QUARK WORKBENCH 2D/3D
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 fit together. The puzzles pieces, as much as possible, 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 either 3D print or cut out 2D puzzle pieces and a "workbench" that students 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 flavor, color charge and electric charge.
- Describe the role of quarks in forming baryons and mesons.
- State the rules for combining quarks to make mesons and baryons.
- Describe the symmetry between particles and anti-particles.
- Describe the role of a scientific framework and give reasons for the claim that the Standard Model is a scientific framework.
- Use the claims-evidence-reasoning to evaluate scientific claims.

PRIOR KNOWLEDGE
Students need to be know and be familiar with the following:

- Notation for particles, anti-particles, color charge and anti-color charge.

- How to add positive and negative fractions.
- Color mixing for light including colors associated with primary colors and secondary colors.

Background Material

As an introduction to the Standard Model, students work with puzzles pieces to build baryons and mesons. Specifically, these bound states must be color charge neutral: red-green-blue (or anti-red, anti-green and anti-blue) for the three baryons, while mesons must be either red with anti-red, green with anti-green, or blue with anti-blue.

Electric charge is either positive or negative. With this choice of naming, it is easy to determine neutral electric charge using simple addition.

Determining Neutral Electric 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.

Particle/Anti-Particle Rules			
Color Charge	**Anti-particle**	**Anti-color**	**Neutral = White**
Red	Anti-red	Green + Blue	Red + Anti-red = white
Green	Anti-green	Red + Blue	Green + Anti-green = white
Blue	Anti-blue	Red + Green	Blue + Anti-blue = white

The quark puzzle pieces 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 charge**.

- **All baryons consist of three quarks or three antiquarks.**
- The three quarks making up each baryon must consist of the three primary color charges: **red, green** and **blue**, or the three **anti-colors: anti-blue** , **anti-green** or **anti-red**.
- All mesons consist of two quarks: one quark and an antiquark.
- The two quarks in any meson must possess a **color charge** and its **anti-color charge**.
- All hadrons possess a total **electric charge** of -2, -1, 0, +1 or +2.
- All mesons possess a total **electric 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.**
- **These pieces describe neither leptons (including electrons) nor WEAK interactions.**
- The **gluons** and **virtual quarks** that bind the **valence quarks** are not represented.
- The quark pieces cannot describe any of the numerous known particles found in **superpositions**, such as the π^0, a superposition of $\boldsymbol{u\bar{u}}$ and $\boldsymbol{d\bar{d}}$.

Resources/Materials

There are two sets of puzzle pieces, a 2D set (which can be printed on paper or 3D printed) and a 3D set.
2D workbench and puzzle pieces are downloadable from the Data Portfolio.
3D printable 2D-puzzle pieces: https://zenodo.org/record/1286989#.Wyd4a6czaUk
3D printable puzzle pieces: https://zenodo.org/record/1252868#.W1tb4FAzaUk

Implementation

There are two ways to approach this activity. One method is to distribute the pieces and instruct your students to find as many rules for combining the pieces as they can. The students report out using chart paper or white boards. If you prefer a more structured approach, we provide student pages in the Data Portfolio as well as an answer key.

Project the Standard Model Chart of Elementary Particles http://vms.fnal.gov/stillphotos/2005/0400/05-0440-01D.hr.jpg and discuss the generations and the difference between leptons, quarks and force carriers. You may choose to have your students research these terms. Information can found 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 particles on the chart are the photon and the gluon. Discuss the fact that these particles 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 puzzles pieces.

Divide the students into groups of two or three students. Encourage the students to construct as many combinations as possible. Each group should be prepared to share their results and the rules they have discovered. Have the other groups challenge the rules and offer evidence for why a shared rule may fail.

