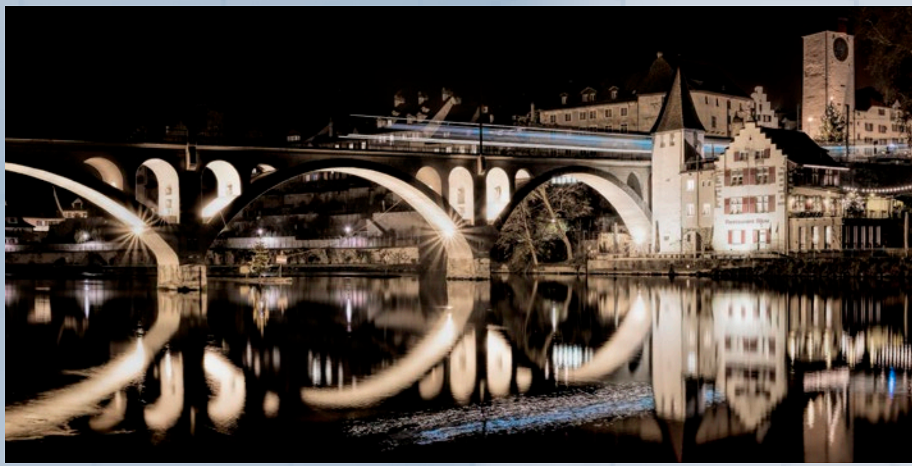
Electrons Go and



As a witty saying goes, "Physics is really nothing more than a search for ultimate simplicity, but so far all we have is a kind of elegant messiness." It is certainly true that physicists take simplicity very seriously, as they believe that seeking simplicity and beauty is key to finding truth. Indeed, in the 20th century, the pursuit for simplicity has been the guiding principle that triggered breakthroughs in many areas of physics, leading to revolutions in atomic theory, particle physics and, of course, condensed matter physics. As time goes by, our understanding of the world evolves to become less messy and more simple and elegant.

Viscous—Zippy

by Leonid Levitov

FIGURE 1

***Symmetric motifs are omnipresent in nature**, reflecting fundamental symmetries of space and time. (From left) bridge doubled by reflection (mirror symmetry); honeycomb (space translation symmetry); and musical tune (time translation symmetry). [Bridge photo: Andrey Zheludev, ETH Zürich, Switzerland; Honeycomb photo: Emmanuel Boutet; Musical manuscript from an undated set of études by Clara Schumann, used by permission of the Irving S. Gilmore Music Library, Yale University]*

Symmetries are our best friends

But what is the thing that makes it elegant? More often than not it is SYMMETRY. Physicists habitually regard symmetry as a proxy for elegance. For centuries, symmetry has remained a subject that captivated philosophers, astronomers, mathematicians, artists, architects, and physicists. As we grow up, we become aware of the numerous repeated motifs around us, both spatial and temporal, such as a reflection, honeycomb or musical tune *(Figure 1)*. There exist countless beautiful examples of geometric symmetry: a sunflower, spider web, nautilus shell, peacock tail; the list goes on and on. No one is quite sure why it is such an ever-present property, or why the mathematics behind it seems to permeate everything around us. But we do know that on a more subtle level, these symmetries reflect the symmetries of space and time. In that sense, the repeated motifs in the world around us are nothing but agents through which the symmetries of space and time are revealed to us.

