

33.5 Quarks: Is That All There Is?

Learning Objectives

By the end of this section, you will be able to:

- Define fundamental particle.
- Describe quark and antiquark.
- List the flavors of quark.
- Outline the quark composition of hadrons.
- Determine quantum numbers from quark composition.

Quarks have been mentioned at various points in this text as fundamental building blocks and members of the exclusive club of truly elementary particles. Note that an elementary or fundamental particle has no substructure (it is not made of other particles) and has no finite size other than its wavelength. This does not mean that fundamental particles are stable—some decay, while others do not. Keep in mind that *all* leptons seem to be fundamental, whereas *no* hadrons are fundamental. There is strong evidence that quarks are the fundamental building blocks of hadrons as seen in Figure 33.15. Quarks are the second group of fundamental particles (leptons are the first). The third and perhaps final group of fundamental particles is the carrier particles for the four basic forces. Leptons, quarks, and carrier particles may be all there is. In this module we will discuss the quark substructure of hadrons and its relationship to forces as well as indicate some remaining questions and problems.

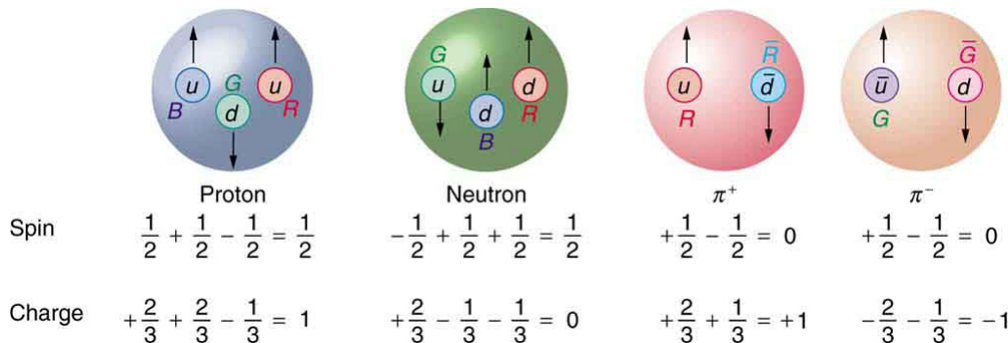


Figure 33.15 All baryons, such as the proton and neutron shown here, are composed of three quarks. All mesons, such as the pions shown here, are composed of a quark-antiquark pair. Arrows represent the spins of the quarks, which, as we shall see, are also colored. The colors are such that they need to add to white for any possible combination of quarks.

Conception of Quarks

Quarks were first proposed independently by American physicists Murray Gell-Mann and George Zweig in 1963. Their quaint name was taken by Gell-Mann from a James Joyce novel—Gell-Mann was also largely responsible for the con-

cept and name of strangeness. (Whimsical names are common in particle physics, reflecting the personalities of modern physicists.) Originally, three quark types—or flavors—were proposed to account for the then-known mesons and baryons. These quark flavors are named up (u), down (d), and strange (s). All quarks have half-integral spin and are thus fermions. All mesons have integral spin while all baryons have half-integral spin. Therefore, mesons should be made up of an even number of quarks while baryons need to be made up of an odd number of quarks. Figure 33.15 shows the quark substructure of the proton, neutron, and two pions. The most radical proposal by Gell-Mann and Zweig is the fractional charges of quarks, which are $\pm(\frac{2}{3})q_e$ and $(\frac{1}{3})q_e$, whereas all directly observed particles have charges that are integral multiples of q_e . Note that the fractional value of the quark does not violate the fact that the e is the smallest unit of charge that is observed, because a free quark cannot exist. Table 33.3 lists characteristics of the six quark flavors that are now thought to exist. Discoveries made since 1963 have required extra quark flavors, which are divided into three families quite analogous to leptons.

How Does it Work?

