

# What is the world made of? What holds it together?

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Why do so many things in this world share the same characteristics?

People have come to realize that the matter of the world is made from a few fundamental building blocks of nature. The word "**fundamental**" is key here. By fundamental building blocks we mean objects that are **simple and structureless** -- not made of anything smaller. Even in ancient times, people sought to organize the world around them into fundamental elements, such as earth, air, fire, and water. Today we know that there is something more fundamental than earth, water, air, and fire...

## Is the atom fundamental?

People soon realized that they could categorize atoms into groups that shared similar chemical properties (as in the Periodic Table of the Elements). This indicated that atoms were made up of simpler building blocks, and that it was these simpler building blocks in different combinations that determined which atoms had which chemical properties.

Moreover, experiments which "looked" into an atom using particle probes indicated that atoms had structure and were not just squishy balls. These experiments helped scientists determine that atoms have a tiny but dense, positive nucleus and a cloud of negative electrons ( $e^-$ ).

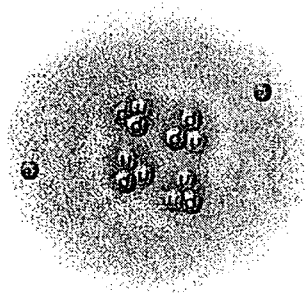
## Is the Nucleus Fundamental?

Because it appeared small, solid, and dense, scientists originally thought that the nucleus was fundamental. Later, they discovered that it was made of protons ( $p^+$ ), which are positively charged, and neutrons ( $n$ ), which have no charge.

## So, then, are protons and neutrons fundamental?

Physicists have discovered that protons and neutrons are composed of even smaller particles called **quarks**. As far as we know, quarks are like points in geometry. They're not made up of anything else.

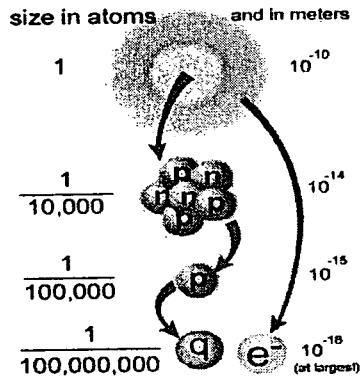
After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental.



Electrons are in constant motion around the nucleus, protons and neutrons jiggle within the nucleus, and quarks jiggle within the protons and neutrons as shown above. This picture is quite distorted. If we drew the atom to scale and made protons and neutrons a centimeter in diameter, then the electrons and quarks would be **less than the diameter of a hair** and the entire atom's diameter would be greater than the length of thirty cricket grounds! 99.999999999999% of an atom's volume is just empty space!

### Scale of the atom.

While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that. We don't know exactly how small quarks and electrons are; they are definitely smaller than  $10^{-18}$  meters, and they might literally be points, but we do not know. It is also possible that quarks and electrons are not fundamental after all, and will turn out to be made up of other, more fundamental particles. (Oh, will this madness ever end?)



Physicists have developed a theory called **The Standard Model** that explains what the world is and what holds it together. It is a simple and comprehensive theory that explains all the hundreds of particles and complex interactions with only:

- 6 quarks.
- 6 leptons. The best-known lepton is the electron. We will talk about these particles later.
- Force carrier particles, like the photon. We will talk about these particles later.

### The Standard Model

All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles. The Standard Model is a good **theory**. Experiments have verified its predictions to incredible precision, and all the particles predicted by this theory have been found. But it does not explain everything. For example, gravity is not included in the Standard Model.

### Quarks and Leptons

As you have read, everything from galaxies to mountains to molecules is made from **quarks** and **leptons**. But that is not the whole story. Quarks behave differently than leptons, and for each kind of matter particle there is a corresponding antimatter particle.

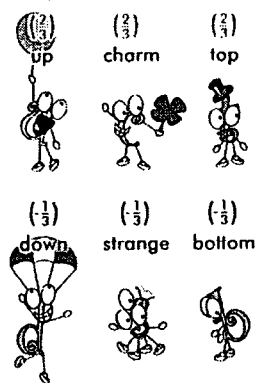
## Matter and Antimatter

For every type of matter particle we've found, there also exists a corresponding **antimatter** particle, or **antiparticle**. Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges. For instance, a proton is electrically positive whereas an antiproton is electrically negative. Gravity affects matter and antimatter the same way because gravity is not a charged property and a matter particle has the same mass as its antiparticle.

