The Standard Model of Particle Physics

The Atom & Fundamentals

- What are things made of? (We thought earth, air, fire, and water)
- However, with time we have come to realize that the matter of the world is made from a few fundamental(simple and structureless -- not made of anything smaller) building blocks of nature.

  By convention there is color,

  By convention sweetness,

  By convention bitterness,

  But in reality there are atoms and space.

  Democritus (c. 400 BCE)

- Around 1900, people thought of atoms as permeable balls with bits of electric charge bouncing around inside.

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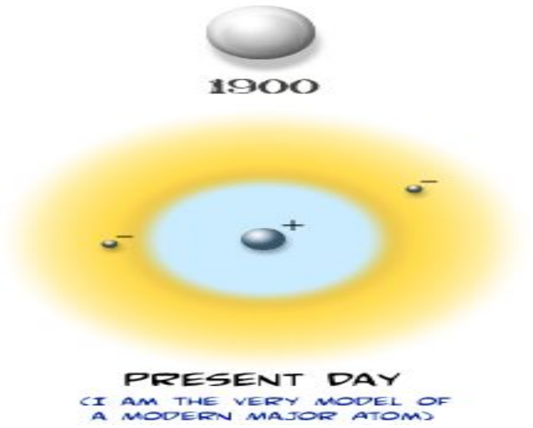
- People soon realized that they could categorize atoms into groups that shared similar chemical properties (as in the Periodic Table of the Elements). This indicated that atoms were made up of simpler building blocks, and that it was these simpler building blocks in different combinations that determined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

- We first thought the atom was fundamental and then the nucleus and then

  protons and neutrons, too - which all turned out to be wrong.



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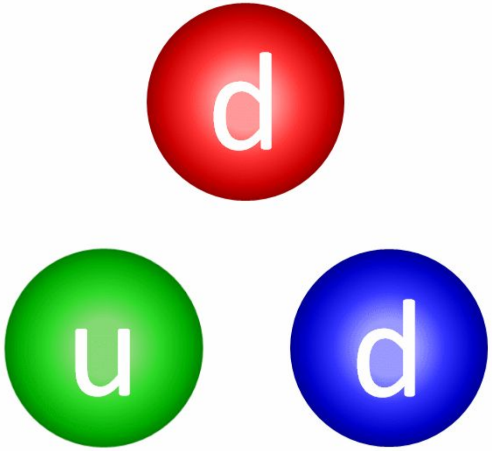
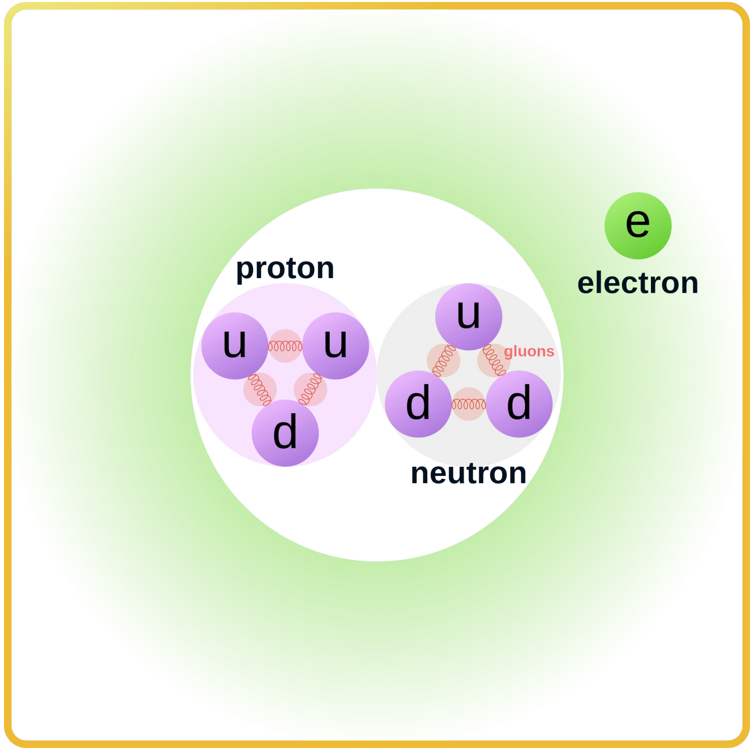
- Physicists have discovered that protons and neutrons are composed of even smaller particles called quarks.
- As far as we know, quarks are like points in geometry. They're not made up of anything else.
- After extensively testing this theory, scientists now suspect that quarks and the electron are fundamental.



