Nothing = \{0, 0, 0, 0, 0, 0, \ldots\} \quad \text{Fock space}

\Hilbert

\text{B I G B A N G}

\Delta E \cdot \Delta t \geq \hbar \quad \Delta t = \text{large} \Rightarrow \Delta E = \text{small}

\sim 700,000 \text{ years}

\text{Inflation}

\text{3000}^\circ \text{K}

\text{e}^\pm \text{condense} + \text{Energy} + - \text{E=Potential} = 0

\text{onto } p = \text{Hat} \quad \text{E} + \text{Mass} \quad \text{gravitational}

\text{so particle density}

\text{universe transparent}

\text{CMBR}

\text{OUR UNIVERSE} \quad \text{nucleo-}

\text{synthesis} \quad \text{13.5 Billion years}

\text{Particles} = \text{Fermions} \quad \text{Force} = \text{Bosons}

8 \text{ generations} \quad n(\frac{1}{2}) \quad \text{spin} \quad n = 0, 1, \ldots

\text{spin}

\text{MBR} \quad \text{weak}

\text{MBR} \quad \text{strong nuc}

\text{18 quarks}

\text{U, d, s, c, b, t, \bar{t}} \quad \text{8 gluons, \ g}_{\text{ab}}

\text{superstrings}

\text{GUT} \quad \text{TBOE} \quad \uparrow
Now let's consider baryons:

Baryons = 3 quark combos

\[ p = u \bar{u} g \]  
but colorless!

Note: the quark is

or...

\[ \Delta^{++} = u \bar{u} g = \text{colorless} \]

*Note: because of this, baryon and Pauli exclusion clear that addit quantum #, color was needed.

Mesons: \[ q \bar{q} \text{ combos} \]

\[ \pi^+ (u \bar{d}) \rightarrow (u g \bar{d} g) \]  

\[ \Sigma \rightarrow (c \bar{c}) = \text{November revolution!} \]

2004: Penta quark = 5 quark combos
New

Classical

1) Newton's laws
2) Max's Equations (E=mc^2)
3) Stat mech. Thermo dynamics

1900

Quantum mechanics

1) Light \[ \sum_\text{particle} = \alpha \]

2) \[ e^{-} \sum_\text{particle} = e^{-} \]

(Quantum mechanics)

Solve Schrödinger's equation

\[ -i \hbar \frac{\partial \Psi(x,t)}{\partial t} = \hat{H} \Psi(x,t) \quad (1933) \]

But what is \( \Psi \)?

\[ \Psi \Psi^* = \text{probability density}! \]

Schrödinger-Born

(Max... Olivia's Grand dad)

Probabilistic interpretation of Q.M.

1954 Nobel Prize.

Tremendously successful! So apply Q.M. to forces!
So look @ 4 Forces.....

1. EM
2. weak nuc
3. strong nuc
4. gravity

Obvious choice... gravity, BUT!

Consider

\[
\begin{align*}
\left| \frac{F_G}{F_E} \right| &= \frac{G m_1 m_2}{r_{12}^2} = \frac{G m_1 m_2}{k q_1 q_2} \\
M_e &= 10^{-31} \text{ kg}, \quad q_e = 1.6 \times 10^{-19} \text{ C} \\
G &= 6.67 \times 10^{-11} \frac{\text{Nm}^2}{\text{kg}^2}, \quad k = 10^1 \frac{\text{Nm}^3}{\text{C}^2} \\
\left| \frac{F_G}{F_E} \right| &= 10^{-72} \approx 10^{-44}
\end{align*}
\]
Clearly $F_e \gg F_x$

what about

weak $\mu c$, weak & short range $\sim 10^{-15}$m

strong $\mu c$, strong BUT act $\sim 10^{-15}$m of $\mu c$

So, @ THE SIZE OF

anything $> atom$

$E \& M$ Dominant!

