**Quark Workbench**

**Teacher Notes**

**Description**

The Standard Model is a theoretical framework designed to help us understand matter. In this activity, students use cleverly constructed puzzle pieces and look for patterns in how those pieces can fit together. The puzzles pieces are constructed, as much as possible, to combine according to the Standard Model’s rules governing the quark composition of bound state particles such as baryons and mesons. We provide a template that allows you to cut out the puzzle pieces and a “workbench” that students can use for assembly.

**Standards Addressed**

*Next Generation Science Standards*

Science and Engineering Practices

1. Asking questions and defining problems

2. Developing and using models

4. Analyzing and interpreting data

5. Using mathematics and computational thinking

6. Constructing explanations and designing solutions

7. Engaging in argument from evidence

Crosscutting Concepts

1. Observed patterns

4. Systems and system models

*Common Core Literacy Standards*

Reading

9-12.3 Follow precisely a complex multistep procedure . . .

9-12.4 Determine the meaning of symbols, key terms . . .

9-12.7 Translate quantitative or technical information . . .

*Common Core Mathematics Standards*

MP2. Reason abstractly and quantitatively.

**Enduring Understandings**

* The Standard Model provides a framework for our understanding of matter.

**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 color, spin and charge.
* Describe the role of quarks in forming particles that are part of the Standard Model.
* State the rules for combining quarks to make mesons and baryons.
* Describe the role of a scientific framework and give reasons for the claim that the Standard Model is a scientific framework.
* Describe the importance of conservations laws in the formation of composite quark particles.

**Background Material**

As an introduction to the Standard Model, students will work with puzzles pieces that are constructed, as much as possible, to combine according to the Standard Model’s rules governing the quark composition of bound state particles such as baryons and mesons. Specifically, these bound states must be color neutral: red-green-blue (or anti-red, anti-green and anti-blue) for the three quark hadrons, while the two quarks comprising a meson must be either red with anti-red, green with anti-green, or blue with anti- blue.

The quark puzzle pieces do follow these rules, forming closed, solid figures for allowed bound states, while stubbornly refusing to fit together for forbidden combinations. Given a set of quark pieces and some time to attempt to manipulate them into bound states, students should be able to recognize certain restrictions on what is allowed. This activity ends with a brief discussion of the Standard Model as the current theoretical framework for our understanding of matter and the Standard Model chart, which includes the basic building blocks—quarks, leptons and force carriers.

**Some rules that students could “discover”:**

* Antiquarks always possess an **anti-color**.
* **All baryons consist of three quarks or three antiquarks.**
* The three quarks making up each baryon must consist of the three primary colors: **red, green** and **blue**, or the three **anti-colors: anti-blue** (yellow), **anti-green** (magenta) or   
  **anti-red** (cyan).
* All mesons consist of two quarks: one quark and an antiquark.
* The two quarks in any meson must possess a **color** and its **anti-color**.
* All hadrons possess a total **charge** of -2, -1, 0, +1 or +2.
* All mesons possess a total **charge** of -1, 0 or +1.

**Some limitations of the quark puzzle pieces:**

* **Of course, quarks are not shaped like the puzzle pieces; nor do they possess true colors.**
* **Neither leptons (including electrons) nor WEAK interactions can be described by these pieces.**
* The **gluons** that bind the quarks into the nucleus are also not represented.
* The quark pieces cannot describe any of the numerous known particles found in   
  **superpositions**, such as the π0, a superposition of **uu** and **dd**.

**Prior Knowledge**

Students need to know about color mixing for light. This includes the colors associated with   
primary colors and the colors associated with secondary colors.

Students also need to know the notation for particles and anti-particles, color and anti-color.

**Resources/Materials**

Here is the link to the workbench and puzzle pieces.

<http://quarknet.i2u2.org/sites/default/files/quarkpuzzleparts.pdf>**.**

The proton and neutron are baryons. As an extension to the activity, ask the students to determine the possible quark combinations to construct these "particles" with which they are familiar. Remind the students that protons and neutrons are matter (they could also make antiprotons and antineutrons), and discuss the results.

1. Proton: **uud**
2. Neutron: **udd**
3. Antiproton: (**uud**)
4. Construct the **pion** family: π+ (**ud**) ; π− (**ud**); and π0 (**uu**) or (**dd**).

You may wish to discuss that each π0 is known to be a superposition of those two states.

