基本粒子與對稱性

Elementary Particle Physics
and
Symmetry

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Outline

- *尺度*
- *對稱性*
- *基本粒子及交互作用*
- *大統一場理論*
- *尚未解決之問題*
- *未來展望*

● 簡介

People have long asked:

物質是由什麼組成的？

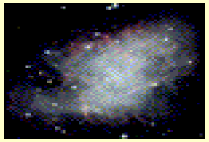
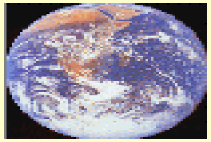
"What is the world made of?"

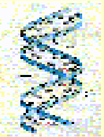
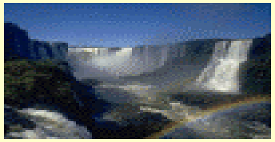
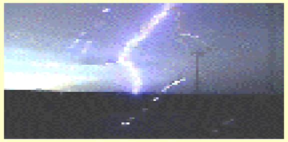
and

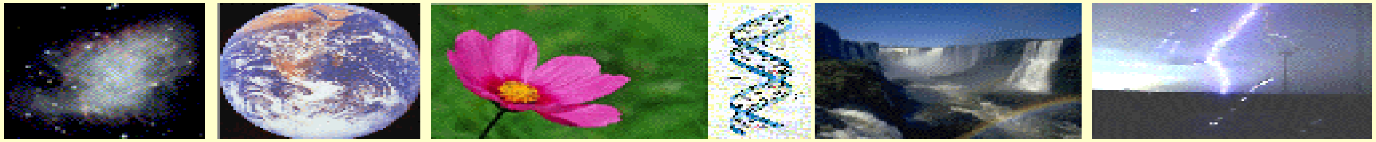
"What holds it together?"

Why do physicists want to study particles?

Because we are made of them ...



... and so is everything else in the Universe!

We now know that just four kinds of building block are needed to account for all of ordinary matter.

They are particles called:

- **up-quarks and down-quarks** 上和下夸克
- **electrons** 電子
- **electron-neutrinos** 電子中微子

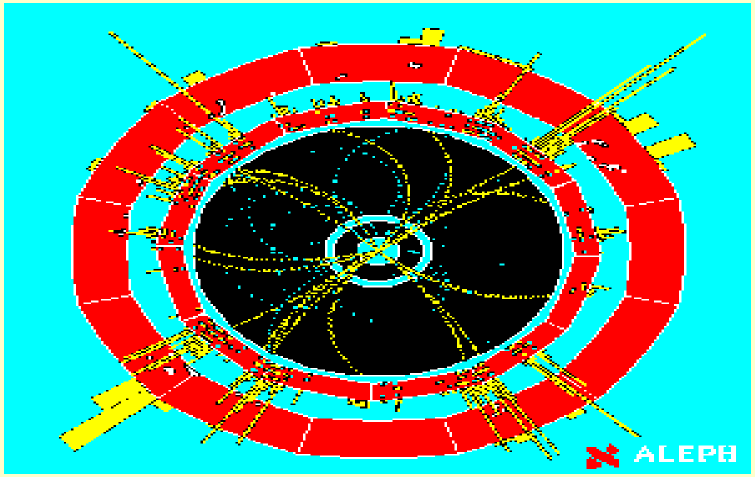
Particles are stuck together by forces: four kinds of forces,

- **gravity** 重力
- **strong** 強作用力
- **electromagnetic and weak** 電磁和弱作用力

The Andromeda galaxy

Looking into outer space means looking back in time. When you look at a galaxy a million light years away, you are looking at it as it was a million years ago. Looking at the sky at night is like reading the history of the Universe.

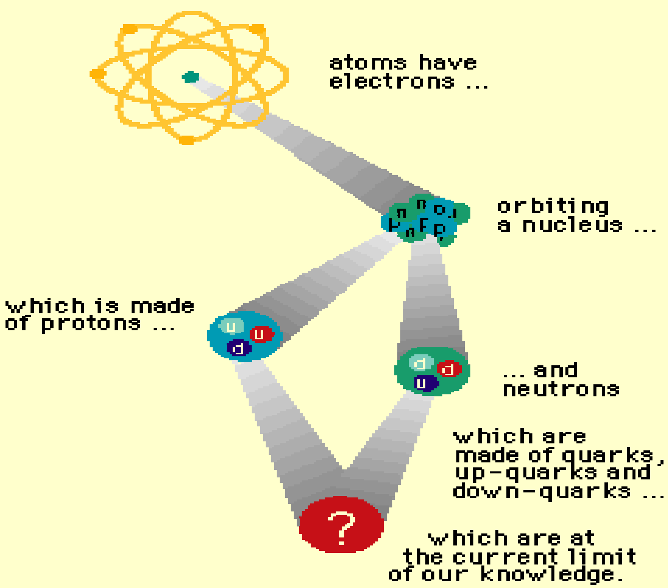
Looking into inner space - into the structure of matter - also provides a view back in time. Experiments today collide together particles at the highest possible energies in order to penetrate into the deepest layers of matter. The enormous concentration of energy leads to the creation of new matter just as when matter was first created in the initial instants after the Big Bang with which the Universe began.



Studies of the smallest structures in the Universe, in high energy particle physics are therefore intimately linked with observations in astronomy of the largest structures. This meeting point between particle physics and cosmology is one of the most fascinating aspects of modern physics. Indeed, through the scenario of the Big Bang, observations in astronomy have testable consequences in particle physics and vice versa.

高能粒子物理 ←→ 天體物理

The world about us and the Universe beyond are built from a huge diversity of materials, and further forms of matter were common in the first instants of the early Universe. Surprisingly, however, this wide variety of matter is made from relatively few simple building blocks.



