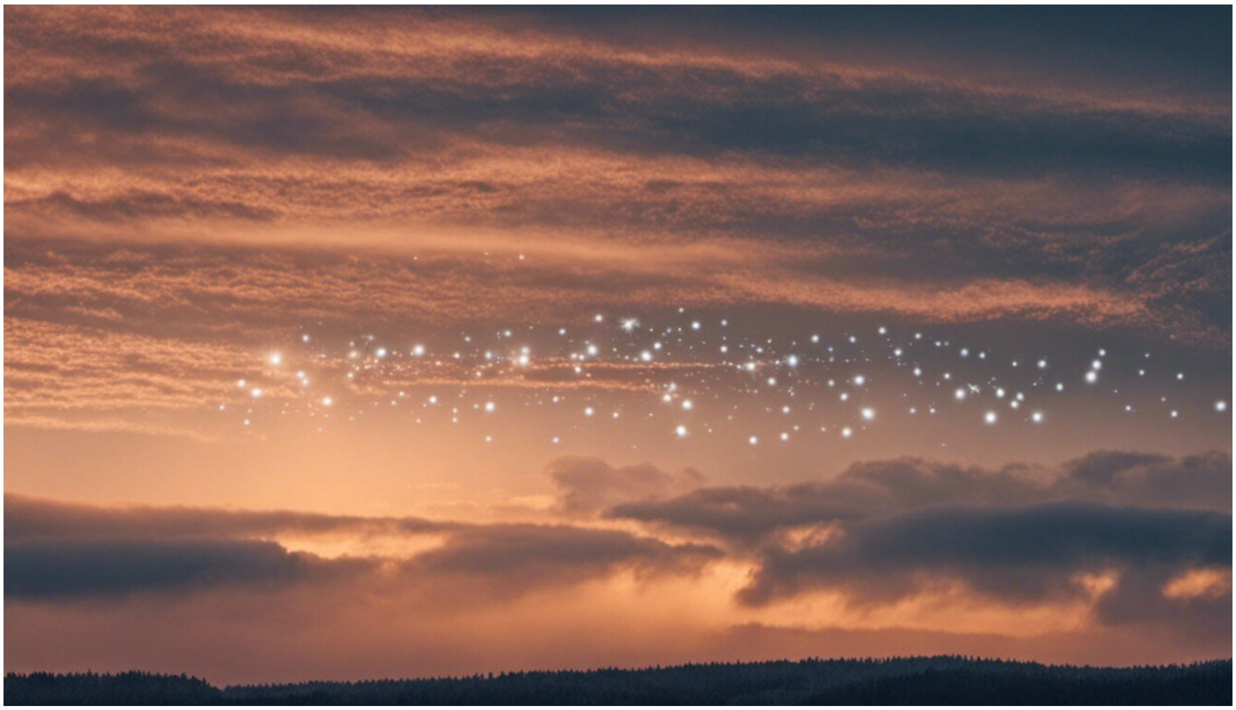
Explainer: What are fundamental particles?

March 20 2015, by Paul Kyberd



Credit: AI-generated image (disclaimer)

It is often claimed that the Ancient Greeks were the first to identify objects that have no size, yet are able to build up the world around us through their interactions. And as we are able to observe the world in tinier and tinier detail through microscopes of increasing power, it is natural to wonder what these objects are made of.

We believe we have found some of these objects: subatomic particles, or fundamental particles, which having no size can have no substructure. We are now seeking to explain the properties of these particles and working to show how these can be used to explain the contents of the universe.

There are two types of fundamental particles: matter particles, some of which combine to produce the world about us, and force particles – one of which, the photon, is responsible for electromagnetic radiation. These are classified in the standard model of particle physics, which theorises how the basic building blocks of matter interact, governed by fundamental forces. Matter particles are fermions while force particles are bosons.

Matter particles: quarks and leptons

Matter particles are split into two groups: quarks and leptons – there are six of these, each with a corresponding partner.

Leptons are divided into three pairs. Each pair has an elementary particle with a charge and one with no charge – one that is much lighter and extremely difficult to detect. The lightest of these pairs is the electron and electron-neutrino.

