The Quark Model (1964)

Why do the hadrons fit into these bizarre patterns?

In 1964, Gell-Mann and Zweig independently proposed

...that all hadrons are composed of even more elementary constituents,

...which Gell-Mann called quarks.

The quarks came in three types (or flavors), forming a triangular pattern.
The Quark Model (1964)

\( u \) (‘up’) quark carries a charge of \( \frac{2}{3} \) and \( S = 0 \).

\( d \) (‘down’) quark carries a charge of \( -\frac{1}{3} \) and \( S = 0 \).

\( s \) (‘strange’) quark carries a charge of \( -\frac{1}{3} \) and \( S = -1 \).

To each quark \( q \) there corresponds an antiquark \( \bar{q} \) with opposite charge and strangeness.
The Quark Model (1964)

The quarks

\[ Q = \frac{2}{3} \]

\[ Q = \frac{-1}{3} \]
The Quark Model (1964)

The antiquarks

\[ Q = -\frac{2}{3} \quad Q = \frac{1}{3} \]
The Quark Model (1964)

There are two composition rules

1. Every baryon is composed of three quarks. (Every anti-baryon is composed of three anti-quarks.)

2. Every meson is composed of a quark and an anti-quark.
The Quark Model (1964)

With this, it’s a matter of elementary arithmetic to construct the baryon decuplet and the meson octet.

All we need to do is to list the combinations of three quarks (or quark-antiquark pairs)

...and add up their charge and strangeness.
## The Quark Model (1964)

The baryon decuplet

<table>
<thead>
<tr>
<th>$qqq$</th>
<th>$Q$</th>
<th>$S$</th>
<th>Baryon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$uuu$</td>
<td>2</td>
<td>0</td>
<td>$\Delta^{++}$</td>
</tr>
<tr>
<td>$uud$</td>
<td>1</td>
<td>0</td>
<td>$\Delta^+$</td>
</tr>
<tr>
<td>$udd$</td>
<td>0</td>
<td>0</td>
<td>$\Delta^0$</td>
</tr>
<tr>
<td>$ddd$</td>
<td>-1</td>
<td>0</td>
<td>$\Delta^-$</td>
</tr>
<tr>
<td>$uus$</td>
<td>1</td>
<td>-1</td>
<td>$\Sigma^{*+}$</td>
</tr>
<tr>
<td>$uds$</td>
<td>0</td>
<td>-1</td>
<td>$\Sigma^{*0}$</td>
</tr>
<tr>
<td>$dds$</td>
<td>-1</td>
<td>-1</td>
<td>$\Sigma^{*-}$</td>
</tr>
<tr>
<td>$uss$</td>
<td>0</td>
<td>-2</td>
<td>$\Xi^{*0}$</td>
</tr>
<tr>
<td>$dss$</td>
<td>-1</td>
<td>-2</td>
<td>$\Xi^{*-}$</td>
</tr>
<tr>
<td>$sss$</td>
<td>-1</td>
<td>-3</td>
<td>$\Omega^-$</td>
</tr>
</tbody>
</table>
# The Quark Model (1964)

## The meson nonet

<table>
<thead>
<tr>
<th>$q\bar{q}$</th>
<th>$Q$</th>
<th>$S$</th>
<th>Meson</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u\bar{u}$</td>
<td>0</td>
<td>0</td>
<td>$\pi^0$</td>
</tr>
<tr>
<td>$u\bar{d}$</td>
<td>1</td>
<td>0</td>
<td>$\pi^+$</td>
</tr>
<tr>
<td>$d\bar{u}$</td>
<td>-1</td>
<td>0</td>
<td>$\pi^-$</td>
</tr>
<tr>
<td>$d\bar{d}$</td>
<td>0</td>
<td>0</td>
<td>$\eta$</td>
</tr>
<tr>
<td>$u\bar{s}$</td>
<td>1</td>
<td>1</td>
<td>$K^+$</td>
</tr>
<tr>
<td>$d\bar{s}$</td>
<td>0</td>
<td>1</td>
<td>$K^0$</td>
</tr>
<tr>
<td>$s\bar{u}$</td>
<td>-1</td>
<td>-1</td>
<td>$K^-$</td>
</tr>
<tr>
<td>$s\bar{d}$</td>
<td>0</td>
<td>-1</td>
<td>$\bar{K}^0$</td>
</tr>
<tr>
<td>$s\bar{s}$</td>
<td>0</td>
<td>0</td>
<td>$??$</td>
</tr>
</tbody>
</table>
The Quark Model (1964)

There are nine combinations here.