[***ordinary matter***]

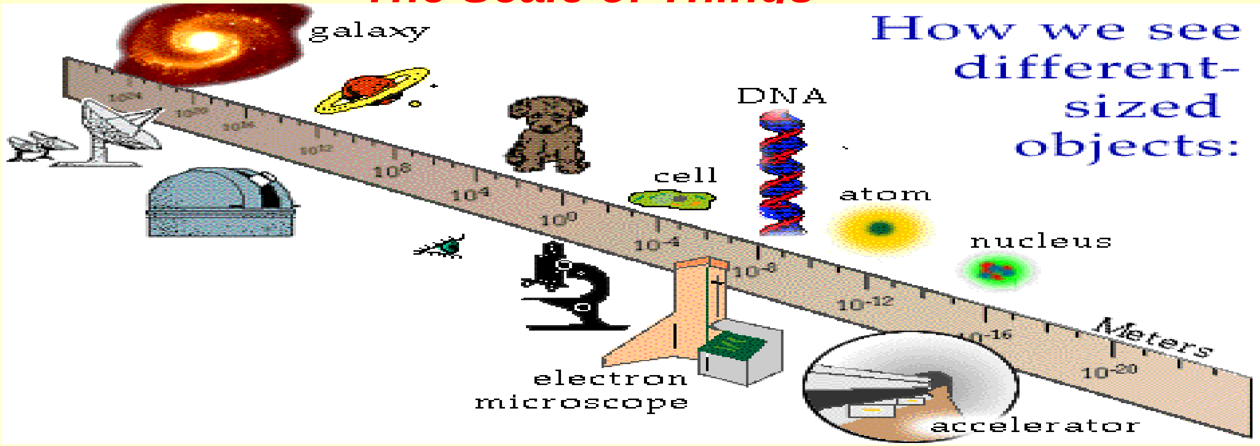
[***cosmic matter***]

[***High-energy matter***]

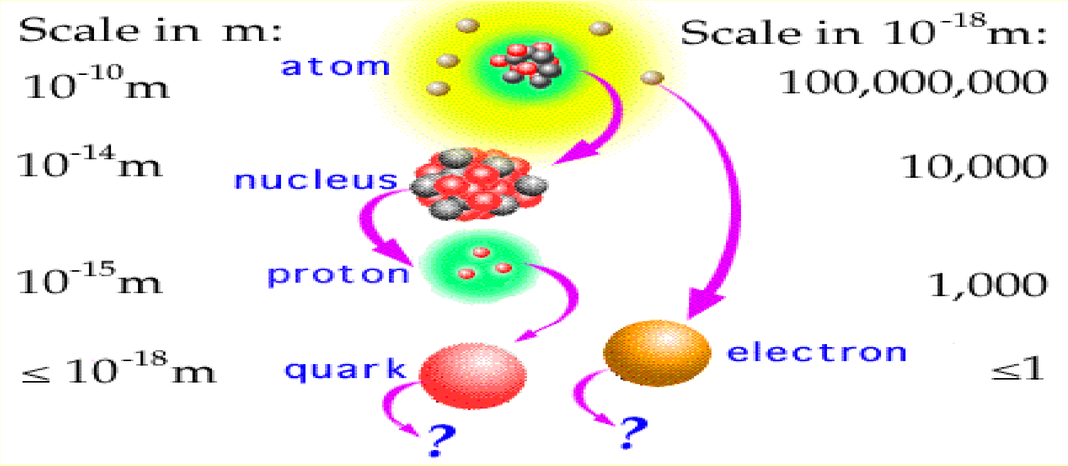
[***antimatter***]

● 尺度

The Scale of Things



Scale of the Atom



In summary, we know that atoms are made of protons, neutrons, and electrons. Protons and neutrons are made of quarks, which are possibly made of more fundamental objects. (Yikes! Will it never end?)

From an Electron-Volt to Trillions of Electron-Volts

Energies are often expressed in units of "electron-volts". An electron-volt (eV) is the energy acquired by a electron (or any particle with the same charge) when it is accelerated by a potential difference of 1 volt.

- ***Typical energies involved in atomic processes (processes such as chemical reactions or the emission of light) are of order a few eV. That is why batteries typically produce about 1 volt, and have to be connected in series to get much larger potentials.***
- ***Energies in nuclear processes (like nuclear fission or radioactive decay) are typically of order one million electron-volts (1 MeV).***
- ***The highest energy accelerator now operating (at Fermilab) accelerates protons to 1 million million electron volts (1 trillion electron volts, 1 TeV =10^{12} eV).***
- ***The Large Hadron Collider (LHC) at CERN will accelerate each of two counter-rotating beams of protons to 7 TeV per proton.***

● *對稱性*

Symmetry is a crucial concept in mathematics, chemistry, and biology. Its definition is also applicable to art, music, architecture and the innumerable patterns designed by nature, in both animate and inanimate forms. In modern physics, however, symmetry may be the most crucial concept of all. Fundamental symmetry principles dictate the basic laws of physics, control structure of matter, and define the fundamental forces in nature.

"I aim at two things: On the one hand to clarify, step by step, the philosophic-mathematical significance of the idea of symmetry and, on the other, to display the great variety of applications of symmetry in the arts, in inorganic and organic nature." And "Symmetry….is an idea which has guided man through the centuries to the understanding and the creation of order, beauty and perfection. "

對稱性是一種觀念，這種觀念在幾千年來一直引導人類理解和創造世界上各種事物之規律，美妙，及完善。

Hermann Weyl (in his book "Symmetry")

"I heave the basketball; I know it sails in a parabola, exhibiting perfect symmetry, which is interrupted by the basket. Its funny, but it is always interrupted by the basket." ***Michael Jordan (former Chicago Bull)***

Symmetries ←→ Conservation Laws

對稱性 → 不可區分性

對稱性破壞 → 可區分性

粒子物理: *三種非常重要的分立對稱性* -- **C**, **P**, *和* **T** *宇稱*

- ***P*** **:** *宇稱 或 空間反演* $\boldsymbol{x \longleftrightarrow -x}$
- ***T*** **:** *時間反演* $\boldsymbol{t \longleftrightarrow -t}$
- ***C*** **:** *粒子和反粒子交換 或 電荷共軛*
- *粒子* ⟵⟶ *反粒子*

很多年來,物理學的規律被認為是 P, C,和 T,守恆的

*在電磁作用中，**P , C** 和 **T** 是守恆的！*
*同樣在強作用中,**P, C** 和 **T** 也是守恆的！*
但在弱作用中,它們是守恆的嗎？

眾所周知,中國著名物理學家李政道和楊振寧博士
*在**1956**年指出：在弱作用力中，**P** 和**C**是破壞的*
*為此他們榮獲**1957**年的**NOBEL**物理學獎*

1964年，在美國BNL國家實驗室，Fitch和Cronin等
人發現了反常的中性K介子衰變：→ CP 破壞。

--Fitch和Cronin榮獲了1980年的NOBEL物理學獎

1998年，在FNAL (KTeV) 和CERN (CPLEAR)分別觀
測到了T破壞現象。

弱交互作用力：P， C， CP 和 T 都是破壞的

● 基本粒子及交互作用

What is the World Made of?

