

Materials with a few weakly coupled layers can have a variety of complex structures, including twist angles, mismatched lattice periods or, as in the present case of rolled layers, different curvatures. It remains to be seen whether the coupling demonstrated by Liu and colleagues has consequences for other

properties of DWCNTs or other types of incommensurate layered systems.

João Lopes dos Santos is at Centro de Física do Porto and Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, P4169-007 Porto, Portugal.
e-mail: jlsantos@fc.up.pt

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FLUID DYNAMICS

Swimming across scales

The myriad creatures that inhabit the waters of our planet all swim using different mechanisms. Now, a simple relation links key physical observables of underwater locomotion, on scales ranging from millimetres to tens of metres.

Johannes Baumgart and Benjamin M. Friedrich

Many animals swim by accelerating the liquid around them, using a regular undulatory motion powered by orchestrated muscle movements. But the movements of goldfish look vastly different from those of alligators, so the idea that they might be described by a universal mechanical principle seems optimistic — if not entirely unrealistic. Now, however, as they report in *Nature Physics*, Mattia Gazzola and colleagues¹ have found that common scaling relations characterize the swimming behaviours of a diverse set of marine creatures.

Gazzola *et al.*¹ used observational parameters, such as beat amplitude and frequency, to estimate physical quantities — including thrust, drag and pressure forces relevant for net propulsion. A measure of the thrust force is given by the mass of the fluid set in motion multiplied by its acceleration. The authors were able to describe the thrust generation of swimming organisms elegantly, using dimensionless numbers that characterize ratios of these quantities.

Dimensionless numbers have a long tradition of describing the scale-invariant features of fluid flow, providing key qualitative insight in fluid mechanics. For example, the so-called Reynolds number is defined as the ratio between two force scales: the relative magnitudes of inertial and viscous forces. Here, it is the typical speed of a swimmer, multiplied by a characteristic length scale and divided by the kinematic viscosity of the surrounding fluid.

The advantage of introducing such ratios is that any absolute force scale can be fully eliminated from the Navier–Stokes equations governing fluid flow, leaving only dimensionless parameters, and providing a reduced set of effective parameters. The form

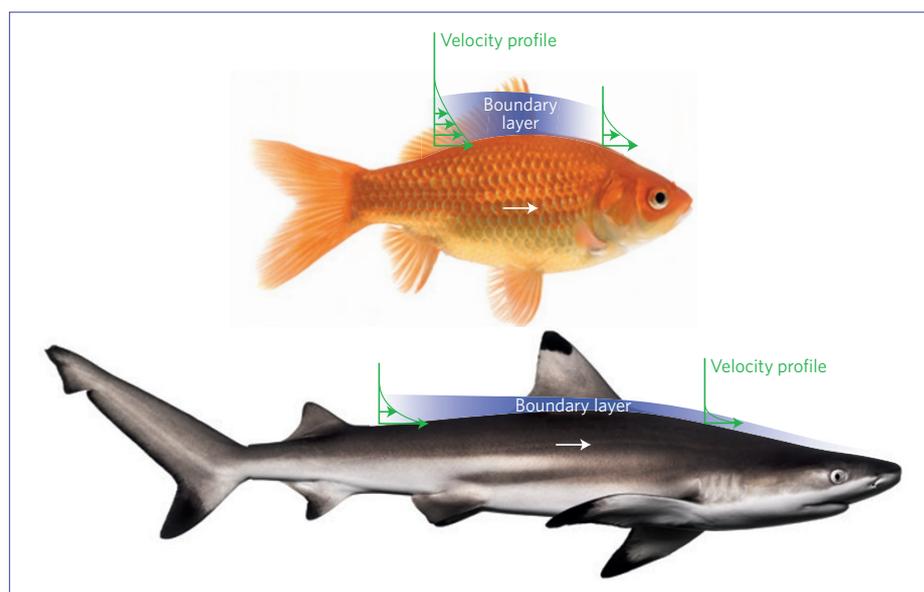


Figure 1 | As a fish swims through viscous water, a layer of fluid is dragged along its body. This so-called boundary layer is proportionally thicker for small fish that experience lower Reynolds numbers compared with larger and fast-swimming fish. The fluid motion is illustrated by velocity profiles. Image of goldfish © David Cook/blueshiftstudios/Alamy; image of shark, © GlobalP/iStock/Thinkstock.

of the solution then depends only on these dimensionless parameters — one has to rescale it to yield a real-world solution. This is exploited in wind-tunnel experiments, for example, in which a scaled-down model is tested at the very same Reynolds number that applies to the real-world analogue. Length, force and time then have to be scaled appropriately.

The Reynolds number dictates the swimming experience. It is well known that swimming bacteria or sperm cells experience extremely low Reynolds numbers, implying that viscous forces dominate. If a sperm

flagellum were to stop beating all of a sudden, it would stop coasting within less than a millisecond — much like if you were to swim in honey. In this inertia-free world, scaling relations between the amplitude of swimming strokes and swimming speed have long been known. They are relatively easy to derive, as the corresponding mathematical equation governing viscous flow is linear, so solutions can simply be summed together.

