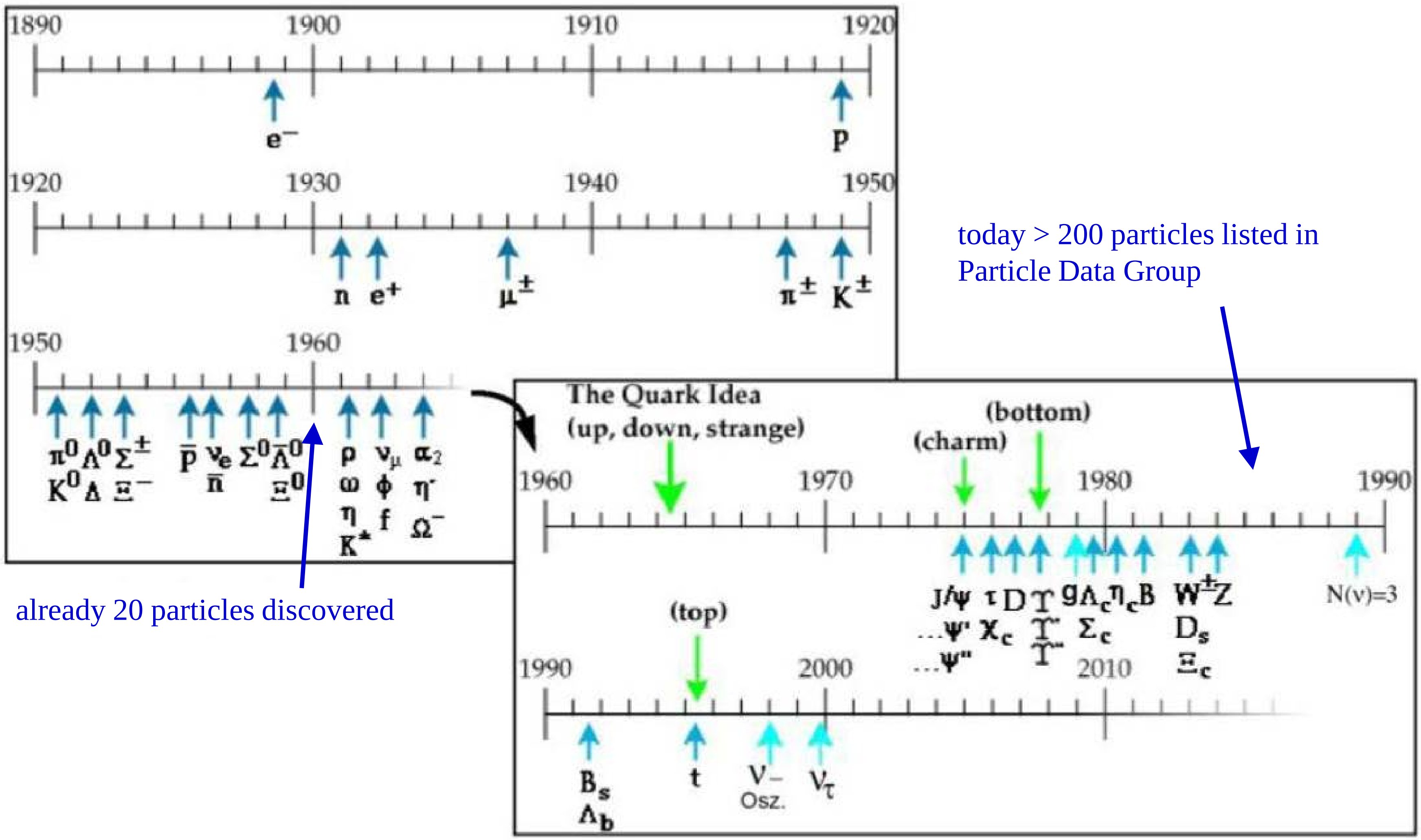
Quarks

Throughout the 1950 – 1960s, a huge variety of additional particles was found in scattering experiments. This was referred to as the “particle zoo”.



Quarks

To escape the "particle zoo", the next logical step was to investigate whether these patterns could be explained by postulating that all Baryons and Mesons are made of other particles. These particles were named ***Quarks***.

