

# How to walk on water

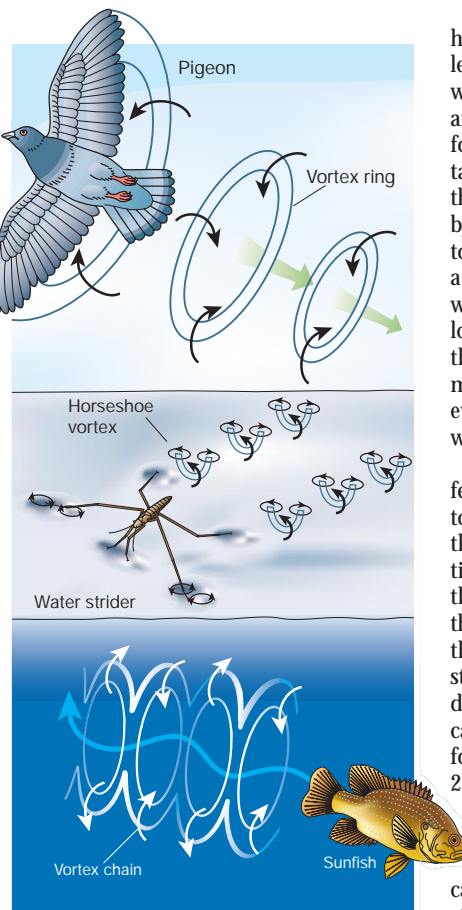
Michael Dickinson

How the short legs of juvenile water striders propel the insects across water has perplexed researchers. It now appears that walking on water shares features with the locomotion of birds, insects and fish.

A glance at the surface of a pond reveals one of the more delightful images of summer: the shimmering ripples made by the graceful strokes of water striders. Water striders are insects that are adapted for locomotion and foraging on top of still water. Long hairy legs keep these animals afloat, but how do they glide so effortlessly across the surface? Models of water-strider locomotion have proposed that the animals move forwards by creating surface waves that carry momentum backwards. An elegant study by Hu, Chan and Bush<sup>1</sup>, described on page 663, shows that this view is, quite literally, superficial. Like the oars of a rowing-boat, a water strider's legs create swirling vortices that carry momentum *beneath* the surface of the water. It is the rearwards motion of these vortices, and not the surface waves, that propels the animal forwards. This insight solves a paradox related to the motion of juvenile water striders, and helps to form a more cohesive picture of animal locomotion.

Much of animal locomotion distils down to a simple application of Newton's third law: to move forwards, animals must push something backwards<sup>2</sup>. Just what that something is depends on the form of locomotion. Large terrestrial animals push against the solid ground, creating reaction forces in the opposite direction. The situation is a bit more complicated for swimming and flying animals, which must push against a fluid (from a physical standpoint, both air and water are fluids). As a fin or wing flaps, the fluid yields to form a pattern of swirling vortices. In some cases, the energy transmitted by an animal to the fluid in one stroke takes the form of a discrete vortex: a doughnut-shaped structure like a smoke ring. Birds<sup>3</sup>, bats<sup>4</sup>, insects<sup>5</sup> and fish<sup>6</sup> have all been shown to create a series of vortices as they move, although the precise arrangement may be complex and notoriously difficult to quantify. By carefully measuring the size, strength and velocity of the vortices generated during each stroke, it is theoretically possible to reconstruct the average force with which an animal propels itself through the air or water<sup>7,8</sup>.

