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Editorial: symmetries and asymmetries in physics

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The present *Topical Collection* focuses on a cluster of much debated issues in the philosophy of physics having to do with the topic of symmetries and asymmetries in physics. The idea behind this editorial initiative had its origin in a series of conferences and workshops that the Guest Editors organized or co-organized, namely the conference "Symmetries and Asymmetries in Physics" at the Institute of Philosophy at the Leibniz University of Hannover (July 7–8, 2017), the workshop "With and without Measure: Symmetry and Symmetry Breaking" in the Munich Centre for Mathematical Philosophy at the Ludwig-Maximilians University (June 20, 2017), and the workshop "Symmetry and Equivalence in Physics" at the Department of Philosophy at the University of Salzburg (September 3–4, 2019). The collection includes some of the contributions presented at these events as well as articles selected through a Call for Papers. Below we first discuss the main philosophical issues germane to the topic of symmetries and asymmetries in physics, and then briefly introduce the individual contributions to this collection.

Historically, the concept of symmetry has both aesthetical and geometrical underpinnings and originally referred to the proportion and harmony between the distinct elements composing regular geometric figures, thereby conveying a sense of beauty and unity of the whole. Subsequently the notion of symmetry began to refer to the possibility of interchanging different parts of a figure without changing the whole figure, for example when one carries out the reflection of the two halves of a square with respect to a diagonal. The geometrical interchangeability of equivalent parts was then generalized to abstract algebraic objects, thus leading to the modern understanding of symmetries in terms of invariance under a given group of transformations. This makes

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mathematically precise the idea of partitioning a collection of objects into equivalent classes, and it is the meaning of symmetry typically adopted in contemporary physics. Indeed, our best physical theories feature various laws that can be characterized in terms of invariance under symmetry transformations. Specifically, a law is invariant under a given transformation just in case it maintains the same form before and after the relevant transformation is applied. Symmetry principles positing the laws' invariance under various transformations turn out to be one of the most effective heuristic and theoretical tools in the search for laws of Nature.

For instance, in non-relativistic classical mechanics, the Galilean symmetry group connects different inertial reference frames in uniform motion with respect to each other by providing transformation rules for the equations of motion. One can show that the formal structure of the dynamical laws of the theory is preserved under Galilean boosts. This reflects the fact that no experiment can detect any difference between relative states of motion of reference frames. Galileo's defense of the Copernican model of the universe against the stationarity of Earth was originally based on such a symmetry argument. Later on, with Einstein's formulation of special relativity at the beginning of the twentieth century, the appeal to symmetry reasoning got elevated to an even more fundamental status: the theory hinges on the postulate that the dynamical laws of electromagnetism are preserved under the Poincaré symmetry group, which in turn underlies the unification of space and time into a four-dimensional manifold. Accordingly, invariance under symmetries informs the geometry of spacetime, a fact that was further enforced by the construction of general relativity based on the principle of covariance. Noether's 1918 famous theorems then forged a formal connection between global and local symmetries with conservation laws.

Likewise, quantum mechanics also employs a symmetry principle, and it does so with a direct application of group theory. In fact, as Heisenberg first observed in 1926, different ensembles of indistinguishable particles, namely bosons and fermions, can be identified on the basis of their statistics being invariant under the permutation group. In fact, this was the first instance of the use of non-spatiotemporal symmetries in contemporary physics. More generally, in quantum theory one represents the relevant group of symmetries defined over a system's state-space by means of operations corresponding to what one takes to be physical observables. The peculiar phenomenon of superposition of states can thus be associated with the existence of the so-called irreducible representations: in particular, as Wigner argued in the 1930s, irreducible unitary representations of the Poincaré group for non-negative energy serve to characterize the invariant properties of elementary quantum systems. The proposed scheme has undergone further refinements to a point that it has now become a standard technique for the search and classification of fundamental particles.

Contemporary physics abounds with many other examples of the application of symmetry principles, especially in sub-atomic theories and spacetime theories. In light of this, one is prompted to ask whether the significance of symmetry principles goes beyond their mere methodological function of providing heuristic and theoretical guidance. Indeed, there arise several philosophical questions concerning ontology, as well as epistemology. To wit: Do physical symmetries reflect the structure of the world or should they be considered superfluous surplus structure that one should remove from the theory? If the latter, how should we remove this surplus structure? Different symmetries may have different implications for possible answers to this question. What kind of symmetries are there and how should they be categorized? How are symmetries related to questions of physical equivalence and inequivalence?

