3.2. PARTICLES AND RADIATION
What are the fundamental forces of nature?

Scientists are currently trying to find a theory (and a set of equations that incorporate everything!) that will bind together the four forces into one - the Grand Unified Theory.
There are four fundamental forces between particles:

1. Gravity, which obeys this inverse-square law:
   \[ F_{\text{gravity}} = G \frac{m_1 m_2}{d^2} \]

2. Electromagnetism, which obeys this inverse-square law:
   \[ F_{\text{static}} = k_e \frac{q_1 q_2}{d^2} \]
   And also Maxwell's equations

   Also what?

3. The strong nuclear force, which obeys, uh...
   \[ \ldots \text{well, umm...} \]
   \[ \ldots \text{it holds protons and neutrons together.} \]

   It's strong.

4. The weak force. It (mumble mumble) radioactive decay (mumble mumble)
   \[ \ldots \text{that's not a sentence.} \]
   \[ \text{You just said 'radio--} \]
   \[ \text{--and those are the four fundamental forces!} \]
It is believed that up to $10^{-43}$ s (what we call the Planck time) after the Big Bang the fundamental forces were one. As temperature decreased there was a spontaneous symmetry breaking and the forces split into the four forces we know today.
# The four fundamental forces

<table>
<thead>
<tr>
<th></th>
<th>Name</th>
<th>Domain</th>
<th>Particle</th>
<th>Relative strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Strong Nuclear Force</td>
<td>Within the nucleus - acts between nucleons over a very short range</td>
<td>Gluons (was thought to be pions)</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>Electromagnetic Force</td>
<td>Between charged particles - binds atoms and molecules together</td>
<td>Photons (quanta of electromagnetic radiation $E = hf$)</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>III</td>
<td>Weak Nuclear Force</td>
<td>Within the nucleus - governs radioactive beta decay - involves leptons</td>
<td>$W$ bosons and $z$-particles (not in the syllabus)</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>IV</td>
<td>Gravitational Force</td>
<td>Acts between all masses - very important for large masses in space such as planets and stars</td>
<td>Gravitons (not yet detected!)</td>
<td>$10^{-38}$</td>
</tr>
</tbody>
</table>
Range of fundamental forces

**Strong**
- Force which holds nucleus together
- Strength: $1$
- Range (m): $10^{-15}$ (diameter of a medium sized nucleus)
- Particle: gluons, $\pi$ (nucleons)

**Electromagnetic**
- Strength: $\frac{1}{137}$
- Range (m): Infinite
- Particle: photon, mass = 0, spin = 1

**Weak**
- Neutrino interaction induces beta decay
- Strength: $10^{-6}$
- Range (m): $10^{-18}$ (0.1% of the diameter of a proton)
- Particle: Intermediate vector bosons $W^+$, $W^-$, $Z_0$, mass $> 80$ GeV, spin = 1

**Gravity**
- Strength: $6 \times 10^{-39}$
- Range (m): Infinite
- Particle: graviton?, mass = 0, spin = 2
Physicists think that all forces are caused by the exchange of particles.

Imagine two friends playing with a ball on a frozen lake. Because of conservation of momentum, when they throw the ball at each other they will be pushed apart.

In the same way the two friends exchange the ball, two electrons (aka friends) can also interact exchanging a photon (aka ball).
### Forces and Their Affects

<table>
<thead>
<tr>
<th>Force</th>
<th>Affects</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>Charged particles.</td>
<td>“virtual” photon</td>
</tr>
<tr>
<td>Gravity</td>
<td>Everything with mass.</td>
<td>Graviton</td>
</tr>
<tr>
<td>Strong</td>
<td>Quarks</td>
<td>Gluon</td>
</tr>
<tr>
<td>Weak</td>
<td>Quarks and leptons</td>
<td>$W^+, W^-, Z^0$</td>
</tr>
</tbody>
</table>
Exchange particles and fundamental forces

There is an exchange particle for every type of force.

