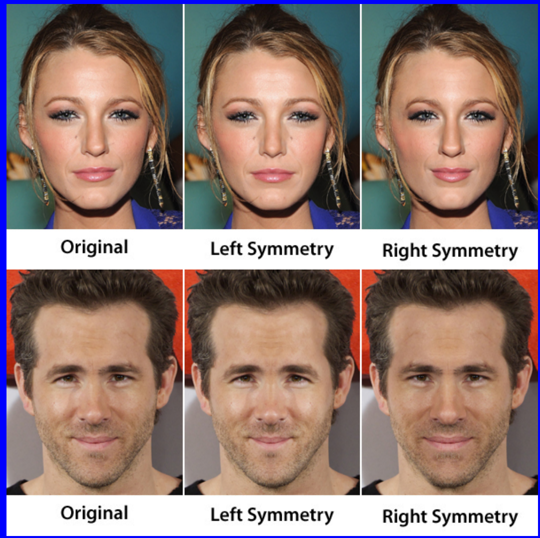
Symmetries II

Are symmetries perfect?

★ the small imperfections make it more interesting . . .

is physics really perfectly symmetric?



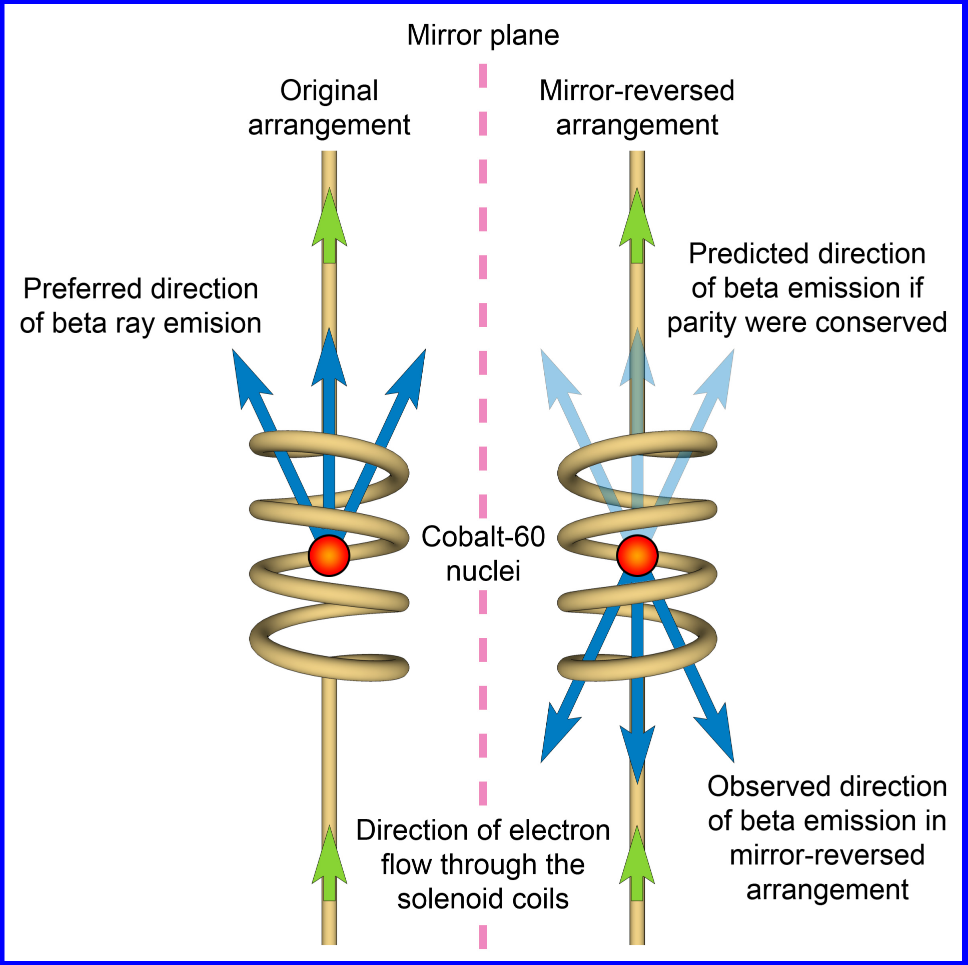
- obviously, many things in our macroscopic world are not symmetric
- but is this also true for the fundamental laws of physics?

