

# Is there a Final Theory?

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## Plan of the Talk

1. Past: Bird's eye view of developments in Fundamental Physics in 20<sup>th</sup> century
2. Present: A closer look at the Gauge Theory of the Fundamental Forces of Nature, that marks the culmination of the above developments at the end of the 20<sup>th</sup> and the beginning of the 21<sup>st</sup> Centuries
3. Future: A glimpse into the Physics of the 21<sup>st</sup> Century: Quantum Gravity, String Theory .....

The earlier part of the 20<sup>th</sup> 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 , QM provided the framework for understanding the atomic nucleus and what lies inside, the MICROCOSM.

Quantum Mechanics :  
1900 - 1925

Planck, Einstein,  
Bohr, de Broglie,  
Schrödinger, Heisenberg,  
Dirac, Bose.....

Relativity :

Special, 1905 }  
General, 1915 }

Einstein

As Richard Feynman once said,  
if a catastrophe is about to annihilate the  
whole of human civilization, and we have  
time to pass on, to a distant world,  
just one sentence summing up all of  
our Science, that sentence will be

"MATTER IS MADE OF ATOMS."

Once the atom was understood, there  
followed the understanding and then the  
control and mastery of matter in all  
its forms - solids, liquids & gases.

Atom was the key to the unravelling of  
Chemistry and Biology too.



At the beginning of the 20<sup>th</sup> 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** & then to the **nucleon** (the proton or the neutron). Now we know that the nucleon itself is made of 3 **quarks**.

↑  
This is the level to which we have reached at the end of 20<sup>th</sup> Century. The depth (or the distance scale) probed thus far is  **$10^{-17}$  cm**.

## INWARD BOUND

Atoms  $\rightarrow$  Nuclei  $\rightarrow$  Nucleons  $\rightarrow$  Quarks  $\rightarrow$  ?

$10^{-8}$  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 & ever deeper levels - has culminated, at the end of the ~~present~~<sup>20<sup>th</sup></sup> Century, in a theory of fundamental strong and weak forces. This theory is called

THE STANDARD MODEL OF HIGH ENERGY PHYSICS

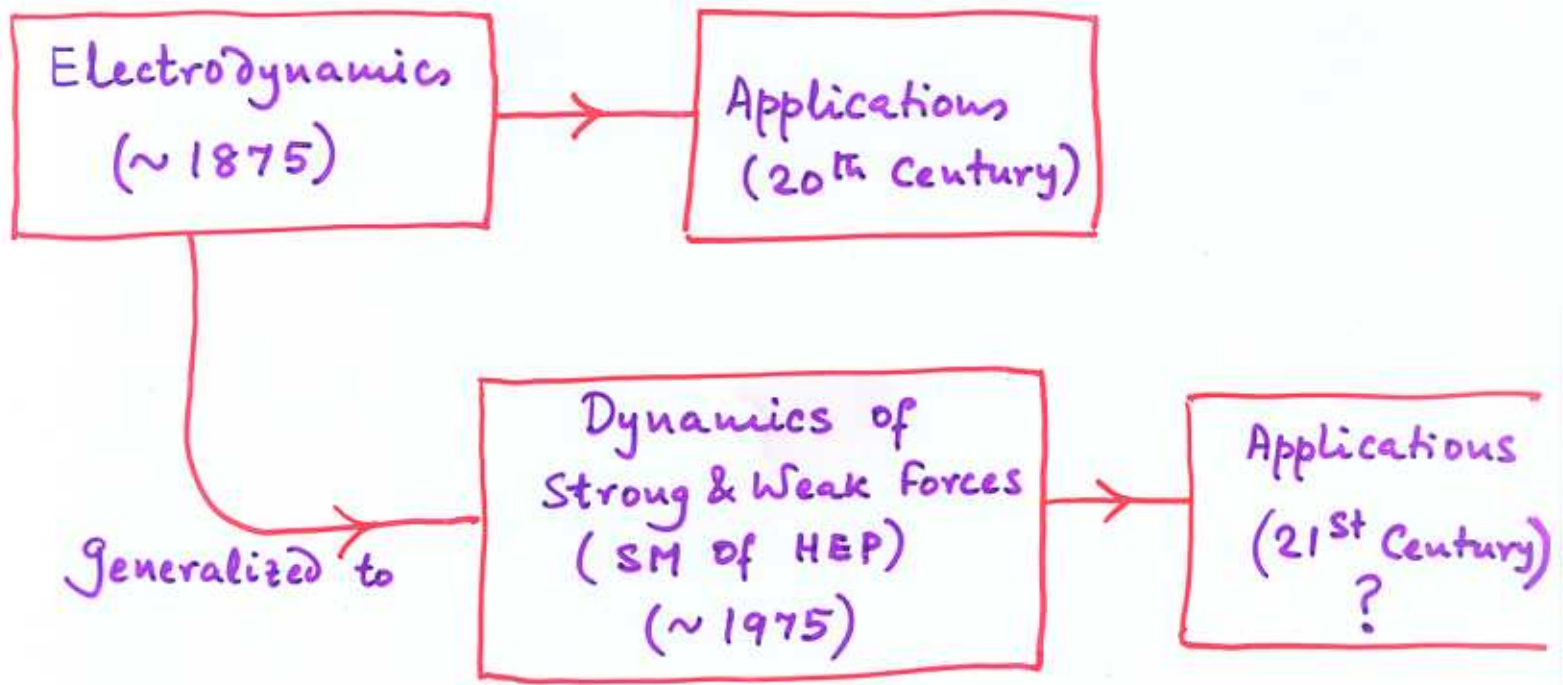
(a rather prosaic name).