- As far as we know, quarks are like points in geometry.
- Quarks possess fractional electric charges (-1/3, 2/3).
- Quarks are spin ½ fermions, subject to all kind of interactions.
- Quarks and their bound states are the only particles which interact strongly.
- After extensively testing this theory, scientists now suspect that quarks and electrons are fundamental.

An elementary particle or fundamental particle is a particle not known to have substructure. If an elementary particle truly has no substructure, then it is one of the basic particles of the universe from which all larger particles are made.

Quarks

- The quark model: ***baryons*** and ***antibaryons*** are bound states of three quarks, and ***mesons*** are bound states of a quark and antiquark.

Analogously to leptons, quarks occur in three generations:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Corresponding antiquarks are:

$$\begin{pmatrix} \bar{d} \\ \bar{u} \end{pmatrix} \quad \begin{pmatrix} \bar{s} \\ \bar{c} \end{pmatrix} \quad \begin{pmatrix} \bar{b} \\ \bar{t} \end{pmatrix}$$

Name ("Flavor")	Symbol	Charge (in units of e)	Mass (GeV/c^2)
Down	d	-1/3	~ 0.005
Up	u	+2/3	~ 0.002
Strange	s	-1/3	~ 0.095
Charmed	c	+2/3	~ 1.3
Bottom	b	-1/3	~ 4.2
Top	t	+2/3	~ 172

Quantum Numbers and Flavours

"Strangeness"	$S = -[N(s) - N(\bar{s})]$	$K^+ = u\bar{s}, \quad K^0 = d\bar{s}$ $K^- = \bar{u}s, \quad \bar{K}^0 = \bar{d}s$ $\Sigma^+ = uus, \Sigma^0 = uds, \Sigma^- = dds$
"Charm"	$C = [N(c) - N(\bar{c})]$	$D^+ = c\bar{d}, \quad D^0 = c\bar{u}$ $D^- = \bar{c}d, \quad \bar{D}^0 = \bar{c}u$
"Bottomness"	$\tilde{B} = -[N(b) - N(\bar{b})]$	$B^+ = u\bar{b}, \quad B^0 = d\bar{b}$ $B^- = \bar{u}b, \quad \bar{B}^0 = \bar{d}b$
"Topness"	$T = [N(t) - N(\bar{t})]$	No composite hadrons are formed that contain the top (anti) quark

- Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass ($\tau \sim 10^{-23}\ s$)
- Hadrons with the lowest possible mass for each quark number (C, S, etc.) may live much longer before decaying weakly ($\tau \sim 10^{-7} - 10^{13}\ s$) or electromagnetically (mesons, $\tau \sim 10^{-16} - 10^{-21}\ s$)

Fractional Charges and Unseen Quarks

- Murray Gell-Mann and George Zweig proposed the idea of the quarks to find some order in the chaos of particles:
  - Baryons are particles consisting of thee quarks (qqq)
  - Mesons are particles consisting of a quark and anti-quark ($q\bar{q}$)

qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	-1	0	Δ^{-}
uus	1	-1	Σ^{*+}
uds	0	-1	Σ^{*0}
dds	-1	-1	Σ^{*-}
uss	0	-2	Ξ^{*0}
dss	-1	-2	Ξ^{*-}
sss	-1	-3	Ω^{-}

$q\bar{q}$	Q	S	Meson
$(u\bar{u} - d\bar{d})/\sqrt{2}$	0	0	π^{0}
$u\bar{d}$	1	0	π^{+}
$\bar{u}d$	-1	0	π^{-}
$u\bar{s}$	1	-1	K^{+}
$d\bar{s}/s\bar{d}$	0	-1	K^{0}
$s\bar{u}$	-1	-1	K^{-}
$\approx (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$	0	-2	η
$\approx (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$	0	-2	η'

Some Examples of Baryons

Particle	Mass (GeV/c^2)	Quark composition	Q (units of e)	S	C	$\tilde{B}$
p	0.938	uud	1	0	0	0
n	0.940	udd	0	0	0	0
Λ	1.116	uds	0	-1	0	0
Λ_c	2.285	udc	1	0	1	0

Strangeness is defined so that S = -1 for s-quark and S = 1 for $\bar{s}$ respectively. Further, C = 1 for c-quark, $\tilde{B}$ = -1 for b-quark and T = 1 for t-quark.

