

A BRIEF INTRODUCTION TO PARTICLE PHYSICS

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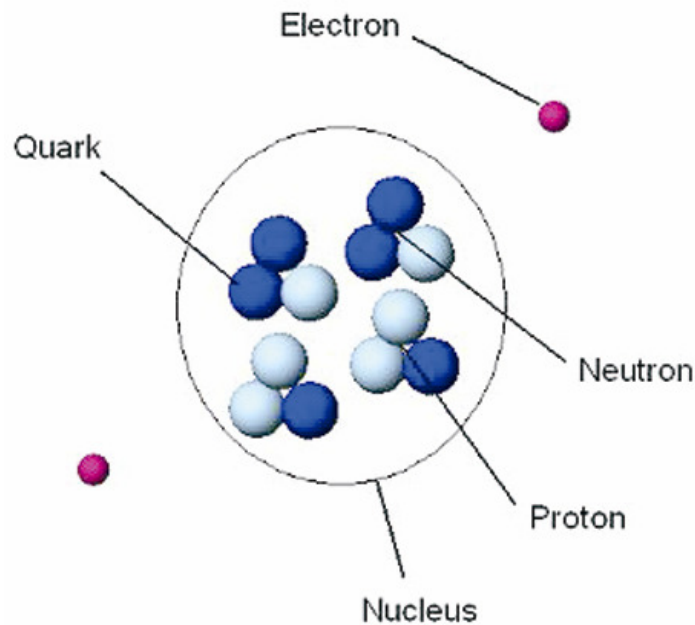
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What is Particle Physics?

Protons, electrons, neutrons, neutrinos and even quarks are often featured in news of scientific discoveries. All of these, and a whole "zoo" of others, are tiny sub-atomic particles too small to be seen even in microscopes. While molecules and atoms are the basic elements of familiar substances that we can see and feel, we have to "look" *within* atoms in order to learn about the "elementary" sub-atomic particles and to understand the nature of our Universe. The science of this study is called Particle Physics, Elementary Particle Physics or sometimes High Energy Physics (HEP).

Atoms were postulated long ago by the Greek philosopher Democritus, and until the beginning of the 20th century, atoms were thought to be the fundamental indivisible building blocks of all forms of matter. Protons, neutrons and electrons came to be regarded as the fundamental particles of nature when we learned in the 1900's through the experiments of Rutherford and others that atoms consist of mostly empty space with electrons surrounding a dense central nucleus made up of protons and neutrons.



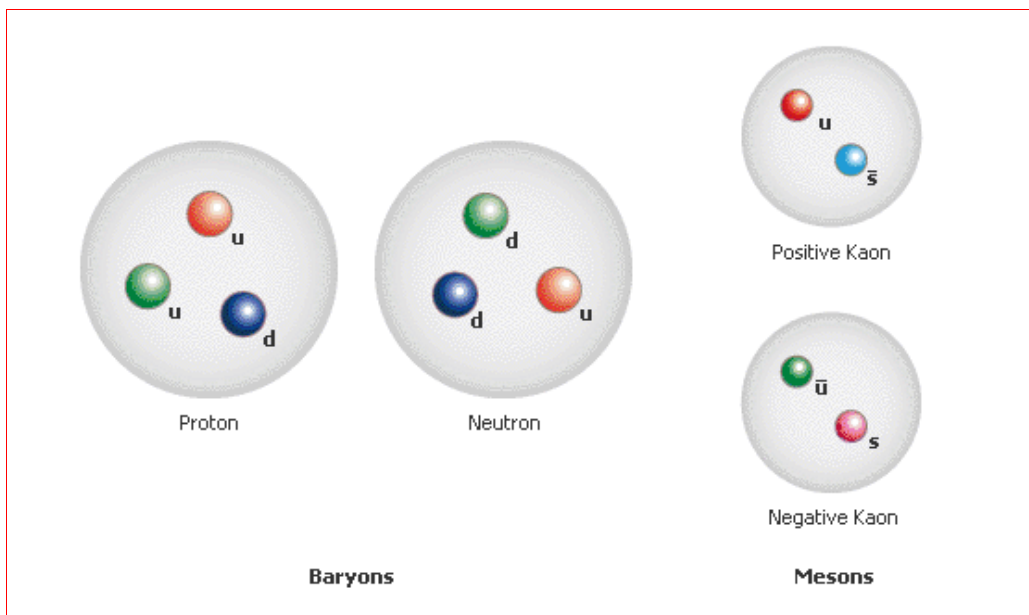
Inside an Atom: The central *nucleus* contains protons and neutrons which in turn contain quarks. Electron clouds surround the nucleus of an atom

The science of particle physics surged forward with the invention of particle accelerators that could accelerate protons or electrons to high energies and smash them into nuclei — to the surprise of scientists, a whole host of new particles were produced in these collisions.