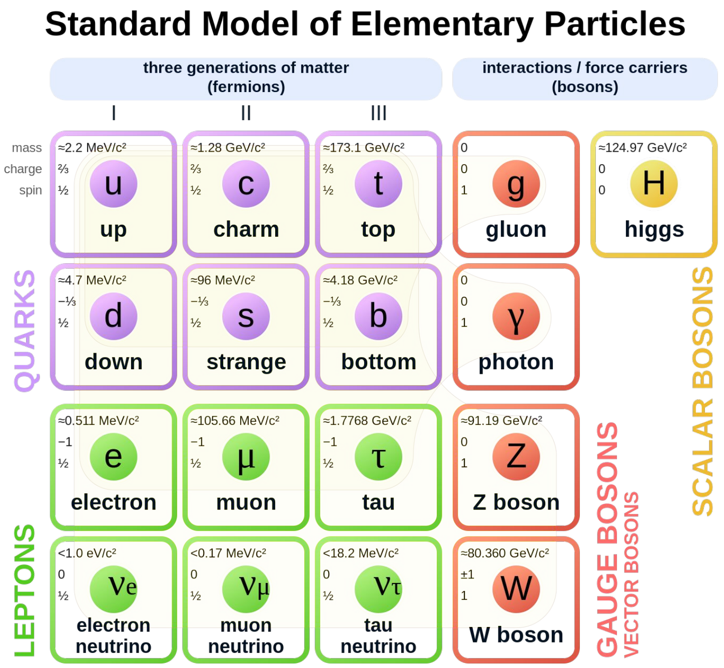
An atom as we know it

- Electrons are in constant motion around the nucleus, protons and neutrons jiggle within the nucleus, and quarks jiggle within the protons and neutrons.
- 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



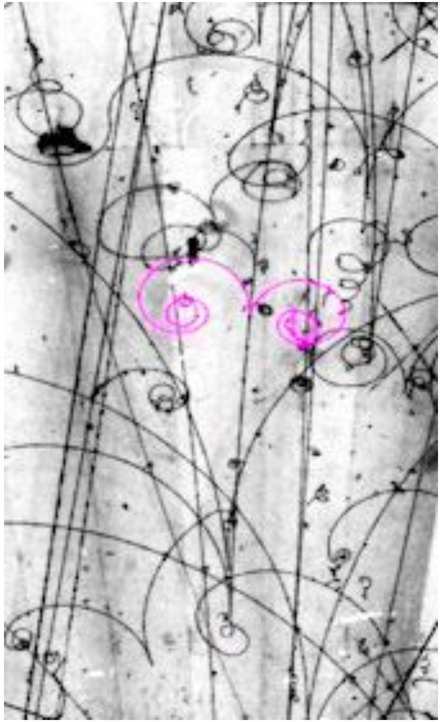
The Standard Model

- Is comprehensive theory that explains all the hundreds of particles and complex interactions with only
  - 6 quarks.
  - 6 leptons(e.g. electron)
  - Force carrier particles(e.g. photon).
- 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 fails explain everything. For example, gravity is not included in the Standard Model.



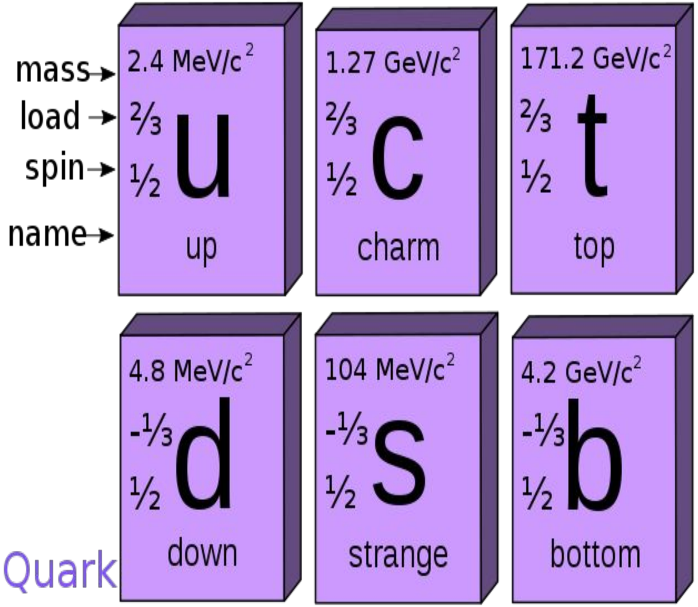
Matter & antimatter

- 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/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.)
- 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.



