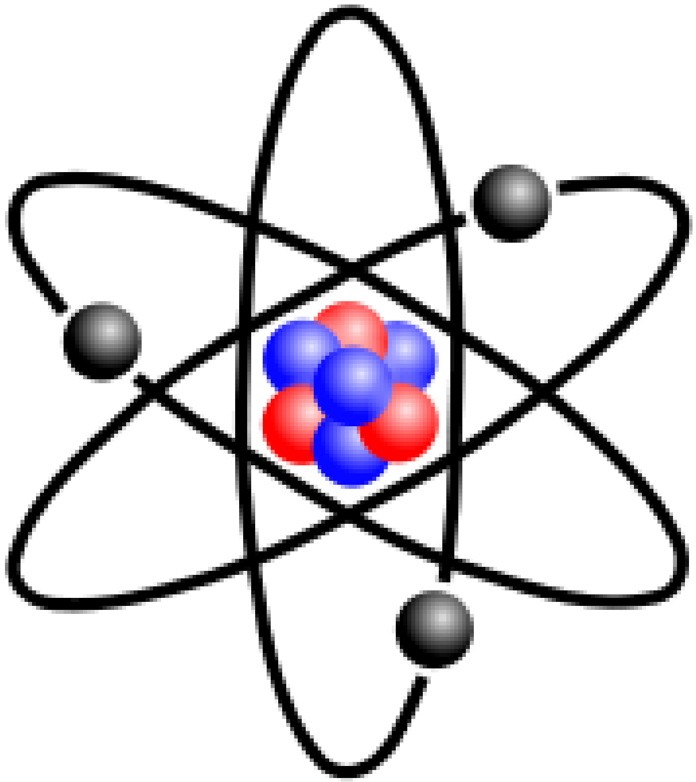

Our bodies are made of neutrons, protons and electrons. Practically all protons and electrons originated 13.8 billion years ago during the Big Bang. At some point in time, some of them come together and form our bodies that carry life and informational environment called 'soul.' During a brief moment of life they stay together, and then disperse in space and time - forever. Most of them will exist trillions of years - as long as the universe itself.

So, enjoy your brief but beautiful moments of life, and welcome to the world of elementary particles.

Sergei Zverev

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Sources of information for this review: multiple different

"Elementary" Particles

More than 200, most of which live $10^{-8} - 10^{-23}$ s. Stable: electron, proton, photon (form regular matter)

Type	Name	Symbol	Mass (MeV/c^2)	Mean lifetime
Lepton	Electron / Positron	e^- / e^+	0.511	$> 4.6 \times 10^{26}$ years
	Muon / Antimuon	μ^- / μ^+	105.6	2.2×10^{-6} seconds
	Tau lepton / Antitau	τ^- / τ^+	1777	2.9×10^{-13} seconds
Meson	Neutral Pion	π^0	135	8.4×10^{-17} seconds
	Charged Pion	π^+ / π^-	139.6	2.6×10^{-8} seconds
Baryon	Proton / Antiproton	p^+ / p^-	938.2	$> 10^{29}$ years
	Neutron / Antineutron	$n / \bar{n}$	939.6	885.7 seconds
Boson	W boson	W^+ / W^-	80,400	10^{-25} seconds
	Z boson	Z^0	91,000	10^{-25} seconds

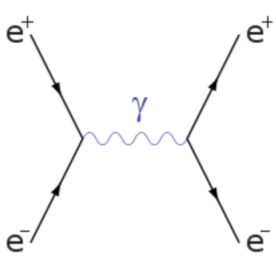
$m_e = 0.911\times10^{-30}$ kg = 0.511 MeV/c^2; $m_p = 1.673\times10^{-27}$ kg = 938.2 MeV/c^2

The diameter of a single proton is believed to be 1.6×10^{-15} m (nucleus of hydrogen), and the diameter of the heaviest nuclei, such as uranium, is about 15×10^{-15} m. The radius of the nucleus can be approximated by the following formula:

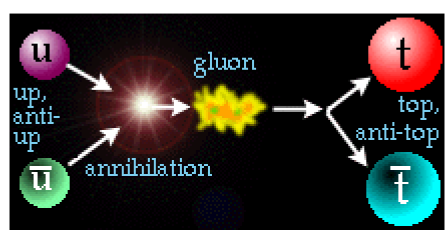
$$R = r_0 A^{1/3},$$

where A = atomic mass number and $r_0 = 1.25 \times 10^{-15}$ m. The neutron has a positively charged core of radius $\approx 0.3\times10^{-15}$ m surrounded by a compensating negative charge of radius between 0.3×10^{-15} m and 2×10^{-15} m. The proton has an approximately exponentially decaying positive charge distribution with a mean square radius of about 0.8×10^{-15} m.

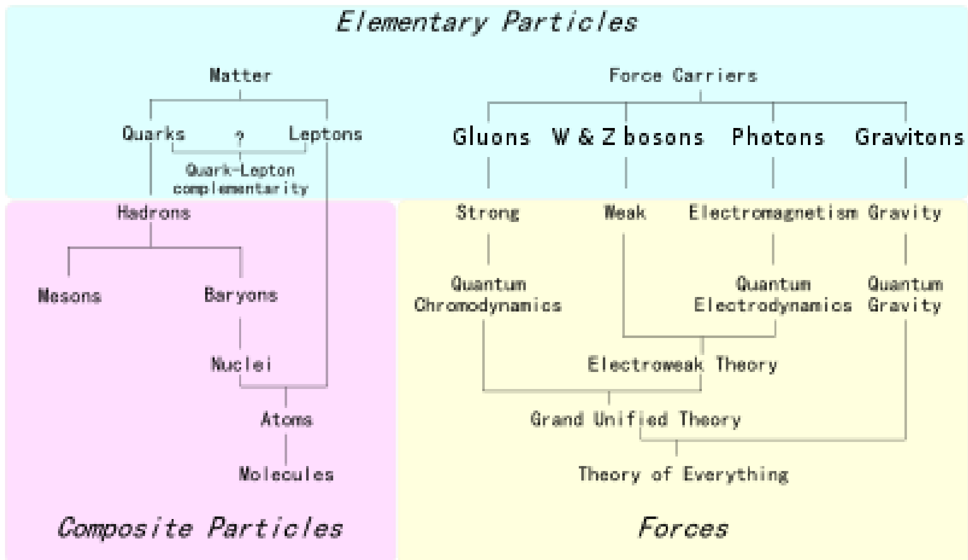
Matter and Antimatter: for every type of matter particle we've found, there also exists a corresponding **antimatter** particle, or **antiparticle.** Antiparticles and behave just like their corresponding matter particles, except they have opposite charges. For example, a proton is electrically positive 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.

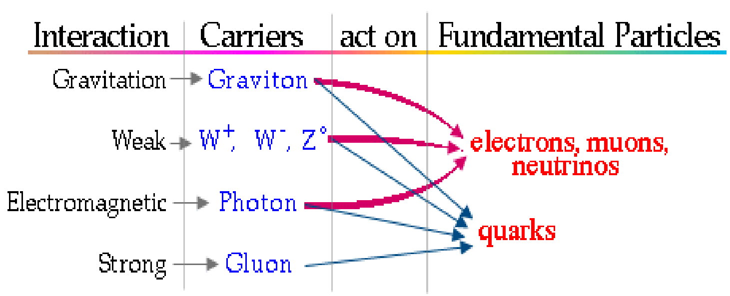


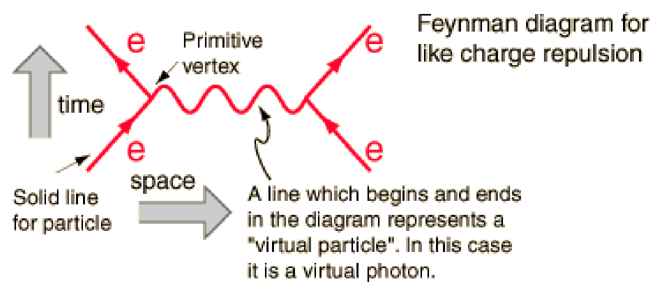
When a matter particle and antimatter particle meet, they annihilate into pure energy. Typical example: an electron and a proton annihilate and produce a photon: $e^- + e^+ \rightarrow \gamma$.