By the early 1960s, as accelerators reached higher energies, a hundred or more types of particles were found. Could all of these then be the new fundamental particles? Confusion reigned until it became clear late in the last century, through a long series of experiments and theoretical studies, that there existed a very simple scheme of two basic sets of particles: the *quarks* and *leptons* (among the leptons are *electrons* and *neutrinos*), and a set of fundamental forces that allow these to interact with each other. By the way, these "forces" themselves can be regarded as being transmitted through the exchange of particles called *gauge*

bosons. An example of these is the *photon*, the quantum of light and the transmitter of the electromagnetic force we experience every day.

Together these fundamental particles form various combinations that are observed today as protons, neutrons and the zoo of particles seen in accelerator experiments. (We should state here that all these sets of *particles* also include their *anti-particles*, or in plain language what might roughly be called their complementary opposites. These make up *matter* and *anti-matter*.)



Matter is composed of tiny particles called quarks. Quarks come in six varieties: up (*u*), down (*d*), charm (*c*), strange (*s*), top (*t*), and bottom (*b*). Quarks also have antimatter counterparts called antiquarks (designated by a line over the letter symbol). Quarks combine to form heavier particles called *baryons*, and quarks and antiquarks combine to form *mesons*. Protons and neutrons, particles that form the nuclei of atoms, are examples of baryons. Positive and negative kaons are examples of mesons.

Today, the ***Standard Model*** is the theory that describes the role of these fundamental particles and interactions between them. And the role of Particle Physics is to test this model in all conceivable ways, seeking to discover whether something more lies beyond it. Below we will describe this Standard Model and its salient features.

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What about the nature of our Universe?



A Hubble Telescope photograph of galaxies deep in Universe

Here is our present understanding, in a nutshell. We believe that the Universe started off with a "Big Bang", with enormously high energy and temperature concentrated in an infinitesimally small volume. The Universe immediately started to expand at a furious rate and some of the energy was converted into pairs of particles and antiparticles with mass—remember Einstein's $E=mc^2$. In the first tiny fraction of a second, only a mix of radiation (*photons* of pure energy) and *quarks*, *leptons* and *gauge bosons* existed. During the very dense phase, particles and antiparticles collided and annihilated each other into photons, leaving just a tiny fraction of *matter* to carry on in the Universe. As the Universe expanded rapidly, in about a hundredth of a second it cooled to a "temperature" of about 100 billion degrees, and quarks began to clump together into *protons* and *neutrons* which swirled around with *electrons*, *neutrinos* and *photons* in a grand soup of particles. From this point on, there were no *free quarks* to be found. In the next three minutes or so, the Universe cooled to about a billion degrees, allowing protons and neutrons to clump together to form the *nuclei* of

light elements such as deuterium, helium and lithium. After about three hundred thousand years, the Universe cooled enough (to a few thousand degrees) to allow the free electrons to become bound to light nuclei and thus formed the first *atoms*. Free photons and neutrinos continue to stream throughout the Universe, meeting and interacting occasionally with the atoms in galaxies, stars and in us!

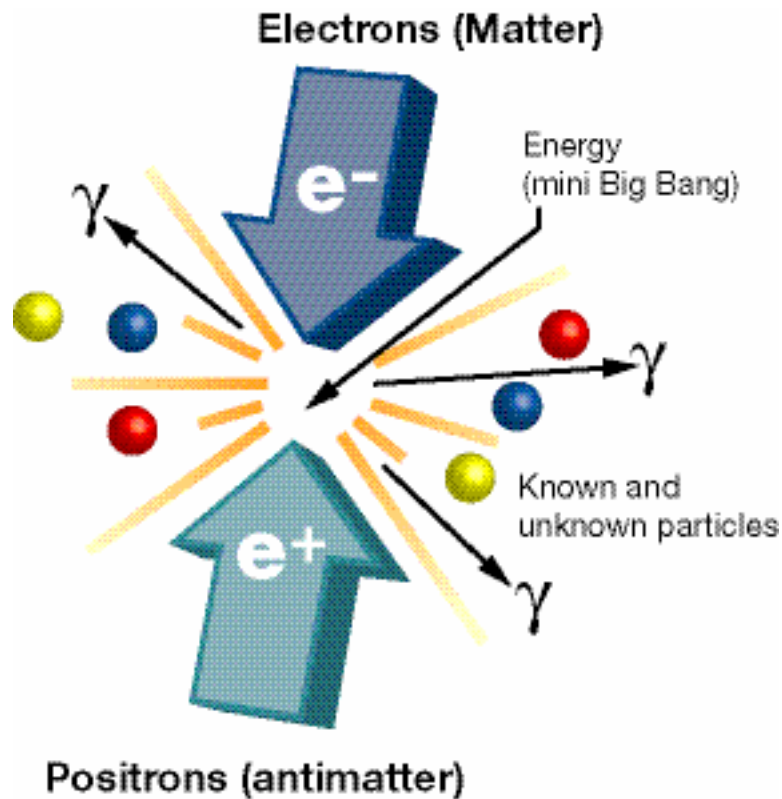
We see now that to understand how the Universe evolved we really need to understand the behavior of the elementary particles: the quarks, leptons and gauge bosons. These make up all the known recognizable matter in our Universe.

