

Murray Gell-Mann  
Quarks and QCD

*A Life of Symmetry*

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# Biographical Background

- Murray Gell-Mann was born in Manhattan on Sept. 15, 1929, to Jewish parents from the Austro-Hungarian empire. His father taught German to Americans.
- Gell-Mann was a child prodigy interested in nature and math. He started Yale at 15 and graduated at 18 with a bachelors in Physics.
- He then went to graduate school at MIT where he received his Ph. D. in physics at 21 in 1951. His thesis advisor was the famous Vicky Weisskopf.
- His life and work is documented in remarkable detail on videos that he recorded on [webofstories](#), which can be found by just Google searching “webofstories Gell-Mann”.

# The Young Murray Gell-Mann



## Gell-Mann's Academic Career (from Wikipedia)

- He was a postdoctoral fellow at the Institute for Advanced Study in 1951, and a visiting research professor at the University of Illinois at Urbana-Champaign from 1952 to 1953. He was a visiting associate professor at Columbia University and an associate professor at the University of Chicago in 1954-55, where he worked with Fermi.
- After Fermi's death, he moved to the California Institute of Technology, where he taught from 1955 until he retired in 1993.
- Web of Stories video of [Gell-Mann on Fermi and Weisskopf.](#)

# The Weak Interactions: Feynman and Gell-Mann

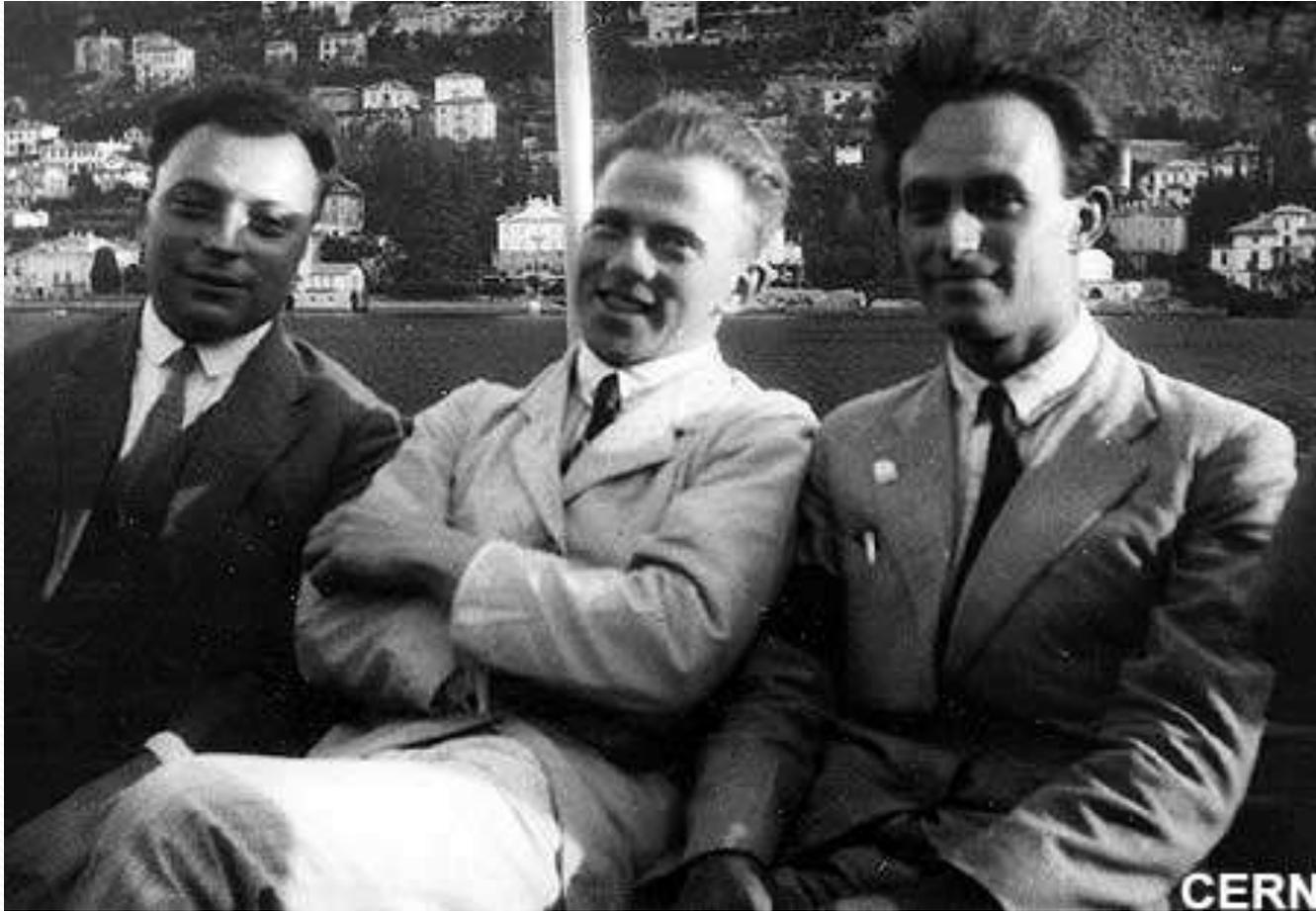
- Feynman and Gell-Mann proposed in 1957 and 1958 the theory of the weak interactions that acted with a current like that of the photon, minus a similar one that included parity violation.
- This theory was also developed by George Sudarshan and Robert Marshak.
- The theory included maximal parity violation in that only left handed neutrinos took part, and only right handed antineutrinos.