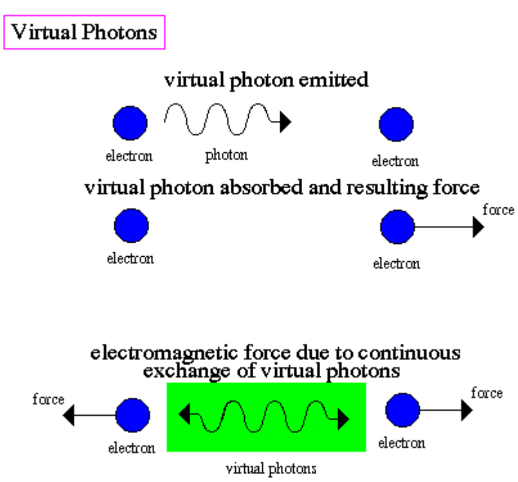


If the energy of a photon is greater than 0.511 x 2 MeV (the sum of mc^2 energies for electron and positron), then this photon in the area of a strong electric fiend near the nucleus can produce an electron-positron pair: $\gamma \rightarrow e^- + e^+$









It was postulated that there is an exchange of force carriers between charged particles. These particles served to transfer momentum between charged particles. Quantum electrodynamics explains the interaction of charged particles and light and extends quantum theory to fields of force, starting with electromagnetic fields. For example, electric charged particles interact by the exchange of virtual photons, photons that do not exist outside of the interaction and only serve as carriers of momentum/force.

The gluon generates a color change for the quarks (blue, green, red). The gluons are in fact considered to be bi-colored, carrying a unit of color and a unit of anti-color. For example, the gluon exchange converts a blue quark to a green one and vice versa. Photon and graviton are massless, move at the speed of light, produce long-range force.

Fundamental Particles

What Does "Fundamental" Mean? In the 1930s, it seemed that protons, neutrons, and electrons were the smallest objects into which matter could be divided and they were termed "elementary particles". The word elementary then meant "having no smaller constituent parts", or "indivisible" -- the new "atoms", in the original sense.

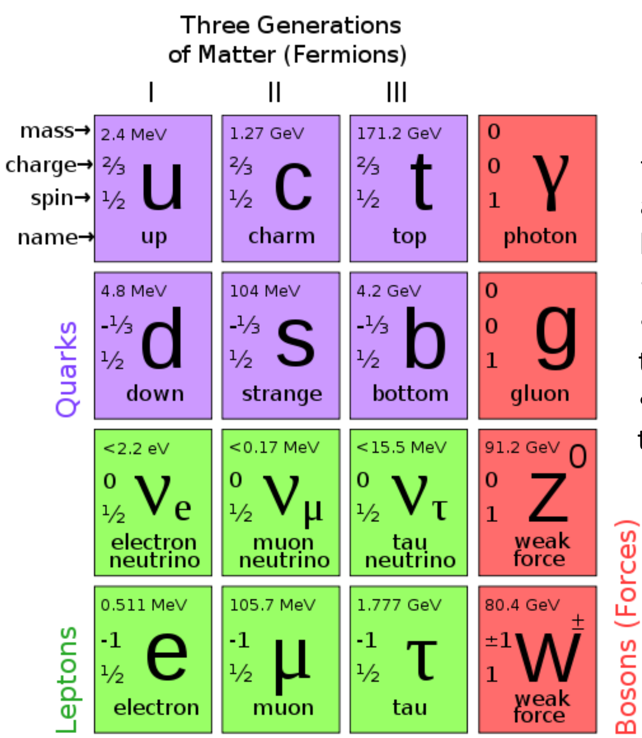
Again, later knowledge changed our understanding as physicists discovered yet another layer of structure within the protons and neutrons. It is now known that protons and neutrons are made up quarks. Over 200 other "elementary" particles were discovered between 1930 and the present time. These elementary particles are all made from quarks and/or antiquarks. These particles are called hadrons.

Once quarks were discovered, it was clear that all these hadrons were composite objects. Leptons, on the other hand, still appear to be structureless.

Today, quarks and leptons, and their antiparticles, are candidates for being the fundamental building blocks from which all else is made. Particle physicists call them the "fundamental" particles denoting that, as far as current experiments can tell, they have no substructure.

What are Fundamental Particles?

All we know is that quarks and leptons are smaller than 10^{-18} meters in radius. As far as we can tell, they have no internal structure or even any size. It is possible that future evidence will, once again, show this understanding to be an illusion and demonstrate that there is substructure within the particles that we now view as fundamental.



The Standard Model

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 leptons in just a few pages.
- **Force carrier particles** , like the photon. We will talk about these particles later.

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.

In the modern theory, known as the Standard Model there are 12 fundamental matter particle types and their corresponding antiparticles. The matter particles divide into two classes: quarks and leptons. There are six particles of each class and six corresponding antiparticles.

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. In addition, there are gluons, photons, and $W^{\pm}$ and Z bosons, the force carrier particles that are responsible for strong, electromagnetic, and weak interactions respectively. These force carriers are also fundamental particles.

We know that quarks and leptons are smaller than 10^{-18} meters in radius. As far as we can tell, they have no internal structure or even any size. It is possible that future evidence will, once again, show this understanding to be an illusion and demonstrate that there is substructure within the particles that we now view as fundamental.

The Generations of Matter

Note that both quarks and leptons exist in three distinct sets. Each set of quark and lepton charge types is called a **generation** of matter (charges +2/3, -1/3, 0, and -1 as you go down each generation). The generations are organized by increasing mass.

All visible matter in the universe is made from the first generation of matter particles -- up quarks, down quarks, and electrons. This is because all second and third generation particles are unstable and quickly decay into stable first generation particles.

Quarks

Quarks only exist inside hadrons because they are confined by the strong (or color charge) force fields. Therefore, we cannot measure their mass by isolating them. Furthermore, the mass of a hadron gets contributions from quark kinetic energy and from potential energy due to strong interactions. For hadrons made of the light quark types, the quark mass is a small contribution to the total hadron mass. For example, compare the mass of a proton (0.938 GeV/c^2) to the sum of the masses of two up quarks and one down quark (total of 0.02 GeV/c^2).

So the question is, what do we mean by the mass of a quark and how do we measure it. The quantity we call quark mass is actually related to the m in F = ma (force = mass x acceleration). This equation tells us how an object will behave when a force is applied. The equations of particle physics include, for example, calculations of what happens to a quark when struck by a high energy photon. The parameter we call quark mass controls its acceleration when a force is applied. It is fixed to give the best match between theory and experiment both for the ratio of masses of various hadrons and for the behavior of quarks in high energy experiments. However, neither of these methods can precisely determine quark masses.

Hadrons, Baryons, and Mesons

Quarks only exist in groups with other quarks and are never found alone. Composite particles made of quarks are called **Hadrons**. 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 (we will try to talk more about this later if we have time). Hadrons have no net strong charge (or color charge) but they do have residual strong interactions due to their color-charged substructure (similar model: two electric dipoles interact despite the fact that their net electric charges are zero).
There are two classes of hadrons: baryons and mesons. Baryons are particles made from three quarks (and anti-baryons from three antiquarks.). Mesons contain one quark.

Protons are made of two up quarks and one down quark (uud). N**eutrons** are baryons too (udd).

One example of a meson is a pion (π^+), which is made of an up quark and a down anitiquark. The antiparticle of a meson just has its quark and antiquark switched, so an antipion (π^-) is made up a down quark and an up antiquark.

Sample Fermionic Hadrons **Baryons** (qqq) **and Anti-baryons** ($\overline{q}\overline{q}\overline{q}$)					
Symbol	***Name***	***Quark Content***	***Electric Charge***	***Mass (GeV/c²)***	***Spin***
p	*proton*	uud	*1*	*0.938*	*1/2*
$\overline{p}$	*anti-proton*	$\overline{u}\overline{u}\overline{d}$	*-1*	*0.938*	*1/2*
n	*neutron*	udd	*0*	*0.940*	*1/2*
Λ	*lambda*	uds	*0*	*1.116*	*1/2*
Ω^-	*omega*	sss	*-1*	*1.672*	*3/2*

Only a very very very small part of the mass of a hadron is due to the quarks in it. For example, a proton (uud) has more mass than the sum of the masses of its quarks:

$$\begin{array}{llcl} & \text{u} + \text{u} + \text{d} & = & \text{proton} \\ \textbf{mass:} & 0.003 + 0.003 + 0.006 & \neq & 0.938 \end{array}$$

Most of the mass we observe in a hadron comes from its kinetic and potential energy. These energies are converted into the mass of the hadron as described by Einstein's equation that relates energy and mass, E = mc ^{2}.

Baryons

Baryons carry an odd half quantum unit of angular momentum (spin) and, hence, are fermions, which means that they obey the Pauli Exclusion Principle rules.

The proton is the only baryon that is stable in isolation. Its basic structure is two up quarks and one down quark. Neutrons are also baryons. Although neutrons are not stable in isolation, they can be stable inside certain nuclei. A neutron's basic structure is two down quarks and one up quark. More massive baryons may be made from any set of three quarks. Baryons containing more massive quarks are all unstable because these quarks decay via weak interactions. There are also more massive baryons that have the same quark content as a proton or a neutron but have additional angular momentum. These are typically very short-lived because they can decay to a proton or a neutron and a meson via residual strong interactions.

Mesons

Mesons are color-neutral particles with a basic structure of one quark and one antiquark. There are no stable mesons. Mesons have integer (or zero) units of spin, and hence are bosons, which means that they do not obey Pauli Exclusion Principle rules.