Beyond that, the Universe holds at least two dark secrets: *Dark Matter* and *Dark Energy*! The total amount of luminous matter (e.g., stars, etc.) is not enough to explain the total observed gravitational behavior of galaxies and clusters of galaxies. Some form of mysterious *Dark Matter* has to be found. Below we will see how new kinds of particles may be discovered that fit the description. Recent evidence showing that the expansion of the Universe may be accelerating instead of slowing down leads to the conclusion that a mysterious *Dark Energy* may be the culprit. Perhaps some new form of interaction may be responsible for that.

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So how do we get to study quarks and such, if they don't exist freely now?

Just as in the Big Bang, if we can manage to make high enough temperatures, we can create some *pairs* of quarks & anti-quarks, by the conversion of energy into matter. (Particles & anti-particles have to be created in pairs to balance charge, etc.)

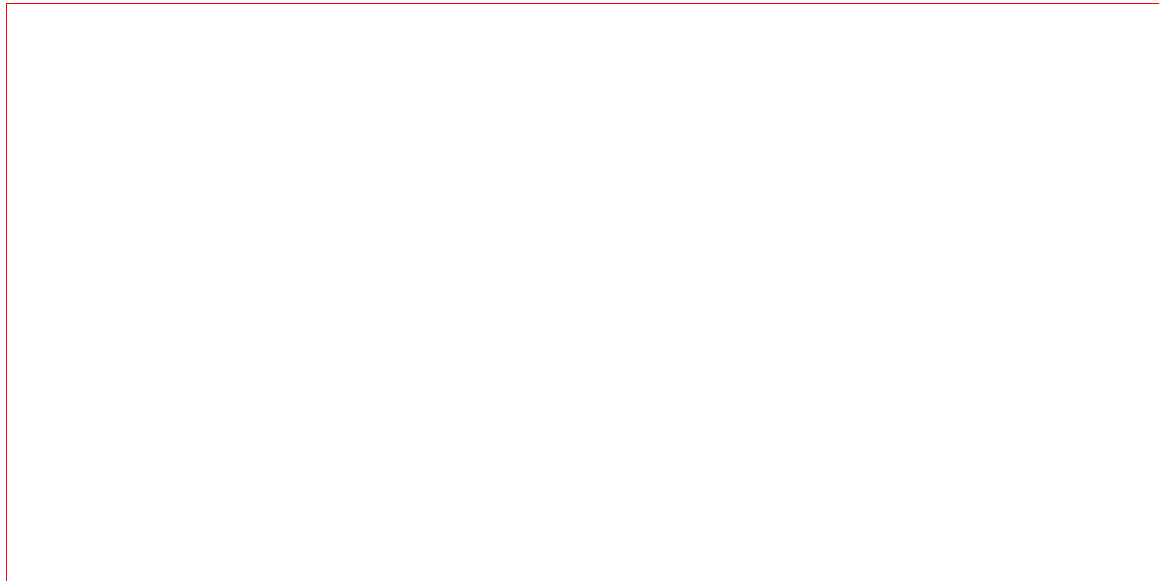


When particles of matter and antimatter collide they annihilate each other, creating conditions like those that might have existed in the first fractions of a second after the big bang.

