At its heart, physics tries to understand the world at its most fundamental level. Why is the universe the way it is? What are the most fundamental aspects of reality? What are the most fundamental laws that govern the universe?

The best framework we currently have to describe the universe at its most fundamental is the Standard Model of Particle Physics. It is an interrelated set of theories that seek to determine and describe nature’s fundamental building blocks and the forces that allow them to interact with each other.
What is fundamental?

[Image of Earth, Fire, Air, Water elements with designs by Nina Canacci]

Ancient atomism

The ancient Greeks, among others, toyed with the idea that matter consists of tiny, indivisible particles, or “atoms”.

The ancient ideas about atoms have very little in common with what we know about today’s atoms. In particular, we know that atoms are not indivisible, although they are the smallest piece of an element that retains the chemical properties of the element.
Elementary particles

Early discoveries

1897 – J.J. Thomson discovers the electron
1914 – the hydrogen atom is proposed to consist of a single proton orbited by a single electron
1932 – James Chadwick discovers the neutron.

If you asked a physicist in 1932 what matter is made of, he/she would answer that ultimately, matter is made up of just electrons, protons, and neutrons.
Since the 1930’s literally hundreds of particles have been discovered.

OK, so let’s define what we mean by a “elementary particle”.

To a particle physicist, the term elementary particle means a particle that does not consist of other particles; it has no internal structure, and is not built up from smaller constituent particles.

All of the known particles can be placed in a framework of particles that themselves, as far as we know, are truly fundamental. Before we discuss this framework, we first introduce antiparticles.
Antiparticles

Every particle has an antiparticle that is in all respects the same as its corresponding particle, except that it has the opposite electric charge.

What about neutral particles, such as neutrons?
   (a) As we will see, neutrons are composed of smaller particles that themselves are charged.
   (b) There are some quantum numbers to which we have not been introduced yet that also change in going from the particle to the antiparticle.
   (c) Some bosons are there own antiparticle (e.g. photons).

The existence of antiparticles cannot be explained by non-relativistic quantum mechanics (i.e. the Schrödinger equation); however they pop out quite naturally from relativistic versions of quantum mechanics.
Antiparticles

These equations are all for free particles (potential energy = 0)

Schrödinger equation

\[-\frac{\hbar^2}{2m} \nabla^2 \Psi = i\hbar \frac{\partial \Psi}{\partial t}\]

Klein-Gordon equation (spin 0 particles)

\[-\frac{1}{c^2} \frac{\partial^2 \Psi}{\partial t^2} + \nabla^2 \Psi = \left( \frac{mc}{\hbar} \right)^2 \Psi\]

\[-\hbar^2 \partial^\mu \partial_\mu \Psi - m^2 c^2 \Psi = 0\]

Dirac equation (spin 1/2 particles)

\[i\hbar \gamma^\mu \partial_\mu \Psi - mc \Psi = 0\]

To fully appreciate the marriage of quantum mechanics and special relativity, and to interpret the implications of the Dirac equation without resorting to negative energy electrons, requires the use of quantum electrodynamics (QED).
Motivations for the wave equations of quantum mechanics

The “quantum prescription”

\[ \tilde{p} \rightarrow -i\hbar \nabla; \quad E \rightarrow i\hbar \frac{\partial}{\partial t} \]

Classical and relativistic energy-momentum relations (for free particles)

\[ \frac{\tilde{p}^2}{2m} + U = E \quad \tilde{p}^2 c^2 + m^2 c^4 = E^2 \]

Schrödinger equation

\[ -\frac{\hbar^2}{2m} \nabla^2 \Psi = i\hbar \frac{\partial \Psi}{\partial t} \]

Klein-Gordon equation

\[ -\frac{1}{c^2} \frac{\partial^2 \Psi}{\partial t^2} + \nabla^2 \Psi = \left( \frac{mc}{\hbar} \right)^2 \Psi \]
Negative energy solutions

\[ \vec{p}^2 c^2 + m^2 c^4 = E^2 \]

\[ \therefore E = \pm \sqrt{\vec{p}^2 c^2 + m^2 c^4} \]

E can be positive, zero, or negative. This is true in for both the Klein-Gordon and Dirac versions of relativistic quantum mechanics.

According to Dirac, the universe is filled with a sea of negative-energy electrons that cannot be observed. However, a hole in this negative-energy sea would act as a positive-energy, positive charge particle that could be observed—the positron.

QED reinterprets the negative-energy solutions of the Dirac equation as particles that have positive mass but opposite electric charge (and some other quantum numbers) – these are the antiparticles.
Where do all the particles come from?

High energy scattering studies show that protons and neutrons consist of three smaller particles, called quarks.

There are six flavors of quark:

up (u)
down (d)
strange (s)
charm (c)
bottom (b)
top (t)

Ordinary matter consists of up and down quarks (and their antiparticles)
The fundamental interactions (forces)

As far as we know, there are only 4 (actually, really only three) forces found in nature. In order of decreasing strength they are:

- strong interaction
- electromagnetic interaction
- weak interaction
- gravitational interaction

Each of these interactions is mediated by exchange of particles, the so-called exchange or field quanta:

- The strong interaction is mediated by **gluons**. (The strong force holds quarks together.)
- The electromagnetic interaction is mediated by **photons**.
- The weak interaction is mediated by $W^+$, $W^-$, and $Z^0$ particles.
- The gravitational interaction is mediated by **gravitons**.
We can now list the elementary particles, as they are known today. There are three families of elementary particles:

1. **Leptons** 6 particles and 6 antiparticles. All have spin 1/2.