Exchange particles can transfer not just force, but also energy, momentum and charge between interacting particles.
Exchange particles and fundamental forces

Electromagnetic force:

Includes magnetic and electric interactions. It accounts for mechanical, electrical and chemical properties of matter.
It has an infinite range.
The exchange particle is the "virtual photon" (virtual means here that it participates in the interaction but we cannot observe it).
Strong nuclear force:

It is the strongest force of the four. The range is however very short ($\sim 10^{-15}$ m).
It is responsible to hold the nucleus of an atom together. The exchange particle is the **gluon**.
Weak force:

Its range is so short that it only plays a role on the scale of the nucleus or smaller. It is responsible for $\beta^-$ and $\beta^+$ decay and nuclear reactions in stars (like our Sun). The exchange particles are $Z^0$, $W^+$ and $W^-$. 
Gravitational force:

It is the weakest of the four forces but has an infinite range. It is responsible for keeping your feet down to the ground and plays a vital role in the motion of planets and satellites. The exchange particle is the graviton, which has not yet been detected (though the discovery of gravitational waves might lead to their discovery....).
What you need to know at A level

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Exchange particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>“Virtual” photon</td>
</tr>
<tr>
<td>Strong</td>
<td>Pion</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^+, W^-$</td>
</tr>
</tbody>
</table>

No need to know about the graviton, the gluon or the $Z^0$. 
Apart from the exchange particles there are others.

In the same way as there is a periodic table in Chemistry, particle physicists have their own Particles table.
How are particles detected?

How small are the smallest constituents of matter?

Atoms and sub-atomic particles are much smaller than visible light wavelength. Therefore, we cannot really “see” them (all graphics are artist’s impressions). To learn about the sub-atomic structure we need particle accelerators.
Quarks detected within protons

Stanford (SLAC), California, late 1960s

Fire electrons at proton: big deflections seen!
Deep inelastic scattering

Electron can hit one quark, and be scattered. Exchange of high energy photons leads to the creation of a jet of particles and antiparticles.

1. What is an elementary or fundamental particle? Provide at least two examples.
2. What are the main differences of particles and antiparticles (or matter and antimatter)?
3. Make a table listing quarks and antiquarks. Include their charge in the table. What is quark flavour?
4. What is the quark content of protons and neutrons? Do they account for the charge of proton and neutrons?
5. Extension: What is the quark content of antiprotons and antineutrons? What is the charge of antiprotons and antineutrons?
Elementary or fundamental particles

- They are sub-atomic particles.
- They are fundamental particles incapable of being subdivided into smaller particles.
- Quarks, electrons and neutrinos are examples of elementary particles.
A reminder: Matter vs. Anti-Matter

- For every particle, there is an anti-particle.
  - Anti-particles have the same mass as the particle.
  - Anti-particles have the same but opposite charge.
  - Anti-particles have the opposite spin.
  - Antimatter can be produced at particle accelerators.
The particle’s family tree

- Particle
  - Leptons
    - Electron
    - Muon
    - Neutrino
  - Hadrons
    - Mesons
    - Baryons
      - Pion
      - Kaon
      - Proton
      - Neutron

Examples
Quarks

- Elementary particles
- Used to create other particles
- Six type of **flavours** or quarks:
  - Up
  - Down
  - Strange
  - Charm
  - Bottom
  - Top
Protons and neutrons in the quark model

Quarks have fractional electric charge!
- u quarks electric charge + $\frac{2}{3}$
- d quarks electric charge $-\frac{1}{3}$

**Proton (charge +1)**

\[
\begin{align*}
    u \left( +\frac{2}{3} \right) u \left( +\frac{2}{3} \right) d \left( -\frac{1}{3} \right) &= p(1) \\
    u \left( +\frac{2}{3} \right) u \left( +\frac{2}{3} \right) d \left( -\frac{1}{3} \right) &= p(1)
\end{align*}
\]

**Neutron (charge 0)**

\[
\begin{align*}
    u \left( +\frac{2}{3} \right) d \left( -\frac{1}{3} \right) d \left( -\frac{1}{3} \right) &= n(0) \\
    u \left( +\frac{2}{3} \right) d \left( -\frac{1}{3} \right) d \left( -\frac{1}{3} \right) &= n(0)
\end{align*}
\]

WHAT ARE YOU TALKING ABOUT
So far we have met electrons, quarks, neutrinos... There are still a few more!

