Symmetry breaking from physics to biology

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What is the developmental source of biological form? The question preoccupied natural philosophers from Aristotle to William Harvey to Rudolf Virchow, and it remains debated today. Early ideas assumed that biological form was either already manifest in some way within the embryo – the preformationist idea, famously illustrated by the Dutch mathematician and microscopist Nicolaas Hartsoeker's drawing of the homunculus in a sperm in the seventeenth century – or emerged via the guidance of a kind of life force or soul, as Aristotle asserted: the essentially teleological position called epigenesis. We might now regard both theories as sleights of hand designed to circumvent rather than to explain what is now seen as an example of symmetry breaking.

With the emergence of modern genetics, questions about form in biology became questions about genes: the phenotype of the developing organism was considered to be programmed by the genotype. DNA could in this view be regarded as a kind of informational homunculus: form already existed in the embryo, but in an encoded format, which Erwin Schrodinger famously called the "code-script" of life.

In his approach to the origins of embryogenesis, Alan Turing was thus going against the grain. It may be partly for this reason that his 1952 paper on morphogenesis had little impact for several decades. His approach follows the physical scientist's instinct to express the problem at hand in the simplest possible terms, and then to explore what the minimal requirements are of a model that captures the essential phenomena. Turing pointed out that the question of how an embryo develops and acquires shape and form – bilateral symmetry, say, and the budding of limbs – seemed indeed to be one of spontaneous symmetry-breaking.

In this presentation I shall set out to explore how, by expressing the question in this manner, Turing aligned it with what is arguably the major theme of twentieth-century physics.

Perhaps the first intimation of the role of symmetry in physical processes was expressed in 1894 by Pierre Curie in a paper titled "On symmetry in physical phenomena". Here he asked the question: what is the relationship between the physical and the symmetry properties of a system? Curie stated the fundamental principle of symmetry breaking by saying that some phenomena occur when a symmetry is *removed*: he said that "asymmetry is what creates the phenomenon".

In Curie's doctorate in the early 1890s on magnetism, he reported that ferromagnets such as iron will lose their magnetism when heated: this falls to zero at a temperature now called the Curie temperature. The onset of spontaneous magnetization by cooling through the Curie temperature occurs when random orientations of the atomic spins due to thermal motion switch to a collective state of mutual alignment.

This phase transition was studied in the 1920s using the Ising model, a lattice model developed by Wilhelm Lenz and his student Ernst Ising. It was soon appreciated that the same model could be used to represent the transition between the gaseous and liquid states of matter, as investigated in the 1870s by Johannes Diderik van der Waals. Here the presence of a particle at a point in the lattice denotes the liquid, while its absence denotes a gas. Cooling a magnet through its Curie temperature then looks equivalent to cooling a fluid through its critical point, where the uniform symmetry of the supercritical state breaks to permit two distinct phases of differing density.

This connection was arguably the first glimpse of *universality* in physics: the idea that there is a deep parallel between systems that look superficially as though they share nothing in common. It stems from the fact that many-body behaviour often does not discriminate between the fine differences in the natures of those bodies: all that matters are the general features of how they interact, such as how many neighbours feel the influence of each body and the dimensionality of the system.

The 1956 proposal by Tsung Dao Lee and Chen Ning Yang that the weak interaction might break left-right symmetry (parity violation), experimentally confirmed by Chien-Shiung Wu that same year in experiments on beta decay, opened the path for the unification of the electromagnetic and weak interactions. The idea was developed in the 1960s by Sheldon Glashow and Abdus Salam, who had to introduce the symmetry breaking by hand. Their theory predicted three massive new bosons, later identified with the W and Z bosons that mediate the weak force, along with the massless photon. In the later 1960s Steven Weinberg showed how this symmetry breaking could happen spontaneously. The theory was verified by the discovery of the W and Z bosons in CERN's Proton-Antiproton Collider in 1983.

This Nobel-winning work on electroweak symmetry breaking was intimately tied up with the theory of the Higgs field and the Higgs boson. The fundamental insight here came in the late 1950s from theoretical physicist Yoichiro Nambu, who saw an analogy between the theory of superconductivity and quantum field theory. The idea won Nambu the 2008 Nobel prize for "the discovery of the mechanism of spontaneous broken symmetry in subatomic physics". But Nambu's work raised new problems, and it was by resolving them in the early 1960s that Peter Higgs and others concluded that space is permeated by the Higgs field, which exerts a drag on the particles and so affords them mass.

Turing's work on morphogenesis takes on a different complexion when considered against this context. Symmetry breaking is, one might say, nature's way of making many from one: of developing complexity out of simplicity. In this way it offers a kind of order and form for free: a distinction between a *here* and a *there* in what was initially a homogeneous system. Biology, it is now clear, exploits this source of organization to produce structure at scales well beyond the molecular. Turing's mechanism is just one among several now known to feature in the living world at scales ranging from the cellular to the ecological.

The broader question is how the palette of shapes and patterns available from spontaneous symmetry breaking interacts with natural selection. To what extent can evolution adapt and modify Turing structures, for example? Are all such structures necessarily adaptive at all? Or are we too readily tempted, when we see order and regularity in biology, to attribute a function to it? Might some of it, at least, represent nothing more than the intrinsic creative potential in the natural world?