What is the most fundamental thing in the world?

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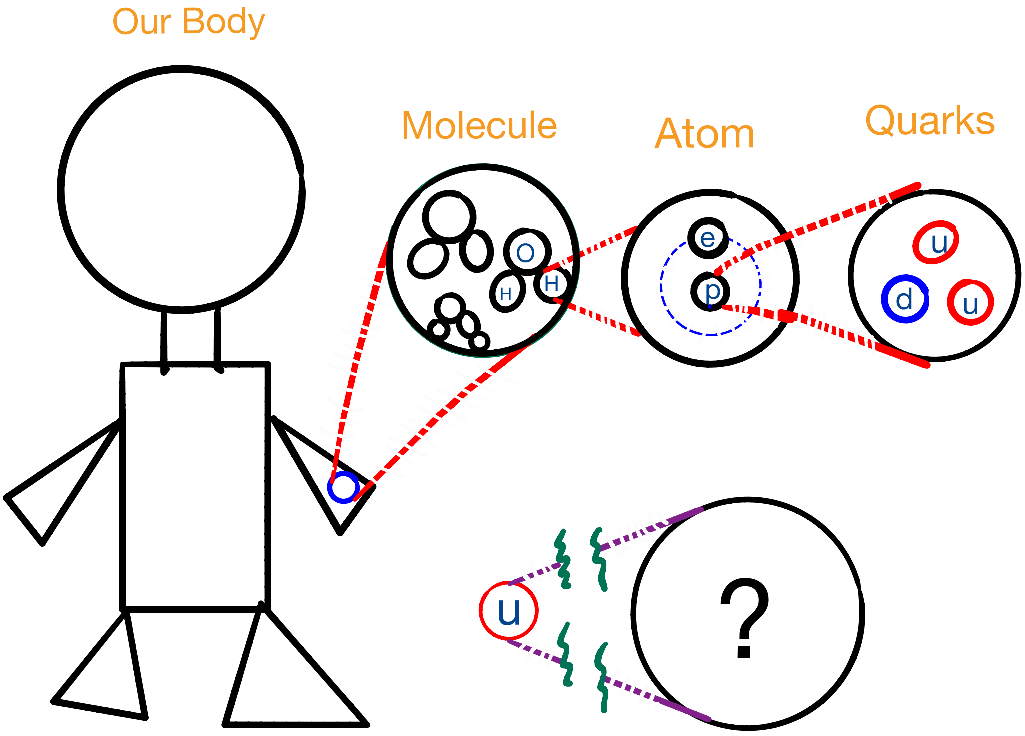
Everyone should think of the question in their youth. You all grow up to find the following description on a school textbook: “Our body is made up of molecules. Molecules are composed of atoms. Atoms consist of electrons and nucleons, which are decomposed further into quarks and leptons.” The success of the Standard Model of particle physics seems to tell us that quarks and leptons are the most fundamental.



But that is not enough. The Standard Model itself implies that there exist more detailed structures deeply hidden from view. You may think this somewhat contradictory. But that`s the way it is. Then, what causes this breakdown and prevents the Standard Model from being the ultimate theory of everything? Moreover, can we go beyond that and put this reductive game to an end? To see what is going on and seek clues to the questions, let`s take a brief look at the history and properties of particle physics.

The notion of particle physics traces back to the philosophy "Atomism" in the ancient Greek, where the physical world consists of fundamental individual components named atoms. Although this reductionistic perspective was introduced in the early period, it was just two hundred years ago that it began to play a vital role in physics. In the early 1800s, John Dalton introduced atoms as the underlying structure of molecules to explain the mechanism of the chemical reaction, in which process molecules are decomposed into atoms and recombined into new ones. Subsequently, in the first half of the nineteenth century, "subatomic" particles such as electrons and nucleons were discovered. And all these observations opened the new framework called *quantum mechanics*.

Quantum mechanics has an essential property called the *wave-particle duality.* The wave-particle duality means that all "particles" also can be described as a wave whose wavelength is $\lambda = \frac{h}{p}$. Here $h \cong 6.6 \times 10^{-34} \mathrm{m^2 kg\, s^{-1}}$ is the Plank constant, and p is the momentum. This relation implies that the more minute structure we explore, the more energy we need. In other words, without enough energy to resolve them, the minute structure is averaged out and can hardly be detected. In general, physics has this kind of hierarchy. That's the reason why we do not care about the structure of atoms and nucleons in our daily life.

In the second half of the nineteenth century, thanks to the technological development of particle accelerators and detectors, we have access to higher energy and more minute structure. At this time, owing to the famous relation $E = mc^2$ pointed out by Albert Einstein, we cannot ignore the effect of particle creation and annihilation anymore. Therefore, we have to combine quantum mechanics and Einstein`s theory of special relativity into a completely new framework called *quantum field theory*.

At this point, one critical problem arises: When we calculate some quantities such as the mass and electric charge of particles in quantum field theory, they diverge inevitably. This difficulty comes from the fact that we must treat a particle as a point rather than a rigid body. (A rigid body cannot exist in special relativity because it violates causality: *In a rigid body, the distances between its segments are fixed. Thus, if we push it from one end, the information travels through the entire body instantaneously faster than the speed of* *light*!) Even in classical electrodynamics, we encounter a similar problem: *The total energy cost* U *to make a uniformly charged spherical particle with electric charge* e *and radius* r *is* $U = 3e^2/5r^2$. *This* U *is divergent when the particle is point-like* $r \to 0$.

However, in classical electrodynamics, we can gain the correct answer just by neglecting the infinity. Similarly, even in quantum field theory, we can obtain the finite and proper results roughly by ignoring infinities. This procedure is called *renormalization*. After performing renormalization, we can sweep the infinities and a more detailed structure under the rug. Then, the Standard Model results calculated through quantum field theory agree very well with experimental data and explain almost everything in the world!

Nevertheless, in the complete theory of everything, all quantities should be finite. The appearance of infinities is the manifestation of the failure in quantum field theory. In this sense, the Standard Model is not the ultimate theory and cannot provide us a lens clear enough to reveal the hidden structure beyond quarks and leptons.

If we gain access to higher energy and improve the resolution, we may find new particles more fundamental than quarks and leptons. However, as long as we perform the renormalization, we end up deferring the problem and fail to attain the ultimate theory. Are there any solutions to this endless cat-and-mouse game? The answer is YES. At ultra-high-energy beyond the "*Planck scale*," the gravitational force neglected in the Standard Model becomes effective. Then, the accelerated particle becomes a *black hole*. As a result, there is no access possible beyond that. The ultimate theory is the one that describes the Planck scale physics!

The strongest candidate for the theory of everything is *string theory*. In string theory, the most fundamental object is a single string rather than particles. Seen from a distance, it looks like a particle. If its vibration mode is different, so is the type of the particle, including the graviton that mediates the gravitational force and is missing in the Standard Model. Besides that, the spatial extent of strings enables us to get finite physical quantities without renormalization. In this manner, string theory exhibits excellent properties and solves many difficulties.

However, there is a huge problem even in string theory: string theory can be defined consistently only in ten-dimensional spacetime. To match our four-dimensional world, we have to roll up an extra six dimensions. Its mechanism remains to be seen and needs further research.

We have grabbed a clue to the question: *what is the most fundamental thing in the world?* We have a long way to go before we offer a complete answer and *unfold the Mechanism of the World*.