# Heisenberg Invents Isospin

- Protons and neutrons are the basic constituents of nuclei that make up the periodic table of all everyday elements. They are called nucleons.
- Thus they were considered as symmetrical under the strong force, and as the same particle, but in an abstract “isospin” space had different isospin projection  $I_z$ .
- The proton had an isospin “up”,  $I_z = +\frac{1}{2}$ , and the neutron had an isospin “down”,  $I_z = -\frac{1}{2}$ , in analogy to spin. The nucleon was an isospin doublet then.
- The pions were an isospin triplet:  $\pi^+$  had  $I_z = +1$ ;  $\pi^0$  had  $I_z = 0$ , and  $\pi^-$  had  $I_z = -1$ .

# Wolfgang Pauli, Werner Heisenberg, and Enrico Fermi



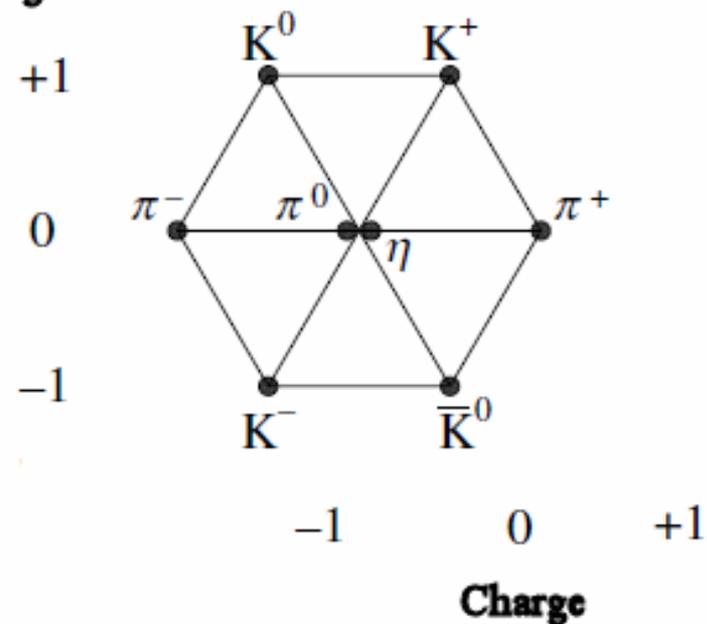
# Gell-Mann Invents Strangeness (1953)

- In collisions of cosmic ray protons with nucleons, particles heavier than nucleons are created, called baryons, and lighter particles called mesons, such as  $\pi$  mesons and K mesons.
- It was observed that K mesons, discovered in 1947, were always created with certain baryons, the  $\Sigma$  or  $\Lambda$ , in what are called the strong interactions.
- Gell-Mann's **strangeness** idea was an explanation for this.
- By postulating a new conserved quantity or quantum number called **strangeness**:  $\Sigma$  and  $\Lambda$  would have the strangeness  $S = -1$ , and  $K^+$  would have strangeness  $S = +1$ , while  $K^-$  would have strangeness  $S = -1$ .

# The Mesons – Spin 0 Octet

- By 1961, accelerators were creating many mesons of spin 0 and spin 1. Gell-Mann realized that he could form an analog to the periodic table using the x direction for isospin, and the y direction for the strangeness of the mesons.
- The pion triplet had isospin 1, and the Kaon doublet had isospin  $\frac{1}{2}$ .

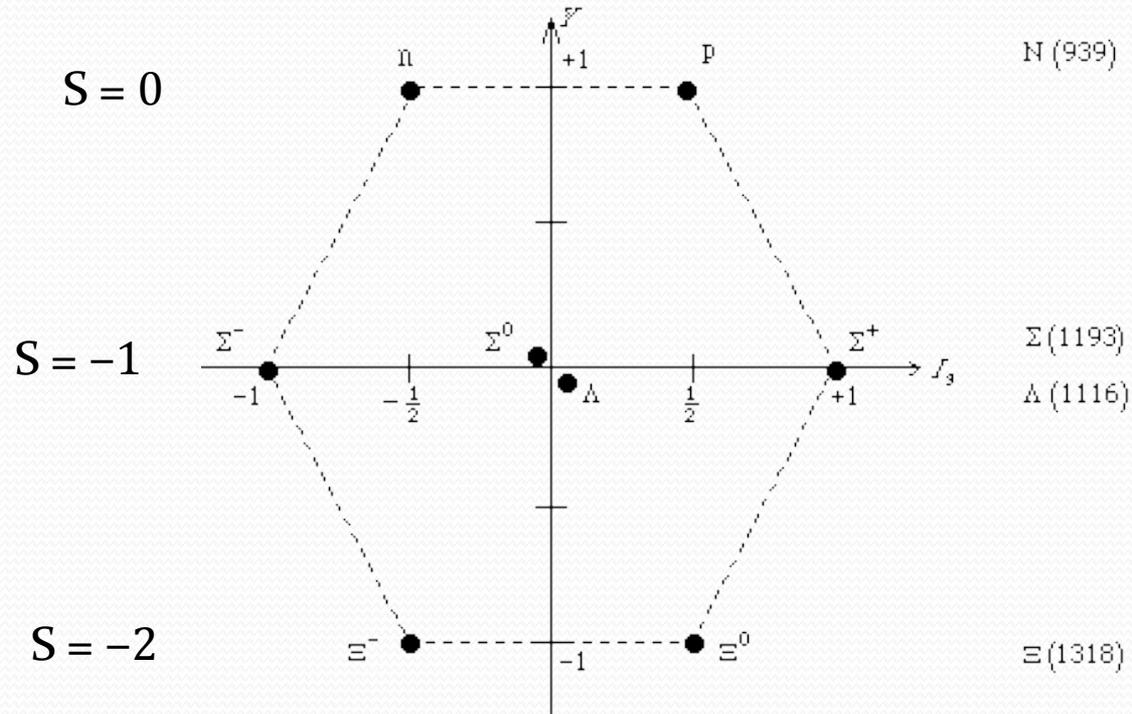
Strangeness



$I_z$  -1 0 +1

# The Baryon Octet

Also, baryons were being discovered of spin  $\frac{1}{2}$  like the proton and neutron. They also fell into an octet.

