Units and Constants

General Remarks

This is the no-nonsense module with the hard facts about units, constants and transformations from one system of units into an another one.

- No explanations, historical roots, really outdated or unusual units are given - for the fun part use this link.

Basics

First, some *basics* about measurements and units.

- In physics we always have two things: a *physical quantity* **-** e.g. the speed of something, or the strain of something under load - and some *units* to measure the quantity in question.
- The *physical quantity* is what it is. It does not depend on how *you* express it in numbers. Somebody on some other planet will do it differently from you and me for sure
- The *number* you will give to the physical quantity is strictly a function of the units that *you* chose. You might use **m/s**, **lightyears/s** or **wersts/year** - that will just change the *number* you assign to the speed of the moving object but not the speed itself. Trivial, but often forgotten.

To make life easier for everybody (at least for scientists), the choice of units was taken away from you and me. Everybody is now required to *strictly adhere* to the **international standard system**, abbreviated in any language as ***SI*** units.

- Well, by now I and most others scientists, do comply with the **SI** system (which was not always the case); about *you* I don't know. The public at large, of course, does not give shit; especially in the **USA**. Tell the gas station attendant any number you like for the tire pressure in **Pascal**, and he (or she) will just look at you as if you escaped from the lunatic asylum. Its ***psi*** or bust! On occasion, even (american) engineers or scientists do *not* use **SI** units **-** with disastrous consequences like satellites lost in space.

The question now is: how many **basic units** do we need, so we can express *everything else* in these units? And which ones do we take?

- This is one of the deeper questions of humankind. Physicists claim that we just need *one more truly* basic fundamental **constant of nature** - and we do not need units *at all* anymore. Velocities, for instance, can always be given using the absolutely constant speed of light (in vacuum) as the unit with the numerical value 1. Your typical car speed than would be something like **0,000001**.
- But redundancy tends to make life easier and more pleasant for some (just look at your typical Sheik and his harem). The **SI** system gives us ***7** basic units* which are independent of each other and plenty of derived (and thus redundant) ones.

Basic Units

Here are the seven basic units of the SI system:

Quantity	Name	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electrical current	Ampere	A
Thermodynamic temperature	Kelvin	K
Amount of substance	Mol	mol

Luminous intensity	Candela	cd

- From this basic units all other **SI** units can be derived. Below are tables with the more important secondary units.
  - First, we look at some secondary units just invoking basic units *and* a length. While we often do use special symbols for these quantities (e.g. ρ for density), these symbols are not really necessary and thus were not pronounced immutable and sacred as, e.g., the "**m** " for meter or the "**s**" for the second.

Quantity	**Name**	**Symbol**
Area	Square meter	m^2
Volume	Cubic meter	m^3
Velocity	Meter per second	m/s; ms^{-1}
Acceleration	Meter per square second	m/s^2; ms^{-2}
Wave number	reciprocal meter	m^{-1}
Density	Kilogram per cubic meter	kg/m^3
Specific volume	Cubic meter per Kilogram	m^3/kg
Electrical current density	Ampere per square meter	A/m^2
Magnetic field strength	Ampere per meter	A/m
Substance concentration	Mol per cubic meter	mol/m^3
Luminance	Candela per sqare meter	cd/m^2

- Now let's look at more involved units - including important quantities like *energy* , *voltage*, and *magnetic* things.
  - They are more involved, because we usually do *not* express them in **SI** basic units - which is perfectly possible - but in *secondary* units. We will also find one case where there is no unit - it just cancels out.
  - These units often have their own symbols for reasons that become clear if you look at the **SI** units. These symbols should not be used for something else

Quantity	**Name**	**Normal Symbol**	**Symbol SI**	
			Secondary	Basic
Plane angle	Radiant	rad		m / m = 1
Frequency	Hertz	Hz		s^{-1}
Force	Newton	N		$m\ kgs^{-2}$
Pressure, stress	Pascal	Pa	N/m^2	$m^{-1}kgs^{-2}$
Energy, work, quantity of heat	Joule	J	Nm	$m^2 \cdot kgs^{-2}$
Power , energy flux	Watt	W	J/s	m^2kgs^{-3}