***When a matter particle and antimatter particle meet, they annihilate into pure energy!***

## Quarks

**Quarks** are one type of matter particle. Most of the matter we see around us is made from protons and neutrons, which are composed of quarks. There are **six quarks**, but physicists usually talk about them in terms of three pairs: **up/down**, **charm/anti-charm**, and **top/anti-top**. (Also, for each of these quarks, there is a corresponding antiquark.) Be glad that quarks have such silly names -- it makes them easier to remember!



Quarks have the unusual characteristic of having a **fractional** electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called **color charge**, which we will discuss later.

The most elusive quark, the **top quark**, was discovered in 1995 after its existence had been theorized for 20 years.

The naming of quarks...began when, in 1964, Murray Gell-Mann and George Zweig suggested that hundreds of the particles known at the time could be explained as combinations of just three fundamental particles. Gell-Mann chose the name "quarks," pronounced "kworks," for these three particles, a nonsense word used by James Joyce in the novel *Finnegan's Wake*: "Three quarks for Muster Mark!"

In order to make their calculations work, the quarks had to be assigned fractional electrical charges of  $\frac{2}{3}$  and  $-\frac{1}{3}$ . Such charges had never been observed before. Quarks are never observed by themselves, and so initially these quarks were regarded as mathematical fiction. Experiments have since convinced physicists that not only do quarks exist, but there are six of them, not three.

## Hadrons, Baryons, and Mesons

Although individual quarks have fractional electrical charges, they combine such that hadrons have a net integer electric charge. Another property of hadrons is that they have no net color charge even though the quarks themselves carry color charge .

Baryons...are any hadron which is made of three quarks

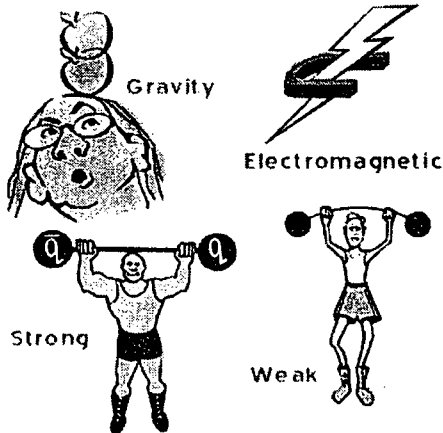
Mesons...contain one quark (q) and one antiquark ( $\bar{q}$ ) .

## Leptons

The other type of matter particles are the **leptons**. There are six leptons, three of which have electrical charge and three of which do not. They appear to be point-like particles without internal structure. The best known lepton is the **electron** ( $e^-$ ). The other two charged leptons are the **muon** ( $\mu$ ) and the **tau**, which are charged like electrons but have a lot more mass. The other leptons are the three types of **neutrinos**. They have no electrical charge, very little mass, and they are very hard to find.

Quarks are sociable and only exist in composite particles with other quarks, whereas leptons are solitary particles. Think of the charged leptons as independent cats with associated neutrino fleas, which are very hard to see. For each lepton there is a corresponding antimatter antilepton. Note that the anti-electron has a special name, the "positron."

## What holds it together?



The universe, which we know and love, exists because the fundamental particles interact. These interactions include attractive and repulsive forces, decay, and annihilation.

There are four fundamental interactions between particles, and **all forces in the world can be attributed to these four interactions!**

That's right: Any force you can think of -- friction, magnetism, gravity, nuclear decay, and so on -- is caused by one of these four fundamental interactions.

## What's the difference between a force and an interaction?

This is a hard distinction to make. Strictly speaking, a **force** is the effect on a particle due to the presence of other particles. The **interactions** of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through. The reason this gets confusing is that most people, even most physicists, usually use "force" and "interaction" interchangeably, although "interaction" is more correct. For instance, we call the particles which carry the interactions **force-carrier particles**. You will usually be okay using the terms interchangeably, but you should know that they are different.

### *How do matter particles interact?*

The problem is that things interact without touching! How do two magnets "feel" each other's presence and attract or repel accordingly? How does the sun attract the earth? We know the answers to these questions are "magnetism" and "gravity," but what are these forces?

At a fundamental level, a force isn't just something that happens to particles. It is a thing which is passed between two particles.