And only eight particles in the meson octet.

The quark model requires that there be a third meson (in addition to the $\pi^0$ and $\eta$) with $Q = 0$ and $S = 0$.

Such a particle had already been found experimentally: the $\eta'$. 
The Quark Model (1964)

In the Eightfold Way, the $\eta'$ had been classified as a singlet, all by itself.

We can, in principle, construct an infinite number of hadrons out of only three quarks.

The quark model, does however suffer from one profound embarrassment.

In spite of the most diligent search, no one has ever seen an individual quark.
The Quark Model (1964)

Experiments failed to produce isolated quarks

Resulted in widespread skepticism about the quark model in the 1960s and early 1970s.
The Quark Model (1964)

One solution to this puzzle was to introduce the notion of quark confinement.

Perhaps, quarks are absolutely confined within baryons and mesons.

No matter how hard you try, you cannot get them out.
The Quark Model (1964)

What is the mechanism behind quark confinement?

How can we prove the existence of quarks?

One can explore the interior of a proton in much the same way as Rutherford probed the inside of an atom.

We can throw things at a proton and try to break it apart.
Such experiments are called *deep inelastic scattering experiments*.

They were strikingly reminiscent of Rutherford’s.

Most of the incident particles pass right through, whereas a small number bounce back sharply.

This means that the charge of the proton is concentrated in small lumps.
The Quark Model (1964)

In the case of a proton the evidence suggested three lumps, instead of one.

This is strong support for the quark model, but still not conclusive.

There was a theoretical objection to the quark model.

It appears to violate Pauli exclusion principle.
The Quark Model (1964)

In Pauli’s original formulation the exclusion principle states that no two electrons can occupy the same state.

However, it was later realized that the same rule applies to all particles of half-integer spin.

(The proof of this is one of the most important achievements of quantum field theory.)

The exclusion principle should apply to quarks as well. They carry spin $\frac{1}{2}$. 
The Quark Model (1964)

The particle $\Delta^{++}$ is supposed to consist of three identical $u$ quarks in the same state.

It appears to be inconsistent with the Pauli principle.

In 1964, O. W. Greenberg proposed a way out of this dilemma.
He suggested that the quarks not only come in three flavors \((u, d \text{ and } s)\) but each of these also comes in three colors (‘red’, ‘green’ and ‘blue’).

To make a baryon we simply take one quark of each color; then the three \(u\)’s in \(\Delta^{++}\) are no longer identical.

Since the exclusion principle applies to \textit{identical} particles, the problem disappears.
The Quark Model (1964)

The introduction of color was extraordinarily fruitful.

Note that the term color has absolutely no connection with the ordinary meaning of the word.

A red quark carries one unit of redness, zero blueness and zero greenness.

Its antiparticle carries minus one unit of redness, zero blueness and zero greenness, and so on.
The color terminology has one nice feature.

All naturally occurring particles are colorless

By colorless we mean that the total amount of each color is zero or all three colors are present in equal amounts.

The only colorless combinations we can make are $q\bar{q}$ (the mesons), $qqq$ (the baryons) and $\bar{q}\bar{q}\bar{q}$ (the antibaryons).

The decade from 1964 to 1974 was a barren time for elementary particle physics.

The quark model

...through it explained the Eightfold Way and correctly predicted the lumpy structure of the proton,

...it had two defects: the experimental absence of free quarks and inconsistency with the Pauli principle.
By 1974, the lumps inside the protons were called *partons*, and it was unfashionable to identify them explicitly with quarks.

What rescued the quark model was not the discovery of free quarks. Or an explanation of the quark confinement, or confirmation of the color hypothesis.

