

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 range⁴ (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 resistance⁴, 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 resistance⁵ 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 group⁶. 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 graphene⁷. 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 spine². 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

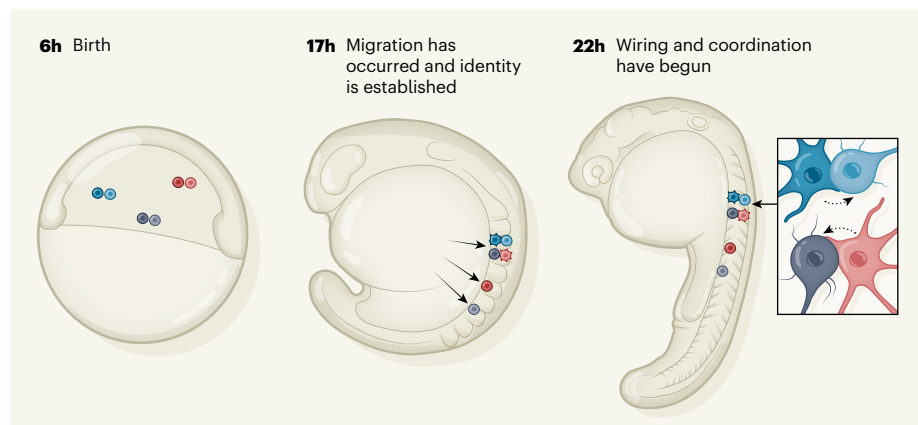


Figure 1 | Tracking the building blocks of a circuit. Wan *et al.*¹ have developed an imaging and computational pipeline to track neurons of the zebrafish spinal cord, from their ‘birth’ 6 hours after embryo fertilization until they begin to show the coordinated activity of a motor circuit at 22 hours. The authors traced newly born sister cells (derived from the same immediate ancestor, indicated by different shades of the same colour). By 17 hours, the cells have migrated to their mature positions and adopted molecular characteristics of either motor neurons (star-shaped cell) or interneurons (circular cell). By 22 hours, the cells become wired into coordinated circuits (inset). Motor neurons are the first to become active, and the authors showed that they then imprint their activity onto other neurons (dotted arrows), leading these neurons to adopt the same activity pattern.

been at the forefront of *in vivo* microscopy, pioneering light-sheet microscopy techniques that can illuminate all of the individual cells that make up developing organisms such as zebrafish without harming them. Zebrafish are well suited to such studies because they are small, transparent and develop rapidly.

The researchers imaged zebrafish from 6 hours after embryo fertilization, when spinal neurons first arise from their progenitors, to 22 hours after fertilization, when the patterns of neuronal activity that trigger tail movements begin. The imaging process generated vast libraries of images that Wan and colleagues processed to extract information about the location of individual cells over time. In addition, the authors optimized their microscope design to allow them to measure emergent patterns of functional activity from individual cells. The result was a data set that enabled the group to track the organization and function of every cell in the zebrafish spinal cord throughout early development.

Motor neurons and interneurons are key neuron types in spinal motor circuits. The former are responsible for triggering muscle-fibre contraction and the latter coordinate signalling within and between circuits³ (for example, to ensure alternating left–right movements during swimming). Motor neurons have often been thought of as passive cells controlled by upstream interneuron inputs, whereas interneurons had been thought to be the driving force behind the assembly and function of spinal motor circuits⁴. But over the past few years, evidence has emerged that both developing⁵ and mature⁶ motor neurons can control their connections to interneurons, and

even control interneuron activity. In zebrafish, motor neurons are the first spinal neurons to display spontaneous activity patterns⁷. As a circuit develops, neurons often first become active on their own, and then coordinate their activity with that of other neurons. Wan *et al.* therefore asked whether this activity originates in the motor neurons themselves, or reflects interneuron control.

The authors found that select motor neurons seem to impose their own activity on neighbouring motor neurons and interneurons, producing pairs of cells that have the same activity patterns. Thus, the earliest patterns of collective activity are initiated by motor neurons. This finding adds to the emerging picture of motor neurons as a fundamental driver of spinal-cord development. Consistent with previous findings, the authors also confirmed that interneurons coordinate the global patterns of activity necessary at later developmental stages for tail movement.

One theory of neural development states that cells that have a shared ancestry are destined to have common connectivity, and to perform similar roles in a circuit⁸. Evidence for such determinism remains contentious, reflecting the challenge of tracing related neurons as they migrate⁹. But Wan and colleagues were able to investigate this issue, thanks to their ability to comprehensively track cells over time.

The authors examined the activity of sister neurons — those that shared an immediate ancestor. In line with ideas of determinism, sister neurons that ended up in close proximity to one another were more likely than unrelated neurons to be co-active. But, intriguingly, most sibling pairs did not remain

close to one another. Indeed, sister neurons were just as likely to migrate to opposite sides of the spinal cord, where they would participate in different phases of movement. Thus, ancestry can explain only a small part of functional organization. That said, Wan and colleagues’ study is limited to the earliest part of development, well before zebrafish hatch and swim freely. It will be interesting to re-evaluate questions of ancestral determinism over longer periods of time.

Another limitation of the authors’ technique is that their cutting-edge microscope is best suited to small model organisms. It would be interesting to analyse whether their findings also apply to more-complex organisms. However, current microscopes cannot be used for such purposes.

Notably, the group that performed the study (and the Janelia Research Campus in Ashburn, Virginia, at which it works) is committed to providing access to the microscope used in the current work. In addition, the authors’ data and analysis pipelines are available to download. Thus, other researchers can further assess the relationship between the developmental history and function outlined in the current study.

Advances in the transcriptional profiling of single cells have revealed remarkable variability among neurons¹⁰, making circuit development ever-more fascinating but incredibly challenging to fully understand. Until we have a greater understanding of the molecular logic that enables neurons to form motor circuits, our ability to prevent, diagnose and treat disorders of movement will remain limited. The apparatus and analysis pipeline developed by Wan *et al.* present a technically demanding but demonstrably fruitful path towards better grasping how a neuron’s birth shapes its future role in a circuit.

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