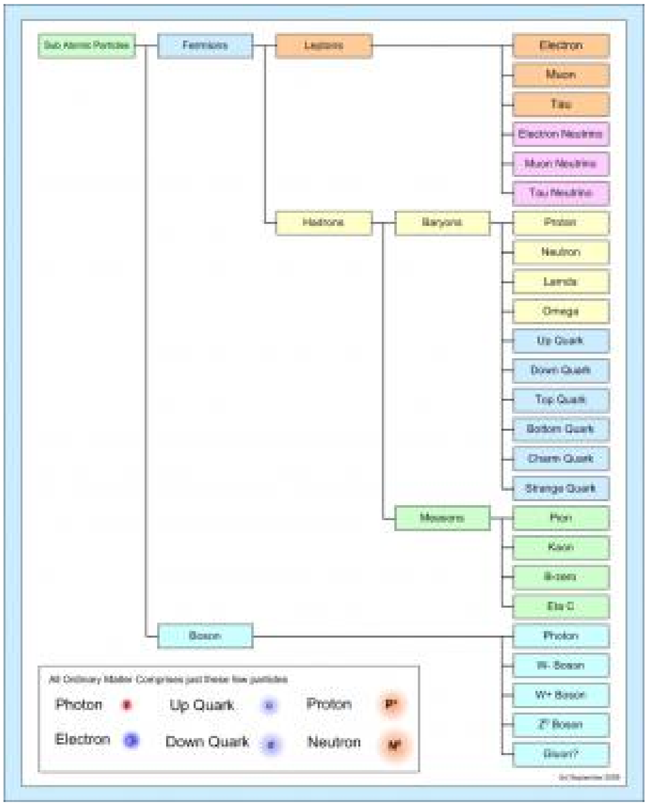
The charged electron is responsible for electric currents. Its uncharged partner, known as the electron-neutrino, is produced copiously in the sun and these interact so weakly with their surroundings that they pass unhindered through the Earth. A million of them pass through every square centimetre of your body every second, day and night.

Electron-neutrinos are produced in unimaginable numbers during supernova explosions and it is these particles that disperse elements produced by nuclear burning into the universe. These elements include the carbon from which we are made, the oxygen we breathe, and almost everything else on earth. Therefore, in spite of the reluctance of neutrinos to interact with other fundamental particles, they are vital for our existence. The other two neutrino pairs (called muon and muon neutrino, tau and tau neutrino) appear to be just heavier versions of the electron.

Since normal matter does not contain these particles it may seem that they are an unnecessary complication. However during the first one to ten seconds of the universe following the Big Bang, they had a crucial role to play in establishing the structure of the universe in which we live – known as the Lepton Epoch.

The six quarks are also split into three pairs with whimsical names: "up" with "down", "charm" with "strange", and "top" with "bottom" (previously called "truth" and "beauty" though regrettably changed). The up and down quarks stick together to form the protons and neutrons which lie at the heart of every atom. Again only the lightest pair of quarks are found in normal matter, the charm/strange and top/bottom pairs seem to play no role in the universe as it now exists, but, like the heavier leptons, played a role in the early moments of the universe and helped to create one that is amenable to our existence.

Force particles



And then some. Credit: James Childs, CC BY

There are six force particles in the standard model, which create the interactions between matter particles. They are divided into four fundamental forces: gravitational, electromagnetic, strong and weak forces.

A photon is a particle of light and is responsible for electric and magnetic fields, created by the exchange of photons from one charged object to another.

The gluon produces the force responsible for holding quarks together to form protons and neutrons, and for holding those protons and neutrons together to form heavier nuclei.

Three particles named the "W plus", the "W minus" and the "Z zero" – referred to as intermediate vector bosons – are responsible for the process of radioactive decay and for the processes in the sun which cause it to shine. A sixth force particle, the graviton, is believed to be responsible for gravitation, but has not yet been observed.

