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The Symmetry-Breaking Paradigm

In physics and philosophy, the creation of concepts plays an extremely important role. In philosophy, concepts are essentially created to enable people to think beyond common sense. As typical concepts in philosophy, we can cite the Being and the Becoming, Existence, Space and Time, among many others. In physics, concepts are created to be able to understand experiments in both quantitative and qualitative terms. Concepts in physics are often as abstract as those in philosophy, but they are usually motivated by experiments. This paper addresses a concept that is important in both physics and philosophy: the concept of symmetry and its (spontaneous) breaking.

Symmetry has been one of the most important components of human culture since antiquity. We see its presence in many constructions and objects from antiquity. Its importance was emphasized in Western philosophy for more than two thousand years. One good example of the symmetry paradigm in philosophy is Plato's *Timaeus*. There, the conjectured elementary constituents of the world, i.e. earth, water, air and fire, were associated with the so-called regular polyhedra. Thus, earth, water, air and fire were associated with the cube, octahedron, icosahedron and tetrahedron, respectively. Interestingly, more than 1000 years later, the German astronomer Johannes Kepler proposed a model of the solar system based on these regular polyhedra, now known as Platonic solids (only five planets were known in Kepler's day).

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Like Plato, physicists of the 20th and 21st centuries have used symmetries as a way to understand the universe. The way this is done in modern physics is, of course, much more involved than in Plato's time. Now we know that the four elementary constituents proposed by Plato are not elementary at all, but are themselves constituted by even more basic elements. Our present knowledge states that matter is composed of atoms, each of which is composed of a certain number of electrons, protons, and neutrons. In turn, protons and neutrons are composed of particles called quarks. As in the case of Plato's 'elementary constituents', a symmetry theory underlies the physics of the elementary particles. However, the symmetry paradigm of modern physics contains an additional ingredient known as *spontaneous symmetry-breaking*. This revolutionary new concept of physics is very important, also outside the physics of elementary particles. It is also fundamental in other fields of physics such as solid state physics, for example. Let us try to understand this concept.

Mathematically speaking, symmetry is characterized by the invariance of some mathematical object under some transformation. For example, the parabola $y=x^2$ is symmetrical with respect to the y-axis, since it is invariant under the transformation that takes the variable x and transforms it into –x. In physics, mathematical symmetries imply conservation laws. For instance, translation invariance implies momentum conservation, while rotational invariance implies angular momentum conservation. What is interesting about symmetry in physics is its universal aspect: the conservation laws implied by them occur in classical as well as quantum physics. This aspect of the symmetry paradigm survives quantization. But what is the symmetry-breaking paradigm? If symmetries are so attractive and lead to conservation laws, why break them?

There are two ways of breaking symmetry: explicitly and spontaneously, the latter being more subtle than the former. To understand the difference in simple terms, let us imagine that we are watching people walking in some square downtown in Oslo. On a sunny day, many people will be walking in random directions. Some walk south, others east, while yet others walk towards the northwest. In other words, there is no preferred global direction for the crowd as a whole. Now suppose that someone suddenly starts to do something spectacular from the top of a building in front of the square. Most of the people will simply stop and look up, very impressed. They will all look in the same direction, instead continuing on their ways in different directions. This is an example of explicit symmetry-breaking, where some action external to the behaviour of people in the square makes all of them to behave in the same way, i.e. they all look up. Spontaneous symmetry-breaking, on the other hand, involves a more subtle mechanism. As a general example, we can imagine that a single person among the people walking randomly in the square stops and starts simply to look up in a very curious manner. When someone else notices this, he or she also stops and looks up. This induces others to do the same, i.e. to stop what they are doing simply to look up like the others. Eventually, everyone (or almost everyone) will be looking up and the symmetry will be broken once again.

The difference from the first situation is that it was the interaction between the people there in the square rather than an external agent that led to the uniform behaviour of the crowd. People looked up not because there was something up there that deserved attention, but simply because they saw others looking up. This is an example of spontaneous symmetry-breaking.

One standard example of spontaneous symmetry-breaking in physics is ferromagnetism. Everybody knows that permanent magnets exist. However, not everyone knows how the phenomenon works. In a ferromagnet, the magnetization of the individual atoms composing the material all point in the same direction. In a paramagnet, on the other hand, the magnetization of individual atoms points in random directions. Since the number of atoms is extremely large, all possible directions occur and the system has rotational invariance. This situation is similar to our example of many people walking in different directions. However, in the case of a ferromagnet, there is a preferred direction in space, since the magnetizations of individual atoms point in the same direction. In this case, rotational invariance is broken. Permanent magnets are said to have *spontaneous magnetization*, since no external magnetic field keeps the sample polarized. This is the result of the spontaneous symmetry-breaking caused by the rotational invariance of the magnetization. In ferromagnets, this occurs if the temperature is low enough. In a ferromagnetic substance, an external field is applied to polarize the sample and, as the temperature is lowered below a certain critical value, the external field is switched off and the magnetization still remains. One important aspect of this phenomenon is that the ferromagnetic state is *ordered,* i.e. the magnetizations all point in the same direction. Thus, this example shows that less symmetry implies more order!

A mechanism similar to the one in our example of ferromagnetism occurs in a much more complicated way in a standard model of elementary particles. Here too, less symmetry implies more order. This is actually the main signature of spontaneous symmetry-breaking in general. In the context of the physics of elementary particles, spontaneous symmetry-breaking provides a consistent mechanism by which the masses of particles are generated. Thus, the symmetry-breaking pattern in the standard model explains why some particles have mass while others have not. Most of the remarkable predictions in respect of the standard model are based on this paradigm.

The building blocks of matter, i.e. elementary particles, are understood through symmetry principles. Thus, we see that we owe a great deal to Plato, who believed that symmetry is the key to understanding the universe. Modern physicists agree.