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The solid which conducts heat best

by Yo Machida [1] | Associate Professor; Kamran Behnia [2] | Senior Researcher

[1]: Department of Physics, Gakushuin University, Tokyo, Japan
[2]: École supérieure de physique et de chimie industrielles de la Ville de Paris (ESPCI), Paris, France

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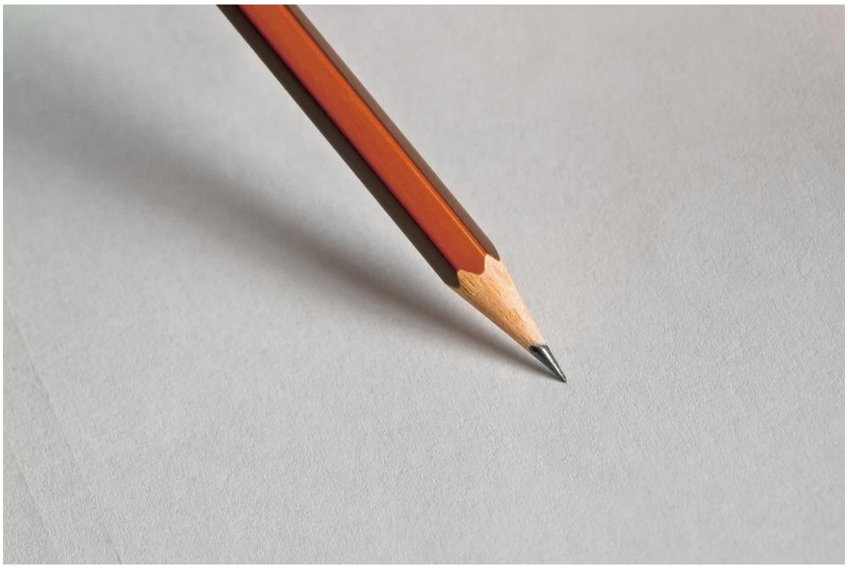
ABSTRACT

A phonon is a quantum of atomic vibrations. According to quantum mechanics, these phonons are what allow heat to travel in any solid medium. The capacity of solids to conduct heat is extremely variable. We identify a stack of graphene sheets as the best-known conductor of heat at room temperature, thanks to carbon atoms' ability to vibrate fast combined to other mysterious properties of a honeycomb lattice.



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Controlling the flow of heat has been one of the earliest technological tasks conceived by humans. Think of putting on clothes and building houses, which emerged well before written communication. However, it was only in the late nineteenth century that the nature of heat was demystified and tracked down to atoms' vibrations. The advent of Quantum Mechanics led physicists to realize that wave-like collective vibrations of atoms are quantized like light. The relevant quanta were dubbed phonons, which are the basis of sound in the same way that photons compose light. Heat travels in solids because confronted with a temperature difference across the solid, phonons flow from the hot side to the cold.

Some solids conduct heat better than others. Our everyday life teaches us that metallic solids are excellent conductors of heat. Think of your cooking instruments in the kitchen. This is because metals have mobile electrons that can carry heat, often better than phonons. However, the best conductor of heat at room temperature is not a metal, but an insulator, and a costly one. Diamond has been known to be the best conductor of heat at room temperature, beating copper by a factor of five. In other words, despite lacking mobile electrons, diamond allows heat to propagate much easier than in any metal. To see why, one needs to consider that a carbon atom is light. Moreover, in the crystal lattice of diamond, each atom has only four immediate neighbors.

This allows phonons to propagate fast and minimizes the dissipative collisions between them. Such collisions are the source of thermal resistance.

Carbon atoms can organize themselves in structures other than diamond’s. One alternative is graphite, familiar to any pencil-loving schoolchild. It is a stack of graphene sheets. Each graphene sheet is a honeycomb lattice of carbon atoms, where each atom has three neighbors. The collisions between phonons is less dissipative in graphene than in diamond. Now, it is true that graphite is just a loose stack of graphene sheets, but a strange and fragile one. It is a very anisotropic solid with very strong interlayer covalent bonds and very weak intralayer bonds. The in-plane and the out-of-plane couplings between atoms differ by two orders of magnitude. This exceptional dichotomy makes graphite easy to cleave and the access to single-layer graphene widely available.

Before our work, graphite samples were found to be less conducting than diamond. This was attributed to the unavoidable propagation of phonons across the sheets. Interlayer phonons are slow and their collisions strongly dissipative. We studied the evolution of thermal conductivity in graphite as the thickness was gradually reduced and made a surprising discovery. The thermal conductivity substantially increases with decreasing thickness. Moreover, a graphite sample thinned down to a few microns (barely thicker than the human hair) conducts heat better than diamond. Its thermal conductivity is as good as small graphene flakes.

There are both fundamental and technological implications. From a purely scientific point of view, the experimentally observed thickness dependence is yet to be understood. We know that in a typical graphite sample, adjacent graphene sheets are tilted or twisted. However, it is not clear how such poorly controlled interfaces affect phonon transmission and reflection. The consequences for the overall conductivity is yet to be understood by theoretical simulations. On the application side, properly designed thin graphite sheets can be used for controlling heat flow at the nanometric level in a variety of industries. One day, advances in heat manipulation at nanoscale would affect our cooking and clothing.