Flavour Physics

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Symmetries in physics

In classical physics there are important conservation laws, associated with symmetries.

In relativity, symmetry is the starting point.
Example: deriving Maxwell's equations from relativistic invariance.

In quantum physics, symmetries arguably play an even more fundamental role.

Quantum ElectroDynamics (QED)

Particle theories are fundamentally lists of:
particles and rules of how they interact.

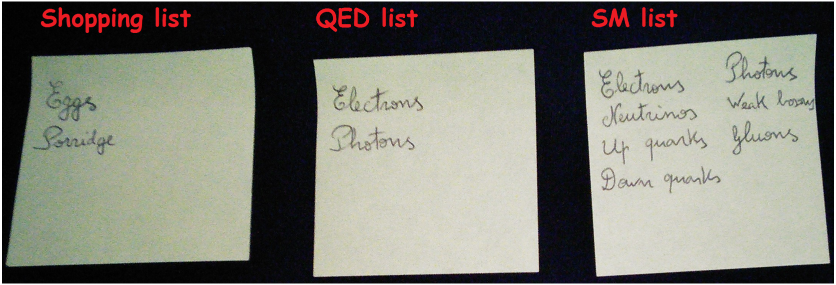
Using the symmetry to build it, QED is a very small list:
electrons and a $U(1)$ symmetry (photons).

Standard Model (SM)

Particle theories are fundamentally lists of:
particles and rules of how they interact.

The Standard Model is a bigger list, more than electrons
and symmetries called $SU(3)$, $SU(2)$ and a $U(1)$
(but not directly the electrodynamics $U(1)$)

Lists


Shopping list
Eggs
Porridge
QED list
Electrons
Photons
SM list
Electrons
Neutrinos
Up quarks
Down quarks
Photons
Weak bosons
Gluons

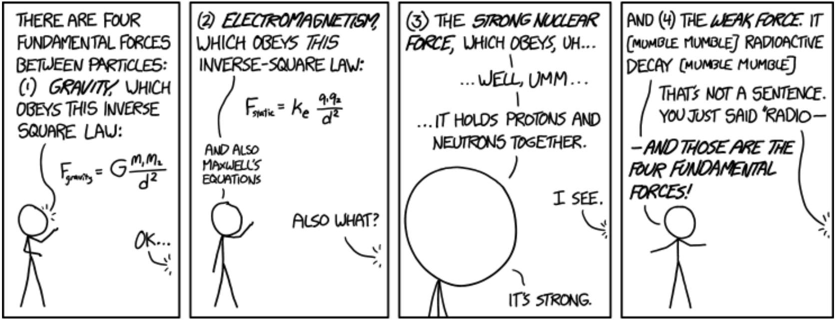
The Standard Model interactions

Gravity not included
$SU(3)_{Colour} \times SU(2)_{Left} \times U(1)_{Hypercharge}$

The strong force becomes stronger at larger distances.
Particles “charged” under it are said to be “coloured”.
They appear in “colourless” combinations
(e.g. protons and neutrons).

The weak force acts only on “Left-handed” particles.
It is not really weak, it just appears that way:
its symmetry is broken.

Fundamental forces (according to XKCD)

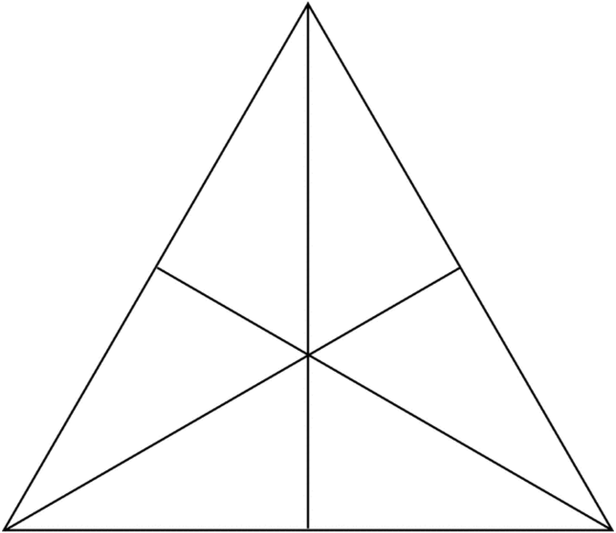


The Standard Model (1 fermion generation)

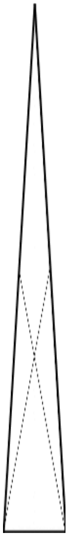
[Neutrino, Electron]$_{Left}$		(Electron)$_{Right}$
[Up, Down]$_{Left}$	(Up)$_{Right}$	(Down)$_{Right}$
[Up, Down]$_{Left}$	(Up)$_{Right}$	(Down)$_{Right}$
[Up, Down]$_{Left}$	(Up)$_{Right}$	(Down)$_{Right}$

The Standard Model has 3 fermion generations

Equilateral action



Equilateral damage!



