STANDARD MODEL, HIGGS BOSON AND WHAT NEXT?

G. Rajasekaran

Institute of Mathematical Sciences, Chennai 600113
and Chennai Mathematical Institute, Siruseri 603103.
e-mail: graj@imsc.res.in

Abstract : One hundred years of Fundamental Physics, starting with discoveries such as radioactivity and electron, have culminated in a theory which is called the Standard Model of High Energy Physics. This theory is now known to be the basis of almost ALL of known physics except gravity. We give an elementary account of this theory in the context of the recently announced discovery of the Higgs boson. We conclude with brief remarks on possible future directions that this inward bound journey may take.

Hundred Years of Fundamental Physics

The earlier part of the 20th Century was marked by two revolutions that rocked the Foundations of Physics.

1. Quantum Mechanics & 2. Relativity

Quantum Mechanics became the basis for understanding Atoms, and then, coupled with Special Relativity, Quantum Mechanics provided the framework for understanding the Atomic Nucleus and what lies inside.

At the beginning of the twentieth century, the quest for the understanding of the atom topped the agenda of fundamental physics. This quest successively led to the unravelling of the atomic nucleus and then to the nucleon (the proton or the neutron). Now we know that the nucleon itself is made of three quarks. This is the level to which we have descended at the end of the twentieth century. The depth (or the distance scale) probed thus far is 10^{-17}cm.

INWARD BOUND

Atoms	$\longrightarrow$	Nuclei	$\longrightarrow$	Nucleons	$\longrightarrow$	Quarks	$\longrightarrow$	?
10^{-8}cm		10^{-12}cm		10^{-13}cm		10^{-17}cm		

This inward bound path of discovery unraveling the mysteries of matter and the forces holding it together – at deeper and ever deeper levels – has culminated, at the end of the 20th century, in the theory of *Fundamental Forces* based on *Nonabelian Gauge Fields*, for which we have given a rather prosaic name :

THE STANDARD MODEL OF HIGH ENERGY PHYSICS

In this theory, the strong forces operating within the nuclei and within the nucleons, as well as the weak forces that were revealed through the discovery of radioactivity hundred years ago are understood to be generalizations of the

ELECTRODYNAMICS OF FARADY AND MAXWELL.

Electrodynamics was formulated around the year 1875 and its applications came in the 20th century. We owe a lot to the Faraday-Maxwell Electrodynamics, for the applications of electrodynamic technology have become a part of modern life. People take out a small gadget from their pockets and speak to their friends living hundreds or thousands of kilometers away; somebody in a spacelab turns a knob of an instrument and controls a spacecraft that is hurtling across millions of kilometers away to a distant planet. All this has been possible only because of electromagnetic waves.

It turns out that the dynamics of strong and weak forces was formulated around 1975 almost exactly 100 years after the year of electrodynamics. We may expect that equally profound applications will follow, once the technologies of the strong and weak forces are mastered. That may be the technology of the 21st century.

After this bird's eye view of one century of developments we now describe the four forces of Nature and then take up the Standard Model.

Fundamental Forces of Nature

The four fundamental forces are the strong, electromagnetic,weak and gravitational forces. Strong forces are responsible for binding nucleons into the nucleus (and for binding quarks into the nucleons). They are characterised by a strength parameter which is roughly one and their range is 10^{-13} cm. Electromagnetic forces bind nuclei and electrons to form atoms and molecules and bind atoms or molecules to form solid matter. Their strength is measured by the fine structure constant whose value is about 1/137 and their range is infinite. Weak interactions cause the beta decay of nuclei and also are responsible for the fusion reactions that power the Sun and stars. Their strength is $10^{-5}m_p^{-2}$ and their range is less than 10^{-14}cm. Here m_p is the mass of the proton. Gravity binds the planets into the solar system, stars into galaxies and so on. Although gravity is the weakest force, its strength being $10^{-40}m_p^{-2}$, it becomes the dominant force for the Universe at large, because of its infinite range and because of its being attractive only (unlike electromagnetism where attraction can be cancelled by repulsion).

