Background information

Title: *Build the Baryons*

Brief Description: *This activity consists in combining three quarks to build baryons, whose characteristics (charge and strangeness) can be inferred from their shape. It can be conducted in several ways, depending on the age of the participants, and on the context. For example, we used it as a challenge for pupils to build a given baryon using its constituent quarks within the framework of an escape room based on particle physics.*

Keywords: Particles, matter, quarks, baryons.

Target audience: *Students, public*

Age range: *11-99*

Context(s): *This activity can be done at school, or during public engagement events.*

Time required: *In school-based work, the activity can be done in 45 minutes. More time can be assigned to out-of-school activities. For example, one can use the scenario to realise a sort of escape room or a treasure hunt: in this case more time can be appropriate.*

Technological tools required: *AR device (currently only Android phones are supported). Depending on the implementation, other tools may be needed.*

Author(s)'s background: *scientist.*

Connection with the curriculum: *The activity is suitable for introducing modern physics to students: in particular, the standard model and the quarks. It can, however, used to informally introduce the constituents of matter to younger students.*

Learning objectives: *Learn about the constituents of matter.*

Guidance for preparation: *The activity does not require preparation, per se, but for the printing of the markers of the AR tools. The AR tool must be previously installed in participants' devices. If the activity is part of a game, the game setup must be prepared. Markers can be found in the attached file.*

Setting the scene

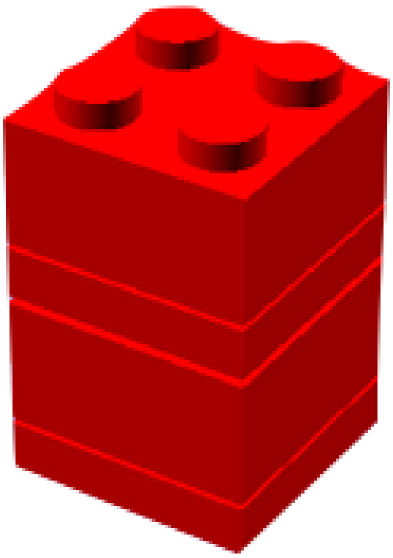
Explain how baryons are made as below.

Baryons are particles made of three quarks. Quarks carry electric charge (either 1/3 or 2/3 that of the proton), and *strangeness*: a quantum number that determines how the particle decays.

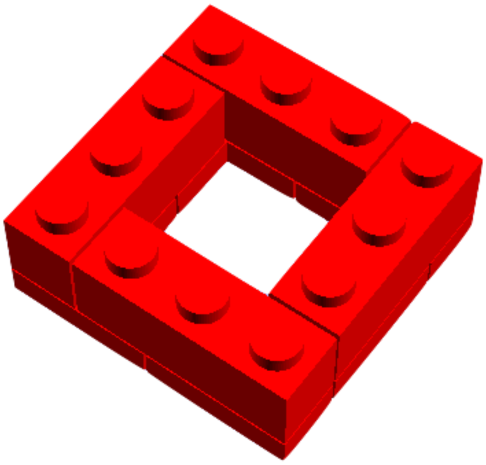
Baryons must have integer electric charge and strangeness, but, because of the Pauli's exclusion Principle, they cannot be made of three quarks of the same type.

There exist three quarks: the up quark, with charge +2/3, and the down quark, with charge –1/3, have no strangeness (actually, there are six quarks, each with a different quantum number, but all of them have either charge +2/3 or –1/3). The strange quark has strangeness equal to –1 and the same electric charge of the down quark.

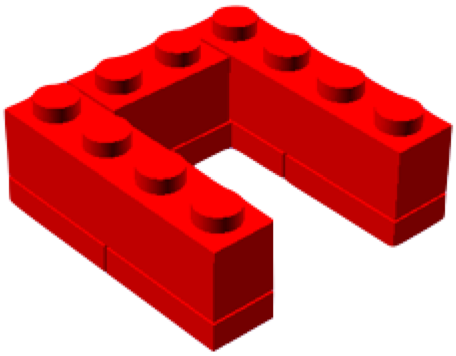
In the scenario, a quark is represented by an assembly of LEGO bricks. The charge of the corresponding quark is given by the height of the corresponding set of bricks, measured in units of number of bricks. Negative charges are represented as the depths of a hole at the center of the set of bricks, whose depth is proportional to the charge. So, the up quark, whose charge is +2/3, is represented as follow:



In fact, each protruding LEGO brick accounts for a charge +1/3. Contrastingly, a down quark is represented as

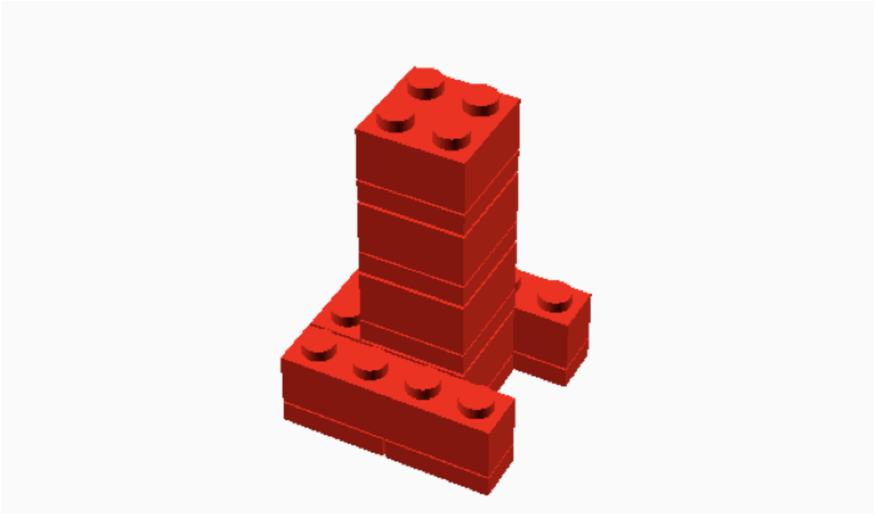


Which has a one brick deep hole at the center. The strange quark is like a down quark, but, being *strange*, has a modified side:



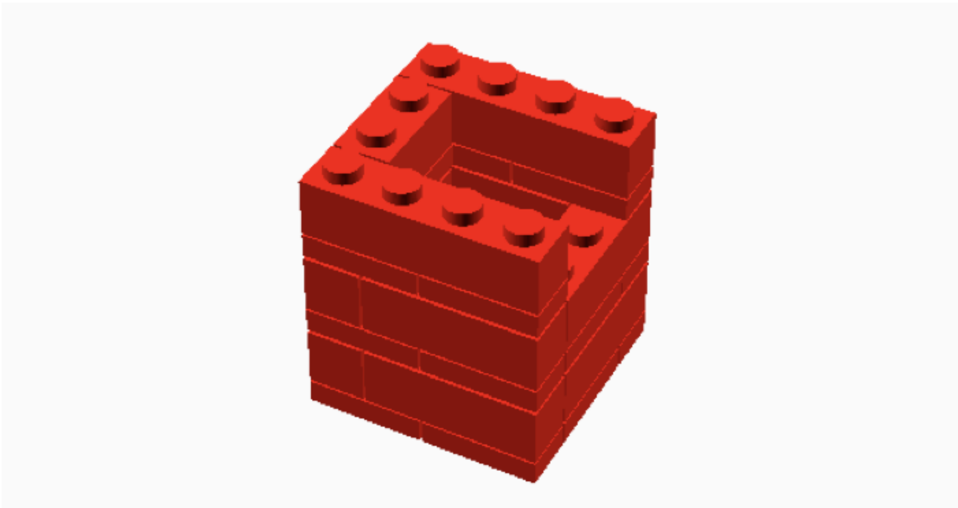
The game consists of combining three quarks and guessing the charge and the strangeness of the generated particle, then looking for its name by means of a search in textbooks or on the Internet.

As a result, a combination like uus, appears as follows:



The combination is made of two up-quarks and one strange-quark, and presents a central protrusion made of three bricks, corresponding to an electric charge of +1/3×3=+1. The s-quark has a missing side, and a hole at the center. The hole is filled by one of the bricks of the u-quarks tower. The presence of a missing side tells us that the corresponding particle has strangeness -1.

Neutral particles have a flat surface on top, while negatively charged particles exhibit a hole at the center, whose depth represents its charge in units of –1/3 per missing brick. The following image represents a Σ^- (pronounced sigma-minus): a particle whose strangeness is –1 with an electric charge opposite to that of the proton



The hole at the center has a depth of 3, such that the electric charge is –1/3 × 3=-1.

Distribute various markers around.

Look around

Look for the markers with the images of the quarks. Looking at them through the AR device will show their 3D model. Study them and get accustomed with their shape, from which you can infer their characteristics.

Select three markers and look at the particle they build, when markers are put side by side, close to each other.

A possible way of using the tool is to ask students to predict the characteristics of a given combination of quarks, then try to collect them and check if the combination is valid, and which particle they give.

Another possibility is to look for the name of the particles that have the observed characteristics, learn their properties, and the history of their discovery.

The scenario can be loaded using this QR-code:

Investigation/creation

Try to make all the possible combinations of u, d and s quarks. Compute their number, and look to what happens if you build the combinations. The uuu, ddd and sss combinations do not work and do not show any result. The reason being that the Pauli’s exclusion principle forbids two or more particles to be in the same state, and this combination is forbidden. Combinations like uud are permitted because the two u quarks can exist in two spin states.

In fact, eventually people discovered particles that could be interpreted as uuu, ddd and sss combinations, which were expected to be forbidden for the reason given above. This observation gave rise to Quantum Chromodynamics: a possible explanation of the existence of these combinations is that quarks carry a further quantum number that was called “colour” (which, of course, has nothing to do with ordinary colours). It is said that quarks exist in three colours (imagine them as three sort of charges): red, green and blue. Only colourless particles can be observed. Colourless particles are formed by quarks of different colours. So, e.g., uuu does not violate the Pauli's Principle because the three u quarks are in different colour state.

Communication and discussion/presentation

The observation is an opportunity to talk about the scientific method. The colour hypothesis cannot be taken as a scientific theory, unless it is verified by some experiment. It is not possible to observe colours directly, because, by definition, only colourless particles can be observed. However, physicists eventually found methods to prove that, indeed, colour exist as a sort of charge: it can be interpreted as the charge that originates the strong force.

One of the methods consists in computing the probability of producing certain combinations of quarks in reactions occurring at accelerators, where particles are smashed against others. It turns out that the probability of observing certain final states after collision is three times larger than expected, when colour is not considered.

The factor three is consistent with the colour hypothesis, because each quark comes in three species, enhancing the probability of observing the final states.

In fact, the latter is not the only proof of the correctness of the colour hypothesis. There are tens of experiments that can be explained only by assuming that each quark has three replicas with different colour.