This is where high energy accelerators come in. In head-on collisions between high-energy particles and their antiparticles, pure energy is created in "little bangs" when the particles and their antiparticles *annihilate* each other and disappear. This energy is then free to reappear as pairs of fundamental particles, e.g., a quark-antiquark pair, or an electron-positron pair, etc. Now electrons and their positron antiparticles can be observed as two distinct particles. But quarks and antiquarks behave somewhat like two ends of a string — you can cut the string and have *two separate strings* but you can never separate a string into two distinct "ends". Free quarks cannot be observed!

So when a quark-antiquark pair is produced in a head-on collision with excess energy (i.e., $E > 2m_q c^2$) the quark and antiquark fly off in opposite directions until "the string breaks into two" and each of the pair finds itself bound with another quark. What we actually observe is a pair of *mesons* being produced, each meson consisting of a quark and an antiquark bound together. With enough excess energy, larger clumps of quarks and antiquarks can be produced: protons, neutrons and heavier particles classed as *baryons*. These mesons and baryons make up the zoo of particles discovered earlier.

What we have thus found is that to study quarks, one has to create them in high energy collisions, but they can only be observed clumped into mesons and baryons. We have to *infer* the properties of individual quarks through the study of the decay and interactions of these mesons and baryons.



Baryons and Mesons contain combinations of quarks and anti-quarks.

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The Standard Model

Particle physicists now believe they can describe the behavior of all known subatomic particles within a single theoretical framework called the Standard Model, incorporating quarks and leptons and their interactions through the strong, weak and electromagnetic forces. Gravity is the one force not described by the Standard Model.

The Standard Model is the fruit of many years of international effort through experiments, theoretical ideas and discussions. We can summarize it this way:

All of the known matter in the Universe today is made up of quarks and leptons, held together by fundamental forces which are represented by the exchange of particles known as gauge bosons.

One guiding principle that led to current ideas about the nature of elementary particles was the concept of *Symmetry*. Nature points the way to many of its underlying principles through the existence of various symmetries.

Quarks

The quark scheme was suggested by the symmetries in the way the many *mesons* and *baryons* seemed to be arranged in families. Theorists Gell-Mann and Zweig independently proposed in 1964 that just three fundamental "constituents" (and their anti-particles) combined in different ways according to the rules of mathematical symmetries could explain the whole zoo. Gell-Mann called these constituents *quarks*, and the three types were named *up*, *down* and *strange* quarks. Evidence for quark-like constituents of protons and neutrons became clear in the late 1960s and 1970s. In 1974, a new particle was unexpectedly discovered at SLAC (Stanford Linear Accelerator Center). It was given the unwieldy dual name *J/Psi*, because of its simultaneous discovery by

two groups of experimenters! The J/Ψ was later shown to be a bound state of a completely new quark-antiquark pair, which nevertheless had been predicted on the basis of a subtle phenomenon. The new fourth quark was named *charm*. (We do not wish to comment here on the choice of names!)

The four-quark scheme was extended to its present state of *six quarks* by the addition of a new pair, in a prediction by theorists Cabbibo and independently, Kobayashi and Maskawa (collectively known as CKM). So now we have the six quarks: *up*, *down*, *strange*, *charm*, *bottom* and *top* quarks and they each have their partner anti-quarks. The quarks are usually labeled by their first letters: *u*, *d*, *s*, *c*, *b* and *t*. In various combinations they make up all the mesons and baryons that have been seen. The six-quark prediction was fulfilled when in 1977 a new heavy meson called the *Upsilon* was discovered at Fermilab and later shown to be the bound state of the *bottom* and *anti-bottom* quark pair. The *B meson*, containing an anti-*b* quark and a *u* or *d* quark was discovered by the CLEO experiment at Cornell in 1983. Finally, in 1998, conclusive evidence of the existence of the super heavy *top* quark was obtained at Fermilab.

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Leptons

What about *leptons*? Only the *electron*, *muon* and *neutrino* were known before the 1960s. These behave differently from the mesons and baryons. First, they are much less massive. The mass of the electron is almost 2,000 times smaller than the mass of the proton, and the muon appears to be just a heavier version of the electron, its mass being nine times smaller than that of the proton. The neutrino has almost no mass at all, and up until recently, its mass was thought to be truly zero. Hence the name "*leptons*" or light particles. Second, the electron and muon interact with matter mainly through their electric charges; the neutrino being neutral, hardly at all. They all have a *weak* interaction with the matter in

nuclei and, in high energy collisions, they do not produce the profusion of new mesons and baryons that protons and neutrons do when colliding with nuclei. In 1962, the first experiment using a high-energy neutrino beam (the PhD thesis of this author) showed that the electron has its own *electron-neutrino*, and the muon its own distinct *muon-neutrino*. This was the very first evidence that there could be *families* or *generations* of pairs of fundamental particles. This notion was dramatically extended in 1974, when shortly after the discovery of the *J/Psi*, a new *heavy lepton* was discovered, called the *tau*, almost *twice* as massive as the proton, but behaving like the other leptons, sharing the *weak interaction* property! This was the first evidence that *three* pairs or families of leptons existed: the *electron* and *electron-neutrino*, the *muon* and *muon-neutrino* and the *tau* and *tau-neutrino*.