In quantum theory the range of a force is inversely proportional to the mass of the quantum that is exchanged. Since the photon mass is zero, electromagnetic force mediated by the exchange of photons is of infinite range. Since the strong interaction between nucleons has finite range, it has to be mediated by a quantum (or particle) of finite mass. This is how Yukawa predicted the particle that was later identified as the pion,which we now know to be a composite of a quark and an antiquark. About the finite range of the weak force and the quantum exchanged we shall say more later. Since gravity has infinite range, quantum theory of gravity (if it is constructed) will have its quantum, called graviton with zero mass.

The above text-book classification of the four fundamental forces has broken down. We now know that weak force and electromagnetism are two facets of one entity called electroweak force. Can one go further and unify the strong force with the electroweak force? It is possible to do so and it is called grand unification, but that is a speculative step which may be confirmed only in the future. The grander unification will be unification with gravitation which we may call "Total Unification" which was the dream of Einstein. Perhaps that will be realized by string theory and in the future.

For the present we have the Standard Model which is a theory of the electroweak and strong interactions and is based on a generalization of elecrodynamics. So let us start with electrodynamics.

Laws of Electrodynamics

The laws of electrodynamics are expressed in terms of the following parial differential equations:

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho \tag{1}$$

$$\vec{\nabla} \times \vec{E} + \frac{1}{c}\frac{\partial \vec{B}}{\partial t} = 0 \tag{2}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{3}$$

$$\vec{\nabla} \times \vec{B} - \frac{1}{c}\frac{\partial \vec{E}}{\partial t} = \frac{4\pi}{c}\vec{j} \tag{4}$$

These laws were formulated by Maxwell on the basis of earlier experimental discoveries by Oerstead, Ampere, Faraday and many others. Actually, from his observations and deep experimental studies of the electromagnetic phenomena,

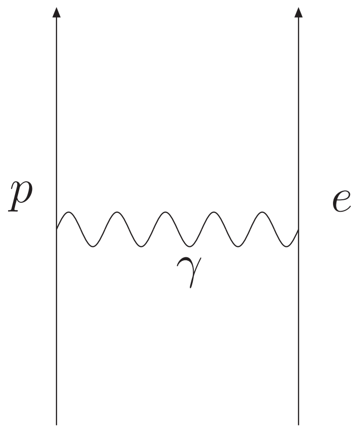

Figure 1

Faraday had actually built up an intuitive physical picture of the electromagnetic field and Maxwell made this picture precise by his mathematical formulation. Once Maxwell wrote down the complete and consistent system of laws, very important consequences followed. He could show that his equations admitted the existence of waves that travelled with a velocity that he could calculate purely from electrical measurements to be 3×10^{10} cm per sec. Since the velocity of light was known to be this number, Maxwell proposed that light was an electromagnetic wave. This was a great discovery since until that time nobody knew what light was. Subsequently Hertz experimentally demonstrated the existence of the electromagnetic waves prediced by Maxwell.

Maxwell's laws have stood the test of time for much more than a century. Even the two revolutions of relativity and quantum mechanics have not invalidated them. In fact Einstein resolved the confrontation between Newton's laws of particle dynamics and Maxwell's laws of field dynamics in favour of the latter. He had to modify Newton's laws to be in conformity with the space-time picture of Maxwell's laws and this is how special theory of relativity was born. Even quantum mechanics left the form of Maxwell's equations unchanged. However there was a profound reinterpretation of the continuous Faraday-Maxwell field with its continuous energy distribution in space-time. It was replaced by discrete field-quanta or discrete packets of energy. This was called field quantization and this was the birth of Quantum Field Theory.