- Since the top-quark is a very short-living one, there are no hadrons containing it, i.e. T = 0 for all hadrons.

Quark numbers for up and down quarks have no name, but just like any other flavour, they are conserved in strong and electromagnetic interactions.

Baryons are assigned own quantum number B. B = 1 for baryons, B = -1 for antibaryons and B = 0 for mesons.

Some Examples of Mesons

Particle	Mass (GeV/c²)	Quark composition	Q (units of e)	S	C	$\tilde{B}$
π^+	0.140	$u\bar{d}$	1	0	0	0
K^-	0.494	$s\bar{u}$	-1	-1	0	0
D^-	1.869	$d\bar{c}$	-1	0	-1	0
D_S^+	1.969	$c\bar{s}$	1	1	1	0
B^-	5.279	$b\bar{u}$	-1	0	0	-1
Υ	9.460	$b\bar{b}$	0	0	0	0

- Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass (lifetime about 10^{-23} s).
- Hadrons with the lowest possible mass for each quark number (S, C, etc.) may live significantly longer before decaying weakly (lifetimes 10^{-7} – 10^{-13} s). Such hadrons are called ***stable particles***.

Isospin

Werner Heisenberg

Isospin was invented by Heisenberg to explain the apparent fact that the strong interaction does not distinguish between neutron and proton.

$$(m_n - m_p)/m_n \approx 10^{-3}$$

Heisenberg's thought was that if you could turn off electromagnetism, then $m_n = m_p$.

We now believe that the isospin symmetry is due the near equality of the **up** and **down quarks** ($m_u \approx m_d$).

We postulate that Isospin is conserved in the strong interaction, but not in the electromagnetic (or weak) interaction.

