QUARK WORKBENCH
TEACHER NOTES

DESCRIPTION

Students use cleverly constructed puzzle pieces and look for patterns in how those pieces can fit together. The puzzles pieces obey, as much as possible, the Standard Model's rules limiting the quark composition of bound states, both 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

Next Generation Science Standards

- Science and Engineering Practices
  - 2. Developing and using models
  - 6. Constructing explanations
  - 7. Engaging in arguments 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 . . .
  - 9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards

- MP2. Reason abstractly and quantitatively.

ENDURING UNDERSTANDING

- The Standard Model organizes what we know about subatomic particles.

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 informing particles that are part of the Standard Model.
- State the rules for combining quarks to make mesons and baryons.

PRIOR KNOWLEDGE

None!

BACKGROUND MATERIAL

As an introduction to the Standard Model, students will work with puzzle pieces that obey, as much as possible, the Standard Model's rules limiting the quark composition of bound states, both 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 should "discover":

- Antiquarks always possess an **anti-color**.
- All baryons consist of three quarks **or** of 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 posses a total **charge** of -2, -1, 0, +1, or +2.
- All mesons posses 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** which bind the quarks into the nucleus are also not represented.
- The quark pieces cannot describe any of numerous known particles found in **superpositions**, such as the π^0, a superposition of **uu** and **dd**.

IMPLEMENTATION

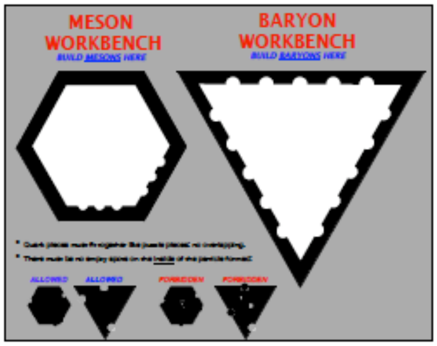
Project the Standard Model Chart of Elementary Particles (http://www-visualmedia.fnal.gov/VMS_Site/gallery/stillphotos/1995/0700/95-0759D.jpg) and discuss the generations, difference between leptons, quarks and force carriers. (You can find some material to prompt this discussion at http://www.fnal.gov/pub/science/inquiring/matter/madeof/index.html.) Point out the large difference in masses between the quarks (this will foreshadow the next activity in this packet.) 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 that the familiar proton is comprised of three valence quarks (up-up-down) and many other virtual quark pairs and gluons.

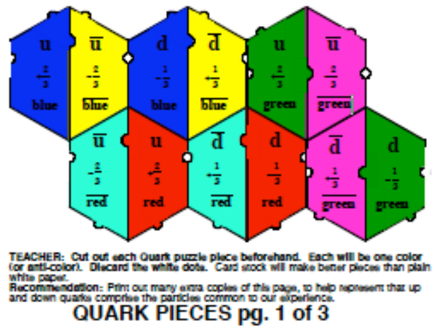
Introduce the Quark Workbench activity as a way to determine the combination rules for the quarks as they form composite particles.

A few important points:

1. The Standard Model *chart* illustrated 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.

We recommend printing the puzzle pieces (the following pages) on card stock and laminating game boards.





ASSESSMENT

During the activity, you might ask:

- 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?

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.

- 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?

ADDITIONAL INFORMATION

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" that they are aware of. 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 π^0 **(uu)** or **(dd)**.

You may wish to discuss that each π^0 is known to be a superposition of those two states.

Variations:

- 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.

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.