What is an elementary particle?

- The smallest fundamental entities that make up matter. They cannot be "made of" smaller pieces.

  molecules $\rightarrow$ atoms $\rightarrow$ nucleus $\rightarrow$ electrons

  nucleus $\rightarrow$ (P, N) $\rightarrow$ neutrons and protons

  neutron and proton $\rightarrow$ quarks

How do we know that the quarks (and the electron) do not have a structure?

Well, we don't. If they do, we haven't seen it yet.

How small are these things?

- H-atom

  $R_H \sim 0.53 \, \text{Å} \quad \text{Å = Angstrom}$

  $1 \, \text{Å} = 10^{-8} \, \text{cm} = 10^{-10} \, \text{m}$

- Proton

  $R_p \sim 1 \, \text{fm} = 10^{-15} \, \text{m} \quad \text{fm = femtometer, Femt}$
Note \( \frac{R_h}{R_p} = 0.5 \times 10^{-20} = 50,000 \) !!

Amazing Fact

An atom is mostly empty space !!

What about quarks and electrons?

We have no evidence for any structure.

They look "point-like" down to \( R \sim \frac{R_p}{5000} \)

(But maybe if we look harder, we'll find something!)

How do we "see" these things?

How do you see a macroscopic object?

You see light reflected from the object. The "eye" is the detector.

For elementary particles, it is the same principle.

There is a detector system, and some physical process that lets you "see" what is going on - e.g., scattering of light, but also scattering of particles. Then you infer from the pattern.

Remember particle wave duality

a wave (light) is a particle (photon)
a particle (electron) is a wave \( (\lambda = \frac{\hbar}{P}) \)
If we are trying to "see" some feature of size $R$, we need to "probe" it with a wave of $\lambda < R$.

\[ \text{OK} \]

will not be able to distinguish small features with $R < \lambda$.

In particle physics, the probes are beams of particles:

\[ \lambda = \frac{h}{p} \]  

So if you want small $\lambda$, you need large $p$ (or large $E$, some way of saying the same thing).

That is why a lot of these experiments are done at giant particle accelerators. Largest particle accelerator, Tevatron at Fermilab outside Chicago.

- $E = 1 \text{ TeV per beam}$
- $T = \text{Tera} = 10^{12}$
- $G = \text{Giga} = 10^9$
- $M = \text{Mega} = 10^6$
$eV = \text{electron-Volt}$

= energy gained by an electron when accelerated through a potential difference of 1 Volt

\[
\text{teV} = 1961 \Delta V = 1.6 \times 10^{-19} \text{ J}
\]

we are already starting to see that conventional SI units are not very useful, or at least that they are cumbersome. We'll come back to that shortly

What is the deBroglie wavelength?

\[
\lambda = \frac{\hbar}{P}
\]

\[
E = 1 \text{ TeV} \quad \text{what is } P?
\]

\[
E = \gamma m_p c^2 \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad \beta = \frac{v}{c}
\]

\[
P = \gamma m_p v
\]

\[
\gamma m_p = \frac{E}{c^2} \quad \Rightarrow P = \frac{E v}{c^2} = E \beta
\]

What is $\beta^2$?

\[
\gamma = \frac{E}{m_p c^2} \quad \frac{1}{1 - \beta^2} = \frac{E^2}{m_p^2 c^4} \quad I = \frac{E^2}{m_p^2 c^4} - \frac{E}{m^2 c^2}
\]

\[
\beta^2 = \frac{m_p c^2}{E^2} \quad \beta = 1 - \frac{m_p c^4}{E^2}
\]

\[
\beta^2 = 1 - \left( \frac{1.67 \times 10^{-27} \text{ kg}}{1 \times 10^{12} \times 1.6 \times 10^{-19} \text{ J}} \right)^2 = 1 - 88 \times 10^{-16} \approx 1
\]

\[
\beta \approx 1 \quad \text{(very close to speed of light!)}
\]
Then \( \lambda = \frac{h}{P} = \frac{h}{E/C} = \frac{hC}{E} = \frac{6.6 \times 10^{-34} J \sec}{3 \times 10^8 m/sec} \approx 2 \times 10^{-29} m \) (pretty small)

**Units**

SI: probably what you are used to
- m, Kg, sec, A

Coulomb law \( F = \frac{1}{4\pi \varepsilon_0} \frac{q_1 q_2}{r^2} \)
- \( q \) in Coulomb, \( 1 C = 1 A \cdot sec \)
- \( \varepsilon_0 = 8.854 \times 10^{-12} \frac{F}{m} \)

**Gausssein Unit**
- \( q \) measured in electrostatic units (esu)
- \( F = \frac{9.9 \times 10^9}{r^2} \) N/C

One thing to remember \( \alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137} \) in Gaussian units

This is the fine-structure constant. It is characteristic of the "strength" of electromagnetism.

