Supplement to the Fundamental Building Blocks Poster

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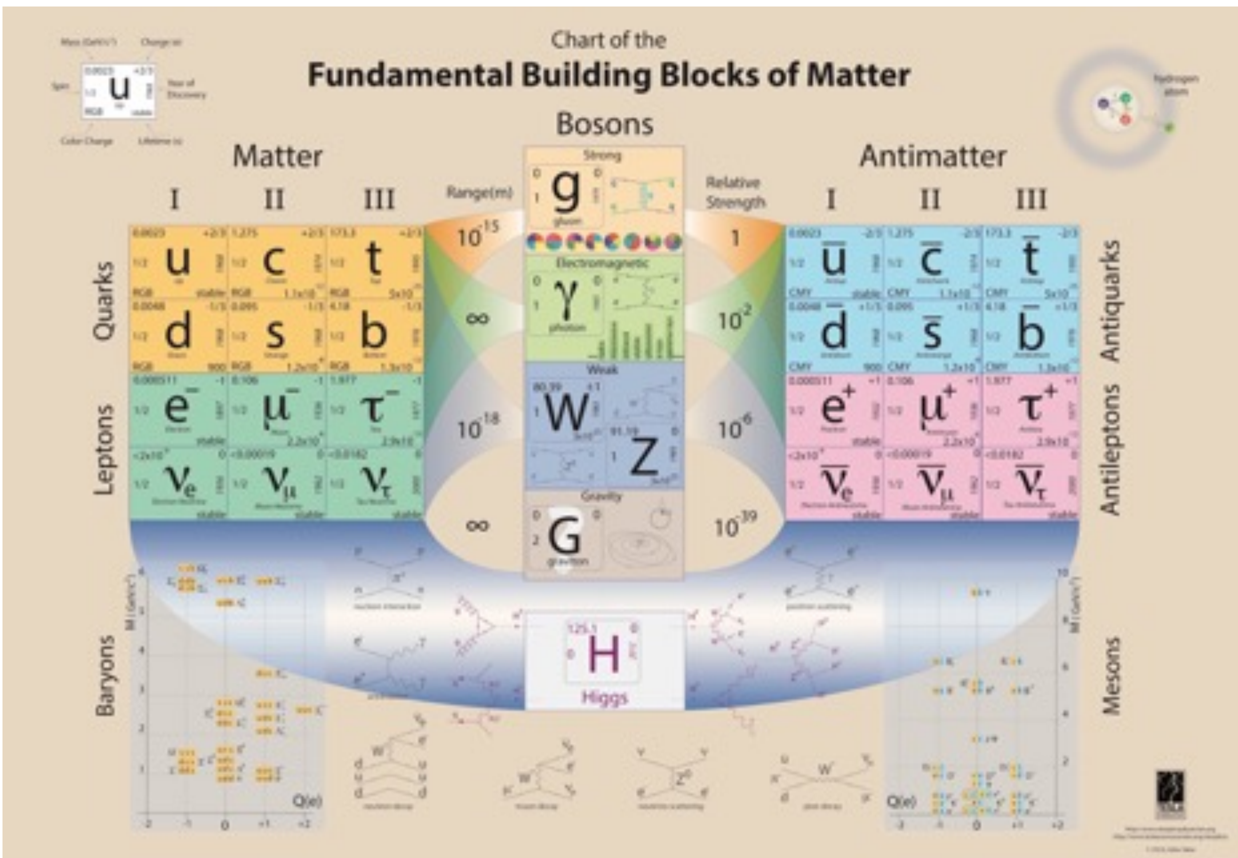

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This supplement describes the key points of the "Fundamental Building Blocks" poster. It is a short description of each part of the poster that will guide you through the elements that are the building blocks of matter.

