The Quark Puzzle

A 3D printable model and/or paper printable puzzle that allows students to learn the laws of colour charge through inquiry.

It is available at this link: https://zenodo.org/record/1252868#.W3FnT-gzaUk

LEARNING OBJECTIVES

As a result of this activity, students will know and be able to:

- Identify the fundamental particles in the Standard Model chart.
- Describe properties of quarks, including flavour, colour charge and electric charge.
- Describe the role of quarks in forming baryons and mesons.
- State the rules for combining quarks to make mesons and baryons.
- Describe the symmetry between particles and anti-particles
- Use the claims-evidence-reasoning to evaluate scientific claims.

PRIOR KNOWLEDGE

Students should be introduced to the notation for particles, anti-particles, colour charge and anti-colour charge. Students also need to know how to add positive and negative fractions.

BACKGROUND MATERIAL

Students attempt to discover the possible combinations of the puzzles pieces. These pieces are designed to follow the laws of colour charge for baryons and mesons. Specifically, these bound states must be colour charge neutral: red-green-blue (or anti-red, anti-green and anti-blue) for baryons and either red with anti-red, green with anti-green, or blue with anti-blue for Mesons.

The quark puzzle pieces follow these rules, forming closed, solid figures for allowed bound states, while refusing to fit together for forbidden combinations. Given a set of quark pieces and some time, students should be able to find certain restrictions on what is allowed.

Some rules that students could “discover”:

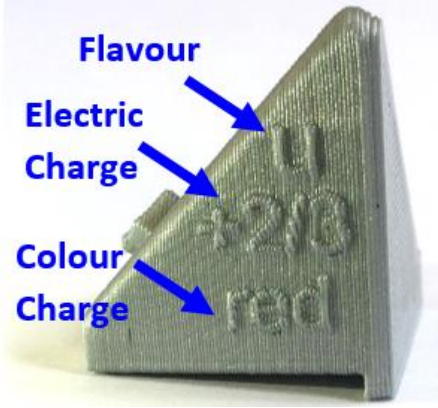
- Antiquarks always possess an anti-colour charge.
- All baryons consist of three quarks or three antiquarks. The colour charges must be red, green and blue together, or the three anti-colours together.
- All mesons consist of two quarks: one quark and an antiquark. They must possess a colour charge and its corresponding anti-colour charge.
- All hadrons possess a total electric charge of -2, -1, 0, +1 or +2.
- All mesons possess a total electric charge of -1, 0 or +1.

Some limitations of the quark puzzle pieces:

- Quarks are not shaped like the puzzle pieces and do not possess actual colour.
- The pieces physically touch while real quarks are bound by virtual gluons and quarks.
- The quark pieces cannot describe particles that are in superposition states such as π^0.

Scaffolded Quark Puzzle Activity - Answers

Each piece is a model that represents a tiny particle that is too small to see, called a “**quark**”. Every quark has a flavour, an electric charge and a colour charge. You can find these properties printed on the side of the quark.



Flavours include up (u), down (d), anti-up ($\overline{\text{u}}$) or anti down ($\overline{\text{d}}$).

+2/3 is an example of **electric charge**.

Examples of **colour charge** are red and anti-blue ($\overline{\text{blue}}$).

Making Groups of Quarks

Quarks form groups. There are two groups with special names, they are ‘**baryons**’ and ‘**mesons**’. In this model baryons and mesons have special shapes.

Baryon

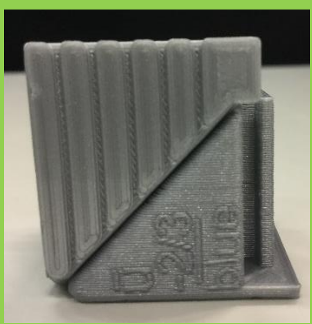
Three quarks that form a cube are called ‘**baryons**’.

Meson

Two quarks that form a double pyramid are called ‘**Mesons**’.

Some combinations fit together nicely, others ones do not. See diagrams below.

Good Joint



Here the pieces fit together nicely.

Bad Joint

Here the pieces do not fit together nicely.