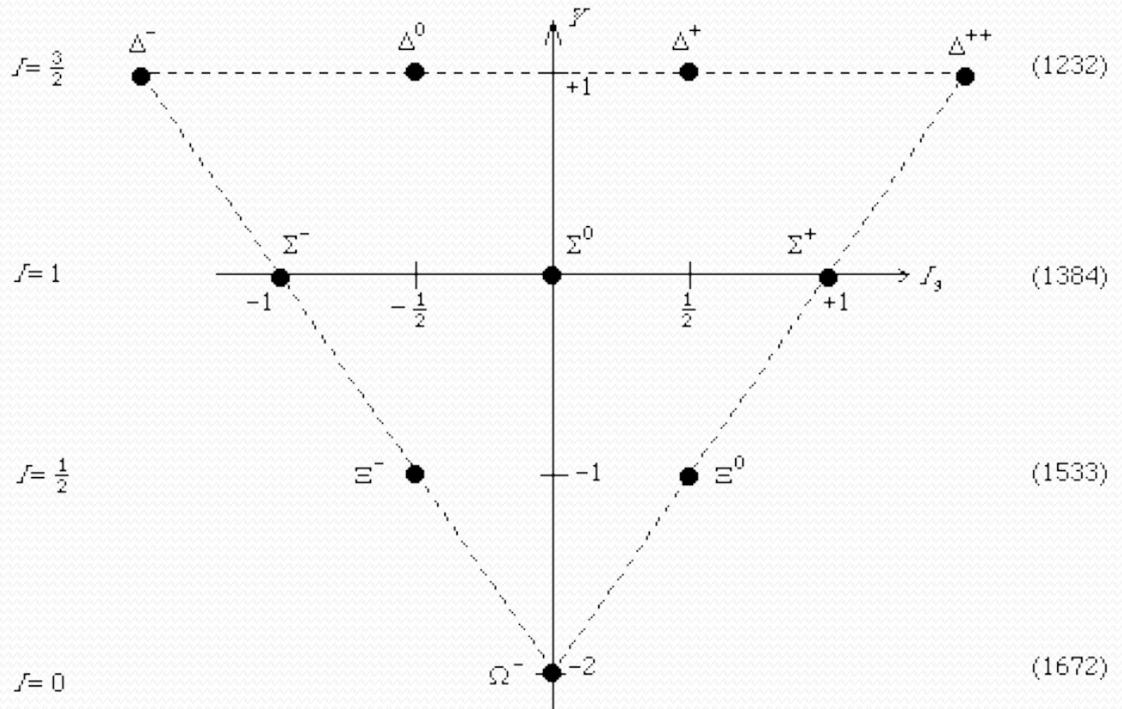


# The Baryon Decimet

Also, spin  $3/2$  baryons could be classified as a decimet. The strangeness  $-3$   $\Omega^-$  (omega minus) was predicted by this picture, and its discovery confirmed the theory.

Here,  $Y = S + B$ .

$B = 1$  for a baryon, and  
 $B = 0$  for a meson.

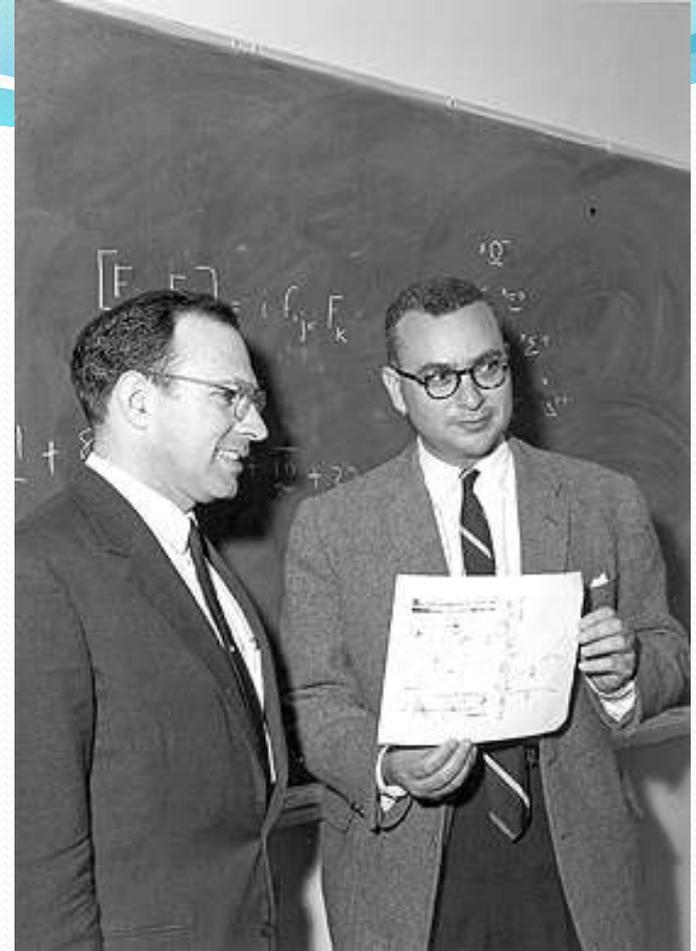


# The Eightfold Way

Gell-Mann and independently Yuval Ne'eman of Haifa, Israel, realized that these multiplets were the patterns or representations of a mathematical group of three identical objects under the strong force, starting with an isospin doublet, and a strange singlet. These objects were considered to be just a mathematical basis set for the group.

