Standard Model, Higgs boson and what next?

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- 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 20^{th} 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, the MICROCOSM.

- At the beginning of the 20^{th} century, the quest for the understanding of the atom, topped the agenda of fundamental physics. This quest successively led to the unravelling of the 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 20^{th} century. The depth (or the distance scale) probed thus far is 10^{-17}cm.

INWARD BOUND

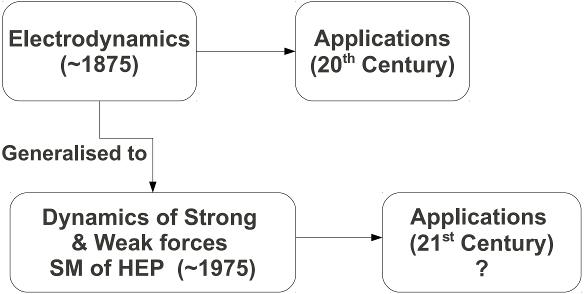
Atoms	$\longrightarrow$	Nuclei	$\longrightarrow$	Nucleons	$\longrightarrow$	Quarks	$\longrightarrow$	?
10^{-8}cm		10^{-12}cm		10^{-13}cm		10^{-17}cm		

- This inward bound path of discovery unravelling the mysteries of matter and the forces holding it together - at deeper and ever deeper levels - has culminated, at the end of the 20^{th} century, in the theory of Fundamental Forces based on Non abelian 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 100 years ago are understood to be generalizations of the

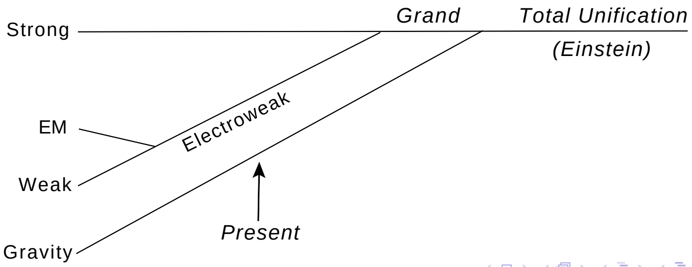
ELECTRODYNAMICS OF FARADAY & MAXWELL



- The 20^{th} century owes a lot to the Faraday - Maxwell Electrodynamics, for, the applications of electrodynamic technology (starting with wireless, ...) have become a part of modern life.
- Equally profound applications will follow, once the technologies of the strong and weak forces are mastered!

The four fundamental forces of Nature

Force	Strength	Range
Strong	1	10^{-13} cm
EM	$\frac{1}{137}$	∞
Weak	$10^{-5}/m_p^2$	$< 10^{-14}$cm
Gravity	$10^{-40}/m_p^2$	∞



Laws of Electrodynamics

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

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

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

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

Oersted

Ampere

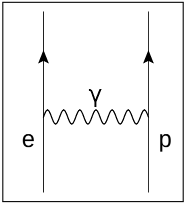
Faraday

Maxwell

Hertz

- Relativity (Special)
- Quantum Mechanics
- Quantum Field Theory

$\Longrightarrow$



(Feynman Diagram)

STANDARD MODEL OF HIGH ENERGY PHYSICS

= ELECTROWEAK DYNAMICS

(based on $SU(2) \otimes U(1)$)

$\bigoplus$

QUANTUM CHROMODYNAMICS

(based on $SU(3)$)

Laws of Electroweak Dynamics

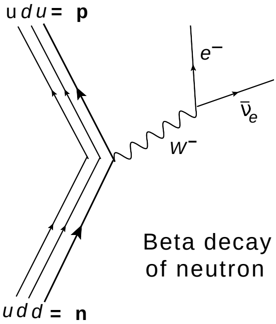
$$(\vec{E}_i, \vec{B}_i): \quad i = 1,\ 2,\ 3,\ 4$$
$$\gamma, W^+, W^-, Z$$

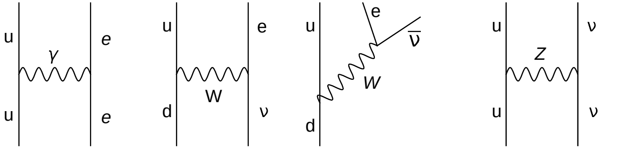
$$\vec{\nabla} \cdot \vec{E}_i + \ldots = 4\pi\rho_i$$

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

$$\vec{\nabla} \cdot \vec{B}_i + \ldots = 0$$

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





Laws of Quantum Chromodynamics (QCD)

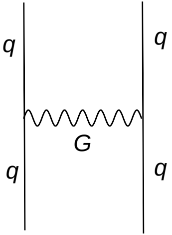
$(\vec{E}_\alpha, \vec{B}_\alpha): \quad \alpha = 1, 2, ..., 8: \quad 8$ Gluons G_α

$$\vec{\nabla} \cdot \vec{E}_\alpha + ... = 4\pi\rho_\alpha$$

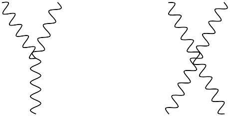
$$\vec{\nabla} \times \vec{E}_\alpha + \frac{1}{c}\frac{\partial \vec{B}_\alpha}{\partial t} + ... = 0$$

$$\vec{\nabla} \cdot \vec{B}_\alpha + ... = 0$$

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

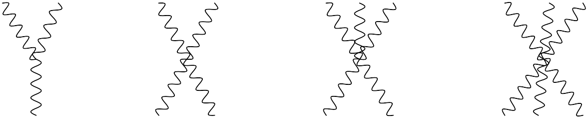


Nonabelian gauge fields (Yang – Mills fields)



CONFINEMENT?

