examples of how even a minor change of one (of few) constants would make life impossible.



http://coldcasechristianity.com



https://www.thenewatlantis.com/

We and our World can exist in extremely small parameter range!

What does it mean actually?

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Thank you very much!

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