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

People have come to realize that the matter of the world is made from a few fundamental building blocks of nature.

The word "fundamental" is key here. By fundamental building blocks we mean objects that are simple and structureless -- not made of anything smaller.

Even in ancient times, people sought to organize the world around them into fundamental elements, such as earth, air, fire, and water.

古代中國文明：世界是由五種星組成

金，木，水，火，土

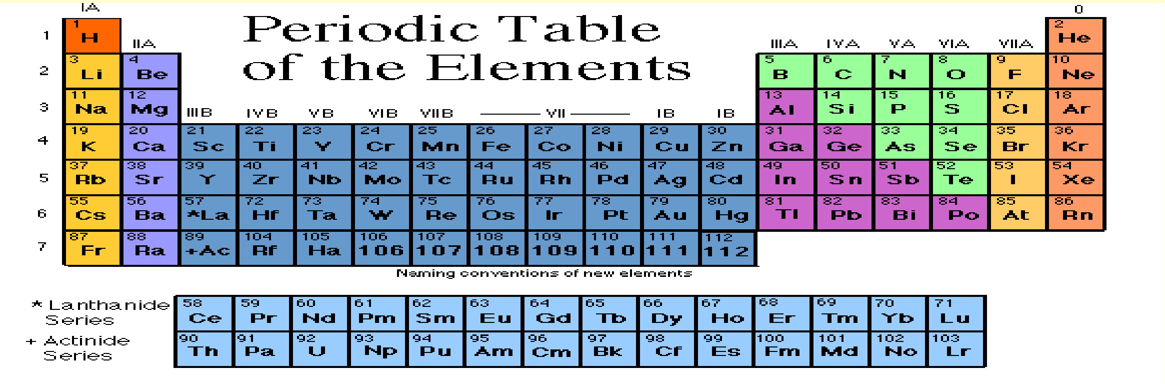
What is Fundamental?

物質是無限可分的嗎？

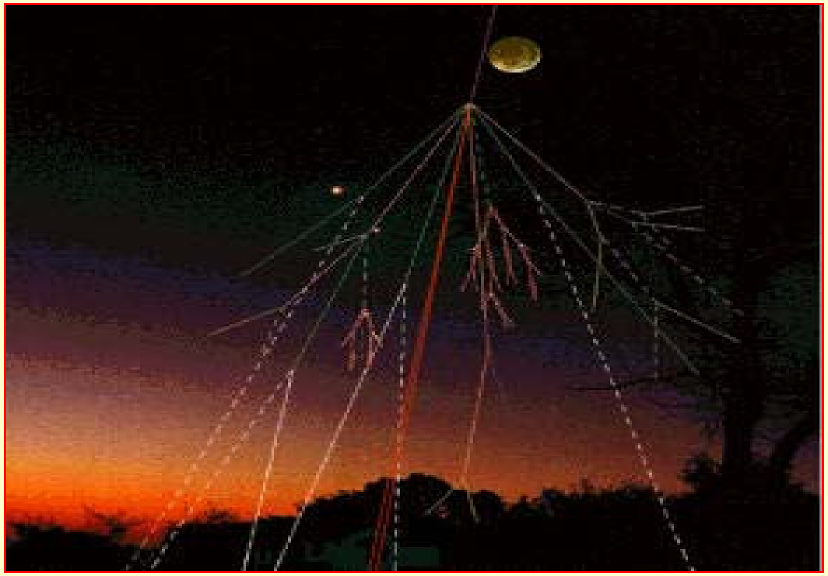
一日之棰，日取其半，萬世不竭

莊子天下篇第三十三（ca. 300 B.C.）

Ordinary matter

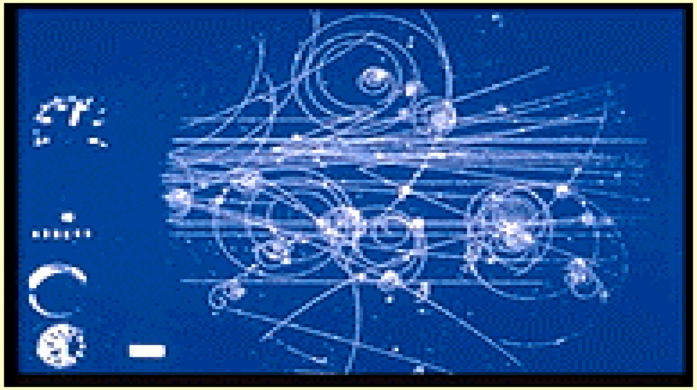


Cosmic Matter



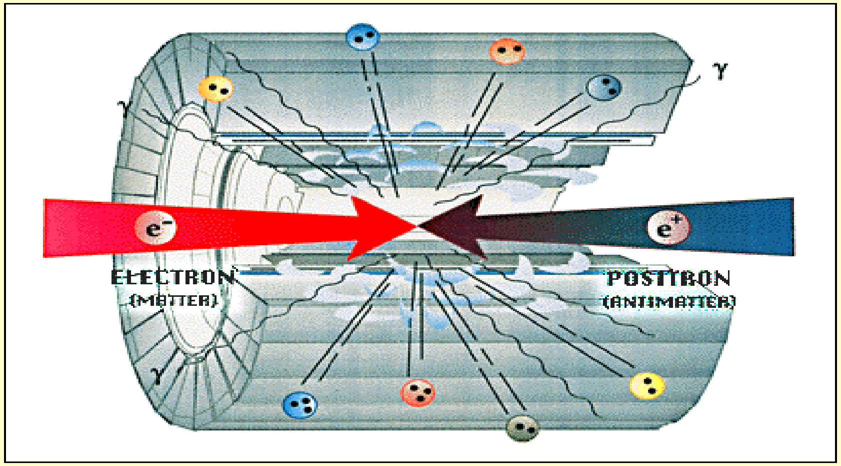
So to understand the matter that exists as cosmic rays, we need more components than we need to make atoms. In addition to the electron, electron-neutrino, up quark and down quark, we need the muon, the muon-neutrino and the strange quark.

