FUNDAMENTAL SYMMETRIES IN MODERN PHYSICS AND THEIR LIMITS

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The concept of symmetry is familiar from geometry where it denotes that certain geometrical properties "look the same" under some transformations. Symmetries also exist in physics where they similarly mean that a physical entity (position, time, theory, etc.) remains invariant when some of its parameters are recombined. A notable example, in this respect, is the special theory of relativity. Thus, if space and time coordinates are replaced by another combination of these coordinates the theory remains invariant.

Such invariances bring symmetry to play a dominant role in physics because they allow it to single out of the complexities of nature certain structures which are characterised by regularity and repetitivity. Indeed, whenever a physical entity is invariant under symmetry operations there usually exists a corresponding conservation law. The space-time symmetries of nature are perfect examples here. Thus, homogeneity and isotropy of space and homogeneity of time are responsible for the conservation of linear momentum, angular momentum and energy, respectively. These are *continuous* symmetries. *Discrete* symmetries also exist. Such are space-reversal, **P** (parity), and time-reversal, **T**. **P** refers to reversing the spatial coordinates (x, y, z) of a physical entity into (-x, -y, -z) and **P** symmetry means that nature does not distinguish between these two coordinate systems; **T** refers to the indifference of nature to the direction of time, i.e., past and future are indistinguishable.

The time-reversal symmetry is of special interest since it seems to be violated in our daily life. Indeed, whereas the equations of classical physics, relativity and quantum mechanics are symmetric (invariant) under time-reversal, there seems to be a fundamental time-asymmetry, a "Time Arrow", in many large scale phenomena in nature. This is particularly noticeable in the second law of thermodynamics. According to this law, entropy, which measures the manifest disorder of a system exhibits a direction, namely, it increases with time. This apparent violation of the underlying time-reversal symmetry, however, can be reasonably explained by the statistical nature of thermodynamics.

The above examples are in the realm of classical physics. However, symmetries are especially important in the "microworld", particularly in elementary particle physics. Indeed, here symmetry arguments together with the mathematics of symmetry, namely, group theory, provide one of the most powerful means in modern physics for developing physical theories. This strength originates perhaps more in what symmetry forbids than what it allows. This is especially noticeable in quantum numbers and selection rules. Some of these quantum numbers are easy to grasp: the mass, the electric charge or the spin. Others have no classical analog. Such are, for example, charge conjugation, **C**, and isotopic spin. **C** refers to viewing particles and their antiparticles as indistinguishable except for their charge and isotopic spin means that the proton and the neutron are viewed as indistinguishable particles (nucleons) differing only in charge. **P** in quantum mechanics may also be added to these examples. Indeed, here **P** means space-reversal of coordinates of wave functions with the result that such a function may assume two states: either even (+) **P** or odd (-) **P**, and this has no classical analog.

With respect to the symmetries of **P** and **C** puzzling symmetry violations were discovered: of the four known interactions (forces) in nature they are symmetries of only the strong interaction (the interaction that holds the nucleons together), the electromagnetic and the gravitational interactions but not of the weak interaction (the interaction that is responsible for radioactive decay). In addition, a certain phenomenon was found in which **T** is also violated. This occurs in the decay of K^0-mesons.

These discoveries are of great significance since it was an "unquestioned" assumption that these symmetries are always exact and fundamental. However, as these discoveries show, they are only approximately so. Another concern related to symmetries is the idea of the existence of exact fundamental symmetries which are subsequently "spontaneously broken". This was a crucial idea in unifying the weak and electromagnetic interactions into one theory, the electroweak theory, in which these two interactions are viewed as two manifestations of a single electroweak interaction. The theory is based on exact symmetries ("gauge symmetries") whereas the lack of symmetry which is generally encountered at the observed level, is attributed to the phenomenon of "spontaneous symmetry breaking" (this idea is also behind the attempts to unify all the interactions of nature into one scheme: the "grand unified theory" (GUT)).

This idea is related to the consideration of the state of the temperature of the universe. Thus, when the ambient temperature of the universe was greater than a certain critical temperature, the physical phenomena respected full symmetry but below this temperature symmetry breaking occurred spontaneusly and left only partial symmetry. This is analogous to the phenomenon of ferromagnetism. Thus, if a bar of iron is above a critical temperature the atoms are at random motion and have full rotational symmetry but when the temperature drops below this critical value the atoms spontaneously allign themselves collectively into a certain direction and the state then has only axial symmetry. Thus, the full rotational symmetry is spontaneously broken.

The above idea explicitly assumes the existence of *exact fundamental* symmetries which are only *subsequently* broken. So, why should one be concerned about these symmetries? The problem is that it raises the following essential question. Is the symmetry indeed to be taken at the fundamental level and the breaking of this symmetry as something more superficial, or is the symmetry itself superficial, being an apparent and approximate phenomenon emerging out of underlying ingredients that do not actually possess this symmetry (Penrose 1993)? As a matter of fact, other routes exist in which effectively the currently accepted electroweak theory may be achieved but where the symmetry is considered as being superficial and not of fundamental nature (Llewellyn Smith 1973).

Thus, the previously mentioned violations of **P, C, T** and the idea of symmetries which are spontaneously broken raise, respectively, the following concerns about fundamental symmetries in physics: 1) that such symmetries may be exact only within a limited domain, and 2) that underlying symmetries of a theory may not be as fundamental as they are assumed to be even if such assumptions are behind a theory which is fruitful. Therefore, any discussion of the outstanding success of fundamental symmetries in modern physics must necessarily also address these concerns. The present paper will proceed along these lines.

Llewellyn Smith, C. H. (1973), in *Links between Weak and Electromagnetic Interactions*, Rutherford Lab. Report RL-73-018.
Penrose, R. (October 1993), *Nature's Biggest Secret*, The New York Review of Books, p. 80.