A Word From the Laureates

Earlier this month, the Royal Swedish Academy of Sciences awarded this year’s Nobel Prize in Physics to David J. Thouless, F. Duncan M. Haldane, and J. Michael Kosterlitz “for theoretical discoveries of topological phase transitions and topological phases of matter.”¹ Though currently affiliated with the University of Washington, Brown University, and Princeton University, respectively, the British-born physicists were honored for work conducted in the 1970s, which revolutionized our understanding of exotic states of matter and created new perspectives on the development of quantum and nanomaterials. Since the first studies in superfluids during the 1930s, supercooled phase transitions had been deemed a well-understood area in physics. However, Kosterlitz and Thouless cooperated to challenge these theories and were able to identify topological phase transitions in 1972.

“It was a piece of work that I did as a very ignorant post-doc,” Kosterlitz said. “Complete ignorance was actually an advantage because I didn’t have any preconceived ideas. I was young and stupid enough to take it on.”²

The existence of these phase transitions has since been hailed as one of the most important discoveries in the theory of condensed matter physics. Key to this discovery was Thouless’s innovative use of topology, which is an abstract branch of mathematics concerning unusual properties of space. Thouless began to tackle other problems in physics with topology and was able to fully explain a paradoxical mystery in electricity conductance known as the quantum Hall effect in 1982. Haldane also began using topological techniques at this time to derive a theory analyzing magnetic atomic chains in an equally unexpected way. For answering these long-standing questions, this year’s prize honors these researchers and their collective introduction of topology to physics research.

The Path to Discovery

Since its development, quantum mechanics has come to reinvent our notion of physics, including our understanding of the states of matter. When a multitude of atoms come together, they interact to form materials based on the amount of energy in the system; at extremely high energies, these atomic interactions form plasma, and as the energy, or heat, leaves the system, gases, then liquids, then solids arise. However, once heat approaches absolute zero (-273 °C, 0 K), quantum and atomic interactions behave very unexpectedly. The atomic interactions form a state called condensate, and the resulting state develops phenomena like magnetism,
superconductivity, and superfluidity. At the time Thouless and Kosterlitz began work in this field, researchers long thought that these properties were only present in three-dimensional spaces.\(^3\)

Figure 1. Aside from the usual phases, matter also assumes plasma at high temperatures and forms a condensate at low temperatures.

At two-dimensions, small thermal fluctuations were thought to destroy all molecular order even when supercooled, and without ordered phases, there would be no phase transitions. Thus, there would be no medium for magnetism, superconductivity, or superfluidity. However, experiments still observed these properties on the surface and in thin layers of different materials. Then, Kosterlitz and Thouless proposed the KT (Kosterlitz-Thouless) Transition. The duo employed mathematical techniques from a field called topology, which had rarely been applied to work in condensed matter, and they were able to show that there existed an unconsidered kind of phase transition originating from defects within these thin materials. By defining the topological structure of these defects, they showed how materials could switch to different topologies to explain the anomalous experimental data. The first half of the Nobel award honors this finding, while the second half honors the discoveries in new phases of matter that followed, which utilized topology as inspired by the KT transition.
A Study in Pastries

Topology is a branch of mathematics that describes geometric properties of objects when they are stretched and twisted, like a rigorous study of Play-doh. Conventional phase transitions are defined by the density of a region, and before Kosterlitz’s and Thouless’s work, it had been mathematically proven that these phase transitions, such as those from ice to water, could not occur in thin layers of molecules and atoms. However, topological phase transitions are defined by the placement of vortices that appear at critical temperatures. A vortex in a material is a topological feature that can be thought of as a parking garage.

“You go around and end up one floor higher before you know it,” said Marcel Den Nijs, physicist from the University of Washington. “You don’t know it exists unless you walk around it.”

In thin films of magnetic materials, superfluids, and superconductors, these vortices appear in pairs at low temperatures. The KT transition mathematically describes how, as temperature rises, vortices drift from each other to form a topologically different structure, thereby transitioning to a new topological phase. By switching topological phases, these materials could then demonstrate the experimentally observed phenomena that were predicted against.