Flavour problem and squashing a triangle

https://www.90segundosdeciencia.pt/episodes/ep-1707-ivo-varzielas/

Num cenário em que a massa de cada partícula é igual, teríamos um triângulo equilátero onde cada partícula é equidistante da outra. No entanto, se a massa for diferente, a simetria é quebrada, e ficamos com um triângulo espalmado em que cada lado é diferente do outro.

Este cenário explicaria, por exemplo, porque é que existem três cópias da mesma partícula, com massas diferentes, como é o caso do eletrão, do muão e do tau.

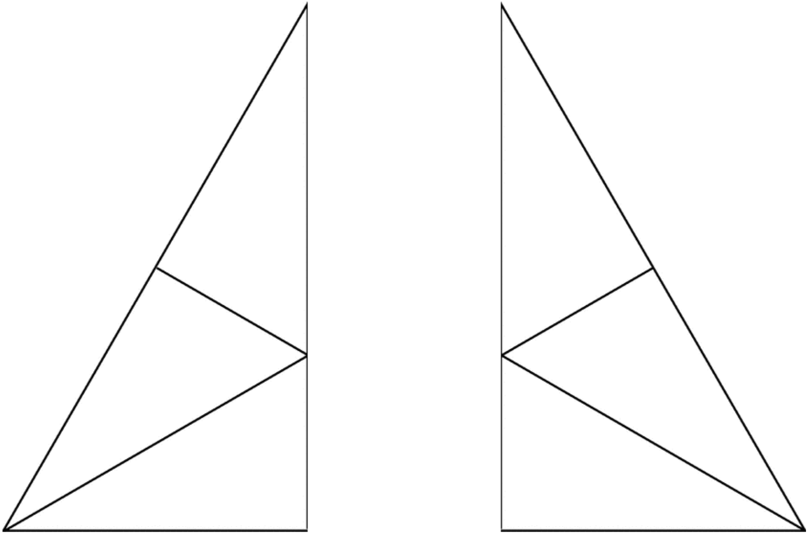
Symmetries

Symmetry if something unchanged
when I act on it with a specific transformation.

Polygon examples

Equilateral triangle (3 mirrors and 3 rotations (0, 120, 240))
Isosceles triangle (1 mirror and 1 rotation (0 degrees))

Building something invariant



Invariants under symmetries

Build something with symmetry (doesn't transform)
from parts that transform in specific ways

Join 2 square brackets [ ] to make a rectangle
Or use 2 minus signs - to build a plus sign
(with the symmetry of the square)

Important example: length of a vector is frame-invariant
(some properties of triangles are also invariant)

Building frame-invariants from vectors

Vectors transform in specific ways under frame transformations (e.g. rotation by an angle θ)
$(x, y) \to (x', y') = (x\cos\theta + y\sin\theta, -x\sin\theta + y\cos\theta)$

But one can build, from vectors, quantities that are frame-independent:
Squared length of a vector (x, y), is $x^2 + y^2 = x'^2 + y'^2$.

More generally, scalar product of two vectors
$(x_1, y_1).(x_2, y_2) = x_1 x_2 + y_1 y_2 = (x'_1, y'_1).(x'_2, y'_2) = x'_1 x'_2 + y'_1 y'_2$

Invariants are very important as Physics should not depend on "arbitrary" choice of frame!

What about Particle Physics?

Particles have specific transformation properties
and interactions respect the invariant combinations

This restricts the “shape” of the theory, leading to predictions
(e.g. conservation of electric charge)

What about $U(1)$?

Particles with "charge" q under a $U(1)$ transformation (θ):
$\psi \rightarrow e^{iq\theta}\psi$
(i.e. get a phase proportional to their respective charge)

If that $U(1)$ is a symmetry of the theory, one must build quantities that remain invariant under any $U(1)$ transformation (for arbitrary θ).

(Scalar) QED mass term

Only have (scalar) electrons with charge $q = -1$, ψ:
$\psi \to e^{-i\theta}\psi$ and $\psi^* \to e^{+i\theta}\psi^*$

$U(1)$ invariant:
$m\psi^*\psi$

And that is basically the (scalar) QED mass term!

(Kind of) SM Yukawa interaction

"Electron doublet-vector" with hypercharge $q = -1$,
$\Psi = (\psi_1, \psi_2)$
"Boson doublet" with hypercharge $q = +1$ $\Phi = (\phi_1, \phi_2)$
the "scalar electron" ψ with hypercharge $q = -2$

$U(1)$ and frame-invariant:
$y(\Psi^*.\Phi)\psi$
which is kind of one of the interactions of the SM.

Note the invariants you can build depend on:
the symmetries of the theory
the particle content of the theory

(Kind of) SM fermion mass term

$U(1)$ and frame-invariant:
$y(\Psi^*.\Phi)\psi$

Φ gets a non-zero “vaccuum expectation value”
a specific value everywhere, in a specific direction
(this breaks both symmetries)
$\langle\Phi\rangle = (0, v)$

Then
$y(\Psi^*.\Phi)\psi = y(\Psi_1^*, \Psi_2^*).(\Phi_1, \Phi_2)\psi \to y(\Psi_2^* v)\psi$
Which looks like $m\psi^*\psi$ for $m = yv$

Thank you for your attention

Any questions?