u-quark: $I = 1/2\,, I_3 = +1/2$

d-quark: $I = 1/2\,, I_3 = -1/2$

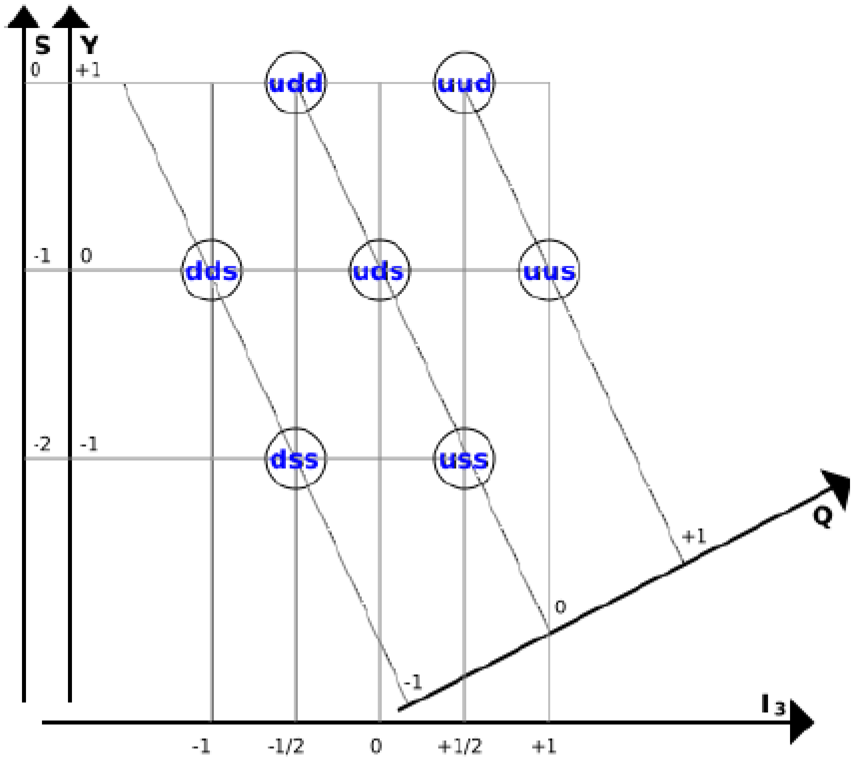
all other quarks have $I = 0$

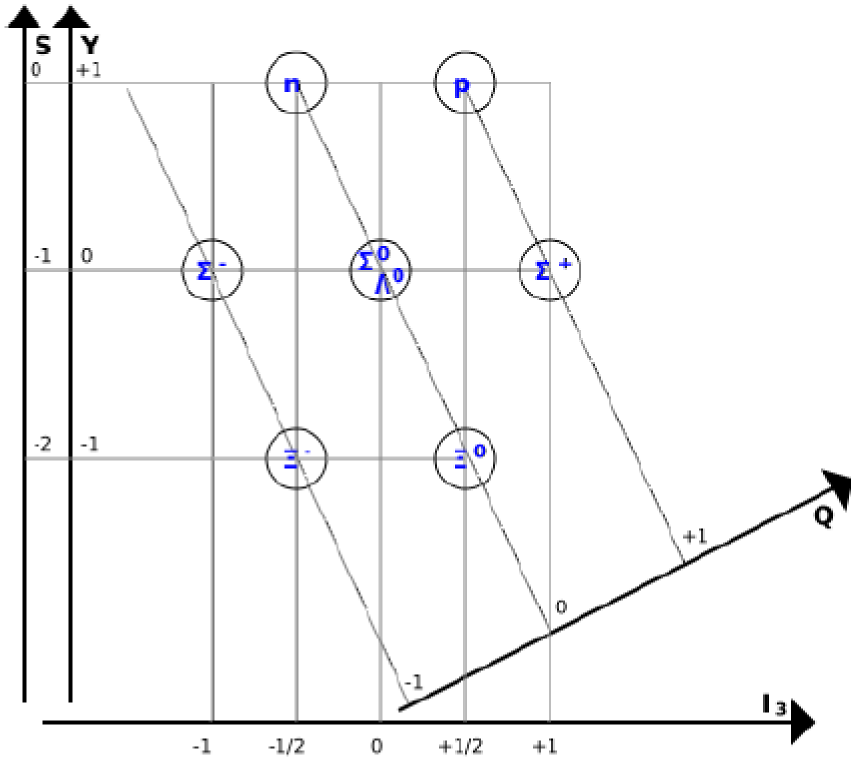
$$I_3 = \frac{1}{2}(n_u - n_d)$$

$\bar{u} - quark\!: I = 1/2\,, I_3 = -1/2$

$\bar{d} - quark\!: I = 1/2\,, I_3 = +1/2$

I = ½ Baryon Octet





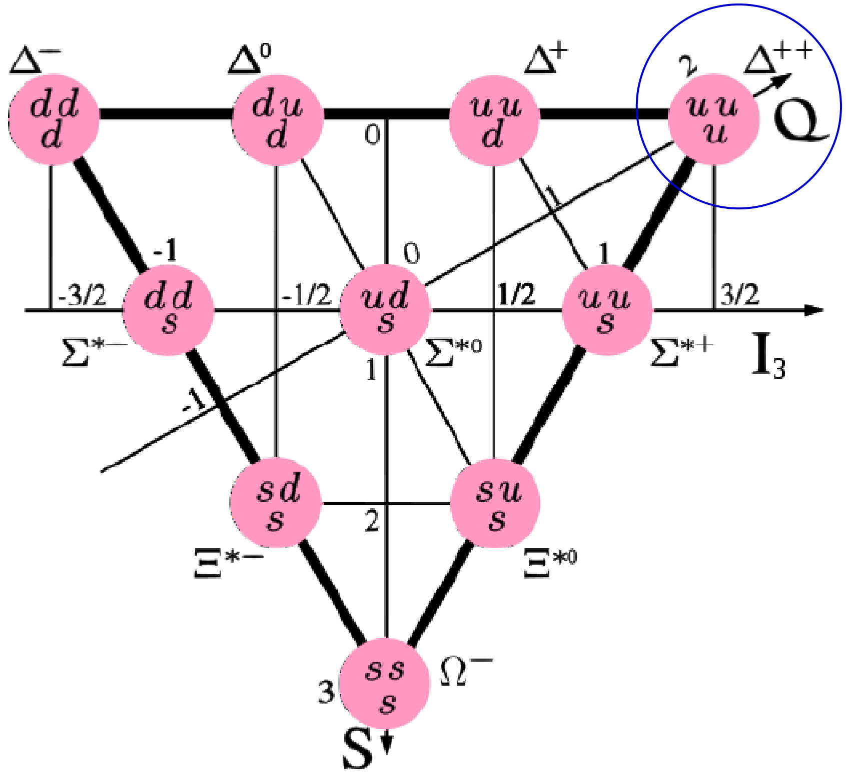
Strangeness (S): $S = -(n_s - n_{\bar{s}})$