Using groups that fit together nicely complete the tasks on the following pages.

Hint: If it is difficult to build a group, try dividing sort the quarks by colour charge first and try one from each pile.

Activity 1 – Building a Proton

A **proton** is a **baryon** made of two **up (u) quarks** and one **down (d) quark**.

There are many possible colour charge combinations. Put the pieces together to find what combinations are possible. Record the colour combinations and electrical charges in the table below. One row has been filled out as an example for you.

Once you put the pieces together, you can find the **electric charge** by adding the electric charge of each quark piece together.

Table of Colour Combinations for Protons

Particle Name and symbol	Baryon or Meson?	Up Quark Colour Charge	Up Quark Colour Charge	Down Quark Charge Colour	Electric Charge
Proton (p)	Baryon	red (r)	blue (b)	green (g)	2/3 + 2/3 - 1/3 = +1
Proton (p)	Baryon	blue (b)	green (g)	red (r)	2/3 + 2/3 - 1/3 = +1
Proton (p)	Baryon	green (g)	red (r)	blue (b)	2/3 + 2/3 - 1/3 = +1
Proton (p)	Baryon				

Questions:

1.) How many different colour charge combinations of the proton did you find? ______3__________

2.) Challenge Question: Is it possible there are other colour charge combinations that you have not found? How can you be sure?

In order to build a proton with the provided pieces all the quarks have to be of different colours.

Therefore the colour of the down quark defines the whole proton. Since there are only 3 colours for

the down quark, there can only be 3 combinations

Activity 2 – Building Anti-Protons

An **anti-proton** is a baryon made of two $\bar{u}$ **quarks** and one $\bar{d}$ **quark**.

Put the anti-quark pieces together to find what combinations are possible. Record the colour charge combinations and electrical charges in the table below.

Table of Colour Combinations for Anti-Protons

Particle Name and symbol	Baryon or Meson?	Anti-Up Quark Colour	Anti-Up Quark Colour	Anti-Down Quark Colour	Electric Charge
Anti-Proton ($\bar{p}$)	Baryon	anti-red ($\bar{r}$)	anti-blue ($\bar{b}$)	anti-green ($\bar{g}$)	-2/3 -2/3+ 1/3 = -1
Anti-Proton ($\bar{p}$)	Baryon	anti-blue ($\bar{b}$)	anti-green ($\bar{g}$)	anti-red ($\bar{r}$)	-2/3 -2/3+ 1/3 = -1
Anti-Proton ($\bar{p}$)	Baryon	anti-green ($\bar{g}$)	anti-red ($\bar{r}$)	anti-blue ($\bar{b}$)	-2/3 -2/3+ 1/3 = -1

3.) How many different colour charge combinations of the anti-proton did you find? ______3________

4.) How does this compare to the colour charge combinations for protons from activity 1?

The colour combinations are the same with the corresponding anti-colour charge rather than the colour charge.____

____

Activity 3 – Building Neutrons and Anti-Neutrons

A **neutron (n)** is a baryon made of one **u quark** and two **d quarks**.

An anti-**neutron ($\bar{n}$)** is a baryon that contains one $\bar{u}$ **quark** and two $\bar{d}$ **quarks**.

Put the quark and anti-quark pieces together to build neutrons and anti-neutrons. Record the colour combinations and electrical charges in the table below.

Particle Name and symbol	Baryon or Meson?	Up/Anti-Up Quark Colour	Down/Anti-Down Quark Colour	Down/Anti-Down Quark Colour	Electric Charge
n	Baryon	red (r)	blue (b)	green (g)	2/3 - 1/3 - 1/3 = 0
n	Baryon	blue (b)	green (g)	red (r)	2/3 - 1/3 - 1/3 = 0
n	Baryon	green (g)	red (r)	blue (b)	2/3 - 1/3 - 1/3 = 0
$\bar{n}$	Baryon	anti-red ($\bar{r}$)	anti-blue ($\bar{b}$)	anti-green ($\bar{g}$)	-2/3 +1/3+ 1/3 = 0
$\bar{n}$	Baryon	anti-blue ($\bar{b}$)	anti-green ($\bar{g}$)	anti-red ($\bar{r}$)	-2/3 +1/3+ 1/3 = 0
$\bar{n}$	Baryon	anti-green ($\bar{g}$)	anti-red ($\bar{r}$)	anti-blue ($\bar{b}$)	-2/3 +1/3+ 1/3 = 0

5.) How many different colour charge combinations of the anti-neutron did you find? 6

6.) How does this compare to the colour charge combinations for protons and anti-protons from activity 1 and 2?