Sample Bosonic Hadrons - Mesons ($q\overline{q}$)					
Symbol	***Name***	***Quark Content***	***Electric Charge***	***Mass (GeV/c^2)***	***Spin***
π^+	*pion*	$u\overline{d}$	*+1*	*0.140*	*0*
K^-	*kaon*	$s\overline{u}$	*-1*	*0.494*	*0*
ρ^+	*rho*	$u\overline{d}$	*+1*	*0.770*	*1*
D^+	*D+*	$c\overline{d}$	*+1*	*1.869*	*0*
η_c	*eta-c*	$c\overline{c}$	*0*	*2.979*	*0*

The most common mesons are:

- Pions (or pi mesons), made from up and down type quarks and antiquarks only (for example, a pi-plus meson is a u and an anti-d quark).
- K mesons, which contain one u or d type quark or antiquark and one s type (for example K-plus is a u and an anti-s quark).

These are the only types of mesons which are long-lived enough to be seen directly by their tracks in a detector.

More massive mesons with the same quark content but higher angular momentum, as well as others containing one or more of the more massive quark types, are all very short lived. They have been found by studies of their decay products, but they decay too quickly to leave a track that can be detected.

Particles that contain the more massive quark types, for example B, D, or N c particles decay via weak interactions slowly enough that their production can be inferred from the fact that the decay product tracks emerge from a vertex point outside the beam collision region. Vertex detectors are precision tracking devices designed chiefly to detect such decay vertex points.

Complex Structure
The quarks inside a meson or baryon are continually interacting with one another via the strong force field. At any instant in time, they may contain many virtual particles: gluons and additional quark-antiquark pairs. The picture of a proton as made of three quarks is thus a gross simplification. For example, we know from measurements that in a high-momentum proton only about half the momentum is carried by quarks, the rest is carried by gluons.

The strong force carrier particles are called **gluons** because they tightly "glue" quarks together.

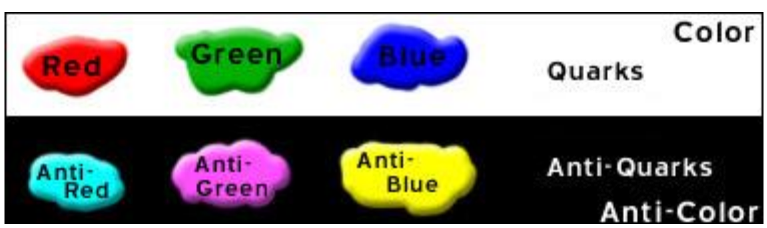
But!

Color charge behaves differently than electromagnetic charge. Unlike photons which do not have electromagnetic charge, gluons have so named color charge. And while quarks have color charge, composite particles made out of quarks have **no net color charge** (they are color neutral). **Important disclaimer:** "Color charge" has nothing to do with the visible colors, it is just a convenient naming convention for a mathematical system physicists developed to explain their observations about quarks in hadrons.

Color Charge

Quarks and gluons are color-charged particles. Just as electrically-charged particles interact by exchanging photons in electromagnetic interactions, color-charged particles exchange gluons in strong interactions. When two quarks are close to one another, they **exchange gluons** and create a very strong **color force field** that binds the quarks together. The force field gets stronger as the quarks get further apart (imagine that they are connected with springs). Quarks constantly change their color charges as they exchange gluons with other quarks.

How does color charge work?



There are three color charges and three corresponding anticolor (complementary color) charges. Each quark has one of the three color charges and each antiquark has one of the three anticolor charges. Just as a mix of red, green, and blue light yields white light, in a baryon a combination of "red," "green," and "blue" color charges is color neutral, and in an antibaryon "antired," "antigreen," and "antiblue" is also color neutral. Mesons are color neutral because they carry combinations such as "red" and "antired."

Because gluon emission and absorption always changes color, and, in addition, color is a conserved quantity, gluons can be thought of as carrying a color and an anticolor charge. Since there are nine possible color-anticolor combinations we might expect nine different gluon charges, but the mathematics works out such that there are only eight combinations. Unfortunately, there is no intuitive explanation for this result.

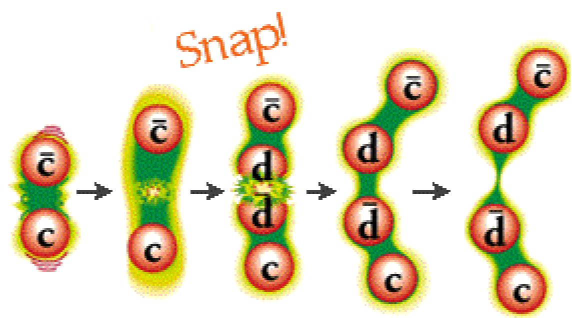
Quark Confinement

Color-charged particles cannot be found individually. For this reason, the color-charged quarks are **confined** in groups (hadrons) with other quarks. These composites are color neutral.

The development of the Standard Model's theory of the strong interactions reflected evidence that quarks combine only into baryons (three quark objects), and mesons (quark-antiquark objects), but not, for example, four-quark objects. Now we understand that only baryons (three different colors) and mesons (color and anticolor) are color-neutral. Particles such as **ud** or **uddd** that cannot be combined into color-neutral states are never observed.

Color-Force Field

The quarks in a given hadron madly **exchange gluons.** For this reason, physicists talk about the **color-force field** which consists of the gluons holding the bunch of quarks together. If one of the quarks in a given hadron is pulled away from its neighbors, the color-force field "stretches" between that quark and its neighbors. In so doing, more and more energy is added to the color-force field as the quarks are pulled apart. At some point, it is energetically cheaper for the color-force field to "snap" into a new quark-antiquark pair. In so doing, energy is conserved because the energy of the color-force field is converted into the mass of the new quarks, and the color-force field can "relax" back to an unstretched state.



Quarks cannot exist individually because the color force increases as they are pulled apart.

Quarks Emit Gluons. Color charge is always conserved.

When a quark emits or absorbs a gluon, that quark's color must change in order to conserve color charge (since gluons carry color charge). For example, suppose a red quark changes into a blue quark and emits a red/antiblue gluon (the image below illustrates antiblue as yellow). The net color is still red. This is because - after the emission of the gluon - the blue color of the quark cancels with the antiblue color of the gluon. The remaining color then is the red color of the gluon.

Quarks emit and absorb gluons very frequently within a hadron, so there is no way to observe the color of an individual quark. Within a hadron, though, the color of the two quarks exchanging a gluon will change in a way that keeps the bound system in a color-neutral state.

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** (μ) and the **tau** (τ), which are charged like electrons but have a lot more mass. The other leptons are the three types of **neutrinos** (ν). They have no electrical charge, very little mass, and they are very hard to detect. Leptons are divided into three **lepton families:** the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino.

The six known types of leptons are shown in the table below. There are also six anti-lepton types, one for each lepton.

Flavor		***Mass (GeV/c ^{2})***	***Electric Charge (e)***
ν_e	*electron neutrino*	*<7 x 10^{-9}*	*0*
e^-	*electron*	*0.000511*	*-1*
ν_μ	*muon neutrino*	*<0.0003*	*0*
μ^-	*muon (mu-minus)*	*0.106*	*-1*
ν_τ	*tau neutrino*	*<0.03*	*0*
τ^-	*tau (tau-minus)*	*1.7771*	*-1*

Electrons and Positrons
The electron is the least massive charged particle of any type. It is absolutely stable because conservation of energy and electric charge together forbid any decay.

Muons
The negatively charged muon (mu-minus) is just like an electron, except it is more massive. Muons are unstable -- they decay to produce a virtual W-boson and the matching neutrino type. The W-boson then decays to produce an electron and an electron-type anti-neutrino.
The antiparticle of a mu-minus is a mu-plus. Particle physicists use the name muon for either mu-plus or a mu-minus a muon. The mu-plus decays to produce an anti-muon type neutrino and a W-plus boson, which then decays to a positron and an electron-type neutrino.
Muons are produced in particle physics experiments. They also are produced by cosmic rays. Because they are much more massive than electrons, muons readily pass through the electric fields inside matter with very little deflection. So, muons do not radiate and slow down as electrons do. However, they can cause ionization and this makes them readily detectable in matter, for example, with a Geiger counter.

Tau Leptons:
The tau-minus is an electron-like particle which is also unstable. The tau-minus decays to produce its matching neutrino and a virtual W-minus boson. The W-minus has enough energy that there are several possible ways for it to decay, such as:

1. An electron and an electron-type antineutrino.
2. A mu-minus and an muon- type antineutrino.
3. A down quark and an up-type antiquark.
4. An s quark and an up-type antiquark.

The quark and antiquark do not emerge individually. One or more mesons emerge from the decay that contains the initial quark and antiquark, and possible additional quark-antiquark pairs produced from the energy in the strong force field between them.
For tau-plus, a similar set of decays occurs -- just replace every particle by its antiparticle (and vice-versa, every antiparticle by the matching particle.) Thus, for example, tau-plus can decay to give a tau type anti-neutrino and a positron and an electron-type neutrino.