To understand how these quark substructures work, let us specifically examine the proton, neutron, and the two pions pictured in Figure 33.15 before moving on to more general considerations. First, the proton p is composed of the three quarks uud , so that its total charge is $+(\frac{2}{3})q_e + (\frac{2}{3})q_e - (\frac{1}{3})q_e = q_e$, as expected. With the spins aligned as in the figure, the proton's intrinsic spin is $+(\frac{1}{2}) + (\frac{1}{2}) - (\frac{1}{2}) = (\frac{1}{2})$, also as expected. Note that the spins of the up quarks are aligned, so that they would be in the same state except that they have different colors (another quantum number to be elaborated upon a little later). Quarks obey the Pauli exclusion principle. Similar comments apply to the neutron n , which is composed of the three quarks udd . Note also that the neutron is made of charges that add to zero but move internally, producing its well-known magnetic moment. When the neutron β^- decays, it does so by changing the flavor of one of its quarks. Writing neutron β^- decay in terms of quarks,

$$n \rightarrow p + \beta^- + \bar{\nu}_e \text{ becomes } udd \rightarrow uud + \beta^- + \bar{\nu}_e.$$

33.9

We see that this is equivalent to a down quark changing flavor to become an up quark:

$$d \rightarrow u + \beta^- + \bar{\nu}_e$$

33.10

| | | | | | | | | | | Mass (GeV/ c^2) |
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| Name | Symbol | Antiparticle | Spin | Charge | Mass | S | c | b | t | |
| Up | u | \bar{u} | 1/2 | $\pm \frac{2}{3}q_e$ | $\pm \frac{1}{3}$ | 0 | 0 | 0 | 0 | 0.005 |
| Down | d | \bar{d} | 1/2 | $\mp \frac{1}{3}q_e$ | $\pm \frac{1}{3}$ | 0 | 0 | 0 | 0 | 0.008 |
| Stranges | s | \bar{s} | 1/2 | $\mp \frac{1}{3}q_e$ | $\pm \frac{1}{3}$ | ∓ 1 | 0 | 0 | 0 | 0.50 |
| Charmed | c | \bar{c} | 1/2 | $\pm \frac{2}{3}q_e$ | $\pm \frac{1}{3}$ | 0 | ± 1 | 0 | 0 | 1.6 |
| Bottom | b | \bar{b} | 1/2 | $\mp \frac{1}{3}q_e$ | $\pm \frac{1}{3}$ | 0 | 0 | ∓ 1 | 0 | 5 |
| Top | t | \bar{t} | 1/2 | $\pm \frac{2}{3}q_e$ | $\pm \frac{1}{3}$ | 0 | 0 | 0 | ± 1 | 173 |

Table 33.3 Quarks and Antiquarks

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The lower of the \pm symbols are the values for antiquarks.

| Particle | Quark Composition |
|---------------|-------------------|
| <i>Mesons</i> | |
| π^+ | $u\bar{d}$ |
| π^- | $\bar{u}d$ |

| Particle | Quark Composition |
|-------------|--|
| π^0 | $u\bar{u}$ $, \bar{d}d$ mixture11 11 These two mesons are different mixtures, but each is its own antiparticle, as indicated by its quark composition. |
| η^0 | $u\bar{u}$ $, \bar{d}d$ mixture12 12 These two mesons are different mixtures, but each is its own antiparticle, as indicated by its quark composition. |
| K^0 | $d\bar{s}$ |
| \bar{K}^0 | $\bar{d}s$ |
| K^+ | $u\bar{s}$ |
| K^- | $\bar{u}s$ |
| J/ψ | $c\bar{c}$ |
| Υ | $b\bar{b}$ |

| Particle | Quark Composition |
|---|-------------------|
| <i>Baryons</i>13,14 | |
| 13 | |
| Antibaryons have the antiquarks of their counterparts. The antiproton \bar{p} is $\bar{u}\bar{u}\bar{d}$, for example. | |
| 14 | |
| Baryons composed of the same quarks are different states of the same particle. For example, the Δ^+ is an excited state of the proton. | |
| p | uud |
| n | udd |
| Δ^0 | udd |
| Δ^+ | uud |
| Δ^- | ddd |
| Δ^{++} | uuu |
| Λ^0 | uds |
| Σ^0 | uds |
| Σ^+ | uus |
| Σ^- | dds |
| Ξ^0 | uss |
| Ξ^- | dss |
| Ω^- | sss |

Table 33.4 Quark Composition of Selected Hadrons15

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These two mesons are different mixtures, but each is its own antiparticle, as indicated by its quark composition.