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Symbol</th>
<th>Charge ($e$)</th>
<th>Weak Isospin $T_z$</th>
<th>Mass (MeV/c$^2$)</th>
<th>Lifetime (s)</th>
<th>Spin ($\hbar$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e$</td>
<td>$-1$</td>
<td>$-1/2$</td>
<td>0.5110</td>
<td>stable</td>
<td>1/2</td>
</tr>
<tr>
<td>Electron neutrino</td>
<td>$\nu_e$</td>
<td>$0$</td>
<td>$1/2$</td>
<td>$\leq2.2$ eV/c$^2$</td>
<td>stable</td>
<td>1/2</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu$</td>
<td>$-1$</td>
<td>$-1/2$</td>
<td>105.659</td>
<td>$2.197 \times 10^{-6}$</td>
<td>1/2</td>
</tr>
<tr>
<td>Muon neutrino</td>
<td>$\nu_\mu$</td>
<td>$0$</td>
<td>$1/2$</td>
<td>$\leq3.5$ eV/c$^2$</td>
<td>stable</td>
<td>1/2</td>
</tr>
<tr>
<td>Tau</td>
<td>$\tau$</td>
<td>$-1$</td>
<td>$-1/2$</td>
<td>1,784</td>
<td>$3.3 \times 10^{-13}$</td>
<td>1/2</td>
</tr>
<tr>
<td>Tau neutrino</td>
<td>$\nu_\tau$</td>
<td>$0$</td>
<td>$1/2$</td>
<td>$\leq8.4$ eV/c$^2$</td>
<td>stable</td>
<td>1/2</td>
</tr>
</tbody>
</table>
The elementary particles

We can now list the elementary particles, as they are known today. There are three families of elementary particles:

2. Quarks 6 particles and 6 antiparticles. All have spin 1/2. Bound-state combinations of quarks form the hadrons.

<table>
<thead>
<tr>
<th>Quark (q)</th>
<th>Symbol</th>
<th>Charge (e)</th>
<th>Weak isospin $T_z$</th>
<th>Mass (MeV/c²)</th>
<th>Spin ($\hbar$)</th>
<th>Baryon number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st generation</td>
<td>up</td>
<td>2/3</td>
<td>1/2</td>
<td>336</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>down</td>
<td>−1/3</td>
<td>−1/2</td>
<td>338</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td>2nd generation</td>
<td>charm</td>
<td>2/3</td>
<td>1/2</td>
<td>1,500</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>strange</td>
<td>−1/3</td>
<td>−1/2</td>
<td>540</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td>3rd generation</td>
<td>top</td>
<td>2/3</td>
<td>1/2</td>
<td>170,900</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td>bottom</td>
<td>−1/3</td>
<td>−1/2</td>
<td>5,000</td>
<td>1/2</td>
<td>1/3</td>
</tr>
</tbody>
</table>
We can now list the elementary particles, as they are known today. There are three families of elementary particles:

2. Quarks

6 particles and 6 antiparticles*. All have spin 1/2. Bound-state combinations of quarks form the hadrons.

\[
\text{quarks} \rightarrow \text{hadrons} \quad \begin{cases}
\text{Mesons are 2-quark combinations. They are bosons.}
\text{Baryons are 3-quark combinations. They are fermions.}
\end{cases}
\]

*If you count the different color charges, there are actually 36 types of quark!
We can now list the elementary particles, as they are known today. There are three families of elementary particles:

3. Field quanta  gluons, photons, $W^\pm$, $Z^0$, gravitons

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Exchange boson</th>
<th>Mass (GeV/c^2)</th>
<th>Spin (h)</th>
<th>Source</th>
<th>Range (m)</th>
<th>Interaction time (s)</th>
<th>Coupling constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Gluon</td>
<td>0</td>
<td>1</td>
<td>Color charge</td>
<td>$10^{-15}$</td>
<td>$10^{-23}$</td>
<td>$\alpha_s \approx 1$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Photon</td>
<td>0</td>
<td>1</td>
<td>Electric charge</td>
<td>$\infty$</td>
<td>$10^{-18}$</td>
<td>$\alpha = 1/137$</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm, Z^0$</td>
<td>81, 91</td>
<td>1, 1</td>
<td>Weak charge</td>
<td>$10^{-18}$</td>
<td>$10^{-16} - 10^{-10}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>Graviton</td>
<td>0</td>
<td>2</td>
<td>Mass</td>
<td>$\infty$</td>
<td>—</td>
<td>$10^{-38}$</td>
</tr>
</tbody>
</table>
The elementary particles summary

1. Leptons 6 particles and 6 antiparticles. All have spin 1/2.

2. Quarks 36 in total. All have spin 1/2. Bound-state combinations of quarks form the hadrons.

3. Field quanta gluons, photons, $W^\pm$, $Z^0$, gravitons

A detailed accounting of all the particles, antiparticles, and field quanta gives a grand total of 61 elementary particles (62, if you count the graviton).
The strong force revisited

From lecture 11-V:

“The strong force is mediated by exchange of $\pi$-mesons (or just pions), which have an experimentally observed mass of 140 MeV/c$^2$.”

The force between nucleons, which we have until now been calling the strong nuclear force, is better termed the residual nuclear force. The actual strong force is the force that binds quarks together, and is mediated by gluons. The situation is a little like the difference between the direct Coulomb force between two charges and the much weaker electrostatic fields that are responsible for the Van der Waals forces.
We’ve never seen an isolated quark – why not?

Quark confinement.