palinal chewing had evolved before the middle ear was separate from the jaw[4].

During transitional evolutionary stages, when the malleus was connected to the mandible, palinal jaw movement would have constrained the plane in which the malleus and incus could have been in contact; had the incus been in the more familiar posterior position found in most mammals today, it would have acted as a stop on backward jaw motion. Once palinal motion for chewing was established, increasing the distance the lower jaw moved forwards and backwards on the jaw joint would have made chewing more efficient. Any remaining tether to the ear would have limited the distance that the lower jaw could travel in a single chew, so selection pressure for a fully separate ear and jaw would have been strong, and full separation could have evolved rapidly.

The other animal known to have a surangular in the ear is *Arboroharamiya,* a member of an ancient group known as euharamiyidans with a palinal element to its chewing and an earlier origin than that of multituberculates[4,5]. *Arboroharamiya,* like *Jeholbaatar*, has its incus positioned above the malleus[4,6]. The relationship between euharamiyidans and multituberculates on the evolutionary tree is a matter of lively debate, with some studies, including that of Wang and colleagues, showing them to be closely related within mammals[3,4,7], whereas others place euharamiyidans on a lineage that branched off before the common ancestor of living mammals evolved[8,9]. If the latter scenario is the case, then euharamiyidans would represent a fourth instance of the independent evolution of a fully detached middle ear.

The question of whether the similarities between the ears of *Jeholbaatar* and *Arboroharamiya* reflect a close relationship on the evolutionary tree or independent (convergent) evolution driven by similar chewing adaptations is further complicated by another consideration: the incus of living platypuses (*Ornithorhynchus*) and echidnas, or spiny anteaters (*Tachyglossus*), also lies above the malleus. These mammals belong to a group called monotremes, whose middle ear evolved independently of that of other mammals. Monotremes do not use a palinal chewing motion, and the teeth of fossil monotremes do not suggest that such a motion occurred in early members of that lineage[10]. They might have this arrangement of their incus and malleus for reasons that are entirely different from those explaining the arrangement of these bones in multituberculates or euharamiyidans. Monotremes do not retain a recognizable surangular. If the similarities in the middle ears of *Jeholbaatar* and *Arboroharamiya* reflect the functional similarity in the way the animals chewed, the unfused surangular in *Jeholbaatar* and *Arboroharamiya* might simply reflect the rapidity with which the transition to detachment of the middle ear from the jaw occurred, spurred on by the increased efficiency in food processing that this complete separation would have provided.

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Condensed-matter physics

Electrons in graphene go with the flow

Klaus Ensslin

Scattering between electrons in the material graphene can cause these particles to flow like a viscous liquid. Such flow, which has previously been detected using measurements of electrical resistance, has now been visualized. **See p.75**

Water in a river shows a variety of flow patterns and whirls. Any obstacle in the river, such as a bridge pillar or simply a rough bank, will lead to a distinctive flow pattern. It has been comparatively less obvious how electrons flow in a solid. But on page 75, Sulpizio *et al.*[1] report an experiment in which the flow pattern of electrons in an electrical conductor is imaged.

The electrical resistance of a metal is caused by electrons being scattered from impurities in the material's atomic lattice or from lattice vibrations called phonons. However, it is not affected by electron–electron scattering. When two electrons scatter off each other, their individual momenta are changed by the scattering event. But the total momentum of the two electrons is conserved, as is the total momentum of a sea of electrons in a metal. Therefore, simply measuring the resistance of a metal will not unveil the effects of electron–electron scattering.

To nail down these effects, materials need to be tuned to a regime in which electron–electron scattering is dominant and the

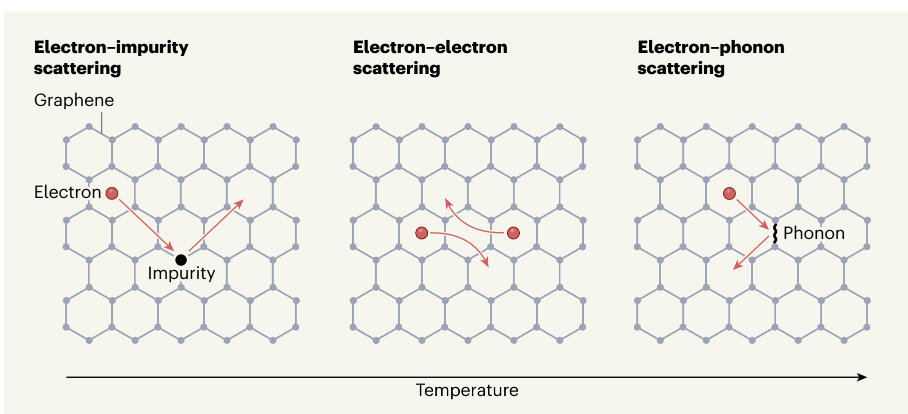

Figure 1 | Electron interactions in graphene. The material graphene consists of a single layer of carbon atoms arranged in a hexagonal lattice. Electrons flowing through graphene can be scattered from impurities (such as foreign atoms in the lattice), from other electrons and from lattice vibrations known as phonons. At low temperatures, electron–impurity scattering dominates. By contrast, at high temperatures, electron–phonon scattering takes over. Sulpizio *et al.*[1] report observations of graphene at intermediate temperatures for which the rate of electron–electron scattering is the largest among all scattering rates.

electrons flow like a viscous liquid[2,3]. At low temperatures, electron–electron (as well as electron–phonon) scattering is suppressed and electron–impurity scattering dominates. Conversely, at high temperatures, electron–phonon scattering takes over. For graphene (a single layer of carbon atoms arranged in a honeycomb lattice), there is an intermediate temperature range[4] (50–250 kelvin) for which the rate of electron–electron scattering is the highest among all scattering rates (Fig. 1). However, even in this case, the material's resistance will not be modified by electron–electron scattering because of momentum conservation.

