Our Theory of Very Nearly Everything

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What is everything made of? Even asking this question may sound a bit naive, let alone expecting a sensible answer, but one of the big miracles of science is that we simply know the answer (to a spectacular level of detail, albeit not quite perfectly). This answer tells an amazing story which, unless you are a physicist, you may well never have been properly told!

Can you name all 17 fundamental particles? What are they made of, if anything? What do the laws of nature actually say? After this journey to the heart of particle physics, you will be able to answer these questions like a proper physicist.

Atoms and beyond

In school, we learn that ordinary matter is made of atoms. Atoms were originally considered the smallest building blocks of matter (the word *atom* means "indivisible") and the 100 or so different types of atoms are collected in the periodic table that hangs on the walls of chemistry classrooms in every corner of the world.

But atoms are not the end of the story; you will remember that an atom consists of electrons orbiting a central "nucleus" made up of protons and neutrons. The electrons arrange themselves in shells around the nucleus and get stuck to the electrons in other atoms to form complicated arrangements; this is the basis of chemistry and of all the variety in the different kinds of matter we see around us.

In fact, protons and neutrons are themselves composed of tiny constituents called *up-quarks* and *down-quarks* (a proton consists of two up-quarks and one down-quark, a neutron of one up-quark and two down-quarks).

This is certainly worth pondering. All the matter in our everyday lives—the air, the oceans, rocks and metal, trees, ducks, human resource managers, our friends and enemies, every planet and every star—is made out of just three particles: the electron, the up-quark and the down-quark. All the differences between these various types of matter stem from how those particles are arranged together.

The particles of our universe

Is there anything in the universe that is *not* made out of quarks and electrons? It may be difficult to think of such a thing immediately, since I eliminated most possibilities in the previous paragraph. But there is one familiar substance that eventually springs to mind: light. It may seem strange to refer to light as a "substance", but modern physics has firmly established that light is in fact quite similar to matter. It moves at a finite speed (the famous number $c \approx 300\,000\,\mathrm{km/s}$), it is affected by gravity (as predicted by Einstein's theory of general relativity) and it even consists of tiny particles, the *photons*.

If even light is made of particles, it seems a fair guess that *everything* is made of particles. Apart from the four we know of so far, can we find any more? The answer is yes; since the birth of modern particle physics, we have discovered a whole slew of them in cosmic rays and in particle colliders. Fortunately, after much head-scratching, it has turned out that they are all different combinations composed from a small set of particles that are—as far

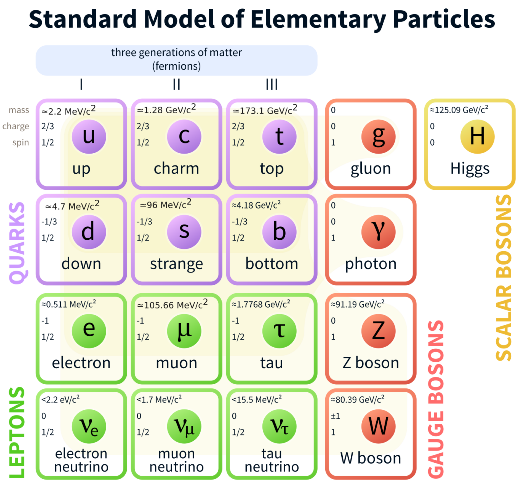

Figure 1: *The known fundamental particles.*

as we know today—fundamental (truly indivisible). There are seventeen[1] of them, shown in Figure 1[2]:

First, we have three families (we call them "generations") each consisting of four matter particles—two quarks and two so-called *leptons*. In the first family we find our by now familiar up-quark, down-quark and electron, as well as a fourth particle, the *electron neutrino*. This is an almost massless particle that is produced in huge quantities in the sun but mostly passes right through ordinary matter. The pattern of two quarks and two leptons is repeated twice more, so that there are twelve matter particles in total, grouped into three generations. Apart from being heavier, the particles in the latter two generations have exactly the same properties as those in the first. This is a rather strange state of affairs, but it seems to just be that way.