But something entirely different.

An almost completely unexpected.

It was the discovery of the psi meson.
This particle is now known as the $J/\psi$ meson.

The $J/\psi$ was an electrically neutral, extremely heavy meson - more than three times the weight of the proton.

What made this particle unusual was its extraordinarily long lifetime.
The typical lifetime of hadrons in this mass range is about $10^{-23}$ seconds.

The lifetime of $J/\psi$ is $10^{-20}$ seconds.

Its long lifetime spoke about fundamentally new physics.

The events that accumulated after the discovery of the $J/\psi$ came to be known as the *November revolution*. 

Among the many explanations one stood out:

the $J/\psi$ is a bound state of a new (fourth) quark, the $c$ (for charm), and its antiquark

$$J/\psi = (c\bar{c}). \quad (1)$$

Soon after this many particles were discovered with a charm quark in them.
1975: Charmed baryons: \( \Lambda_c^+ = udc, \Sigma_c^{++} = uuc, \Xi_c = usc, \Omega_c = ssc. \)

1976: Charmed mesons: \( D^0 = c\bar{u}, D^+ = c\bar{d}. \)

1977: Charmed strange meson: \( D_s^+ = c\bar{s}. \)
With these discoveries, the interpretation of the $J/\psi$ and $c\bar{c}$ was established beyond reasonable doubt.

The quark model gained back its reputation.

The story does not end here.

In 1975 a new lepton was discovered.

It was the $\tau$ lepton. It has its own neutrino: $\nu_\tau$. 

In 1977 a new heavy meson (the upsilon) was discovered.

It contained a fifth type of quark, \( b \) (for *beauty* or *bottom*).

Upsilon: \( \Upsilon = b\bar{b} \).

In the 1980s the first bottom baryon was observed: \( \Lambda_b^0 = udb \).
The second bottom baryon was observed in 2006: \( \Sigma_b^+ = uub \).

In 2007 the first baryon with a quark from all three generations was discovered: \( \Xi_b^- = dsb \).

In 1983 the first bottom mesons were found: \( \bar{B}^0 = b\bar{d} \) and \( B^- = b\bar{u} \).

At this point, a prediction came. The sixth quark would be discovered.
The $t$ quark ($t$ for truth or top.)

The top quark was very hard to detect since it is extremely heavy: 174 GeV.

In 1995, it was discovered in Tevatron (at Fermilab).

The basic reaction is $u + \bar{u} \rightarrow t + \bar{t}$ or $d + \bar{d} \rightarrow t + \bar{t}$

Until LHC began operation, Fermilab was the only accelerator in the world capable of producing top quarks.
In 1933 Fermi proposed a theory of beta decay.

In that theory he treated the process as a contact interaction.

At high energies one would eventually need a mediating particle.

This mediator is known as *intermediate vector boson*. 
Intermediate Vector Bosons (1983)

The challenge for theorists was to predict the properties of this intermediate vector boson.

For experimentalists, the challenge was to produce them at laboratories.

The *electroweak theory* of Glashow, Weinberg, and Salam predicted the masses of the vector bosons.

In this theory there are three intermediate vector bosons: two of them are charged ($W^{\pm}$) and one neutral ($Z$).
Their masses were calculated to be

\[ \begin{align*}
M_W &= 82 \pm 2 \text{ GeV}, \\
M_Z &= 92 \pm 2 \text{ GeV}.
\end{align*} \]

\[ \begin{aligned}
\{ &\text{Predicted} \quad (2) \\
&\text{In 1983 the } W \text{ and } Z \text{ particles were discovered at CERN.}
\end{aligned} \]
Intermediate Vector Bosons (1983)

Their measured masses are

\[
\begin{align*}
M_W & = 80.403 \pm 0.029 \text{ GeV}, \\
M_Z & = 91.188 \pm 0.002 \text{ GeV}.
\end{align*}
\]

\[\{ \text{Measured} \] \quad (3)\]

Unlike the strange particles or the \( J/\psi \), the intermediate vector bosons were long awaited and universally expected.

And so there was no shock or surprise.
References

End