The role of the (Planck) constants in physics

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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.”

Physical artefacts  →  Atomic properties  →  Fundamental constants
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!*).
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…

\[
l_P = 1.616 \times 10^{-35} \text{m}, \quad t_P = 5.391 \times 10^{-44} \text{s}, \quad m_P = 2.177 \times 10^{-8} \text{kg}
\]
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

\[ e \lambda = \frac{C \lambda^{-5}}{e^{c'/\lambda T} - 1} \]
Planck constant(s): birth


§ 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:

\[ S_N = k \log W + \text{const.} \]

§ 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 $\varepsilon$ proportional der Schwingungszahl $v$ sein muss, also:

\[ \varepsilon = h \cdot v \]

Hierbei sind $h$ und $k$ universelle Constante.

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

\[ h = 6,55 \cdot 10^{-27} \text{ erg sec}, \]

\[ k = 1,346 \cdot 10^{-16} \text{ erg/grad}. \]
Planck constant \([h]\): Einstein input

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
The Planck-Einstein relation applies to all particles.

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

\[
\begin{align*}
\text{Particle: } & E = h\nu \\
& p = h/\lambda \\
\text{Wave: } &
\end{align*}
\]

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

<table>
<thead>
<tr>
<th>Unit of</th>
<th>Enters in the definition of</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>velocity</td>
</tr>
<tr>
<td>h</td>
<td>action</td>
</tr>
<tr>
<td>e</td>
<td>charge</td>
</tr>
<tr>
<td>k_B</td>
<td>entropy</td>
</tr>
</tbody>
</table>

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.