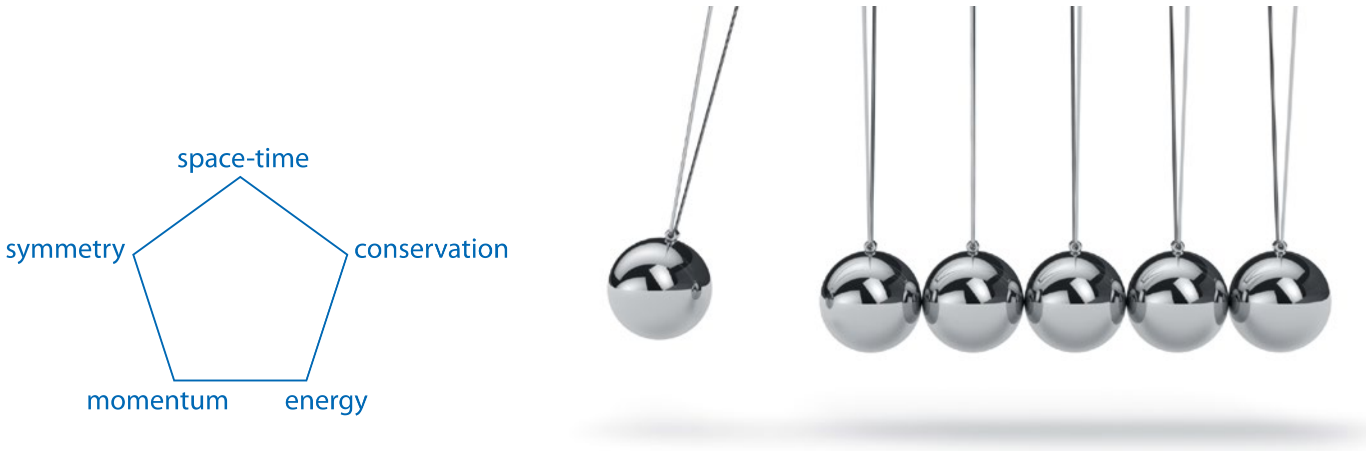


FIGURE 2

Symmetries and conservation laws: *if a physical process exhibits the same outcome regardless of place or time, then it obeys translation symmetry of space and time. By Noether's theorem, illustrated by the pentagon, these symmetries underpin the conservation of linear momentum and energy, respectively. Elastic collisions of swinging spheres in Newton's cradle provide a beautiful demonstration of these conservation laws: when one swinging sphere at the end is lifted and released, it strikes the stationary spheres, transmitting momentum through these spheres and pushing the last sphere upward.*

Symmetries play a special role in physics—uniquely important and far reaching—since they give rise to fundamental conservation laws that govern the behavior of all physical systems. Energy and momentum conservation in mechanics originate from translation symmetry of space and time. Angular momentum conservation originates from rotation symmetry, and so on. These conservation laws, as all MIT freshmen first learn in 8.01, allow us to tackle tricky mechanics questions with near-magical ease and efficiency *(Figure 2)*.

And this is just the beginning. Modern physics does not render symmetries and conservation laws useless or irrelevant. On the contrary, the power granted to us by symmetries grows as the problems researchers are attacking become more complex and challenging. Understanding the fundamental symmetries of space and time has led to the discovery of special relativity and Einstein's theory of gravity. Understanding the "hidden" isospin and chiral symmetries were key for the development of modern particle theory, for example.

Condensed matter physics has come forward over the last half-century as a unique playground for exploring symmetries, both traditional and exotic. A great appeal of condensed matter systems is that, while they typically consist of zillions of strongly interacting particles exhibiting complex collective behaviors, symmetry provides a powerful guiding principle that helps to uncover simplicity and regularity in this messiness.

Here, too, symmetry-based ideas have been remarkably successful. Famously, they helped in understanding phase transitions, a paradise for symmetries of all different kinds. The symmetry approach explained the emergence of long-range order as a result of symmetry breaking. It helped to unlock the mysteries of superfluidity and superconductivity. It catalyzed the discovery of topological order and topological phases. In recent years it brought to light topological materials, a subject of ongoing revolution.

"There's method in this madness"

Understanding the dynamics of many interacting particles is a formidable task in physics. Recently symmetries and conservation laws helped to achieve progress through developing a detailed picture of chaotic quantum systems. It is an exciting

