Nobel Prize in Physics 2016[1]

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The article describes the theorietical work in the field of condensed matter physics for which the 2016 Nobel Prize in Physics was awarded.

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Introduction

The 2016 Nobel Prize in Physics was awarded for theoretical discoveries of topological phase transitions and topological phases of matter. It honours people whose pioneering work began the ongoing realization of the crucial role that topology can play in condensed matter systems. The announcement says, "The Nobel Prize in Physics 2016 is awarded with one half to David J Thouless, University of Washington, Seattle and the other half to F Duncan M Haldane, Princeton University and J Michael Kosterlitz, Brown University, Providence. Their discoveries have brought about breakthroughs in the theoretical understanding of condensed matter's mysteries and created new perspectives on the development of innovative materials."

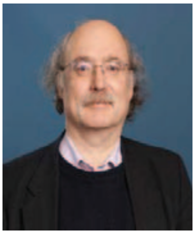
The physics of condensed matter has evolved largely from a somewhat obscure branch called solid state physics (dubbed squalid state physics by Pauli in the late nineteen twenties; Niels Bohr had not heard of the name in the early fifties). It is now that part of physics in which the large majority of physicists work worldwide. Of the forty five Nobel laureates in Physics from 2000 till now, twenty two are in this field. Perhaps the emergence of unexpected behaviour when things are close together, encapsulated in the 1972 rallying cry of Anderson that "more is different" is behind it; perhaps the applications which surround us (*e.g.*the cell phone, the laptop, the TV display) are; perhaps both. The pioneering basic research of 2016's Nobel laureates points to a new direction which has already resulted in much exciting new science, and also in totally unforeseen applications.

[1]Reprinted with permission from *Current Science*, Vol.111, No.8, 2016.

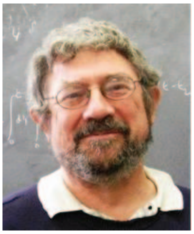
Keywords
Topological transitions, condensed matter, quantum materials, solid state, Hall conductance, Haldane gap, Chern number.

Figure 1. The Nobel Prize in Physics 2016 was awarded jointly to David J Thouless, Duncan M Haldane, and J Michael Kosterlitz "for theoretical discoveries of topological phase transitions and topological phases of matter."

David J Thouless
University of Washington
Seattle, WA, USA



Duncan M Haldane
Princeton University
Princeton, NJ, USA



J Michael Kosterlitz
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Thouless and Kosterlitz found, unexpectedly, that the behaviour of topological defects in the system (inevitably present in them as thermal excitations) undergoes a qualitative change at a certain temperature, and that this has far reaching consequences.

These physicists showed in the seventies and eighties of the twentieth century that ideas of topology are at the heart of the existence and behaviour of many strange phases as well as phenomena in condensed matter systems. While it is a truism now that qualitatively new phenomena emerge when things are put together, as in condensed matter, the idea that topology is at the back of many of them is quite unexpected. Since their work, and largely inspired by their pioneering ideas, the field has exploded scientifically. In the last decade or more, a number of families of materials which embody them have been located and created; a quantum materials revolution spearheaded by topologically nontrivial materials is underway. Perhaps the consequent development of new materials will form the basis for new ways of computing as well as of storing and manipulating information. Many ideas of great elegance and explanatory power are flowering.

It all started with a fresh look by Thouless and Kosterlitz in the early 1970s into the question of whether long-range[2] order is possible in a two-dimensional system, *i.e.* one which is extended in two directions and is about as thick as the size of the constituent entities, namely atoms or molecules, in the third. The standard belief (buttressed by rigorous arguments) is that because of spatial fluctuations enhanced by reduced dimensionality, long-range order is not possible in them. Thouless and Kosterlitz found, unexpectedly, that the behaviour of topological defects[3] in the system (inevitably present in them as thermal excitations) undergoes

[2]A perfect three dimensional crystal is an example of long range order. Looking at a small part – even one unit cell – enables us to predict the location of all other atoms in the crystal, however far away they may be. This is true even at a finite temperature when the atoms undergo thermal vibrations.

a qualitative change at a certain temperature, and that this has far reaching consequences. The defects bind, pairwise, below this temperature; there are no 'free' defects, and the system is stiff against deformation[4], like a solid. Above this temperature, it is like a fluid, not stiff. No breaking of symmetry is involved; there is no long-range order, but there is a 'stiff' phase.

[3] An edge dislocation in a crystal is an example of a 'topological defect'. This is an extra plane of atoms ending in a line inside the crystal. Travelling in a closed path around that line will reveal the presence of this defect.

