There are two complimentary philosophies that underlie modern frontier science. The combination of quantum physics and electromagnetism is enough to "understand" all of chemistry & biology—however—as the great physicist Paul Dirac once said—the equations they give are much too complicated to solve! Understanding how the diversity of nature—from crystals, to superconductors & magnets—to biology & life itself—the understanding of how the microscopic laws give rise to all this richness, is the study of emergence. By contrast, if we seek to reduce the
universe to its most fundamental components, to its most fundamental forces - we are following a reductionist approach to science. Both approaches are needed if we are to understand the world we live in.

However, for the remaining four lectures, we will take a journey into the subatomic world - the world within the nucleus.
<table>
<thead>
<tr>
<th>Force</th>
<th>Range</th>
<th>Strength</th>
<th>Mediating Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravity</td>
<td>$\infty$ ($\frac{1}{r^2}$)</td>
<td>$10^{-38}$</td>
<td>Graviton, $S=2$</td>
</tr>
<tr>
<td>electromagnetism</td>
<td>$\infty$ ($\frac{1}{r^2}$)</td>
<td>$\frac{1}{137}$</td>
<td>Photon, $S=1$</td>
</tr>
<tr>
<td>strong</td>
<td>$10^{-15}$ m</td>
<td>1</td>
<td>Gluon, $S=1$</td>
</tr>
<tr>
<td>weak</td>
<td>$10^{-18}$ m</td>
<td>$10^{-9}$</td>
<td>$W^\pm$, $Z^0$, $S=1$</td>
</tr>
</tbody>
</table>

**Fundamental Particles**

**Electron/Positron**:
- **Antiparticle Concept**

**Schrödinger**:
- $E = \frac{p^2}{2m} + U(x)$

**Dirac**
- **Relativity + Quantum**
- 1928
- $E^2 = p^2c^2 + m^2c^4$
- $E = \pm \sqrt{(mc^2)^2 + p^2c^2}$

**Filled Negative Energy Sea**


Position = absence of negative energy electron

\[ \text{Anti-} \quad \text{All conserved charges reversed} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>Q</th>
<th>B</th>
<th>L_e</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td>+1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>$e^-$</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>$p^+$</td>
<td>+1</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>$\bar{p}^-$</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>$n$</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\bar{n}$</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
\text{Dick Feynman:}
\]

position = electron going backwards in time

\[ \text{Energy to pair-create} = E_{\text{min}} = 2mc^2 \]

\[ = 2 \times (9.109 \times 10^{-31}) (2.998 \times 10^8)^2 \]

\[ \approx 1.637 \times 10^{-19} \text{J} \]

\[ \approx 1.022 \text{ MeV}. \]
Electron & positron both have kinetic energy $K = 2\text{ MeV}$. Calculate energy & wavelength of photons produced when they annihilate each other.

$$E = (K + m_e c^2) = 2 + 0.511 = 2.511 \text{ MeV}$$

$$= 4.02 \times 10^{-13} \text{ J}$$

Total energy

$$2E = 2 \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E} = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{4.02 \times 10^{-13}}$$

$$= 5 \times 10^{-13} \text{ m}$$

$$E_{\text{photon}} = 4.02 \times 10^{-13} \text{ J}$$

\[\text{(Feynman)}\]
PARTICLES AS FORCE MEDIATORS

Quantum Electrodynamics

\( F \quad \rightarrow \quad \text{electron} \quad \rightarrow \quad F \)

(Feynman, Schwinger, Tomonaga, 1948)

\[ \Delta E \Delta t \approx \hbar \]

"The more you borrow, the sooner you have to pay it back"

The nuclear force is short-ranged, given by

\[ V(r) = -\frac{f^2 e^{-r/r_0}}{r} \]

Yukawa

\[ \Delta t = \frac{r_0}{c} = \frac{1.5 \times 10^{-15}}{3 \times 10^8} = 5 \times 10^{-24} \text{s} \]

\[ \Delta E = \frac{\hbar}{\Delta t} = \frac{(1.4 \times 10^{-34} \text{Js})}{5 \times 10^{-24}} = 2 \times 10^{-11} \text{J} \approx 130 \text{MeV} \sim m c^2 \]

\[ m \sim 130 \text{MeV}/c^2 \]
Historically misidentified as the muon \( (\mu^-, M_{\mu} = 207 \text{Me}) \).

1947 - Pions or pi-meson. \( \pi^+, \pi^0, \pi^- \)

\[ \Delta t \sim \frac{r_0}{c} \]
\[ \Delta E \sim \frac{hc}{r_0} \sim mc^2 \]
\[ m \sim \frac{h}{cr_0} \]

\[ \begin{cases} \Gamma_0 = \infty & m \sim 0 \quad \text{(photons, gravitons)} \\ \Gamma_0 \sim 1 \text{fm} & m \sim 100 \text{MeV} \quad \text{(pions)} \\ \Gamma_0 \sim 10^3 \text{fm} & m \sim 100 \text{GeV} \quad \text{(vector bosons)} \end{cases} \]

\[ [f^2] = Jm \quad \frac{f^4}{hc} = \text{dimensionless} \quad \text{coupling constant} \]

\[ \frac{f^2}{hc} \sim 1 \quad \text{strong force} \quad \frac{e^2}{4\pi\varepsilon_0 hc} \approx \frac{1}{137} \quad \text{E.M.} \]
Two major subdivisions

Fermions

half integer spin \( \frac{1}{2}, \frac{3}{2}, \ldots \)

(e\(^-\), p, \(\nu_e\), ...)  

integer spin \(0, 1, 2\)

(\(\pi^\pm, K^\pm, W^\pm, \text{graviton}\))

Bosons

Leptons

\[
\begin{align*}
(e) & \quad (\mu) & \quad (\tau^-) \\
L_e = 1 & \quad L_\mu = 1 & \quad L_{\tau} = 1 \\
\end{align*}
\]

Baryons \(S = \frac{1}{2}, \frac{3}{2}\).

\[
\begin{align*}
(p, n) & \quad B = 1 \\
(\bar{p}, \bar{n}) & \quad B = -1 \\
\end{align*}
\]

Mesons

\[
\begin{align*}
(\pi^+, K^+, \eta) & \quad S = 0 \\
(\eta^+) & \quad S = 1 \\
\end{align*}
\]

"Hadrons"

In all interactions, lepton numbers & baryon number are conserved.

\[
\begin{align*}
\mu^- & \rightarrow e^+ + \bar{\nu}_e + \nu_\mu \\
L_\mu = 1 & \quad L_e = 1 & \quad L_{\nu} = -1 & \quad L_{\mu} = +1 \\
\end{align*}
\]