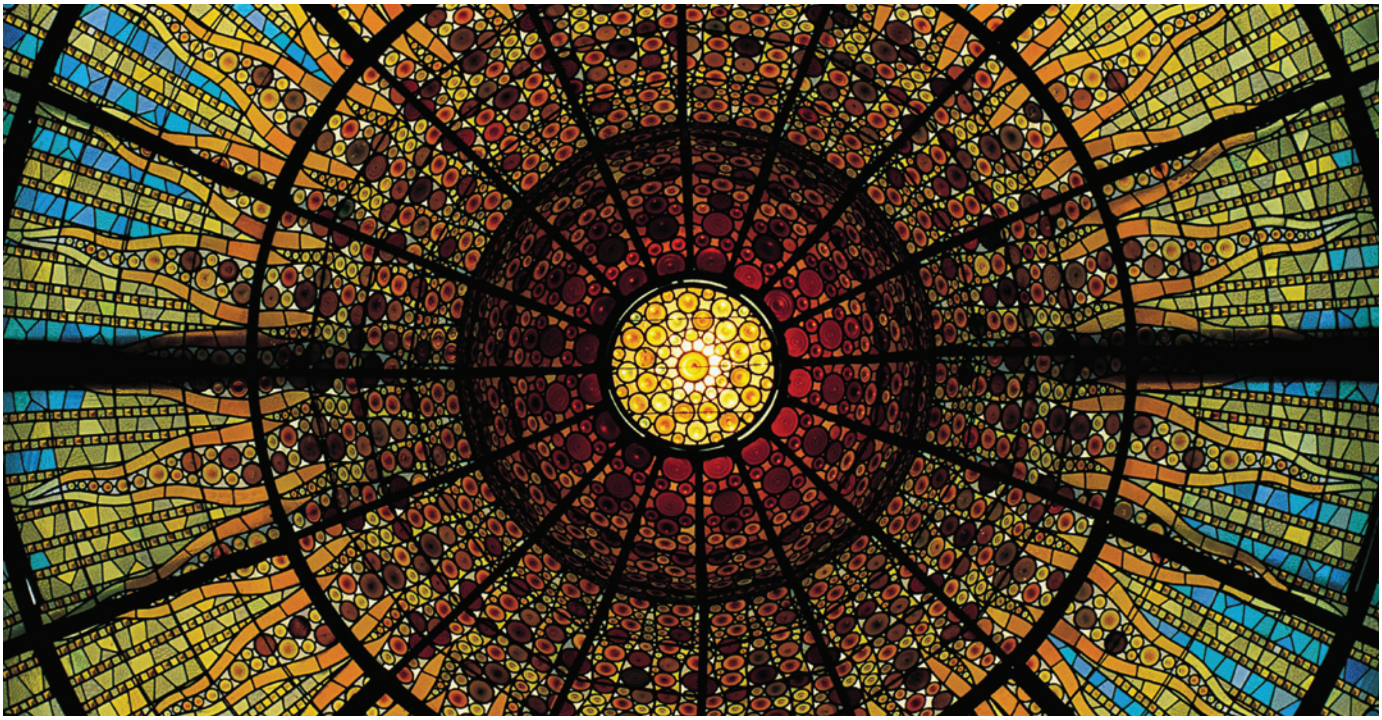

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Symmetries feature in the stained-glass ceiling of the Palace of Catalan Music in Barcelona, Spain.

Why symmetry matters

Mario Livio celebrates the guiding light for modern physics.

Symmetries lie at the heart of the laws of nature. Early scientific giants such as Galileo Galilei, René Descartes and Isaac Newton did not speak in those terms, but symmetries were implicit in their ideas of a comprehensive framework of the Universe. And symmetries lie explicitly at the basis of modern physics, from general relativity to quantum field theory.

To a physicist, symmetry is a broader concept than the reflective form of butterfly wings, or the rotational similarity of a triangular roundabout sign. In physics, to be symmetrical is to be immune to possible changes. Symmetry represents those stubborn cores that remain unaltered even under transformations that could change them.