Fig. 2. In thin layers of cold material, vortex pairs form as topological defects in the film. At the temperature of the phase transition, these vortices drift away from each other in a topological phase transition, denoting a structurally different material. Due to these effects, two-dimensional materials could exhibit unexpected phenomena.

Following his proposal of the KT transition, Thouless again used topological concepts to explain new developments in condensed matter. To explain, Nobel Committee Member Thor Hans Hansson joked that he “brought [his] lunch” as he pulled out a pretzel, a bagel, and a cinnamon bun. He noted the number of holes in each of these pastries, using this as an example of how topological properties change states through abrupt jumps, as opposed to the continuous
change of geometric properties. This can be thought of as the difference between ripping apart a bagel versus stretching apart a donut.

“The number of holes is what a topologist would call a topological invariant, and you cannot have half a hole or two and two-thirds,” said Hansson. “You can only have integer numbers.”

Figure 3. Thors Hans Hansson of the Nobel Committee explains the intuition and importance of the honored discoveries using pastries.

Thouless used integer steps to describe the quantum mechanics determining how certain materials conduct electricity. Most work on conduction had already been derived decades before, but in 1980, German physicist Klaus von Klitzing found unusually precise electrical conductance measurements while observing a thin conducting layer at near absolute zero temperatures. Klitzing saw that, even with changes in the magnetic field and temperature, the conductance of this film changed in steps rather than continuously and that these steps were very precise. This was called the quantum Hall effect, and Klitzing later won a Nobel award for this discovery, riddle unsolved. In 1983, Thouless was able to show that the physical knowledge was incomplete and that these discrete measurements resembled the integer steps of topologically invariant holes, tying in KT transitions. Therefore, the integer number of holes, or vortices, in the material allowed a greater degree of electron movement to explain the stepwise change in conductance.
Figure 4. Topology is a branch of mathematics studying properties of structures that are preserved through deformations and stretching. Thouless used topological principles that describe step-wise changes to show why electrical conductivity in thin layers change the integer steps.

At the same time that Thouless began using topology to explain the quantum Hall effect, Duncan Haldane was employing different, but equally original, topological methods to develop theories on atomic chains. There exist two types of atomic magnets: even and odd. Haldane showed that in chains of these atomic magnets, only the chains formed by even magnets are topological, while the chains of odd magnets are not. Haldane observed that there were incongruities at the ends of certain chains and hypothesized their topological nature, and he was able to discover a new type of topological material against the presiding intuition of the field. Together, Thouless, Klitzing, and Haldane identified new materials and explained puzzling phenomena, each with their own innovative techniques but all from the field of topology.

Bright Futures

Alfred Nobel intended for his prize to honor achievements that would benefit mankind and change the way we live our daily lives. In many ways, these discoveries have done so; the identification of these topological phases and materials overturned long-standing beliefs in physics and reinvigorated fields that were previously thought well-understood. Furthermore, the use of topology provided a novel method to analyze physical structures.

“This was the first time that concepts of topology became relevant in condensed matter physics,” said Eduardo Fradkin, physicist from the University of Illinois Urbana-Champaign. “It’s a tool most physicists didn’t have before then.”

Since the publication of their findings, application has been catching up with theory. The introduction of new quantum structures has had a major impact in the development of quantum computers. Topological holes in condensed materials create new opportunities for faster information encoding techniques, where zeroes and ones may one day be replaced with much more memory space. However, the true importance and impact of the work by Thouless,
Kosterlitz, and Haldane lies in its elegance.

“It has combined beautiful mathematics and profound physics insights, and achieved unexpected results that has been confirmed by experiments,” said Hansson.

The three not only dared to challenge physics, but did so in an entirely novel way to inspire entire fields based on their work. Current research now reveals the potential of their discoveries, as the work of these Nobel laureates continues to fulfill Alfred Nobel’s wish to revolutionize and benefit our lives.

Sources

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