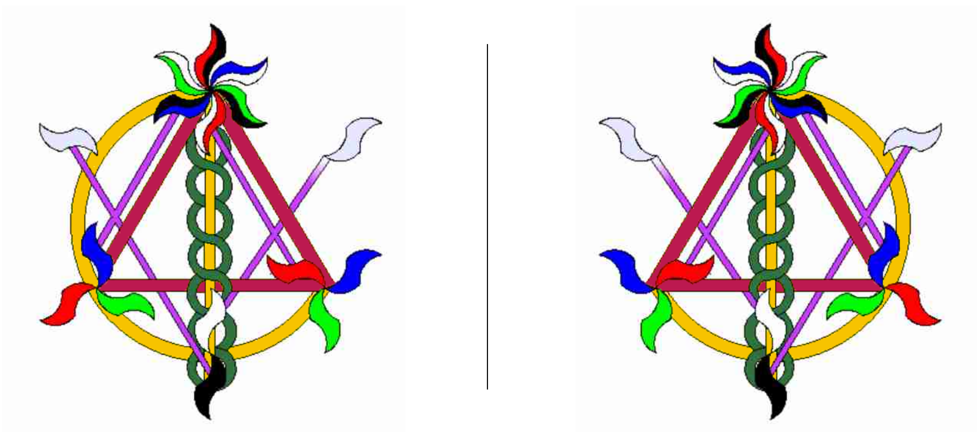
The Matter Mandala — it's as easy as one-two-three

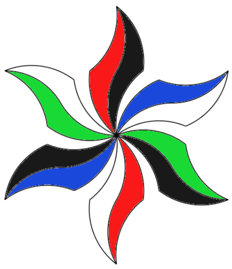
The Matter Mandala© is a pictorial representation of the fundamental particles of the standard model of particle physics and the intricate way in which they are woven together by the forces between them. The coloured lines represent different fundamental forces and the flowers and petals the different kinds of matter.

Before going on the describe the different parts of the Mandala, first look at the overall shape — it is asymmetric. The Mandala looks different when it is reflected in a mirror

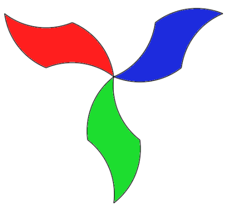


This is a fundamental property of matter. It goes by the name of chirality, from the Greek word for "hand" or "handedness", our world is not chirally symmetric. This lack of symmetry is not obvious in the everyday world around around us, though many chemical molecules (such as levo and dextro sugars and your left-handed DNA) have different chiralities this is not generally believed to be due to the chiral nature of the underlying fundamental matter. It has been suggested that they might be connected but this is hard to justify because at low energies (and for a particle physicist chemical binding energies are very low) the world looks symmetric. Electromagnetism for example is chirally symmetric, it is a nuclear force, called the weak force, that is not, and at low energies the weak force is too weak to account for the chiral asymmetries in chemistry. However the weak force increases with energy and at high energies the chiral asymmetry of the Natural world become more obvious.

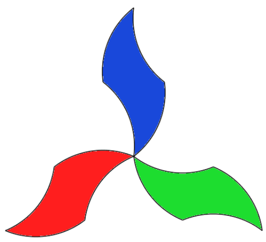
First let us list the elements in the Matter Mandala and then go on to explain what they mean:



Left handed up-down quark doublet.

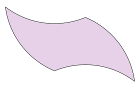


Right handed down quark.

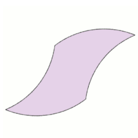


Right handed up quark.

Left handed electron-neutrino lepton doublet.



Right handed electron.



Right handed neutrino.

Electromagnetism (photon)

Colour force (gluons)

Weak force (W's and Z).

Higgs' boson

So what are these?