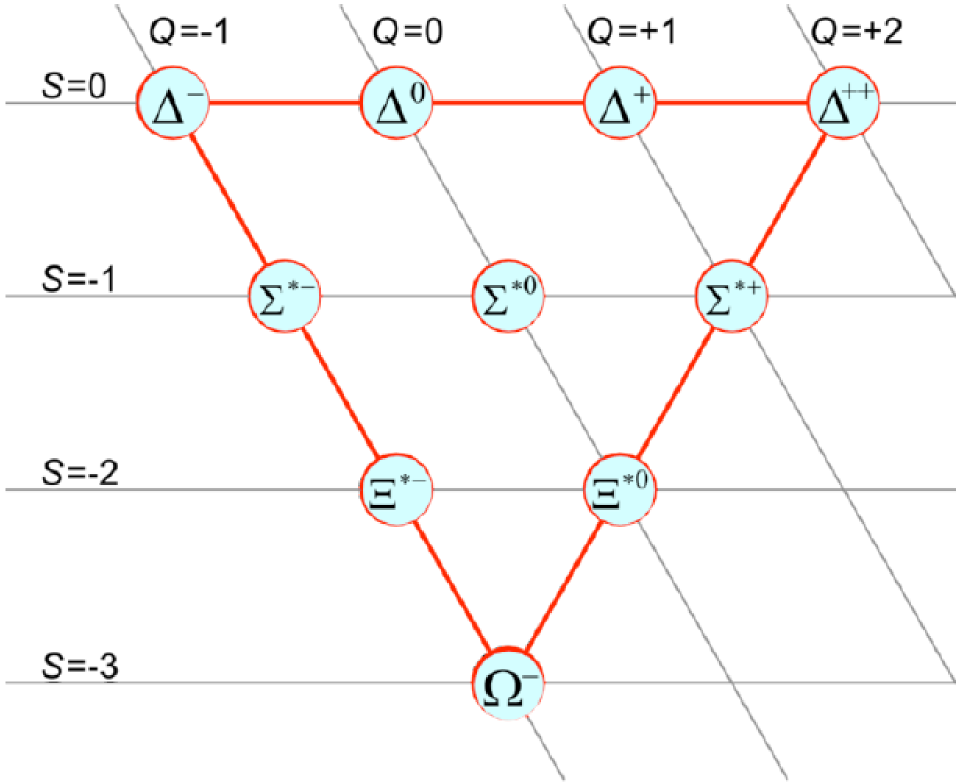
Hypercharge (Y): $Y = 2 \cdot (Q - I_3)$

Electric charge (Q):

Isospin (I_3): $I_3 = \frac{1}{2} \cdot (n_u - n_d)$

I = 3/2 Baryon Decouplet





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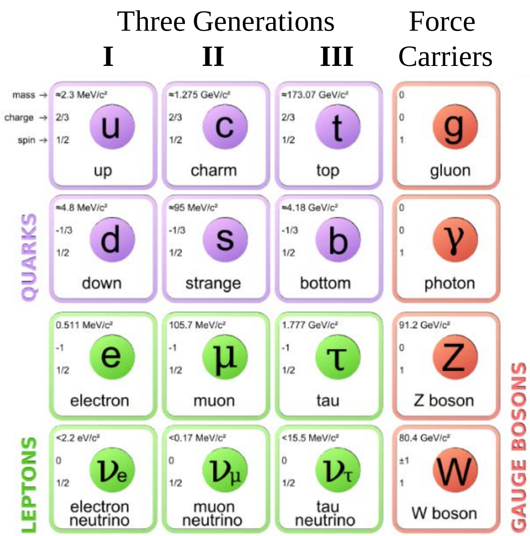
Why colored Quarks?