A Note on Masses & Energies: We give all masses in terms of the proton mass. Since energy is related to mass by $E = mc^2$ the proton mass is given in energy units as 938 *MeV* (Million electron Volts), the energy required to create a proton, or approximately 1 *GeV* (Giga electron volt), which will henceforth serve as the unit of energy too.

Quarks and leptons have an intrinsic angular momentum called *spin*, equal to a half-integer (1/2) of the basic unit and are labeled as *fermions*. Particles that have zero or integer spin are called *bosons*.

QUARKS	(<i>u</i>) up-quark mass = 0.005	(<i>c</i>) charm-quark mass = 1.5	(<i>t</i>) top-quark mass = 186	Charge = +2/3
	(<i>d</i>) down-quark mass = 0.009	(<i>s</i>) strange-quark mass = 0.16	(<i>b</i>) bottom-quark mass = 5.2	Charge = -1/3
LEPTONS	(<i>ν_e</i>) elec-neutrino mass ~ 0	(<i>ν_μ</i>) muon-neutrino mass ~ 0	(<i>ν_τ</i>) tau-neutrino mass ~ 0	Charge = 0
	(<i>e</i>) electron mass = 0.00054	(<i>μ</i>) muon mass = 0.11	(<i>τ</i>) tau mass = 1.9	Charge = -1

Table 1: The Quark and Lepton families. All masses are given relative to the proton mass, which is 938 *MeV*. All of the above have a *spin* (angular momentum) of 1/2 unit.

However, the fundamental questions still remain: *why are there quarks and leptons, with different charges and interaction characteristics? Why are there three generations, and so many different masses?*

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Forces and Interactions

Now we must tackle the *fundamental forces* or *interactions* among the quarks and leptons: *Gravity*, the *Weak Force*, *Electromagnetism*, and the *Strong Force*. Of these, our everyday world is controlled by gravity and electromagnetism. The strong force binds quarks together and holds nucleons (protons & neutrons) in nuclei. The weak force is responsible for the radioactive decay of unstable nuclei and for interactions of neutrinos and other leptons with matter.

The intrinsic strengths of the forces can be compared relative to the *strong* force, here considered to have *unit strength* (i.e., =1.) In these terms, the *electromagnetic* force has an intrinsic strength of (1/137). The *weak* force is a billion times weaker than the strong force. The weakest of them all is the *gravitational* force. This may seem strange, since it is strong enough to hold the massive Earth & planets in orbit around the Sun! But we know that the gravitational force between two bodies a distance *r* apart is proportional to the product of the two masses (*M* & *m*) and inversely proportional to the distance *r* squared:

$$F_G = \frac{GMm}{r^2}$$

We see now what is meant by *intrinsic* strength. It is given by the magnitude of the universal force constant, in this case, *G*, independent of the masses or distances involved. In similar terms, the electromagnetic force between two particles is proportional to the product of the two charges (*Q* & *q*) and inversely to the distance *r* squared:

$$F_{em} = \frac{\alpha Qq}{r^2}$$

Here the universal constant alpha, *α*, gives the intrinsic strength.

We can compare the relative strengths of the electromagnetic *repulsion* and the gravitational *attraction* between two protons of unit charge using the above equations. Independent of the distance, the ratio turns out to be 10^{36} ! Thus the two protons will repel each other and fly apart, easily overcoming the puny

gravitational attraction.

As we noted before, forces can be represented in the theory as arising from the exchange of specific particles called *gauge bosons*, the *quanta* of the "force field". Just as photons are *real* (i.e., quanta of light!) and can be radiated (shaken off) when charged particles are accelerated or decelerated, the other gauge bosons (see below) can also be created and observed as real particles. All the bosons have 0 or integer spins.

FORCE	Relative Strength	Gauge Boson	Mass (rel. to proton)	Charge	Spin
Strong	1	Gluon (g)	0	0	1
Electromagnetic	1/137	Photon (γ)	0	0	1
Weak	10^{-9}	W^{\pm}, Z	86, 97	$\pm 1, 0$	1
Gravity	10^{-38}	Graviton (G)	0	0	2

Table 2: Forces and their quanta, the gauge bosons. Charge is in units of electron charge.