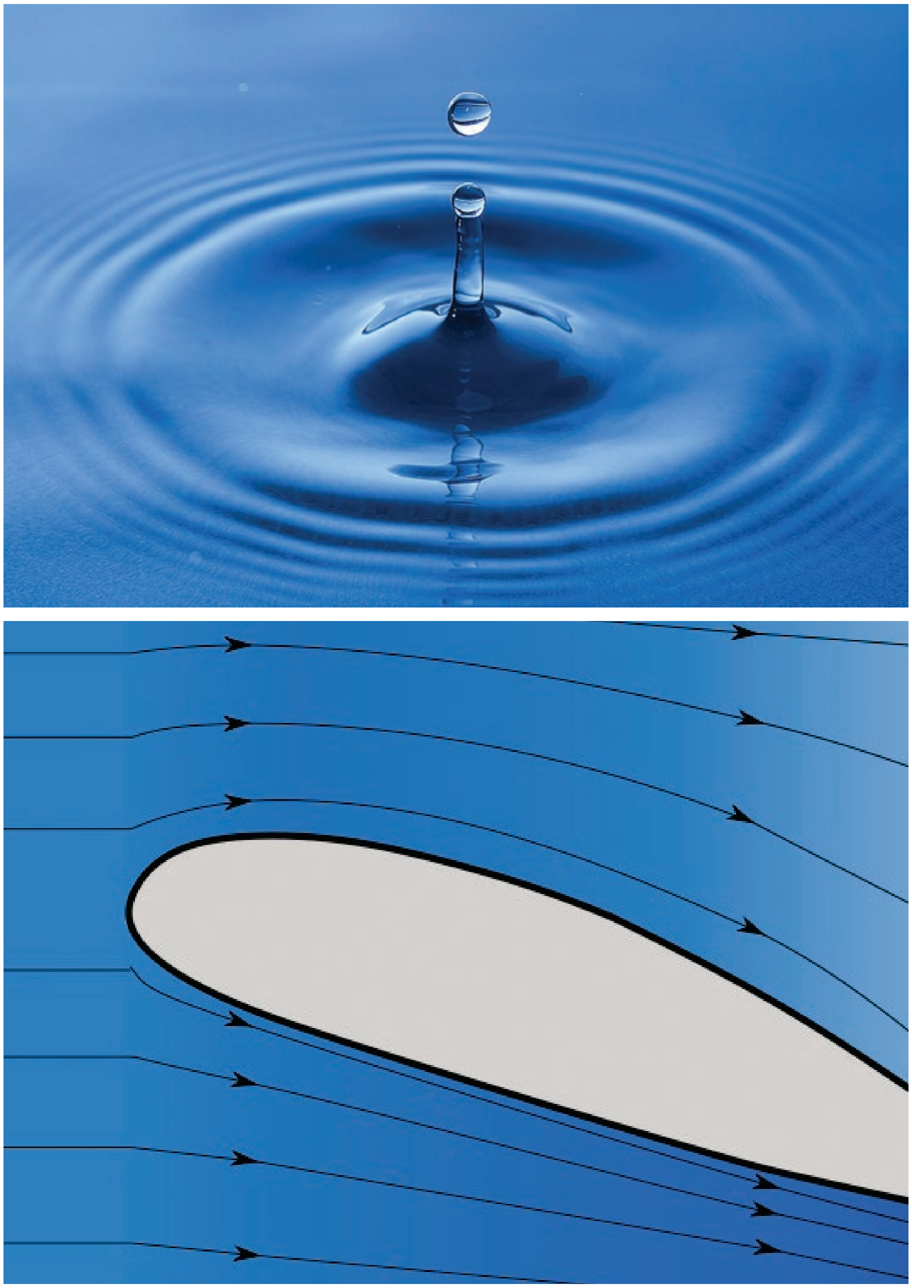


FIGURE 3

Order from chaos in fluid dynamics: *atoms in a fluid move chaotically on microscales, similar to marbles in a pinball machine. On the macroscopic scales, on the contrary, conservation of momentum and energy leads to an orderly behavior. Atoms self-organize into collective flows that can transport mass, energy and momentum, and exert forces. Shown are two examples of this general behavior: a droplet bouncing off a liquid surface, and a gas flow around an airfoil producing a lift force.*

direction in current research that explores the collective behavior of many strongly-interacting particles. In strongly-interacting fluids, particles undergo rapid collisions, losing their identity nearly instantly in the process. The momenta and energies of the particles, while quickly passed from one particle to another, remain conserved overall, taking on a new role of collective variables. As a result, the system is truly chaotic on a microscale but at larger length scales obeys conservation laws and behaves in an orderly manner described by classical hydrodynamics *(Figure 3)*.

Diverse systems of current interest fall into that framework, ranging from ultracold atomic gases to ultrahot quark-gluon plasmas generated in heavy-ion colliders. Other examples include strongly-interacting matter described by string theory, as well as electron fluids in strange metals—a condensed matter system which is believed to hold the key to understanding high-temperature superconductivity.