In this theory, the strong forces operating within the nuclei and within the nucleons, as well as the weak forces that were revealed thro' the discovery of radioactivity 100 years ago are understood to be generalizations of the

ELECTRODYNAMICS

OF FARADAY & MAXWELL.





The ~~present~~<sup>20<sup>th</sup></sup> 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 & Weak forces are mastered!

The discovery of the laws of QM have led to enormous developments in atomic & molecular physics, condensed matter physics, chemistry and biology.

This is a continuous development, enriching our understanding of more and more complex systems and at the same time revealing the unifying role of Physics as providing a deeper link between all Sciences.

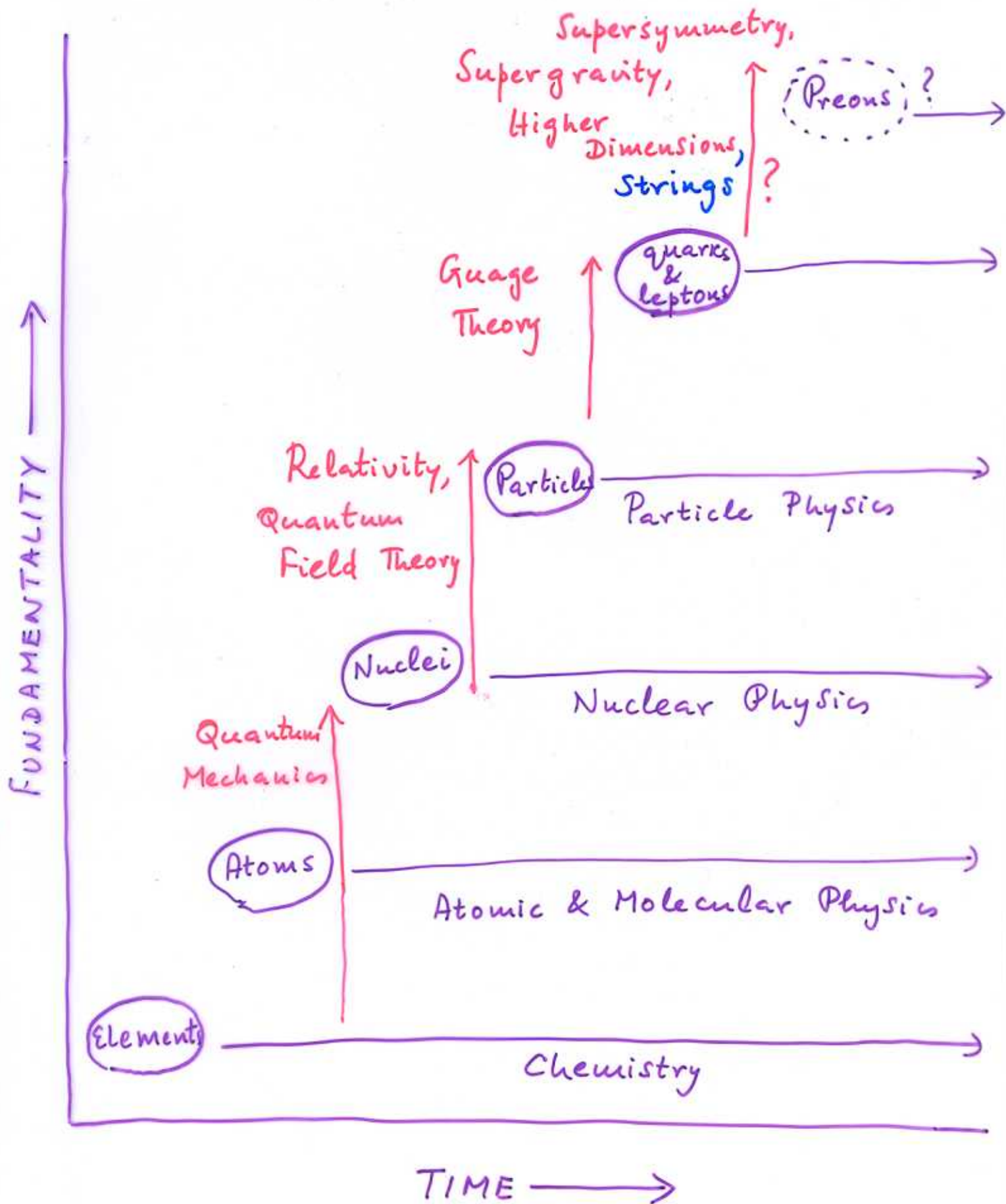
Quantum Mechanics → Atoms & Molecules → CMP → Chemistry → Biology