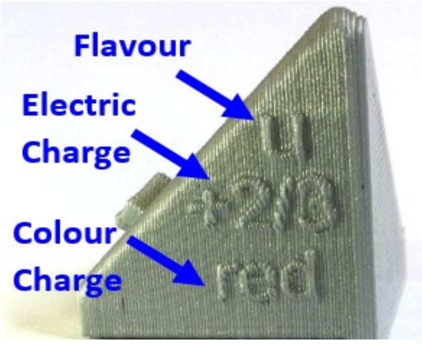

Figure 1: Quark Characteristics

When using the 3D instructions, download and print all the puzzle pieces. You may want to print several extra up and down quark puzzle pieces.

As shown in Figure 1, the 3D puzzle pieces have flavor, electric charge and color charge printed on the side.

Make sure the students are aware of what constitutes a "good" fit. The figure below shows difference between a "good" fit (Figure 2) and a "bad" fit (Figure 3) which has gaps

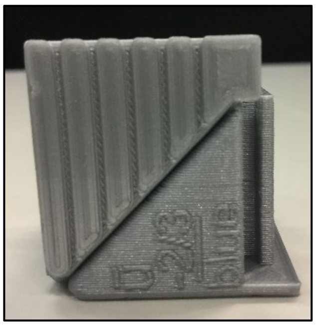
Figure 2: Good Joint

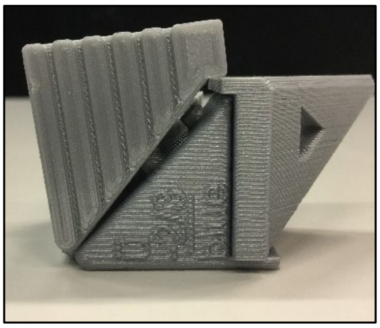
Figure 3: Bad Joint

A few important points:

1. The Standard Model *chart* illustrates the fundamental building blocks of matter and the force carriers that govern their interactions.
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— how the fundamental particles interact, governed by four fundamental forces.

Give students time to come up with their own rules; halfway through the class have some students share what they have found to make sure they are on track to discover the rules. You can help students by walking around the room to ask formative questions. Useful comments or questions may be:

- Sometimes students will say "the electric charge always has to be 1 or 0." Ask them to see if they can make a negative number or give hints that a +2 or -2 are also possible.
- What is the color charge of the bound states that you have discovered?
- What is the net electric charge of the bound states that you have discovered?
- How many bound quarks are required to make a meson? A baryon?

Questions for 3D puzzles:

- Are there particular shapes associated with completed baryons?
- Are there particular shapes associated with completed mesons?

We recommend printing the 2D 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 students to determine the possible quark combinations to construct these particles.

1. Proton: **uud**
2. Neutron: **udd**
3. Antiproton: (**uud**)
4. Construct the **pion** family: $\pi+$ (**ud**) ; $\pi-$ (**ud**); and π^0 (**uu**) or (**dd**).

Remind the students that protons and neutrons form every day matter. Students could also make antiprotons and antineutrons. Discuss the results. You may wish to discuss that each π^0 is known to be a superposition of those two states.

Open-ended Variations: 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.
- Have students research the differences between the puzzle quarks and real quarks to address the limitations of the puzzle. Provide the students with specific categories to research such as shape, size or amount of empty space.
- Use the quarks in a game similar to gin rummy. Each student 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 construct 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 quark from a draw pile and wait a turn to construct a particle.

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 the formation of baryons and mesons. There is more to learn about the Standard Model— both for students and 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?

A type of summative assessment is to have students post their rules using chart paper or white boards. "Peers" go around the room to ask questions or challenge the rules with their own evidence.

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

In a more traditional type of summative assessment, ask students to write claims to answer some subset of the following statements, providing evidence from their investigations:

- Identify the fundamental particles in the Standard Model chart.
- Describe properties of quarks, including flavor, color charge, and electric 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.

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

Lachlan McGinness is an Australian physics teacher and visiting fellow at the Australian National University. He created the 3D puzzle activity while appointed as Teacher in Residence at CERN in 2018.