High Energy Matter



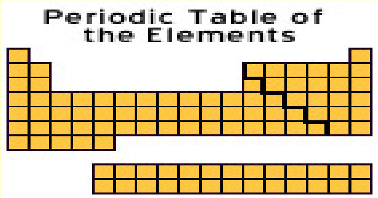
To study high energy particle collisions under more controlled conditions, particle physicists use laboratories such as CERN, where high-energy particle colliders mimic the actions of cosmic rays in the atmosphere. Nowadays, these experiments reach energies that were common in the Universe only in the first instants of its existence.

Antimatter



For each of the basic particles of matter, there also exists a "mirror" version - or antiparticle - in which properties such as electric charge are reversed.

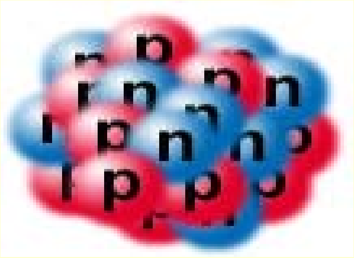
Is the Atom Fundamental ?



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

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

Is the Nucleus Fundamental?



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

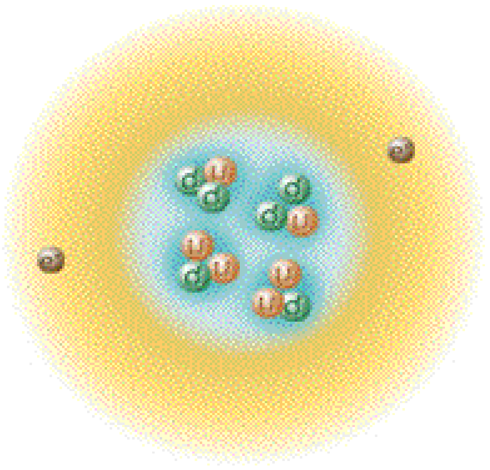
So, then, are protons and neutrons fundamental?

Physicists have discovered that protons and neutrons are composed of even smaller particles called quarks.

As far as we know, quarks are like points in geometry. They're not made up of anything else.

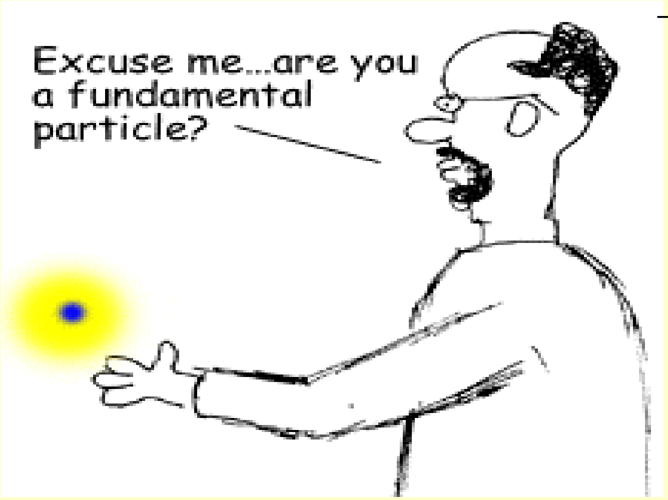
After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental

The Modern Atom Model



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

This picture is quite distorted. If we drew the atom to scale and made protons and neutrons a centimeter in diameter, then the electrons and quarks would be less than the diameter of a hair and the entire atom's diameter would be greater than the length of thirty football fields! 99.999999999999% of an atom's volume is just empty space!



Physicists constantly look for new particles. When they find them, they categorize them and try to find patterns that tell us about how the fundamental building blocks of the universe interact.

We have now discovered about two hundred particles (most of which aren't fundamental).

To keep track of all of these particles, they are named with letters from the Greek and Roman alphabets.

Of course, You should not be discouraged if you have trouble remembering them. Take heart: even the great Enrico Fermi once said to his student (and future Nobel Laureate) Leon Lederman,

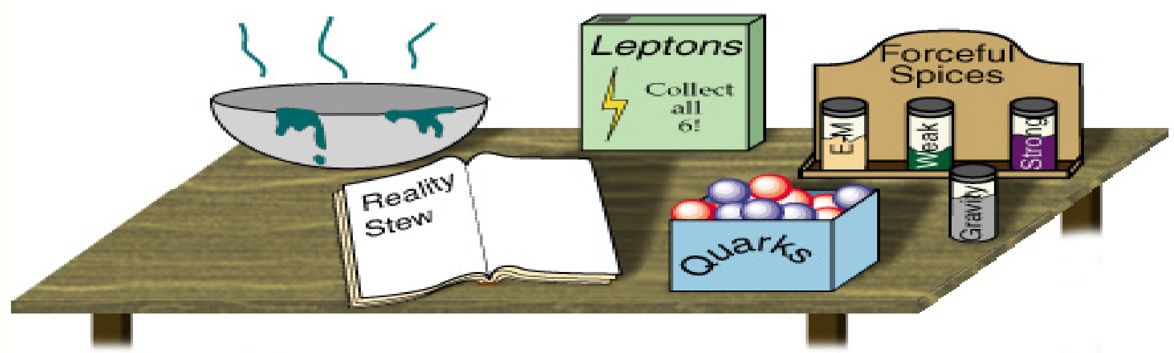
"Young man, if I could remember the names of these particles, I would have been a botanist!"