Let us briefly compare the Faraday-Maxwell picture with quantum field theory. In the former, a charged particle, say, a proton is surrounded by an electromagnetic field existing at every point in space-time. If another charged particle, an electron is placed in this field, the field will interact with the electron and that is how the electromagnetic interaction between proton and electron is to be understood in the classical electromagnetic theory. In quantum field theory,the proton emits an electromagnetic quantum which is called the photon and the electron absorbs it and this is how the interaction between the proton and electron is to be understood. Exchange of the field-quanta is responsible for the interaction. This is depicted in the "Feynman diagram" shown in Fig 1. This is our brief description of quantum field theory which is the basic language in which Standard Model of High Energy Physics is written.

Standard Model of High Energy Physics

Standard Model consists of two parts, electroweak dynamics that unifies electromagnetic and weak interactions and chromodynamics that governs strong interactions.

In electrodynamics we have an electromagnetic field described by the pair of vector fields $(\vec{E}, \vec{B})$ and the corresponding quantum is the photon. Analogously, in electroweak dynamics we have four types of generalized electromagnetic fields $(\vec{E_i}, \vec{B_i})$ with the index i going over 1 to 4, one of them being the old Faraday-Maxwell electromagnetic field. Correspondingly there exist four elecroweak quanta, also called electroweak gauge bosons. One of them is the photon γ, mediating electromagnetic interaction and the other three W^+,W^- and Z mediate weak interaction.

In Fig 2 we illustrate an example of weak interaction, namely the decay of the neutron into proton,electron and antineutrino. Neutron and proton are depicted as composites of three quarks udd and uud respectively. The d quark turns into a u quark by emitting the weak quantum W^- which turns into a pair of "leptons" (electron and antineutrino). The electromagnetic and weak interactions among the quarks and the leptons mediated by the electroweak quanta are pictured in the Feynman diagrams of Fig 3 (a to d).

The laws of electroweak dynamics (EWD) are given by the equations:

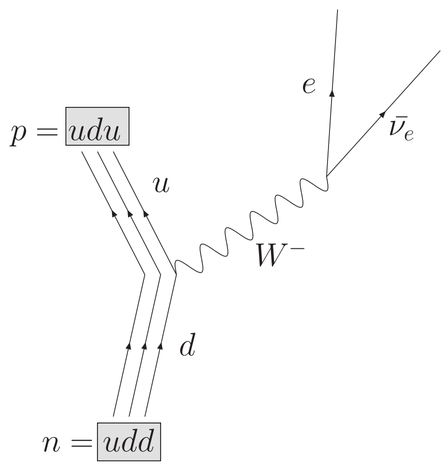

Figure 2

$$\vec{\nabla} \cdot \vec{E}_i + ... = 4\pi\rho_i \tag{5}$$

$$\vec{\nabla} \times \vec{E}_i + \frac{1}{c}\frac{\partial \vec{B}_i}{\partial t} + ... = 0 \tag{6}$$

$$\vec{\nabla} \cdot \vec{B}_i + ... = 0 \tag{7}$$

$$\vec{\nabla} \times \vec{B}_i - \frac{1}{c}\frac{\partial \vec{E}_i}{\partial t} + ... = \frac{4\pi}{c}\vec{j}_i \tag{8}$$

We shall explain the dots in the equations soon.

In Quantum Chromodynamics(QCD) governing strong interactions we have eight types of generalized electromagnetic fields $(\vec{E}_\alpha, \vec{B}_\alpha)$ with the index α ranging over 1 to 8. The corresponding quanta are called gluons G_α since it is their exchange between quarks that bind or glue the quarks together to form the proton or neutron. This exchange of gluons between the quarks q (which may be u or d) is shown in Fig 4. The laws of QCD are given by the same equations as those given above for EWD with the index i replaced by α.The analogy of the laws of EWD and QCD to the original laws of electrodynamics is obvious.