But what about tiny creatures such as water striders, that live between air and water? What do they push backwards to move forwards, and how do they stay afloat



**Figure 1 Locomotion in fluids.** Vortices carry the momentum to move animals forwards in both air and water, but their pattern varies with the style and speed of locomotion. A slow-flying bird (pigeon) makes a single vortex ring with one downstroke. Its wake consists of a series of rings that move backwards and downwards. Each stroke of a fish's tail (sunfish) creates a vortex ring, which fuses with those of prior strokes to form a linked 'zig-zag' chain. The long legs of a water strider create tiny U-shaped vortices with their free ends attached to the water surface. In all cases, the circular flow around the vortex filament shoots fluid backwards through the centre of the ring, propelling the animal in the opposite direction.

in the first place? Resting statically on the water surface poses no great problem to a small organism<sup>9</sup>. Surface-tension forces at an air–water interface result from the mutual attraction of water molecules through

hydrogen bonds. As the wax-covered, hairy legs of an insect dip the water downwards, these surface-tension forces push the animal upwards. Whereas the total upward force is proportional to the perimeter of contact, which increases linearly with body size, the mass of the animal that must be supported by the tension forces increases proportionally to the cube of its body length. Thus, whereas a small water strider can easily stand atop water, larger insects need proportionally longer legs to ensure that they can rest on the surface with suitable safety. As documented by Hu *et al.*<sup>1</sup>, this requirement for ever-longer legs limits the maximum size of a water strider to about 25 centimetres.

Understanding how water striders transfer momentum to move forwards is much tougher. One possible explanation is that they transfer momentum backwards in the tiny surface ripples created as they sweep their legs. Unlike the more familiar waves of the open ocean that are dominated by gravity, the tiny ripples generated by the legs of water striders are termed capillary waves and are dominated by surface tension. To generate a capillary wave, an insect leg (or any object, for that matter) must move faster than about  $25 \text{ cm s}^{-1}$  — the minimum speed at which any surface wave can travel. Exceeding this speed is no problem for the long legs of water-strider adults, but is beyond the capacity of the juveniles. If juvenile water striders cannot move the tips of their legs fast enough to create the surface waves, how do they propel themselves? This enigma was identified by Mark Denny<sup>9</sup>, and is known to water-strider enthusiasts as Denny's paradox.

The resolution of Denny's paradox, as described by Hu *et al.*, is that water striders transfer momentum not by surface ripples, but rather by vortices beneath the water surface. Unlike the circular vortices shed by fish, those created by water striders are squat affairs — a 'U-shaped' filament with two free ends attached to the water surface (Fig. 1). This peculiar shape is an elegant example of Helmholtz's laws, which govern the structure of vortex filaments. Vortex filaments cannot end abruptly within a fluid, and so must join end to end, as in a smoke ring, or attach to a wall or surface discontinuity, as in a tornado. By measuring the size and speed of the vortices formed behind the legs, the authors were able to show that the rearward

momentum created was large enough to explain the insect's forward motion, whereas the contribution of the capillary waves was much too small. So, despite their small size, the legs of water striders are analogous to the oars of a rowing-boat, which also move forwards by sending a series of vortices backwards through the fluid. This more accurate understanding of water striders fits well with the emerging picture of animal locomotion. Through their use of vortices, water striders share general features with animals flying above and swimming below them. ■

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## Nanotechnology

# A barrier falls

J. Tersoff

Electronic devices based on carbon nanotubes have a bright future — even more so now that a way has been found to eliminate the 'Schottky barrier' that hinders the injection of electrons into them.

Since the days of vacuum tubes, a key problem in the use of electronic devices has been getting electrons into the device from a metal connecting wire. Even the tiny transistors now being made from semiconducting carbon nanotubes share this classic problem: their performance is limited by an energy barrier that hinders electrons entering the nanotube. But now it seems that this barrier has fallen. In a paper on page 654 of this issue, Javey *et al.*<sup>1</sup> report the fabrication of

nanotube transistors with improved performance, achieved by reducing or eliminating the barrier that electrons must cross from the metal wire into the semiconducting nanotube.

To be sure, nanotube transistors are already performing impressively in device applications<sup>2</sup>. But eliminating the barrier to electron flow is an important advance that will open the way for further improvements. The key, according to Javey *et al.*, is to use the correct combination of metal wire and

nanotube. With little or no barrier to overcome, electrons have a good chance of shooting through the nanoscale device ballistically, without being slowed by scattering. In this way, much higher currents and lower resistances are achieved than ever before — within a factor of two of the ultimate quantum limit for such a device<sup>1</sup>.

