Intro to Quantum Physics F3241

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Recap : LMT dimensions

To get a grip and do useful science, we should think about what it is important.

- Length [L]
- Mass [M]
- Time [T]

The dimension of area is L^2.

a What is the dimension of volume?

b What is the dimension of density (mass/volume)?

c What is the dimension of acceleration?

d What is the dimension of force?

e What is the dimension of energy?

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What is a fundamental constant?

Things that change depending on where and when you measure them:

Things that do not change depending on where and when you measure them:

The speed of light in a vacuum

A lot of smart people in history thought that the light did not travel, or travelled at an infinite speed.

How would you go about trying to measure the speed of light?

Einstein proved that c is constant in 1905 with his theory of Special Relativity.

As measurements of c became more sophisticated, the uncertainty on the definition of the metre became a problem

The Atomic Clock

In the 20th century, we started to realised that there were some things that were in fact more regular than clockwork, and more stable than lumps of metal

The atom is like a mechanical clock!

Redefining the second (1967)

The frequency of light emitted when a Caesium 133 atom undergoes a transition (a hyperfine ground state transition) was constant, enormous, and precisely measurable.

The light associated with this transition had a measured frequency of 9.19263177 GHz:

$$1\text{s} = \frac{9.192631770 \times 10^9}{\Delta\nu_{Cs}}$$

Or equivalently:

$\Delta\nu_{Cs} = 9.192631770 \times 10^9 \text{ Hz} = 9.192631770 \times 10^9 \text{ s}^{-1}$

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Redefining the metre (1983)

The speed of light in a vacuum must be constant according to special relativity. Using this, and the exact definition of a second, we can redefine the metre:

$$1\text{m} = \left(\frac{9.192631770 \times 10^9}{\Delta\nu_{Cs}}\right)\left(\frac{c}{2.99792458 \times 10^8}\right)$$

Or equivalently, $c = 2.99792458 \times 10^8\ \text{ms}^{-1}$

Fundamental: measurements of c are no longer meaningful. We have fixed its value to exactly that of the world best measurement, and redefined the units accordingly.

Redefining the kilogram (2019)

Planck's constant h can be measured in all sorts of ways (as we shall see later), and is known very precisely from these measurements.

We now use the fixed value of $h = 6.62607015 \times 10^{-34}$ (units?) to define the kilogram:

$$1\text{kg} = \left(\frac{9.192631770 \times 10^{9}}{\Delta\nu_{Cs}}\right)\left(\frac{c}{2.99792458 \times 10^{8}}\right)\left(\frac{h}{6.62607015 \times 10^{-34}}\right)$$

Note that we are **not** claiming to know the exact value of h with no uncertainty, even though it kind of feels like we are.

Redefining the Ampere (and Coulomb)

The SI base unit Ampere is the unit of current, and the Coulomb is the unit of charge: 1 A = 1 Coulomb per second

We can measure the charge on an electron very precisely (as we shall see), and we know that all electrons have exactly the same charge

The elementary charge $e = 1.602176634 \times 10^{-19}$ C

$$1 \text{ C} = \frac{e}{1.602176634 \times 10^{-19}}$$

and so

$$1 \text{ A} = \left(\frac{e}{1.602176634 \times 10^{-19}}\right)\left(\frac{\Delta\nu_{Cs}}{9.192631770 \times 10^{9}}\right)$$

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The other three

We have used ν_{Cs}, c, h, and e to define seconds, metres, kilograms, and Amperes.

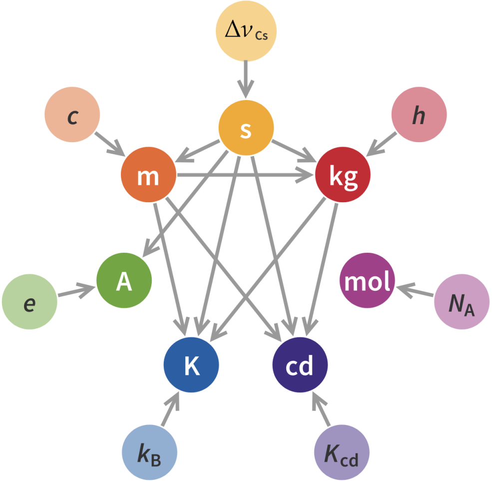
Three more fundamental constants $\rightarrow$ three more SI base units!

$k_B = 1.380649 \times 10^{-23}$ Joules per Kelvin (base units?)

