



The role of the (*Planck*) constants in physics

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The new system of units

Proposition to define base units from the choice of a set of fundamental constants;

Not a new idea — the meter is derived from the value of the *speed of light* the numerical value of which has been fixed in 1983;

Shift from concrete objects/artefacts/phenomena to the more abstract concept of fundamental constants.

Why?

Looking for the most fundamental structures

James Clerk Maxwell (1870)

« If we wish to obtain standards of length, time and mass which shall be absolutely permanent, we must seek them not in the dimensions, or motion or the mass of our planet, but in the wavelength, the period of vibration, and absolute mass of these imperishable and unalterable and perfectly similar molecules. »



What is a constant?

Constant : PHYS., Numerical value of **some** quantity that allows to characterize a body. Quantity whose value is fixed (**e.g.** mass and charge of the electron, speed of light) and that plays a **central** role in physical theories.

This definition asks more questions than it gives answers!

- How many constants?
- Are they all on the same footing?
- What role do they play in laws of physics?
- Can they vary? (*according to the dictionary, NO!*)

Constants depend on a theoretical framework

Looking at books of physics from different epochs makes us realize that constants

- appear

e.g. Planck constant in 1900

- can be explained in terms of other constants

e.g. proton mass

- can disappear

e.g. Joule constant (proportionality
heat/work)

- may “become a unit”

e.g. speed of light since 1983

Redefining « constant »

Given a set of physical theories, thought to describe well nature (*epoch dependent statement*)

Definition: Any parameter not determine by this set of theories

- *no equation, nothing more fundamental*
- *reproductibility of experiments*
- *the theory cannot determine them*
- *we can only measure them*

Today:

22 unknown parameters

All are measured

Other constants can (in principle) be derived from them.

Two kinds of parameters

Dimensionless constants

$$\frac{m_{\text{proton}}}{m_{\text{electron}}} = 1\,836.152\,673\,89$$

crucial (unexplained) numbers

changing their values changes the physical phenomena

Constants with units

can be used to define the units (kg, m,...)

need as many as the number of base units

Max Planck (1900)

« It offers the possibility of establishing units for length, mass, time and temperature which are independent of specific bodies or materials and which necessarily maintain their meaning for all time and for all civilizations, even those which are extraterrestrial and nonhuman, constants which therefore can be called fundamental physical units of measurement »

Recipe: fix the value of (c,G,h,k) to 1.

usual in theoretical physics but...

$$l_{\text{P}} = 1.616 \times 10^{-35} \text{m}, \quad t_{\text{P}} = 5.391 \times 10^{-44} \text{s}, \quad m_{\text{P}} = 2.177 \times 10^{-8} \text{kg}$$

How to choose constants to define units ?