Apart from gravity, which makes everything accelerate the same way, there are three known fundamental forces: electromagnetism (electricity and magnetism unified into a single force, quantum electrodynamics at the quantum level, or QED for short) and two different nuclear forces, rather prosaically called the "strong" nuclear force and the "weak" nuclear force. Associated with each of these forces is a force field. The strong force is a manifestation of an underlying force called the colour force (more technically quantum chromodynamics, or QCD for short). The strong force binds neutrons and protons together inside atomic nuclei, while chromodynamics binds quarks together to form protons and neutrons.*

*This a bit like the way the electric force binds electrons and atomic nuclei together

We think of these forces as arising from fields. Force fields such as electric and magnetic and fields can oscillate giving rise to waves, like electromagnetic waves in electromagnetism. But in the theory of quantum mechanics the energy of waves is quantised and is thought of as being carried by particles, the photon for electromagnetism. Is light made up of waves or particles? In quantum mechanics it is both, a wave is a collection of particles. In quantum mechanics each of the three fundamental forces is mediated by an exchange of particles: photons for electromagnetism, gluons for the colour force (eight different kinds of them, called gluons because they constitute the "glue" that binds quarks into protons and neutrons) and three particles, rather unimaginatively called W^+, W^- and Z particles for the weak force. Photons, particles of light, are themselves electrically neutral but are associated with electromagnetic waves — they move at the speed of light and have no mass. Gluons are associated with waves the colour field, they are also electrically neutral and are also believed to be massless, moving at the speed light, though no one has ever seen a gluon directly (they are confined within protons and neutrons because the colour force is so strong). The weak force is different in two ways: firstly W and Z particles are massive and secondly W particles carry electric charge, there is a W^+ and a W^-, though the Z is electrically neutral and is often denoted Z^0 to remind us of this. One more particle is the Higgs' boson, h^0. The Higgs' boson is massive and electrically neutral, but it is not so clear as to whether or not it should be classified as a particle of matter or a particle of force, it is really in a class of its own, but it is viewed as a force particle in the Matter Mandala.

The coloured lines in the Matter Mandala represent these three fundamental force fields, together with the Higgs' field: gold is electromagnetism (the photon); maroon is the colour force (gluons); green is the weak force (W's and Z) while the Higgs' field, with its associated Higgs' boson, is purple. The flowers and petals in the Matter Mandala represent the different kinds of matter particles in the standard model of particle physics. The great theoretical physicist Richard Feynman has said that, if all of scientific knowledge were lost and we could only pass one piece of information on to future generations, it should be that all matter is made up of particles. Matter particles are not the same as force particles, in fact they could hardly have more different personalities. Force particles are gregarious, they congregate together and like to form waves — a laser beam is a quantum mechanical wave of light in which every photon is in the same quantum state. Matter particles are anti-social, two identical particles of matter cannot be in the same place at the same time — they exclude each other. This is a very im-

to form electrically neutral atoms and molecules, but there are residual electromagnetic forces, called van der Waals forces, between neutral atoms and molecules that cause liquids and solids to form. Chromodynamics binds quarks into protons and neutrons, but there is a residual force, the strong nuclear force, that binds protons and neutrons into atomic nuclei.

portant property, without it the periodic table of elements would not exist and all atoms would be unstable.

The fundamental particles that make up all of the matter that we see around us fall into two basic types: quarks and leptons. The name "quark", which many people pronounce "kwork", comes from James Joyce's famously unreadable masterpiece "Finnegans Wake". Murray Gell-Mann, the physicist who coined the name quark, was reputedly reading Finnegans Wake when he was developing these ideas and he took the name from a line in Joyce's the book: *"Three quarks for Muster Mark!"*. This supposedly rhymes with the noise a seagull makes, in which case it should clearly be pronounced "kwaark". The word "lepton" comes from the Greek work for light, as in not heavy. There are two different kinds of quarks, called up u and down d quarks, a proton is uud and a neutron is udd. A down quark is about twice as heavy as an up quark which in turn is some five times heaver than an electron.