Next, there are four so-called *gauge bosons*, of which the photon is one. The gauge bosons are associated with three of the *four fundamental forces of nature*: The gluon corresponds to the strong nuclear force, the photon to the electromagnetic force, and the *W* and *Z* bosons to the weak nuclear force (the fourth fundamental force is gravity). More on this below.

Finally, there is the Higgs boson, world-famous since its discovery at the Large Hadron Collider at CERN in 2012. The Higgs boson is perhaps the strangest of the known fundamental particles (even stranger than the aptly named strange quark). If you followed its discovery, you may recognize the claim that *particles gain mass through their interactions with the Higgs boson*.

The particles shown in Figure 1, together with Einstein's theory of gravity, account for *every observation ever made in physics*, with only a small handful of exceptions (mostly in astronomy). In particular, all of the things we encounter in our regular lives ultimately arise from these particles interacting with each other; the interactions individually rather simple, but together adding up to all the complexity we observe, like a complex machinery where each component on its own behaves according to simple rules. Next, if you are still with me, I will tell you about these rules in a little more detail.

Matter and forces

I previously claimed that light has a lot in common with matter. Despite this, we don't usually refer to light as "matter". In fact, as Faraday realized, light is related to the electromagnetic *force*. The electric field (which makes like charges repel and opposite charges attract) and the magnetic field (which makes like magnetic poles repel and opposite magnetic poles attract) are in fact parts of a single field, the *electromagnetic field*, and light consists of waves in this field.

This unified description of light and electromagnetism is extremely successful, and you directly rely on it every time you use a mobile phone or any other wireless gadget. In this description, the electromagnetic field affects, and is affected by, charged particles like the electron. Matter, consisting of particles, interacts with forces, represented by fields.

But how do we square this with the view of light as consisting of photon particles? As we shall see in a moment, *quantum field theory* provides the answer, and will somewhat blur the line between forces and matter.

[1] Somewhat depending on how you count them; some come in different varieties.

[2] Attribution: By MissMJ - Own work by uploader, PBS NOVA [1], Fermilab, Office of Science, United States Department of Energy, Particle Data Group, Public Domain, `https://commons.wikimedia.org/w/index.php?curid=4286964`

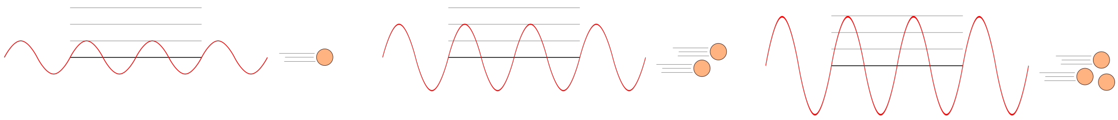

Figure 2: *A particle is the weakest possible wave in a field—the central idea of quantum field theory.*

Apart from electromagnetism, it has turned out that there are only three other forces in nature: the *strong force*, the *weak force* (both terrible names) and gravity. The strong force holds protons and neutrons together in the nucleus, and also the quarks inside those protons and neutrons. The weak force is involved in radioactivity and is the main way stars produce energy. I will keep using electromagnetism as my running example, but the story is similar for the strong and weak forces (gravity is the odd one out).

Quantum fields

If you have read anything at all about modern physics, you will have heard countless testimonies about the incredible strangeness of quantum mechanics, the physics of the very small. This article will be no exception. In fact, taking the principles of quantum mechanics (originally formulated for tiny point-like particles) and applying them to fields (like the electromagnetic field) makes ordinary quantum mechanics seem like a breeze, and kept even the most brilliant physicists banging their heads against various walls for decades. Luckily for us, their struggles have left us with a marvellous theory, *quantum field theory* (QFT), which is currently the language of all our physical laws (except gravity).[3]

QFT makes sense of our confusion about whether light consists of waves or particles. In very simplified language, the essence is this: Quantum mechanics says that waves in a field can't be arbitrarily weak. Instead, you create a large wave by adding together a large number of tiny, "indivisible" waves. A particle is, more or less, such a weakest allowed wave. I have made a cartoon of this in Figure 2.