While these open problems deal with the status of symmetries, equally important from both a physical and a philosophical perspective are issues stemming from the failure of invariance principles. Indeed, the so-called 'breaking' of symmetries is a wide-spread phenomenon. How, then, should we understand this latter concept? A particularly important class of asymmetries, which have been the subject of long-standing controversies, are temporal asymmetries. Examples are the asymmetry of macroscopic phenomena embodied in the Second Law of thermodynamics or the radiation asymmetry, according to which we naturally observe radiation coherently diverging from a source but not coherently converging radiation. Nevertheless, the dynamical laws of our best microscopic theories are invariant under time-reversal (or so it is often argued). Lots of ink has been spilled over the question of how to account for the thermodynamic asymmetry and the asymmetry of radiation in a world with time-reversal invariant micro-laws, but a consensus has yet to emerge.

Another unresolved issue concerns symmetry-breaking, for example in phase transitions, when matter suddenly moves into another state characterized by different symmetries. The first systematic analysis of this issue was Pierre Curie's study of the behaviour of crystals towards the end of the nineteenth century, which relates symmetries and causality. According to him, in order for a phenomenon to take place in a medium, the symmetry group of the latter must be lowered (and hence broken) to the symmetry group of the former, for effects cannot be more symmetrical than their own causes. In other words, as Curie put it, it is the asymmetry with respect to the medium that, so to speak, creates the phenomenon. Be that as it may, most cases of interest in contemporary physics manifest themselves for quantum systems with infinite degrees of freedom, like in quantum field theory, where a ground state, e.g. the vacuum, does not remain invariant under the relevant symmetry transformation but it is mapped onto another ground state, owing to the unitary inequivalence between the respective irreducible representations. Symmetry-breaking is actually implemented in the Standard Model of elementary particles and is underlying Goldstone's theorem and the celebrated Higgs mechanism.

Finally, it is worth stressing that the discussion of symmetries and asymmetries in physics has further ramifications for the topic of equivalence between theories. To see why that is the case, recall that the two competing versions of non-relativistic quantum mechanics originally proposed by Schrödinger and Heisenberg, respectively, were proven to be equivalent, and thereby subsumed under the same Hilbert space formulation of the theory, via the Stone-von Neumann theorem, which establishes the uniqueness up to unitary equivalence of the representations of the canonical commutation relations. So, since by Wigner's theorem quantum symmetries are implemented by unitary operators, the possibility of connecting different theoretical descriptions by means of symmetry transformations is often taken to underwrite their equivalence. In a similar vein, symmetry-breaking calls physical equivalence into question, as in the case of unitary inequivalent vacuum representations in quantum field theory. The issue whether, and in what sense, two theories are equivalent or not can be cast in terms of the concept of dualities, which extends the idea of symmetries acting on the state-space of a single theory to general transformations between theories. For example, such a concept enables one to connect Lagrangian and Hamiltonian theories on the basis of the symmetry encoded in the canonical map preserving the symplectic structure of classical phase-space. Furthermore, it is usefully employed in the treatment of more sophisticated cases concerning the ongoing development of fundamental theories, most notably the relationship between quantum field theory and string theory in terms of the gauge-gravity duality.

This topical collection covers the various applications of symmetry and asymmetry in modern physics. We will now give a brief overview of the papers included in this topical collection.

When we speak of two theories being equivalent to each other, being related by some symmetry transformation or being dual to each other, we always mean that there is something that remains the same under some given change. This calls for an analysis of how the concepts of symmetry, duality and theoretical equivalence bear on each other. Recently, De Haro and Butterfield (2018); De Haro (2020) have proposed a general formal schema for dualities. Two contributions of the topical collection rely on such a formal schema in order to assess how dualities bear on the concepts of theoretical equivalence and symmetry, respectively. Much of the literature on theoretical equivalence has been concerned with providing a formal account of theoretical equivalence. In the first essay, **Sebastian de Haro** offers a duality-inspired conceptualization of theoretical equivalence, which emphasizes the methodological importance of a semantic interpretation based on isomorphisms between models. As he argues, the interpretative lessons he draws from his purported analysis should impact more generally any account of theoretical equivalence in the physical sciences. In the other relevant essay, **Sebastian De Haro** and **Jeremy Butterfield** discuss in detail the formal schema's conception of models and theories, which they then apply to the concept of symmetry. Their guiding idea is that dual theories correspond to isomorphic representations of a common core, namely the bare theory, intended as the theory devoid of any interpretation. The systematic study of the relation between the symmetries of the bare theory and the symmetries of one of the dual theories then leads them to provides a partition of symmetries into three mutually exclusive classes: stipulated and accidental symmetries of the theory as well as proper symmetries of models.

