QUARK WORKBENCH 2D/3D
STUDENT PAGES

Mission Briefing: Fugitive Particles

Purpose: To find a set of rules that govern the mysterious, elusive quarks by discovering various patterns.

Discussion: Discover the rules that the quarks obey. Unfortunately, even though these particles make up everything all around you, they are so small that you cannot see individual quarks. Luckily, we have obtained a model composed of puzzle pieces which obey the same rules as actual quarks.

Your mission is to use these puzzle pieces to discover the laws that dictate how quarks form other particles. You must present your findings as a series of rules that someone else could use to determine possible and impossible combinations of quarks.

GUIDE TO COLOR MIXING

Electric charge only comes in two charge types: positive and negative. With this choice of naming, it is easy to determine electric charge using simple addition.

Determining Neutral Charge			
Electric Charge	**+1**	**-1**	**0 = neutral**
Hydrogen Atom	(+1) + (-1) = 0		Neutral
Oxygen Ion	(+6) + (-8) = -2		Electric Charge -2
Proton	(+1) + (0) = +1		Electric Charge +1

When there are three charge types as with color charge: red, green, blue neutral has a new meaning. With this choice of naming three color charges, neutral follows the patterns of color mixing.

Rules of Color Mixing			
Primary Color	**Complementary Combination**	**Complementary Color**	**Neutral = White**
Red	Green + Blue	Cyan	Red + Cyan = white
Green	Red + Blue	Magenta	Green + Magenta = white
Blue	Red + Green	Yellow	Blue + Yellow = white

So how does this play out for quarks? Instead of complementary colors, we have anti-particles. However, neutral particles follow the same rules. See the chart below:

Particle/Anti-Particle Rules			
Color Charge	**Anti-particle**	**Anti-color**	**Neutral = White**
Red	Anti-red ($\bar{r}$)	Green + Blue	Red + Anti-red = white
Green	Anti-green ($\bar{g}$)	Red + Blue	Green + Anti-green = white
Blue	Anti-blue ($\bar{b}$)	Red + Green	Blue + Anti-blue = white

The quark puzzle pieces follow these rules, forming closed figures for 2D puzzle pieces or solid figures for 3D puzzle pieces for allowed bound states, while stubbornly refusing to fit together for forbidden combinations.

GUIDE TO QUARK PUZZLE PIECES

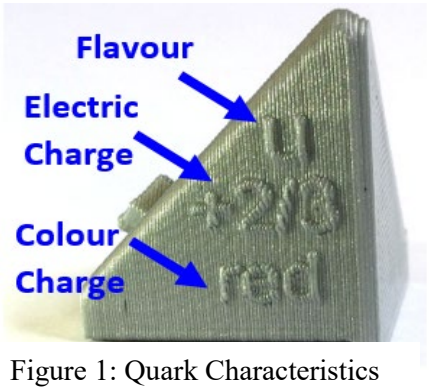

Figure 1: Quark Characteristics

As shown in Figure 1, the 3D puzzle pieces include flavor, electric charge and color charge. Find combinations that fit well together to discover the rules and complete the mission.

What makes a good fit? Note the difference between a "good" fit (Figure 2) and a "bad" fit (Figure 3) which has gaps.

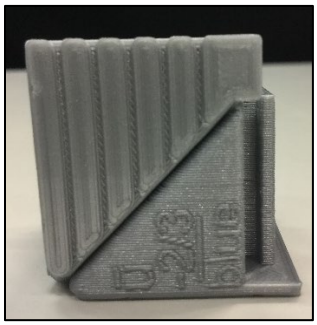

Figure 2: Good Joint

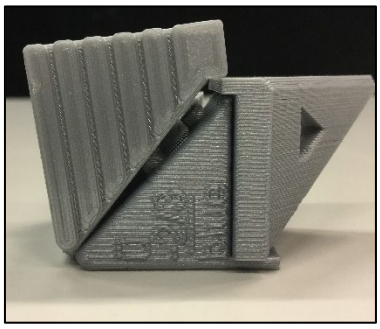

Figure 3: Bad Joint

Hint: If it is difficult to construct a particle, try sorting the quarks by color charge first and try one from each pile.

For each of the tasks that follow:

Put the pieces together to find the possible combinations.