[3]Professor David Tong has given an excellent public talk about QFT at the Royal Institution; this was part of the inspiration for this article. `https://youtu.be/zNVQfWC_evg`

QFT also explains, in a unified way, many of the science fiction-sounding concepts that, let's be honest, are a big part of the allure of physics: for example that some particles have an antimatter partner (just a different type of wave in the same field) and that particles can be created and destroyed, turning into other types of particles (a wave in one field can be transferred into waves in some other field).

The fields of our universe

Let us look back to the table of particles in Figure 1 in the light of quantum field theory. Instead of seventeen fundamental *particles*, we now have seventeen fundamental *fields*, for example the electromagnetic field (also called the photon field), the electron field, the up-quark field, the muon neutrino field, the Higgs field... Viewing the particles in terms of fields makes it a lot easier to quantitatively describe how the particles behave, by means of an equation. For example, to describe the physics of photons, we must first write down the equation governing the electromagnetic field. This equation has long been known to physicists, and it reads

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}.$$

Don't worry about what the symbols in this equation mean; I am just including it to illustrate that this very short equation captures everything we know about electromagnetism and light.

We play a similar game when we want to describe other particles. For example, the equation for the electron field is called the Dirac equation and reads

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi.$$

For describing how electrons and photons interact, the equation looks like

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(iD\!\!\!\!/ - m)\psi.$$

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}W_a^{\mu\nu}W_{\mu\nu}^a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + (D_\mu\phi)^\dagger(D^\mu\phi) - \mu^2|\phi|^2 - \lambda|\phi|^4 \\ &+ \sum_i \left(\bar{L}^i i\not{D} L^i + \bar{R}^i i\not{D} R^i + \bar{Q}_L^i i\not{D} Q_L^i + \bar{u}_R^i i\not{D} u_R^i + \bar{d}_R^i i\not{D} d_R^i\right) \\ &- \sqrt{2}\sum_{ij}\left(\lambda^{ij}\bar{L}^i\phi R^j + \lambda_d^{ij}\bar{Q}_L^i\phi d_R^j + \lambda_u^{ij}\bar{Q}_L^i\phi^c u_R^j + \text{h.c.}\right) \\ &- \frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a + \sum_f \bar{q}^f i\not{D}_{\text{QCD}} q^f\end{aligned}$$

Figure 3: *The equation for the Standard Model. It encodes all known particle interactions.*

For describing *all the known interactions between all the known fields*, the equation is displayed in Figure 3. Together with the list of particles in Figure 1, this equation is known as the *Standard Model* of particle physics. If you find it daunting, you are not alone. But considering that this equation captures *all the known laws of nature*, except—again—gravity, it really isn't all that bad!

Defining all the symbols in this equation is a bit messy and might take a few pages, and learning exactly how to interpret them would take you the better part of a year at university or, depending on the level of detail you are aiming for, a research career in physics. Suffice it to say that some of the symbols represent the actual fields[4], and that the appearance of the letters L and R refers to left-handed and right-handed particles (in a certain sense spinning clockwise and counter-clockwise, respectively) which, in a strange twist, Nature treats very differently from each other.

Physicists can doodle, too!

Having written down the equation governing the field, we would now like to make use of it to calculate something about the particles arising in the field. For example, say we want to figure out what happens when an electron and a positron (the antimatter partner of the electron) collide. Several things could happen, but let us focus on the case where an electron and a positron emerge after the collision. We write this process as $e\bar{e} \to e\bar{e}$ (e is the electron and $\bar{e}$ is the positron).

QFT provides us with the tools to compute exactly how often this process happens. We start with the equation I gave above for the photon field interacting with the electron field, and apply the rules of quantum mechanics to it. On the face of it, the maths required is simply horrifying. But the brilliant Richard Feynman found a visual way of organizing it, the so-called *Feynman diagrams* (earning him a Nobel Prize in 1965).

