The Origin of Mass

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When you step on your bathroom scale, what does the number you read off really tell you (other than cutting back on cookies would be a good idea)? What does it mean to say that somebody (or something) weighs so-and-so many pounds? Most scales measure simply the force of attraction between you and the planet Earth. But we have learned (since Newton first discovered his laws of gravitation) that this force of attraction is simply proportional to our mass, so the pounds we read off the bathroom scale tell us how massive we are (what our inertia is). Now humans are made of atoms of (mostly) the elements hydrogen, oxygen, nitrogen and carbon, with a smattering of some heavier elements. Each atom in turn is made of a nucleus, which contains nearly all of its mass (99.95%), and electrons, which are rather lightweight. All nuclei are built from a number of positively charged protons and nearly equally massive but neutral neutrons. So ultimately, when you measure your "weight", you are really counting (in a sense) how many protons and neutrons (collectively called "nucleons") your body contains. In fact, each pound of weight is due to about 270 trillion trillion nucleons. So instead of saying "I should shed a few pounds", you could also say "I should lose a few gazillion nucleons".

But what determines the mass of each nucleon? One could guess that maybe the game just continues – the nucleons themselves are made of even tinier particles, called "quarks" that are bound together by "gluons", so maybe their mass is just the sum of all the masses of these "constituents". This could go on forever, but it turns out that this is not the correct answer. We know we need at least three quarks (of the lightest kind) to make a nucleon, but surprisingly these quarks (called "Up" and "Down") turn out to weigh nearly nothing – together, they make up little more than 1% of the nucleon mass. And the gluons that bind them together even have exactly zero mass. So instead of, say, 150 lbs, we humans should really weigh no more than maybe 2 lbs altogether if we just count the mass of all quarks (and electrons) in our body. Where do the remaining 148 lbs come from?

Enter Albert Einstein and his $E=mc^2$! He was the first to realize that mass (inertia) and energy (potential for work) are really two sides of the same coin – they can be converted one into the other, and if you calculate the mass of a composite object, you always have to add the contribution from all its internal energy.

There are actually two kinds of energy at work here. One is called "kinetic energy" and is due to the (very rapid) motion of the quarks inside the nucleons. This motion is due to one of the weird rules of quantum mechanics (called "Heisenberg's Uncertainty Principle"): if you confine a particle to a really tiny space, it has to be moving around with high (but uncertain) velocity. The resulting kinetic energy is always positive and adds to the inertia of the protons and neutrons. A series of experiments since the 60's and 70's of last century have shown that about 1/2 of the nucleon's (and therefore, our) mass is due to this rapid movement of the quarks inside. The other half comes from the interaction (potential) energy of these quarks with each other through the gluons that bind them together. This is at first glance counterintuitive – in most familiar cases, the potential energy due to some binding force is always **negative**, i.e., it should **reduce** the mass of the bound object (otherwise, it could just blow up into its pieces!). Indeed, this is how it works in nuclei: The mass of most nuclei is about 8% **smaller** than the masses of its protons and neutrons combined, due to the strong attractive force (and the resulting negative potential energy) that binds them together. That's why the sun can generate net energy by fusing protons and neutrons into helium nuclei.

But in the case of the quarks inside each proton and neutron, the total interaction energy is positive. So why do they not fly apart? The reason has to do with a quite perplexing feature (named "confinement") of the so-called "color force" that binds the quarks and gluons – and it is still at the center of much active experimental research and theoretical investigations. Premier among other laboratories worldwide, Jefferson Lab is dedicated to exploring all aspects of this strong binding of quarks and gluons, which apparently is so strong that no single quark can escape its grip. In some sense, this force resembles a rubber band (made of gluons), which is stretched between the quarks inside the nucleon (yielding positive energy) but prevents them from simply flying apart. (The technical term for this band is "flux tube" or "string".) When you put more and more energy into this band (by moving the quarks at its end further and further apart), it will eventually break – but the excess energy gets converted into **new** quarks (and their antiparticles), so that each end of the string still has a quark (or antiquark) attached to it. These new bits and pieces simply rearrange themselves into new "hadronic" particles like nucleons or mesons (which are made of quark—antiquark pairs). So even in this case, we never get separate quarks – only the subatomic particles we already know.

Sometimes pumping energy into a nucleon does not lead immediately to its breakup into other hadrons, but instead to a heavier, internally excited state (called a resonance). This leads to the next question: what determines the mass of these excited nucleon states, most prominent among them the "Delta resonance"? After all, a Delta resonance is nearly 1/3 heavier than our more familiar nucleons, and if we were all made of Deltas instead of protons and neutrons, our weight would increase from 150 to 200 pounds, for example. One could guess that the quarks inside a Delta are just moving faster (kinetic energy = additional mass). However, that doesn't seem to be the case (as far as nuclear and particle physicists can tell). Or maybe the rubber band is stretched even tighter within a Delta – but what would be responsible for that? In fact, all indications are that a Delta and a nucleon are very much the same thing – until, that is, we include another quirky property of subatomic particles, called "spin".

Spin is another one of these "quantum" phenomena that our brain is really not quite equipped to fully understand (just like the incessant "zero-point" motion of particles in a confined space). The best way to visualize spin is some kind of rotation of an elementary particle around its own axis – just like Earth is spinning around once every 24 hours, giving us night and day. It turns out that all quarks have exactly the same amount of spin – 1/2 in the units of the subatomic world ($\hbar$). The nucleon as a whole also has that same spin of 1/2. This raises the question of how the quark spins arrange themselves inside the nucleon so that the total sum comes out right – obviously, they can't all be spinning in the same direction because then their spins would simply add to 3 times 1/2, more than the nucleon spin. The Delta resonance, on the other hand, has spin 3/2 and therefore can have all quark spins aligned. Maybe that's what makes it heavier!