Neutrinos:
The neutrino was first postulated to preserve the conservation of energy, conservation of momentum, and conservation of angular momentum in beta decay—the decay of an atomic nucleus (not known to contain or involve the neutron at the time) into a proton, an electron and an antineutrino:

$$n^{\circ} \rightarrow p^{+} + e^{-} + \nu_e^{\circ}$$

There are three types of neutrinos, one associated with each type of charged lepton. All are particles that are somewhat like electrons: they have half a quantum unit of spin angular momentum, and do not participate in strong interactions. However, neutrinos differ from electrons in that they have zero electric charge and small masses: In 2009 lensing data of a galaxy cluster were analyzed to predict a neutrino mass of about 1.5 eV. All neutrino masses are nearly equal.

The only known difference between the three neutrino types is which type of the charged lepton they are associated with during production or decay processes.

Since neutrinos have no electric charge, they participate only in weak interaction or gravitational processes. Because of that they are very difficult to detect. Most neutrinos pass **right through the earth** without ever interacting with a single atom of it. We observe them only by the effects they have on other particles with which they interact. For example, a high-energy electron-type neutrino can convert to an electron by exchanging a W-boson with a neutron (which becomes a proton when it absorbs the W boson). This rarely happens. With an intense source of neutrinos and a large detector containing many neutrons, one can observe events with no visible initiating particles that can only be explained as neutrino-initiated processes. What is seen in the detector is the recoiling electron and proton after the process occurs.

Even harder to see is the process where the neutrino is deflected by exchanging a Z-boson with a proton or neutron. The proton or neutron gains energy from this exchange, so one searches for events where a recoiling proton or neutron is seen with no associated electron and no visible initiating particle.

In high-energy particle experiments, we often use energy and momentum conservation to infer that production of one or more neutrinos occurred. If the detector detects everything but neutrinos, then an event where the total final energy detected (or the total final momentum) does not match the initial energy (or momentum) in the incoming particles, then neutrinos must have been produced. The neutrinos carried off the missing energy (and momentum).

Lepton Decays

The heavier leptons, the muon and the tau, are not found in ordinary matter at all. This is because when they are produced they very quickly **decay,** or transform, into lighter leptons. Sometimes the tau lepton will decay into a quark, an antiquark, and a tau neutrino. Electrons and the three kinds of neutrinos are stable and thus the types we commonly see around us.
When a heavy lepton decays, one of the particles it decays into is always its corresponding neutrino. The other particles could be a quark and its antiquark, or another lepton and its antineutrino.

Physicists have observed that some types of lepton decays are possible and some are not. In order to explain this, they divided the leptons into three **lepton families:** the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino. The number of members in each family must **remain constant** in decay: a particle and an antiparticle in the same family "cancel out" to make the total of them equal zero.

Lepton Type Conservation

Leptons are divided into three **lepton families:** the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino. We use the terms "electron number," "muon number," and "tau number" to refer to the lepton family of a particle. Electrons and their neutrinos have electron number +1, positrons and their antineutrinos have electron number -1, and all other particles have electron number 0. Muon number and tau number operate analogously with the other two lepton families.

One important thing about leptons, then, is that electron number, muon number, and tau number are **always conserved** when a massive lepton decays into smaller ones.

Let's take example decay. A muon decays into a muon neutrino, an electron, and an electron antineutrino:

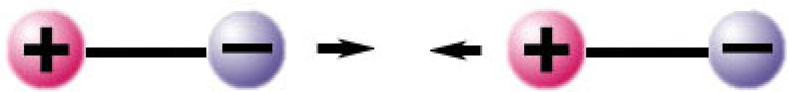
	muon		muon neutrino		electron		e^- antineutrino
equation:	μ	$\rightarrow$	ν_μ	+	e^-	+	$\bar{\nu}_e$
electron number:	0	=	0	+	1	+	-1
muon number:	1	=	1	+	0	+	0
tau number:	0	=	0	+	0	+	0

As you can see, electron, muon, and tau numbers are conserved. These and other conservation laws are what we believe define whether or not a given hypothetical lepton decay is possible.

Now, let's take another look at four interactions.

Residual E-M Force

Atoms usually have the same numbers of protons and electrons. They are electrically neutral, therefore, because the positive protons cancel out the negative electrons. Since they are neutral, what causes them to stick together to form stable molecules? The answer is a bit strange: we've discovered that the charged parts of one atom can interact with the charged parts of another atom. This allows different atoms to bind together, an effect called the **residual electromagnetic force.** The simplest example – attraction of two neutral dipoles (because the combined force of attraction between the opposite charges is greater than the combined force of repulsion between like charges – due to the fact that electric force is inversely proportional to the distance between the chargers squared):



So the residual electromagnetic force allows atoms to bond and form molecules, allowing the world to stay together and create the matter you interact with all of the time. All the structures of the world exist simply because protons and electrons have opposite charges!

Residual Strong Force

So now we know that the **strong force** binds quarks together because quarks have **color charge.** But that still does not explain what holds the nucleus together, since positive protons repel each other with electromagnetic force, and protons and neutrons **are color-neutral**. So what holds the nucleus together?
A residual effect of the strong force works similar to the residual effect of electromagnetic force. The residual strong force acts between hadrons, such as protons and neutrons in atomic nuclei. It is a minor residuum of the strong force which binds quarks together into protons and neutrons. This same force is much weaker *between* neutrons and protons, because it is mostly neutralized *within* them, in the same way that electromagnetic forces between neutral atoms are much weaker than the electromagnetic forces that hold the atoms internally together, but at the same time residual strong force of attraction between hadrons, such as protons and neutrons, is much greater than the electromagnetic force of repulsion between them.
Unlike the strong force itself, the residual strong force, *does* diminish in strength with distance. The decrease is approximately as a negative exponential power of distance, though there is no simple expression known for this. This fact, together with the less-rapid decrease of the disruptive electromagnetic force between protons with distance, causes the instability of larger atomic nuclei, such as all those with atomic numbers larger than 82.

Weak Interactions

Weak interactions are responsible for the decay of massive quarks and leptons into lighter quarks and leptons (that is why the only matter around us that is stable is made up of the smallest quarks and leptons, which cannot decay any further). We observe the fundamental particle vanishing and being replaced by two or more different particles.

Only weak interactions can change a fundamental particle into another type of particle. Physicists call particle types "flavors." The weak interaction can change a charm quark into a strange quark while emitting a virtual W boson (charm and strange are flavors). Only the weak interaction (via the W boson) can change flavor and allow the decay of a truly fundamental particle.

Fundamental weak interactions occur for all fundamental particles except gluons and photons. Weak interactions involve the exchange or production of W or Z bosons.

Weak forces are very short-ranged. In ordinary matter, their effects are negligible except in cases where they allow an effect that is otherwise forbidden. There are a number of conservation laws that are valid for strong and electromagnetic interactions, but broken by weak processes. So, despite their slow rate and short range, weak interactions play a crucial role in the make-up of the world we observe.

W Bosons

Any process where the number of particles minus the number of antiparticles of a given quark or lepton type changes is a weak decay process and involves a W-boson. **Weak decays are thus responsible for the fact that ordinary stable matter contains only up and down type quarks and electrons**. Matter containing any more massive quark or lepton types is unstable. If there were no weak interactions, then many more types of matter would be stable.

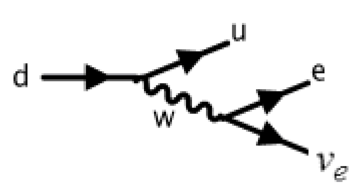
Z Bosons

Processes involving Z-bosons (called "neutral current processes") are even more elusive than W-boson effects, and were not recognized until after the electroweak theory had predicted they must exist in the early 1970s. Careful searches then found events that could not be explained without such processes.

Beta Decay: the First Known Weak Interaction

The weak interaction was first recognized in cataloging the types of nuclear radioactive decay chains, as alpha, beta, and gamma decays. Alpha and gamma decays can be understood in terms of other known interactions (residual strong and electromagnetic, respectively). But, to explain beta decay required the introduction of an additional rare type of interaction -- called the weak interaction.

Beta decay is a process in which a neutron (two down quarks and one up) disappears and is replaced by a proton (two up quarks and one down), an electron, and an anti-electron neutrino. According to the Standard Model, a down quark disappears in this process and an up quark and a virtual W boson is produced. The W boson then decays to produce an electron and an anti-electron type neutrino. This can be represented by the Feynman diagram:



When a quark or lepton changes type (for example, a muon changing to an electron) it is changing **flavor**. All flavor changes are due to the weak interaction.

Reminder: 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.

Gravitational Interactions

Gravitational interactions occur between any two objects that have energy. Mass is just one possible form of this energy. (Photons are massless, but they experience gravitational forces).