The carriers of the strong force are called *gluons*, the *glue* that holds quarks together in protons and neutrons and also helps form nuclei. The carriers of the weak force come in three forms, and are called *weak bosons*: the W^{\pm} and the Z^0 . The carriers of the gravitational field are called *gravitons* and are unique in having a spin of 2.

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Unification!

For a universal theory, four forces are too many. Why is there not just *one* universal force? For decades physicists have been striving for the *unification* of the four forces into one universal force that existed at least in the primordial stage of the Universe. In such a picture, the four forces we observe today are just manifestations of the original single force. However, we must understand that our existence depends on having these different forces now. If gravity were not so weak, there might only have been one massive black hole instead of galaxies, stars and planets. If electromagnetic forces were not in delicate balance with the strong force, nuclei would disintegrate — no atoms or molecules, chemistry or biology! The weak force allows more subtle phenomena —the slow burning of stars like our Sun may not be possible without the weak interaction; supernova explosions which create all elements heavier than iron also depend on just the right strength of neutrino interactions; and radioactivity in its bowels allows the Earth to remain a warm hospitable body.

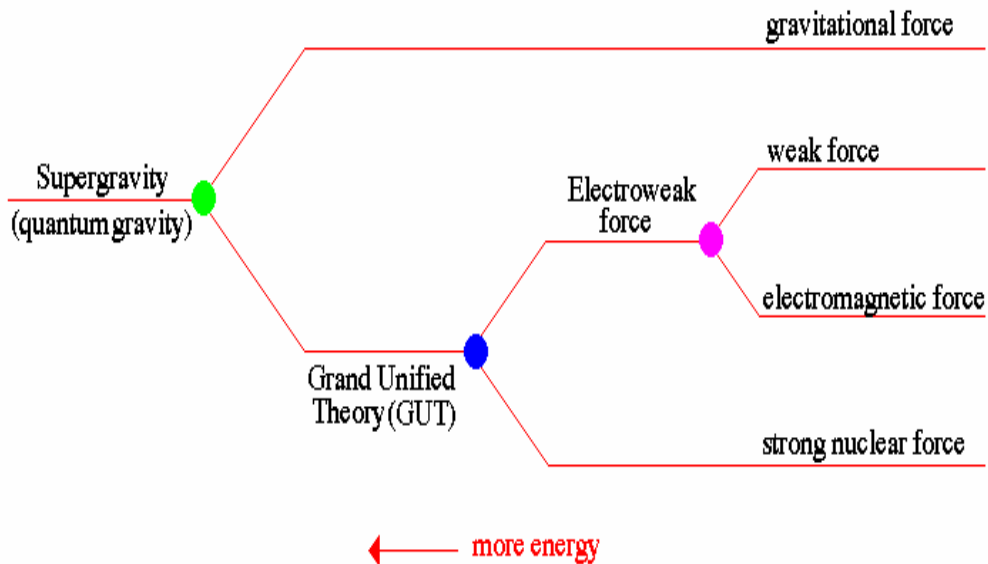
It is not quite satisfactory to have four different theories to account for these four forces. The electromagnetic interaction of particles is explained by a well established modern theory of Quantum Electrodynamics (*QED*). The weak interaction had its own theory but these two have now been combined as the Electroweak Theory in the Standard Model. The strong interaction between quarks and gluons has another theory called Quantum Chromodynamics (*QCD*), where the equivalent of electric charge is named "color". And Einstein's *General Theory of Relativity* explains how the gravity we know is a manifestation of the basic geometry of space-time.

Just as Maxwell showed that electricity and magnetism were manifestations of the same basic phenomenon of electromagnetism, the *Electroweak* theory, which in 1979 won the Nobel Prize for Glashow, Salam and Weinberg, succeeds in unifying the Weak and Electromagnetic interactions into what is called the

Electroweak force. When we noted the intrinsic strengths of the four different interactions in Table 2, we omitted to say that these strengths could depend on the "temperature" or energy level of the interaction. Although these strengths are quite different at present temperatures (e.g., at 300K or equivalent energy of about 1/40 eV), the weak interaction depends strongly on the energy, and in collisions at near 1000 GeV, it gets just as strong as the electromagnetic interaction! The Electroweak theory of the Standard Model explains all this. The basic equations are symmetric in the way the two interactions occur and in fact the masses of all the quanta are zero. However, as the temperatures drops, the symmetry is broken and the quanta split up into four different gauge bosons of different masses: the W^+ and W^- (both 80 GeV), the Z^0 (91 GeV) and the photon γ with zero mass. At "room temperature" , the massive W and Z do not play an important part. But at very high energies of 300 GeV or more, the difference between the zero mass photon and the heavier W and Z bosons is erased, and they all act equally strongly. In 1983 the W boson and in 1984 the Z boson were observed at the CERN laboratory in Geneva, in high energy collisions of protons with antiprotons. They had the predicted masses. The Standard Model was on its way!