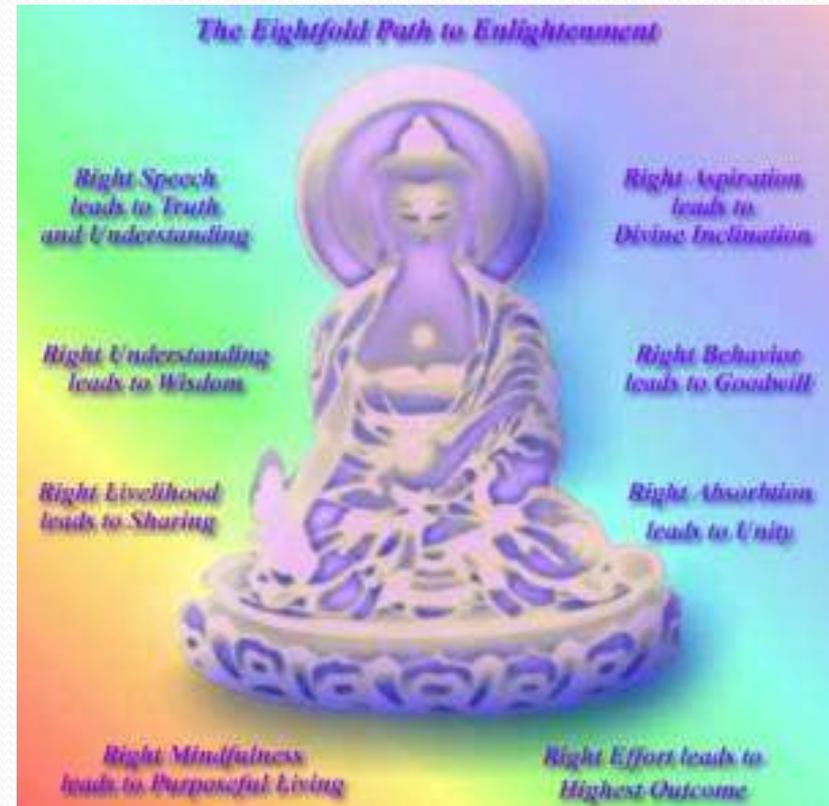
Gell-Mann wrote his findings up in a rather abstract paper, and it was rejected for publication. He then published it as a book, which still was pretty abstract.

He called it the “Eightfold Way” in a reference to the Buddhist eightfold path to enlightenment.



# Enlightenment

- “Right Understanding leads to Wisdom”
- Then in 1964, Gell-Mann, and independently George Zweig in Switzerland, realized that three objects that encompassed separately the up isospin, the down isospin, and the strangeness could form all the baryons by combining three of them, and the meson octets by combining the object and its anti-object.



## Gell-Mann Names Quarks

Gell-Mann called these “quarks” after the phrase in the esoteric work *Finnegan’s Wake* by James Joyce: “Three Quarks for Muster Mark”. Later he said he “knew” the sound the name should have, like *kwork*, and he found it there.

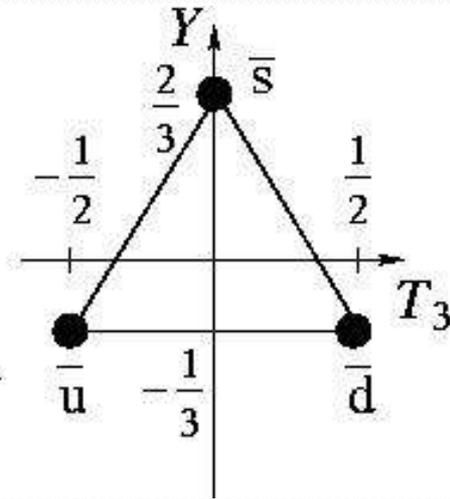
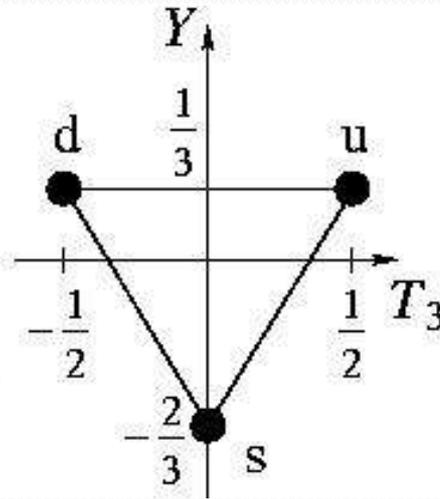


# Quark Triplets

$u$  and  $d$  form the isospin doublet, with  $u$  being isospin up, and  $d$  being isospin down.

$s$  is the lone strange quark singlet.