The struggle to overcome energy barriers in electronic devices has a long history. In the venerable vacuum tube (Fig. 1), electrons face a large energy barrier to moving from the metal wire into the vacuum. The energy to overcome this vacuum barrier is provided by heating the wire until it glows brightly — an approach with obvious limitations. A similar problem plagued early devices made from familiar semiconductors such as silicon. There is an energy barrier, called the 'Schottky barrier', that electrons must overcome to get from a metal wire into the semiconductor. Modern silicon transistors circumvent the problem by replacing the metal wire with a silicon wire that is 'doped' with special impurities so that it can carry current to the device without any Schottky barrier.

Semiconducting nanotubes have the same problem: there is typically a Schottky barrier between the incoming metal wire and the nanotube. Nanotubes can be doped<sup>3–5</sup>, and replacing the metal wire with a doped nanotube should also work here, just as it does for silicon<sup>6</sup>. But to form useful contacts in this way would require heavy doping with nanoscale spatial control — a formidable challenge. Instead, nanotube transistors have tended to rely on a geometrical advantage that they have over silicon. Because the tube is almost a one-dimensional wire, an external electric field can penetrate right to the metal–nanotube interface and reshape the barrier. If an appropriate voltage is applied, the Schottky barrier can be made so thin that electrons 'tunnel' quantum-mechanically through it. In this way, good device performance has been achieved despite any barrier<sup>2</sup>, and there is room for further improvement by designing devices with this effect in mind<sup>5</sup>.

Nevertheless, such tunnelling always entails extra resistance: although an electron may tunnel through the thin Schottky barrier, it also has some probability of being reflected. A device's performance would be substantially improved if the Schottky barrier could be eliminated altogether, but this has not proved possible for silicon and similar semiconductors. It was anticipated that, for nanotubes, the Schottky barriers might be more easily controlled, either because the nanotube itself does not bond chemically to the metal contact, or because the nanoscale geometry makes the bonding less effective in 'pinning' the barrier height<sup>7</sup>. Experimental measurements support this idea<sup>5</sup>.

Despite these tantalizing suggestions, there had been no clear demonstration that

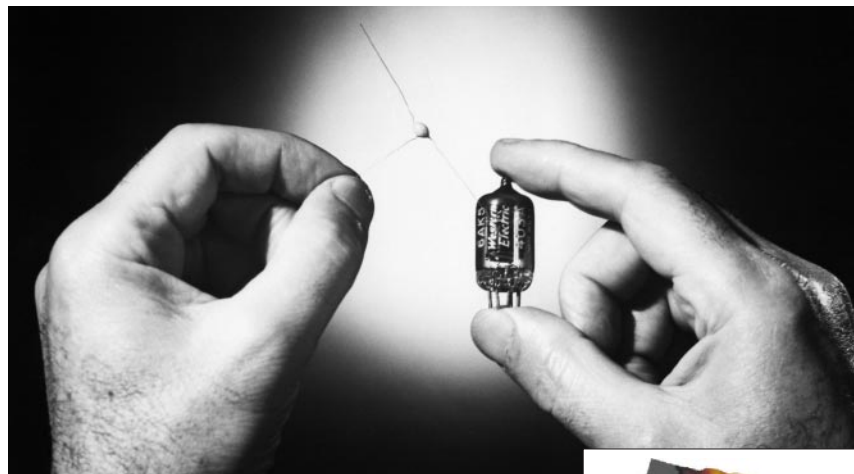


Figure 1 State of the art. Fifty years ago (when the image above was taken), the vacuum tube that had revolutionized electronics, especially in radio communications, was superseded by the transistor, a new electronic component many times smaller. Since then, transistors have shrunk to microscopic size. Now attention is turning to carbon nanotubes (an example is shown, right, in this scanning-tunnelling-microscope image; reproduced from ref. 8). Nanotubes are little more than a nanometre in diameter, but share a common problem with their electronic predecessors — how best to get electrons into the device. Javey *et al.*<sup>1</sup> have now found a solution.