Unification

all the forces of Nature should be capable of being described by a single theory. But only at high energies should the behavior of the forces combine, this is called unification



before the unification point, the forces are indistinguishable and have symmetry. After the unification point, the forces act differently and the symmetry is broken.

There is however one piece of evidence yet to be found. We mentioned above that the basic symmetry of the electroweak theory is broken as the temperature drops and the forces separate in strength as the bosons gain mass. The culprit that causes this is actually a new field called the *Higgs field*. It is possible to visualize how this works. Recall that *mass* is a manifestation of *inertia* or resistance to acceleration. If a Higgs field suddenly permeates all of space as the Universe cools, it can act as a *drag* on every particle moving in space, the drag depending on how well each interacts with the Higgs field. This drag shows up as *inertia* and thus a measurable *mass* of the particles that were originally massless. But now we have to look for the boson that carries this field — the *Higgs boson*. This is now the one feature of the Standard Model still needed to clinch the

picture. It is expected to have a mass of about 100 GeV, within the reach of the largest accelerators planned for the immediate future.

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Beyond the Standard Model

Theories, called "Grand Unification Theories" or GUTs, have been proposed to unify the *electroweak* force with the *strong* force. But so far no concrete evidence has been found for them. Beyond that, the holy grail of unification has long been the unification of *gravity* with all the other forces. Einstein himself labored in vain to fit gravity into a scheme where it could be compatible with quantum theory.

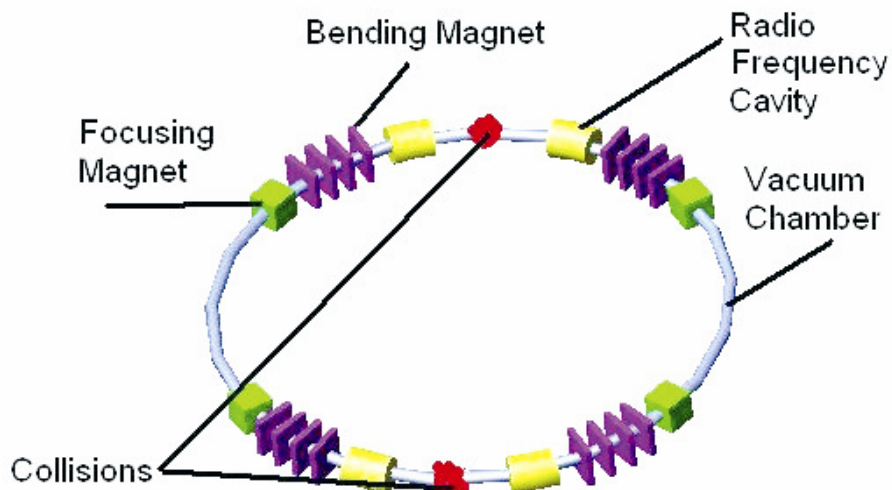
The theory of *Supersymmetry* requires a whole new set of particles beyond the Standard Model complement: a heavy partner for each quark, lepton and gauge boson of the old set, together all of them making up one great super-family of particles. The three forces strong, electromagnetic and weak all have *exactly* equal strengths in this theory at a very high energy. And of course, it gives experimentalists a whole new game of looking for new particles. It is just possible that one of these new super particles is a primordial relic of the Big Bang and makes up the *Dark Matter* in the Universe, a further incentive to discover these super-partners.

Meanwhile theoretical studies range far and wide in a search for the *Theory Of Everything* (TOE). Most familiar is *String Theory*, which pictures particles as infinitesimal little vibrating loops of strings in 10 dimensions. Further refinements lead to *Membrane Theory*, with the entire Universe regarded as existing on multidimensional sheets or membranes, with particles as loops anchored on "our" sheet and *gravitons* ranging into the continuum between sheets. We await predictions that can be tested.