Gravity



. . . .

Field Sector

Bosons

(Bose-Einstein Statistics)

Spin: $0, 1, 2, ...$

γ

W^+, W^-, Z

$G_\alpha : \quad \alpha = 1, ..., 8$

H

$- - - - - - - - -$

$g_{\mu\nu}$

Particle Sector

Fermions

(Fermi-Dirac Statistics)

Spin: $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, ...$

$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}$

p ∼ uud
n ∼ ddu

$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

Symmetry Breaking and Higgs

- Remember the vast disparity between EM and weak force as regards their ranges; one is of infinite range and the other is short ranged. How does EW unification cope with this breakdown of the EW Symmetry that is intrinsic to unification?
- This is achieved by a Spontaneous Breakdown of Symmetry (SBS) engineered by the celebrated Higgs mechanism which keeps photon massless while raising the masses of W & Z to finite values.
- Thus Weak interaction gets a finite range ($\sim 10^{-15}$cm). The experimental discovery of W and Z with the masses (80 and 91 GeV) predicted by the EW theory was a great triumph for the theory. That happened in 1982.

- The idea of SBS in HEP 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 (called Nambu-Goldstone boson) as the consequence of SBS and prevented the application of SBS to construct any physically correct theory, since such a massless boson is not observed.
- Thus apparently one had to choose between the devil (massless W boson) and the deep sea (the Nambu-Goldstone boson).
- It was Higgs who, in 1964, showed that this is not correct. 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 (N. G. boson) is left.

- This is called Higgs mechanism. Many others (especially Kibble) have contributed to this.
- Earlier, Glashow had identified the correct version $(SU(2) \otimes U(1))$ of the Yang-Mills theory for the electroweak unification. By combining that with Higgs mechanism, Weinberg & Salam independently constructed the EW 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 by product of the Higgs mechanism: a massive spin zero boson, called 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 discovery of the Higgs boson in 2012 at a mass of 125 GeV, at the gigantic particle collider, called LARGE HADRON COLLIDER (LHC) at CERN, Geneva, has been welcomed by everybody.

- In the last 4 decades, experimenters have succeeded in confirming every component of the full SM with three generations of the fermions.
- Higgs boson remained as the only missing piece.
- So, with its discovery, SM has emerged as the STANDARD THEORY describing Nature.
- This is a great scientific, engineering and technological achievement.

Nobel Prizes for the Standard Model

1979:	Glashow, Salam & Weinberg	Construction of the Electroweak theory
1984:	Rubbia & Van der Meer	Discovery of W & Z bosons
1990:	Friedman, Kendall & Taylor	"Observation" of quarks inside the proton
1999:	't Hooft & Veltman	Proof of renormalizability of electroweak theory
2004:	Gross, Politzer & Wilczek	Asymptotic freedom of YM theory (QCD)
2008:	Nambu Kobayashi & Maskawa	Spontaneous breaking of symmetry Matter-antimatter asymmetry
2013:	Englert & Higgs	Higgs mechanism

Standard Model of HEP ($SU(3) \otimes SU(2) \otimes U(1)$ gauge theory)

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4}\left(\partial_\mu G^i_\nu - \partial_\nu G^i_\mu - g_3 f^{ijk} G^j_\mu G^k_\nu\right)^2 - \frac{1}{4}\left(\partial_\mu B_\nu - \partial_\nu B_\mu\right)^2 \\
&- \frac{1}{4}\left(\partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g_2\, \varepsilon^{abc}\, W^b_\mu\, W^c_\nu\right)^2 \\
&- \sum_n \bar{q}_{nL}\gamma^\mu\left(\partial_\mu + i g_3 \frac{\lambda^i}{2} G^i_\mu + i\frac{g_2 \tau^a}{2} W^a_\mu + i\frac{g_1}{6} B_\mu\right) q_{nL} \\
&- \sum_n \bar{u}_{nR}\gamma^\mu\left(\partial_\mu + i g_3 \frac{\lambda^i}{2} G^i_\mu + i\frac{2}{3} g_1 B_\mu\right) u_{nR} \\
&- \sum_n \bar{d}_{nR}\gamma^\mu\left(\partial_\mu + i g_3 \frac{\lambda^i}{2} G^i_\mu - i\frac{g_1}{3} B_\mu\right) d_{nR} \\
&- \sum_n \bar{l}_{nL}\gamma^\mu\left(\partial_\mu + i\frac{g_2 \tau^a}{2} W^a_\mu - i\frac{g_1}{2} B_\mu\right) l_{nL} - \lambda(\phi^\dagger \phi - v^2)^2 \\
&+ \left|\left(\partial_\mu + i g_2 \frac{\tau^a}{2} W^a_\mu + i\frac{g_1}{2} B_\mu\right)\phi\right|^2 - \sum_n \bar{e}_{nR}\gamma^\mu\left(\partial_\mu - i g_1 B_\mu\right) e_{nR} \\
&- \sum_{m,n}\left(\Gamma^u_{mn}\bar{q}_{mL}\, \phi^c\, u_{nR} + \Gamma^d_{mn}\bar{q}_{mL}\, \phi\, d_{nR} + \Gamma^e_{mn}\bar{l}_{mL}\, \phi\, e_{nR} + h.c.\right)
\end{aligned}
$$