~~The recent award of NF in Chemistry for the calculation of QM wavefunctions of biomolecules testifies to the strength of this chain.~~

(Fig)

In parallel with it, or rather, in perpendicular to it, there is another line of development marked by discrete (quantum) jumps involving conceptual advances in unanticipated directions. The quantum and relativity revolutions belong to this category.





(Fig)

I have already referred to the continuous development of Physics over time and the discontinuous conceptual advances that occur from time to time that change the programme of Physics itself.

Roughly speaking, the former may be called Complexity and the latter as Fundamentality.

Sometimes, there is a quarrel among physicists as to which is more important. I think both lines of development are important and both are essential for the progress & vitality of Physics.



The role of Quantum Mechanics coupled with Special Relativity in providing the basis for the understanding of microcosm was already mentioned. 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 (whose inner meaning has not yet been unravelled) that the twin revolutions of quantum and relativity that powered the conceptual advances of ~~the~~ <sup>the 20<sup>th</sup></sup> 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.



GRAVITY which gets subsumed as 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 has become the most fundamental problem of Physics at the turn of the Century.

This is in contrast to all the other fundamental forces of Nature, namely Electromagnetic, Strong & Weak forces, which have all been successfully incorporated into the quantum mechanical framework. The Standard Model of HEP mentioned earlier is just that, and Standard Model leaves out Gravity.

That 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 glimpse 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. (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 21st Century.

\* Read it



$$E = mc^2$$

In any discussion of Physics in the 20<sup>th</sup> Century, the topic of Nuclear Energy cannot be omitted. It was inevitable that during their inward bound journey, physicists encountered the tremendous energy locked up inside the nucleus and devised the means to release it. But, it was to our eternal shame that it was first released for the destruction of humanity.

.....

The genie which was let out of the bottle more than half a century ago, is still at large.

We have yet to put it back  
into the bottle.

This is of vital importance for the safety of mankind... and in fact for the safety of all living beings on this planet.



It is perhaps not out of place to point out that the Nuclear Energy we have learnt to release is only a small fraction of energy-releases that can be contemplated in contemporary physics.

For instance, in the release of nuclear energy (be it fission or fusion), only a small fraction of the nucleonic mass is converted into energy. [Think of Einstein's famous formula  $E = Mc^2$ .]

Processes in which the whole nucleonic mass disappears into energy are among the phenomena studied in present-day High Energy Physics.

Even more cataclysmic events are envisaged in (High Energy) Astrophysics!