I have drawn some Feynman diagrams in Figure 4. Photons are drawn as wiggly lines, while electrons and positrons are drawn as a straight line with an arrow showing which way negative electric charge is flowing. The incoming and outgoing particles have an extra arrow next to the line, showing the direction of motion. In principle, Feynman diagrams don't depict what is actually happening in the collision; they are just a useful visual shorthand for mathematical expressions. But it is tempting, and useful for your intuition, to interpret them as "movies" of the collision, with time on the x-axis and space on the y-axis. For example, the first diagram looks like an electron and a positron colliding and turning into a photon, which then turns back into an electron and a positron. The second diagram looks like the two particles exchanging a photon and then continuing on their merry ways. The third diagram is like the first one, except that the intermediate photon spends some time as an electron-positron pair.

[4] ϕ is the Higgs field, the L^i and R^i represent the lepton fields, Q_L^i, u_R^j, d_R^j and q^f all represent the quark fields in various ways, $W_a^{\mu\nu}$ and $B^{\mu\nu}$ represent the electromagnetic (photon) field as well as the W and Z boson fields while $G_a^{\mu\nu}$ represents the gluon field.

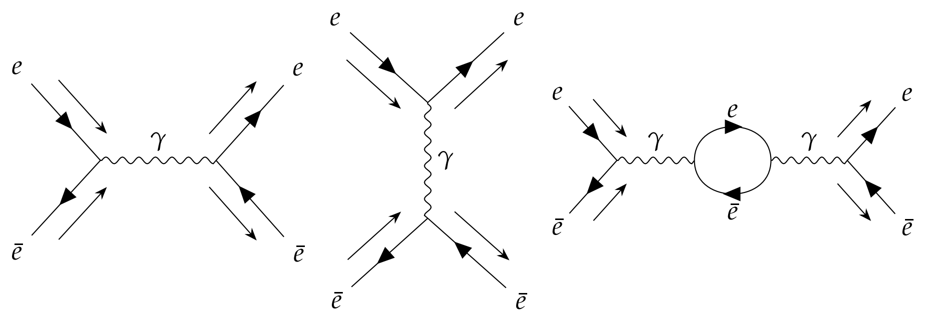

Figure 4: *Some Feynman diagrams for $e\bar{e} \to e\bar{e}$.*

Feynman diagrams are useful in calculations because, although in principle you have to draw all possible diagrams (which can be arbitrarily complicated) and add them all up, in practice the simplest diagrams tend to be the most important.

The QFT rabbit hole

Quantum field theory contains a huge number of utterly fascinating details that would take many pages to explain properly. One of the great things about QFT is that it is a very rich subject—starting from its basic principles, you can reach many surprising conclusions. I am just going to give you a quick taste of two of the most important ones: symmetry and zooming.

In physics, a *symmetry transformation* is a change that has no observable effect on the world. For example, if somebody moved the whole Universe a few metres to the left, or rotated it by some amount, this would be completely impossible to detect. Symmetries are a very rich aspect of QFT. For example, the mathematical definition of a *charge*—like electric charge, or the less well-known *hypercharge* and *isospin*—is just a matter of how a field changes in a given symmetry transformation. The Standard Model has quite a lot of symmetries—a lot of different charges—and the way they interplay to form the physics we observe is an intriguing subject where the Higgs field ends up "breaking" the original symmetries. This is the *Higgs mechanism*, the discovery of which earned the 2013 Nobel Prize in physics.

You might also be surprised to hear that *zooming*[5] takes on a highly important role in QFT. When we zoom in and out, the theory changes appearance, so two superficially different theories might in fact be the same theory, just at different levels of zoom. Mathematically, the Standard Model looks rather zoomed out, so we expect that it is only a zoomed out version of some unknown, more fundamental theory. Most theories get less complicated when you zoom out. The unexpected discovery that the theory of quarks and gluons actually gets *more* complicated when you zoom out was awarded the Nobel Prize in 2004.