Particle physicists prefer to work in *Natural Units*. This is because they are sick and tired of carrying through all these factors of \( \hbar \) and \( c \).

They set \( \hbar = c = 1 \)
Why are these “natural units”? Because \( c \) is the natural unit of velocity, and \( h \) is the natural unit of angular momentum —

(Angular momentum quantization \( \frac{1}{2}h, \frac{1}{4}h, \frac{3}{2}h, \ldots \))

This choice has peculiar consequences:

\[
\begin{align*}
[c] &= \left[ \frac{L}{T} \right] \\
\Rightarrow \quad [L] &= [T]^1 \\
\text{length and time are measured in the same units!!}
\end{align*}
\]

\( h = 1 \Rightarrow \text{ANGULAR MOMENTUM IS A NUMBER} \)

\[
\begin{align*}
\overline{[P]} &= [L][P] \\
\Rightarrow \quad [P] &= [L]^{-1}
\end{align*}
\]

\[
\overline{[L]} = \overline{P} \times \overline{P}
\]

\[
\begin{align*}
\text{Mass:} \quad P = m \overline{V} &\Rightarrow [M] = [P] = \frac{1}{[L]} = [T] \\
\text{Energy:} \quad E = mc^2 &\Rightarrow [E]^{\times 2}
\end{align*}
\]

\[
\begin{align*}
\text{Charge:} \quad \alpha = \frac{e^2}{hc} \text{ is a number, } \frac{1}{h} \text{ and } c \text{ are numbers} &\Rightarrow [\alpha] \text{ is a number}
\end{align*}
\]

So, measure everything in this with just one unit — customarily energy.

Then at the end restore factors of \( h \) and \( c \) to get units that are more familiar.
### Summary of N.U.

<table>
<thead>
<tr>
<th>Velocity/Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbf{v} )</td>
<td></td>
</tr>
<tr>
<td>( \mathbf{J} ) (Ang. Momentum)</td>
<td></td>
</tr>
<tr>
<td>( \mathbf{E} )</td>
<td>GeV (TeV, MeV...)</td>
</tr>
<tr>
<td>( \mathbf{P} )</td>
<td>GeV, GeV/c</td>
</tr>
<tr>
<td>( \mathbf{m} )</td>
<td>GeV, GeV/c²</td>
</tr>
<tr>
<td>( \mathbf{T} )</td>
<td>1/GeV</td>
</tr>
</tbody>
</table>

**Conversion factor**

\[
\begin{align*}
\mathbf{c} &= 3 \times 10^8 \text{ m/sec} \\
\hbar &= 1.05 \times 10^{-34} \text{ J sec} \\
1 \text{ GeV} &= 1.6 \times 10^{-10} \text{ J} \\
1 \text{ GeV/c} &= 1.6 \times 10^{-18} \text{ J/c} \\
1 \text{ GeV/c}^2 &= 1.6 \times 10^{-19} \text{ J/c}^2 \\
\frac{1}{\text{GeV}} &= \frac{\hbar}{1.6 \times 10^{-10}}
\end{align*}
\]

Griffiths likes to keep all factors of \( \hbar \) and \( \mathbf{c} \) although this goes against my habit as a particle physicist, I will do my best to keep track of them too!!
What are the masses

1st $m_u = m_d = 380$ GeV/c$^2$
   $m_u$ = 3 MeV   $m_d$ = 6 MeV

2nd $m_c$ = 1.2 GeV/c$^2$
   $m_s$ = 900 GeV/c$^2$

3rd $m_b$ = 4.2 GeV/c$^2$
   $m_t$ = 175 GeV/c$^2$ $(!!)$

$m_b \neq 0$ if I gave this lecture 10 years ago
I would have said $m_b = 0$ or $m_b$ probably $= 0$