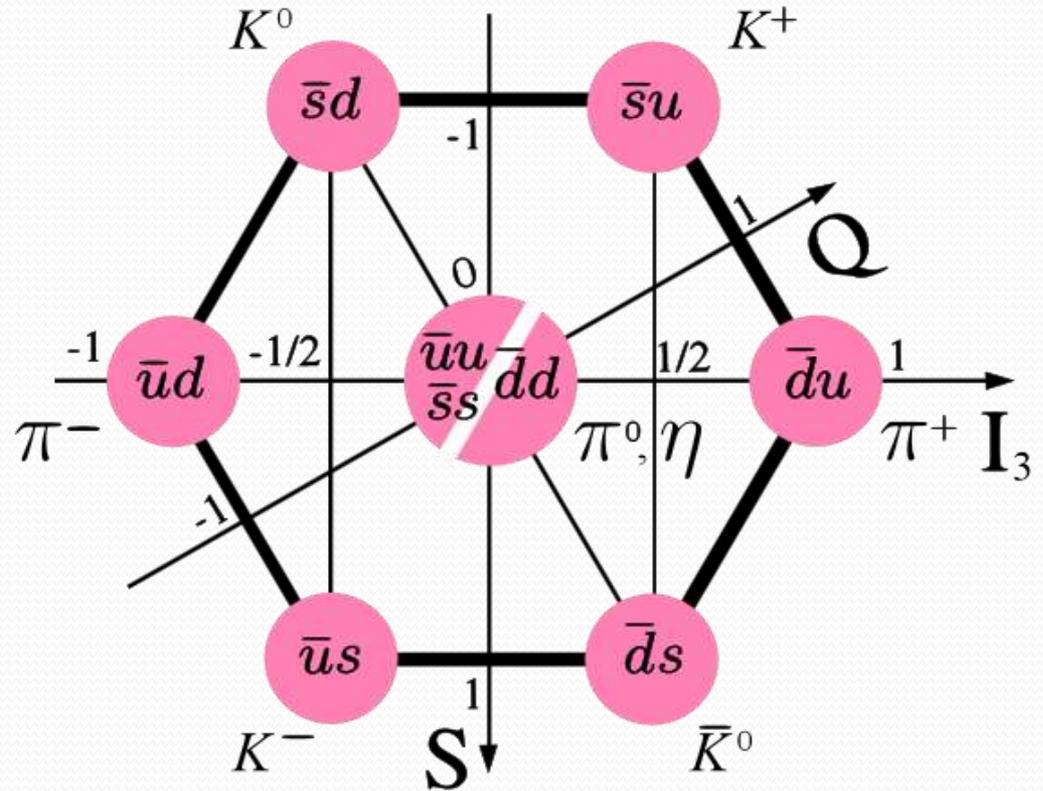
Antiquarks have opposite isospin and strangeness.



$T_3$  and  $I_3$  are the same as  $I_z$

# Quarks with Anti-Quarks form Mesons

So all of the abstractness just reduced to a child's tinker toy set of putting together u, d, and s quarks with their anti quarks.

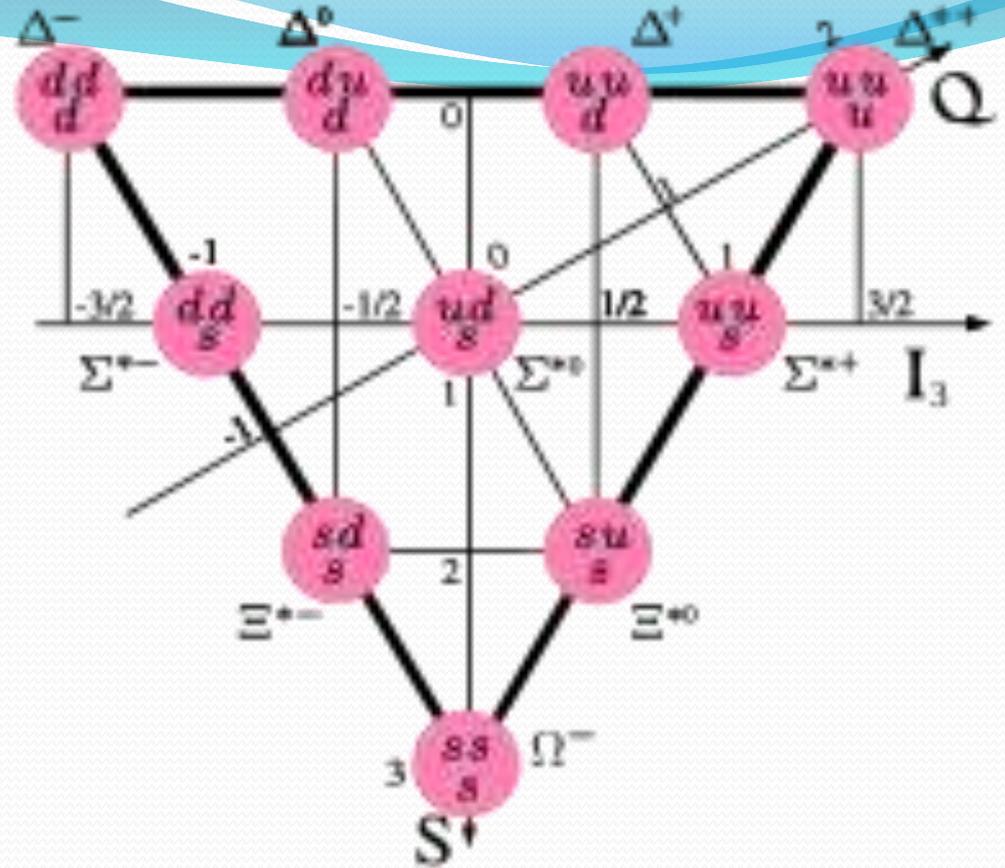


# Spin 3/2 Baryon Decimet

Putting together three quarks aligned to spin 3/2 in all combinations gives the baryon decimet.