If these generalizations of Maxwell's equations are as simple as made out above, why did Standard Model take another hundred years to be constructed? The answer lies in the dots in the equations expressing the laws of EWD and

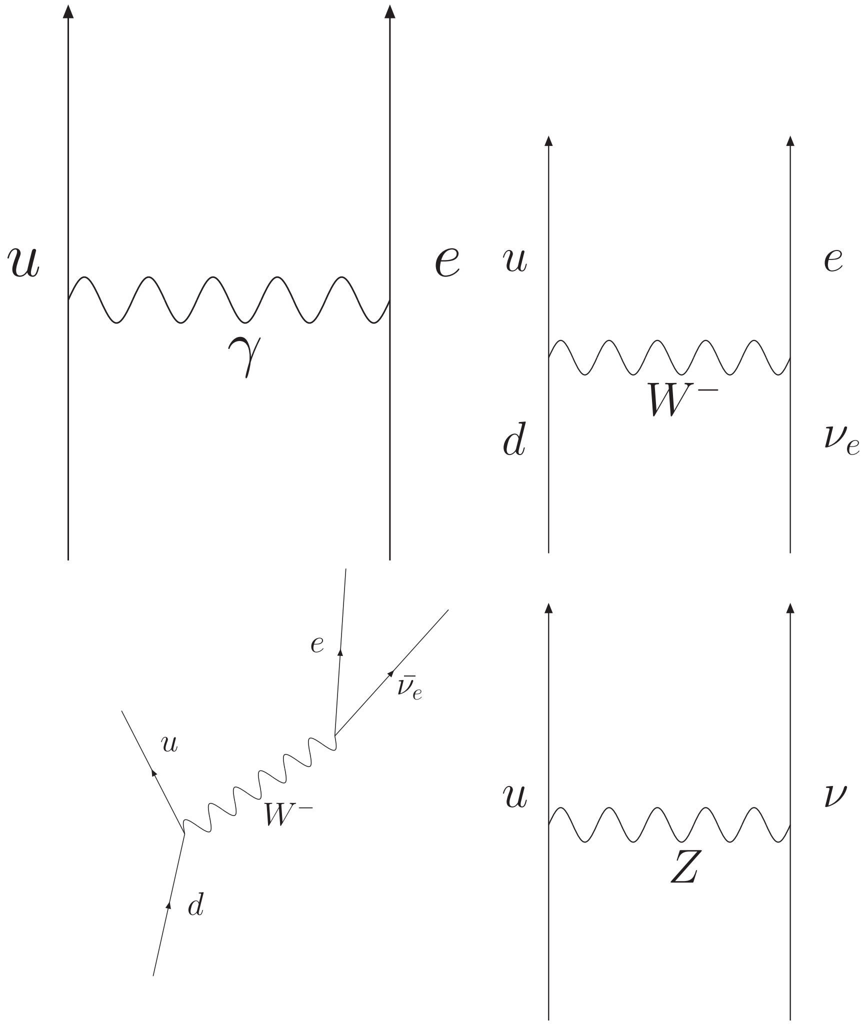

Figure 3

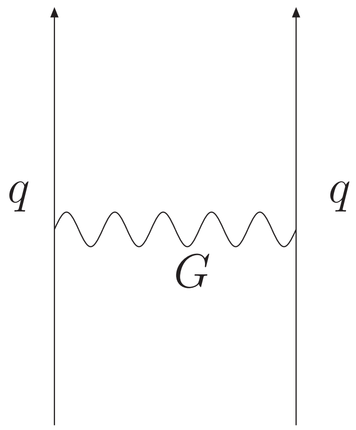

Figure 4

QCD. Let us go back to electrodynamics in which every electrically charged particle interacts with the electromagnetic field or (in the quantized version) emits or absorbs a photon. But photon itself does not have charge and hence does not interact with itself. In the generalization described above, there are twelve generalized charges, four in EWD and eight in QCD, corresponding to the similar number of generalized electromagnetic fields. In contrast to electric charge which is just a number (positive, negative or zero), these generalized charges are matrices which do not commute with each other and hence can be called nonabelian charges. (In mathematics, algebras with commuting and noncommuting objects are respectively called abelian and nonabelian algebras.) Electrodynamics which is based on the abelian charge is called abelian gauge theory and the generalization based on nonabelian charges is called nonabelian gauge theory. In contrast to photon, which is the abelian gauge quantum and does not carry the abelian electric charge, the nonabelian gauge quanta themselves carry the nonabelian charges and hence are self-interacting. These self-interactions are shown in Fig 5; both a cubic and a quartic coupling exist. The nonlinear terms expressing these couplings are hidden behind our dots and it is these which make the theory of nonabelian gauge fields much more complex than the simple Maxwell theory. Nonabelian gauge fields were introduced by Yang and Mills in 1954 and hence are also called Yang-Mills(YM) fields, but it took many more important steps in the next two decades before this theory could be used to construct the correct Standard Model.