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.
- **Force carrier particles,** like the photon.

All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.

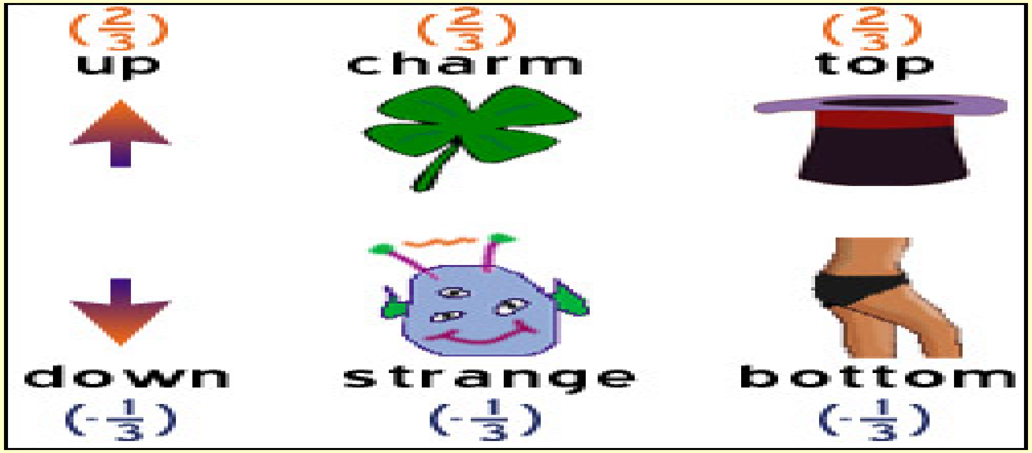


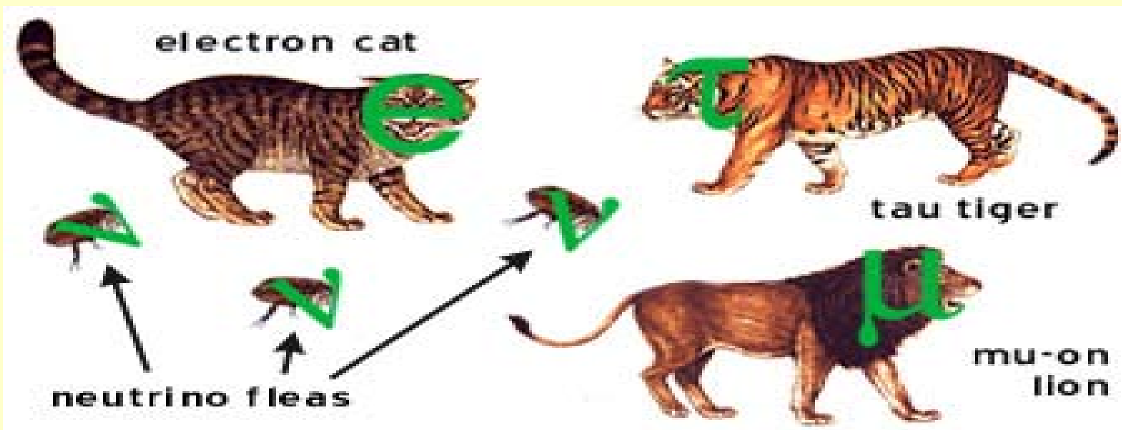
The Standard Model is a good theory. Experiments have verified its predictions to incredible precision, and all the particles predicted by this theory have been found. But it does not explain everything. For example, gravity is not included in the Standard Model.

What is the World Made of?

Quarks and Leptons

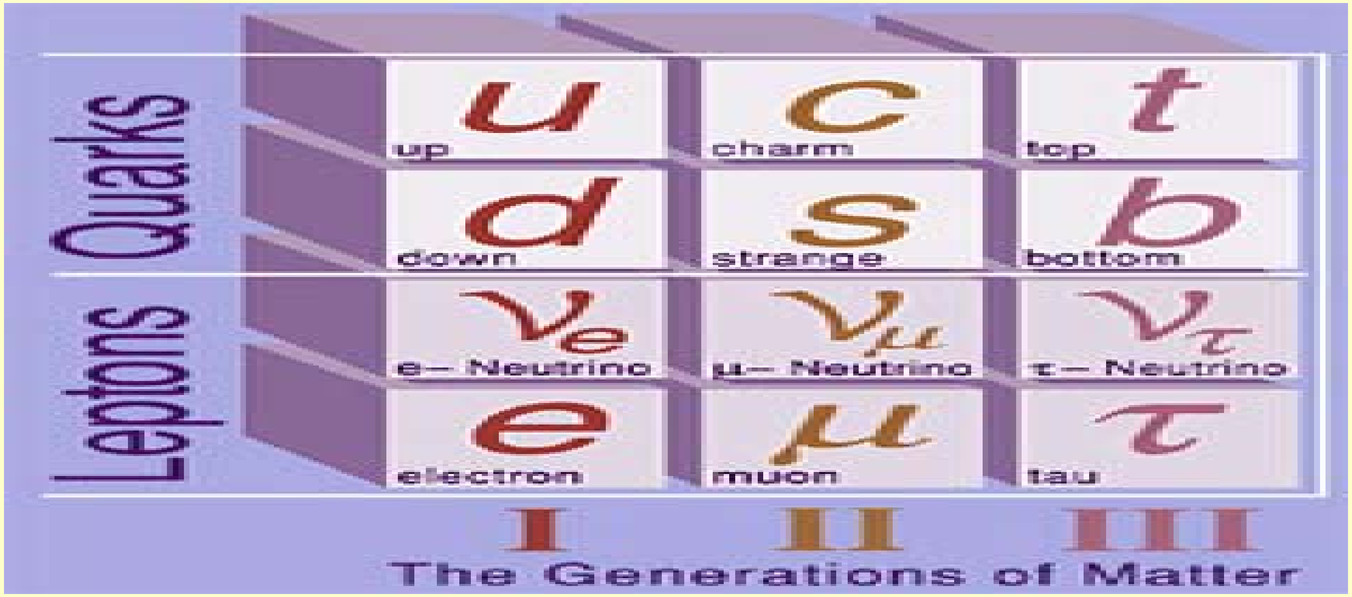
As you have read, everything from galaxies to mountains to molecules is made from quarks and leptons. But that is not the whole story. Quarks behave differently than leptons, and for each kind of matter particle there is a corresponding antimatter particle.