Legend

Just as the Periodic Table includes a legend rectangle, the "Fundamental Building Blocks" poster provides one in the upper left corner. In the center of the rectangle is the symbol of the particle with the name written underneath. In the upper left corner of the rectangle is the particle's mass, given in Giga-electronvolts divided by the square of the speed of light in vacuum (GeV/c^2). This is a common unit used by particle physicists to display mass and is derived from Einstein's famous equation, $E = mc^2$. Moving clockwise around the rectangle, electric charge is given in the upper right corner of the rectangle. The charge is given as a fraction of the elementary charge, *e*, which is 1.60×10^{-19} coulomb. Below the charge is the year of discovery. In the lower right corner of the rectangle is the mean lifetime of the particle given in seconds. This is how long, on average, the particle exists before it decays. If a particle has a mean lifetime greater than 10^{26} years, it is listed as "stable". In the lower left corner is the color charge, sometimes simply referred to as color. Color charge has nothing to do with the visual perception of color; rather, it is a quantum property that behaves somewhat analogously to the mixing of the primary colors of visible light, red (R), blue (B), and green (G). Color charge is associated with the strong force, so it only applies to quarks, antiquarks, and gluons. The anticolors on the "Fundamental Building Blocks" poster are given in terms of their complementary colors in visible light, so anti-red is cyan (C), anti-green is magenta (M), and anti-blue is yellow (Y). Directly above the color charge is the spin of the particle. Spin, a quantum mechanical phenomenon, is an intrinsic form of angular momentum carried by elementary particles. Fermions (quarks, antiquarks, leptons, and anti-leptons) have spin one-half, while bosons may have spins of 0, 1, or 2.

Matter

All of the everyday items we encounter are composed of ordinary matter. The "Fundamental Building Blocks" poster displays the particles that make up matter on the left side. The "Matter" table is divided in two ways: horizontally into quarks and leptons and vertically into three generations. The two top rows list the quarks. Quarks and antiquarks make up hadrons. Quarks are affected by the strong force (also called the

About the Poster

The "Fundamental Building Blocks" poster was conceived by a group of educators convened by Helio Takai of Brookhaven National Laboratory as a different way of displaying information about the Standard Model. Some of the available charts provide a bare-bones view of the particles comprising the three generations of matter with the gauge bosons added as a fourth column in a sometimes confusing way. Antimatter is either left out altogether or added as a reference in a footnote. Spurred by the discovery of the Higgs boson in 2012, the educator group felt that a fresh visualization of the Standard Model might address some of these deficiencies and also provide teaching materials that lend themselves to the high school classroom. Each section of the poster may be downloaded in pdf format for use in various display formats from. The information in this supplement serves to add some context to the poster and briefly explain its components.

strong interaction), which binds the quarks together into larger particles, such as protons and neutrons. Quarks possess color charges of red, blue, or green. The idea of color as a separate quantum state was necessary to prevent violations of the Pauli Exclusion Principle. The two bottom rows list the leptons. Leptons are not affected by the strong force, so they do not have a color charge. The quarks and leptons exist in three distinct sets or generations. Roman numerals at the top of each column refer to the generation. All visible matter in our universe is composed of first generation particles (up quarks, down quarks, electrons, and electron neutrinos), which are the most stable. The diagram in the upper right corner of the poster shows a hydrogen atom, consisting of a proton, which is composed of two up quarks and one down quark, one of which is red, another blue, and the third green, with a single electron occupying the electron cloud. Depending on the color assignment of the quarks, there are three possible versions of the proton. Generation II and III particles have higher masses and quickly decay into lighter, more stable generation I particles. Generation II and III particles are produced by high energy collisions that occur naturally when cosmic rays enter the Earth's atmosphere and artificially in particle accelerators.

Antimatter

The antimatter particles are shown on the right side of the "Fundamental Building Blocks" poster. Every matter particle has a corresponding antiparticle possessing the same mass and an opposite electrical charge. Antiparticles are typically symbolized by drawing a horizontal bar over the corresponding matter symbol. Two exceptions are the positron, or anti-electron, which is symbolized by e^+, and the anti-muon, which is symbolized by μ^+. As with the matter particles, there are two rows of antiquarks, two rows of anti-leptons, and three vertical columns of generations. Unstable generation II and III particles again decay into stable generation I particles. When an antimatter particle encounters its matter counterpart, both are annihilated resulting in the production of varying proportions of high energy photons (usually gamma rays), neutrinos, and lower mass particle-antiparticle pairs. Antiparticles bind with each other to form antimatter just as ordinary particles bind to form normal matter. An anti-hydrogen atom would consist of an antiproton, made up of two anti-up quarks and one anti-down quark, one of which is cyan (anti-red), another yellow (anti-blue), and the third magenta (anti-green), with one positron occupying its cloud. The observable universe appears to be composed almost entirely of matter. The asymmetry of matter and antimatter in the observable universe is a major unsolved problem in physics

Bosons

Bosons are listed in the central column on the "Fundamental Building Blocks" poster. According to the Standard Model, bosons do not take up any space and can pile on top of one another. Because of this, bosons may be force-carrying particles that can combine to make a macroscopic force field. The bosons associated with the four forces (strong, electromagnetic, weak, and gravity) are grouped together in the central column. Because these bosons are associated with vector fields, they are also referred to as gauge bosons.