The colour charge combinations for neutrons and anti-neutrons are identical to those for the protons and anti-protons.

7.) What electric charges are possible? Is this the same as for protons and anti-protons?

For a neutron and anti-neutron only an electric charge of 0 is possible. For protons the electric charge must be +1, but anti-protons the charge must be -1.

Activity 4 – Building Pions

A **pion** is a **meson** made of **u, d**, $\bar{u}$ and $\bar{d}$ **quarks**.

For **pions** there are many different flavours, values for the colour charge and electric charge.

Build **pions** out of the pieces and fill in the combinations you find in the table below:

Table of Colour Combinations for Pions

Particle Name	Baryon or Meson?	Flavour Combination	Colour Charge Combinations	Electric Charge
Pion (π)	Meson	$u\bar{d}$	$r\bar{r}$, $b\bar{b}$, $g\bar{g}$	+1
Pion (π)	Meson	$d\bar{d}$	$r\bar{r}$, $b\bar{b}$, $g\bar{g}$	0
Pion (π)	Meson	$u\bar{u}$	$r\bar{r}$, $b\bar{b}$, $g\bar{g}$	0
Pion (π)	Meson	$d\bar{u}$	$r\bar{r}$, $b\bar{b}$, $g\bar{g}$	-1

4.) What are the different possible values of electric charge for pions? -1, 0 and 1

5.) (Challenge) Are there any other possible values for electric charge for pions? How can you be sure?

Since the only flavour provided are u, d, $\bar{u}$ and $\bar{d}$ and a quark must always be paired with an antiquark, there are only 4 possible combinations. Therefore the electric charge values are restricted to those found in the table.

Activity 5 - Claims, Evidence and Reasoning

Using the combinations you have found in the tables (or using the pieces to explore other combinations if necessary) state whether the following claims are supported or not. After this, write down the evidence and reasoning that led you to this conclusion.

The first claim is completed for you as an example.

Claim 1: Neutrons can have an electric charge of +1.

True or False ___False_______

Evidence and Reasoning: A neutron is made of two down quarks and one up quark. The provided down quarks always have an electric charge of -1/3 and the up quarks have charge +2/3. Therefore when these are combined the net charge is always 0. Therefore it is not possible to have a neutron with charge +1.

Claim 2: Protons can have an electric charge of +1.

True or False ____True_____

Evidence and Reasoning: All combinations of two up quarks and one down quark have a charge of +1. Therefore +1 is a possible charge.

Claim 3: Mesons must have one blue and one anti-blue quark.

True or False ____False_____

Evidence and Reasoning: It is also possible to build a meson with colour charges pairs of green and anti-green or red and anti-red.

Claim 4: It is possible for a baryon to have an overall electric charge of -2.

True or False ___True_______

Evidence and Reasoning: Combining 3 anti-up quarks creates a baryon with a charge of -2. Note this is called the $\overline{\Delta^{++}}$ anti-baryon.

Claim 5 (Challenge): It is possible for a meson to have an overall electric charge of +1/3.

True or False False

Evidence and Reasoning: A meson must always consist of a baryon and an anti-baryon. The only electric charges for a baryon are -1/3 and +2/3. The options for an anti-baryon are -2/3 and +1/3. Trying all combinations gives: -1/3 + -2/3 = -1, -1/3 + 1/3 = 0, +2/3 + -2/3 = 0 and +1/3 + 1/3 = 1.

Claim 6 (Challenge): All particle systems (mesons or baryons) can only have whole number electric charge.