Particle	Mass (Gev/c^2)	Electr. Charge
U (up)	.005	+2/3
D (down)	.01	-1/3
C (charm)	1.5	+2/3
S (strange)	0.2	-1/3
T (top)	180	+2/3
B (bottom)	4.7	-1/3

Particle	Mass (Gev/c^2)	Electr. Charge
electron-neutrino	$<7x10^{-9}$	0
electron	.000511	-1
muon-neutrino	<.0003	0
muon	0.106	-1
tau-neutrino	<.03	0
tau	1.7771	-1

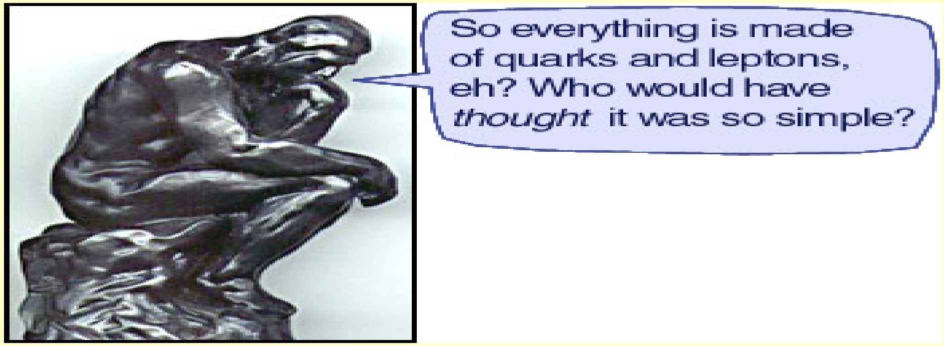


In fact, when the muon was discovered physicist I.I. Rabi asked,

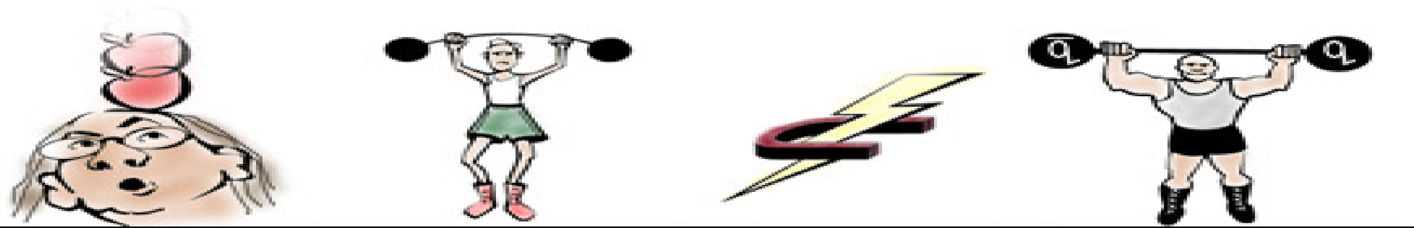
So why do we have generations of matter at all? Why three of them?

為什麼物質要有代呢？ 為什麼又只有三代？

We don't know. And without understanding why the second and third generation particles exist, we cannot rule out the possibility that there are yet more quarks and leptons that we have not discovered yet. Or perhaps the answer is that quarks and leptons aren't fundamental, but are made up of even more elementary particles whose composite particles we observe as quarks.



What Holds it Together? The Four 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

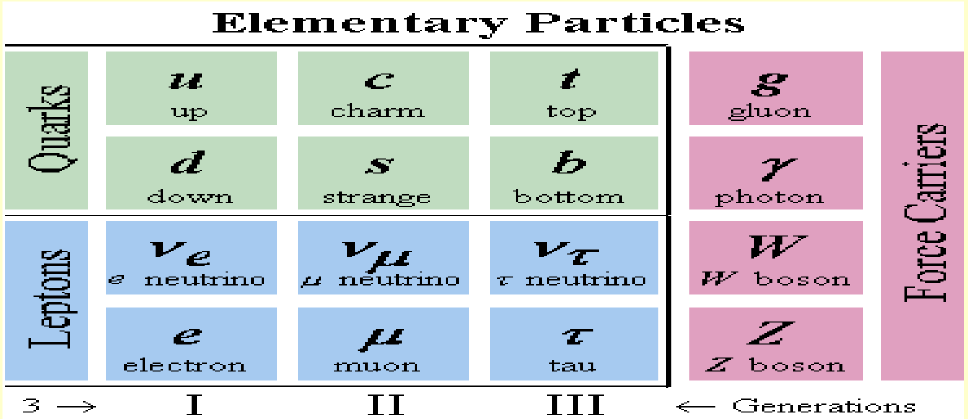
Fermions ***(費米子，自旋=1/2….): Quarks &Leptons***

Bosons ***(玻色子，自旋=0,1,….) : W^+,W^- , Z^0,光子, 膠子***

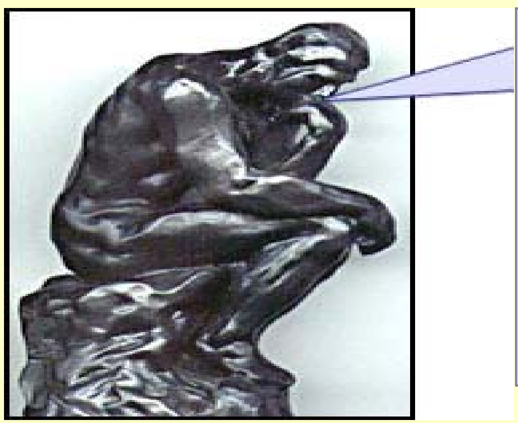
The Pauli Exclusion Principle

Particles that do obey the Pauli Exclusion Principle are called fermions, and those that do not are called bosons.