★ Originally it seemed that nature does not only exhibit the previously discussed continuous symmetries, but the discrete symmetries as well:

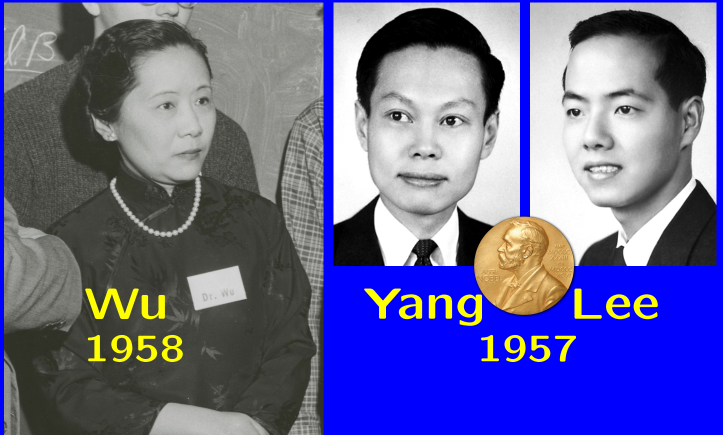
- P (parity transformation = mirror symmetry)
- T (time reversal)
- C (charge conjugation)

Are symmetries perfect?

★ the Wu experiment



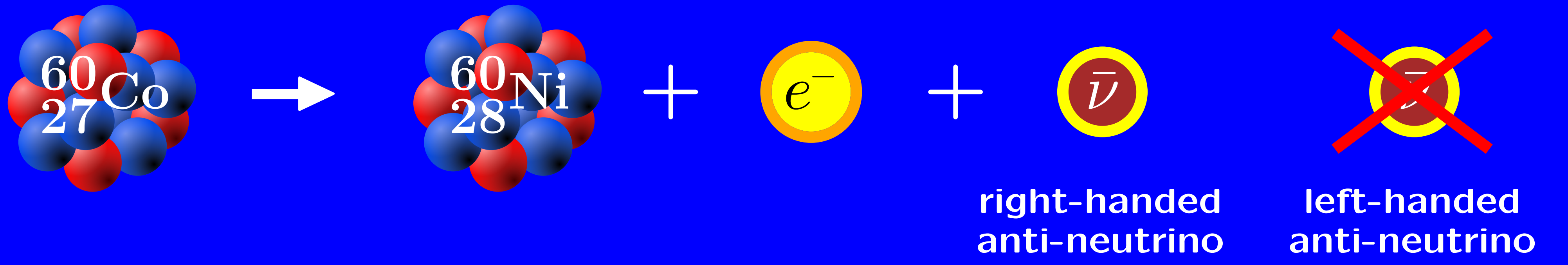
- originally, all experiments indicated that the microcosmic world is perfectly mirror-symmetric
- 1956 Tsung-Dao Lee and Chen Ning Yang postulated a violation of parity for the weak interaction
- in the same year, Chien-Shiung Wu demonstrated the violation experimentally



→ nature is <u>not</u> mirror-symmetric, P-symmetry (parity) is <u>violated</u>

Are symmetries perfect?

★ a deeper understanding of the Wu experiment



- also (undetected) anti-neutrinos are emitted
- anti-neutrinos have a spin that is always orientated in the direction of movement (they are "right-handed")
- since a P-transformation changes the direction of movement, but not the spin, it produces a "left-handed" anti-neutrino
- as it turns out, we do not see a left-handed anti-neutrino in nature at all!
- therefore, Parity is said to be maximally violated

Are symmetries perfect?