The effective range in meters of each force is indicated to the left of the "Bosons" column. These values are taken from the Hyperphysics website (http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html). Both the electromagnetic and gravitational forces extend to infinity making them long range forces. Because both the strong and weak forces are extremely short-ranged, they are also referred to as nuclear forces. The value of 10^{-15} meter given for the strong force is the range of the residual strong force. This is the nuclear force between two nucleons mediated by the pion. The fundamental strong interaction between quarks is mediated by the gluon and has direct effects inside a hadron at distances around 10^{-17} meter.

To the right of the "Bosons" column is an indication of the order of magnitude of each force, relative to the strong force, given for a separation distance of 10^{-15} meter. This distance is about the size of a nucleon and the maximum distance for the strong force to produce an effect. These values are also taken from the Hyperphysics website and are based upon the dimensionless coupling constant for each force. It should be noted that the gravitational coupling constant value is dependent on the masses of the particles chosen, and in this case, it is for two protons.

Gluons carry the strong force, which binds quarks together. The poster shows that there are eight different types of gluons. Gluons possess color charge, but it is more complicated than for the individual quarks. The poster represents this by showing eight particles with multi-coloration. Simple probability suggests that there should be nine gluons, but since the ninth gluon combination would be "color neutral" according to SU(3) theory, there are only eight. On the poster, there are curved, colored regions, or arcs, connecting the bosons to the matter and antimatter particles. The orange colored arcs emanating from the strong force box indicate that the strong force only affects quarks and antiquarks. The Feynman diagram in the strong force box shows the attraction between two quarks by the exchange of a gluon. Feynman diagrams are discussed in a separate section of this supplement.

The electromagnetic force is carried by photons, the particles of light. Although there are multiple regions in the electromagnetic spectrum, there is only one type of photon, usually represented by the Greek letter gamma. The green colored arcs emanating from the electromagnetic force box indicate that this force only affects charged fermions. The Feynman diagram in the electromagnetic force box shows the exchange of a photon when two electrons repel each other.

The weak force is carried by three bosons, the W^+, the W^-, and the Z. Unlike the other gauge bosons, these have mass and two of them are charged. The weak force is associated with various nuclear reactions, such as beta decay and nuclear fusion. The violet colored arcs emanating from the weak force box indicate that the weak force acts on all the fermions. The top Feynman diagram in the weak force box shows the reaction by which a down quark changes into an up quark. The bottom Feynman diagram shows a neutrino scattering off an electron.

Gravity is the force of attraction between objects containing mass. More generally, according to relativity, gravity also affects any object with a nonzero momentum, which includes photons and gluons. Gravity is believed to be carried by the graviton, a particle which has not yet been observed.

The rules of quantum mechanics and relativity predict that gravitons exist, but how they fit into the Standard Model has yet to be determined. The poster includes questions marks in the gravity box to express this unknown information.

On the poster, the Higgs boson is slightly separated from the others because it is associated with a scalar field rather than a vector field. The blue colored arcs emanating from the Higgs box indicate that it interacts with all the other particles, both fermions and the other bosons. Simplistically, it has been said in popular literature that the Higgs boson is responsible for the masses of the other particles. This is not quite true. The Higgs boson is the result of a vibration in the pervasive Higgs field. How particles interact with the Higgs field is what leads to their mass values. The violet Feynman diagrams connected to the Higgs box show two reactions that result in the formation of a Higgs and three possible decay reactions. It should be noted that the time axis on a Feynman diagram does not follow a rigid convention. These diagrams follow the custom dating back to the 1980s in which time is depicted horizontally and space vertically with the incoming particles at the left.