A remark on gravity is appropriate at this point. What plays the role of

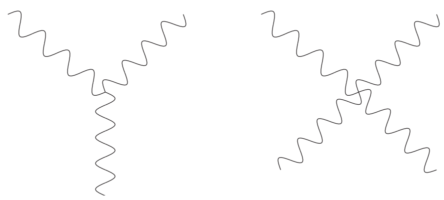

Figure 5

"charge" in gravity? Obviously it is mass in Newton's theory, but is replaced by energy in Einstein's theory. Since the gravitational field itself has energy, it has to be self-interacting exactly as in the case of the nonabelian gauge field carrying the nonabelian charge. However, unlike in that case where Yang and Mills showed a cubic and a quartic interaction completes the theory, in the gravitational case one has to add vertices of all orders (quintic, sextic...). This is what makes Einstein's theory of gravitation much more intractable in the quantized version. In complexity, Yang-Mills theory comes between the simple Maxwell theory and the complex Einstein theory.

The Field and Particle Sectors

The constituents of the universe according to the Standard Model come in two categories which may be called the field sector and the particle sector.

In the field sector, we have the twelve gauge fields γ, W^+, W^-, Z, G_1, G_2,....G_8. Their quanta are all particles with spin 1 (in units of $\hbar$), exactly like the first and most familiar one among them, the photon (γ). All such particles having spin equal to integral multiple of $\hbar$ belong to the great family of "bosons" (particles obeying Bose-Einstein statistics).

The particle sector consists of spin $\frac{1}{2}$ particles belonging to the other great family of "fermions" (particles that obey Fermi-Dirac statistics.) Among these, we have already encountered the two quarks (u,d) and the two "leptons" (ν,e). The quarks make up the nucleon and the nucleons make nuclei. Nuclei and electrons make atoms, molecules and all known matter. The weak radioactive decays involve the ν. Thus the quartet of particles consisting of a quark doublet and a lepton doublet seems to be sufficient to make up the whole universe. However Nature has chocen to repeat this quartet twice more, so that there actually exist three "generations" of particle quartets each consisting of a quark doublet and a lepton doublet:

1. (u,d), (ν_e,e)
2. (c,s), (ν_μ,μ)
3. (t,b), (ν_τ,τ)

The existence of three generations is required to explain (the experimentally observed) matter-antimatter asymmetry which can solve the cosmological puzzle: how did the universe which started as a fireball with equal proportion of matter and antimatter evolve into a state which has only matter? But we shall not delve into this question here except to mention that Kobayashi and Maskawa predicted, on this basis, the existence of three generations of quarks, even before the three generations were experimentally discovered.

An important remark about quantum field theory is in order here. Although we divided the stuff of the universe into a field sector and a particle sector, fields have their quanta which are particles and in quantum field theory each particle in the particle sector also has its quantum field; electron, for instance, is the quantum of the electron field. Thus quantum field theory unifies field and particle concepts.

There is an incompleteness in our description of the QCD sector. Both quarks and gluouns are not seen directly in any experiment. They are supposed to be permanently confined inside the proton and neutron. But this hypothesis of confinement which is supposed to be a property of QCD has not been proved. This important theoretical challenge remains as a loophole. This problem is so intractable that it has been announced as one of the millennium problems of mathematics.