This is an example of the general fact that **the weak nuclear force can change the flavor of a quark**. By general, we mean that any quark can be converted to any other (change flavor) by the weak nuclear force. Not only can we get $d \rightarrow u$, we can also get $u \rightarrow d$. Furthermore, the strange quark can be changed by the weak force, too, making $s \rightarrow u$ and $s \rightarrow d$ possible. This explains the violation of the conservation of strangeness by the weak force noted in the preceding section. Another general fact is that **the strong nuclear force cannot change the flavor of a quark**.

Again, from Figure 33.15, we see that the π^+ meson (one of the three pions) is composed of an up quark plus an antidown quark, or $u\bar{d}$. Its total charge is thus $+\left(\frac{2}{3}\right)q_e + \left(\frac{1}{3}\right)q_e = q_e$, as expected. Its baryon number is 0, since it has a quark and an antiquark with baryon numbers $+\left(\frac{1}{3}\right) - \left(\frac{1}{3}\right) = 0$. The π^+ half-life is relatively long since, although it is composed of matter and antimatter, the quarks are different flavors and the weak force should cause the decay by changing the flavor of one into that of the other. The spins of the u and \bar{d} quarks are antiparallel, enabling the pion to have spin zero, as observed experimentally. Finally, the π^- meson shown in Figure 33.15 is the antiparticle of the π^+ meson, and it is composed of the corresponding quark antiparticles. That is, the π^+ meson is $u\bar{d}$, while the π^- meson is $\bar{u}d$. These two pions annihilate each other quickly, because their constituent quarks are each other's antiparticles.

Two general rules for combining quarks to form hadrons are:

1. Baryons are composed of three quarks, and antibaryons are composed of three antiquarks.
2. Mesons are combinations of a quark and an antiquark.

One of the clever things about this scheme is that only integral charges result, even though the quarks have fractional charge.

All Combinations are Possible

All quark combinations are possible. Table 33.4 lists some of these combinations. When Gell-Mann and Zweig proposed the original three quark flavors, particles corresponding to all combinations of those three had not been observed. The pattern was there, but it was incomplete—much as had been the case in the periodic table of the elements and the chart of nuclides. The Ω^- particle, in particular, had not been discovered but was predicted by quark theory. Its combination of three strange quarks, sss , gives it a strangeness of -3 (see Table 33.2) and other predictable characteristics, such as spin, charge, approximate mass, and lifetime. If the quark picture is complete, the Ω^- should exist. It was first observed in 1964 at Brookhaven National Laboratory and had the predicted characteristics as seen in Figure 33.16. The discovery of the Ω^- was convincing indirect evidence for the existence of the three original quark flavors and boosted theoretical and experimental efforts to further explore particle physics in terms of quarks.

Patterns and Puzzles: Atoms, Nuclei, and Quarks

Patterns in the properties of atoms allowed the periodic table to be developed. From it, previously unknown elements were predicted and observed. Similarly, patterns were observed in the properties of nuclei, leading to the chart of nuclides and successful predictions of previously unknown nuclides. Now with particle physics, patterns imply a quark substructure that, if taken literally, predicts previously unknown particles. These have now been observed in another triumph

of underlying unity.

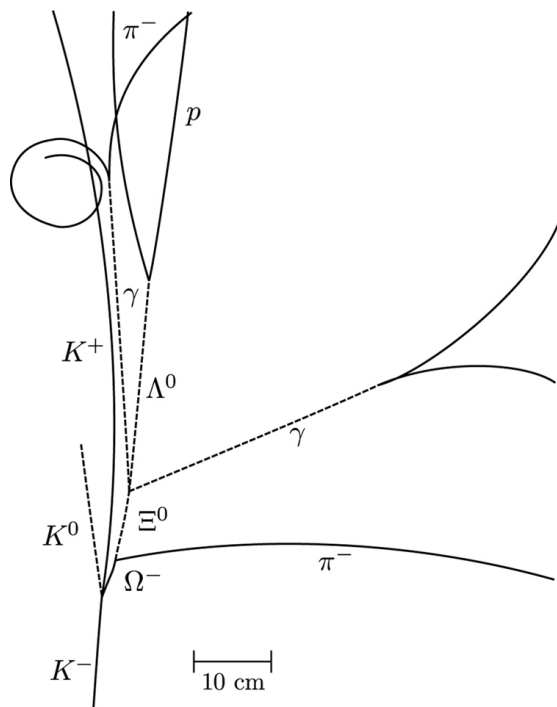


Figure 33.16 The image relates to the discovery of the Ω^- . It is a secondary reaction in which an accelerator-produced K^- collides with a proton via the strong force and conserves strangeness to produce the Ω^- with characteristics predicted by the quark model. As with other predictions of previously unobserved particles, this gave a tremendous boost to quark theory. (credit: Brookhaven National Laboratory)