Universal

are not restricted to a single physical phenomenon

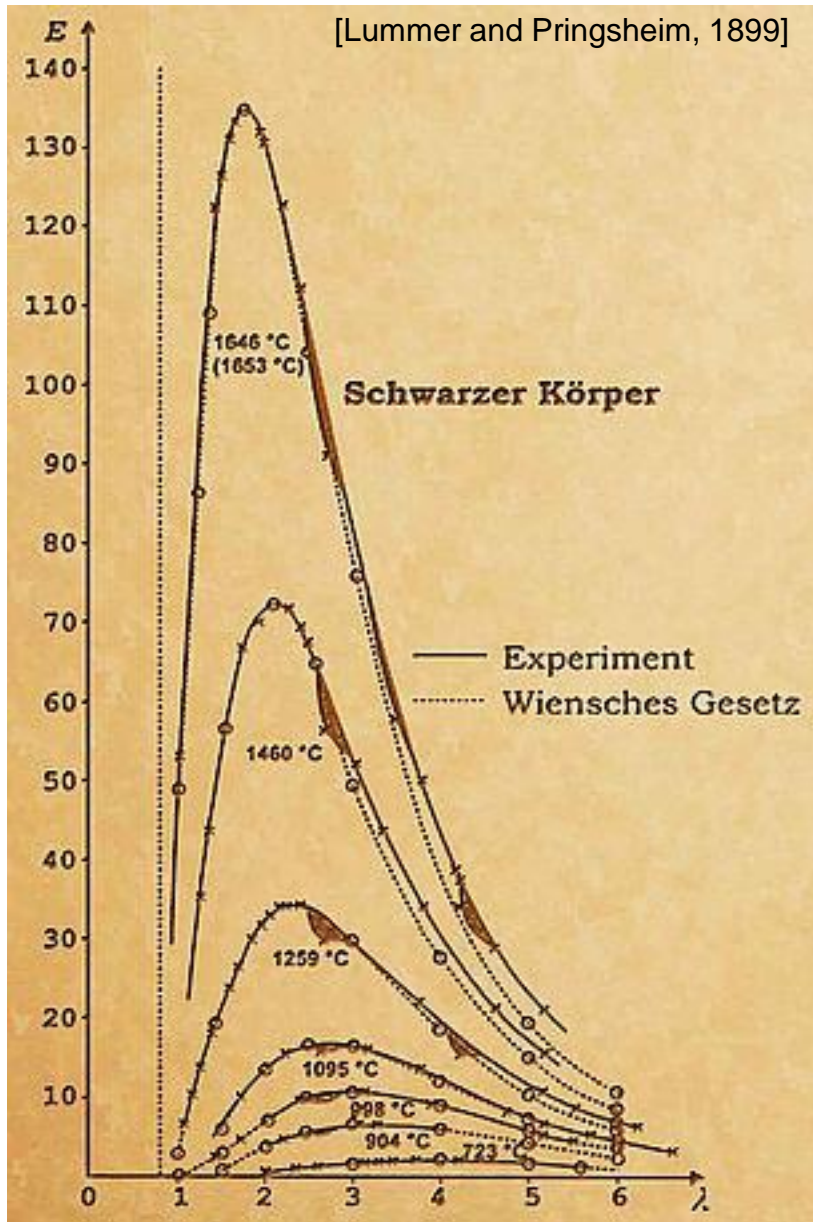
Fundamental

cannot be expressed in terms of other constants

Experimental pragmatism

need to be measurable with the highest accuracy

Planck constant(s): context



IV.
Verhandlungen der physikal. Gesellschaft 2, p. 202; 1900.
Ueber eine Verbesserung der Wienschen Spektralgleichung. (1)
(Vorgetragen in der Sitzung vom 19. Oktober 1900.)

$$e_{\lambda} = \frac{C\lambda^{-5}}{e^{c'/\lambda T} - 1}$$

Planck constant(s): birth

9. Ueber das Gesetz der Energieverteilung im Normalspectrum; von Max Planck.

(In anderer Form mitgeteilt in der Deutschen Physikalischen Gesellschaft,
Sitzung vom 19. October und vom 14. December 1900, Verhandlungen
2. p. 202 und p. 237. 1900.)

§ 2. Wir setzen nun die Entropie S_N des Systems, bis auf eine willkürlich bleibende additive Constante, proportional dem Logarithmus der Wahrscheinlichkeit W dafür, dass die N Resonatoren insgesamt die Energie U_N besitzen, also:

$$(3) \quad S_N = k \log W + \text{const.}$$

§ 10. Wenden wir das Wien'sche Verschiebungsgesetz in der letzten Fassung auf den Ausdruck (6) der Entropie S an, so erkennen wir, dass das Energieelement ε proportional der Schwingungszahl ν sein muss, also:

$$\varepsilon = h \cdot \nu$$

Hierbei sind h und k universelle Constante.

Hieraus und aus (14) ergeben sich die Werte der Naturconstanten:

$$(15) \quad h = 6,55 \cdot 10^{-27} \text{ erg} \cdot \text{sec} ,$$

$$(16) \quad k = 1,346 \cdot 10^{-16} \frac{\text{erg}}{\text{grad}} .$$

Planck constant [h]: Einstein input

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1905

3. Über einen
die Erzeugung und Vericandlung des Lichtes
betreffenden heuristischen Gesichtspunkt;
von A. Einstein.

From *macroscopic* thermodynamics of heat radiation
to
microscopic nature of radiation

The consequences (photo-electric effect) are observed by R. Milikan (1914)

A.H. Compton attributes a particle-like momentum to photon to explain the scattering of X-ray quanta on electrons (1923).

The word *photon* is coined in 1926

Planck constant: Even more universal

1118

ACADÉMIE DES SCIENCES.

1924

PHYSIQUE MATHÉMATIQUE. — *Corpuscules et ondes Ψ* .

Note (1) de M. **LOUIS DE BROGLIE**, présentée par M. M. de Broglie.

Dans une Note récente (2), nous avons établi une liaison générale entre le mouvement des corpuscules de matière et de lumière et la propagation des ondes Ψ de la Mécanique ondulatoire. En conservant les mêmes notations,

The Planck-Einstein relation applies to all particles.

This leads to the emergence of the *new concept* of wave function

$$\text{Particle} \left\langle \begin{array}{l} E = h\nu \\ p = h/\lambda \end{array} \right\rangle \text{Wave}$$

And also, it enters

- properties of atomic spectra
- solid state physics
-

Planck constant and quantum mechanics

The Planck constant appears as soon as *quantum mechanics* is at work

- $h/2\pi$ is the quantum of action [*Planck, 1911*]
- Uncertainty principle [*Heisenberg, 1927*]

The Planck constant controls the *classical limit* and signals when quantum effects cannot be neglected.

Quantum theory is a frame theory.

As such h inherits its truly fundamental and universal status

Choice of the fundamental « units »

These properties are shared with the fundamental constants chosen to become fundamental units.

	Unit of		Enters in the definition of
c	velocity	relativity	m
h	action	quantum	kg
e	charge	electromagnetism	A
k_B	entropy	large number systems	K

The evolution of the nature and status of each of them is related to the progresses of physics.

Conclusions

The mathematical formulation of the laws of nature involves constants.

Most fundamental “object” of a theory *but* cannot be explained by the theory, just measured.

Constants split in

- dimensioned constants (c, h, e, k_B)
 - *they can be used to define units*
- dimensionless parameters
 - *their numerical values are not arbitrary.*

Almost reaches the idea of Planck units but still, a clock remains.

Science is always a human construction.