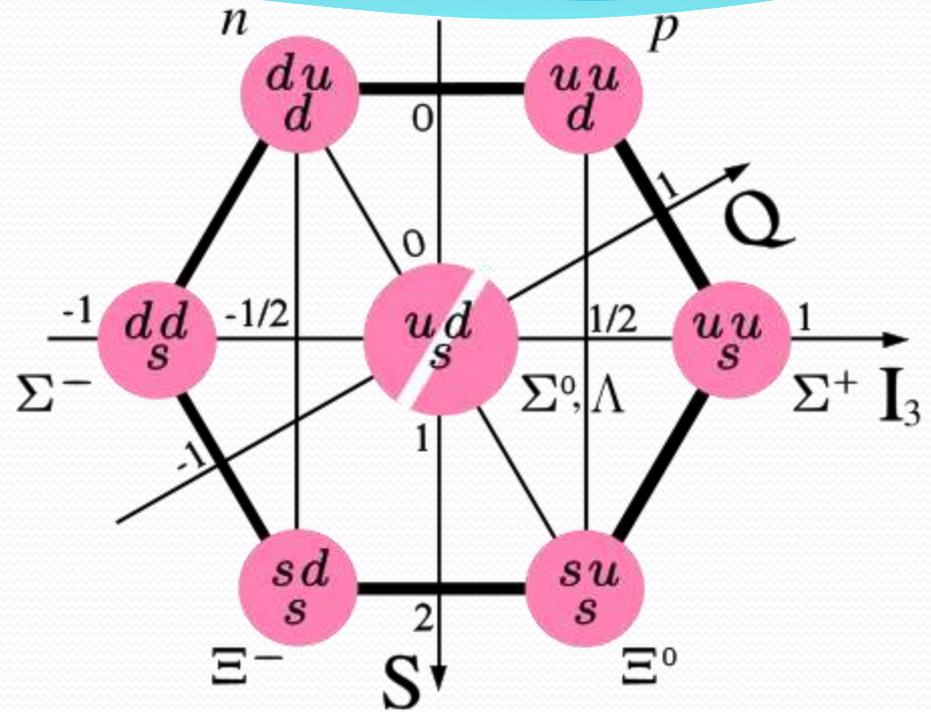
Yet there is another problem here. The three identical up quarks in the  $\Delta^{++}$  are in the same zero angular momentum space state, and the same spin up state, which is not allowed for identical Fermions.

There must be something else!



# Spin 1/2 Octet

The baryon octet has the three quarks of spin 1/2 coupled in a more complicated way to just form a total spin 1/2.



# Murray Gell-Mann Is Awarded the 1969 Nobel Prize in Physics

Murray Gell-Mann was awarded the 1969 Nobel Prize in Physics *"for his contributions and discoveries concerning the classification of elementary particles and their interactions"*.

He used part of his prize money to buy his blue Victorian house in Aspen.



## George Zweig

George Zweig is also given credit for quarks in the physics community, but his paper wasn't published, and he didn't win a prize.

Disgusted, he turned to biology, where is making significant contributions.

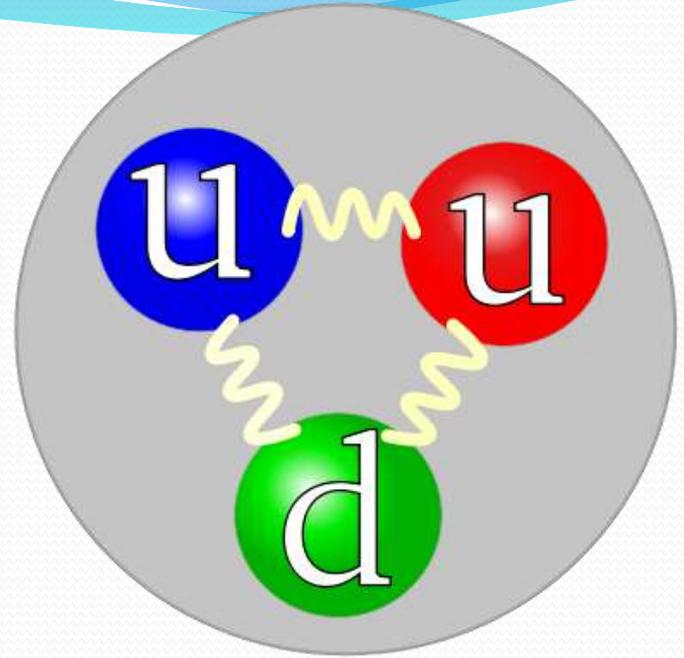
Web of Stories [Gell-Mann on Zweig.](#)



## Color “Charge”

The way out of the Pauli Exclusion problem for the  $\Delta^{++}$  was to add yet another quantum number or “color charges”: red, green or blue to each quark. Making the colors different for the three quarks in a baryon, meant that the three quarks were no longer identical. This is the proton with the three different color quarks, making the proton “colorless” as a whole by antisymmetrizing them.

This was introduced in 1972 by Gell-Mann and Harald Fritzsch.