Example 33.4

Quantum Numbers From Quark Composition Verify the quantum numbers given for the Ξ^0 particle in Table 33.2 by adding the quantum numbers for its quark composition as given in Table 33.4.

Strategy The composition of the Ξ^0 is given as uss in Table 33.4. The quantum numbers for the constituent quarks are given in Table 33.3. We will not consider spin, because that is not given for the Ξ^0 . But we can check on charge and the other quantum numbers given for the quarks.

Solution The total charge of uss is $+\left(\frac{2}{3}\right)q_e - \left(\frac{1}{3}\right)q_e - \left(\frac{1}{3}\right)q_e = 0$, which is correct for the Ξ^0 . The baryon number is $+\left(\frac{1}{3}\right) + \left(\frac{1}{3}\right) + \left(\frac{1}{3}\right) = 1$, also correct since the Ξ^0 is a matter baryon and has $B = 1$, as listed in Table 33.2. Its

strangeness is $S = 0 - 1 - 1 = -2$, also as expected from Table 33.2. Its charm, bottomness, and topness are 0, as are its lepton family numbers (it is not a lepton).

Discussion This procedure is similar to what the inventors of the quark hypothesis did when checking to see if their solution to the puzzle of particle patterns was correct. They also checked to see if all combinations were known, thereby predicting the previously unobserved Ω^- as the completion of a pattern.

Now, Let Us Talk About Direct Evidence

At first, physicists expected that, with sufficient energy, we should be able to free quarks and observe them directly. This has not proved possible. There is still no direct observation of a fractional charge or any isolated quark. When large energies are put into collisions, other particles are created—but no quarks emerge. There is nearly direct evidence for quarks that is quite compelling. By 1967, experiments at SLAC scattering 20-GeV electrons from protons had produced results like Rutherford had obtained for the nucleus nearly 60 years earlier. The SLAC scattering experiments showed unambiguously that there were three pointlike (meaning they had sizes considerably smaller than the probe's wavelength) charges inside the proton as seen in Figure 33.17. This evidence made all but the most skeptical admit that there was validity to the quark substructure of hadrons.

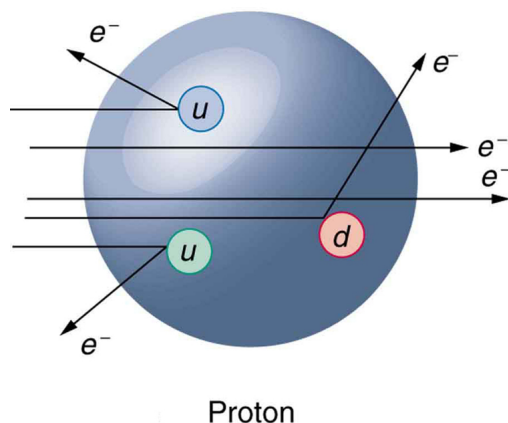


Figure 33.17 Scattering of high-energy electrons from protons at facilities like SLAC produces evidence of three point-like charges consistent with proposed quark properties. This experiment is analogous to Rutherford's discovery of the small size of the nucleus by scattering α particles. High-energy electrons are used so that the probe wavelength is small enough to see details smaller than the proton.

More recent and higher-energy experiments have produced jets of particles in collisions, highly suggestive of three quarks in a nucleon. Since the quarks are

very tightly bound, energy put into separating them pulls them only so far apart before it starts being converted into other particles. More energy produces more particles, not a separation of quarks. Conservation of momentum requires that the particles come out in jets along the three paths in which the quarks were being pulled. Note that there are only three jets, and that other characteristics of the particles are consistent with the three-quark substructure.