The masses are not the main issue though, a more important distinction is that quarks feel the colour force while leptons, such as electrons, do not. Another important difference between chromodynamics and electrodynamics is that there is only one kind of electric charge, which can be either positive or negative, but there are three types of colour charge (hence the moniker **chromo**-dynamics). The three types of colour charge are called red, blue and green and they add up to a bland white, which is neutral. Mixing red, blue and green gives white but mixing blue and green gives cyan, so mixing red and cyan is also white — cyan is the opposite of red. The opposite colours to red, green and blue are cyan, magenta and yellow, mixing cyan, magenta and yellow gives black — the opposite of white. Painters and artists think of red, yellow and blue as primary colours. Physicists use red, green and blue as primary with cyan, magenta and yellow as their opposites. Printers use cyan, magenta and yellow with red, green and blue as their opposites. Red, yellow and blue cancel each other out and mix to black, as do cyan, magenta and yellow. Physicists like red, green and blue because they mix to white, as famously demonstrated by Isaac Newton. Printers use cyan, magenta and yellow because they mix to give black ink — white ink would probably be of little use!

Protons and neutrons are both made up of three quarks each of which have a different colour, making protons and neutrons white, for example uud and udd respectively, they are colour neutral. Gluons carry one colour and one anti-colour, there is a green-cyan gluon for example. Since there are three colours and three anti-colours there are nine possible gluons, but one of the nine combinations, red-cyan + green-magenta + blue-yellow, is redundant — it is completely colour neutral and has no role — there are only eight gluons.

The weak force is completely different to the strong force and it makes some nuclei unstable. It is responsible for beta-decay and is the source of energy in the Sun and in all radioactive minerals, and hence is ultimately the energy source for all life on Earth. Just as electrons have an electric charge they also have a "weak force" charge, but they do not have a "chromo", or colour, charge. Quarks on the other hand carry all types of charge: electric, weak and colour charge. The weak charge is not the same as either the electric charge or the colour charge, there are two types of weak charge which are shown as black and white in the diagram (not a bland neutral white, as in the mixing of red, green and blue, but a completely different vibrant kind of white). In a technical sense black and white weak charges can be viewed as opposites but not like positive and negative electric charges. We should think of black and white weak charged particles as being different because a black lepton is a very different beast to a white lepton, they are different particles with different electric charges. An electron is a black lepton but a white lepton has no electric charge and a tiny mass compared to that of an electron, it is called a neutrino — a little neutral one.

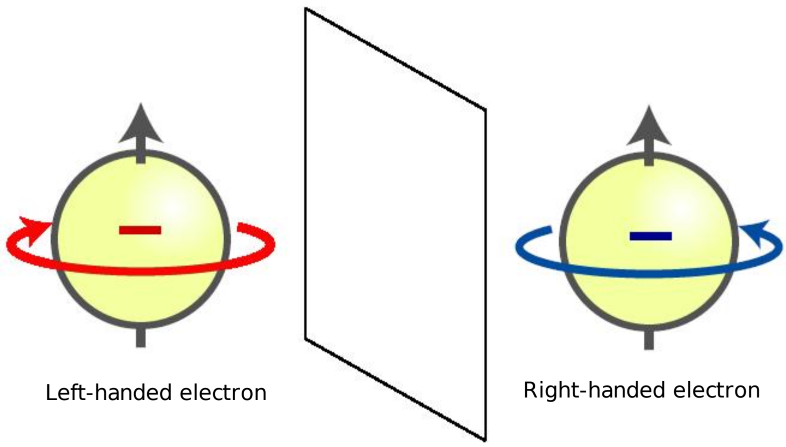
So there are three different colour charges (quarks are triplets, but not identical), two different weak charges (doublets, but not twins) and one type of electric charge, together with their opposites, their anti-charges. This may seem complicated, but what could be easier than "one-two-three".

To fully explain the Matter Mandala though, we need to introduce anti-matter and explain how it relates to chirality.

An inevitable consequence of marrying Einstein's theory of relativity with quantum mechanics is that every particle has an associated anti-particle with exactly same mass as the particle but the opposite charge. For example the electron, with a negative electric charge, has a positively charged anti-particle, called a positron. The anti-particle of a green-cyan gluon is a magenta-red gluon but the photon is its own anti-particle. The W^+ is the anti-particle of the W^- and the Z^0, like the photon, is its own anti-particle. If a matter particle and an anti-matter particle get too close to each other they annihilate in a burst of radiation: electrons and positrons annihilate into photons, a quark and an anti-quark could annihilate into gluons, or perhaps photons if their colours are opposite. A black lepton is not the anti-particle of a white lepton, they are really different particles and do not annihilate into energy when they meet. The Matter Mandala only shows the matter particles, not their corresponding anti-particles (the force particles include their own anti-particles).