# Harald Fritzsch and Murray Gell-Mann



# Three Colors of Quarks



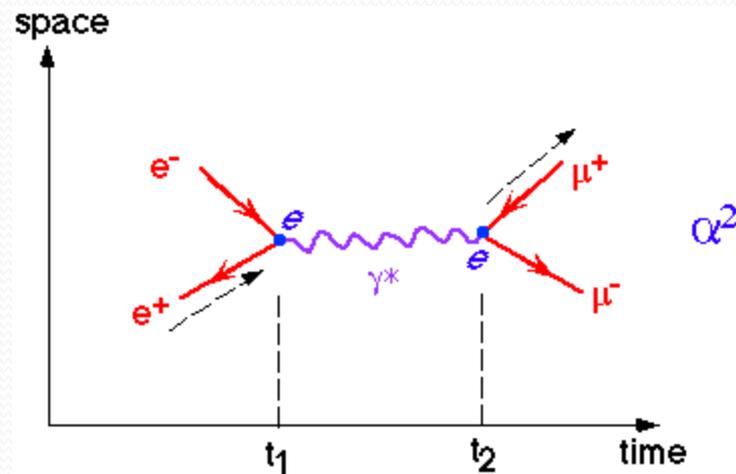
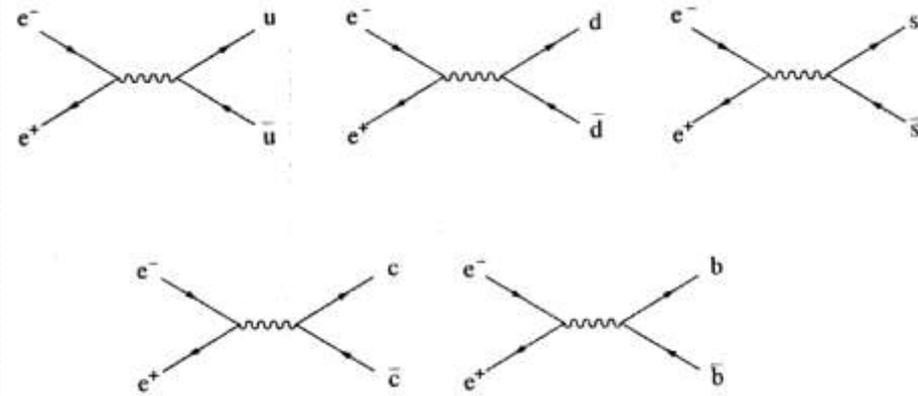
# Colors Count!

In  $e^+ e^-$  annihilation, quarks will be produced proportional to their charges squared. At high enough energies to produce five flavors of quarks, the ratio to  $\mu$  production of charge  $e$  is

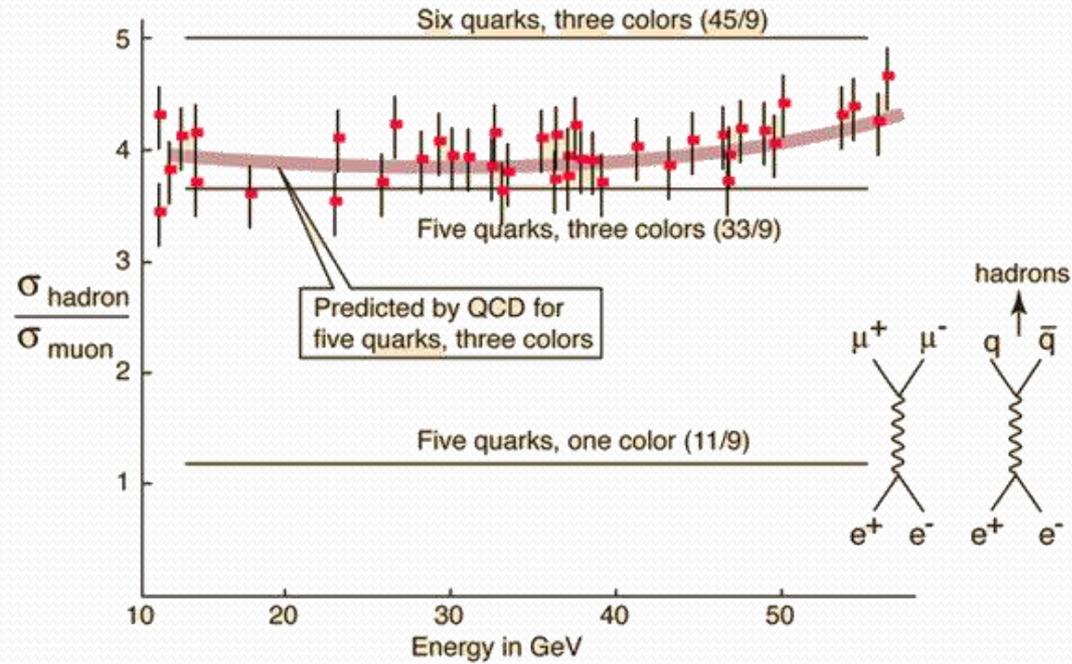
$$R' = (2/3)^2 + (-1/3)^2 + (-1/3)^2 + (2/3)^2 + (-1/3)^2 = 11/9.$$

Experiment shows a number which is larger. By producing three colors of each quark,

$R = 3 R' = 3 (11/9) = 11/3 = 3.67$ , close to experiment.



# Experimental Verification of Three Quark Colors



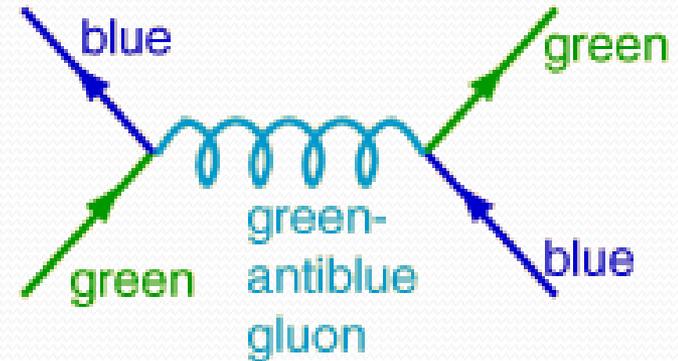
# Quantum Chromodynamics --QCD

If the colored quarks are to be interchanged anywhere as a symmetry, there can be force particles that change one color to another. These are the **gluons** that each carry a color and an anti-color.

At first count you can have three colors combined with three anti-colors giving nine gluons. But the symmetric combination of (Red anti-red + blue anti-blue + green anti-green) is colorless, eliminating one combination, leaving only eight “colored” gluons.

Like the photon, the gluons are massless.

This theory was developed by Gell-Mann and Harald Fritzsch.



Feynman diagram for an interaction between quarks generated by a gluon.