Symmetry breaking and Higgs

Remember the vast disparity between electromagnetism and the weak force as regards their ranges; one is of infinite range and the other is short-ranged. How does electroweak unification cope with this breakdown of the electroweak symmetry that is intrinsic to the unification? This is achieved by a spontaneous breakdown of symmetry engineered by the celebrated Higgs mechanism which keeps photon massless while raising the masses of W and Z to finite values. Thus weak interaction gets a finite range. The experimental discovery of W and Z with the masses predicted by the electroweak theory was a great triumph for the theory.

The idea of spantaneous breakdown of symmetry (SBS) in high energy physics originates from Nambu although he applied it in a different context. But the stumbling block was the Goldstone theorem. This predicted the existence of a massless spin zero boson as the consequence of SBS and prevented the application of SBS to construct any physically relevant theory, since such a massless particle is not observed. [See the Appendix at the end of this article for more on SBS.] Thus apparently one had to choose between the devil (massless W boson) and the deep sea (massless spin zero boson).

It was Higgs who, in 1964, showed that this is not correct. By using Goldstone's model (which is much simpler than the original Nambu model), he showed that there is no Goldstone theorem if the symmetry that is broken is a gauge symmetry. The devil drinks up the deep sea and comes out as a regular massive spin one gauge boson. No massless spin zero boson is left. This is called Higgs mechanism. Many other authors also contributed to this idea.

Earlier, Glashow had identified the correct version of the Yang-Mills theory for the electrowaek unification. By combining that with Higgs mechanism Weinberg and Salam independantly constructed the elecroweak part of SM in 1967.

There is a bonus. Higgs mechanism postulates the existence of a universal all-pervading field called the Higgs field and this field which gives masses to W and Z also gives masses to all the fermions of the particle sector, except to the neutrinos. Thus, in particular, the masses of the quarks and electron come from the Higgs field.

But there is an important byproduct of the Higgs mechanism: a massive spin zero boson, called the Higgs boson, must exist as a relic of the original Higgs field. High energy physicists searching for it in all the earlier particle accelerators had failed to find it. So the announcement on 4 July 2012 that the Higgs boson has been sighted finally at a mass of 125 GeV at the gigantic particle collider called Large Hadron Collider(LHC) at CERN, Geneva has been welcomed by everybody. More tests have to be performed to establish that the particle seen is indeed the Higgs boson.

In the last four decades, experimenters have succeeded in confirming every component of the full SM with three generations of fermions. Higgs boson remained as the only missing piece. So with its discovery (assuming that the discovery will be established by further tests), Standard Model has emerged as the Standard Theory describing Nature. This is a great scientific achievement. SM now deserves a better name!

We have now completed our description of the SM. We list below the Nobel Prizes sofar awarded to some of the makers of the SM, the theorists who proposed it and the experimentalists who proved it to be right.

Year	**Winners**	**Contribution to SM**
1978	Glashow,Salam,Weinberg	Construction of Electroweak Theory
1983	Rubbia, Van der Meer	Discovery of W and Z
1990	Friedman,Kendal,Taylor	"Observation" of quarks inside proton
1999	't Hooft, Veltman	Proof of renormalizability of EW Theory
2004	Gross, Politzer, Wilczek	Asymptotic freedom of YM Theory
2008	Nambu	Spontaneous breaking of symmetry
2008	Kobayashi, Maskawa	Matter-antimatter asymmetry

Beyond Standard Model

Neutrinos: Neutrinos are massless in the Standard Model. As already mentioned, Higgs mechanism does not give mass to neutrinos. About 15 years ago, experimenters discovered that neutrinos do have tiny masses and this has been hailed as a great discovery since this may show us how to go beyond the Standard Model. Neutrino may be the portal to go beyond SM and that is the importance of the India-based Neutrino Observatory (INO) which is about to come up in Tamil Nadu.

Dark matter: Astronomers have discovered that most of the matter in the universe is not the kind we are familiar with. It is called dark matter since it does not emit or absorb light. Although this discovery has been made already, nobody knows what this dark matter is and only physicists can discover that. A dark matter experiment also will be mounted in the INO cavern (suitably extended).