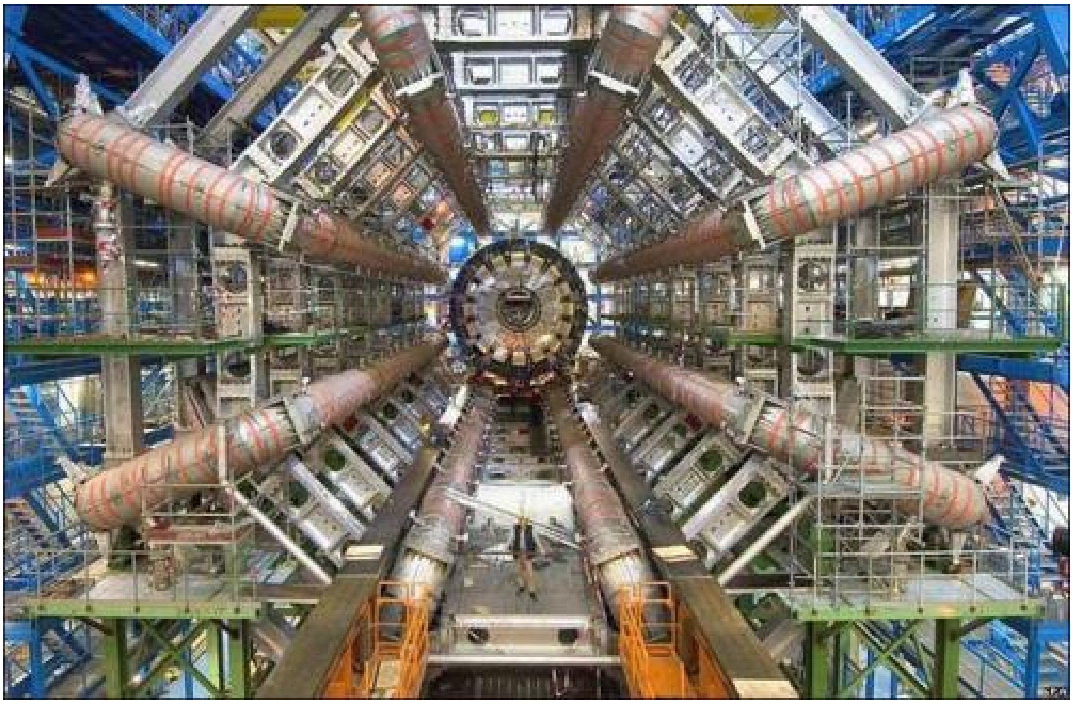
Anti-matter: the science fiction reality

We also know of the existence of anti-matter. This is a concept much beloved by science fiction writers, but it really does exist. Anti-matter particles have been frequently observed. For example, the positron (the anti-particle of the electron) is used in medicine to map our internal organs using positron emission tomography (PET). Famously when a particle meets its anti-particle they both annihilate each other and a burst of energy is produced. A PET scanner is used to detect this.

Each of the matter particles above has a partner particle which has the same mass, but opposite electric charge, so we can double the number of matter particles (six quarks and six leptons) to arrive at a final number of 24.

We give matter quarks a number of +1 and anti-matter quarks a value of -1. If we add up the number of matter quarks plus the number of anti-matter quarks then we get the net number of quarks in the universe, this never varies. If we have enough energy we can create any of the matter quarks as long as we create an anti-matter quark at the same time. In the early moments of the universe these particles were being created continuously – now they are only created in the collisions of cosmic rays with the atmosphere of planets and stars.

The famous Higgs boson



The great collider.

There is a final particle which completes the roll call of particles in what is referred as the standard model of particle physics so far described. It is the Higgs, predicted by Peter Higgs 50 years ago, and whose discovery at CERN in 2012 led to a Nobel Prize for Higgs and Francois Englert.

The Higgs boson is an odd particle: it is the second heaviest of the standard model particles and it resists a simple explanation. It is often said to be the origin of mass, which is true, but misleading. It gives mass to the quarks, and quarks make up the protons and neutrons, but only 2% of the mass of protons and neutrons is provided by the quarks, and the rest is from the energy in the gluons.

At this point we have accounted for all the particles required by the standard model: six force particles, 24 matter particles and one Higgs particle – a total of 31 fundamental particles. Despite what we know about them, their properties have not been measured well enough to allow us to say definitively that these particles are all that is needed to build the universe we see around us, and we certainly don't have all the answers. The next run of the Large Hadron Collider will allow us to refine our measurements of some of these properties – but there is something else.

Yet the theory is still wrong

The beautiful theory, the standard model, has been tested and re-tested over two decades and more; and we have not yet made a measurement that is in contradiction with our predictions. But we know that the standard model must be wrong. When we collide two fundamental particles together a number of outcomes are possible. Our theory allows us to calculate the probability that any particular outcome can occur, but at energies beyond which we have so far achieved it predicts that some of these outcomes occur with a probability of greater than 100% – clearly nonsense.

Theoretical physicists have spent much effort in trying to construct a theory which gives sensible answers at all energies, while giving the same answer as the standard model in every circumstance in which the standard model has been tested.

The most common modification implies that there are very heavy undiscovered particles. The fact they are heavy means lots of energy will be needed to produce them. The properties of these extra particles can be chosen to make sure that the resulting theory gives sensible answers at all energies, but they have no effect on the measurements that agree so well with the standard model.

The number of these undiscovered and as-yet-unseen particles depends on which theory you choose to believe. The most popular class of these theories are called supersymmetric theories and they imply that all the particles which we have seen have a much heavier counterpart. However, if they are too heavy, problems will arise at energies we can produce before these particles are found. But the energies that will be reached in the next run of the LHC are high enough that an absence of new particles will be a blow to all supersymmetric theories.

Source: The Conversation

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