At higher Reynolds numbers, applicable to the swimming of penguins and whales, convective effects dominate and new qualitative features emerge. Consider this

experiment: put a candle at a distance and try to extinguish it by either exhaling or inhaling. You'll find that reversing the sign of the boundary conditions does not simply reverse the flow — at large Reynolds numbers fluid dynamics is highly nonlinear and convective effects dominate. These flows are also prone to deterministic chaos, known in this context as turbulence.

These effects are all captured by the Navier–Stokes equations, which also describe the intricate flow patterns of whirling eddies, turbulent flows and the shock waves of transonic flights. Computing high-Reynolds-number flows is still very demanding, even on the fastest computers available. Although knowing the exact flow patterns in detail is an appealing idea, in the end one is quite often interested only in scalar quantities — in this case, the swimming speed of fish. Furthermore, in biology there is no need to squeeze out the last digit of precision, as is necessary, for example, in turbine design. Gazzola *et al.*¹ therefore took a promising approach by estimating the magnitude of such scalar quantities based on available experimental data.

The speed of swimming is determined by a balance of thrust and drag. Hydrodynamic friction arises from the relative motion of the fish skin with respect to the surrounding liquid. Specifically, the rate at which the fluid is sheared shows a characteristic decay as a function of distance from the swimmer, defining the boundary layer in which the viscous losses take place and kinetic energy is dissipated as heat². This boundary layer becomes thinner, the faster the flow — a classic effect, well known to engineering students for the more simplified geometry of a flat plate. More than a century ago, Blasius investigated this type of problem³. He found self-similar solutions of the velocity profile, rescaled according to the Reynolds number. Gazzola *et al.*¹ applied this idea of

a viscous boundary layer to estimate the friction of a marine swimmer (Fig. 1), and its dependence on the swimmer's size, to derive a scaling exponent for the swimming speed. The theoretical prediction is indeed consistent with the biological data, as long as the amplitude of the undulatory body movements is smaller than the thickness of the boundary layer.

What happens for swimmers that are even faster? At such high Reynolds numbers, the viscous boundary layer is very thin and the deceleration of the fluid towards the body becomes important, resulting in a load through the conversion of kinetic energy into dynamic pressure, as known from Bernoulli's law. This effect is used by pilots, for example, when measuring their velocity with a pitot tube. Gazzola *et al.*¹ found a second scaling relation for this regime of high Reynolds numbers.

The authors' analysis showed that data from fish larvae, goldfish, alligators and whales can all be fitted with these two scaling laws, revealing a cross-over between viscous- and pressure-dominated regimes. An extensive set of two-dimensional simulations — treating the swimming creatures essentially as waving sheets — corroborates their findings. Two-dimensional calculations have a long tradition in fluid dynamics and have already been used⁴ to understand self-propulsion at low Reynolds numbers. Strictly speaking, ignoring the third spatial dimension is a strong simplification. However, Gazzola *et al.*¹ compared selected three-dimensional simulations, some of them the largest ever conducted, to their two-dimensional results, and confirmed an analogous scaling relation.

What remains elusive is the transition point between the drag and pressure force regimes. It is an appealing idea that biology may have found ways to shift this point to low values and minimize the overall losses.

Indeed, at high Reynolds numbers, sharks are known to reduce drag through special patterning of their skin⁵.

The present work is an example of how physical laws — in this case, the physics of fluid flow — determine the operational range of biological mechanisms such as swimming. Physics sets effective constraints for biological evolution. The beauty of physical descriptions is that they often hold irrespective of a given length scale, and can thus describe phenomena occurring over a wide range of sizes. The absolute scale of lengths, times and forces can always be eliminated from a physical equation, leaving only dimensionless physical quantities. As these dimensionless quantities usually reflect biological design principles that are conserved across scales, universal scaling laws emerge.

It is interesting to compare this instance of physics constraining biological function to earlier work of allometric scaling laws, where it was argued that the hydrodynamics of blood flow in the transport networks of terrestrial animals define scaling relations that relate body size and metabolic activity⁶. The dawn of quantitative biology may yet reveal novel examples of such general scaling laws. □

Johannes Baumgart and Benjamin M. Friedrich are at the Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany. e-mail: benjamin.friedrich@pks.mpg.de

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MULTILAYER NETWORKS

Dangerous liaisons?

Many networks interact with one another by forming multilayer networks, but these structures can lead to large cascading failures. The secret that guarantees the robustness of multilayer networks seems to be in their correlations.

Ginestra Bianconi

Natural complex systems evolve according to chance and necessity — trial and error — because they are driven by biological evolution. The expectation is that networks describing

natural complex systems, such as the brain and biological networks within the cell, should be robust to random failure. Otherwise, they would have not survived under evolutionary pressure. But many

natural networks do not live in isolation; instead they interact with one another to form multilayer networks — and evidence is mounting that random networks of networks are acutely susceptible to failure.