Explainer: What is mass?

12 November 2015, by Csaba Balazs

You can feel the weight of an object on Earth because of its mass. But what is mass? Flickr/Jeremy Brooks , CC BY

When it comes to electrons, Higgs bosons or photons, they don't have much going for them. They possess spin, charge, mass and … that's about it.

Sometimes they only carry a vanishing amount of some of these features at that. So the mass of a particle is an important property to understand, because it goes to the root of fundamental particle physics.

What is mass then, in the sense of its physical meaning? Why do some particles have mass and others don't? And you may not think this would be important, but the biggest question is: why do particles have mass at all?

To answer those questions, and go well beyond what Albert Einstein knew about mass, let's dive into particle physics and general relativity.

The measure of it

A professor once told me that the best definition of a physical property is its way of measurement. Following this definition, let's see how we measure mass.

When you step on a scale, like it or not, it registers your weight. This is because the Earth attracts you with the gravitational force. The force between you and the Earth exists because both you and the Earth have mass.

If you stepped on the same scale on the moon it would register a fraction of your weight on Earth. About one sixth, to be precise. (There has never been a more effective diet plan: lose 83% of your body weight just by flying to the moon.)

Your moon weight is less because the mass of the moon is less than Earth's mass, and the gravitational force between the moon and you is proportional to the mass of the moon (M) and your mass (m). This is given by the formula $F = GMm/(R^2)$ where R is the radius of the moon and G is called Newton's gravitational constant.

Mass is the charge of the gravitational interaction and without it no gravitational force exists. Physicists refer to this manifestation of mass as gravitational mass.

When you open a door, you have to push it with a force, otherwise the door won't move. This is because the door has mass manifested as inertia, that is, it counteracts you to change the state of its motion.

Newton's second law says that the force you need to change the state of motion of an object is proportional to its inertial mass ($F = ma$). It's easier to push a light door than a heavy one with the same acceleration.

Mass unified

Einstein connected gravitational and inertial mass via his gravitational equivalence principle. The equivalence principle simply says that gravitational and inertial mass are one and the same thing.

This simple statement, however, coupled with the mathematical idea that the equations of physics should not depend on the reference frame, leads very far. A main consequence of the equivalence principle are Einstein's gravitational equations. These equations specify how mass curves space and warps time.

The meaning of Einstein's gravitational equations is simple: mass warps space-time and curved space-time moves mass around. If you have ever seen a coin spiralling down a funnel shaped wishing well, you know what I'm talking about.

According to Einstein's geometric picture of gravity, the Earth orbits around the sun because the latter creates a funnel shaped gravitational well in the fabric of space-time and Earth rotates in it just as the coin rotates in the wishing well.

Your weight is a based on your mass on Earth. Flickr/Stephanie Sicore, CC BY

If the sun had no mass, the gravitational well around it wouldn't exist and Earth would fly straight away. If Earth had no mass, it wouldn't feel the curvature of the well and would fly away in a straight line. That's general relativity in a funnel shaped nut-shell.

Einstein knew all this and much more. After all, he wrote the books on relativity – both on special and general. He figured out how mass is connected to gravity and energy.

The first relation is encapsulated by his gravitational field equations, and the second is the widely known $E = mc^2$. Unfortunately, he never had a chance to learn WHY anything has the property of mass.

There's more to mass

Modern fundamental particle physics gave us the answer in 2012 when the Higgs boson was finally discovered.

The question is fairly important because, as we saw earlier, without mass there's no gravity. Or is there? Well, actually, there is.

Take a photon, for example. A photon is the quintessence of masslessness. According to our present understanding, one of the deepest fundamental laws of particle physics, called gauge symmetry, prevents any force carrier particles, including photons, from acquiring even the tiniest of mass.

Yet, a photon is attracted by the sun. Observations clearly show that light from a galaxy far far away, positioned exactly behind the sun, can be observed on either side of the sun. The fact that the sun's gravitational field bends light was used to prove that general relativity was correct in 1919.

Light interacts with gravitational fields because of $E = mc^2$. This equation tells us that, from the gravitational perspective, energy and mass are equivalent. A photon carries a tiny bit of energy, so it is slightly attracted by the sun.

The fact that energy gravitates is important, because the bulk of mass around us is, in fact, energy. All the visible parts of galaxies and stars are known to be made mostly of hydrogen, which is just protons and electrons.

Earth is made of many different atoms, but those are just made of nucleons (protons and neutrons) and electrons. Electrons are 2,000 times lighter than nucleons, so they bring much less to the table in terms of mass. And remarkably, most of the mass of protons and neutrons is energy stored in glue.

Glue (or gluon, in scientific terms) is the stuff that keeps protons and neutrons together. It is the carrier of the strong force. Binding energy stored in gluons makes up most of the mass of protons, neutrons, hydrogen and any atom for that matter.

The role of the Higgs boson

We could stop here, because we've understood the origin of most of the visible mass in the universe. Einstein didn't know where the mass of macroscopic objects came from, but particle physics revealed this late in the 20th century.

There is, however, one more twist in the story. Perhaps the most amazing one. If Einstein had known about it, he would certainly have loved it.

It is the role of the Higgs boson in generating mass. The Higgs boson, which is the excitation of the Higgs field, is what provides mass at the fundamental level: it lends mass to the elementary particles.

The Higgs story began with a serious problem in particle physics. By the late 20th century it was evident that gauge symmetries, mentioned earlier, are fundamental laws and they forbid any mass of force carriers.

Yet in 1983 massive force carries, the W and Z bosons, were discovered by the Large Electron-Positron (LEP) (the predecessor of the Large Hadron Collider (LHC)).

This was a serious conundrum: one of the most fundamental laws of nature, gauge invariance was at stake. Giving up gauge invariance would have meant starting particle physics over from scratch.

Amazingly, smart theorists figured out a way to have their cake and eat it too! They introduced the Higgs mechanism, which allows us to preserve gauge symmetries at the fundamental level but break them such that in our particular universe massive W and Z particles are still possible.

This incredible trick won Sheldon Glashow, Abdus Salam, and Steven Weinberg the 1979 Nobel Prize in Physics. Besides force carriers, the Higgs mechanism also lends mass to fundamental matter particles, explaining why electrons, neutrinos or quarks have mass.

The contribution of fundamental electron, quark or neutrino mass, however, is negligible compared to the mass generated by glue around us. So does this mean that the Higgs is negligible at the atomic level?

The answer is no! Without the Higgs boson, electrons would have no mass and all atoms would fall apart. Neutrons would not decay, so even atomic nuclei would look very different. Altogether, the universe would be a very-very different place, lacking galaxies, stars and planets.

And then came the dark stuff

So, now we know everything about mass, right? Unfortunately not. Only 5% of the mass in the whole universe comes from ordinary matter (the mass of which is understood).

Nearly 70% of the mass of the universe comes from dark energy and about 25% from dark matter.

Not only do we not have a clue about what kind of mass that is, we don't even know what the dark sector is composed of. So stay tuned because the story of mass continues, well into the millennium.

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