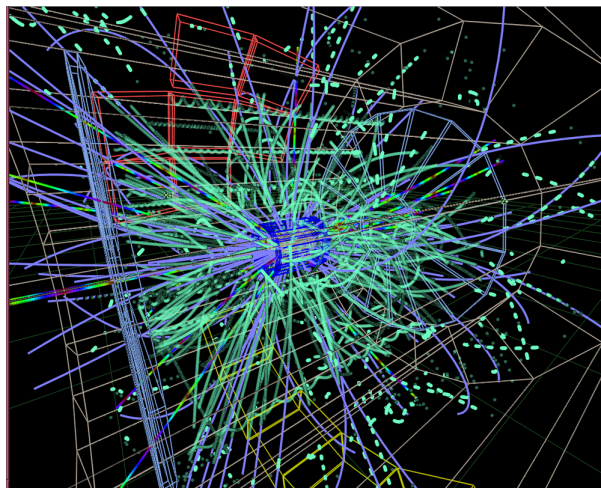


Figure 33.18 Simulation of a proton-proton collision at 14-TeV center-of-mass energy in the ALICE detector at CERN LHC. The lines follow particle trajectories and the cyan dots represent the energy depositions in the sensitive detector elements. (credit: Matevž Tadel)

Quarks Have Their Ups and Downs

The quark model actually lost some of its early popularity because the original model with three quarks had to be modified. The up and down quarks seemed to compose normal matter as seen in Table 33.4, while the single strange quark explained strangeness. Why didn't it have a counterpart? A fourth quark flavor called charm (c) was proposed as the counterpart of the strange quark to make things symmetric—there would be two normal quarks (u and d) and two exotic quarks (s and c). Furthermore, at that time only four leptons were known, two normal and two exotic. It was attractive that there would be four quarks and four leptons. The problem was that no known particles contained a charmed quark. Suddenly, in November of 1974, two groups (one headed by C. C. Ting at Brookhaven National Laboratory and the other by Burton Richter at SLAC) independently and nearly simultaneously discovered a new meson with characteristics that made it clear that its substructure is $c\bar{c}$. It was called J by one group and psi (ψ) by the other and now is known as the J/ψ meson. Since then, numerous particles have been discovered containing the charmed quark, consistent in every way with the quark model. The discovery of the J/ψ

meson had such a rejuvenating effect on quark theory that it is now called the November Revolution. Ting and Richter shared the 1976 Nobel Prize.

History quickly repeated itself. In 1975, the tau (τ) was discovered, and a third family of leptons emerged as seen in Table 33.2). Theorists quickly proposed two more quark flavors called top (t) or truth and bottom (b) or beauty to keep the number of quarks the same as the number of leptons. And in 1976, the upsilon (Υ) meson was discovered and shown to be composed of a bottom and an antibottom quark or $b\bar{b}$, quite analogous to the J/ψ being $c\bar{c}$ as seen in Table 33.4. Being a single flavor, these mesons are sometimes called bare charm and bare bottom and reveal the characteristics of their quarks most clearly. Other mesons containing bottom quarks have since been observed. In 1995, two groups at Fermilab confirmed the top quark's existence, completing the picture of six quarks listed in Table 33.3. Each successive quark discovery—first c , then b , and finally t —has required higher energy because each has higher mass. Quark masses in Table 33.3 are only approximately known, because they are not directly observed. They must be inferred from the masses of the particles they combine to form.

What's Color got to do with it?—A Whiter Shade of Pale

As mentioned and shown in Figure 33.15, quarks carry another quantum number, which we call color. Of course, it is not the color we sense with visible light, but its properties are analogous to those of three primary and three secondary colors. Specifically, a quark can have one of three color values we call **red** (R), **green** (G), and **blue** (B) in analogy to those primary visible colors. Antiquarks have three values we call **antired or cyan** (\bar{R}), **antigreen or magenta** (\bar{G}), and **antiblue or yellow** (\bar{B}) in analogy to those secondary visible colors. The reason for these names is that when certain visual colors are combined, the eye sees white. The analogy of the colors combining to white is used to explain why baryons are made of three quarks, why mesons are a quark and an antiquark, and why we cannot isolate a single quark. The force between the quarks is such that their combined colors produce white. This is illustrated in Figure 33.19. A baryon must have one of each primary color or RGB, which produces white. A meson must have a primary color and its anticolor, also producing white.