Gravitational interactions between fundamental particles are extremely weak, at least thirty orders of magnitude (that is 10^{-30}) smaller than the weak interaction. Hence, gravitational effects can be ignored in particle physics processes involving small numbers of particles.

Why is Gravity so Obvious to Us?
The only reason we experience gravity as an important force is that there is no such thing as negative energy and, thus, the gravitational effects of all objects add -- there is never any cancellation. The earth exerts a much stronger gravitational pull on us than its electric pull. The electric charges in the earth are all balanced out (the positive charges of atomic nuclei screened by the negative charges of the electrons), but the masses of all the atoms in the earth add together to give a large gravitational effect on objects at the surface of the earth.

Quantum Gravity
The carrier particle for gravitational interactions has been named the **graviton**. However, no fully satisfactory quantum theory of gravitational interactions via graviton exchange has been identified. Thus the combination of gravity and particle physics remains a major outstanding problem. Much work in theoretical physics today is focused on this problem.

If we want to understand the big bang -- the very earliest moments in the history of the universe -- we will need to understand quantum gravity. The universe, at that time, was a very dense fluid of very-high energy particles. Gravitational interactions are comparable in strength to other particle interactions in that environment, so we need a consistent theory that can treat both interactions together to really understand that era.

”Theory of Everything”

It is hypothesized that a “Theory of Everything” (TOE) will bring together all the fundamental forces, matter and curved spacetime under one unifying picture. For cosmology, this will be the single force that controlled the Universe at the time of formation. The current approach to the search for a TOE is to attempt to uncover some fundamental symmetry, perhaps symmetry of symmetries. There should be predictions from a TOE, such as the existence of the Higgs particle, the origin of mass in the Universe.
One example of an attempt to formulate a TOE is **supergravity**, a quantum theory that unities particle types through the use of ten dimensional spacetime (see diagram below). Spacetime (4D construct) was successful at explaining gravity. What if the subatomic world is also a geometric phenomenon?

Many more dimensions of time and space could lie buried at the quantum level, outside our normal experience, only having an impact on the microscopic world of elementary particles.

It is entirely possible that beneath the quantum domain is a world of pure chaos, without any fixed laws or symmetries. One thing is obvious, that the more our efforts reach into the realm of fundamental laws, the more removed from experience are the results.

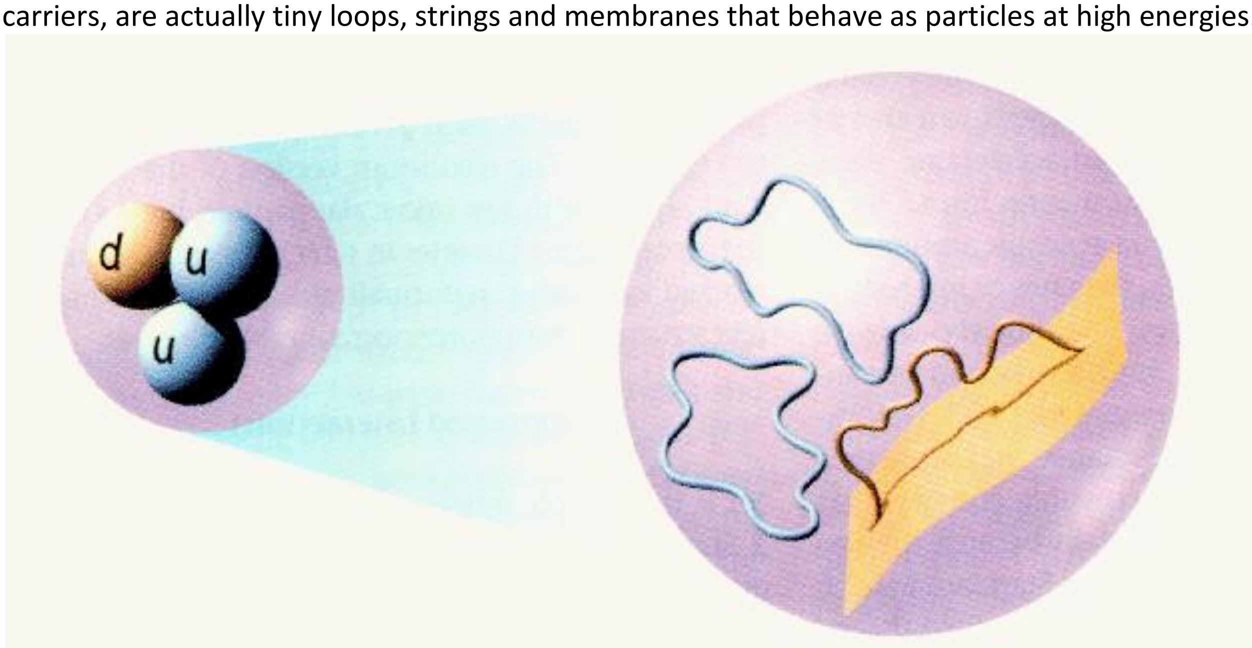
Higgs Physics

One part of the Standard Model is not yet well established. We do not know for sure what causes the fundamental particles to have masses. The simplest idea is called the Higgs mechanism. This mechanism involves one additional particle, called the Higgs boson, and one additional force type, mediated by exchanges of this boson.

The Higgs particle has not yet been observed. Today we can only say that if it exists, it must have a mass greater than about 80GeV/c^2. Searches for a more massive the Higgs boson are beyond the scope of the present facilities at SLAC or elsewhere. The Large Hadron Collider at CERN, or upgrades of present facilities to higher energies are intended to search for the Higgs particle and distinguish between competing concepts.

String Theory

Another recent attempt to form a Theory of Everything is through M (for membrane) or string theory. String theory is actually a high order theory where other models, such as supergravity and quantum gravity, appear as approximations. The basic premise to string theory is that subatomic entities, such as quarks and force carriers, are actually tiny loops, strings and membranes that behave as particles at high energies.



One of the problems in particle physics is the confusing number of elementary particles (muons and pions and mesons etc). String theory answers this problem by proposing that small loops, about 100 billion billion times smaller than the proton, are vibrating below the subatomic level and each mode of vibration represents a distinct resonance which corresponds to a particular particle. Thus, if we could magnify a quantum particle we would see a tiny vibrating string or loop.

According to M-theory (M for membrane), the leading version of String Theory, all particles that make up matter are composed of strings (measuring at ≈ 1.616×10^{-35} meters) that exist in an 11-dimensional universe. These strings vibrate at different frequencies which determine mass, electric charge, color charge, and spin. A string can be open (a line) or closed in a loop (a one-dimensional sphere, like a circle). As a string moves through space it sweeps out something called a *world sheet* (in string theory, the world sheet is a two-dimensional manifold which describes the embedding of the string in spacetime.). String theory predicts 1- to 10-branes (a 1-brane being a string and a 10-brane being a 10-dimensional object) which prevent tears in the "fabric" of space using the uncertainty principle (e.g. the electron orbiting a hydrogen atom has the probability, albeit small, that it could be anywhere else in the universe at any given moment). String theory posits that our universe is just a 4-brane, inside which exist the 3 space dimensions and the 1 time dimension that we observe. The remaining 6 theoretical dimensions are either very tiny and curled up (and too small to affect our universe in any way) or simply do not/cannot exist in our universe (because they exist in a grander scheme called the "multiverse" outside our known universe).

Some predictions of the string theory include existence of extremely massive counterparts of ordinary particles due to vibrational excitations of the fundamental string and existence of a massless spin-2 particle behaving like the graviton.

The fantastic aspect to string theory, that makes it such an attractive candidate for a TOE, is that it not only explains the nature of quantum particles but it also explains spacetime as well. Strings can break into smaller strings or combine to form larger strings. This complicated set of motions must obey self-consistent rules and the constraint caused by these rules results in the same relations described by relativity theory.

Another aspect of string theory that differs from other TOE candidates is its high aesthetic beauty. Like general relativity, the string theory describes objects and interactions through the use of geometry and does not suffer from infinities or what is called normalization problems such as quantum mechanics. It may be impossible (unfortunately) to test the predictions of string theory since it would require temperature and energies similar to those at the beginning of the Universe. Thus, we resort to judging the merit of this theory on its elegance and internal consistence rather than experiment data.

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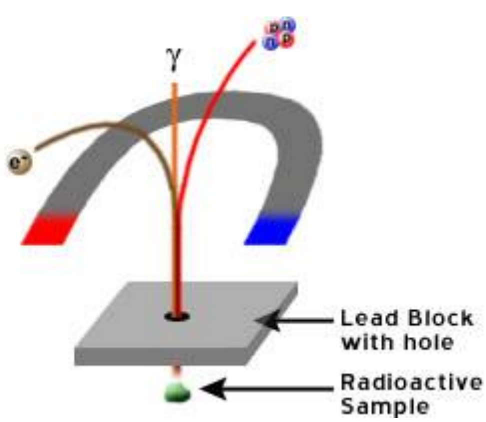
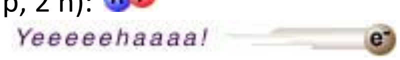
Now let’s go up the scale from fundamental particles to composite particles, nuclei and atoms.