~~1783~~

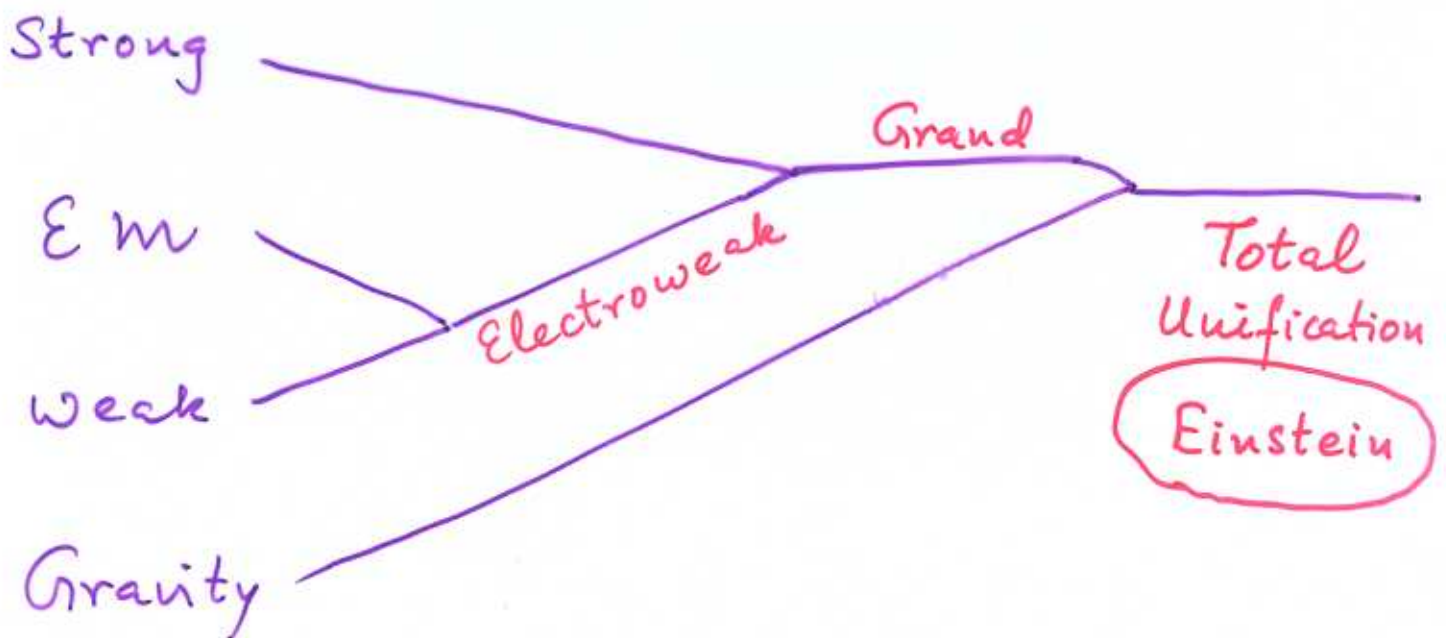
~~W, Z Bosons~~

② 1  
9 5

~~Quanta of Weak force~~

# The four fundamental forces of Nature

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



# Laws of Electrodynamics

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

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

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

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

Oerstead  
Ampere  
Faraday  
Maxwell  
Hertz

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





# STANDARD MODEL OF HIGH ENERGY PHYSICS

= Electroweak Dynamics

⊕

Quantum Chromodynamics (QCD)

~~Electroweak Dynamics~~

# Standard Model of High Energy Physics

= Electroweak Dynamics + QCD  
 (SU(2) × U(1) × SU(3))

## Laws of Electroweak Dynamics

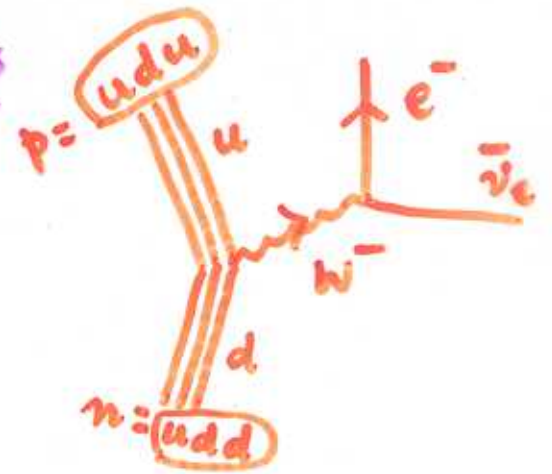
$(\vec{E}_i, \vec{B}_i) : i = 1, 2, 3, 4$   
 $\gamma, W^+, W^-, Z$

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

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

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

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



## Laws of Quantum Chromo Dynamics

$(\vec{E}_\alpha, \vec{B}_\alpha) : \alpha = 1 \dots 8$   
 $G_\alpha$

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

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

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

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



Nonabelian gauge fields  
 (Yang-Mills fields)



Gravity?