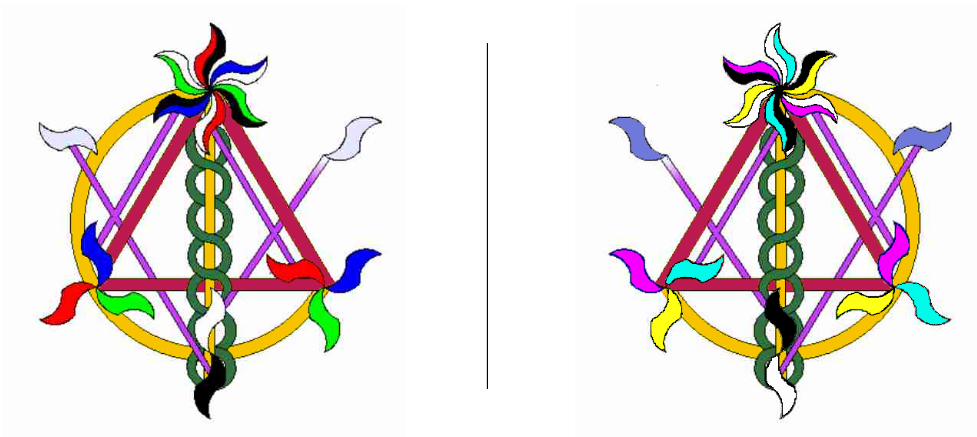
Electromagnetism and the weak nuclear force are inextricably intertwined by the Higgs' boson. As already mentioned, in the theory of quantum mechanics all particles have fields associated with them, the photon is associated with the electromagnetic field for example, and the Higgs' boson is no exception, its field is called the Higgs' field. The vacuum is full of Higgs' field, you cannot see it, feel it, touch it, taste it or smell it, but it is everywhere, it is a real uniform physical background field present throughout all space. In quantum mechanics this not at odds with the statement that there are particles associated with fields, particles are quanta of energy associated with excitations of the field, that is waves, but we can also have a uniform Higgs field that is constant everywhere and has no excitations, like the flat surface of a very still pond — that is a vacuum.

There is a further twist to the story though. Quarks and leptons have an inbuilt handedness, left-handed and right-handed, this is the source of the chirality described at the earlier. Fundamental particles are like little gyroscopes, spinning on an axis, and if we look at them in a mirror they spin the opposite way:



The mirror image of an electron or quark is not the same as the original electron or quark: left-handed quarks and leptons have weak charge, they are either black or white and form weak doublets, right-handed quarks leptons have no weak charge at all. A left-handed, white quark is called an "up" quark while a left-handed black quark is called a "down" quark. There are also right-handed up and down quarks with no weak charge. A left-handed electron is a black lepton, the corresponding left-handed white lepton is called a "neutrino" because it is electrically neutral and has a tiny mass. Neutrinos are extremely hard to detect precisely because they have no electric charge, there are about 100,000,000,000 neutrinos passing through your eyes every second, coming from weak interactions in the core of the Sun, but you cannot see them. Low energy neutrinos can pass though the entire Earth without being affected, though they do become easier to detect as their energy increases. Neutrinos are produced in vast quantities in supernova explosions of distant stars. There is also a right-handed electron with the same electric charge as a left-handed electron but no weak charge.