Sometimes symmetries break down. The announcement on 4 July that two teams at the Large Hadron Collider (LHC) at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, had discovered a Higgs-like boson marked the end of a heroic quest to confirm a 'symmetry-breaking' mechanism. That such a process endows particles with mass was suggested in 1964 by theoretical physicist Peter Higgs and two other groups (Robert Brout and François Englert; and Gerald Guralnik, Carl Hagen and Tom Kibble).

If the new boson is confirmed as the long-sought Higgs, our faith in symmetry as a core concept in physics will be cemented. Further tests of symmetry's power as a guide to physical laws will follow, in the quantum realm and through concepts such as supersymmetry. But what is symmetry and how is it broken?

THE LAWS OF NATURE

Universal laws are symmetric under translation in space and time — they don't change from place to place or from today to tomorrow. As astronomers know, hydrogen atoms billions of light years away are subject to the same physics as on Earth. Because physics has no preferred direction, natural laws are also symmetric under rotation. Whether we measure orientation with respect to the farthest quasar or the nearest coffee shop, the rules are the same.

Such symmetries are true of Newton's laws of gravity and motion, which he applied in the seventeenth century to falling apples, ocean tides, the Moon and planetary orbits. They are also true of those laws' twentieth-century successors: Albert Einstein's special and general theories of relativity, with their revolutionary ideas about the constancy of the speed of light, the equivalence of acceleration and gravity, and the warping of space-time by masses.

Imposing symmetry on all frames of reference was Einstein's motivation for developing relativity theory. He wanted to find a way of describing the laws of nature that would look the same to all observers, whether at rest, moving at a constant velocity or accelerating.

In looking for symmetries, Einstein was following in the footsteps of James Clerk Maxwell, a physicist who died the same year Einstein was born, in 1879. Purely for mathematical balance, Maxwell added to equations describing electromagnetism an extra term that related electrical currents to a resulting magnetic field. In doing so, he unified all electric and magnetic phenomena then known, as well as the laws of optics.

INTERNAL SYMMETRIES

The symmetries that give rise to the Higgs boson are different. They originate in the probabilistic world of quantum physics — 'internal symmetries' reflect the robustness of universal laws to changes in the identity of some elementary particles. Just as a particle's position may be uncertain according to quantum rules, so may its identity. Some types of particles are thus interchangeable within the equations.

Electrons and neutrinos can be swapped without altering the laws of nature. This symmetry is central to the 'electroweak theory', developed in the 1960s by physicists Steven Weinberg, Sheldon Glashow and Abdus Salam. The theory unifies electromagnetism with the weak nuclear force, which is responsible for some radioactive decays (such as a neutron to a proton) and underlies nuclear reactions in stars. The Higgs boson has a role in breaking the symmetry of weak interactions.

The strong nuclear force, which acts among quarks to make up protons and neutrons, and binds protons and neutrons to form atomic nuclei, is also subject to symmetries. The laws of physics are blind, for instance, to exchanges of up quarks and down quarks (protons are made of two up quarks and one down quark).

The standard model of particle physics combines the electroweak theory with quantum chromodynamics, the theory of strong interactions within the nucleus. The model's great achievement is that it unifies three of the four known forces through which particles interact (gravity stubbornly continues to resist unification).

Internal symmetries are local, or independent of the locations of particles. Quarks (or electrons and neutrinos) at different points in space and time may be exchanged without consequence. Fields, with their associated gauge bosons, mediate these remote interactions. The electromagnetic interaction is carried by the photon. In electroweak theory, the photon is joined by the three carriers of the weak nuclear force: W^+, W^- and Z^0 particles. Gluons shepherd the strong force between quarks.

The symmetries associated with a given fundamental force act on all associated elementary particles, not just the force mediators. The same electroweak symmetry that treats the W^+, W^- and Z^0 particles as equivalent, for instance, applies to the electron and neutrino. The symmetry requirement dictates which particles and interactions are necessary for a given theory.

Yet the cosmos does not always manifest perfect symmetry. The equations describing the electroweak interaction, for example, are symmetrical. They do not change when a photon is swapped with a W or Z particle. But the solutions to these equations — the particles themselves — are not identical. The photon is massless, and the W and Z particles are about 100 times heavier than a proton. The symmetry of the governing equations is somehow lost, or broken, in physical reality.