Imagine there is a large family of identical fermion siblings spending the night at the Fermion Motel, and there is another large family of identical boson siblings spending the night at the Boson Inn. (Since fermions rent more rooms than bosons, motel owners prefer doing business with fermions. Some motels even refuse to rent rooms to bosons!)



A Lot to Remember



We have answered the questions, "What is the world made of?" and "What holds it together?"

The world is made of six **quarks** and six **leptons**. Everything we see is a conglomeration of quarks and leptons.

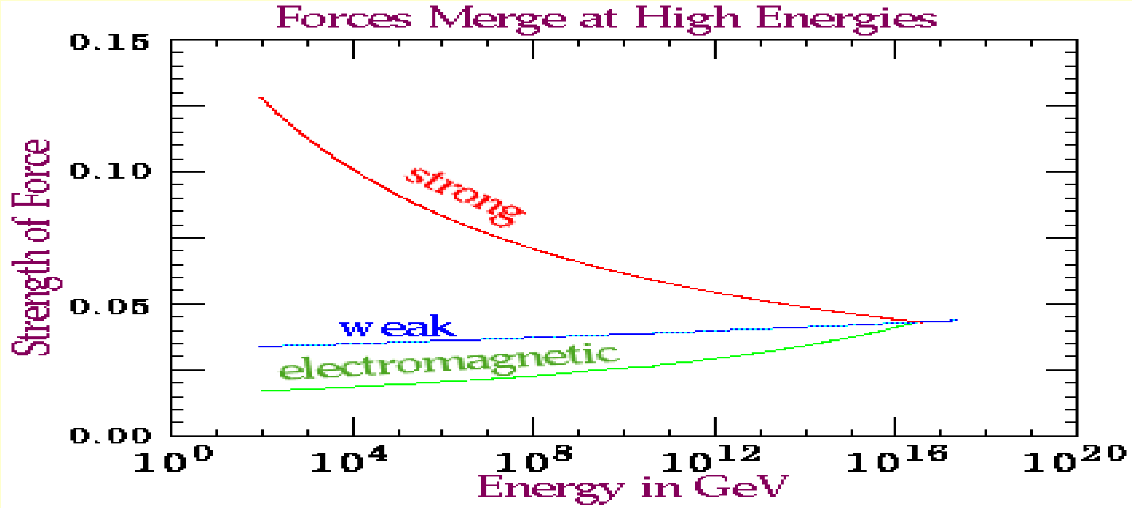
There are four fundamental forces and there are **force carrier particles** associated with each force.

These are the essential aspects of the Standard Model. It is the most complete explanation of the fundamental particles and interactions to date.

● 大統一場理論

Grand Unified Theories

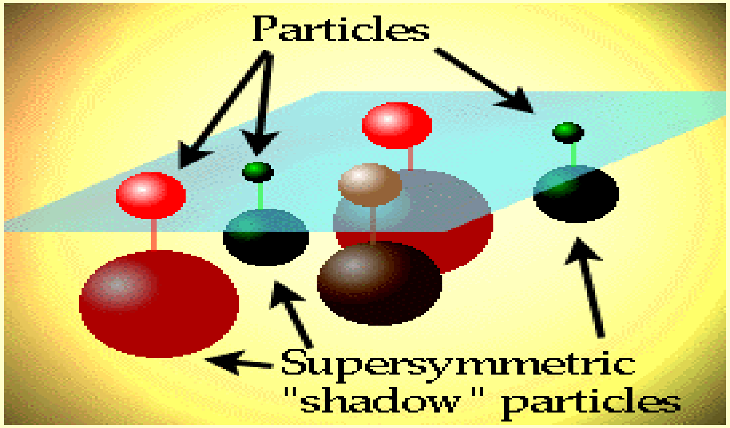
The theory which (we hope!) will unify the strong, weak, and electromagnetic interactions is called the "Grand Unified Theory." If a Grand Unification of all the interactions is possible, then all the interactions we observe are all different aspect of the same, unified interaction. However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect? Strangely enough, current data and theory suggest that these varied forces merge into one force when the particles being affected are at a high enough energy.



Contemporary work on GUT also suggests new force-carrier particles that could cause the proton to decay. Such decays must be extremely rare; otherwise our world would not exist today. Measurement tells us the lifetime of the proton is greater than 10^{32} (10 to the power of 32) years!

Supersymmetry 超對稱

Many physicists have developed theories of supersymmetry, particularly in the context of Grand Unified Theories. The supersymmetric theories postulate that every particle we observe has a massive "shadow" particle partner. For example, for every quark there may be a so-called "squark" tagging along.



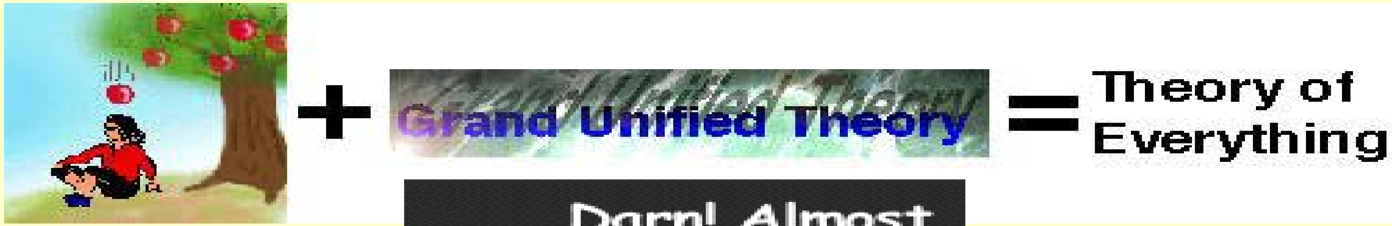
No supersymmetric particle has yet been seen, but experiments underway at CERN are searching for the partner of the W boson, and experiments at Fermilab are looking for the partners of the quarks and gluons. One of the supersymmetric particles (the "neutralino") might make up the missing dark matter in the universe.