Radioactivity



Scientists identified several distinct types of **radiation**, the particles resulting from radioactive decays. The three types of radiation were named after the first three letters of the Greek alphabet: α (alpha), β (beta), and γ (gamma).

Alpha particles are helium nuclei (2 p, 2 n): 

Beta particles are speedy electrons: 

Gamma radiation is a high-energy photon:

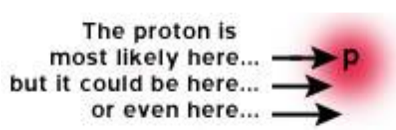
These three forms of radiation can be distinguished by a magnetic field since

• the positively-charged alpha particles curve in one direction,
• the negatively-charged beta particles curve in the opposite direction,
• and the electrically-neutral gamma radiation doesn't curve at all.

Alpha particles can be stopped by a sheet of paper, beta particles by aluminum foil, and gamma radiation by a block of lead. Gamma radiation can penetrate very far into a material, and so it is gamma radiation that poses the most danger when working with radioactive materials, although all types of radiation are very dangerous. Sadly, it took scientists many years to realize the danger of radioactivity...

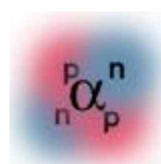
If It Can Happen, It Will

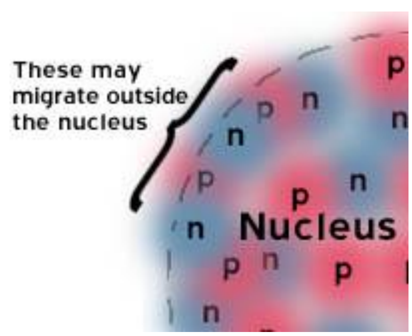
Subatomic particles do not behave like everyday objects. We can't really say what a particle **will** do, only what a particle **might** do. Particles move around like everyday objects and have energy and momentum, but they also have wave properties. Quantum mechanics is statistical theory that explains the behavior of particles in terms of probabilities.



Since particles are wave-like, it is impossible to know precisely both their position and their momentum. While it is easier to think of particles as point-like spheres this is misleading since they are better thought of as fuzzy regions in which you are most likely to find the particle.

Protons and neutrons migrate around inside a nucleus. There is a tiny, tiny chance that a conglomeration of two protons and two neutrons (which form an alpha particle) may, at the same instant, actually migrate **outside** the nucleus. There is a greater chance of this happening in a large nucleus than in a small one. The alpha particle would then be free of the residual strong force trapping it inside the nucleus, and like a suddenly released spring, the charged alpha particle would fly away from the nucleus.

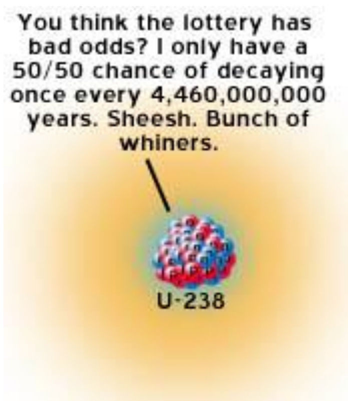




This idea that **"if it can happen, it will happen!"** is fundamental to quantum mechanics. For some atoms there is a certain probability that it will undergo radioactive decay due to the possibility that the nucleus may -- for the shortest of instants -- exist in a state that allows it to blow apart. You cannot predict when a particular atom will decay, but you can determine the *probability* that it will decay in a certain period of time. For some it is upsetting to think that chance can rule physical properties. In response to this theory Einstein proclaimed "God doesn't play dice!" mening that by definition our Universe is deterministic.

Half-Life

A lump of uranium left to itself will gradually decay, one nucleus at a time. The rate of decay is measured by how long it would take for half of a given bunch of uranium atoms to decay (the **half-life)**. The decay of an individual uranium nucleus is completely unpredictable, but we can accurately predict the way a



The decay of an unstable nucleus is random. However, it is equally likely to decay at any time. Therefore, for N nuclei of a particular radioisotope, the number of decay events −dN expected to occur in dt seconds is proportional to the number of atoms present (change in number of nuclei –dN is negative since N decreases with each decay event). Then the probability of decay (−dN/N) is proportional to dt:

$$\left(-\frac{dN}{N}\right) = \lambda \cdot dt.$$

Where λ is decay constant which has units of 1/time. The solution to this first-order differential equation is the following function:

$$N(t) = N_0\, e^{-\lambda t} = N_0\, e^{-t/\tau}.$$

Where N_0 is the value of N at time zero (t = 0).

The differential decay constant λ can also be represented as 1/τ, where *τ* is a characteristic time for the process. This characteristic time is called the time constant of the process, and it is the mean lifetime for decaying atoms. Each atom "lives" for a finite amount of time before it decays, and it may be shown that this mean lifetime is the arithmetic mean of all the atoms' lifetimes, and that it is *τ*, which again is related to the decay constant as τ = 1/ λ.

Missing Mass (Mass Defect)

Uranium-238 has a mass of 238.0508 atomic mass units (u). It can decay into thorium (234.0436 u) and an alpha particle (4.0026 u). But uranium's mass minus the mass of its decay products is 0.0046 u. **Why is there missing mass?**
When uranium nuclei undergo radioactive decay, some of their mass is converted into kinetic energy (the energy of the moving particles). This conversion of energy is observed as a loss of mass.

Definition of mass defect: mass defect = the difference between (sum of masses of protons and neutrons) - (measured mass of nucleus). When protons and neutrons are grouped together to form a nucleus, they lose a small amount of mass, i.e., there is mass defect. This mass defect is released as energy (radiant and kinetic energy of products) according to the relation $E = mc^2$. This energy is a measure of the forces that hold the protons and neutrons together, and it represents energy which must be supplied from the environment if the nucleus is to be broken up. It is known as binding energy, and the mass defect is a measure of the binding energy because it simply represents the mass of the energy which has been lost to the environment after binding.

Let’s go back to the “elementary” particles.

Particle Decays

How does a fundamental particle decay into other fundamental particles? Fundamental particles cannot split apart, because they have no constituents, but still they somehow turn into other particles. It turns out that when a fundamental particle decays, it changes into a less massive particle and a force-carrier particle (always a W boson for fundamental particle decays). These force carriers may then re-emerge as other particles. So, a particle does not just change into another particle type; there is an intermediate force-carrier particle which mediates particle decays.

In many cases, these temporary force-carrier particles seem to violate the conservation of energy because their mass is greater than the available energy in the reaction. However, these particles exist so briefly that, because of Heisenberg's Uncertainty Principle, no rules are broken. These are called **virtual particles.** For example, a charm quark (c) decays into a less massive particle (strange quark, s) and a force carrier particle (W boson) which then decays to u and d quarks.

In 1927, Werner Heisenberg determined that it is impossible to measure both a particle's position *and* its momentum exactly. The more precisely we determine one, the less we know about the other. This is called the **Heisenberg Uncertainty Principle,** and it is a fundamental property of quantum mechanics. The precise relation is:

$$\Delta x \bullet \Delta p \geq \frac{\hbar}{2}$$

The uncertainty in position...

...times the uncertainty in momentum...

...cannot be zero: it must be at least this constant

This constant is Planck's constant divided by two; Planck's constant is represented by the symbol ħ, or "h-bar," and equals 1.05 x 10^{-34} joule*seconds, or 6.58 x 10^{-16} eV*seconds.

The act of measuring a particle's position will affect your knowledge of its momentum, and vice-versa. We can also express this principle in terms of energy and time:

$$\Delta E \bullet \Delta t \geq \frac{\hbar}{2}$$

Personally I like the explanation which emphasizes the *probabilistic* nature of the Universe: the Uncertainty Principle is a property of quantum states, and the measurement in quantum mechanics has statistical properties. For example, a physicist is measuring an electron in a particular quantum state. The physicist repeats this procedure 200 times, and for 100 times measures the *position*, and 100 times measures the *momentum*. The answers will be different in each of the first 100 and second 100 experiments, and they will cluster around some mean with some spread, measured by the standard deviation. The standard deviation of the position times the standard deviation of the momentum is never less than ħ/2:

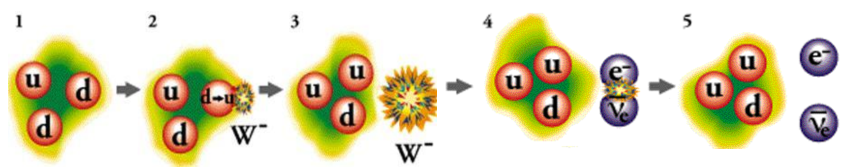
$$\sigma_x \sigma_p \geq \frac{\hbar}{2}$$

This means that if a particle exists for a very brief time, you cannot precisely determine its energy. A short-lived particle could have a tremendously uncertain energy, which leads to the idea of **virtual particles.** Virtual particles do not violate the conservation of energy. The kinetic energy plus mass of the initial decaying particle and the final decay products is equal. The virtual particles exist for such a short time that they can never be observed.