$$\boxed{\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\begin{pmatrix}u_\alpha\\ d_\alpha\end{pmatrix};\ \mathsf{n}=1}$$

$$\Downarrow$$

$$\boxed{\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L\begin{pmatrix}u_\alpha\\ d_\alpha\end{pmatrix}_L\quad e^-_R\quad u_{\alpha R}\quad d_{\alpha R};\quad \alpha=1,2,3}$$

$$\boxed{\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\begin{pmatrix}c_\alpha\\ s_\alpha\end{pmatrix};\ \mathsf{n}=2}\qquad\boxed{\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}\begin{pmatrix}t_\alpha\\ b_\alpha\end{pmatrix};\ \mathsf{n}=3}$$

Beyond Standard Model

- Neutrinos:

  Neutrinos are massless in the SM. As already mentioned, Higgs mechanism does not give mass to neutrions. 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 SM. Neutrinos 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 know. It is called dark matter since it does not emit, absorb or scatter 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).

Other things?

- In the last 4 decades after the SM was constructed, theoreticians have not been idle but have constructed many theories that go beyond the SM. Of these, grand unification (already mentioned) is one. Another is Supersymmetry: 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 QFT 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 100 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 so far, 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, but it is still an incomplete theory. So, Quantum Gravity is the next frontier and the journey continues.

- 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. 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 & relativity that powered the conceptual advances of the 20^{th} 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 & 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 20^{th} 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 SM of HEP is just that, and SM 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 SM of HEP also, within a unifying framework that includes gravity.
- It must be pointed out that there are other approaches to quantum gravity too; only future can tell us which is the right one.

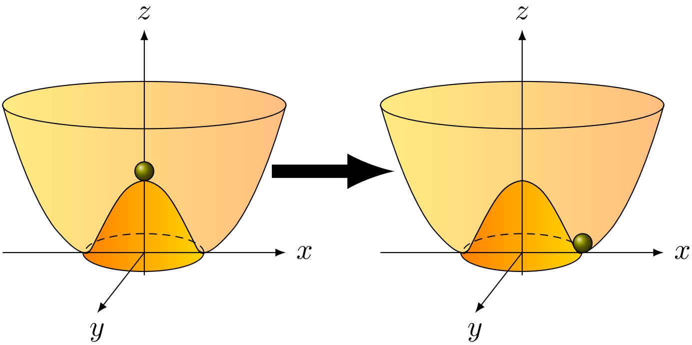
In any case, String Theory has been hailed as the Theory of Everything and some theoretical physicists have even had Dreams of a Final Theory. (Title of Weinberg's book)

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

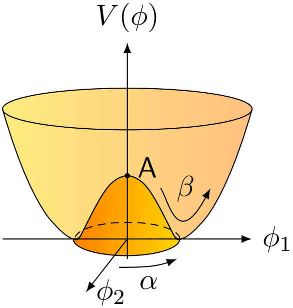
I do not believe that String Theory or any theory (for that matter) will be a Theory of Everything or a Final Theory.

But, there is no doubt that String Theory is the Fundamental Theory for the 21^{st} century.

Spontaneous Breakdown of Symmetry



Consider a simple mechanical example: a ball placed on the top of a hill of circular cross section surrounded by a circular valley. 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 is broken.



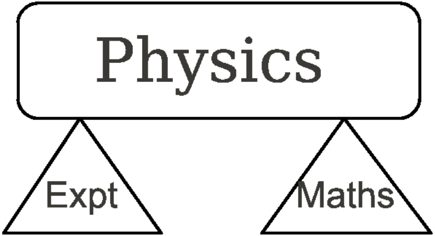
α : massless mode (N G boson)
β : massive mode (Higgs boson)

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 system and has circular symmetry in the field space. It has a maximum energy at point A where ϕ_1 and ϕ_2 are zero and a minimum 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 is zero at that point since it is a state of unstable equilibrium. We can choose any one point along the circle of 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 breakdown 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). 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 & Weinberg) which states that SBS of any continuous symmetry results in the existence of the spin zero massless N. G. boson.

- By the addition of a massless spin one gauge boson to the Goldstone model (thus elevating the original circular symmetry to a gauge symmetry), 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 β mode) however exists and this is the Higgs boson which was eagerly searched for, and presumably discovered 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.



- Laws of Nature are written in the language of Mathematics. ("God is a Mathematician")
- The Laws can be discovered only through Experiments.