Entropy and Symmetry in the Universe

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Abstract

Professor Rigopoulou presents two topics that are central in physics, symmetry and entropy. The role of symmetry is mentioned in the context of conservation laws, as well as the discovery of Gell-Mann's eightfold way. Rigopoulou describes charge, parity and time-translation symmetries that were once thought to be true. She then considers whether combinations of these symmetries hold as well like charge-parity symmetry combined. On entropy, she discusses the arrow of time.

The fundamental 2nd law of thermodynamics states that the entropy of the Universe always tends towards a maximum. If the Universe had been born into a high entropy state there would have been no galaxies, no stars, no planets and no life. Hence, the primary reason why we are here is the initial low entropy of the Universe. But entropy is a measure of the 'disorder' of a physical system. In terms of the underlying quantum description, entropy is a measure of the number of quantum states that are necessary in order to describe a system in terms of macroscopic variables, such as temperature, volume, and density, all of these variables increase as the universe evolves.

Yet, our everyday life is full of 'symmetries'. For most of us, when we hear the word symmetry, we think about reflecting images in a mirror. The standard model of particle physics also has three related (near) symmetries, the combination of which is also a symmetry (known as the CPT symmetry).

In this essay I will further explore the concepts of entropy and symmetry in the Universe and explain how each of these apparently 'inconsistent' properties have shaped the world we live in.

The Meaning of Symmetry

The word symmetry comes from the Greek word συμμετρια and means same measure, often referring to items that are 'equally proportioned'. Symmetry is an expression of exact correspondence between things or, in some sense, a measure of indistinguishability. Everyday life is full of such examples, humans experience symmetry from a very young age: babies recognise symmetry in the facial features of their parents and children experience mathematical symmetry when practising additions such as 1+2=2+1. Symmetry also reveals itself in the physical world, the cycle of the seasons and in music in the tones of the songs. In science, symmetry is used to describe the properties of the microscopic and macroscopic world, from atoms and molecules to the structures of the Universe.

In physics, symmetry is an extremely powerful concept. The laws of physics, which govern the observations of what can and cannot happen in the Universe, are a natural consequence of such universal symmetries. Take conservation of energy: in an isolated system the total energy remains constant. This principle can never be violated. If this were the case, then the activity in the cells in our bodies would change at any time changing the way our bodies work. The energy released when nuclei fuse would fluctuate, altering the sun's energy and drastically affecting life on Earth. The symmetry embedded in the laws of nature, such as the conservation of energy, has shaped the nature of our world.

Symmetry also led to the discovery of the cornerstones of matter called quarks [1, 2]. In the early 1950s, physicist Murray Gell-Mann looked for regularity in the "zoo" of particles produced by particle accelerators. In his research he used the principles of symmetry to predict the existence of fundamental particles which he named quarks. Physicists first observed quarks in the early 1970s at the Stanford Linear Accelerator [3,4,5].

So far, we have talked about the laws of physics and established that they obey symmetries. But is the Universe symmetric? This is a really important question to know the answer to when doing calculations because symmetries tend to make the mathematical description much easier. Most of the physics discovered over the last century, including general relativity and quantum mechanics, is based on three main symmetries: *Charge, Parity,* and *Time*.

Charge symmetry means that we could swap all the Universe's positive charges for negative charges and vice versa without changing anything important. Parity symmetry means we could flip the Universe right-to-left like a mirror and nothing would change. And time symmetry means that we could run the Universe backward in time without changing any of the laws of physics.

Of course, not all of these symmetries hold. As we shall discuss in the next section time symmetry is broken by the laws of thermodynamics, which state that entropy can only increase forward in time. But what about charge and parity symmetries? As it turns out, these symmetries are also broken in specific circumstances, which can complicate a lot of established physics:

For decades, the charge and parity symmetries seemed pretty solid, but in 1956 they began to fall apart. The first to fall was parity: An experiment by Chien-Shiung Wu [6] found a case where this symmetry didn't hold. The experiment involved rotating cobalt atoms that gave off photons, which flew off in certain directions. The photons followed parity symmetry, but the rotating cobalt atoms didn't, because the rotations don't change when you flip left and right. The result was that this experiment proved that parity symmetry doesn't always hold, so physicists proposed combining parity symmetry with charge symmetry, to form a charge-parity symmetry. According to this theory, if you flip left and right along with positive and negative charges, physics should still work the same way.

Unfortunately, that turned out also to not be true. An experiment in 1964 involving exotic particles called kaons violated charge-parity symmetry. So physicists had only one option left: to combine charge-parity symmetry with time symmetry to form charge-parity-time symmetry. Surely this symmetry can't be broken, right? So far, it actually looks like this final type of symmetry might be safe. Physicists have been trying for over half a century to break it, and they've been unsuccessful. But all it takes is one instance where charge-parity symmetry doesn't hold, and all of physics might have to be rewritten. Hopefully this last symmetry stays safe.