★ Parity violation – but maybe a CP symmetry?

right-handed anti-neutrino | left-handed anti-neutrino | left-handed neutrino

- there is no left-handed anti-neutrino, but there is a left-handed neutrino (and only a such-handed!)
- obviously, this violates C-symmetry (Charge conjugation, the symmetrie between matter and anti-matter)
- BUT: the combined symmetry transformation CP (exchange matter/anti-matter plus mirroring) works:

right-handed anti-neutrino

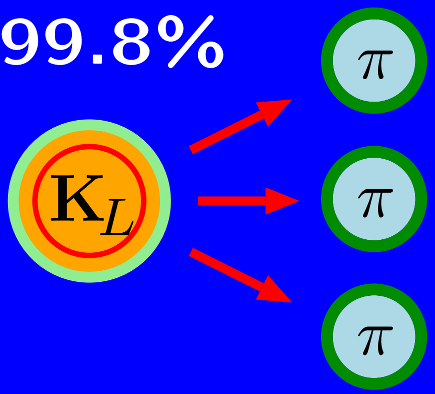
$\Leftarrow$ CP $\Rightarrow$

left-handed neutrino

Are symmetries perfect?

★ the kaon experiment of 1964

99.8%



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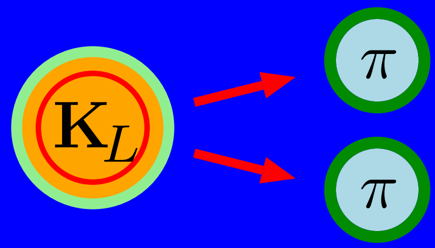
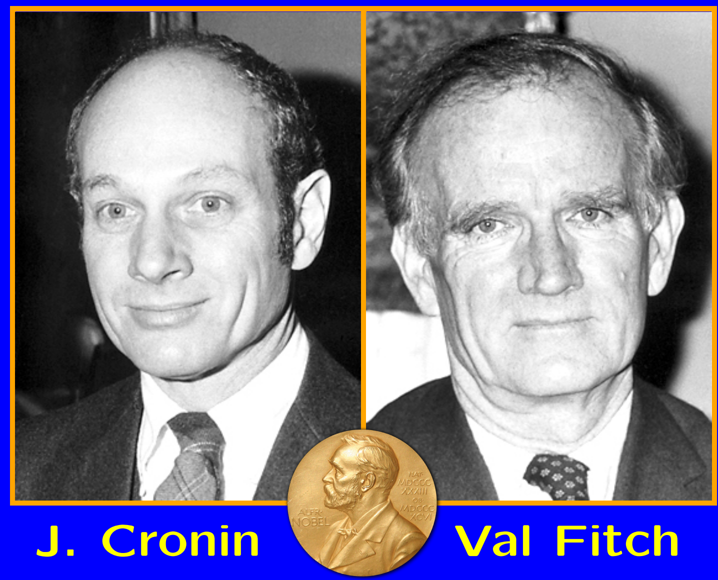




J. Cronin Val Fitch

1980

- if there is a CP-symmetry in nature, by Noether's theorem there is also a corresponding conserved quantum number "CP"
- kaons and pions are pseudo-scalars
  $\Rightarrow \quad \mathrm{P}\mathrm{K} = -\mathrm{K}$ and $\mathrm{P}\pi = -\pi$
- therefore, CP is conserved for the decay of the long-lived kaon into three pions, but not for the decay into two

→ CP is (slightly) violated

Are symmetries perfect?

★ "last hope" CPT ?

the CPT-theorem states:

- under very general conditions

  i.e.: transformations of the Poincaré group

  are symmetries of microscopic physics

- quantum field theories (the "language" of particle physics) always have CPT as a symmetry

. . . also experimentally, no violations have been observed so far

→ CPT is (as far as we know today) <u>not violated</u>

interesting side remark:

- CPT-symmetry together with CP-violation, gives also T-violation
- that means: the fundamental laws of nature are not time-symmetric, there is a special direction of time even at the microscopic level

"the future IS different from the past, after all!"

Overview

discrete symmetries

symmetry	valid in the universe?
P (parity: ”mirroring”)	✘
C (charge conjugation)	✘
T (time reversal)	✘
CP (combination of C and P)	✘
CPT (combination of C, P, & T)	✔

How symmetries make theories

★ QED, the quantum theory of light

remember:

- physics is invariant under a global U(1)-transformation of the field Ψ:

$$U(1)\Psi(t,x,y,z) = e^{i\alpha}\Psi(t,x,y,z)$$

- global means a synchronous phase transformation of all particles in the whole universe!

the idea:

- replace the global transformation by a local one:

$$U(1)\Psi(t,x,y,z) = e^{i\alpha(t,x,y,z)}\Psi(t,x,y,z)$$

(different particles at different positions get transformed independently)

How symmetries make theories

★ QED, the quantum theory of light

result of a local U(1) transformation:

- **if only particles are transformed**
  - ★ not changing the electromagnetic interaction
  - ➡ **the theory is not invariant** under local U(1) transformations!
- **if the electromagnetic interaction is included in the transformation**
  - ➡ **the theory becomes invariant** under local U(1) transformations!

