> **In the beginning there was nothing.**
> **And the Lord said: "let there be light"**
> **and there was still nothing,**
> **but now you could see it.**
>
> ***Terry Pratchett***

Advanced

Elementary Particles

The Gang of Four

To repeat myself: "Everything you can see - the stars in the sky, your wife, the TV set, the mountain range, the ocean, your boss or your underlings, the dust mites dancing in a ray of light, everything—and that includes you—consists of *atoms* and *photons*. That's it. There is nothing else for non-scientists like you. It's my and my fellow scientists privilege that on rare occasions we can also "look" at things that are different from atoms (including their constituents) and photons".

- So let's talk elementary particles here. Only *four* of them are of any importance to normal people:

1. The **electron**. We need it for *electr*icity and *electron*ics - and for a lot more, like making atoms and ions.
2. The **proton**. We need it for nuclear magnetic resonance tomography (***NMR***), for ionized hydrogen and, not to forget, for making all the atoms.
3. The **neutron**. We need it for making nuclear bombs, nuclear reactors, neutron beam technologies, and - like protons - for making atoms.
4. The **photon**. Whenever you think about electromagnetic waves in terms of particles, you call that particle a photon. We need photons so we can see, but also for Radio, TV, X-rays γ-rays and for connecting charges.

- That's it. You can go rather far with this *gang of four:*

1. With ***z*** *protons* and a similar number of *neutrons*, you can make the **nuclei** of all the isotopes that belong to an atom with the atomic number ***z***. Like ***z* = 1** for hydrogen (H) ***z* = 2** for helium (He), ***z* = 14** for silicon (Si), ***z* = 26** for iron and ***z* = 92** for uranium (U). This is how the periodic table is organized.
2. Add ***z*** *electrons* to an nuclei with ***z*** protons, and you have an **atom**. The atoms around us, in us and all over the universe, typically consist of a mix of a few **isotopes**, differing just by the numbers of neutrons in the nucleus. Iron, for example, consists of:
   - 5.845% ^{54}Fe,
   - 91.754% ^{56}Fe,
   - 2.119% ^{57}Fe,
   - 0.282% ^{58}Fe.

   Then there are are 24 known *radioactive* iron isotopes that we have to make in a nuclear reactor if we need them.
   It's similar for all the other elements.
3. Throw in a lot of *photons* with all kinds of energies (if it's around 2 eV we call it light), and you have pretty much all it takes to make an old-fashioned universe. For a modern universe you may need a little more, but the four elementary particles given so far are definitely all it takes to make a planet like the earth or some slime bag like you and me.

Basic Link

Isotopes

Everybody with a halfway decent general education knows, of course, that there are hell of a lot *more* elementary particles. Take the "naked bottom quark" for example, the Higg's boson, or those neutrinos that appear to be doing the ultimate speeding right now, going above the speed of light[1]. So what about this crowd?

- Well, forget them. They are important for us scientists. Some of them we actually use in Materials Science but they are of no importance for you and me in everyday life. That's why I will only mention some of them briefly in what follows.
  What I will do is to go into some of the more fundamental things that are common to *all* elementary particles

Basic Properties of Elementary Particles

- What, exactly, are elementary particles? It used to be that they were considered to be the smallest units of something that you could not divide into smaller things. Another word for such an entity used to be "**atom**", a Greek word for "indivisible".
  - After atoms were firmly established in the beginning of the 20th century, it didn't take long before physicists started to take them apart. Physicists then were almost exclusively male and thus liked to break things. Experimentally that culminated in the atomic bomb, theoretically in quantum theory, supplanting old-fashioned Newtonian mechanics by quantum mechanics. Atoms ever since are fully understood compounds of protons, neutrons and electrons and no longer elementary.
    Then protons and neutrons were given the axe. They consist of things like *quarks* and *gluons* and we don't want to go into that, since this fundamental and exciting insight has absolutely no practical consequences so far (and for the foreseeable future).
- So instead of enumerating a large and growing crowd of elementary, or perhaps not-so-elementary, particles, let's look at some basic properties first.
  - **Size**. Forget it. All that one can say is that elementary particles are small. A "size" of $\mathbf{10^{-15}\ m = 10^{-6}\ nm}$ gives an idea of how small. Otherwise size of elementary particles is not a well-defined property. What *precise* size has the acoustic wave you just emitted by yelling "what kind of BS is that?" Same thing for elementary particles.
  - **Mass**. Or, being precise: "*rest mass*", the mass you get when the particle isn't moving *relative* to you (yes, the theory of relativity lurks somewhere in the background!). Since photons (and some other elementary particles like neutrinos) *always* move with the speed of light relative to you (and it doesn't' matter how you move; that already *is* the special theory of relativity!), they have no rest mass, but only mass according to $\boldsymbol{m = E/c^2}$.
    Otherwise *all* elementary particles have well-defined (rest) masses that we know quite well. Why they have masses, and why those masses have the values they have, still eludes us to some extent. The multi-billion Euro enterprise to find the elusive so-called *Higg's Boson* that is going on right now, is all about that. 3)
    We know the masses of our three important elementary particles with high precision:

    - Mass of proton: $\mathbf{m_P = 1{,}672\ 621\ 777 \cdot 10^{-27}\ kg}$.
    - Mass of neutron: $\mathbf{m_N = 1{,}674\ 927\ 351 \cdot 10^{-27}\ kg}$. Note that a neutron is a bit heavier than a proton.
    - Mass of electron: $\mathbf{m_e = 9{,}10938291 \cdot 10^{-31}\ kg}$. That is about **1/1836** of the proton mass.
  - **Electrical Charge**. In contrast to mass, electrical charge always comes in multiples of the **elementary charge** $\mathbf{e = \pm\ 1.602\ 176\ 565 \cdot 10^{-19}\ C}$. The electron carries one negative elementary charge, the proton a positive one. The neutron, as the name implies, is neutral.
- Let's stop for a second and ask ourselves if we *know* what mass or charge actually *is*? I don't know about you - but I for one, do not really know this.
  - All *I* know is:

    - Mass or charge is some property that elementary particles carry around, and that is added up or compounded in certain well-known ways if elementary particles bunch up to form atoms, crystals or you.
    - Masses and charges "emit" some field (all of them a gravitational field, and if they are charged also an electrical field) that interacts with other masses and charges in a way that we can calculate.
    - We can measure what these interaction produces (keep the earth in an orbit around the sun, keep the ions in an ionic crystal stuck together, ...) and then conclude back to the properties of the particles.

    I don't think that this kind of knowledge means that I really know what "charge" is. We just got used to the concepts of mass and charge because we encounter the consequences of these properties everyday. You may not ponder the meaning of charge every time you turn on an electric appliance, but you sure use the property "charge" when those electrons move around at your command. However, to your forebears less than two centuries ago, the concept of "charge" would have been just as strange as the concept of:
  - **Spin**. If you imagine an elementary particle as a little ball made from - yes? Elementary particle stuff? The "made from" implies that you can take the particle apart, running you into a nice paradox. Whatever, if it would be a little ball (which it is not), it would be a rotating little ball, a ball with a *spin*. Instead of imagining a rotating something, it is far better to accept the thought that spin is just some other kind of "charge", in particular because it comes in elementary units of **±½S**. The factor ½ has historical roots and need not worry us. The important thing is *how* the spin of an elementary particle affects its behavior. Here are the spins of our gang of four:

    - Spin of proton: $\mathbf{S_P = \pm ½}$.
    - Spin of neutron: $\mathbf{S_P = \pm ½}$
    - Spin of electron: $\mathbf{S_P = \pm ½}$
    - Spin of photon: $\mathbf{S_{Ph} = \pm 1}$. Yes, *light* has a spin. If you like to think about light in terms of waves, spin is related to polarization.
  - **Magnetic dipole** "charge". If particles with a rest mass have a spin, they also have a **magnetic dipole moment**. I will not go into what photons do in this respect since that gets a bit messy. What "dipole moment" means is explained in this link; here it suffices to realize that particles with a magnetic dipole moment behave like tiny bar magnets with a magnetic north and south pole.

  - **Isospin**, *hypercharge*, *strangeness*, "*color*", "*flavor*", ... Let's stop here. There are a hell more basic and always "strange" properties that elementary particles can have, and they are just as important as the other ones if you want to *understand*.
    However, if you are only concerned about properties that can go to work for you, like the properties "electric charge" and "spin + magnetic dipole moment" (even if you are not sure about the latter), you can forget those things. So will I.

Bringing Order into Chaos

- The important thing for all elementary particles is that there are a couple of universal rules about what happens when elementary particles interact. With this in mind, we can group particles in families, peer groups, clubs, or whatever entity you prefer, with the understanding that all members of a certain club behave the same way in certain circumstances.
  - You might, for example, group humans in two groups according on how they react to a new far-out feature in expensive cars, like being able to change the tire pressure while you drive:
    - Reaction of group 1: Cool!!!
    - Reaction of group 2: Why???

    I trust that you can figure out who belongs in which group. Just like people, elementary particles can belong to more than one club. You can be female *and* a good car driver, for example. Or a scientist *and* quite normal.
- Let's start with some **Universal Laws** that *all* elementary particles must obey:
  - Simple. First we have the *universal* conservation laws.
    - Conservation of energy, momentum, and angular momentum. These conservation laws quite simply express basic symmetry properties of our universe, for example that it doesn't matter when, where, and in which direction you do some experiment under otherwise identical conditions. The outcome will be always the same. In other words: The basic fabric of the universe is the same at all times, places and directions.
    - Conservation of other things like (net) electric charge, spin, and so on. A large part of elementary physics consists of finding the basic symmetries that are behind those conservation laws (and why some things, surprisingly, are almost conserved but not quite).
- Now let's split the bunch in two fundamental groups: **Fermions** and **Bosons**, named after **Enrico Fermi** and **Satyendra Nath Bose**, two of the giants of Science in the early 20th century.
  - It is just as easy to tell the difference between fermions and bosons than it is to tell the difference between boys and girls. It is easier, in fact, because there are *no* exceptions:
    - All particles with "half number" spin (S = 1/2, 3/2) are *fermions*
    - All particles with integer spin (S = 1, 2) are *bosons*.