**Implementation**

Project the Standard Model Chart of Elementary Particles <http://vms.fnal.gov/stillphotos/2005/0400/05-0440-01D.hr.jpg> and discuss the generations, difference between leptons, quarks and force carriers. (You can find some material to prompt this discussion at <http://www.fnal.gov/pub/science/inquiring/matter/madeof/index.html> or http://www.particleadventure.org/.) Point out the large difference in masses among the quarks and the fact that the only massless particle on the chart is the photon. Discuss the fact that the particles here represent the “building blocks” of nature; everything else in the universe is comprised of these particles. Everything. Point out that the familiar proton is comprised of three valence quarks (up-up-down) and many other virtual quark pairs and gluons. Introduce the idea that quarks combine to make bound state particles. The challenge for the students is to find these rules using the workbench and puzzle pieces.

A few important points:

1. The Standard Model *chart* illustrates the fundamental building blocks of matter and the force carriers that govern their interactions with one another.
2. It is surprising that only the up and down quarks and the electron make up all the ordinary matter around us.
3. Once we understand the rules for combining these fundamental particles, we can make hundreds of other particles.
4. The Standard Model, usually illustrated by the Standard Model chart is, of course, much more than the chart and is the current theoretical framework for our understanding of matter.

It can be very helpful to the students if the teacher walks around the room and asks formative questions. Useful comments or questions may be:

* Sometimes the students will say "the charge always has to be 1 or zero" and then ask them to try seeing if they can make a negative number, or give hints that a +2 or -2 are also possible.
* Give students time to come up with their own rules; halfway through have some students share what they have found to make sure they are on track to discovering the rules.
* What color are all of the bound states that you have discovered?
* What is the net charge of the bound states that you have discovered?
* How many bound quarks are required to make a meson? A baryon?

We recommend printing the puzzle pieces on card stock and laminating game boards.

**Pro tip from Jeremy Smith:** I printed out the puzzle pieces on card stock and laminated them   
before cutting, and this makes them a whole lot more durable. Also, as the directions instructed, I printed out extra copies of the up and down puzzle pieces to make protons and neutrons more common. My mentor here at Johns Hopkins University said that it was kind of bogus to include the top quark in the puzzle pieces, since top quarks can't form hadrons. But I just let that ride and mentioned it to the students later.

**Extension:**

As an extension to the activity, ask the students to determine the possible quark combinations to construct these particles that are listed below. Remind the students that protons and neutrons are matter (they could also make antiprotons and antineutrons), and discuss the results.

1. Proton: **uud**
2. Neutron: **udd**
3. Antiproton: (**uud**)
4. Construct the **pion** family: π+ (**ud**) ; π− (**ud**); and π0 (**uu**) or (**dd**).

You may wish to discuss that each π0 is known to be a superposition of those two states.

**Variations:**

This variation is more open-ended in which the students must come up with the rules and develop the meaning behind the rules.

* Print and cut out an excess of **up** and **down** quarks, in order to suggest that all quark types are not equally prevalent; in fact, the other quark types are quite rare in the universe we are used to.
* Use the quarks in a game similar to gin rummy. Each “player” starts with ten quark pieces; the object of the game is for a player to be the first to use up all of their ten pieces by building several composite particles (baryons or mesons). Players take turns, each trying to   
  develop ONE particle—only one per turn is allowed. If a particle is constructed, it and its quark constituents leave the player’s hand and remain on the table for the remainder of the game. If unwilling or unable to form a particle, the player must select a “random” quark from a stockpile and wait a turn to construct.

**Assessment**

When the students have finished the activity, project the Elementary Particles chart again. Discuss the fact that they have investigated a small part of the Standard Model—one that describes formation of baryons and mesons. There is more to learn about the Standard Model— both for the students and for physicists. Discussion topics may include:

* What rules did you discover that determine the composition of baryons? Mesons?
* What role did quarks play in forming the mesons and baryons?
* In addition to quarks, what other particles are "fundamental"?
* What do physicists call the current theoretical framework for our understanding of   
  matter?
* How do the conservation laws help explain how particles ‘fit’ together?

A type of summative assessment is to have students post their rules using chart paper or white boards. Then “peers” go round the room and ask questions or challenge the rules with evidence they found.

Another summative approach is to post a list of the particles made along with how they were made and the class work as a group of the whole to develop rules.

In a more traditional type of summative assessment, students can also be asked to write claims to answer some subset of the following statements providing evidence from their experimentation:

* Identify the fundamental particles in the Standard Model chart.
* Describe properties of quarks, including color, spin, and charge.
* Describe the role of quarks in forming particles that are part of the Standard Model.
* State the rules for combining quarks to make mesons and baryons.
* Describe the role of a scientific framework and give reasons for the claim that the Standard Model is a scientific framework.
* Describe the importance of conservations laws in the formation of composite quark particles.

**Acknowledgement:**

Eric Gettrust is a physics teacher in Madison, Wisconsin. He created this puzzle activity for his students in the summer of 2008 after a summer appointment as a QuarkNet lead teacher in the physics department at the University of Wisconsin. He published the idea in *The Physics Teacher* during the spring of 2010.