BROKEN SYMMETRIES

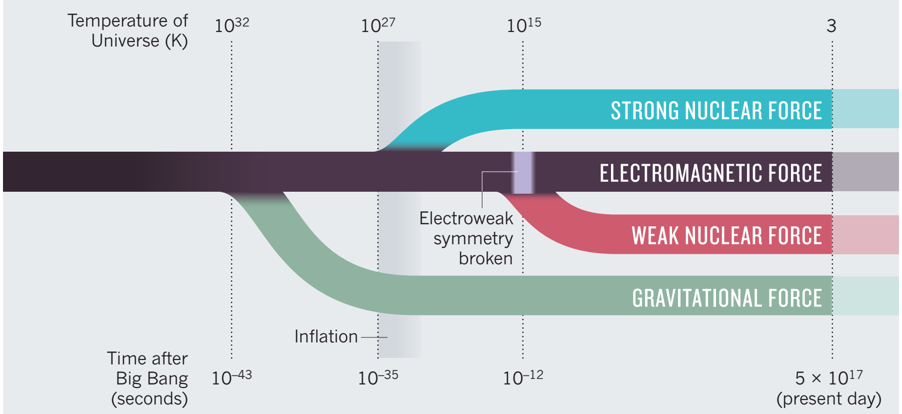
The concept of spontaneous symmetry-breaking allows physicists to preserve a symmetric theory while confronting puzzling observations.

In the 1930s, the Jewish–Russian physicist Lev Landau realized that phase transitions are accompanied by a loss of symmetry. Take magnetic materials. When hot iron is cooled below its Curie temperature (around 770 °C), it acquires bulk magnetism. Its internal magnetic fields, pointing in random directions when hot, collectively settle on one orientation. The symmetry is broken. The equations describing the magnetic field within the iron are symmetric — they have no preferred orientation. It is the physical state of the iron that changes.

Higgs and his colleagues realized in 1964 that symmetry-breaking could be applied to particle physics. They proposed that a fraction of a second after the Big Bang, as the Universe expanded and cooled, it went through a dramatic phase transition (see 'Fundamental forces'). The internal symmetry of the weak interactions, which held true at very high energies, broke when the Universe's energy dropped below some threshold.

FUNDAMENTAL FORCES

After the Big Bang, the four forces divided as the cooling Universe underwent phase transitions. The Higgs boson broke the symmetry between the electromagnetic and weak nuclear forces.



The mechanism by which it did so (the Higgs mechanism) involves a quantum field (the Higgs field), which has a non-zero value associated with every point in space. The Higgs particle is a ripple, a parcel of energy, in the Higgs field.

The Higgs field tugs on W and Z particles, restricting their communication of the weak force to an extremely short range (less than about one-ten-thousand-trillionth of a centimetre). In other words, it gives the W and Z particles inertia, or mass. In similar fashion, the molasses-like Higgs field gives mass to other fundamental particles, such as electrons and quarks.

Because the vacuum does not carry electrical charge, the photon travels unhindered. So the photon remains massless and can render the electromagnetic force over long distances.

So far, the particle discovered in July at the LHC looks a lot like the Higgs boson. More tests are needed to prove it. First, the experimentalists must determine the quantum spin of the new boson (the Higgs is predicted to have no spin). Second, they need to measure the rates at which it decays into other particles and compare those to theoretical expectations. Even if the boson passes these tests, symmetry and its breaking do not leave centre stage.

One of the major steps beyond the standard model involves supersymmetry — the idea that each particle we know has a not-yet-discovered superpartner, with a spin removed by half a quantum-mechanical unit. Supersymmetry is manifestly broken; otherwise the superpartners would have had the same masses and charges as the known particles and would have been detected already. A broken supersymmetry opens the door to a host of other potential bizarre processes, such as an electron transforming into a muon.

There are no signs as yet from the LHC of supersymmetric particles, but this could change. Although the simplest versions of supersymmetry seem to have been ruled out, no one knows what to expect when the LHC increases its energy in two years.

Of course, the ultimate goal remains an all-embracing theory that will unify gravity with the other interactions. We still do not know if the underlying principle of such a theory is symmetry, but a confirmation of the newfound boson as the Higgs will show, once again, that symmetry is a guiding light through nature's labyrinth. ■

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