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Symmetry in Physics – A Perspective

Physics is a natural Philosophy and the law of nature, it is ought to be symmetric!

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Abstract: This article attempts an introductory short journey of symmetry for appreciating its need, importance, inherence and consequences in Physics in a simpler manner suitable for the general reader.

Generally, the word "symmetry" immediately reminds you some systematic regularity in geometry (or shape or space or topology) which you see around in Nature. Various objects, buildings, rangoli and the likes all possess some kind of symmetry, lower or higher. These are examples of geometrical (or spatial or topological) symmetry. However, the concept of symmetry in Physics is not limited only to this. There are several other kinds of symmetry in Physics, some of which I will discuss in this article.

Let me formally define "symmetry" in the most general way: when you perform some operation on an object, if the object looks the same after this operation, that is, it is invariant under this operation, the object is said to possess symmetry. This formal preliminary definition has the essentiality of the operation, the object and its invariance under the operation. The definition is open for both, the kind of object and the type of operation. Take a simple example of a square to understand. Rotating the square in its plane around the central perpendicular axis clockwise (or anti-clockwise) by 90◦, or by 120◦, 270◦, or 360◦ leaves the square looking the same, that is, invariant under these operations. A few other operations, such as reflection across its own plane and perpendicular planes will also leave the square invariant. Rotations and reflections are termed as symmetry operations and their corresponding axes and planes are known as symmetry elements. Doing nothing can also be considered as a symmetry operation as it leaves the object same. Very interestingly, this set of symmetry operations follow mathematical laws (or theory) known as 'Group Theory' abstractly developed by mathematicians. Once they have mathematical structure, it is quite easier to adopt them in Physics. Similarly, other geometrical shapes such as triangle, pentagon and hexagon also possess symmetry (or symmetry elements). A circle is totally symmetric if it is rotated by any angle about an axis passing through its center and being perpendicular to the plane. We can extend these to any arbitrarily shaped three dimensional objects to find their symmetry elements as well. Thus, we can systematically build the folders called 'Symmetry Groups' starting from no symmetry element to maximum symmetry elements to classify any object. Obviously, any object belongs to one of these logically formed groups in increasing order of symmetry starting from no symmetry group.

The physics of all molecules (simplest to most complicated) is completely governed by this symmetry. Almost all properties of the molecules can be predicted, analyzed or calculated from their spatial symmetry, especially, their vibrational properties such as Infrared and Raman spectra. However, it should be noted that their vibrational frequencies cannot be calculated from the knowledge of their symmetry. Number of vibrations whether they can appear in Infrared or Raman spectra can be predicted very accurately which greatly helps in the analysis of measured spectra. On a lighter note, the symmetry group of a molecule can be treated as its "horoscope"!!! Since a solid can be treated as a systematic assembly of molecules, they also possess symmetry and can be largely understood and analyzed in a similar way. Therefore, the spatial symmetry governs largely the assembly of atoms or larger entities. Spatial symmetry is easy to comprehend as we have seen so far. Spatial symmetry is of no use for atomic and subatomic entities such as proton, neutron, electron and all other elementary particles because all atoms are spherical which is totally symmetric and we cannot classify them by their spatial symmetry. Therefore, we can explore other kinds of symmetries which may be hard to comprehend for the general readers. Nevertheless, I will mention and touch them only to the extent that can be appreciated. Symmetry plays an incredibly important and essential role in Physics.

Let me now mention a few (if not all) important other types of symmetries in Physics, However, only for the purpose of appreciation, I will very briefly mention their context without much technicality as it will be out of scope for the general reader.:

- ✓ *Space-time symmetry*: related to invariance under space and time operations or transformations. That is, the invariance of the outcomes of the experiments carried out at any place at any time. They can be identified in classical mechanics. However, more necessary and important to fundamental Physics, the space-time symmetries are required for the special theory of relativity as well as quantum-mechanics.
- ✓ *Gauge symmetry*: Required for the choice of local phases in wave functions that can fix the interaction between concerned particles or the four fields that mediate the interactions. The four fundamental fields, namely, gravitational, electromagnetic, weak and nuclear forces (or forces of nature) possess this symmetry.
- ✓ *Dynamical symmetry*: These are the symmetries largely encountered in Quantum Physics and therefore, the most important for atomic, nuclear and sub-nuclear physics as they determine the spectral properties of these quantum systems.
- ✓ *Permutation symmetry*: It is concerned with the invariance of wave functions of many particle systems with the exchange of particles. This symmetry leads to two distinguished basic entities in fundamental physics, known as the boson and fermion.
- ✓ *Duality symmetry*: It refers to the mapping of two theories or two different descriptions of a theory mutually exchangeable. Famous example is the self-duality of Maxwell's theory. That is, Maxwell's equations are invariant under the exchange of electric and magnetic fields. However, without this the separate descriptions of electricity and magnetism seemed much more complicated and

would have taken many more words or equations to narrate. Maxwell was the first to see and identify this hidden symmetry. Another very well-known simple example is the invariance of Quantum Physics under the two different representations, known as Schrödinger's wave equation or Heisenberg's matrix mechanics.

