

Fifty years of Anderson localization

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What began as a prediction about electron diffusion has spawned a rich variety of theories and experiments on the nature of the metal-insulator transition and the behavior of waves—from electromagnetic to seismic—in complex materials.

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Very few believed [localization] at the time, and even fewer saw its importance; among those who failed to fully understand it at first was certainly its author. It has yet to receive adequate mathematical treatment, and one has to resort to the indulgence of numerical simulations to settle even the simplest questions about it.

— Philip W. Anderson, Nobel lecture,
8 December 1977

The study of the conductance of electrons belongs to the very heart of condensed-matter physics. The classical Drude theory of electronic conductivity was built on the idea of free electrons scattered by positive ions in metal lattice sites. A key concept in that description was the mean free path, the average length an electron travels before it collides with an ion. According to classical theory, the electronic conductivity should be directly proportional to the mean free path, which experiment had established as large in metals—around 100 nm, some two orders of magnitude larger than the lattice constant.

Physicists had to wait for the discovery of quantum mechanics to understand why electrons apparently do not scatter from ions that occupy regular lattice sites: The wave character of an electron causes the electron to diffract from an ideal crystal. Resistance appears only when electrons scatter from imperfections in the crystal. With that quantum mechanical revision, the Drude model can still be used, but in the new picture an electron is envisaged as zigzagging between impurities. The more the impurities, the smaller the mean free path and the lower the conductivity.

Will any increase in the degree of lattice disorder lead to just a decrease in the mean free path and thus to a lower conductivity, or might something unusual happen along the way? That question was raised a half century ago by Philip Anderson, pictured in figure 1. Beyond a critical amount of impurity scattering, he discovered, the diffusive, zigzag motion of the electron is not just reduced, it can come to a complete halt.¹ The electron becomes trapped and the conductivity vanishes.

To appreciate how that's possible, at least intuitively, one can start with elementary wave mechanics. Suppose an electron propagates in a disordered medium from point A to

point B. One has to sum the amplitudes of all possible paths and square the complex-valued end result to obtain the total probability that the electron arrives at B. That probability consists of a sum of squares—the classical, incoherent contribution—plus many cross-product, interference terms. One could argue that in disordered media, the phases of the interference terms are so random that their sum vanishes on average. That assumption would bring us back to the diffusion model of metallic conductance.

But that neglect of interferences is not always justified. Imagine a wave that travels from point A along a random path to point B and then goes back to A. In figure 2, two possible paths are depicted: a randomly chosen path and the same path traversed in the opposite sense. The two paths interfere constructively and should be treated coherently—that is, summed before being squared. The probability of the electron's returning to A is then twice as large as it would have been if probabilities were added by first squaring and then summing. The enhanced backscattering, known as weak localization, lowers the conductance between A and B by increasing the electron's likelihood of returning to its starting point. But can it eventually localize the electron around A?

Metal-insulator transition

Anderson had been confronted with experiments performed by George Fisher's group at Bell Labs—experiments that showed anomalously long relaxation times of electron spins in doped semiconductors. The concept of localized electrons could explain the observation but would break with the conventional diffusion picture. To explain the effect, Anderson used a tight-binding model of an electron in a disordered lattice; at each lattice site an electron feels a random potential and is allowed to tunnel between nearest neighbor sites with a constant rate (see figure 3).

Electrons are waves, of course. But rather than thinking of conduction electrons as extended plane waves with short lifetimes and small mean free paths, one should instead view them as standing waves that are confined in space and thus have long lifetimes. Moreover, not just one or two electrons are localized by a random well in the landscape of the random potential energy; nearly all conduction electrons be-

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