In the context of order parameters characterized by a single phase-angle (such as planar spins, or complex numbers as in superconductors and superfluids) the topological defect involved is a vortex, on going round which along any closed path, the phase-angle which describes the putative order changes by an integral multiple of 2π. Such a defect is robust, characterized by an integer! This is a topological reality just as the following is: A coffee mug with a handle (as also a doughnut) is characterized by a genus number of unity (the handle has one hole) while a mug without a handle (*e.g.* a bowl or a beaker) is characterized by the number zero, being of the same genus for this purpose as a saucer. The difference cannot be erased by any smooth deformation, and is noticeable only in a global property; a little bit of a bowl is similar to a little bit of the cup with a handle, but they are qualitatively different when looked at as wholes. The discovery by Kosterlitz and Thouless of topological phases opened up a whole new universe of systems which were explored; these were found in detail to be of the kind predicted by them and by others following this direction. This period also saw a deep exploration of possible topological defects in various kinds of condensed matter. The new phases are qualitatively different phases of matter; they exist only because of topologically mandated defects which can bind.

[4] A solid resists change in shape, *i.e.* shear deformation, while a fluid does not.

About a decade later, quite independently, a strange low temperature effect (quantized Hall Effect) was observed in a thin two-dimensional fluid of electrons sandwiched between two semiconductors. When a large magnetic field is applied perpendicular to the plane of the electron fluid, the ratio between the electrical current in plane and the voltage perpendicular to it (but still in the same plane), called the Hall conductance, is seen to be quantized.

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[5]See *Resonance*, Vol.10, No.4, 2005, for more about the Chinese-American Mathematician S S Chern and his contributions, including the Chern number.

The quantization , in multiples of a universal value, is found to be both unbelievably accurate (to about a part per billion) and robust. It does not change with carrier concentration, disorder, or temperature of the electron fluid. It became clear that we are seeing a new state of matter now called the quantum Hall fluid. Thouless and coworkers showed that the robustness and precision of the quantized Hall conductance have a topological origin. The Hall conductance, a long length scale, global, property is proportional to a topological integer, called the Chern number[5]. Properties such as the Hall conductance are 'topologically protected'. This is the basic characteristic of the state. It also turns out that there are necessarily zero energy modes present at the boundary between such a phase and another which is topologically different.

Duncan Haldane's pioneering journey started in an apparently obscure bylane. In 1983, he showed that a chain consisting of magnetic moments (spins) interacting with their nearest neighbours had very different properties depending on whether the spins were integral or half integral in units of $(h/2\pi)$ where h is the Planck's constant – the basic quantum constant. Both classes of systems lack long-range order. For the former, there is no gap between the ground state and the lowest excited state, while for the latter, there is. This stunning result was not quite believed by experts. However, the Haldane gap exists; it has been measured experimentally. Presciently, he tracked down the origin of this gap; it is a direct consequence of a non-zero topological term in the effective action of the entire system, this action being expressed as a function of the spin field. So one has, in such chains, two different quantum fluids arising because of a topological distinction. A few years later, in unrelated work, he showed that even in the absence of an external magnetic field, a special two-dimensional lattice system is a topological quantum Hall fluid. Interestingly, such a system has been recently synthesized in a cold atom lattice (this consists of about fifty thousand potassium atoms hopping around in a special lattice generated by crossed laser beams, the whole thing being at a temperature of about 10^{-7} K above absolute zero). This creative work by Haldane was quite directly the inspiration for later developments of models of topological insulators, mentioned below.

These contributions had an enormous direct and indirect effect on the community of physicists, by pointing to the crucial (and unsuspected) role of topology in condensed matter systems, by stimulating the search for other kinds of topologically nontrivial matter, as well as by providing actual models and methods.

One well-known instance of the far-flung consequences of the work and ideas of the laureates has to do with topological insulators. These are semiconducting or insulating in the bulk, like so many other materials of that kind. However, because of a topological peculiarity in their electronic structure, they inevitably have a metallic surface; there are free electrons there. These electrons are quite unusual. Their intrinsic spin always points perpendicular to their direction of motion, in a specific sense. Bi_2Se_3 is one out of dozens of examples. There is great promise that these electronic states indicate even more unusual possibilities. There are many road maps for the realization of these. For example, it is likely that their nature will be the basis for robust, intrinsically quantum, ways of computing. We are in the middle of a great creative ferment[6]. It is therefore wonderful that the physicists whose curiosity and work very clearly started it all, are recognized by their peers.

[6]For a more technical account of such systems, refer to the article Emerging Trends in Topological Insulators and Topological Superconductors. by Arijit Saha and Arun Jayannavar in this issue.

Suggested Reading

[1] The area of topological phenomena in condensed matter physics is one of explosive research activity and there are a number of books, review articles, conference proceedings, *etc*., on the subject. An accessible introduction is the writeup of the Nobel Foundation on the 2016 Nobel Prizes in Physics (available on the internet). John Baez, a mathematical physicist at UC Riverside, has a webpage called *Azimuth* which has animated pictures illustrating vortices and the Kosterlitz Thouless work.

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