So go about Describing $E \& M$ Force w/ Quantum Mechanics 1st

Feynman

Schwinger Nobel Prize 1965

Tomonaga

Quantum Field Theory $E \& M$ & Field $e^3 \sim E$ particle field some sewing!
So

<table>
<thead>
<tr>
<th>Size</th>
<th>Speed</th>
<th>Relativity ~1900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulky</td>
<td>Slow</td>
<td>Albert Einstein</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\frac{v}{c}$, say 1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rocket $\approx 20,000$ mph $\approx 2 \times 10^6 \frac{\text{m}}{\text{s}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\frac{</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>But $\text{atmo} \uparrow$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M \approx 0.94 \text{e} \text{ sphere } \downarrow$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M$ lifetime $\approx 3 \times 10^{-6}$ sec</td>
</tr>
</tbody>
</table>

**Quantum Mechanics 1900 - 1930**

- $m = 1.67 \times 10^{-27}$ kg
- $\text{H}^+$
- $V_{\text{atom}} \approx 10^6 \text{m/s}$
- $V_e \approx 10^6 \text{m/s}$

So $\frac{V_e}{c} \approx 1\%$ relativistic effects

- Mole $= 12$ grams (6.022 x 10$^{23}$ atoms)
- Finger nail $\approx 10^{23}$

- $10^7 \text{ seconds in universe} \approx 1.7 \text{ years}$
- $13 \times 10^8 \text{ year} \times 13.5 \times 10^8 \text{ y} = 10^2 \text{ sec}$

**Small**

- Atom $\approx \text{Q.M.}$
- External $\approx \text{classical}$
- Small $\approx \text{semi-classical}$

**Quantum Field Theory**

- Q.M. "needs" relativity to be "more" right?
- $\rightarrow$'s
- Particle - anti-particle pairs "it needs "consistent" treatment of force fields!"

So QFT

- Particles $\rightarrow$ fields
- Forces $\rightarrow$ Electromagnetic fields
- Weak, strong, gravity
QED: most successful, precise Theory ever!

H-atom

\[ \begin{align*}
\text{energy levels} & \quad \sim 2 \text{ eV} = \\
\text{orange light} & \\
\text{Balmer series} & \quad \rightarrow n \rightarrow 2
\end{align*} \]

QED correction

\[ \begin{align*}
\text{Lamb Shift} & \quad \nu \frac{1}{10^6} \text{ eV} \\
\text{virtual } e^- + e^+ \text{ pair} &
\end{align*} \]

So experiment:

Theory (no Lamb) \quad \rightarrow 2.0000000000000003 \quad \text{(Wow!)}

Theory (w/Lamb) \quad \rightarrow 2.000000000000036
Great. But deeper? From nothing can you show that you, the universe needs to have

\[ \mathcal{L} = \text{particle fields} \]

1. \( E \)
2. \( u \text{ nuc} \)
3. \( s \text{ nuc} \)
4. \( \text{gravity} \)

Almost!

\textbf{Gauge Theories}

Idea: Symmetries necessitate the force fields & maybe even the particle fields


Based on Noether’s Theorem

Lo Emily... (mathematician)

Student of Hilbert, she had held of time getting professor job in Germany forced to flee to US in 1933 and died 2 years later
Brief Sketch of Gauge Theory

Symmetry \implies Conservation: when you enforce this symmetry from global to local, you have to add a gauge field so it works (i.e., consistent mathematically).

Ex: Relativity:

Invariance of "Frames":

To keep the physical laws of motion invariant:

\[
\begin{align*}
\text{conserved } \vec{p} & \quad \text{conserved } \vec{E} \\
\text{invariance of } x_0 & \quad \text{invariance of } \vec{E} \\
\text{invariance of } t_0 & \quad \text{invariance of } \vec{E}
\end{align*}
\]

invariant to all frames, inertial & non-inertial (accelerating)

Need to include GRAVITY if you want it Lorentz Invariant locally.