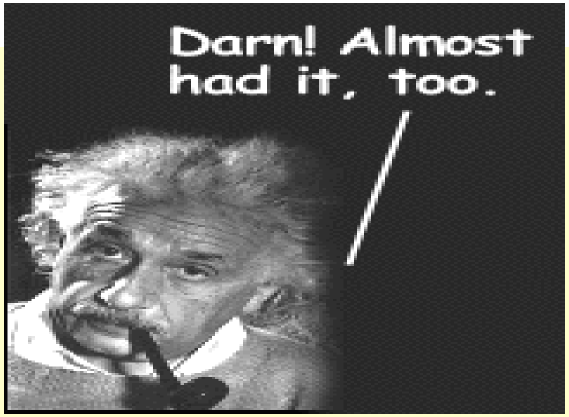
The Theory of Everything (TOE)

The long range goal of physics is to unify all the forces, so that gravity would be combined with the future version of the Grand Unified Theory. Then the gravitational interaction would be thought of as quantized, like the other forces, so that the gravitational force is transmitted by particles called *gravitons*.

This poses a formidable problem. Einstein showed us that the gravitational force arises due to curvature in the fabric of spacetime. Thus, the task is to quantize spacetime to produce the desired gravitons. Achieving this type of quantum field theory is quite a challenge both conceptually and mathematically.

The HEP Experiment may guide us toward a Grand Unified Theory, so that ultimately humankind will understand a complete, unified Theory of Everything.





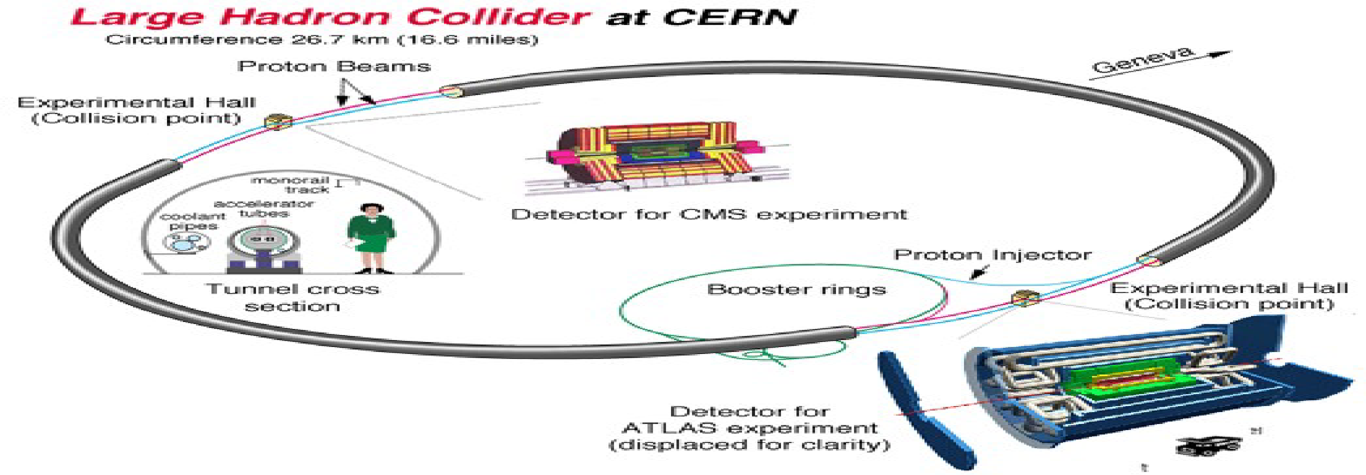
尚未解決之問題

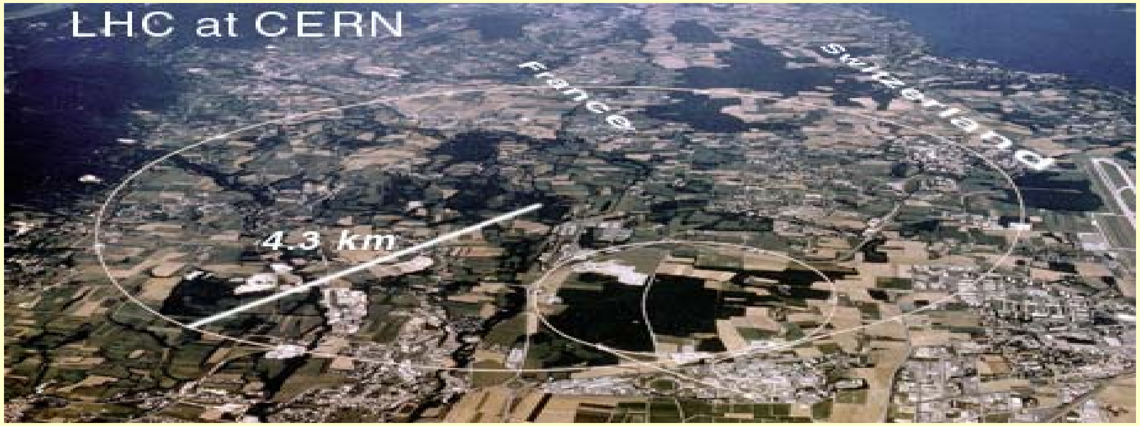
What Questions Remain?

The Standard Model answers many of the questions of the structure and stability of matter with its six types of quarks, six leptons, and the four forces. But the Standard Model leaves many other questions unanswered:

- ***Why are there three types of quarks and leptons?***
- ***Is there some pattern to their masses?***
- ***Are there more types of particles and forces to be discovered at yet higher energy accelerators?***
- ***Are the quarks and leptons really fundamental, or do they, too, have substructure?***
- ***What particles form the dark matter in the universe?***
- ***How can the gravitational interactions be included in the standard model?***

● 未來展望





Physics with LHC: The Higgs Particle

One of the main goals of the LHC program is to discover and study the Higgs particle. The Higgs particle is of critical importance in particle theories and is directly related to the concept of particle mass and therefore to all masses.