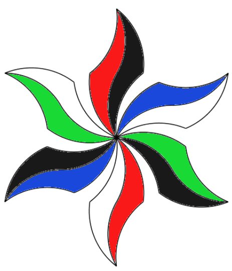
The anti-particle has the opposite handedness to the particle: the anti-particle of a black left-handed electron is a white right-handed positron, the anti-particle of a white left-handed neutrino is a black left-handed anti-neutrino, the anti-particle of right-handed blue quark is a left-handed magenta anti-quark, and so on. When reflecting the Matter Mandala in a mirror we should also interchange particles and anti-particles, like this



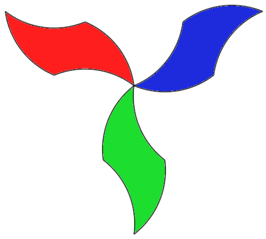
The left-hand image represents the particles of our world, the right-hand image would be an anti-world.

As far as the colour and electromagnetic forces are concerned left and right-handed particles are identical, it is only the weak force that treats them differently. In the standard model of particle physics there is no right-handed neutrino, the model is perfectly consistent without one, and the left-handed neutrino is strictly massless (for technical reasons for a matter particle to have mass it must have both left and right-handed forms). But a right-handed neutrino would be almost impossible to detect, it has no colour charge, no electric charge and no weak charge.

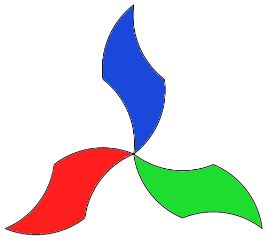
So now we are in a position to understand (most of) the Matter Mandala. The yellow, orange and green lines represent the three forces: yellow for electromagnetism (photons); orange for the colour force (gluons) and green for the weak force (W's and Z).
As for the matter:



represents the left-handed quark doublet, up and down (white and black) left-handed quarks each with one of the three colours. Six particles in all and these all feel all three forces, orange for the colour force and gluons, green for the weak force and W's and Z, yellow the electromagnetic force and photons.

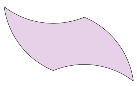


represents the right handed down quarks. These have no weak charge, so there are only the three colours to account for. The green W and Z bosons do not touch them, as they have no weak charge, but the orange (gluons) and yellow (photon) lines do.

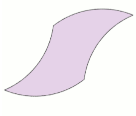


represents the right handed up quarks. Again these have no weak charge, so there are only the three colours to account for. The green W and Z bosons do not touch them but the orange (gluons) and yellow (photon) lines do.

The left handed electron-neutrino lepton doublet. These have weak charge, but no colour. The orange line passes behind them but does not touch them. The green lines touch them and the yellow line touches them.



The right handed electron. Only the yellow line touches this, it has electric charge but no colour or weak charge.



The right handed neutrino. No force touches it, it can only be detected via the Higgs field (or, in principle, by its gravitational pull — but this is probably negligible.

Not much is known about the right handed neutrino, they have no colour, weak or electric charge and are sometime called sterile neutrinos. They have never been seen directly in any experiment — they just pass straight through any detector that has ever been built. Strictly speaking they are not part of the standard model, but it is included in the Matter Mandala because we know something like this must be there because neutrinos so have mass, albeit it very small, and there must be a right-handed neutrino for the mass to be non-zero. A right-handed neutrino does however see the Higgs' field and, at least in principle could be detected via the Higgs' field, or perhaps through their gravitational interactions.

And this brings us to the purple lines, the Higgs' boson. Just as the W's and Z acquire their mass only by virtue of their interaction with the Higgs' field, the same is true of all the matter particles — at high energies the Higgs' field drops to zero and all matter particles become massless.†

One last, but extremely important, comment is that the matter particles are triplicated, there are three separate copies of the matter! Not only are there up and down quarks, electrons and their associated neutrinos (electron neutrinos), there is a second copy of charmed and strange quarks, leptons called muons and muon neutrinos and yet a third copy of top and bottom quarks with leptons called tau leptons and tau neutrinos. These three copies are called the three **generations** of matter. Apart from the neutrinos, whose masses are not very well determined but are extremely small, these other quarks and leptons are much heavier than up and down quarks and electrons. Up and down quarks in the first generation are lighter than charm and strange quarks in the second generation which are in turn lighter than top and bottom quarks in the third generations and there is a similar patter for leptons, electrons are lighter than muons which are in turn lighter than tau leptons. On average the third generation is 120 times heavier than the second generation which is 200 times heavier than the first.

