QUARK WORKBENCH 2D/3D
ANSWER KEY

TASK 1: BUILDING A PROTON

Table of Color Combinations for Protons (Example in first row)

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	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

1. WHAT DO YOU THINK?

- How many different color charge combinations of the proton did you find?
  There are three unique combinations.
- Challenge Question: Is it possible there are other color charge combinations that you have not found? How can you be sure?
  To build a proton with the puzzle pieces, all the quarks have to be of different colors to get good fits. Since there are only three colors for the down quark, there can only be three combinations.

TASK 2: BUILDING AN ANTI-PROTON

Table of Color Combinations for Anti-Protons (Example in first row)

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 ($\bar{g}$)	-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

2. WHAT DO YOU THINK?

- How many different color charge combinations of the anti-proton did you find?
  There are three unique combinations.
- How does this compare to the color charge combinations for protons from activity 1?
  The color combinations are the same with the corresponding anti-color charge rather than the color charge.

TASK 3: BUILDING NEUTRONS AND ANTI-NEUTRONS

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
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

3. WHAT DO YOU THINK?

- How many different color charge combinations of the neutron did you find?
  There are three unique combinations.
- How many different color charge combinations of the anti-neutron did you find?
  There are three unique combinations.
- How does this compare to the color charge combinations for protons and anti-protons from Task 1 and Task 2?
  The color charge combinations for neutrons and anti-neutrons are identical to those for the protons and anti-protons.
- What electric charges are possible? Is this the same as for protons and anti-protons?
  For a neutron and anti-neutron, the electric charge was 0 in every case. For protons, the electric charge must be +1, but for anti-protons, the electric charge must be -1.

TASK 4: BUILDING PIONS

Table of Color Combinations for Pions (Example in first row)

Particle Name	Baryon or Meson?	Flavor Combination	Color 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 DO YOU THINK?

- What are the different possible values of electric charge for pions?
  The possible values are -1, 0, +1.
- (Challenge) Are there any other possible values for electric charge for pions? How can you be sure?
  Since the only flavors provided are u, d, $\bar{u}$ and $\bar{d}$ and a quark must always be paired with an antiquark, there are only four possible combinations. Therefore, the electric charge values are restricted to those found in the table.

TASK 5: CLAIMS, EVIDENCE AND REASONING

The first claim is completed 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 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 an electric charge of +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 an electric charge of +1. Therefore, +1 is a possible electric 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 color charge 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 three anti-up quarks {-2/3 + -2/3 + -2/3 = -2} creates a baryon with an electric 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 quark and an anti-quark. The only electric charges for a baryon are -1/3 (down) and +2/3 (up). The options for anti-quarks are -2/3 (anti-up) and +1/3 (anti-down). Trying all combinations gives: {-1/3 + -2/3 = -1}, or {-1/3 + 1/3 = 0}, or {+2/3 + -2/3 = 0} or {+1/3 + 1/3 = 1} or integer values.

Claim 6 (Challenge): All particle systems (mesons or baryons) can only have whole number electric charge.
True or False ____True_____
Evidence and Reasoning: Claim 5 supported that pions can only have whole number electric charge. Since pions are mesons, we can generalize to a claim that mesons can only have whole number electric charge. The possible combinations for baryons are three quarks:

Quark Combination	Net Electric Charge	Anti-Quark Combination	Net Electric Charge
3 Down	{-1/3 + -1/3 + -1/3 = -1}	3 Down	{1/3 + 1/3 + 1/3 = 1}
1 Up + 2 Down	{2/3 + -1/3 + -1/3 = 0}	1 Up + 2 Down	{-2/3 + 1/3 + 1/3 = 0}
2 Up + 1 Down	{2/3 + 2/3 + -1/3 = 1}	2 Up + 1 Down	{-2/3 + -2/3 + 1/3 = 1}
3 Up	{2/3 + 2/3 + 2/3 = 2}	3 Up	{-2/3 + -2/3 + -2/3 = -2}

The chart shows that baryons and anti-baryons must have integer electric charge. Therefore, baryons, anti-baryons and mesons must have whole number electric charge.

TASK 6: COMPARING THE PUZZLE RESULTS TO REAL PARTICLES (Example in first row)

Category	Quark Puzzle Results	Particles
Shape and Size	2D Puzzle: Baryons are triangular and Mesons are hexagonal 3D Puzzle: Protons are cubes. Pions are a double pyramid shape.	Protons and pions have no well-defined shape that humans can see or even imagine.
Empty Space	In the puzzle, quarks are very close together, often actually touching. There is almost no empty space between them.	For mesons and baryons, the space around the quarks is much larger than the quarks themselves. The quarks are spread out. Quarks do not touch each other; instead, gluons hold the quarks together.
Color Charge	The quark pieces are colored and have color labels; this represents a color charge.	Quarks do not have a color that we can see. They come in three types, which for convenience are referred to as "color charge." This is the property associated with the strong nuclear interaction.
Anti-Particles (Challenge)	Anti-particles look the same as the corresponding particle. They have opposite electric charges and a bar is placed above the particle symbol and color.	Anti-particles are identical to their corresponding particles, but they contain opposite electric charge. When a 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 (color force) interacts identically with up and down quarks.