Gravity = Field that travels \( c \)
More abstract...

\[ \Phi \rightarrow e^{i\alpha} \Phi \]

arbitrary phase

Then Schrödinger prob interet

\[ \Psi^* \Psi = e^{i\alpha} \Psi^* e^{i\alpha} \Psi = \Psi^* \Psi \]

so Q.M. wavefunct is invariant to \( e^{i\alpha} \)

\[ i\partial_t \Psi = \mp \nabla \times \Psi \]

\( \Psi \) is \( e^{i\alpha(\xi,\tau)} \) global, everywhere

presserves the "invariance"

But is demand it to be local

\[ \Psi = e^{i\alpha(x,\tau)} \]

Then

\[ \Psi^* \left( \frac{\partial}{\partial x} \right) \Psi = e^{i\alpha(x,\tau)} \Psi^* \left( \frac{\partial}{\partial x} \right) e^{i\alpha(x,\tau)} \Psi \]

so loose invariance on "local" symmetry
Eisenberg & Resnick does it well...

time dep Schrödinger

\[
\frac{i\hbar \partial \Psi}{\partial t} = \hat{H} \Psi
\]

is transform \( \Phi \) globally \( \Phi \rightarrow \Phi e^{i\sigma} \)

is \( \sigma \neq \sigma(x,t) \) then this transformation leads to Schröd invariant.

But... is local \( \Phi \rightarrow e^{i\sigma(x,t) \Phi} \)

Then

\[
\frac{i\hbar}{\partial t} \left( e^{i\sigma(x,t) \Phi} \right) = \left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V(x)\right) e^{i\sigma(x,t) \Phi}
\]

The temporal & spatial derivatives destroy the invariance of Schrödinger to local transformation.
However,

\[ \mathbf{\mathbf{F}} \rightarrow (e^{i\mathbf{E} \cdot \mathbf{r}}) \mathbf{F} + \mathbf{F} \]

Then \( \mathbf{F} \cdot \frac{d}{dx} \mathbf{F} \) is completely invariant locally.

Is you investigate what \( \mathbf{F} \)

needs to be to make \( \mathbf{F} \) locally invariant.

**SURPRISE** exactly = E&M Field described by Max's Equations.
where are we?

D) Invariance of phase $\Rightarrow$ cons of charge $\quad \gamma = \text{photon of EM Force}$

\[ \begin{align*}
\text{Need} & \quad \text{mass less renormalizable} \\
\text{Isospin} & \quad \text{problem Not } \\
\{ z^0, w^- \} & \quad \text{renormalizable} \\
\text{But, add another field} & \\
\text{Higgs field that give mass to} & \\
\{ z^0, w^- \} & \quad \text{mass by spontaneous} \\
\text{broken symmetry} & \end{align*} \]

The entire theory becomes invariant.

And renormalizable (Gerard 't Hooft in 1971)

Nobel Prize in 2001?

Wow!

This is electro weak!

$\gamma = \text{photon} = \text{EM}$

(CERN in the 1960's $\omega^-$, $\omega^+$, $\text{neutral} \& \text{charge currents}$)

see
4) "Color" charge conservation, invariance
quarks can come in \((r, g, b)\)
\(\Rightarrow\) is made "Gluon" \(\vec{q} \vec{g} \vec{b}\)
8 of Them

which explains \(\xi\)
(all know Mesons, Baryons, \(\rho, K, \ldots\))

1) asymptotic freedom, why quarks seem "Free"
inside of \(p \& n\)

2) quark combination -- yet never see individual
(anti-)screening cause gluons carry charge

them selves
Seems like should get the Quantum field for gravity! (graviton)

Then the particles?

Super symmetry $\leftrightarrow$ all the bosons should have
  
  Super symmetric
  
  Fermion, 'super partner'

  
  Bosons
  
  photon, pion

  Fermions
  
  st electron

Ex: Superstrings!