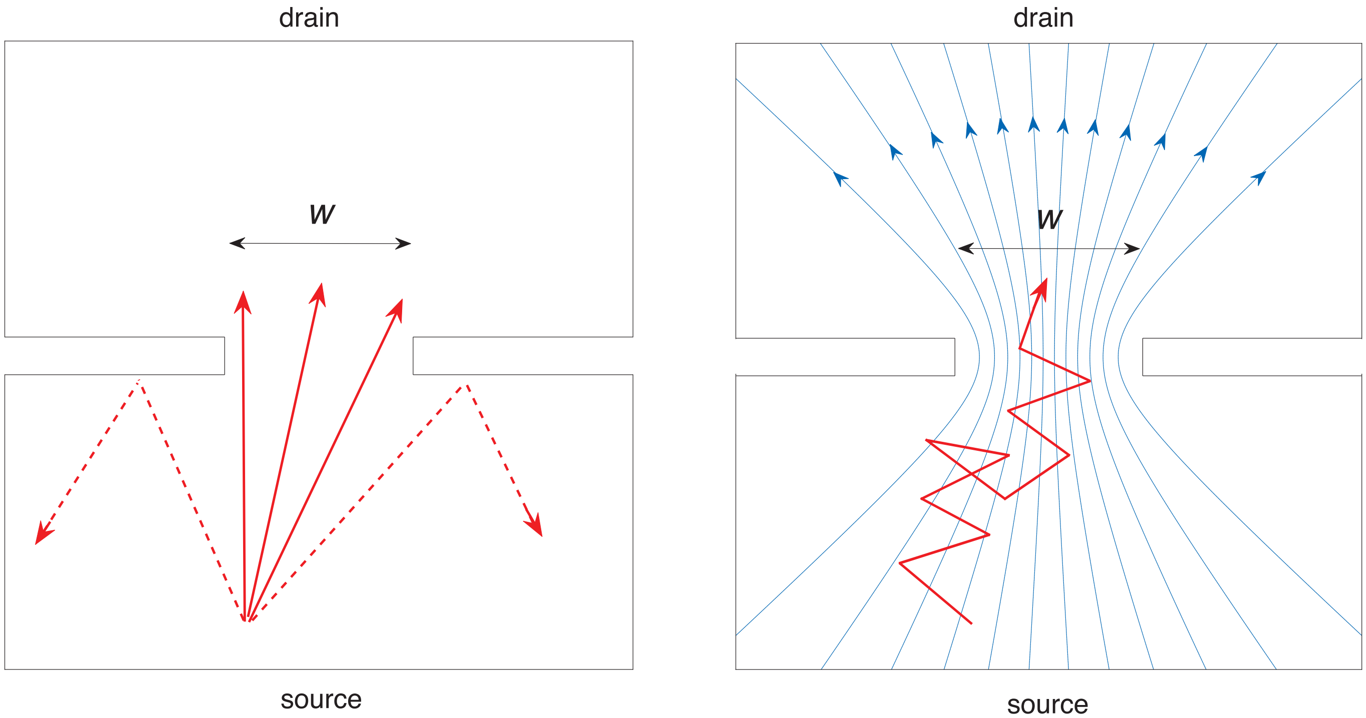


FIGURE 4

Mechanism of higher-than-ballistic conduction *for transport through a slit. For ballistic transport (left), electrons travel in straight trajectories. In this case, only those electrons that have their velocities oriented properly will make it through the slit; other electrons will be reflected. Finite reflection probability is seen in experiments as an electrical resistance. In the hydrodynamic regime (right), electrons are entrained by the flow and are being pulled through the slit in a collective manner. Each electron travels in a zig-zag path and can make it through the slit regardless of its individual velocity orientation. Such collective behavior suppresses reflection and enhances conduction. The conductance in the ballistic case is proportional to the slit width w, whereas the hydrodynamic conductance scales as* w^2 *and is therefore greater than the ballistic conductance.*

Quite remarkably, all these systems share common long-wavelength behavior due to conservation laws originating from fundamental symmetries of space-time.