Field Sector

Bosons

Bose-Einstein Statistics

Spin 1, 2

 $\gamma$ , $W^+, W^-, Z$  $G_\alpha \quad \alpha = 1 \dots 8$  $g_{\mu\nu}$ Particle Sector

Fermions

Fermi-Dirac Statistics

Spin  $1/2$ 

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix}$$
 $p \sim uud$  $n \sim ddu$ 

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

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



## Electroweak Sector

- Spontaneous Breakdown of Symmetry
- Higgs mechanism:  $\langle 0|\phi|0\rangle \neq 0$
- $m_H > 115 \text{ GeV}$

## QCD Sector

- Colour Confinement
- QGP ?

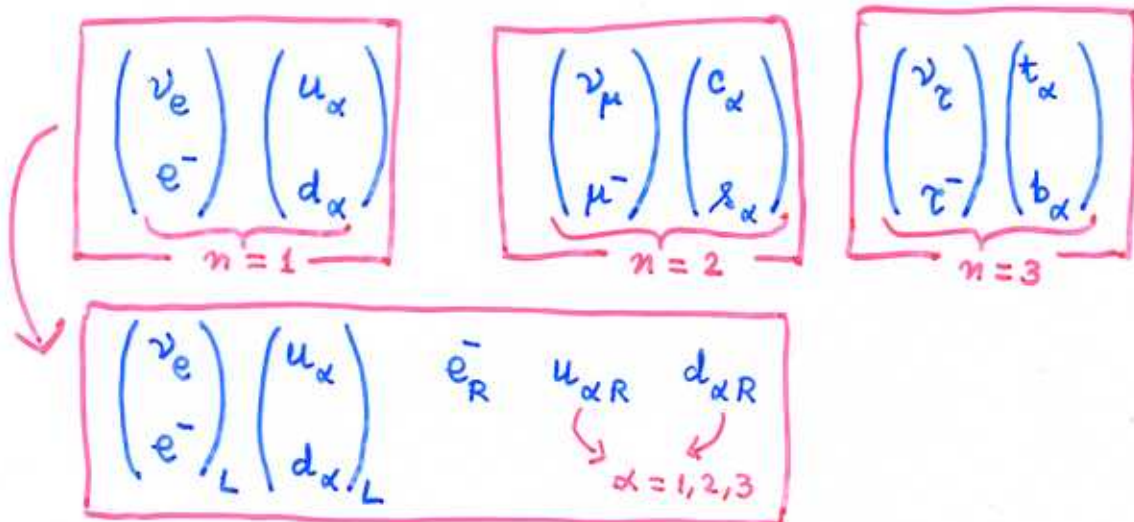
## Nobel Prizes for the Standard Model

- 1978 : Glashow, Salam } Construction of the  
& Weinberg } Electroweak theory
- 1983 : Rubbia & } Discovery of W & Z  
Van der Meer } bosons
- 1990 : Friedman, Kendal } "Observation" of quarks  
& Taylor } inside the proton
- 1999 : t'Hooft & Veltman } Proof of renormalizability  
of the electroweak theory
- 2004 : Gross, Politzer } Asymptotic freedom of  
& Wilczek } YM theory (QCD)
- 2008 :

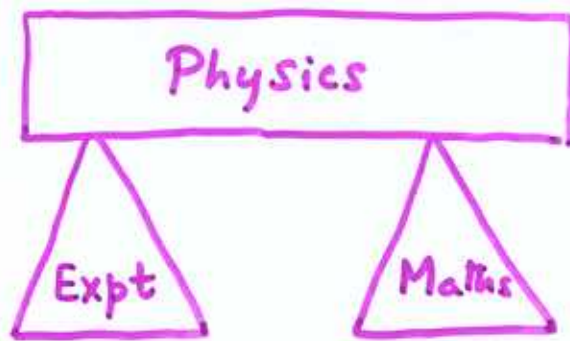
# Standard Model of High Energy Physics

( $SU(3) \otimes SU(2) \otimes U(1)$  gauge theory)