The next contribution takes up a connected, albeit somewhat orthogonal, issue that has recently received much attention (De Haro and Butterfield themselves briefly comment on it at the end of their Sect. 1). That is, given that different models of a theory may be related by symmetries, should these symmetry-related models be regarded as physically equivalent? And what does that entail for the ontology of these related models? **Niels Martens** and **James Read** address these distinct questions by arguing against a recent prominent proposal by Dewar (2019). One oft-discussed strategy, concerned with the second question, is to focus on the invariant features across the symmetry-related models and construct an ontologically more parsimonious theory out of it by relying only on the invariant structures. This, however, can lead to explanatory deficits within the so-called reduced theory, which Dewar's "sophisticated" approach does not seem to suffer from. Martens and Read critically assess the viability of Dewar's proposal and argue that while Dewar's "sophisticated" approach does have certain explanatory advantages, these do not quite hold universally.

Just as the presence of a symmetry prompts questions concerning how to characterize equivalence, the fact that a symmetry is broken, in the sense that some property fails to remain invariant under the relevant transformation, raises the problem whether distinct mathematical descriptions connected by such a transformation are physically equivalent or inequivalent. In particular, that is a controversial issue in the literature on quantum symmetry breaking. In his contribution, **Giovanni Valente** counters a claim by Baker (2011) to the effect that, even though they give rise to unitarily inequivalent representations, the two ground states of a ferromagnet would be physically equivalent due to the fact that they are connected by the so-called flip-flop symmetry. Based on an analysis of the mathematical and conceptual intricacies of symmetry breaking in quantum theory, especially in relation to Wigner's (1931) famous result on the preservation of transition probabilities, Valente details the reasons why the two ground states correspond to empirically distinct thermodynamical phases, and hence they must be regarded as physically inequivalent.

In her contribution, **Arianna Borrelli**, provides a historical and epistemological analysis of the concept of spontaneous symmetry breaking, which she claims provides an "overarching framework for conceiving the relationship between symmetry and asymmetry". A common assumption underlying much of the conceptual analysis regarding theoretical constructs in high energy physics relies on the idea that most concepts allow for a purely logico-mathematical analysis. Relying on the concept of narrative knowing, Borrelli argues against this widespread attitude and regards spontaneous symmetry breaking as a multi-medial narrative, comprising mathematical formulas, verbal statements, images, and other media, which work together within a narrative to provide us with an understanding of what spontaneous symmetry breaking is. Thereby, she does not only provide a fuller picture of spontaneous symmetry breaking but also argues more generally for the constitutive epistemic role of narratives in science.

In another contribution of this collection, **Vincent Grandjean** tackles what is probably the most apparent case of asymmetry in our universe, namely that holding between a putatively open future and a fixed past. The problem at stake is how to philosophically ground the intuition that, while we can affect what will happen, there seems to be no way to affect the past. Grandjean offers a much-needed survey, covering alethic, epistemic, metaphysical and ontological ways of characterizing the temporal asymmetry by taking into account relevant elements from the literature both in the philosophy of physics and in metaphysics. He argues that an ontological characterization of the asymmetry is preferable to other available characterizations due to its explanatory advantages, as well as to its ability to capture an interesting sense of openness.

So far, we have been talking about symmetries as if they are either exact or broken. However, in scientific practice one often encounters symmetries that are only approximate. To provide and fruitfully apply a formal explication of the concept of approximate symmetry is the focus of **Samuel C. Fletcher**'s final contribution in this topical collection. Approximate symmetries are often either associated or identified with broken symmetries, or alternatively they are related to exact symmetries in the sense of reducing their range of applicability. Fletcher provides good reasons for why one should consider approximate symmetries to be a distinct concept. In his formal explication he turns the standard perspective around by making exact symmetries a special case of approximate symmetries. This characterization is then used by Fletcher as a "tool" to provide a novel perspective on symmetries in the context of inter-theoretic reduction, on the Curie-Post principle and on the concept of accidental symmetries. Further fruitful applications of the proposed formal explication are also suggested.

The essays featured in this topical collection thus illustrate the continued importance of symmetries and asymmetries in modern physics and its significance for many technical and conceptual discussions in philosophy of physics, as well as in philosophy of science broadly-construed. Beside contributing to the existing literature with respect to specific open problems, the contributions to this collection also suggest and develop new lines of research that deserve further enhancement and critical scrutiny, especially regarding the ontological and epistemological status of symmetries, the application of the invariance principle, the understanding of different instances of symmetry-breaking, and the evaluation of physical and theoretical equivalence. Among the various prospects for future work, we would like to emphasize a somewhat broader aspect of the topic that calls for further elaboration, namely the need to connect the mathematical treatment of the relevant issues, which is often applied at a meta-level of discussion, with the actual practice of physicists involved in using symmetry-based methods to investigate the natural world. We think that forging such links requires a balanced interplay between focusing on concrete case-studies, both historical and current, and the development of formalisms that can relate and encompass their distinctive features in accordance with that scientific practice. Arguably, this can lead to a more overarching philosophical comprehension of the multi-faced topic of symmetries and asymmetries in physics.

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