# QCD and Interacting Gluons

Since the gluons are color with anti-color pairs, they also have net color charges, and can interact with other gluons.

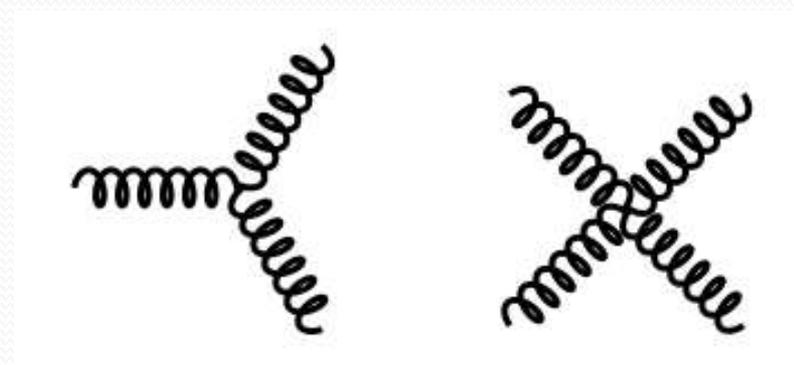
This is unlike the photon, which has no charge.

These self couplings make the theory “non-linear” and very hard to calculate.

Also, at low energies where the mesons and baryons are formed, the color coupling is strong.

Thus QCD is the theory of the real strong interactions, but at low energies it has to be calculated on a lattice with powerful computers because of its complexity.

Web of Stories video on [Feynman and QCD](#).



Update to six quarks, six leptons, and three weak force particles:  $W^+$ ,  $W^-$ , and  $Z^0$

- We now know that the original quarks of the eightfold way multiplets were just the lowest energy quark states because the u, d, and s quarks are the lightest.
- There are also mesons and baryons from the charm and bottom quarks.
- The top quark is so heavy that it decays too rapidly to form bound states.

## Elementary Particles

Quarks	$u$ up	$c$ charm	$t$ top	Force Carriers
	$d$ down	$s$ strange	$b$ bottom	
	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino	
Leptons	$e$ electron	$\mu$ muon	$\tau$ tau	$Z$ Z boson
				$W$ W boson
	I	II	III	

**Three Families of Matter**

# Personal Life

Murray was married to Margaret from 1955 until her death in 1981. He has two children from that marriage.

He married Marcia Southwick in 1992.



Margaret and Murray Gell-Mann



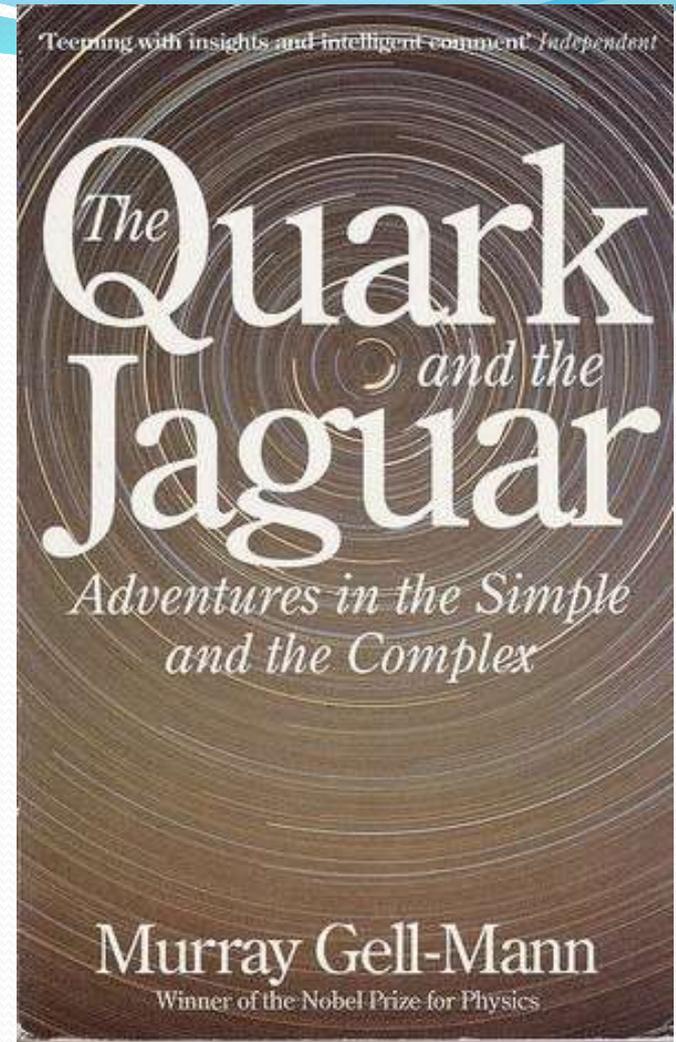
# The Quark and the Jaguar

In 1994 he wrote *The Quark and the Jaguar* on simplicity and complexity.

[Web of Stories video](#) on *The Quark and the Jaguar*.

He co-founded the [Santa Fe Institute](#) in 1984 to study complex systems.

Gell-Mann now lives in Santa Fe.



## Gell-Mann the Leader

Murray was a board member of the [Aspen Center for Physics](#), and spent the summers there in Aspen.

He was a director of the [MacArthur Foundation](#) from 1979 to 2002.

He was a board member of the [Wildlife Conservation Society](#) from 1994 to 2006.

He was on the President's Science Advisory Committee from 1969 to 1972, and the President's Committee of Advisors from 1994 to 2001.

Web of Stories video on the [World Resources Institute](#).

# Aspen Center for Physics outdoor lecture room

## Aspen Music Tent next door