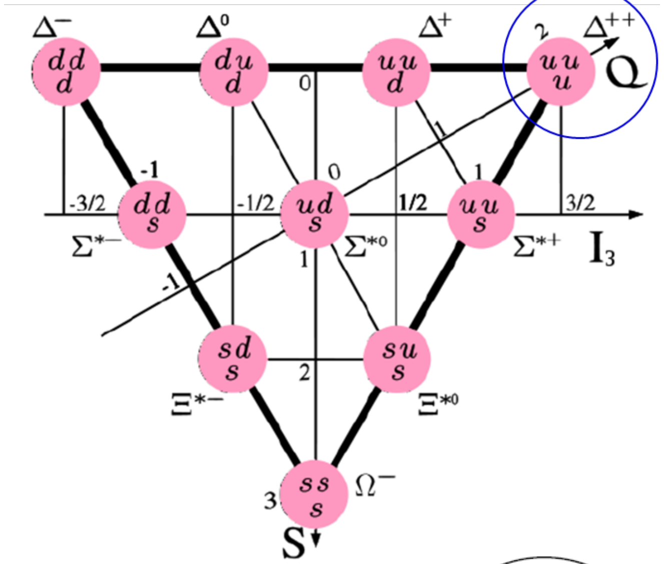


Strong Interactions

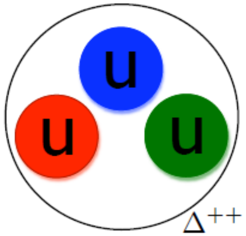
Electromagnetism

Weak Interactions

Δ^{++} is a isospin **3/2** particle with 3 "identical" up quarks!



Pauli principle



Eight gluon colors

$$(r\bar{b} + b\bar{r})/\sqrt{2} \qquad -i(r\bar{b} - b\bar{r})/\sqrt{2}$$

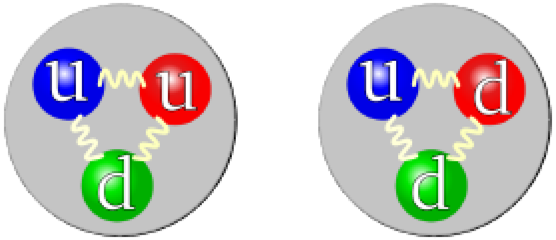
$$(r\bar{g} + g\bar{r})/\sqrt{2} \qquad -i(r\bar{g} - g\bar{r})/\sqrt{2}$$

$$(b\bar{g} + g\bar{b})/\sqrt{2} \qquad -i(b\bar{g} - g\bar{b})/\sqrt{2}$$

$$(r\bar{r} + b\bar{b})/\sqrt{2} \qquad (r\bar{r} + b\bar{b} - 2g\bar{g})/\sqrt{6}$$

Why Quarks need Color?

- Combinations as proton (uud) and neutron (udd)



- $\Delta^{++}=$ ***uuu*** with ***I*= *I*$_3$ = 3/2** would have three identical fermions ***u*** in a completely symmetric ground state
  ⇒ forbidden by the Pauli exclusion principle

⇒ Introduction of a new quantum number for quarks: ***"Color"***

"Color charge" has nothing to do with visible colors, it is just a convenient naming convention for a mathematical system physicists developed to explain their observations about quarks in hadrons.

- What about the other possibilities such as $qq, \bar{q}\bar{q}$ or a single quark q

Quarks

➢ ***Free quarks are not observed***

There is an elegant explanation for this:

➢ Every quark possesses a new quantum number: the ***color***. There are three different colors, thus each quark can have three distinct color states.

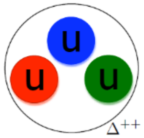
➢ Colored objects can not be observed.

➢ Therefore quarks must confine into hadrons immediately upon appearance.

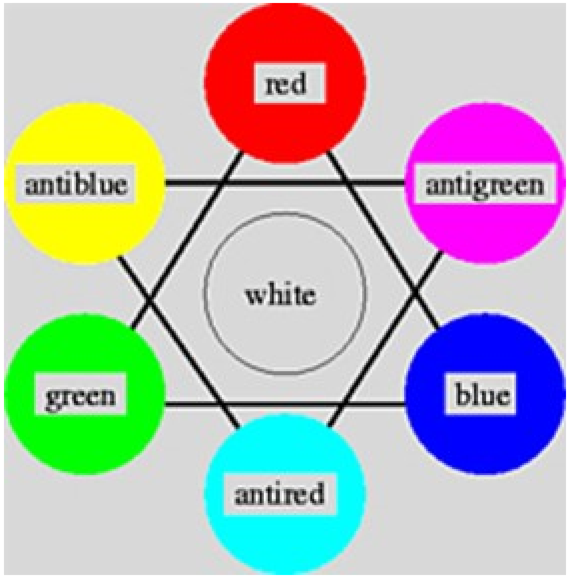
Strange, charmed, bottom and top quarks each have an additional quantum number: ***strangeness*** S, ***charm*** C, ***bottomness*** $\tilde{B}$ and ***topness*** T respectively. All these quantum numbers are conserved in strong interactions, but not in weak ones.