Record the color combinations and electrical charges in the table below.

Find the **electric charge** by adding the electric charge of each quark piece together.

Answer the questions to **WHAT DO YOU THINK** in your journal or log book.

Provide evidence to support your answer using the data collected.

TASK 1: BUILDING A PROTON

A **proton** is a **baryon** made of two **up (u) quarks** and one **down (d) quark**. There are many possible color charge combinations. One row has been filled out as an example for you. Make this example combination first. Add more rows in your journal or log book as needed.

Table of Color Combinations for Protons

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

WHAT DO YOU THINK 1:

- How many different color charge combinations of the proton did you find?
- Challenge Question: Is it possible that there are other color charge combinations that you have not found? How can you be sure?

TASK 2: BUILDING ANTI-PROTON

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. One row has been filled out as an example for you. Make this example combination first. Add more rows in your journal or log book as needed. Determine the electric charge for each row.

Table of Color Combinations for Anti-Protons

Particle Name and symbol	Baryon or Meson?	Anti-Up Quark Color	Anti-Up Quark Color	Anti-Down Quark Color	Electric Charge
Anti-Proton ($\bar{p}$)	Baryon	anti-red ($\bar{r}$)	anti-blue ($\bar{b}$)	anti-green ($\bar{g}$)	
Anti-Proton ($\bar{p}$)					

WHAT DO YOU THINK 2:

- How many different color charge combinations of the anti-proton did you find?
- How does this compare to the color charge combinations for protons from activity 1?

TASK 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 color combinations and electrical charges in the table below. Add more rows in your journal or log book as needed.

Table of Color Combinations for Neutrons and Anti-Neutrons

Particle Name and symbol	Baryon or Meson?	Up/Anti-Up Quark Color	Down/Anti-Down Quark Color	Down/Anti-Down Quark Color	Electric Charge

WHAT DO YOU THINK 3:

- How many different color charge combinations of the neutron did you find?
- How many different color charge combinations of the anti-neutron did you find?
- How does this compare to the color charge combinations for protons and anti-protons from Task 1 and Task 2?
- What electric charges are possible? Is this the same as for protons and anti-protons?

TASK 4: BUILDING PIONS

A **pion** is a **meson** made of **u, d**, $\bar{u}$ and $\bar{d}$ **quarks**. For **pions** there are many different flavors, values for the color charge and electric charge. Build **pions** out of the pieces to find what combinations are possible. One row has been filled out as an example for you. Be sure and check that you can make that example combination. Add more rows in your journal or log book as needed.

Table of Color Combinations for Pions

Particle Name	Baryon or Meson?	Flavor Combination	Color Charge Combinations	Electric Charge
Pion (π)	Meson	$u\bar{d}$		+1

WHAT DO YOU THINK 4:

- What are the different possible values of electric charge for pions?
- (Challenge) Are there any other possible values for electric charge for pions? How can you be sure?

TASK 5: CLAIMS, EVIDENCE AND REASONING

For each of the claims given below:

State whether the following claims are supported or not.
Document the evidence and reasoning that led you to this conclusion.
Record your answers in your journal or log book.

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

down quarks always have an electric charge of -1/3 and the up quarks have electric charge +2/3. Therefore, when these are combined the net electric charge is always 0. Therefore, it is not possible to have a neutron with electric charge +1.

Claim 2: Protons can have an electric charge of +1.
True or False _____

Evidence and Reasoning:_____

Claim 3: Mesons must have one blue and one anti-blue quark.
True or False _____

Evidence and Reasoning:_____

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

Evidence and Reasoning:_____

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

Evidence and Reasoning:_____

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

Evidence and Reasoning:_____

TASK 6: COMPARING THE PUZZLE TO REAL PARTICLES (RESEARCH TASK)

The puzzle is only a model and does not show what quarks actually look like. Do some research and record the differences and similarities between puzzle results and quarks in the table. One row has been completed for you an example:

Category	Quark Puzzle Results	Particles
Shape and size	2D Puzzle: Baryons are triangular. Mesons are hexagonal. 3D puzzle: Protons are cubes. Pions are a double pyramid shape.	Protons and pions have no well-defined shape that we can see or even imagine.
Empty Space		
Color Charge		
Anti-particles (Challenge)		
Difference between up and down quark (Challenge)		