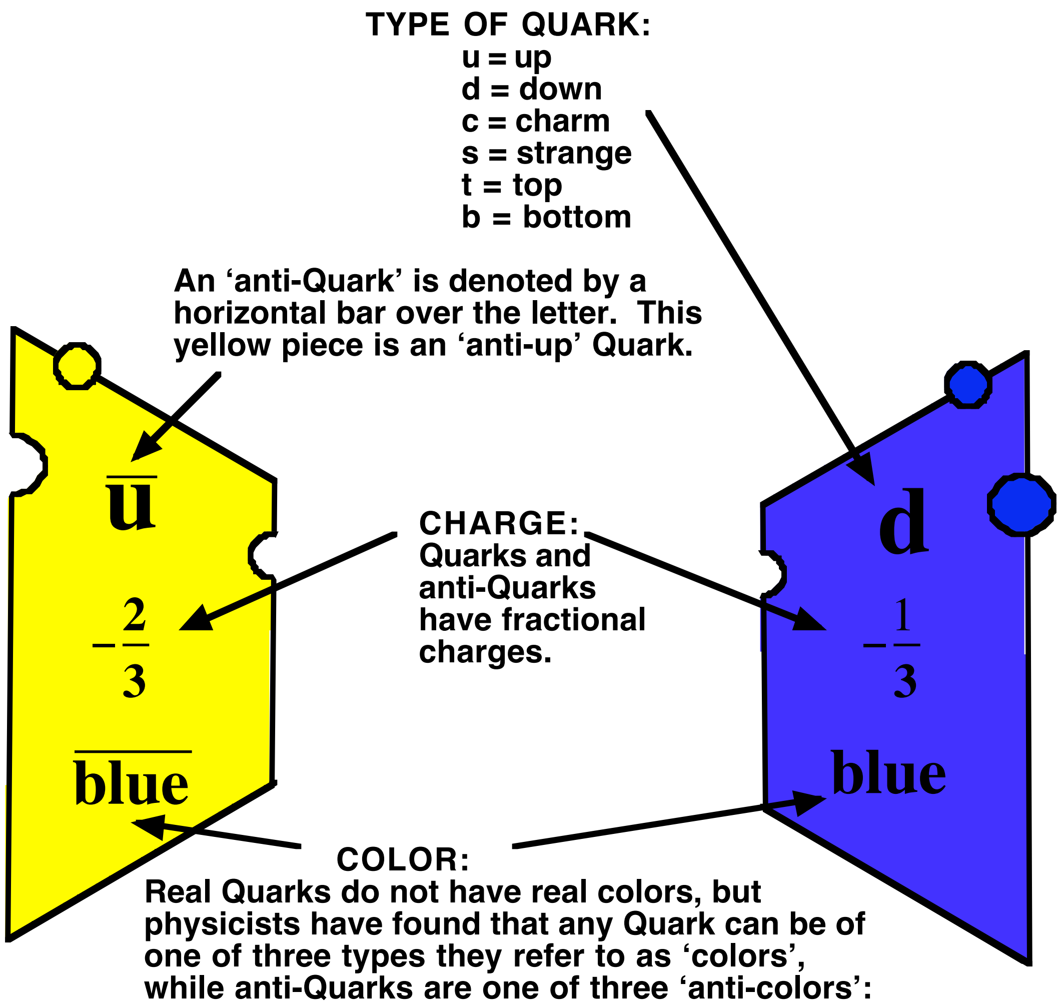
The Quark Puzzle

Physicists believe that protons, neutrons and many other particles are made up of still smaller particles they call Quarks. In this game, puzzle pieces represent these Quarks. In nature, Quarks are never observed alone; they are only found inside particles made up of **groups** of Quarks.

However, not all arrangements of Quarks will fit together! Nature allows only certain combinations. **Your task** is to assemble the Quark puzzle pieces into larger particles called **Baryons** and **Mesons,** and more importantly, to discern the rules determining what combinations are allowed. These rules describe color and charge combinations as well as other observables. You might start by noticing what these observables are for each of the Quark pieces. Then work towards the rules.

Using the **Baryon** and **Meson Workbenches**, build as many Baryons and Mesons as you can, while trying to notice any RULES governing the Quark combinations that work. Baryons will resemble an equilateral triangle with a few bumps on its perimeter while Mesons will form a smaller hexagon with a couple of bumps. If Quark pieces truly fit together, there will be no empty spots on the INSIDE of the grouping. Once you assemble a Baryon or Meson, write down the combination: quark types, total charge, and colors. You can then disassemble the particle to re- use the pieces for the next particle.



QUARKS:	ANTI-QUARKS:
red	anti-red (cyan)
green	anti-green (magenta)
blue	anti-blue (yellow)

Try to discover rules about color, charge, matter vs. anti-matter, or anything else!

FOR THE TEACHER

The motivation for creating this activity was primarily to construct a group of objects (puzzle pieces) which obeyed, as much as possible, the Standard Model's rules limiting the quark composition of bound states, both hadrons 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 recognise certain restrictions on what is allowed.

SOME RULES THAT STUDENTS SHOULD 'DISCOVER':

- anti-quarks always possess an **anti-color**.
- all hadrons consist of three quarks **or** of three anti-quarks.
- the three quarks making up each hadron 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 anti-quark.
- 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 can not describe any of numerous known particles found in **superpositions**, such as the π^0, a superposition of $\mathbf{u\bar{u}}$ and $\mathbf{d\bar{d}}$.

OTHER EXERCISES:

The proton and neutron are baryons. As an extension to the activity, have the students determine the possible Quark combinations to construct these "particles" that students are aware of. Remind the students that protons and neutrons are matter (they could also make anti-protons and anti-neutrons) and discuss the results.

1. proton: $\mathbf{uud}$
2. neutron: $\mathbf{udd}$
3. anti-proton: $(\mathbf{\bar{u}\bar{u}\bar{d}})$
4. construct the **pion** family: $\pi^+ (\mathbf{u\bar{d}})$; $\pi^- (\mathbf{u\bar{d}})$; and $\pi^0 (\mathbf{u\bar{u}})$ or $(\mathbf{d\bar{d}})$.

   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 prevelent; 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 10 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 (hadrons or mesons). Players take turns, each trying to develop ONE particle -- on ly one per turn is allowed. If a particle is constructed, it and its Quark constituents leave the players 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 stock pile and wait a turn to construct.

To offer suggestions or ask questions, please e-mail **egettrust@madison.k12.wi.us**.