Baryons

Baryons are hadrons composed of three quarks or three antiquarks. They are "color neutral", so there must be one red quark, one blue quark, and one green quark for matter. In the color theory of light, red plus blue plus green produces white light, and this analogy is used for baryons. For antimatter, the corresponding anti-colors are combined to produce a color neutral "anti-white" particle. The Particle Data Group lists over one hundred baryons. To make sense of this, first, consider the quarks. Eliminate the top quark from consideration because its lifetime is too short for a gluon exchange to occur between a top and another quark. This is because the distance between a top quark and another quark (or antiquark in a meson) would be about 10^{-15} meter, and a gluon traveling at the speed of light would take about 10^{-23} second to propagate between the quarks. Since the top quark lifetime is around 10^{-25} second, there would not be enough time for the interaction to occur before the top quark decays. That leaves five quarks, which could combine to form 125 possible three-quark combinations. Quark spin considerations also lead to more possible baryons. For example, both the sigma-zero particle and the lambda-zero particle consist of an up, a down, and a strange quark, but in the sigma, the up and strange spin opposite from the down, and in the lambda, the up and down spin opposite from the strange. Various resonances further increase the number of baryons. Then, one doubles the total number of baryons when antiquarks are included to get an even bigger number.

The "Fundamental Building Blocks" poster has a graph involving baryons in the lower left corner. The graph plots baryon charge horizontally and baryon mass vertically. Charge is measured as a multiple of the elementary charge, e; and mass is measured in GeV/c^2. A small number of the possible baryons are shown including the proton, the neutron, and the antiproton. While most baryons have charges of +1, 0, or -1, other charges are possible, as shown by the Σ_c, which has a +2 charge.

Mesons

Mesons are hadrons composed of one quark and one antiquark. As with baryons, they must be color neutral, so a quark of one color must be matched with an antiquark of the corresponding anti-color. Since there are six quarks and six antiquarks, it might be expected that there would be 36 mesons. However, the lifetimes of the top quark and the anti-top antiquark again preclude them from entering into a combination involving a gluon exchange. That leaves five quarks and five antiquarks suggesting 25 possible mesons, but quantum mechanics reduces this to 24. All 24 mesons are shown on the graph in the lower right corner of the "Fundamental Building Blocks" poster. As with the baryon graph, charge is plotted horizontally and mass vertically. It is easily seen that only three charges occur: +1, 0, and -1. Only 21 meson labels are shown because three of them involve mixed states that include two quark-antiquark combinations. For example, the π^0 meson includes both the *up-antiup* and *down-antidown* combinations.

Feynman Diagrams

A Feynman diagram is a simple, pictorial way to show what can happen when elementary particles interact. In the Feynman diagrams on the "Fundamental Building Blocks" poster, fermions are shown as solid lines, photons as wavy lines, gluons as spirals, and W, Z, and Higgs bosons as dashed lines. Various interactions are shown in and around the boson boxes and are discussed in the "Bosons" section. Seven example diagrams of various interactions are shown in black in the center-bottom portion of the poster. As mentioned in the "Bosons" section, there is no agreed upon convention for depicting time and space. In these seven diagrams time is depicted horizontally and space vertically with the incoming particles on the left, just as in the "Bosons" section. "Nucleon interaction" shows the exchange of a pi meson between a proton and a neutron in a nucleus. The nuclear force that binds nucleons together is associated with the exchange of mesons and is a residual effect of the strong force. "Annihilation" depicts the reaction between an electron and a positron that results in the complete conversion of both particles into energy in the form of gamma ray photons. The positron arrow is directed away from the interaction vertex because reactant antiparticles are typically shown traveling backward in time. Similarly, decay product antiparticles are shown traveling forward in time. "Neutron decay" shows a neutron (one up quark and two down quarks) undergoing a weak interaction that produces a proton (two up quarks and one down quark), an electron, and an electron antineutrino. Note that the product antineutrino is traveling forward in time. "Muon decay" shows a muon undergoing a weak interaction to decay into an electron, an electron antineutrino, and a muon neutrino. "Neutrino scattering" depicts a neutrino interacting with an electron by exchanging a Z boson without altering the identity of either fermion, although energy and momentum would be transferred. "Pion decay" shows a π^- meson, consisting of a down quark and an anti-up antiquark, decaying via the weak interaction into a muon and a muon antineutrino. "Positron scattering" displays the electric repulsion between two positrons by the exchange of a photon.