$N_A = 6.02214076 \times 10^{23}$ per mole of stuff

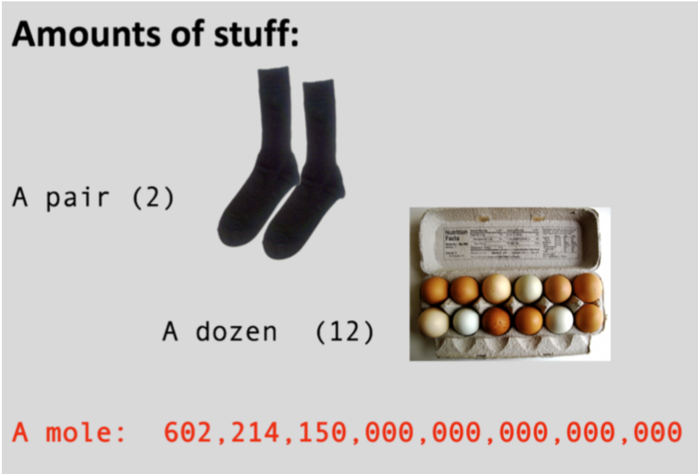
$K_{cd} = 683$ candela - steradian -per kilogram -per metre squared -seconds cubed

Summary



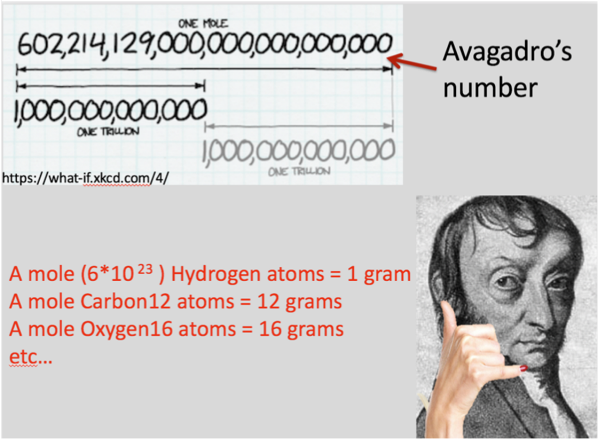
Nobody's favourite constant (?) N_A

Avagadro's number N_A



Avagadro's number N_A (1811)

$$N_A = 6.02214076 \times 10^{23} \text{ mol}^{-1}$$



Back to dimensions: L, T, M, I

ν_{Cs} :

c :

h :

e :

Natural Units

When dealing with complex formulae and tiny scales, it makes sense to adjust our system.

$c = 2.99792458 \times 10^{8}\ \mathrm{ms}^{-1}$

There exist some units in which I can write $c = 1$. It still has the dimensions LT^{-1}, but it has the value 1.

I could similarly do the same thing for other constants that appear regularly in the equations I have to solve.

The electronVolt, eV

The electronVolt is a unit of energy that I use every single day.

It is small: $1\text{eV} = 1.602176634 \times 10^{-19}$ J

A Joule is the energy required to accelerate a 1 kg mass at 1 ms^{-2} through a distance of 1 m.

An electronVolt is the energy gained by an electron accelerated through a potential difference of 1 Volt in a vacuum.

The eV is a better unit of energy for the kind of physics we are going to be doing.

The electronVolt, eV

$$1\text{eV} = 1.602176634 \times 10^{-19} \text{ kg m s}^{-2} : \text{Energy in eV}$$

With this better unit for energy, and the understanding that there exist some units in which I can write $c = 1$, we are all set.

$$1\text{eV} = 1.782662 \times 10^{-36} \text{ kg } (\times c^2) : \text{Mass in eV}$$

$$1\text{eV} = 5.344286 \times 10^{-28} \text{ kg m s}^{-1} (\times c) : \text{Momentum in eV}$$

Things in eV

The mass of the electron:

$m_e = 9.11 \times 10^{-31}$ kg $\rightarrow$ 510 keV

Planck's constant multiplied by the speed of light:

$hc = 1.99 \times 10^{-25}$ Jm $\rightarrow$ 1.24 eV μm

So we get more manageable numbers, in addition to being able to seamlessly relate mass, energy, momentum, ...

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Fully Natural Units

In particle physics and similar fields, we use the **natural units**:
$c = 1$, $\hbar = 1$, $m_e = 1$, $\epsilon_0 = 1$

Such that:

$1 \text{ s} = 1.519 \times 10^{15}\ \hbar\ \ \text{eV}$

$1 \text{ m} = 5.068 \times 10^{6}\ c\hbar\ \ \text{eV}^{-1}$

$1 \text{ kg} = 5.610 \times 10^{35}\ c^{-2}\ \ \text{eV}$

Although this seems confusing now, you may gradually learn to love it over the next few years!

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End of part 1.2

End of part 1.2 : Constants

Next lecture (Friday 4pm) will be on tips & tricks to help you get the most out of this module.