In the last four decades after the Standard Model was constructed, theoreticians have not been idle but have constructed many theories that go beyond the

SM. Of these we have already mentioned one, namely grand unification. Another is supersymmetry that postulates the existence of a boson corresponding to every known fermion and vice versa. This is a very elegant symmetry that leads to a better quantum field theory than the one on which SM has been built. But if it is right, we have to discover a whole new world of particles equalling our known world; remember we took a hundred years to discover the known particles starting with the electron.

There are many more theoretical speculations apart from grand unification and supersymmetry. But none of them has seen an iota of experimental support sofar, even in the LHC. However LHC will have many more years of operation; let us hope new things will be discovered.

Quantum Gravity

The biggest loophole in SM is that gravity has been left out. The most successful attempt to construct quantum gravity is the String Theory.

The role of quantum mechanics coupled with special relativity in providing the basis for the understanding of what lies inside the atomic nucleus (the microcosm) was mentioned at the beginning of this article. On the other hand, it is General Relativity, which is also the theory of Gravitation that provides the framework for understanding the Universe at large (the macrocosm).

It is a deep irony of Nature that the twin revolutions of quantum and relativity that powered the conceptual advances of the 20th century and that underlie all the subsequent scientific developments, have a basic incompatibility between them. The marriage between quantum mechanics and relativity has not been possible. By relativity, here we mean general relativity since special relativity has already been combined with quantum mechanics leading to quantum field theory.

Gravity which gets subsumed into the very fabric of space and time in Einstein's General Relativity has resisted all attempts at being combined with the quantum world. Hence, Quantum Gravity had become the most fundamental problem of physics at the turn of the twentieth century.

This is in contrast to all the other fundamental forces of Nature, namely electromagnetic, strong and weak forces, which have all been successfully incorporated into the quantum mechanical framework. The Standard Model of High Energy Physics that we have described is just that, and the Standard Model leaves out Gravity. This is the reason for the rise of String Theory, for it promises to be a theory of Quantum Gravity. For the first time in history, we may be glimpsing at a possible solution to the puzzle of Quantum Gravity. Actually, String Theory offers much more than a quantum theory of gravity. It provides a quantum theory of all the other forces too. In other words, it can incorporate the Standard Model of HEP also, within a unifying framework that includes gravity.

So, String Theory has been hailed as the ”Theory Of Everything” and some theoretical physicists have even had ”Dreams of a Final Theory” - which is actually the title of an excellent book by Weinberg. But one is tempted to say

”There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy” - Shakespeare (in Hamlet, Act I, Scene V)

I do not believe that String Theory or any Theory will be a Theory of Everything or a Final Theory. But it is very likely that String Theory is the Fundamental Theory for the 21st century.

In string theory, a point particle is replaced by a one-dimensional object called string as the fundamental entity. Its length is about 10^{-33} cm which is the length scale of any theory of quantum gravity including string theory. The various vibrational modes of the string correspond to all the elementary particles. String theory automatically contains quantum gravity and that is its chief attraction. However that is bought at a price. It works only if the number of space dimensions is 9 and including time it is 10. Where are the extra six dimensions? They are curled up to form space bubbles existing at distance scales of the same 10^{-33} cm! Both the string and the extra curled-up dimensions will be revealed only when we can access such length scales. Remember we have sofar reached only 10^{-17} cm. We have a long way to go.

Apart from string theory there are other approaches to quantum gravity. Only future will tell us which is the right one. In any case, quantum gravity is an important (albeit distant) frontier and the journey continues.

Appendix: A Tutorial on SBS

Consider a simple mechanical example: a ball placed on the top of a hill of circular cross section surrounded by a circular valley (Fig 6). This system has a circular symmetry, but the ball is in an unstable equilibrium and will roll down into the bottom of the valley where it will reach a point of stable equilibrium. The ball could have come to any point along the circular bottom of the valley, but once it has done it, the circular symmetry has been broken.