One way to investigate the viscous-flow regime has been to measure a local resistance, known as vicinity resistance[4], on an extremely small scale. The value of this quantity changes sign in the case of viscous flow. Another option has been to observe an effect called superballistic resistance[5] for electrons flowing through a narrow opening in a material. Here, the resistance is reduced below the value expected for a ballistic system, in which there is effectively no scattering. Such pioneering experiments were crucial for demonstrating that viscous electron flow can be important in electron transport. However, they provide only indirect evidence for the existence of such flow and do not give insights into the spatial arrangements of flow patterns.

Electrons passing through a sample of a conducting material are driven by an electric field. As a result, there is a voltage gradient along the direction of current flow. Unfortunately, this local voltage gradient is independent of the flow regime. But when a weak magnetic field is applied to the sample, another voltage, known as a Hall voltage, is produced perpendicular to the direction of current flow. The spatial profile of the Hall voltage does provide information about the flow characteristics.

Sulpizio and colleagues use a sensitive electric-field sensor that enables local probing of this Hall voltage. The sensor is an innovative technology developed by this research group[6]. It consists of an electronic device called a single-electron transistor, the conductance of which depends sensitively on its electrostatic environment.

In the present work, the sensor is made from ultraclean carbon nanotubes. Individual electrons are confined within these nanotubes by electrodes. Such an arrangement provides the required sensitivity for detecting weak electric fields or voltage gradients, such as those associated with the Hall voltage. The spatial resolution of the sensor is limited by its size and the distance of the sensor to the object to be probed.

Changing the temperature and the number of charge carriers per given area in the sample induces different flow regimes, which lead to different Hall-voltage profiles. Sulpizio *et al.* use this property to image local electric fields in a uniform layer of graphene, and investigate the transition between the regime in which electron–electron scattering dominates and those in which electron–phonon or electron–impurity scattering takes over.

The authors demonstrate experimentally how electron–electron scattering alters the Hall-voltage profile of a uniform conductor. Viscous flow in liquids leads to turbulence and whirls, depending on the viscosity of the liquid and on obstacles to the flow. However, the observation of such features in electron transport is beyond the scope of the present work and could require different experimental tools, such as sensitive magnetic-field sensors, or samples that have complex geometries.

What do Sulpizio and colleagues' results mean for our understanding of electron transport in conductors? In the viscous regime, the flow of electrons is described by a universal hydrodynamic concept known as Poiseuille flow. The authors' imaging of electronic Poiseuille flow is a breakthrough in the study of electron transport as well as a demonstration of a sophisticated imaging technique that combines high spatial resolution with extreme sensitivity. We now know that electron flow can be diffusive, ballistic or viscous, and that there are experimental tools for differentiating between these regimes.

For solid-state systems in general, electron–electron interactions are relevant for phenomena as diverse as ferromagnetism (the familiar type of magnetism found in iron bar magnets) and the fractional quantum Hall effect (whereby electrons in a strong magnetic field act together to behave like particles that have a fractional electric charge). The authors' technique could also be used to investigate, on a local scale, the superconductivity that was discovered last year in a twisted bilayer of graphene[7]. The potential to extract local information about strongly interacting systems of electrons will have far-reaching consequences for this field. Further applications of the technique could enable local probing of electric fields as they arise in complex quantum circuits — which might one day lead to a quantum computer.

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Neurodevelopment

Birth of a motor circuit visualized

Kristen P. D'Elia & David Schoppik

A sophisticated imaging pipeline has been developed to track neurons in early-stage zebrafish embryos over time and space. It reveals how newborn neurons come together to build a spinal cord capable of locomotion.

Where a person comes from and what they do are often considered key parts of their identity. Similarly, neurons can be categorized by both their developmental history and their role in the nervous system. But, just as knowing someone's job title does not necessarily tell you what part they play in a team at work, knowing what role a neuron has does not mean that we understand how it comes together with other diverse neuron types to form circuits — for instance, to permit movement. Writing in *Cell*, Wan *et al.*[1] describe an imaging protocol that will help researchers determine how neural circuits form. They use their method to comprehensively chart motor-circuit assembly and emerging function in the spinal cord of zebrafish.

In vertebrate embryos, the first neuronal circuits to respond to sensory information and orchestrate movement are found in the spine[2]. These motor circuits are assembled from dozens of molecularly specialized types of neuron. Nonetheless, this is a relatively simple set-up, making it a useful system for studying how neuronal circuits come together to produce behaviour — in this case, muscles contracting in distinct patterns.

Wan *et al.* set out to study the formation of these early motor circuits in zebrafish embryos (Fig. 1). This research group has long