Electric charge	Coulomb	C		As
Electric potential, voltage	Volt	V	W/A	$mkgs^{-3}A^{-1}$
Capacitance	Farad	F	C/V	$m^{-2}kg^{-1}s^{4}\cdot A^{2}$
Electric resistance	Ohm	Ω	V/A	$m^{2}kgs^{-3}\cdot A^{-2}$
Conductance	Siemens	S	A/V	$m^{-2}kg^{-1}s^{3}A^{2}$
Magnetic flux	Weber	Wb	Vs	$m^{2}kgs^{-2}A^{-1}$
Magnetic flux density	Tesla	T	Wb/m^2	$kgs^{-2}\ A^{-1}$
Inductance	Henry	H	Wb/A	$m^{2}kgs^{-2}A^{-2}$
Celsius temperature	Degree Celsius	^oC		K
Radioactivity	Becquerel	Bc		1/s

- Mercifully, the members of the "Comite International des Poids and Mesures" are human (up to a point). They did *not* outlaw all older units in one fell stroke, but sorted them into *three* groups:
  - "Old" units which may be used together with **SI** units *without restrictions* .
  - Old units which may be used *for some time* in parallel to **SI** units.
  - Old units which are definitely out and *must not be used at all* any more.
- Some of the units in the second category are regional and you probably have never heard of them. I will not include them here. The number of outlawed units is legion, we just include the still tempting ones.
- Here is the first category: Some of the non-**SI** units *you still may use without restrictions*:

Quantity	Name	Unit
Minute	min	1 min = 60 s
Hour	h	1h = 60 min = 3600 s
Day	d	1 d = 24 hr = 86400 s
Angle Degree Angle minute Angle second	o ' "	$1^o = (\pi/180)$ rad 1 ' = (1/60) ^{o} 1 " = (1/60) ' = (1/3600) ^{o}
Liter	l, L	$1\ l = 1\ dm^3 = 10^{-3}\ m^3$
Ton	t	$1\ t = 10^3$ kg
Electronvolt	eV	1 eV = 1,602 540 2 · 10^{-19} J
Atomic mass unit	u	1 u = 1,660 540 2 · 10^{-27} kg

- Now to the *old units you may use for some more time* to come in parallel to the **SI** units:

Quantity	Name	Unit
Ångstrom	Å	1 Å = 0,1 nm
Ar	a	1 a = 100 m^2
Hectar	ha	1 ha = 100 a
Bar	bar	1 bar = 0,1 MPa
Barn	b	1 b = 100 fm = 10^{-28} m^2
Curie	Ci	1 Ci = 3,7 · 10^{10} Bq
Roentgen	R	1 R 0 2,58 · 10^4 Ci/kg

- Now to the *units you must not use anymore!* . We might put them into two groups:
  - **1.** The forerunners of the **SI** units, the **cgs** units; i.e. the units based on the *centimeter*, the *gram* and the *second*.
  - **2.** The simple old fashioned no-no's.
- While it may appear that the **cgs** system is practically the same as the **SI** system, *this is not so*!
  - Of course, the *cm*, *g*, and *s* are essentially the same basic units as in the **SI** system, the abbreviation "**cgs**", however, does not tell you anything about the other necessary basic units in this system - and *that* is where the problems come in!
  - In fact, there were *several* **cgs** systems - the *electrostatic*, the *electromagnetic*, and the *Gauss* **cgs** system! I will not go deeper into this, however.
- Finally, some still fondly remembered old units *you simply do not use anymore*:

Quantity	Name	Unit
Torr	torr	1 Torr = (101 325/760) Pa = 133.32 Pa
Physical atmosphere	atm	1 atm = 101 325 Pa
Kilopond	kp	1 kp = 9,806 65 N
Calory	cal	1 cal = 4,186 8 J
Micron (Micro*meter* is what you use!)	µ	1 = 1 µm

Fundamental Constants

- Fundamental constants are some numbers with units that cannot (yet) be calculated from some physical theory but must be measured.
  - This may have three possible reasons:

1. There is presently no theory, and there *never* will be a theory, that allows to calculate fundamental constants. They have the value they have because of an act of God (or, as it should be written in our enlightened times: an act of one or more gods and/or godesses), or they are purely random. In this case we just happen to live in an universe where their value is what we measure. In some other universe, or some other corner of our universe, it might be different.
2. There is presently no theory, but *some day* there will be one. Fundamental constants will then be

calculated from scratch and then are no longer fundamental.