Now replace the hill and valley problem with a problem of field theory. This is Goldstone's model of the scalar field which has two components ϕ_1 and ϕ_2. The quanta of the scalar field have spin zero and hence are bosons. The potential energy V of the field system as a function of the field components is chosen to be exactly like in the mechanical example and has circular symmetry in the field space (see Fig 7). It has a maximum energy at point A where ϕ_1 and ϕ_2 are zero and a minimum all along a circle.

It is wrong to choose the maximum of the potential (point A) as the ground state of the field system although the field has zero value at that point since it is a state of unstable equilibrium. We can choose any one point along the circle of the minimum of V, as the ground state of the system; however once we choose it, the circular symmetry is broken. This is the mechanism of spontaneous breaking of symmetry.

An important consequence follows. Since it does not cost any energy to move around the circular trough of minimum potential, there exists a massless particle (the α mode). As can be seen from Fig 7, movement along a direction normal to this circle (the β mode) costs positive potential energy and this corresponds to the massive particle. The massless mode is called the Nambu-Goldstone boson and this result is called the Goldstone Theorem (proved by Goldstone, Salam and Weinberg) which states that SBS of any continuous symmetry results in the existence of the spin zero massless Nambu-Goldstone boson.

By the addition of a massless spin one gauge boson to the Goldstone model, Higgs showed that the massless spin zero boson is eaten up by the massless spin one boson and as a result, the massless spin one boson becomes massive and the massless spin zero boson disappears.This is the Higgs mechanism. The massive spin zero boson (the beta mode) however exists and this is the Higgs boson which was eagerly searched for, and presumably found now.

Note that in the ground state, the field is not zero, but is equal to the radius of the circle of minimum potential. This is the universal Higgs field existing everywhere, that gives mass to all the particles.

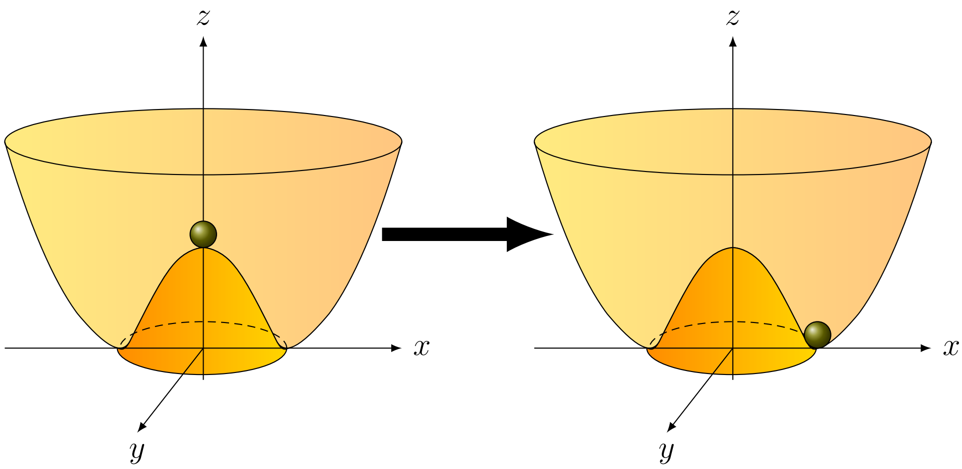

Figure 6

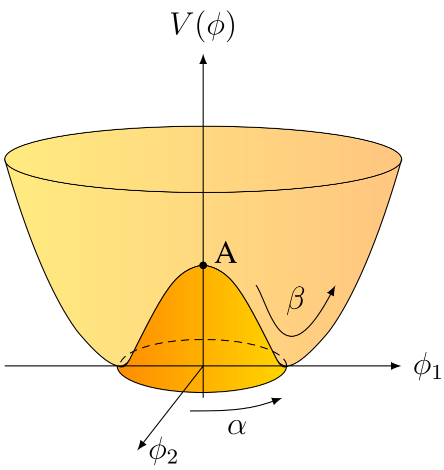

Figure 7