Now we know that $m_b > 0$ but the dust has yet to settle on what these masses are - for now let us just say $0 < m_b \leq \frac{1}{10}$ eV

1st $m_c = 0.511$ MeV
2nd $m_\mu = 105$ MeV
3rd $m_\tau = 1.776$ GeV = 1776 MeV

Everything you see in the world is made up of
$n, p, e$ i.e. quarks and leptons from the 1st generation. So

1) how do we know that there are more generations?
2) why isn't stuff from the 2nd and 3rd generation not around?
3) where is the antimatter?
Continue the introduction
So what are these fundamental building blocks

"QUARKS", "LEPTONS", INTERACTION CARRIERS

Quarks and leptons come in pairs

Q: (u) up (c) charm (t) top
   (d) down (s) strange (b) bottom, beauty

L: (νe) electron-neutrino (νμ) muon (ντ) tau
   (e−) electron (μ−) muon (τ−) tau

All have $S = \frac{1}{2}$

<table>
<thead>
<tr>
<th>Quark</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u, c, t</td>
<td>$+\frac{2}{3}e$</td>
</tr>
<tr>
<td>d, s, b</td>
<td>$-\frac{1}{3}e$</td>
</tr>
</tbody>
</table>

We will often drop the factor of "e"

These pairs are called generations

(1st, 2nd, 3rd generation)

Members of the 2nd (3rd) generation are identical to those of the 1st except they are more massive

Why are there generations?
Why are there three generations?
Why are the masses what they are?

? If you can answer this question you can book your trip to Stockholm to pick up your Nobel Prize!!

And there are antiparticles too! Antiquark is operator-like

eg Positron = like an electron (same m, S, etc) but the charge
Answers


   - 
   - p in cosmic ray
     → nucleus in atmosphere
     particles produced in collisions can include 2nd or 3rd generation stuff.

2. Or p from particle accelerator → target

Production of additional, possibly heavier, particles exists. \( E = mc^2 \), i.e. some of the kinetic energy of the projectile is used up in making transformed into mass of new particles.

Much of the early progress of particle physics came from the study of cosmic rays.

2. Particles decay to other particles that are lighter.

   - Everything is. Every decay heavy → light which you can write down is allowed subject...
to conservation laws (energy, angular momentum, charge but also other like baryon number)

\[ \text{eg } \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \quad t \sim 2 \mu\text{sec} \quad \text{we'll see later} \]

So, 2nd or 3rd generation particles decay to 1st generation

8. Big-Bang: we believe equal amount of matter & anti-matter produced.

Then

\[ \text{If matter and anti-matter behaved in exactly the same way, all (anti)matter would have been annihilated, only photons left. The only reason that there is some matter left-over in the universe is some matter left-over in the universe to make the planets, stars, planets, people, is that at some level there must be a small difference in the behavior of matter vs anti-matter. We have not understand where it comes from. (Another Nobel prize waiting for you.) In expt we have seen some of this, but not enough to account for the Universe!} \]
Interactions

There are four types of interactions

- **Strong**: Responsible for holding the 3-quarks in a proton together. Theory is called QCD, Quantum Chromo Dynamics

- **Electromagnetic (EM)**: Macroscopically you should be familiar with this: $E^2$, $B^2$ QED Quantum Electrodynamics

- **Weak**: Responsible for $\beta$ decay, e.g. $n \rightarrow p + e^- + \bar{\nu}_e$

- **Gravitational**: You know what I mean here also - Do not have a self-consistent theory of Quantum Gravity - Maybe strings, EM and Weak are unified in a common framework called ELECTROWEAK theory. We'll come back to this later in the course

Why is the Strong Int called strong - Well because it is stronger than the others!

Strength of an interaction is a not well-defined concept - Even relative strength of an interaction w.r.t. another is not well defined.

For example consider classical EM and gravitational interaction between ee and ep

\[ V_{\text{em}}(r) = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r}, \quad V_{\text{g}}(r) = G \frac{m_e^2}{r}, \text{ or } V_{\text{g}}(r) = 6 \frac{\text{mep}}{r} \]

Since $m_e \sim \frac{1}{2000} m_p$ the relative strengths of EM and gravitational interaction are different by $\sqrt{3}$ orders of magnitude depending on whether you look at ee or ep.