The notion of an electron system behaving as a viscous fluid may seem paradoxical. And yet, recently it proved to be particularly useful for understanding electronic properties of graphene. An amazing material made from a layer of carbon one-atom thick (discovered a decade ago), graphene is the strongest material in the world and is more conductive than copper. This is because of its perfect honeycomb atomic structure which is essentially defect-free, and also because electrons in graphene behave as relativistic particles that move like optical rays, similar to light shining through window glass. Soon after its discovery, it has become a benchmark system for modern nanoscience, and at present researchers are convinced that it may harbor some unbelievable applications for us in the not so distant future.

The reason graphene is providing many sought-after qualities of an electron fluid is that electrons in this two-dimensional material are coupled by long-range electric forces through the three-dimensional space. Unlike electric forces in conventional materials, here they are completely unscreened, and as a result are pretty strong. With a possible exception of exotic fluids such as quark-gluon plasmas, electrons in graphene may be closer to the notion of a perfect strongly interacting fluid than any other system we know.

Electrons go superballistic

But while that is true in theory, the question is, even if we have this fluid-like behavior, how do we detect it? Unlike ordinary fluids, where, for example, you can directly track the flow by putting some beads into it, here we do not have a way to view it directly. Luckily, it was recently predicted that viscous electron fluids can flow more easily than electron gases. The tendency of electron collisions to suppress electric resistance and create low-loss viscous flows is not just surprising, it seemingly goes against traditional theory. Indeed, in a typical solid, electron interactions and