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4} (\partial_\mu G_\nu^i - \partial_\nu G_\mu^i - g_3 f^{ijk} G_\mu^j G_\nu^k)^2 \\
 & -\frac{1}{4} (\partial_\mu W_\nu^a - \partial_\nu W_\mu^a - g_2 \epsilon^{abc} W_\mu^b W_\nu^c)^2 - \frac{1}{4} (\partial_\mu B_\nu - \partial_\nu B_\mu)^2 \\
 & - \sum_n \bar{q}_{nL} \gamma^\mu (\partial_\mu + ig_3 \frac{\lambda^i}{2} G_\mu^i + ig_2 \frac{\tau^a}{2} W_\mu^a + i \frac{g_1}{6} B_\mu) q_{nL} \\
 & - \sum_n \bar{u}_{nR} \gamma^\mu (\partial_\mu + ig_3 \frac{\lambda^i}{2} G_\mu^i + i \frac{2}{3} g_1 B_\mu) u_{nR} \\
 & - \sum_n \bar{d}_{nR} \gamma^\mu (\partial_\mu + ig_3 \frac{\lambda^i}{2} G_\mu^i - i \frac{g_1}{3} B_\mu) d_{nR} \\
 & - \sum_n \bar{l}_{nL} \gamma^\mu (\partial_\mu + ig_2 \frac{\tau^a}{2} W_\mu^a - i \frac{g_1}{2} B_\mu) l_{nL} \\
 & - \sum_n \bar{e}_{nR} \gamma^\mu (\partial_\mu - ig_1 B_\mu) e_{nR} \\
 & + |(\partial_\mu + ig_2 \frac{\tau^a}{2} W_\mu^a + i \frac{g_1}{2} B_\mu) \phi|^2 - \lambda (\phi^\dagger \phi - v^2)^2 \\
 & - \sum_{m,n} (\Gamma_{mn}^u \bar{q}_{mL} \phi^c u_{nR} + \Gamma_{mn}^d \bar{q}_{mL} \phi d_{nR} \\
 & \quad + \Gamma_{mn}^e \bar{l}_{mL} \phi e_{nR} + h.c)
 \end{aligned}$$