We see examples of attractive forces in everyday life (such as magnets and gravity), and so we generally take it for granted that an object's presence can just affect another object. It is when we approach the deeper question, "How can two objects affect one another without touching?" that we propose that the invisible force could be an exchange of force carrier particles. Particle physicists have found that we can explain the force of one particle acting on another to INCREDIBLE precision by the exchange of these force carrier particles.

The electromagnetic force causes like-charged things to repel and oppositely-charged things to attract. Many everyday forces, such as friction, and even magnetism, are caused by the electromagnetic, or E-M force. For instance, the force that keeps you from falling through the floor is the electromagnetic force which causes the atoms making up the matter in your feet and the floor to resist being displaced.

The carrier particle of the electromagnetic force is the **photon**. Photons of different energies span the electromagnetic spectrum of x rays, visible light, radio waves, and so forth.

Photons have zero mass, as far as we know, and always travel at the "speed of light",  $c$ , which is about 300,000,000 meters per second, or 186,000 miles per second, in a vacuum.

## **We have another problem with atoms, though. What binds the nucleus together?**

The nucleus of an atom consists of a bunch of protons and neutrons crammed together. Since neutrons have no charge and the positively-charged protons repel one another, **why doesn't the nucleus blow apart?** We cannot account for the nucleus staying together with just electromagnetic force. What else could there be? Gravity? Nope! The gravitational force is far too weak to overpower the electromagnetic force.

### **So how can we account for this dilemma?**

To understand what is happening inside the nucleus, we need to understand more about the quarks that make up the protons and neutrons in the nucleus. Quarks have electromagnetic

charge, and they also have an altogether different kind of charge called **color charge**. The force between color-charged particles is very strong, so this force is "creatively" called **strong force**. The strong force holds quarks together to form hadrons, so its carrier particles are whimsically called **gluons** because they so tightly "glue" quarks together.



### So what holds the nucleus together? Huh?

The answer is that, in short, they don't call it the strong force for nothing. The strong force between the quarks in one proton and the quarks in another proton is strong enough to overwhelm the repulsive electromagnetic force. This is called the **residual strong interaction**, and it is what "glues" the nucleus together.

There are six kinds of quarks and six kinds of leptons. But all the stable matter of the universe appears to be made of just the two least-massive quarks (up quark and down quark), the least-massive charged lepton (the electron), and the neutrinos.

**Weak interactions** are responsible for the decay of massive quarks and leptons into lighter quarks and leptons. When fundamental particles decay, it is very strange: we observe the particle vanishing and being replaced by two or more different particles. Although the total of mass and energy is conserved, some of the original particle's mass is converted into kinetic energy, and the resulting particles always have less mass than the original particle that decayed.

The only matter around us that is stable is made up of the smallest quarks and leptons, which cannot decay any further. When a quark or lepton changes type (a muon changing to an electron, for instance) it is said to change **flavor**. All flavor changes are due to the weak interaction.

The carrier particles of the weak interactions are the  $W^+$ ,  $W^-$ , and the  $Z$  particles. The  $W$ 's are electrically charged and the  $Z$  is neutral.

The Standard Model has united electromagnetic interactions and weak interactions into one unified interaction called **electroweak**.

**Electroweak:** In the Standard Model the weak and the electromagnetic interactions have been combined into a unified **electroweak** theory. Physicists had long believed that weak forces were closely related to electromagnetic forces.

Eventually they discovered that at very short distances (about  $10^{-18}$  meters) the strength of the weak interaction is comparable to that of the electromagnetic. Physicists concluded that, in fact, the weak and electromagnetic forces have essentially equal strengths. This is because the strength of the interaction depends strongly on both the mass of the force carrier and the distance of the interaction. The difference between their observed strengths is due to the huge difference in mass between the  $W$  and  $Z$  particles, which are very massive, and the photon, which has no mass as far as we know gravity.

Gravity is weird. It is clearly one of the fundamental interactions, but the Standard Model cannot satisfactorily explain it. This is one of those major unanswered problems in physics today.

In addition, the gravity force carrier particle has not been found. Such a particle, however, is predicted to exist and may someday be found: the **graviton**.

Fortunately, the effects of gravity are extremely tiny in most particle physics situations compared to the other three interactions, so theory and experiment can be compared without including gravity in the calculations. Thus, the Standard Model works without explaining gravity.

**So, The world is made of six quarks and six leptons. Everything we see is conglomeration of quarks and leptons. There are four fundamental forces and there are force carrier particles associated with each force.**