Most particle processes are mediated by virtual-carrier particles. Examples include neutron beta decay, the production of charm particles, and the decay of an eta-c particle.

Particles decay via strong, electromagnetic, and weak interactions. However, **fundamental** particles decay only via **weak** interactions. Physicists call particle types "flavors." For example, the weak interaction can change a charm quark into a strange quark while emitting a virtual W boson (charm and strange are flavors). Only the weak interaction (via the W boson) can change flavor and allow the “decay” (or transformation) of a truly fundamental particle.

Example of weak decay: **Neutron Beta Decay** $\mathbf{n \rightarrow p e^- \bar{\nu}_e}$

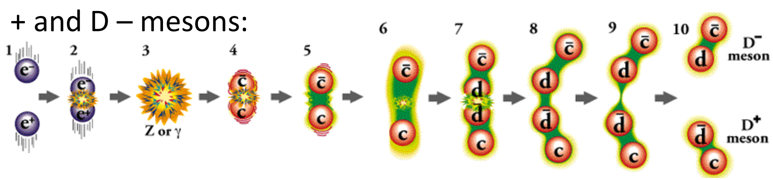


A neutron (udd) decays to a proton (uud), an electron, and an antineutrino.

• Frame 1: The neutron (charge = 0) made of up, down, down quarks.
• Frame 2: One of the down quarks is transformed into an up quark. Since the down quark has a charge of -1/3 and the up quark has a charge of 2/3, it follows that this process is mediated by a **virtual** W^- particle, which carries away a (-1) charge (thus charge is conserved!).
• Frame 3: The new up quark rebounds away from the emitted W^-. The neutron now has become a proton.
• Frame 4: An electron and antineutrino emerge from the virtual W- boson.
• Frame 5: The proton, electron, and the antineutrino move away from one another.
The intermediate stages of this process occur in about a billionth of a billionth of a billionth of a second, and are not observable.

Example of electromagnetic decay: the π^0 (neutral pion) is a $q\bar{q}$ meson. The quark and antiquark can annihilate; from the annihilation come two photons.

Another electromagnetic decay example: Electron/Positron Annihilation $\mathbf{e^+e^- \rightarrow D^+ D^-}$
When an electron and positron collide, they can annihilate to produce charm quarks which then produce D + and D – mesons:

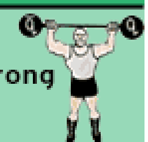
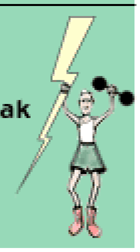


• Frame 1: The electron and positron zoom towards their certain doom.
• Frame 2: They collide and annihilate, releasing tremendous amounts of energy.

• Frame 3: The electron and positron have annihilated into a photon, or a Z particle, both of which may be virtual force carrier particles.
• Frame 4: A charm quark and a charm antiquark emerge from the virtual force carrier particle.
• Frame 5: They begin moving apart, stretching the **color force field** (gluon field) between them.
• Frame 6: The quarks move apart, further spreading their force field.
• Frame 7: The energy in the force field increases with the separation between the quarks. When there is sufficient energy in the force field, the energy is converted into a quark and an anti-quark (remember $E = mc^2$).
• Frames 8-10: The quarks separate into distinct, color-neutral particles: the D^+ (a charm and anti-down quark) and D^- (an anti-charm and down quark) mesons.
The intermediate stages of this process occur in about a billionth of a billionth of a billionth of a second, and are not observable.

Strong decay: The particle is a $c\bar{c}$ meson. It can undergo a strong decay into two gluons (which emerge as hadrons).

So, the weak force-carrier particles, W + and W - , mediate decays in which particles change flavor (and electric charge). The strong force-carrier particle, the gluon, mediates decays involving color changes:

A decay with...	Mediated by:	Interaction:
Color change No electric change	Gluon	Strong 
No color change Electric change	W^+ or W^-	Weak 

Beyond The Standard Model

The Standard Model answers many of the questions about the structure and stability of matter with its six types of quarks, six types of leptons, and four forces. But the Standard Model is not complete; there are still some unanswered questions:

1. Why do we observe matter and almost no antimatter if we believe there is symmetry between the two in the universe?
2. Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

3. What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos? What is “dark energy?”
5. How does gravity fit into all of this?

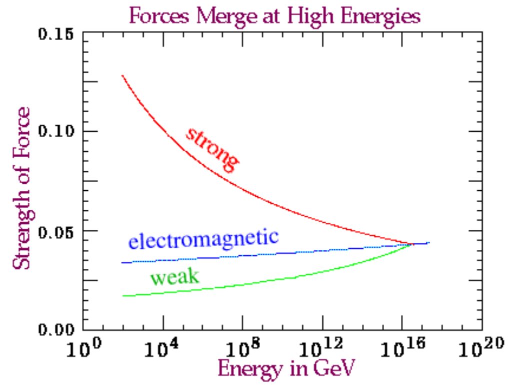
Grand Unified Theory

Today, one of the major goals of particle physics is to unify the various fundamental forces in a **Grand Unified Theory** (GUT) which could offer a more elegant understanding of the organization of the universe. Such a simplification of the Standard Model might well help to answer our questions and point toward future areas of study.

James Maxwell took a big step toward this goal when he unified electricity and magnetism, and physicists now understand that at **high energies** the electromagnetic and weak forces are aspects of the same force.

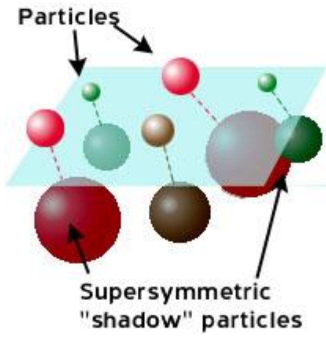
Physicists hope that a **Grand Unified Theory** will unify the strong, weak, and electromagnetic interactions. There have been several proposed Unified Theories, but we need data to pick which, if any, of these theories describes nature.

If a Grand Unification of all the interactions is possible, then all the interactions we observe are all different aspects of the same, unified interaction. However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect? Strangely enough, current data and theory suggests that these varied forces merge into one force when the particles being affected are at a high enough energy.



Current work on GUT suggests the existence of another force-carrier particle that causes the proton to decay. Such decays are extremely rare; a proton's lifetime is more than 10^{32} years. You know what will happen after that - a lepton "death" of the Universe.

Supersymmetry



Some physicists attempting to unify gravity with the other fundamental forces have come to a startling prediction: every fundamental matter particle should have a massive "shadow" force carrier particle, and every force carrier should have a massive "shadow" matter particle. This relationship between matter particles and force carriers is called **supersymmetry** . For example, for every type of quark there may be a type of particle called a "squark."

No supersymmetric particle has yet been found, but experiments are underway at CERN and Fermilab to detect supersymmetric partner particles.

Flavor

Flavor in particle physics
Flavor quantum numbers: • Baryon number: *B* • Lepton number: *L* • Strangeness: *S* • Charm: *C* • Bottomness: *B′* • Topness: *T* • Isospin: **I** or I_3 • Weak isospin: **T** or T_3 • Electric charge: *Q* • X-charge: *X*

The name used for the different quarks types (up, down, strange, charm, bottom, top) and for the different lepton types (electron, muon, tau). For each charged lepton flavor there is a corresponding neutrino flavor. In other words, flavor is the quantum number that distinguishes the different quark/lepton types.

Leptons may be assigned the six *flavor* quantum numbers: electron number, muon number, tauon number, and corresponding numbers for the neutrinos. These are conserved in electromagnetic interactions, but violated by weak interactions. All leptons carry a lepton number $L = 1$. In addition, leptons carry weak isospin, T_3, which is $-^1\!/_2$ for the three charged leptons (i.e. electron, muon and tauon) and $+^1\!/_2$ for the three associated neutrinos.

All quarks carry a baryon number $B = ^1\!/_3$. In addition they carry weak isospin, $T_3 = \pm^1\!/_2$. The positive T_3 quarks (up, charm, and top quarks) are called *up-type quarks* and negative T_3 ones are called *down-type quarks*. Each doublet of up and down type quarks constitutes one generation of quarks.

Quarks have the following flavor quantum numbers:

- Isospin which has value $I_3 = ^1\!/_2$ for the up quark and value $I_3 = -^1\!/_2$ for the down quark.
- Strangeness (*S*): a quantum number introduced by Murray Gell-Mann. The strange quark is defined to have strangeness −1.
- Charm (*C*) number which is +1 for the charm quark.
- Bottomness (*B′*) number which is −1 for the bottom quark.
- Topness (*T*) quantum number which is +1 for the top quark.
-

These quantum numbers are conserved by both the electromagnetic and strong interactions (but not the weak interaction).