Using your A level book answer the following questions:

1. What are leptons?
2. Make a table with the names and charges.
3. What are hadrons?
4. What is the main difference between leptons and hadrons?
Leptons

- They are believed to be **fundamental particles**. Have no measurable size or structure.
- Leptons **do not feel the strong nuclear force**.
- Known leptons:
  - Electron & electron neutrino
  - Muon & muon neutrino
  - Tau & tau neutrino
- The **neutrinos do not have electric charge**.
- And each of the six has an anti-particle.
Meet the leptons

- The electron, muon and tau have a relative charge of -1.
- Neutrinos have no charge and no mass.
- Only the electron and the electron neutrino are stable. The rest of the leptons have short lifetimes and decay into these two.
Hadrons

- Consist of particles that interact through the strong force.
- Hadrons are made up of quarks
- Separated into two categories
  - Baryons & Mesons
- These are distinguished by their internal structure
Hadrons: Baryons

- Baryons are composed of **three quarks**. Antibarions are composed of three **antiquarks**.
- All but two baryons are very unstable, they are:
  - The proton and neutron!!
- Most baryons are excited states of protons and neutrons.
Protons & Neutrons

- Protons and neutrons are baryons. They are made of three quarks.

- Knowing the charge and that protons and neutrons are made of up and down quarks, try to find out their quark composition.
Protons & Neutrons

- Protons are baryons. They are made of three quarks, two up quarks and a down quark
  - This is written as $uud$

- Neutrons are also baryons, made up of three quarks, one up quark and two down quarks
  - This is written as $udd$
**Hadrons: Mesons**

- Composed of a **quark and anti-quark**
- All are very unstable
- They are not part of everyday matter
- Have a mass between that of the electron and the proton
- All decay into electrons, positrons, neutrinos and photons.
Hadrons: Mesons

• The mesons you need to know of at A level are kaons and pions. Remember that kaons decay into pions.

• Try to deduce the quark composition of the following kaons and pions (use your data booklet and their charges as hints):
  • $K^+$, $K^-$, $K^0$,
  • $\pi^+$, $\pi^-$, $\pi^0$
There are three generations of matter.

Mass increases from 1 generation to the next.

Going down in each generation, the charges are:

+2/3, -1/3, 0, -1

(These are all in multiples of the elementary charge)
We believe these to be the fundamental building blocks of matter
Quark masses

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>0.003</td>
</tr>
<tr>
<td>Down</td>
<td>0.006</td>
</tr>
<tr>
<td>Strange</td>
<td>0.095</td>
</tr>
<tr>
<td>Charm</td>
<td>1.2</td>
</tr>
<tr>
<td>Bottom</td>
<td>4.5</td>
</tr>
<tr>
<td>Top</td>
<td>175</td>
</tr>
</tbody>
</table>

The mass grows larger in each successive family

$E = mc^2$

1 proton mass $\sim 1$GeV ($10^{-27}$ Kg)

Top (discovered 1995)
The particles of ordinary matter

Leptons:  
ν = neutrino  
e = electron

Quarks:  
u = up  
d = down

All stable matter around us can be described using electrons, electron neutrinos, u and d “quarks”. That is, all ordinary matter is made up of first generation particles.
"Young man, if I could remember the names of these particles, I would have been a botanist!"

E. Fermi to his student
L. Lederman (both Nobel laureates)

Most particles are not stable and can decay to lighter particles.
Luckily you only need to remember those on p. 393 in your book.
Physicists believe that quarks cannot be isolated. When you try to kick a quark out of a proton, the strong field that was holding it in gets stretched, rather like an elastic band.

Eventually the elastic band breaks, and at the break a new quark (actually a quark-antiquark pair) is created out of the energy in the field.

The idea that quarks can never be isolated is called confinement.
Do questions 2 and 4, p. 393, A level book

Build a particle family tree

Do online assessment at: mtrphysics.weebly.com (Yr12 Assessments – Particle quiz)