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The tao of modern physics

Philip Anderson's role in the Higgs particle discovery has been overlooked, but it points to the intellectual unity of the discipline.

Shivaji Sondhi

In the bulk of the commentary on the discovery of the Higgs particle at CERN and the recent award of the Nobel prize to Peter Higgs and François Englert, one astonishing aspect has been largely overlooked. This discovery points to one of the most central aspects of postwar physics its unity across domains at distances (or energies) separated by vast gulfs that have allowed ideas to jump between very different physical problems. In the case of the Higgs particle, its discovery at an energy of one hundred billion electron volts in a complicated special purpose machine is, in a mathematical sense, a precise analogue of a well-understood phenomenon in ordinary metals at an energy of a thousandth of an electron volt one hundred trillion times lower!

Indeed, this analogy is how the puzzle underlying the Higgs particle was first solved by Philip Anderson in 1963, a year before the papers by Higgs and Englert and Robert Brout that were honoured with the Nobel. Anderson, now 89, is widely regarded as the greatest living condensed matter physicist, a maestro of the part of physics that tries to understand how the small set of subatomic forces and particles can lead to the infinite variety of the matter we see around us. He has led a spectacular career during which he picked up a Nobel in 1977 for completely different work, and could have collected at least two more.

Back in 1963, Anderson had already played a key role in understanding the general phenomenon of spontaneous symmetry breaking in condensed matter physics in parallel with important developments in particle physics. An everyday example of this phenomenon is the formation of ice from water. While the molecules in water resemble the crowd in Times Square on a busy day with no clear preference for where they want to be, the molecules in ice are arranged in an array like an honour guard at attention. Their choice of particular positions breaks the symmetry embodied in a lack of positional preference.

More immediately, Anderson had been one of the central players in elucidating the physics of superconductivity, or why metals permit electric current to flow without loss when sufficiently cold. Superconductivity involves an unusual broken symmetry, but with the complication of electromagnetic forces that act over large distances. It was understood by Anderson that a massless gauge field (describing ordinary electromagnetic forces) could combine with a massless Goldstone mode (a signature of symmetry breaking) to yield purely massive excitations. Roughly, this reflects the dislike that superconductors exhibit for magnetic fields, termed the Meissner effect and often dramatised by levitating magnets above pieces of superconductors.

At this point, Anderson came across particle physicists trying to rescue an appealing potential description of short-ranged forces among the zoo of particles being discovered in accelerators. This description had one key thing wrong the gauge fields were massless and thus described long-ranged forces. Anderson realised that by introducing a second wrong a massless Goldstone boson due to symmetry breaking he could make a right. Today, this magic trick is commonly referred to as the Anderson-Higgs mechanism, to credit Higgs with the subsequent realisation that the mechanism implied a specific additional massive particle Anderson had overlooked. In any event, by staring into a piece of metal, Anderson had divined the solution to a puzzle about fundamental particles.

Now, the energy involved in superconductivity is a thousandth of an electron volt while the energy of the Higgs particle is a hundred trillion times larger, or alternately the size of the Higgs particle is a hundred trillion times smaller than the size of the smallest superconducting unit,the so-called Cooper pair of electrons. Why is it that the same mathematics can be used to describe both?

The explanation for this astonishing fact is a central meta-idea in postwar physics, that of the effective field theory. It states that if you don’t look too closely at the spatial details, the mathematics simplifies greatly into a set of field theories”, which then provide a unifying mathematical framework for a vast range of phenomena. This meta-idea itself has a precise mathematical formulation known as universality under renormalisation group flows.

Metals are made of electrons and nuclei, but when we smooth over such detail, we end up with the field theory Anderson considered. In particle physics, the details being smoothed over are unknown perhaps described by string theory and we end up with a close cousin of Anderson’s field theory. What Anderson called a mode, Higgs called a particle, but both were describing a disturbance in an underlying medium, one known and the other unknown.

The ubiquity of effective field theories means that the Anderson-Higgs mechanism is by no means the only example of tight analogies between far separated phenomena in modern physics. To take one recent example, the work of particle physicist Edward Witten on topological field theories in the 1980s, for which he won a Fields medal in mathematics, has turned out to be central to our understanding of the quantum Hall effect in semiconductor systems, even though it was designed to do no such thing. Even this writer, also a condensed matter physicist, has had the (far more modest) pleasure of discovering in the same semiconductor systems skyrmions 15 orders of magnitude larger than those considered by particle physicist Tony Skyrme as descriptions of protons and neutrons.

So, the discovery of the Higgs particle is a triumph for this syncretic view built into modern physics. It turns out that space devoid of visible particles has something deeply in common with a superconducting metal. Further, it tells us that it was not always so: when the universe was younger and hotter, it resembled more a piece of superconductor heated to the point where the superconductivity vanishes, and thus there was no Higgs particle to speak of.

This brings me to the Nobel prize. I believe the committee missed an opportunity in not including Anderson along with Higgs and Englert. It would have been a more accurate accounting of the credit on this particular discovery and a deserved honour for a man whose contributions are legion. Above all, it would have paid tribute to the remarkable intellectual unity of modern physics.

The writer is a professor of physics at Princeton University, US