Flavor can change in particle reactions only through the agency of the weak force. Absolutely conserved flavor quantum numbers are

- electric charge (*Q*)
- baryon number (*B*)
- lepton number (*L*)

The Summary

Particles Prior to Accelerators
By the mid 1930s, the understanding of the fundamental structure of matter seemed almost complete. Decades before, Rutherford had shown that atoms have relatively tiny but massive *nuclei.* The *quantum theory* had made sense of atomic spectra and electron orbitals. The discovery of the *neutron* had explained nuclear isotopes. So *protons, neutrons,* and *electrons* provided the building blocks of all matter. Some puzzles remained, however:

What holds the protons and neutrons together to form the nucleus?

What are the forces involved in the radioactive decays of nuclei that make alpha, beta, and gamma rays?

Enter the Accelerator
To study the nucleus and the interactions of neutrons and protons that form it, physicists needed a tool that could probe within the tiny nucleus, as earlier scattering experiments had probed within the atom. The *accelerator* is a tool that allows physicists to resolve very small structures by producing particles with very high momentum and thus short wavelength (the wavelength λ of the associated wave is inversely proportional to the momentum p of the particle: $\lambda = h/p$), where h = Planck's constant).

The Particle Explosion
To the surprise of the physicists, accelerator experiments revealed that the world of particles was very rich; many more particle types similar to protons and neutrons (called *baryons)* - and a whole new family of particles called *mesons* - were discovered. By the early 1960s a hundred or so types of particles had been identified, and physicists still had no complete understanding of the fundamental forces.

The Quark Proposal
In 1964, two physicists - Murray Gell-Mann and George Zweig - independently hit upon the idea that neutrons and protons and all baryons and mesons could be explained by a few types of yet smaller objects; Gell-Mann called them *quarks*. They could explain all the observed baryons and mesons with just three types of quarks (now called *up, down*, and *strange)* and their *antiquarks*. The revolutionary part of their idea was that they had to assign the quarks electric charges of 2/3 and -1/3 in units of the proton charge; such charges had never been observed!
Antiquarks are the antimatter partners of quarks; they have the same masses but the opposite charge from the corresponding quarks. When a quark meets an antiquark, they may *annihilate*, disappearing to give some other form of energy.

The Standard Model
Nearly thirty years and many experiments later, the quark idea has been confirmed. It is now part of the *Standard Model of Fundamental Particles and Interactions*. New discoveries have shown that there are six types of quarks (given the odd names of *up, down, strange, charm, bottom,* and *top,* in order of increasing mass). Also, there are six types of particles (including the electron), called *leptons.* The Standard Model accounts for the *strong, weak, and electromagnetic interactions* of the quarks and leptons, and thus explains the patterns of nuclear binding and decays.

Matter particles consist of six *quarks* and six *leptons* that together are divided into three families. For each matter particle there is a corresponding *antiparticle* with the same properties as the normal particle except that it has the opposite charge. Only the matter particles of the first family exist today. The others were important in the early universe but have since then decayed into particles of the first family.

The Particles Made from Quarks

The quarks have both mass and charge. Different combinations of quarks form composite particles called *hadrons*. The reason that fractional electric charges like those of quarks have not been seen is that the quarks are never found separately, but only inside *hadrons.* There are two classes of hadrons: *baryons,* which contain three quarks, and *mesons,* which contain one quark and one antiquark. Particles made from the first five quark types have been produced and studied at accelerators. The top quark is so massive it took many years and very high-energy accelerators to produce it. The top quark was finally discovered in April 1995 at Fermilab.

Force carriers are particles that mediate an interaction (force). There are three different kinds of force carriers: *photons, gluons* and *vector bosons.* The photon is a massless and neutral elementary particle that mediates the electromagnetism. This is the interaction that acts between electrically charged particles. There are eight gluons that mediate the strong interaction that acts between quarks and keeps hadrons together. The third group of force carriers is the vector bosons (W^+, W^-, and Z^0). These mediate the weak interaction that makes particles transform into each other.

The Leptons

The *electron* is the best known lepton. Two other charged leptons, the *muon*, (discovered in 1936) and the *tau* (discovered in 1975) differ from the electron only in that they are more massive than it. The other three leptons are very elusive particles called *neutrinos*, which have no electric charge and very little mass. There is one type of neutrino corresponding to each type of electrically charged lepton. There are three charged and three neutral leptons. The neutral leptons are very difficult to detect. For each of the six leptons there is an antilepton with equal mass and opposite charge. The leptons are elementary (or fundamental) particles, meaning they do not consist of other particles.

The *Higgs particle* (Higgs boson) is neither a force carrier nor a matter particle. It appeared in the equations of the Standard Model when these where changed to allow particles with mass. The scientists hope to prove the existence of the Higgs particle at CERN.

Forces and Interactions

Now we know the building blocks of matter, but we must also ask: what holds it together? All forces are due to the underlying interactions of the particles. Interactions come in four types: *gravitational, electromagnetic, strong, and weak*. *Gravity* is perhaps the most familiar force to us, but it is not included in the Standard Model because its effects are tiny in particle processes and, furthermore, physicists have not yet figured out how to include it.

Electromagnetic forces are also familiar; they are responsible for binding the electrons to the nucleus to form electrically-neutral atoms. Atoms combine to form molecules or crystals because of electromagnetic effects due to their charged substructure. Most everyday forces, such as the support of the floor or friction, are due to the electromagnetic forces in matter that resist displacement of atoms or electrons from their equilibrium positions in the material.

In particle processes the forces are described as due to the exchange of particles; for each type of force there is an associated carrier particle. The carrier particle of the electromagnetic force is the photon.

For distances much larger than the size of an atomic nucleus, the remaining two forces (weak and strong nuclear) have only tiny effects -- so we never notice them in everyday life, but we depend on them for the existence of all the stuff from which the world is made, and for the decay processes that make some types of matter unstable.

The *strong* force holds quarks together to form hadrons; its carrier particles are called *gluons* because they so "glue" the quarks together. The binding of protons and neutrons to form nuclei is a residual strong interaction effect due to their strongly-interacting quark and gluon constituents. Leptons have no strong interactions.

Weak interactions are the only processes in which a quark can change to another type of quark, or a lepton to another lepton. They are responsible for the fact that all the more massive quarks and leptons decay to produce lighter quarks and leptons. That is why stable matter around us contains only electrons and the lightest two quark types (up and *down)*. The carrier particles of weak interactions are the $W^{\pm}$ and Z *bosons.*

Beta decay of nuclei was the first observed weak process: in a nucleus where protons and neutrons have sufficient energy a neutron becomes a proton and gives off an electron and an electron antineutrino. This decay changes the atomic number of the nucleus (beta ray is the name given to emerging electrons).

The *alpha particle* is a helium nucleus - one of the products of a nuclear fission. Fission is the breakup of a massive nucleus into smaller nuclei; this occurs when the sum of the masses of the smaller nuclei is less than the mass of the parent nucleus. This is a residual strong interaction effect.

What Questions Remain?

The predictions of the Standard Model agree very well with the results of experiments that investigate properties of elementary particles. Finally, one important theoretical assumption was confirmed experimentally: the **Higgs boson,** a hypothetical massive elementary particle predicted to exist by the Standard Model was discovered in 2012.

The Higgs mechanism explains how the carriers of the fundamental forces (called gauge bosons) can get a nonzero mass. According to this approach, the Standard Model requires an extra Higgs field which interacts with the gauge fields, and which has a nonzero value in its lowest energy state. In other words, the space is filled with the background Higgs field, so-called Higgs condensate. Interaction with this background field changes the low-energy spectrum of the gauge fields, and the gauge bosons become massive. The Higgs boson is the only Standard Model particle that has not been observed and is thought to be the mediator of mass.

The Higgs field has a non-trivial self-interaction, which leads to spontaneous symmetry breaking: in the lowest energy state the symmetry of the potential (which includes the gauge symmetry) is broken by the condensate. Analysis of small fluctuations of the fields near the minimum reveals that the gauge bosons and other particles become massive. In the standard model, after symmetry breaking, three of the four degrees of freedom in the Higgs field mix with the W and Z bosons, while the one remaining degree of freedom becomes the Higgs boson – a new scalar particle. The Higgs mechanism in the Standard Model successfully predicts the mass of the $W^{\pm}$, and Z weak gauge bosons and explains the difference between the massless photon, which mediates electromagnetism, and the massive W and Z bosons, which mediate the weak force.

The evidence for the Higgs mechanism was overwhelming, and finaly the CERN collider produced the Higgs boson, and the scientists evaluated its physical properties. On 14 March 2013 CERN confirmed that: "CMS and ATLAS have compared a number of options for the spin-parity of this particle, and these all prefer no spin and even parity [two fundamental criteria of a Higgs boson consistent with the Standard Model]. This, coupled with the measured interactions of the new particle with other particles, strongly indicates that it is a Higgs boson." This also makes the particle the first elementary scalar particle to be discovered in nature.