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.
- A weird thing about hadrons is that only a very very very small part of the mass of a hadron is due to the quarks in it.

Hadrons

Mesons - ...contain one quark and one antiquark.
E.g. pions(u & antidown) - meson are very unstable.
K-mesons are exceptions

Baryons - ...are any hadron which is made of
three quarks (qqq).
E.g. protons(uud) & neutrons(udd)

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(v). They have no electrical charge, very little mass, and they are very hard to find.
- Quarks 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.cay.

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- Leptons are divided 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 a decay.
- 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.

Decay Exercises

- Let’s determine if these decays are possible based on the example to the right.

$$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$$

$$\tau^- \rightarrow \mu^- + \nu_\tau$$

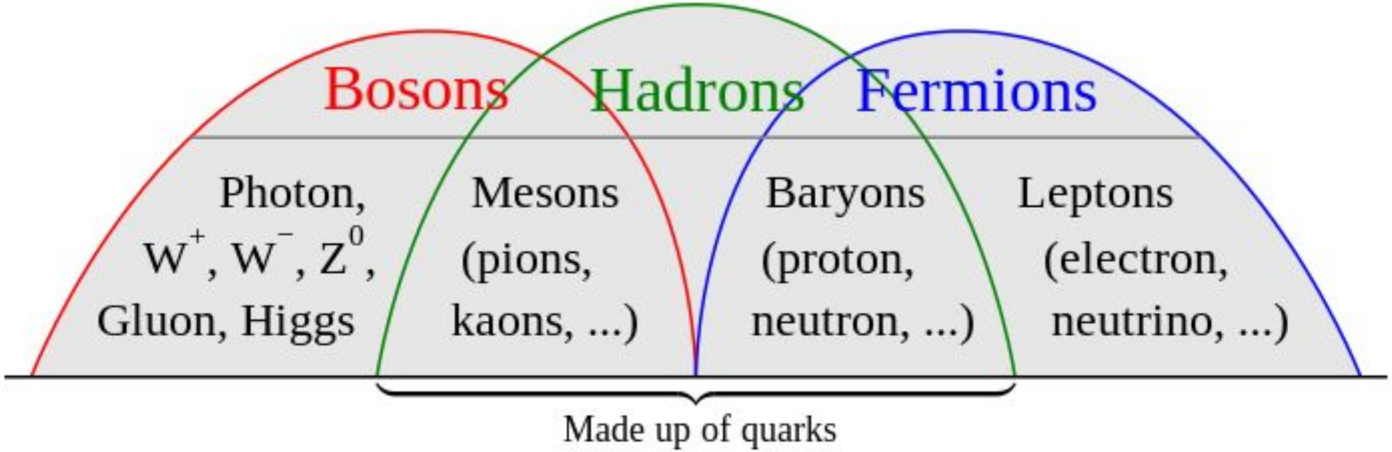
$$e^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_e$$

	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

Neutrinos

- Neutrinos are, as we've said, a type of lepton. Since they have no electrical or strong charge they almost never interact with any other particles. Most neutrinos pass right through the earth without ever interacting with a single atom of it.
- How neutrinos were discovered;
  - In a radioactive nucleus, a neutron at rest (zero momentum) decays, releasing a proton and an electron
  - Because of the law of conservation of momentum, the resulting products of the decay must have a total momentum of zero, which the observed proton and electron clearly do not. (Furthermore, if there are only two decay products, they must come out back-to-back.)
  - Therefore, we need to infer the presence of another particle with appropriate momentum to balance the event.
  - We hypothesize that an antineutrino was released; experiments have confirmed that this is indeed what happens.
- Because neutrinos were produced in great abundance in the early universe and rarely interact with matter, there are a lot of them in the Universe. Their tiny mass but huge numbers may contribute to total mass of the universe and affect its expansion.(We recently began using neutrino imaging instead of other conventional methods for this very reason. E.g. Icecube Neutrino observatory)

The Four Interactions



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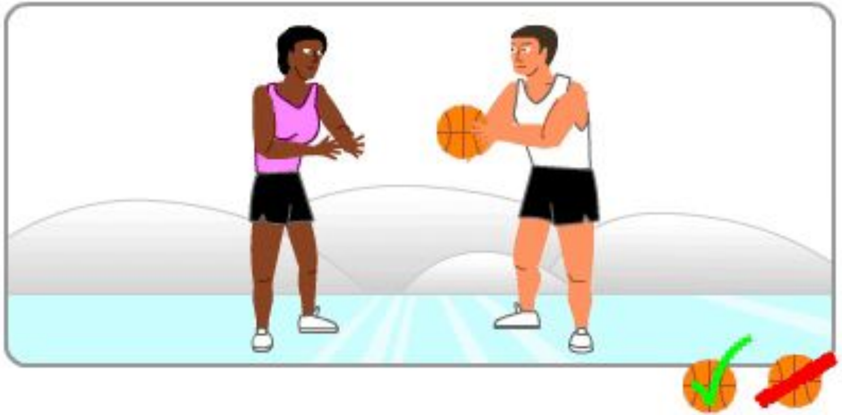
- Forces v. Interactions: Strictly speaking, a force is the effect on a particle due to the presence of other particles. The interactions of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through.