No-one know where this hierarchy of masses comes from, it is one of the mysteries of the modern particle physics but it does have an important consequence: the two heavier generations are extremely unstable and rapidly decay to up and down quarks and electrons, so we don't see them around except in high energy cosmic rays or if we can create them in high energy accelerators, such as the Large Hadron Collider at CERN in Geneva. But their existence is crucial to our existence. We are only here because there are more protons and neutrons in the Universe than there are anti-protons and anti-neutrons and more electrons than anti-electrons (positrons), there is an asymmetry between matter and anti-matter that is crucial for the existence of life. For rather technical reasons, which we won't go into here, this asymmetry between matter and anti-matter is only possible in the standard model of particle physics if there are three or more generations. If there were only two generations there could be no asymmetry between matter and anti-matter. In the immediate aftermath of the Big Bang all matter particles and anti-matter particles would have annihilated into pure radiation and there

†It is often said that all particles only have a mass because of the Higgs' field, but this is only true of the fundamental particles. Almost all of the mass that we are familiar with in rocks, trees and gold bars is due to protons and neutrons which do not get their masses from the Higgs' field. They are massive because the colour force is so strong and energetic and $E = mc^2$.

would be no quarks left to make protons and neutrons and no electrons —- we would not be here! However, while the dynamical interactions of the three generations of matter in the standard model allow for more matter than anti-matter (and the Higgs' field is again crucial for this) the standard model alone cannot produce enough matter for us to exist – there must be more to it. Perhaps sterile right-handed neutrinos can do it or perhaps there is something else. Indeed there is astrophysical evidence coming from galactic dynamics among other things that there is some unknown kind of matter out there that has not been detected on Earth. It is electrically neutral and, like neutrinos, does not emit light (hence it is called "dark matter") and is extremely hard to detect, but it must be there. Indeed most of the matter in the Universe, perhaps even as much as 85%) is this unknown dark matter. The kind of matter that we see in rocks and trees around us and scientists have been studying for over a hundred years gives us the standard model of particle physics, but is only about 15% of the story, the other 85% is a mystery!

The Matter Mandala shows only the matter particles of one generation of the standard model of particle physics, not the corresponding anti-particles. It does not show dark matter because we simply do not know enough about it or what it is to represent it in any meaningful way. To show all three generations requires three copies of the mandala:

Up and down quarks, electron and electron neutrino.

Strange and charm quarks, muon and muon neutrino.

Top and bottom quarks, tau lepton and tau neutrino.

in increasing size to represent the increase in mass between the generations. Only the matter particles are replicated in the three mandalas, not the force particles. All matter particles have exactly the same charges in each mandala, indeed each type of particle in any mandala has exactly the same physical characteristics as in the other two mandalas, except for their mass. They have very different masses because they interact with the background Higgs' fields with different strengths.

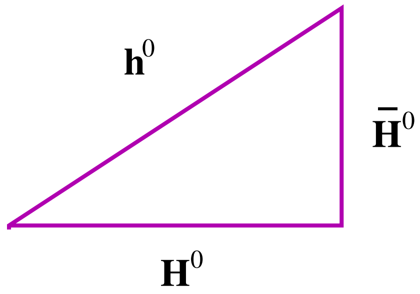
More about the Higgs

It is notoriously difficult to explain what the Higgs boson is and what it does without a good understanding of relativistic quantum field theory, but I'll try to say a little bit more about it here. The Higgs is central to our understanding of how the standard model works and how fundamental particles acquire mass, even though we do not understand the reason for the mass hierarchy between the three generations.