The curious case of gravity

So far, I have been sweeping one big part of physics under the rug: gravity. The first theory of gravity was Newton's, and it describes gravity as a force between any two objects, pulling them together. However, our current best theory of gravity is Einstein's theory of general relativity. While both theories give approximately the same results in everyday situations, they are conceptually very different: In Einstein's theory, gravity isn't really a force, but more like the shape of spacetime. The theory also predicts phenomena like black holes and gravitational waves. Experimental tests show that it is rock solid. For example, the LIGO experiment (awarded the Nobel Prize in 2017) has recently enabled us to "listen" to astronomical events using gravitational waves. Like the theories of particle physics that I have already told you about, we can summarize general relativity in a short

[5]The technical term is *renormalization*.

equation, the *Einstein equation*:

$$R_{ab} - \frac{1}{2} R g_{ab} = 8\pi T_{ab}$$

(again, don't worry about what it means mathematically). Together, this equation and the one for the Standard Model (Figure 3) basically constitute all known laws of physics.

There is a problem, however: We don't know exactly how gravity works together with quantum mechanics. Actually, gravity is the only force of nature that we haven't yet been able to describe as a quantum field. This is the problem of *quantum gravity*, one of the major remaining mysteries in physics. Most physicists think that QFT isn't sufficient to describe gravity, but that we need something entirely new (for example *string theory* or *loop quantum gravity*).

What else is missing?

The picture that I have laid out for you—that nature consists of a fairly small number of quantum fields (those in Figure 1) that interact with each other, and that the elementary particles are the weakest possible waves in these fields—is very nearly a complete picture of reality. Apart from the (big!) issue of quantum gravity, there are only a few loose ends, which nevertheless reveal that there is still much to discover. I won't go into any detail, just give a five-second introduction to some of them:

- *Dark matter*. Through its gravitational effect on galaxies, we have detected some kind of invisible matter. We don't know what it is, but we have a few ideas.
- *Dark energy*. Since the Big Bang, the universe has been expanding. But the expansion is *speeding up* while ordinary general relativity says that it should be slowing down. We don't know why.
- *Inflation*. In the first few instants after the Big Bang, the universe seems to have gone through a mind-bogglingly quick expansion. A good guess is that this process was caused by some quantum field that we call the *inflaton field* (corresponding to a particle called the *inflaton*). This is probably a new field, outside of the Standard Model.
- *Neutrinos*. In the Standard Model, neutrinos don't interact with the Higgs field, which means that they have no mass (as I haven't explained the Higgs mechanism in any depth, I will just ask you to trust me here). However, the discovery of *neutrino oscillations* (awarded the 2015 Nobel Prize) shows that neutrinos change over time. Since massless particles don't experience the flow of time (again, trust me, or ask Einstein), neutrinos must have mass. We are not quite sure how this works, and there are many more unsolved mysteries to do with neutrinos.

End of the road?

Congratulations! You now know, as far as we can answer it today, the answer to the question from the first paragraph: *What is everything made of?* What we know so far is enough to explain basically everything we experience in our lives: *Everything is made out of the seventeen quantum fields of the Standard Model, and waves in these fields are the fundamental particles.*

You have reached the edge of our current knowledge. We haven't found anything smaller than a quark, or anything more fundamental than a quantum field. The Standard Model describes all but a few experiments perfectly. Yet, physicists are never content with a theory of *very nearly* everything. Historically, small discrepancies in experiments have often led us to discover a completely different new theory, to which the conventional theory was just an approximation. This happened with Newton's theory of gravity, and we hope to make it happen again with the Standard Model.

We are certain that the remaining mysteries hold the key to a deeper understanding of our world. From this point on, we have only a long list of speculations and not yet proof of any of them. Nobody knows where the next discoveries will take us; we can only be sure that it will be far.