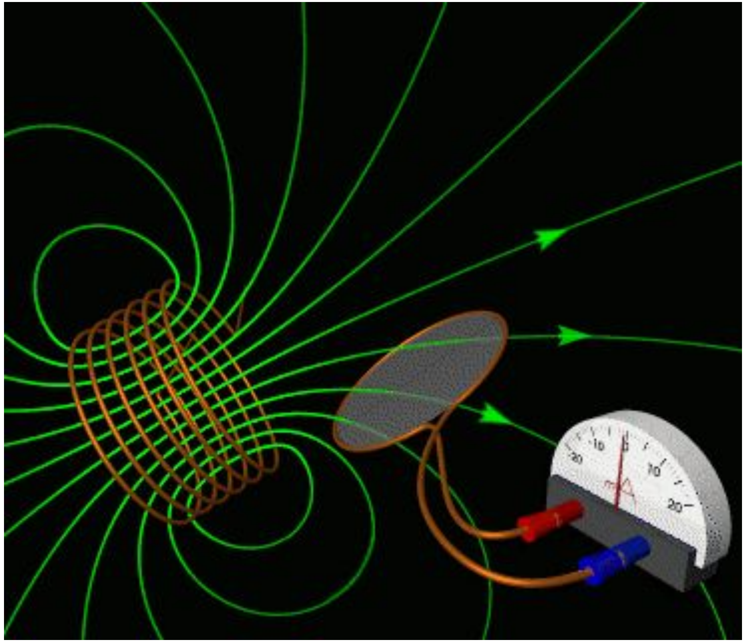
How do things interact?

- It turns out that all interactions which affect matter particles are due to an exchange of force carrier particles, a different type of particle altogether.
- What we normally think of as "forces" are actually the effects of force carrier particles on matter particles.
- One important thing to know about force carriers is that a particular force carrier particle can only be absorbed or produced by a matter particle which is affected by that particular force. For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.



Electromagnetism

- 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 and always travel at the 300,000,000 meters per second.
- 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. Basically why all life exists



The Strong Force

- All the other forces fail to explain the nucleus itself.
- 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.
- The strong force holds quarks together to form hadrons, so its carrier particles are whimsically called **gluons** because they so tightly "glue" quarks together.
- Color charge behaves differently than electromagnetic charge. Gluons, themselves, have color charge, which is strange and not at all like photons which do not have electromagnetic charge. And while quarks have color charge, composite particles made out of quarks have no net color charge.
- For this reason, the strong force only takes place on the really small level of quark interactions, which is probably why you are not aware of the strong force in your everyday life.

Color charges (QCD)

- 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. Quarks constantly change their color charges as they exchange gluons with other quarks.
- 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 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.

The Weak Interaction

- 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.
- 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.

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.
- They discovered that at very short distances (about 10e-18 meters) the strength of the weak interaction is comparable to that of the electromagnetic. On the other hand, at thirty times that distance (3x10e-17 m) the strength of the weak interaction is 1/10,000th than that of the electromagnetic interaction. At distances typical for quarks in a proton or neutron (10e-15 m) the force is even tinier.
- 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.

Summary of the Interactions

	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Quantum Numbers

- Electric charge. Quarks may have 2/3 or 1/3 electron charges, but they only form composite particles with integer electric charge. All particles other than quarks have integer multiples of the electron's charge.
- Color charge. A quark carries one of three color charges and a gluon carries one of eight color-anticolor charges. All other particles are color neutral.
- Flavor. Flavor distinguishes quarks (and leptons) from one another.
- Spin. Spin is a bizarre but important physical quantity. Large objects like planets or marbles may have angular momentum and a magnetic field because they spin. Since particles also to appear to have their own angular momentum and tiny magnetic moments, physicists called this particle property spin. This is a misleading term since particles are not actually "spinning." Spin is quantized to units of 0, 1/2, 1, 3/2 (times Planck's Constant,) and so on.-