    Big deal, you might think, but the differences in behavior are dramatic:
    - Fermions must *never* do the same thing. This is called the "**Pauli** principle".
    - Bosons can do whatever they like without regard to other bosons.
  - What that means is that atoms that have an integer spin after summing up the spins of all their constituents, could *all* have zero energy when you cool them down, and then do really strange things. However, if their combined spin would be a "half number", they cannot do this. They can't all have the same energy. This might seem to be bit far-fetched, so all I'm going to say to this is

    > **If the Pauli principle would cease to hold, all atoms would immediately collapse into a very small point, and the universe would blow up.**

  - Atoms are only so (relatively) huge because the electrons "in" there must keep out of each others "reach".
  - The Pauli principle is one of the strangest axioms we have in basic physics. It cannot be derived from deeper laws, and their is no simple or intuitive "explanation". It comes up all the time as soon as we start calculating anything "electrical", e.g. in semiconductor science and technology.
- The difference between fermions and bosons goes even deeper. Fermions are the carriers of properties like *mass* or *electrical charge*. Bosons are the carriers of the interaction between fermions.

  - So far, I have told you that particles with a rest mass produce some fields that affect other particles at some distance. That's true enough but the deeper view is that there is no "field" but an exchange of bosons. If an electron repels another electron at some distance, it's because they constantly exchange some photons. All of those photons get emitted and absorbed by just those two guys - and that's why you cannot "see" these photons, just their effect: the electrons repel each other. The theory behind that is called "**quantum electrodynamics**". It is certainly one of the best theories we have, because it allows to calculate tough stuff with extreme precision. But here we need not worry about that at all.

- Its time for looking at another distinction: *particles* and their **antiparticles.**.
  For fundamental reasons, every particle has an evil twin, its *antiparticle*. The anti-particles for protons, neutrons and so on are called called anti-proton, anti-neutron, and so on. The only exception is the electron. Its not-so-evil twin is called **positron**. The photon is a bit boring in that context, because its anti-particle is another photons with the same properties.

  - If a particle meets its anti-particle, they always engage in maximum violence, destroying themselves completely in the process. They only leave back some "smoke" in the form of high-energy photons that we call γ-rays (energy, and so on, must be conserved!). That's why there are no antiparticles out there. They have long since destroyed themselves.
    If you want an anti-particle, you have to make one. That is not all that difficult. Some radioactive isotopes decay by emission of positrons, and any decent particle accelerator can be used to produce anti-particles if so desired. They just do not live very long since they are bound to meet a partner for self-destruction rather quickly.
    Anti-particles are not only great stuff for science fiction writing (Star Trek couldn't get off the ground without them), they are quite useful. Positrons are not only used routinely for Materials Science but also in medicine for what is called **Positron Emission Tomography** or ***PET*** (look it up yourself).

  - Anti-particles generally have the signs of all properties reversed, except for mass. The positron has exactly the same positive mass as an electron but a *positive* elementary charge and reversed signs for all those strange "charges" we won't consider here. That's why annihilation is so easy. Their combined properties (except mass) always add up to zero, the same number you have if they don't exist.

- Finally, I just mention that one can divide (almost) all elementary particles into **hadrons** and **leptons**.

  - *Leptons* are the ones that do not feel the so-called strong interaction, in contrast to the hadrons. The lepton group contains our friend, the electron *and* its "neutrino", a kind of close relative. Of course, it also contains the respective antiparticles. Then comes a certain mystery: This particular gang of particles reproduces itself more or less two more times. The *muon*, together with its muon neutrino, and the *tau*, with its tau neutrino (plus the respective antiparticles) are just somewhat oversized (and therefore not stable) copies of their hard-working relatives: the electron and its neutrino. It looks like that there is no fourth level of relatives hidden somewhere, but nobody knows for sure.
    Leptons are believed to be elementary, i.e. they cannot be subdivided into something smaller.

  - That is in pronounced contrast to *hadrons*, who either consist of three quarks plus gluons (like our familiar protons and neutrons), or of a quark and an anti -quark plus gluons. The first kind constitutes the *baryons*, the second kind the *mesons*...

- Since by now I'm just a little less confused than you are, let's drop the subject here. All we need for most of everything are atoms, ions, electrons and photons, and these four we now have covered.

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1) Presently (end of 2011) Italian researchers claim that found some neutrinos *speeding*, i.e. going faster than the speed of light. Just a little bit faster but that doesn't matter. Nothing will ever go faster than the speed of light says Einstein. If he would be wrong the whole majestic building of modern physics coming down in small pieces. So who are we going to believe? Einstein, who after all was my Suebian fellow scientist, or some Italian guy? We shall see 2)
We did see (beginning of 2012): Measurement error, some bad connection.

2) 2) Thou shall live in interesting times.
Chinese curse
We sure do. And we shall see.

3) I had hardly written that and - Bingo! - Nobel price 2013 for the Higgs Boson!