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Particle Physics Experiments

Throughout the history of Physics, experimental discoveries and theoretical ideas and explanations have moved forward together, sometimes playing leap-frog, but always drawing inspiration one from the other. Modern versions of Rutherford's table-top experiment on the scattering of alpha particles occupy many square kilometers of land, with massive and costly apparatus in underground tunnels tens of kilometers long. These are the *particle accelerators* that speed protons, antiprotons, electrons, or positrons to near the speed of light and then make them collide head-on with each other or with stationary targets.



In an accelerator, focusing magnets and bending magnets guide the beam of particles around a ring. (Only a few of the bending magnets are shown here).

High frequency microwave (*RF*) cavities accelerate the beams as they pass through.

The quest has mostly been for higher and higher collision energies. To make a pair of massive new particles and observe them flying apart, one has to generate excess energy over and above the equivalent of the mass ($2m_X$) of the pair :

$E_{\text{collision}} > 2m_x c^2$. High energy is also needed to probe deeper and deeper to smaller length scales in studying the unknown — this is the equivalent of using X rays of shorter wave-lengths to probe smaller crystal structures. On the other hand, to look for rare phenomena, it is necessary to increase the *intensity* of particle beams and the *collision rates*. So accelerators have proceeded along parallel paths of ever higher energies and ever higher intensities.

To observe and interpret the results of collisions, *particle detectors* have to be developed that can track and analyze the particles that fly apart and disappear in nanoseconds. The detector consists of many different types of complex apparatus and electronics, requiring a cadre of experts in every conceivable technology. Collider experiments use large detectors completely surrounding the "interaction point" where high energy particles and antiparticles collide head-on.

Typical are *electron-positron* colliders, *proton-antiproton* colliders and massive detectors at the interaction points.

Other experiments study the collisions of intense beams with fixed (stationary) solid targets. Typical are several experiments with intense high energy *neutrino beams* and massive detectors in which neutrinos can interact. Many are studying the *conversion* of one type of neutrino (the *muon-neutrino*) into another (e.g., the *tau-neutrino*). Evidence for this is now pretty definite after decades of research, and precise measurements may pin down the non-zero mass of each neutrino. Relic neutrinos from the Big Bang populate the Universe, and even a tiny mass can explain some of the *Dark Matter*.

The art and science of particle accelerators and detectors has depended heavily on *technology*. The technology of solid state devices, superconducting magnets, electronics, computers and exotic materials, all have played leap frog with developments in experimental particle physics, sometimes driving and sometimes being driven by the inventions of particle physicists.

All these very complex detectors are built and operated by large numbers of physicists, in collaborations ranging from 100 to almost 1000 personnel. The collaborations extend across boundaries of countries and continents, in a typical illustration of science extending the hand of cooperation and friendship across national and political barriers.

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Looking to the Future

One of the primary goals for the new and upgraded facilities in Fermilab near Chicago (the *Tevatron*) and CERN in Geneva Switzerland (the Large Hadron Collider or *LHC*) is to find the *Higgs boson*, the one missing element of the Standard Model.

Evidence for *supersymmetric partners* of the known particles is a goal in all experiments, as part of the search for the true particle theory beyond the Standard Model. Beyond that is the need to find anything that can point to a real *Grand Unification* with the gravitational force.

A different kind of e^+e^- collider is being planned internationally — the International Linear Collider or *ILC*, a very high energy linear collider, with two opposing linear accelerators tens of kilometers long. The technical challenges are many and this is likely to be the first truly world-wide accelerator collaboration.

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Where to Get More Information

BOOKS:

1. The Particle Odyssey: A Journey to the Heart of the Matter

by Michael Marten, Christine Sutton, Frank Close. Oxford Press (2002)

2. The Charm of Strange Quarks : Mysteries and Revolutions of Particle Physics

by R. Michael Barnett, Henry Muehry, Helen R. Quinn. American Institute of Physics, (2000)

WEBSITES:

1. The Particle Adventure (Lawrence Berkeley Lab)

<http://www.particleadventure.org/particleadventure/>

2. Inquiring Minds (Fermi National Lab.)

<http://www.fnal.gov/pub/inquiring/index.html>

3. The World of Beams (Center for Beam Physics, Lawrence Berkeley Lab),

<http://cbp-1.lbl.gov/>

4. Big Bang Science, (Particle physics & Astronomy Research Council, UK)

<http://hepwww.rl.ac.uk/pub/bigbang/part1.html>

FOR A GLOSSARY OF TERMS, see:

<http://www.particleadventure.org/particleadventure/frameless/glossary.html#top>

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