- **this works only, because the electromagnetic interaction has "just the right form"**

"coincidence or deeper truth?"

How symmetries make theories

★ QED, the quantum theory of light

the modern viewpoint
("gauge principle"):

- a non-interacting theory,
  - invariant under a global symmetry

  can be made locally symmetric
  - by introducing
    - ★ additional fields
    - ★ and interactions

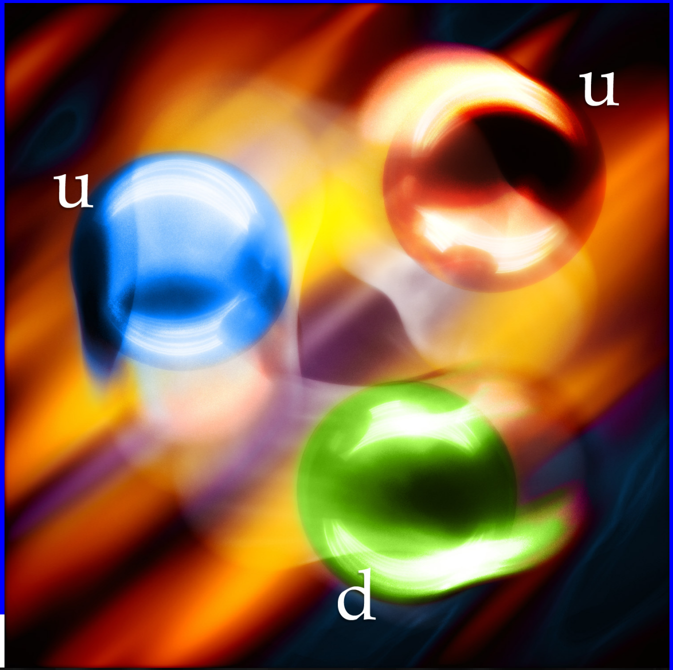
➡ **the full theory is now** for QED:

- ★ **locally symmetric** invariant under local phase transformations
- ★ **and interacting** the electro-magnetic gauge field A_μ, describing photons

each local symmetry produces an interaction plus new particles which mediate it

How symmetries make theories

★ Quantum-Chromo-Dynamics (QCD) the theory of the strong force



- experiments show that protons (and neutrons) have an inner structure
- observations suggest the existence of
  - ★ fermions (quarks) with
  - ★ 3 inner degrees of freedom (color)

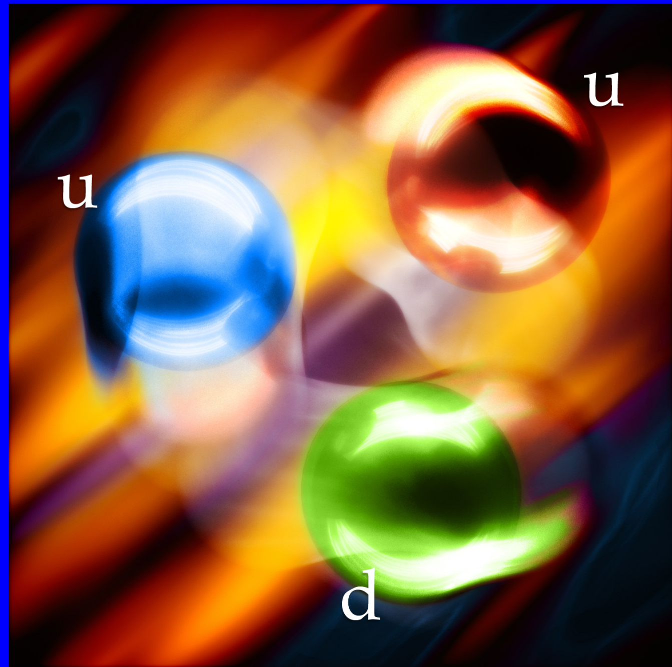
  inside the nucleon

there are three color states:

red, green, blue

How symmetries make theories

★ Quantum-Chromo-Dynamics (QCD) the theory of the strong force



- we do not see "color"
- color states can be redefined
  - ★ without changing the theory!