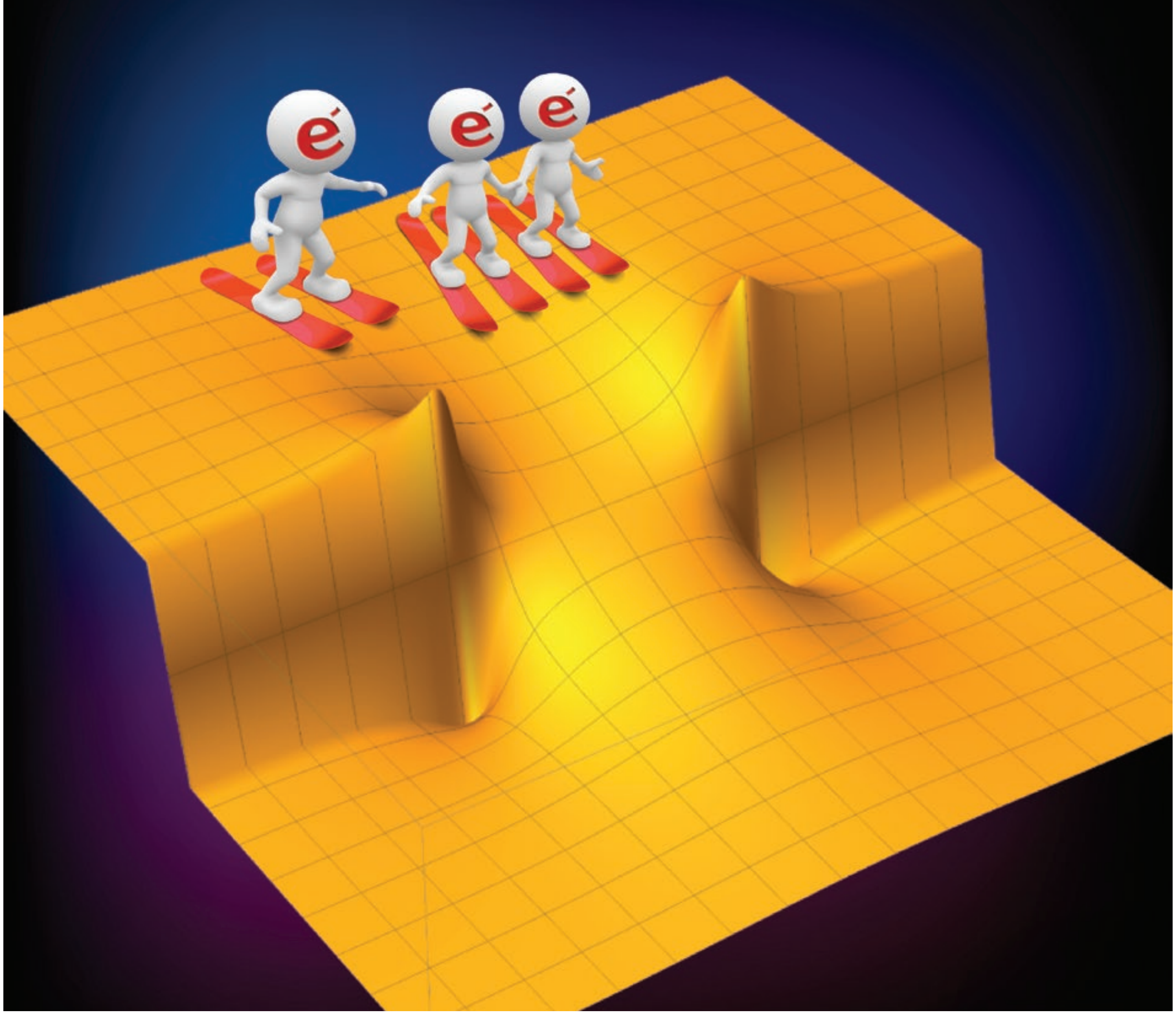


FIGURE 5

Together, we can! *Interactions turn ideal electron gas into a viscous fluid, producing a collective many-body behavior. In the hydrodynamic regime, strongly-interacting electrons "cooperate" by exchanging momenta through two-body collisions. They can speed up and, together, squeeze through the slit more easily than they would do in the absence of collisions. In this manner, electrons achieve collectively what they cannot accomplish individually, overcoming the ballistic conduction limit. [Credit: Genia Brodsky, Graphic Designer/ Weizmann Institute of Science]*

scattering hinder conduction, whereas here, to the contrary, interactions facilitate electron movement. However, even though some researchers found this prediction at first hard to believe, it was quickly verified in transport measurements, so now we have a very distinctive behavior that can serve as a litmus test of electron hydrodynamics.

To understand why viscous flows are low-loss, consider an ideal gas flowing through a slit *(Figure 4)*. Ideally, gas particles travel unimpeded along straight lines. Moving at random, most of them will quickly hit the walls and bounce off, losing some of their energy to the wall in the process and thus slowing down every time they hit. But in the presence of rapid collisions with other particles, most of them will bump into other particles more often than they will hit the walls. Collisions with other particles are "lossless," because the total energy of the two particles that collide is preserved, and no overall slowdown occurs. In other words, collisions bring particles in a gas in balance with each other and help them to achieve through "cooperation" what they cannot accomplish individually.

As the density of particles or their collision rate goes up, you reach a point where the hydrodynamic pressure you need to push the gas through goes down, even though the particle density goes up. In short, as strange as it may seem, the crowding makes the particles speed up *(Figure 5)*. Furthermore, in this regime electrons can flow at a rate that exceeds what had been previously considered a fundamental limit, known as Landauer's ballistic limit, which asserts that free-particle dynamics provides the highest conduction. The new effect, dubbed "superballistic" flow, represents a considerable drop in the electrical resistance of the metal—though it is much less of a drop than what would be required to produce the zero resistance in superconducting metals. However, unlike superconductivity, which requires extremely low temperatures, the new phenomenon may take place even at room temperature and thus may be far easier to implement for applications in electronic devices. In fact, the effect actually grows stronger as the temperature rises. In contrast to superconductivity, superballistic flow is assisted by temperature, rather than hindered by it.

While previous attempts to connect electron theory with fluid mechanics had limited success, the prediction and observation of superballistic flows finally put the idea of electron fluids on a firm ground. These developments open a wide array of exciting possibilities. Graphene, which can be easily patterned into any shape without compromising its excellent qualities, can become a basis of electronic microfluidics, leading to novel applications in information processing and nanoscale charge and energy transport. Or, imagine using viscous graphene electronics as an on-chip simulator of complex nonlinear behaviors in classical fluids, such as formation of vortices and turbulence *(Figure 6)*. Furthermore, magnetic fields can be used to drive electron fluids into a magneto-hydrodynamic state. If realized in the lab, it will provide a table-top model of ultrahot magnetically confined plasmas comprised of relativistic particles, found under extreme conditions in astrophysics, as well as on earth in controlled thermonuclear fusion experiments. Those ideas, rather than being a mere fantasy, are actively pursued by researchers worldwide and we will soon find out what Nature has in store for us.