The W's and the Z bosons are clearly different to to gluons and photons in that they are massive, but they only acquire their mass through interaction with the all pervading background Higgs' field. But at high energies this background Higgs' field drops to zero and the W's and the Z become massless and start travelling at the speed of light. At low energies the Z is distinguished from the photon because it is massive but at high energies, when the Z becomes massless, they are indistinguishable (they are both electrically neutral). It is as if there are two photons at high energies and these mix together and loose their separate identities to be replaced by two other massless electrically neutral force particles, called the W^0 and the B^0 boson. The W^0 is so named because it has all the characteristics of an electrically neutral W, at high energies the W^+, W^0 and W^0 are a triplet of massless weak force bosons. The B^0 on the other hand is more like a high energy photon, but it is not associated with electric charge, it is associate with a different kind of charge that we call hypercharge — the electric charge disappears at high energy and is replaced by a new kind if charge called hypercharge.

There is a symmetry of the massless W^+, W^- and W^0 triplet at high energy which disappears when the background Higgs' field becomes non-zero at low energies, the symmetry is said to be "broken". Broken symmetry is the hallmark of the standard model of particle physics at low energy.

The low energy all pervasive neutral Higgs boson h^0, that like the photon is its own anti-particle, is responsible for giving all the fundamental particles their mass. But at high energies there are actually two Higgs bosons, not just one, and they are *not* the same as their anti-particles. In fact they form a weak black and white doublet and, like the electron and the neutrino, the black Higgs boson H^- has electric charge while the white Higgs boson H^0 is electrically neutral. Their anti-particles are denoted by H^+ (which is white) and $\bar{H}^0$ (black). They are not shown separately on the Matter Mandala for two reasons: 1) they are not being considered as matter and 2) they do not have a separate existence at low energies. This second property is a consequence of a rather subtle effect called the Higgs mechanism. The quantum version of Einstein's theory of relativity requires that massive particles be represented differently to massless particles. A massive $W^\pm$ is actually a combination of a massless $W^\pm$ and an $H^\pm$ while a massive Z^0 is a combination of a massless W^0 and a B^0 together with an H^0 and an $\bar{H}^0$. Three of the four Higgs bosons $H^{\pm}$, H^0 and $\bar{H}^0$ are "eaten" by the massless $W^{\pm}$, W^0 and the B^0 to give massive W^+, W^- and Z^0's, leaving the photon massless. One combination of H^0 and $\bar{H}^0$ is left behind at low energies, this is the h^0 whose corresponding field is an everywhere non-zero background field in our present day Universe, giving all the fundamental matter particles their mass. We can picture the relation between h^0, H^0 and $\bar{H}^0$ as being like Pythagoras' theorem,



where h is for hypotenuse.

We said that a left-handed electron looses its weak charge it it's reflected in a mirror to become a right-handed electron, which has no weak charge. You would expect that reflecting in a mirror would not change the charge of a particle but, while this is true for colour and electric charges, it is not true for weak charges — reflecting a weakly charged particle off a mirror can change the weak charge and even turn it off! How can this be? Charge is conserved, how can it be turned off? Reflecting a charged particle off a mirror is not simple as it seems. Charged particles, such as electrons, radiate energy when they are accelerated. This is how radio waves are produced in a transmission antenna, an oscillating AC current is forced through the antenna's electrical circuits causing electrons to slosh back and forth and radiate electromagnetic waves, radio waves. For a particle to be reflected off a mirror it must be accelerated, even if doesn't lose any energy the direction in which it is moving changes and this is an acceleration. If we reflect light off a mirror the light need not lose energy, photons are electrically neutral and they do not radiate when accelerated by the reflection, but electrons will radiate and must necessarily lose energy and at low enough energies they only do this by radiating photons. This does not change the electron's electric charge of course because photons are electrically neutral. But a left handed electron also has a black weak charge and at high energies, when the background Higgs' field associate with the h^0 turns off, $W^{\pm}$ bosons are massless and $H^{\pm}$ boson, together with H^0 and $\bar{H}^0$'s come into play. At high energies a left-handed electron (the black member of a weak doublet) can emit an $\bar{H}^0$ (black) and lose its weak charge completely to become a right-handed electron with no weak charge. At low energies something similar still happens but we do not see the $\bar{H}^0$ directly, it is absorbed into the uniform h^0 field of the vacuum which we cannot detect, but the electron still loses its black charge when it reflects to a right-handed electron. This might sound weird but it all fits together and makes the standard model of particle physics logically consistent and complete.