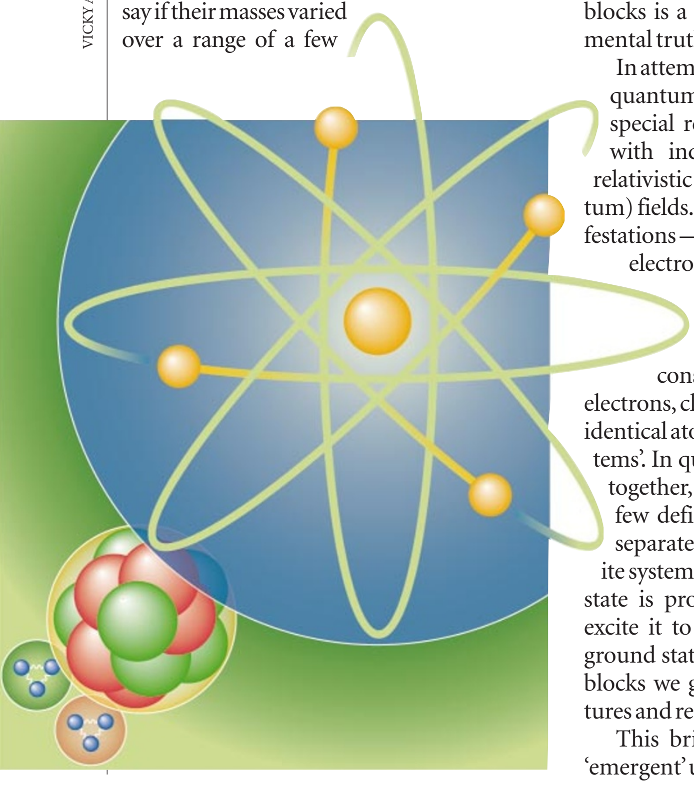
Setting standards

Frank Wilczek

Rough conceptions of universality predate science, and even human consciousness. A swimming fish implicitly assumes that the laws of hydrodynamics are universally valid, and the basic properties of its watery environment invariable. Newton's universal law of gravitation defined an ideal model for classical physics, which was consciously emulated in the early study of electricity, magnetism and speculative atomic theories. Spectroscopy revealed the accurate and detailed similarity of terrestrial and celestial matter. But it was only in the twentieth century that universality evolved from a metaphysical assumption into a physical concept, the precision, origin and limits of which could be powerfully addressed.

The deepest and most revolutionary insights arose from quantum theory. They are at two levels. First is the very basic fact that matter is built up from vast numbers of copies of a few fundamental components (such as electrons, quarks, photons and gluons). The properties of these elementary building-blocks are always and everywhere the same — universal. If this were not the case, there could be no laws of chemistry, because every atom would have its own quirky properties.

From the perspective of classical physics, this universality is both non-essential and surprising. If elementary components such as electrons were not quite precisely identical, say if their masses varied over a range of a few parts per billion, it would be conceivable that future observations, more accurate than those possible today, might reveal small differences between them. Indeed, such differences might be expected to arise, because over its long lifetime each electron might change as a result of accidents of its individual history. And this, of course, begs the question of why they were accurately similar to begin with!



VICKY ASKEW

In quantum mechanics, the view is fundamentally shifted, as there is a radical difference between two particles being precisely identical and being merely similar. If A and B are identical, then when A travels from position $x1$ to $y1$ and B from $x2$ to $y2$, the final result is the same as when A goes to $y2$ and B to $y1$. In quantum mechanics, the basic goal is to calculate amplitudes, the square of which gives the probability of an event. To get the total amplitude to find particles at $y1$,$y2$, we must add (for identical bosons) or subtract (for identical fermions) the amplitudes for these two possibilities, and then square to get the probability. If the particles are distinguishable, then so are the two final states, so we must square first, then add.

The mathematics of quantum statistics works only if we have precisely identical — that is, indistinguishable — particles. It underlies a host of observed physical phenomena, from lasers to neutron stars, as well as the existence of the periodic table and the recondite details of quark and gluon scattering. Thus, the universality of building-blocks is a rigorously demonstrable experimental truth. But why?

In attempting to reconcile the principles of quantum mechanics with the demands of special relativity, we cannot deal directly with individual particles. To construct relativistic quantum theories we need (quantum) fields. Particles arise as secondary manifestations — excitations of the fields. Thus, all electrons are indistinguishable because each is minted at the same press.

The second level of revolutionary insight is that of construction. Even with identical electrons, classical physics would not arrive at identical atoms, but a continuum of 'solar systems'. In quantum theory, it is different. Put together, the basic components snap into a few definite structures. Energy levels are separated by quantum jumps. If a composite system in its minimum-energy (ground) state is probed with insufficient energy to excite it to the next level, it remains in its ground state. Thus, from universal building-blocks we get universal, reproducible structures and reactions — in a word, chemistry.

This brings us to the powerful idea of 'emergent' universality. A theory of low-energy behaviour can ignore structure that is definitely present (and that would be revealed to high-energy probes) yet still be perfectly rigorous. Conversely, one can have many distinct alternative theories of fundamental interactions at high energy, or equivalently short distance, that all map onto exactly the same effective theory for low energies.

For fundamental physics, emergent universality is both a blessing and a curse. It provides a sense in which understanding, once achieved, will never be superseded. But in doing so it marks off wide domains as immune to further discovery. It shows how the reductionist programme, to base physical science on ever more rigorous laws, could end "not with a bang, but with a whimper".

There is another 'miracle' of emergent universality, with the emphasis on 'Universe'. Distant parts of the Universe are broadly similar to one another, yet even physical laws that apply universally can nevertheless engender non-universal behaviour, if they act within different environments. Big Bang cosmology postulates physical conditions that change with time, and different parts of the Universe need not have been accurately synchronized. Also, there can be pervasive fields, the values of which could vary in space. The discovery of at least one such field, the axion, is widely anticipated. The idea of inflation reclaims the universality of the observed Universe, for if it originated through expansion of a tiny patch, there is less scope for variation.

A better understanding of the origins of universality teaches us to conceive its possible limitations. Emergence, in emergent universality, need not be complete. Small energies are not infinitely small, and rare processes can hint at a deeper-lying structure. Inflation does not occur by an infinite factor, and would not enforce perfect uniformity even if it did. Indeed, some (quantum?) fluctuations are required to seed the formation of structure in the Universe — which is to say, its deviation from perfect universality! As always, great answers lead to great questions. ■

Frank Wilczek is at the Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA.

Universality

The general occurrence, in widely different circumstances, of a common structure or behaviour.

FURTHER READING

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