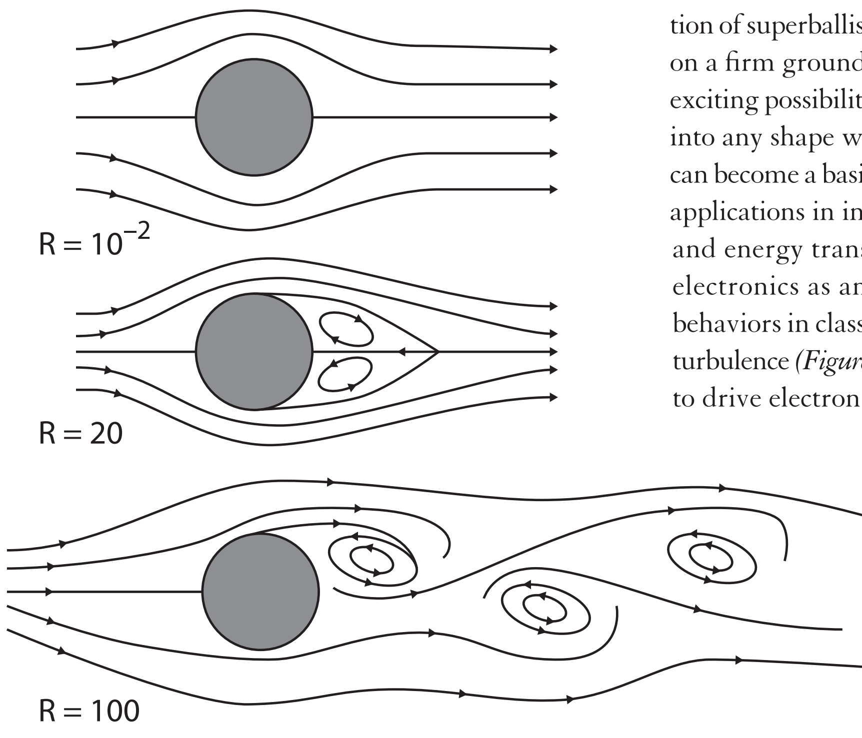


FIGURE 6

The sequence of transitions *from a simple laminar flow to the flows with complex vorticity patterns and, eventually, to turbulence, expected to occur upon increasing the flow rate. As the Reynolds number* R *(the flow rate parameter) grows, symmetries disappear one-by-one, giving rise to progressively more complex and interesting flows. [Credit: François Gieres, Institut de Physique Nucléaire de Lyon, Université de Lyon]*

LEONID LEVITOV *is a professor of physics in the condensed matter theory group of the MIT Department of Physics. Levitov is a pioneer in the theory of quasicrystals—orderly materials with "forbidden" non-crystallographic symmetries, discovered in 1985. He co-authored a theory explaining the structural properties of quasicrystals by introducing the concept of a structure projected from a high-dimensional periodic structure. In the '90s, Levitov pioneered the theory of quantum noise in coherent electron transport. He formulated the counting statistics approach, which evolved into a new tool in the field of quantum transport. In 1993 he developed the concept of coherent current pulses allowing the transmission of electrical signals in a noise-free fashion. These pulses, observed in 2013 and dubbed 'levitons,' have become the basis of electron optics.*

In the last 10 years, Levitov developed a theory of electronic properties of graphene, a newly discovered two-dimensional electron system. He introduced new concepts of graphene optoelectronics, identifying a new mechanism of optoelectronic response involving multiple generation and proliferation of hot carriers. He proposed graphene as a platform to generate topological valley currents, which was experimentally observed in 2014. These are chargeless currents that do not dissipate any energy, a possible information carrier in next-generation electronics and optoelectronics. Levitov also proposed graphene as a platform for electron hydrodynamics and predicted low-dissipation electron flows with higher-than-ballistic conduction (observed in 2017).

A native of Russia, Leonid Levitov earned his MA Diploma in physics at the Moscow Physical-Technical Institute (1985), and his PhD in theoretical physics at the Landau Institute (1989). He joined the MIT Physics faculty in 1991, becoming an associate professor in 1996 and full professor of physics in 1997.