True or False True

Evidence and Reasoning: Claim 7 showed that mesons can only have whole number charge. If baryons must have integer charge then anti-baryons must as well since they have opposite electric charge. For baryons must be made of real quarks for which there are only two possible charges -1/3 or +2/3. Therefore the possible combinations are: -1/3 + -1/3 + -1/3 = -1, 2/3 + -1/3 +-1/3 = 0, 2/3 + 2/3 + -1/3 = 1 and 2/3 + 2/3 + 2/3 = 2.Therefore baryons, anti-baryons and mesons must have whole number charge.

Activity 6 – Comparing the Puzzle to Real Particles (Research Task)

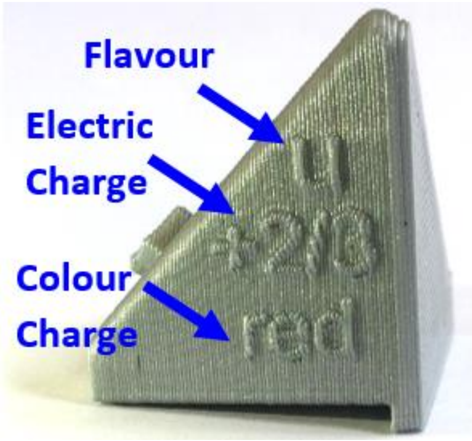
The puzzle provided is only a model and it does not show what real quarks look like. Do some research and in the table below write down the differences and similarities between the puzzle and real quarks. One row has been completed for you an example:

Category	Quark Puzzle	Real Particles
Shape and size	In this puzzle, a proton has a cube shape. Pions have a double pyramid shape. The particles are big and you can touch them.	Real protons and pions have no well-defined shape that humans can see or even imagine. Real baryons and mesons are so small you cannot see them.
Empty Space	In the puzzle, quarks are very close together (they actually touch) and there is almost no empty space between them.	In real protons, the space around the quarks is much larger than the quarks themselves. The quarks are spread out. Real quarks do not touch each other; instead gluons hold them together.
Colour Charge	The quark pieces are coloured and have colour labels, this represents a colour charge.	Real quarks don't have a colour that we can see. However they have a "colour charge", this is the charge of the strong nuclear interaction.
Anti-particles (Challenge)	Anti-particles look the same as the corresponding particle. They have opposite charges and a bar is placed above the particle symbol and colour.	Anti-particles are identical to their corresponding particles but they contain opposite electric charge. When a real particle and anti-particle meet they annihilate, both particles transform into energy.
Difference between up and down quark (Challenge)	In the quark puzzle up and down quarks differ only by the symbols on the side of the quark.	Up and down quarks have very similar mass in particle physics, but differ in electric charge. The strong nuclear force (colour force) interacts identically with up and down quarks.

Open Inquiry with the Quark Puzzle

Guide to Quark Puzzle Pieces

Each piece is a model that represents a “**quark**”. Every quark has a flavour, an electric charge and a colour charge. You can find these properties printed on the side of the quark.



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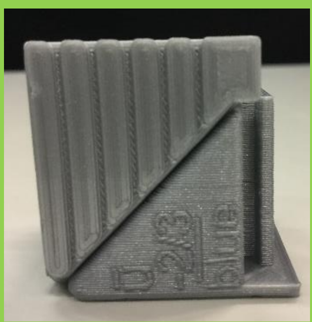

Here the pieces fit together nicely.

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Using groups that fit together nicely to discover the laws and complete the mission.

Hint: If it is difficult to build a group, try dividing sort the quarks by colour charge first and try one from each pile.

Mission Briefing: Fugitive Particles

Purpose: To discover patterns of various kinds to find a set of rules that govern the mysterious and elusive quarks.

Discussion: It has been trusted to you to discover the rules that the quarks obey. Unfortunately even though the particles make up everything all around you, they are so small there is no way that you are able to see them individually. Luckily, we have obtained a model of puzzle pieces, which obey the same rules as actual quarks.

Your mission ~~should you choose to accept~~ is to use these puzzle pieces to discover the laws that dictate how these particles form groups.

You must present your findings as a series of rules that someone else could use to determine possible and impossible combinations of quarks.

For a hint to get started, see guidelines on the back of this sheet.