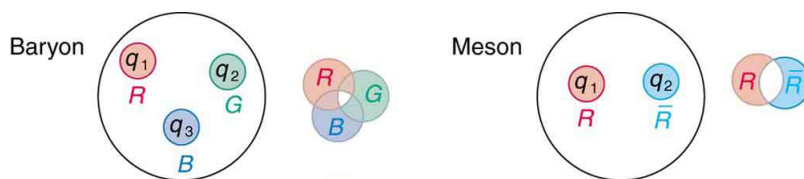


Figure 33.19 The three quarks composing a baryon must be RGB, which add to white. The quark and antiquark composing a meson must be a color and anticolor, here $R\bar{R}$ also adding to white. The force between systems that have

color is so great that they can neither be separated nor exist as colored.

Why must hadrons be white? The color scheme is intentionally devised to explain why baryons have three quarks and mesons have a quark and an antiquark. Quark color is thought to be similar to charge, but with more values. An ion, by analogy, exerts much stronger forces than a neutral molecule. When the color of a combination of quarks is white, it is like a neutral atom. The forces a white particle exerts are like the polarization forces in molecules, but in hadrons these leftovers are the strong nuclear force. When a combination of quarks has color other than white, it exerts *extremely* large forces—even larger than the strong force—and perhaps cannot be stable or permanently separated. This is part of the theory of quark confinement, which explains how quarks can exist and yet never be isolated or directly observed. Finally, an extra quantum number with three values (like those we assign to color) is necessary for quarks to obey the Pauli exclusion principle. Particles such as the Ω^- , which is composed of three strange quarks, sss , and the Δ^{++} , which is three up quarks, uuu , can exist because the quarks have different colors and do not have the same quantum numbers. Color is consistent with all observations and is now widely accepted. Quark theory including color is called quantum chromodynamics (QCD), also named by Gell-Mann.

The Three Families

Fundamental particles are thought to be one of three types—leptons, quarks, or carrier particles. Each of those three types is further divided into three analogous families as illustrated in Figure 33.20. We have examined leptons and quarks in some detail. Each has six members (and their six antiparticles) divided into three analogous families. The first family is normal matter, of which most things are composed. The second is exotic, and the third more exotic and more massive than the second. The only stable particles are in the first family, which also has unstable members.

Always searching for symmetry and similarity, physicists have also divided the carrier particles into three families, omitting the graviton. Gravity is special among the four forces in that it affects the space and time in which the other forces exist and is proving most difficult to include in a Theory of Everything or TOE (to stub the pretension of such a theory). Gravity is thus often set apart. It is not certain that there is meaning in the groupings shown in Figure 33.20, but the analogies are tempting. In the past, we have been able to make significant advances by looking for analogies and patterns, and this is an example of one under current scrutiny. There are connections between the families of leptons, in that the τ decays into the μ and the μ into the e . Similarly for quarks, the higher families eventually decay into the lowest, leaving only u and d quarks. We have long sought connections between the forces in nature. Since these are carried by particles, we will explore connections between gluons, W^\pm and Z^0 , and photons as part of the search for unification of forces discussed in GUTs: The Unification of Forces..

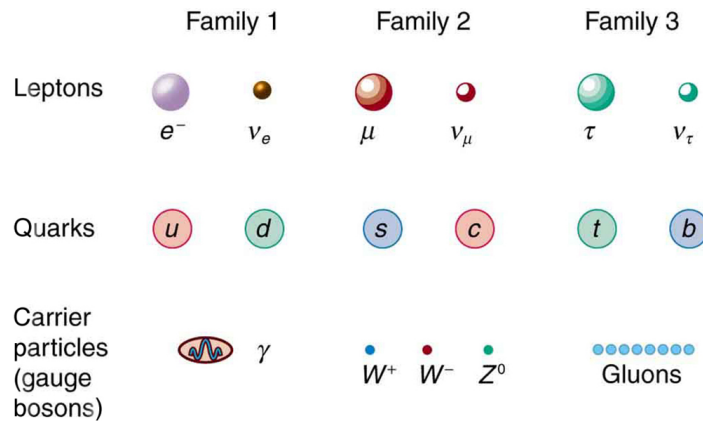


Figure 33.20 The three types of particles are leptons, quarks, and carrier particles. Each of those types is divided into three analogous families, with the graviton left out.