3. There already *is* a theory for some of those constants, we just are not yet smart enough to see the obvious or to do the numerics. Masses of elementary particles, e.g., might fall into this category.

- Hot-shot physicists have some ideas, which constants might fall into which category. Speculations along this line are a lot of fun **-** but of no consequence so far. So *I* will not dwell on this. Of course, *you* may check for yourself which one of the three possibilities you are going to embrace and thus get some idea of what kind of person you are.

Fundamental physical theories usually introduce one new fundamental constant. Mechanics (including gravitation) needs the gravity constant **G**, quantum theory has Plancks constant **h**, statistical thermodynamics introduces Boltzmanns constant **k**, the special theory of relativity (or Maxwells theory of electromagnetism which is really part of the relativity theory) needs the speed of light **c**.

- New theories sometimes "explain" old constants of nature because they can calculate them, or replace them by something more fundamental. Boltzmann's constant **k**, for example, is more fundamental than the "fundamental" gas constant **R**, because it relates its number to a fundamental unit of matter (**1 particle**) and not to an arbitrary one like **1 Mol**.

How many truly fundamental constants are there? Why do they have the values they have? Interestingly, just slight deviations in the values of some constants would make carbon based life impossible; this is where the so-called "**anthropic principle**" comes in. Will we eventually be able, with a "Theory of Everything" (***TOE***) to calculate all natural constants?

- Nobody knows. We run against the deepest physical questions at this point.
- So let's just look at what we have. Since it is customary to list as natural constants also some quantities that are actually computable from others by now, I include some of these "constants" here, too (together with the conversion formula).

Symbol and formula	Numerical value	Magnitude and unit	Remarks
Speed of light in vacuum			
c_0, c	2,997 924 58	10^8 ms^{-1}	Truly fundamental
Gravitational constant			
G	6,673	10^{-11} $m^3kg^{-1}s^{-2}$	Truly fundamental
Planck's constant			
h	6,626 068 76	10^{-34} Js	Truly fundamental
	4,1356	10^{-15} eVs	
Elementary charge			
e	1,602 176 462	10^{-19} C	Truly fundamental ? Maybe not
Fine structure constant			
$\alpha = \mu_0 ce^2/2h$	7,297 352 533	10^{-3}	Unitless, maybe more fundamental than others.
Mass of a electron at rest			
m_e	9,109 381 88	10^{-31} kg	Not truly fundamental; can be calculated in principle
	0,510 998 902	MeV	
Mass of a proton at rest			

m_p	1,672 621 58	10^{-27} kg	Not truly fundamental, can be calculated in principle
	1,007 276 466	u	
	938,271 998(38)	MeV	
Lohschmidt constant (also known as **Avogadro constant**)			
N_A	6,022 141 99(47)	10^{23} mol^{-1}	Not truly fundamental
Faraday constant			
$F = e \cdot N_A$	96 485,3415(39)	$C \cdot mol^{-1}$	Not truly fundamental any more
Universal gas constant			
R	8,314 472(15)	$Jmol^{-1}K^{-1}$	Not truly fundamental any more
Boltzmann constant			
$k = R/N_A$	1,380 6503	10^{-23} JK^{-1}	Truly fundamental
	8,617269	10^{-5} eVK^{-1}	
Magnetic permeability of vacuum			
$\mu_0 = 1/\epsilon_0 c^2$	12,566 370 614	10^{-7} $VsA^{-1}m^{-1}$	Not truly fundamental
Electric susceptibility of vacuum			
$\epsilon_0 = 1/\mu_0 c^2$	8,854 187 817	10^{-12} $AsV^{-1}m^{-1}$	Not truly fundamental
Magnetic flux quant			
$\Pi = h/2e$	2,067 833 636	10^{-15} Wb	Smallest possible magnetic flux Not truly fundamental