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

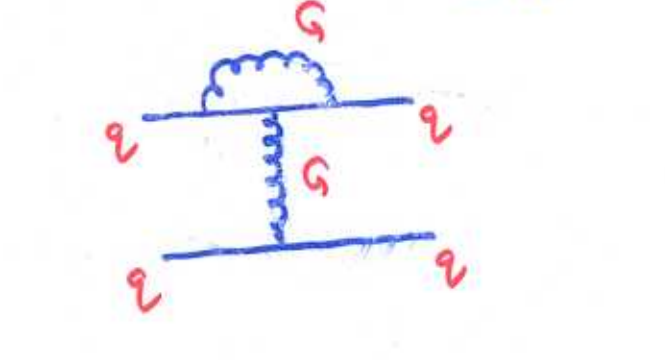
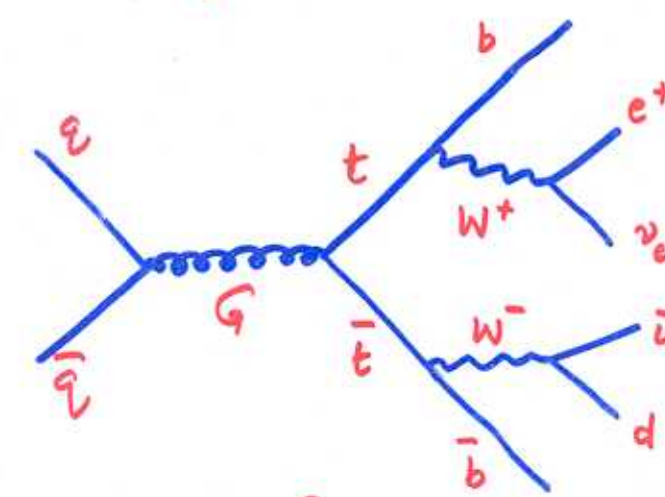
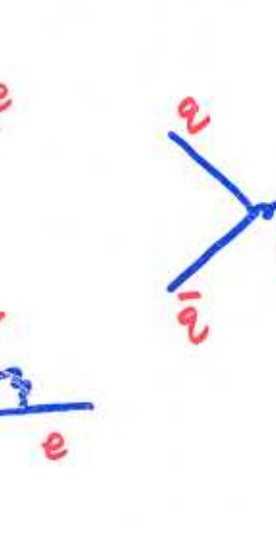
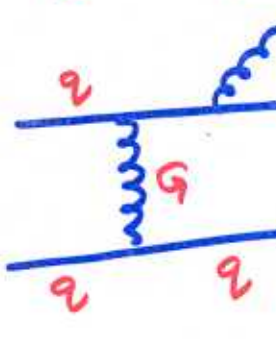
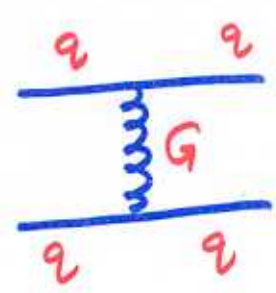
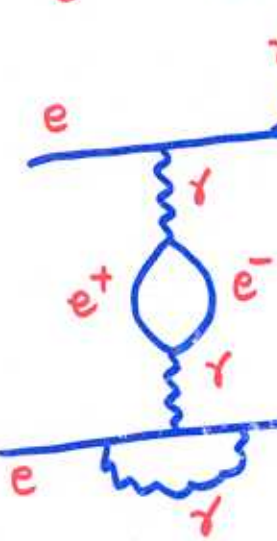
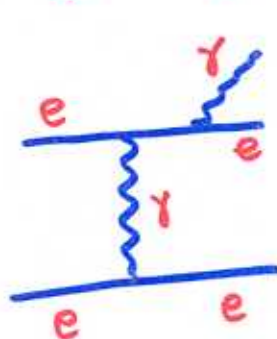
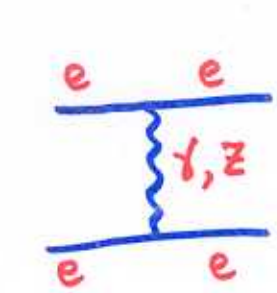
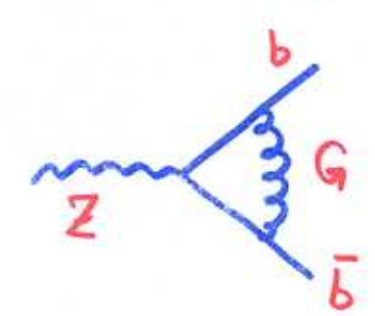
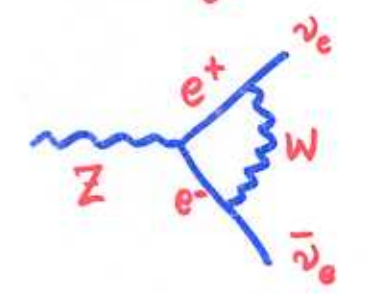
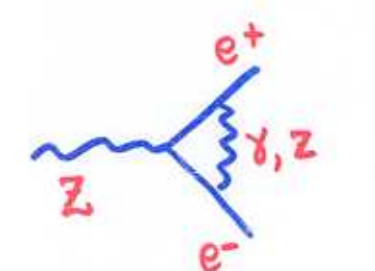
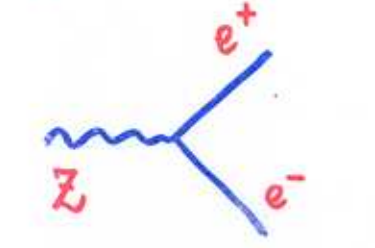
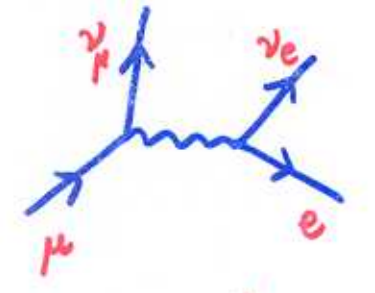
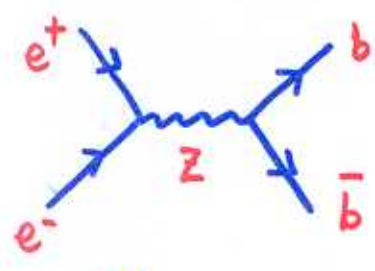
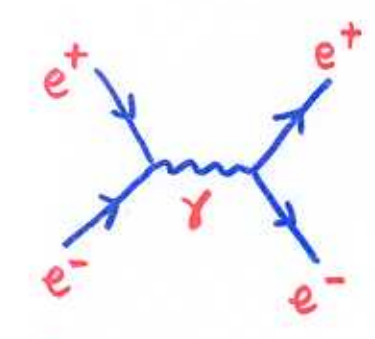
## Main message