Color of the Quarks – Quantum Chromodynamics

- Quarks come in three primary colors: **red (R)**, **green (G)**, **blue (B)**
- all particle states (baryons, mesons) observed in nature are postulated to be **colorless/white**
- this solves problem for the Δ^{++}



- explains also the existence of
  - baryons (RGB)
  - antibaryons $(\bar{R}\bar{G}\bar{B})$
  - mesons $(R\bar{R} + G\bar{G} + B\bar{B})$
- and that the others do not exist



- Strange, charmed, bottom and top quarks each have an additional quantum number: ***strangeness*** S, ***charm*** C, ***bottomness*** $\tilde{B}$ and ***topness*** T respectively. All these quantum numbers are conserved in strong interactions, but not in weak ones.

Gluon

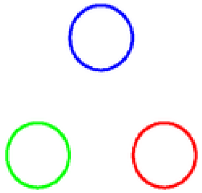
- The force carrier between color-charged quarks is called "***Gluon***"
- The gluon is a vector boson, like the photon, and has a ***spin of 1***.
- Gluons are ***carrying two colors***. The eight gluon colors are:

$$(r\bar{b} + b\bar{r}/\sqrt{2}) \qquad -i(r\bar{b} - b\bar{r})/\sqrt{2}$$

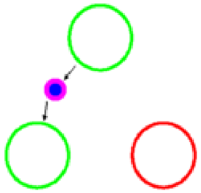
$$(r\bar{g} + g\bar{r}/\sqrt{2}) \qquad -i(r\bar{g} - g\bar{r})/\sqrt{2}$$

$$(b\bar{g} + g\bar{b}/\sqrt{2}) \qquad -i(b\bar{g} - g\bar{b})/\sqrt{2}$$

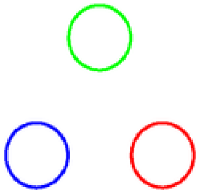
$$(r\bar{r} - b\bar{b}/\sqrt{2}) \qquad (r\bar{r} + b\bar{b} - 2g\bar{g})/\sqrt{6}$$



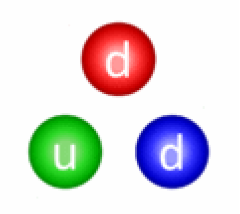
A hadron with 3 quarks (red, green, blue) before a color change



Blue quark emits a blue-antigreen gluon



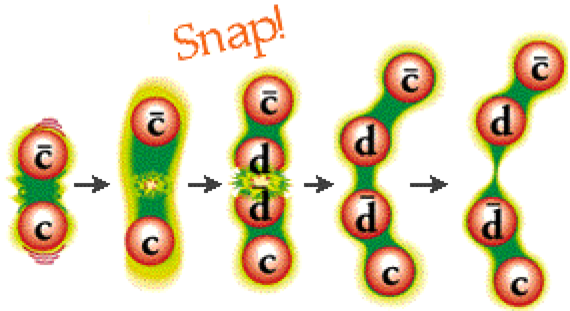
Green quark has absorbed the blue-antigreen gluon and is now blue; color remains conserved



Interaction inside a neutron

Gluons and Quarks

The quarks in a given hadron madly ***exchange gluons***. For this reason, physicists talk about the ***color-force field*** which consists of the gluons holding the bunch of quarks together.



Quarks cannot exist individually because the color force increases as they are pulled apart.

What holds the nucleus together?

Since positive protons repel each other with electromagnetic force, and protons and neutrons are color-neutral.

The strong force between the quarks in one proton and the quarks in another proton is strong enough to overwhelm the repulsive electromagnetic force.