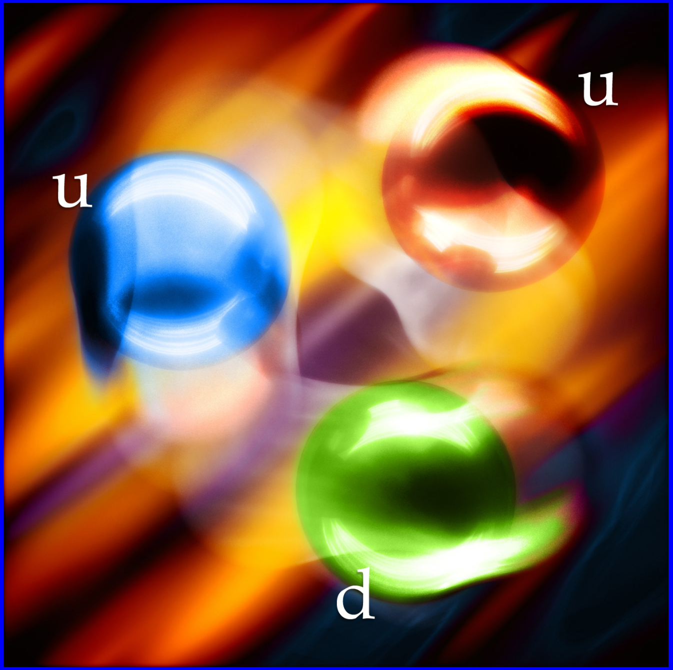
"new colors" = mixture of old colors

$$q = A_{rr}\, q + A_{rg}\, q + A_{rb}\, q$$
$$q = A_{gr}\, q + A_{gg}\, q + A_{gb}\, q$$
$$q = A_{br}\, q + A_{bg}\, q + A_{bb}\, q$$

- mathematically, this corresponds to a **unitary** 3×3 **matrix A**
- the symmetry group is called $SU(3)$

How symmetries make theories

★ Quantum-Chromo-Dynamics (QCD) the theory of the strong force



gauge principle:

- making the $SU(3)_{\text{color}}$-symmetry local we get
  - ★ the strong force with
  - ★ the gluon as the force carrier

- the strong force binds the quarks into mesons and baryons
- it is also (indirectly) responsible for the stability of nuclei
  (binding of proton and neutron, the nuclear force)

the color symmetry of quarks enables the existence of atoms!

How symmetries make theories

★ sketch of electro-weak interaction

- proton and neutron behave similar inside the nucleus
  - ★ iso-spin symmetry
- extending this iso-spin symmetry to all left-handed fermions
  - ★ groups them in pairs (doublets)
  - ★ is a symmetry of the free theory

"new flavor" = mixture of old flavors

$$\nu_e' = A_{uu}\,\nu_e + A_{ud}\,e_L^-$$
$$e_L^{-\prime} = A_{du}\,\nu_e + A_{dd}\,e_L^-$$

$$u_L' = A_{uu}\,u_L + A_{ud}\,d_L$$
$$d_L' = A_{du}\,u_L + A_{dd}\,d_L$$

gauge principle:

- making the $SU(2)_L$-symmetry local (and "mixing" it with a local $U(1)_Y$-symmetry) we get
  - ★ the electro-weak force
  - ★ with W- and Z-bosons (and photons) as force carriers

Overview

Symmetries and Interactions

symmetry		interaction	
$U(1)$	symmetry of all leptons and quarks	$U(1)_Y$	electro-weak
$SU(2)$	symmetry of left-handed leptons and quarks	weak	
$SU(3)$	symmetry of quarks alone	strong	
?	is it a symmetry of space-time geometry itself, or something qualitatively different?	(quantum-) gravity	