- Future Technology will depend on the STANDARD MODEL
- Standard Model is as true as MAXWELL'S ELECTRODYNAMICS
- Standard Model must be taught in Schools and Colleges

The importance of the SM cannot be overemphasized. Whatever happens in the future, SM will stand. SM is as true as Maxwell's Electrodynamics. In fact, it must be taught in Schools & Colleges.



Neutrinos are massless in  
Standard Model



- Fundamental Units:  $\hbar = c = 1$

$$E \text{ (in GeV)} = \frac{0.192}{L \text{ (in } 10^{-13} \text{ cm)}}$$

- Scales in HEP:

L →	$10^{-8}$	$10^{-13}$	$10^{-17}$	$10^{-33}$
(cm)				
E →		200 MeV	2 TeV	$10^{19}$ GeV

Planck Scale  
(Scale of Quantum Gravity  
& String Theory)



$$E_p \sim \sqrt{\frac{1}{G_N}} > L_p \sim \sqrt{G_N}$$

- Accelerator Energies:

LEP : 200 GeV

Tevatron : 2 TeV

LHC : 14 TeV



When does Gravity become as strong as other interactions?



$$\sigma_{SM}(E) \sim \frac{1}{E^2}$$



$$\sigma_G(E) \sim G_N^2 E^2 \sim \frac{E^2}{M_P^4}$$

(where  $M_P \sim \frac{1}{G_N^{1/2}}$ )

So,

$$\sigma_G(E) \sim \sigma_{SM}(E)$$

for  $E \sim M_P \sim 10^{19} \text{ GeV}$   
 $\hookrightarrow G_N^{-1/2}$

Comparison between  
Gravity & EM

$$\frac{G_N m_p^2 / r^2}{e^2 / r^2} \approx 10^{-36}$$

$$\frac{G_N E^2 / r^2}{e^2 / r^2} \approx 1$$

$\Rightarrow$

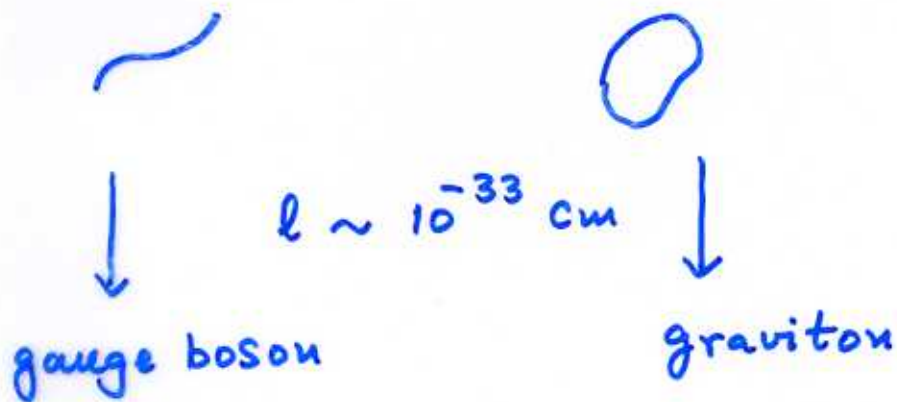
$$\frac{E^2}{m_p^2} \approx 10^{36}$$

or,

$$E \approx 10^{18} \text{ GeV}$$

# String Theory

11  
~~11~~  
~~20~~



- Supersymmetry
- Higher dimensions ( $d=10$ )
- Strings, membranes, p-branes .....
- M Theory