The Concept of Entropy

The identification of entropy is attributed to Rudolf Clausius (1822–1888), a German mathematician and physicist. However, it was a young French engineer, Sadi Carnot (1796–1832), who first hit on the idea of thermodynamic efficiency; although, the idea was so foreign to people at the time that it had little impact. Clausius was oblivious to Carnot's work but hit on the same ideas.

Clausius studied the conversion of heat into work. He recognised that heat from a body at a high temperature would flow to one at a lower temperature. This is how coffee cools down the longer it's left out — the heat from the coffee flows into the room. This happens naturally. But if you want to heat cold water to make the coffee, you need to do work — you need a power source to heat the water.

From this idea Clausius proposed that the entropy of any *isolated* or *closed* system will increase with time [7]. The meaning of the term entropy has its roots in the Greek words 'εν' and 'τροπή' which translate as 'towards conversion', therefore describing the change of energy when moving from one state to another. Clausius' suggestion applies to all *irreversible* processes and is summed up in the second law of thermodynamics: the entropy of an *isolated* system either remains constant or increases with time [8].

But it was thanks to Boltzmann in 1877 that entropy, a concept whose real meaning is hard to grasp, was linked to the properties of atoms in a macroscopic system [9]. Boltzmann suggested that the exact properties of a macroscopic system can vary considerably, in other words, particular atoms that are *indistinguishable* from our macroscopic perspective can arrange themselves in various ways. Moreover, he suggested that low-entropy objects are more delicate with respect to such rearrangements. The situations that we characterise as "low entropy" seem to be easily disturbed by rearranging the atoms within them, while "high-entropy" ones are more robust. So the concept of entropy can now be expressed as a measure of the number of particular microscopic arrangements of atoms that appear indistinguishable from a macroscopic perspective.

This new definition of entropy has far reaching implications, not least because entropy is no longer a phenomenological concept of thermodynamics but a concept that can be derived from physical principles linked to a macroscopic system. Moreover, it is now clearer why entropy tends to increase in an isolated system: because there are more ways that atoms can arrange themselves in a system with high entropy than in one with low entropy.

The Universe: the arrow of time and its asymmetry

The Boltzmann definition of entropy while simple in its conception, makes a crucial assumption: that the system starts in a state of low entropy. Although this may seem like a sensible assumption, its implications are far more important. If we assume a system with a high entropy at the start then the system will reach equilibrium and nothing will happen at all. By assuming a low entropy state at the start, we implicitly introduce a *time asymmetry: entropy is low at the start state and not the end one*. And this is exactly the situation we encountered during the Big Bang when the entropy of the Universe was low. For whatever reason, of the many ways we could arrange the constituents of the Universe, at early times they were in a very special, low-entropy configuration.

To deal with this concept of time asymmetry, physicists have introduced the concept of the *arrow of time*. In his book *A Brief History of Time*, Stephen Hawking introduces the thermodynamical arrow of time, as the direction of time in which the entropy of a closed particle system grows, according to the second law of thermodynamics [10]. A classic thermodynamic system consists of a huge number of particles. At the microscopic level, the physical laws governing the motion of an individual particle do not distinguish motion from the future from that from the past. But if we consider the behaviour of the whole system, we will notice that some natural processes never occur in reverse order, even if they do not violate the laws of physics such as conservation of energy. Take as an example a drop of ink. The drop will diffuse into a glass of liquid, however, we will never observe the reverse effect where the diffuse molecules reassemble spontaneously to form the drop (unless we cause it with some artificial intervention in the system).

The initial drop of ink represents a system of high order (and low entropy), just like the young Universe right after the Big Bang. As time goes on (the arrow of time moves in one direction) the ink molecules diffuse in the water, order is destroyed and the entropy of the system increases. So, the arrow of time (the asymmetry) works in such a way that the entropy of the system (or the Universe) increases. It is worth however mentioning that the second law of thermodynamics is a 'statistical law' not an absolute law (like that of the conservation of energy). And although moving from high entropy to low entropy (from chaos to order) is not prevented from a thermodynamical point of view such a move is very unlikely to happen. If this were the case then the arrow of time would be reversible but that has never been observed.

The arrow of time is evident everywhere in the Universe: light from the Sun heats the Earth. As a consequence of the second law of Thermodynamics heat flows from the hot object (the Sun) to the colder object (the Earth). If this process was the only thing happening then there would come a point where the Earth-Sun system would reach equilibrium and the Earth would become a hot and unpleasant planet. Luckily, this does not happen. The reason our planet doesn't reach the temperature of the Sun is that the Earth loses heat by radiating it out into space. This happens because space is much colder than the Earth. Because the Sun is a hot spot in a mostly cold sky the Earth doesn't just heat up, but rather absorbs the sun's energy, processes it, and radiates any excess back into space. Throughout this process, entropy increases. *All these events* are possible because of the second law of thermodynamics. In other words, entropy and the arrow of time enable life on our planet.

So, where does this leave our original argument about symmetry in the Universe? As Nobel Laureate David Gross remarked, if it weren't for symmetry-breaking the world would be an extremely boring place. In every microscopic examination you would see the same thing over and over again.[11]

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11. This essay is reproduced from *The Language of Symmetry* (Eds. Rattigan, Noble & Hatta), 2023