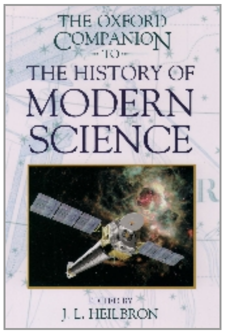

The Oxford Companion to the History of Modern Science
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Publisher: Oxford University Press
Print ISBN-13: 9780195112290
eISBN: 9780199891153
Print Publication Date: 2003
Published online: 2003

symmetry and symmetry breaking.

The modern scientific notion of symmetry begins with the geometric symmetries of objects, both mathematical and physical. A perfect snowflake rotated through 60° about its center is indistinguishable from its original appearance. Rotation through 90°, however, yields an appearance distinguishable from both. Rotating the snowflake transforms it relative to something external. Symmetry transformations of an object leave the initial and final states indistinguishable (at least with respect to the properties we specify as relevant). This concept of symmetry— indistinguishability under transformations— has blossomed in science over the past 400 years. Here, three developments are fundamental: the extension of the concept to "physical symmetries," the development of group theory and its scientific applications, and the increasing importance of "symmetry-breaking."

In science, the distinction between geometric and physical symmetries is the distinction between symmetries of objects and of laws. An object may fail to possess a given geometric symmetry, and still evolve in accordance with laws that do possess that symmetry. For example, a chair is not rotationally symmetric (turn it through any angle other than 360° and the initial and final positions will be distinguishable), but since the laws of nature are rotationally symmetric in the absence of external influences, the natural behavior of the chair does not change with the direction it faces.

Galileo made an early and famous application of a physical symmetry in the debate over the system of Copernicus. Opponents of heliocentrism claimed that if the Earth moved around the Sun, the behavior of terrestrial objects would show it. In his *Dialogue Concerning the Two Chief World Systems* (1632), Galileo claimed that no such observations are possible, and he argued for this using an analogy with a ship. He pointed out that someone shut up in a windowless cabin on a ship would be unable to distinguish by means of any experiments carried out within that cabin whether the ship was at rest or in smooth, uniform motion. This so-called "Galilean relativity" is a symmetry of space and time; it quickly found its way to the heart of seventeenth-century natural philosophy, being used by Christiaan Huygens in his solution to the problem of colliding bodies, and appearing in Newton's *Principia* as Corollary V to his laws of motion. The Galilean group of symmetries also includes spatial translations and rotations, and temporal translations. The principle of relativity remains at the heart of modern physics as one of the two postulates of Einstein's 1905 special theory of relativity. Here, however, it belongs to a different group of space-time transformations, the Poincaré group. This brings us to the second key development: group theory in mathematics.

The group concept emerged from developments in late eighteenth- and early nineteenth-century mathematics. In the early 1830s, Evariste Galois used discrete groups (groups consisting of a finite number of elements) to characterize polynomial equations via the structural properties of their solutions. In the 1870s, Sophus Lie set about extending Galois's theory from algebraic equations to differential equations, and this led him to the concept of continuous analytic groups (Lie groups). Felix Klein's 1872 “Erlanger Program” used group theory to characterize geometries, putting NON-EUCLIDEAN GEOMETRY (so important for the general theory of relativity) on an equal footing with Euclidean geometry.

One of the first applications of group theory in science was in CRYSTALLOGRAPHY. René-Just Haüy had used symmetry to characterize and classify crystal structure and formation in his *Traité de mineralogie* (1801). With this application, crystallography emerged as a discipline distinct from mineralogy. From Haüy's work, two strands of development led to the 32 point transformation crystal classes and the 14 Bravais lattices, all of which may be defined in terms of discrete groups. These were combined into the 230 space groups by E. S. Fedorov (1891), Artur Schönflies (1891), and William Barlow (1894). The theory of discrete groups continues to be fundamental in SOLID STATE PHYSICS, CHEMISTRY, and MATERIALS SCIENCE, and in QUANTUM FIELD THEORY through the CPT (charge conjugation, parity, and time-reversal) theorem.

Continuous symmetries come in two kinds: global symmetries, such as Galilean translations and rotations, and local symmetries, such as the gauge symmetry of ELECTROMAGNETISM and the invariance under general coordinate transformations of the field equations of general relativity (1915). The importance of continuous symmetries in physical theories, and the power of symmetries in theory construction, was increased in 1918 when Emmy Noether proved the existence of a general connection between continuous symmetries and conserved quantities, and shed new light on the structure of theories with continuous local symmetries. Group theory and symmetries can provide powerful constraints on theories. For example, in particle physics global symmetries are used to classify particles and to predict the existence of new particles, such as the omega-minus particle (predicted in 1962, detected in 1964) via the SU(3) symmetry classification scheme. In 1918, Hermann Weyl introduced local scale symmetry to construct his unified theory of gravitation and electromagnetism, intended to succeed the general theory of relativity; this theory failed, as did the 1954 proposal of Chen Ning Yang and Robert Mills, today credited as the first “modern” local gauge theory. Following the developments of the 1970s, however, theories with local gauge symmetry have come to dominate fundamental physics.

Symmetry breaking has become as important in modern science as symmetry itself. In 1894, Pierre Curie highlighted the importance of symmetry breaking and asserted the so-called “Curie principle”—that an effect cannot be less symmetric than its cause. This assertion was challenged in the 1950s in two ways. First, the phenomenon of spontaneous symmetry breaking came to the attention of physicists in the context of superconductivity (and was later reapplied in the context of QUANTUM FIELD THEORY). In fact, the symmetric solution of a symmetric problem may be unstable; in such cases, the observed stable outcome will be less symmetric than the cause, in apparent violation of Curie's principle. Nevertheless, theoretically there exists a set of equally likely effects (only one of which is observed in any given instance) that together possess the symmetry of the cause, and in this “sophisticated” sense, Curie's principle survives the challenge of spontaneous symmetry breaking. The second challenge is the violation of parity, in which one possible outcome of an experiment dominates its mirror-image. This violation, predicted by Tsung Dao Lee and Chen Ning Yang in 1956, was detected soon afterward experimentally by Chien Shiung Wu and her colleagues. The law governing the weak nuclear interaction breaks the symmetry, and the Curie principle can only be saved by including the law within the cause.

During the latter half of the twentieth century, spontaneous symmetry breaking also became important in biology. Brian Goodwin described one such application in *How the Leopard Changed Its Spots* (1994). All organisms start off as highly symmetric entities, such as a single spherically symmetric cell. As the organism grows, this highly symmetric state becomes unstable, owing either to internal stresses and strains, or to influences from the environment. Enter spontaneous symmetry breaking: the organism will move to one of a set of possible stable, but less symmetric, states. In this way, the dynamics of stability and spontaneous symmetry breaking constrain the possible general forms that an organism may take during its growth. Which of the possible states the organism moves to at each stage can be controlled internally (by a nudge from the DNA, for example) or by the environment (through temperature or a chemical). All this has radical implications for the theory of EVOLUTION. On the standard Darwinian approach, evolution is free to explore a huge variety of possibilities, constrained only in general terms by the laws of physics and chemistry. This approach leaves us several major puzzles, two of the most important being the emergence of the same general forms in different lineages, and the fact that we don’t see evolution exploring all possibilities, but instead a rather limited subset. A response to this is to suggest that the domain of the “biologically possible” is highly constrained by dynamical stability, in which spontaneous symmetry breaking plays a key role.

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