Therefore, invariance of an entity exclusively indicates its symmetry under the concerned transformations/operations and the two are almost synonymous. Very interestingly, in 1918 Noether's theorem provided a fundamental connection between symmetries and conservation laws deriving conserved quantities from symmetries, stating "For every continuous symmetry of a physical system, there is a corresponding conservation law". This theorem is crucial for understanding how symmetries in nature lead to conserved quantities like energy, momentum, and angular momentum. For instance, time translation symmetry leads to the conservation of energy. Conservation of momentum corresponds to the space translation symmetry. Similarly, the rotational symmetry gives rise to conservation of angular momentum. Therefore, this theorem indicates that the "Laws of Physics" are consequent of conservation laws those come directly from symmetries.

However, till the 20th century symmetry was not taken so seriously or ignored without understanding its importance, essentiality and inherence in Physics, especially in theoretical Physics, although Greeks believed that symmetry is the part of structure of Nature. Kepler tried to impose symmetry on the motion of planets in his laws. Principle of equivalence of inertial frames, or Galilean invariance indicates the inherent symmetry in Newton's laws. These symmetries imply conservation laws. However, conservation laws of momentum and energy were treated of fundamental importance, regarding them as the consequences of dynamical laws of Nature rather than as due to symmetries underlying these laws. Even Maxwell's equations formulated in 1865 were both Lorentz invariant and gauge invariant. However, the importance and requirement of these symmetries of electrodynamics were not fully appreciated for many years till the beginning of 20th century.

The heroic eminence of Einstein completely changed this scenario in 1905 by bringing the symmetry to frontline, regarding the symmetry principles as constraining the dynamical laws of Nature. He showed that the transformation properties of the electromagnetic field are the consequences of the relativistic invariance which indeed largely dictate the form of Maxwell's equations. This profound change in attitude resulted in elevating the symmetry of Maxwell's equations to the symmetry of space-time itself. With his construction of general relativity, the symmetry witnessed a spectacular success leading to the principle of equivalence (a principle of local symmetry, the invariance of the laws of nature under local changes of the space-time coordinates) which dictated the dynamics of gravity and of space-time itself. Further, the development of quantum mechanics in the 1920s, symmetry came to play an even more fundamental role. Since 1920 and later, symmetry has been the most dominant and necessary concept in the exploration and formulation of the fundamental laws of physics. Undoubtedly, today it is a guiding principle in the search for further unification and progress in Physics.

I quote here few statements or opinions of well-known theoretical Physicists of 20th century for the benefit of the readers to understand and appreciate how important and inseparable symmetry is in Physics.

- " . . . if we knew all the laws of nature, or the ultimate Law of nature, the invariance properties of these laws would not furnish us new information" E.Wigner
- "As far as I see, all *a priori* statements in physics have their origin in symmetry" H. Weyl
- "The most important lesson that we have learned in this century is that the secret of Nature is symmetry. Today we realize that symmetry principles dictate the form of the laws of nature" D. Gross
- "Symmetry principles have moved to a new level of importance in this century and especially in the last few decades: there are symmetry principles that dictate the very existence of all the known forces of nature" S. Weinberg

- "... profound guiding principles are statements of symmetry" F. Wilzcek
- "If you can identify Nature's complete symmetry group, you will know everything" Gerard 't Hooft.

In fact, many of us are already symmetrophobic even if you are not aware of it. For instance, we always say "It is not looking nice or something is wrong" when we see at any slightly asymmetrical structure or object. Even a slight asymmetry is noticed anywhere you see without any training. Lastly, I think symmetry is everywhere even if you do not notice. Even philosophically, the invariance of mind under both happiness and sorrow as mentioned in *Bhagavdgeeta* as *Sthitaprajna* indicates the symmetry of the mind.

After all, Physics is a natural Philosophy and the law of nature, it is ought to be symmetric!!!

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