Water's Tough Skin

Surface tension is a force to be reckoned with, especially if you are small

An ant could step off a cliff and land unharmed. But if it dips a leg in a raindrop, the insect can be caught in a life-threatening morass, all because of the surface tension of water. The result of polar interactions among water molecules, surface tension is what draws a water droplet into a sphere. It creates an elastic surface that can deform without breaking—think of a water strider oaring its way across the surface of a pond. At the same time, it enables water to cling like quicksand to an ant unlucky enough to blunder in. Creatures of our size barely acknowledge surface tension's existence, but for the tiny, "it becomes a dominant force," says David Hu, a mechanical engineer at the Georgia Institute of Technology in Atlanta.

Because of surface tension, a rat can't pee a steady stream, but instead must slowly push out urine drop by drop. (It can take 10 minutes for a single drop to fall.) Surface tension thwarts juvenile flying fish: When they try to escape into the air like the larger adults, they sometimes bounce off the underside of the water's surface layer. Dew forming on a mosquito's wing will cause the wing to fold up, grounding the insect until the wing dries out.

Physicists have a pretty good understanding of how surface tension arises. The clingy water molecules attempt to minimize their connections with other types of molecules. So when something deforms the water surface, the displaced water molecules work to return to their minimum-energy configuration—unless the intruder itself attracts water molecules, in which case the water clings like glue. But biologists have tended to ignore the air-water interface, Hu says. His own eyes were opened a decade ago when he began to study how water striders skate so effortlessly along the surfaces of ponds. Using dyes and high-speed video, Hu and his colleagues found that by vigorously rowing along the surface, striders cre-

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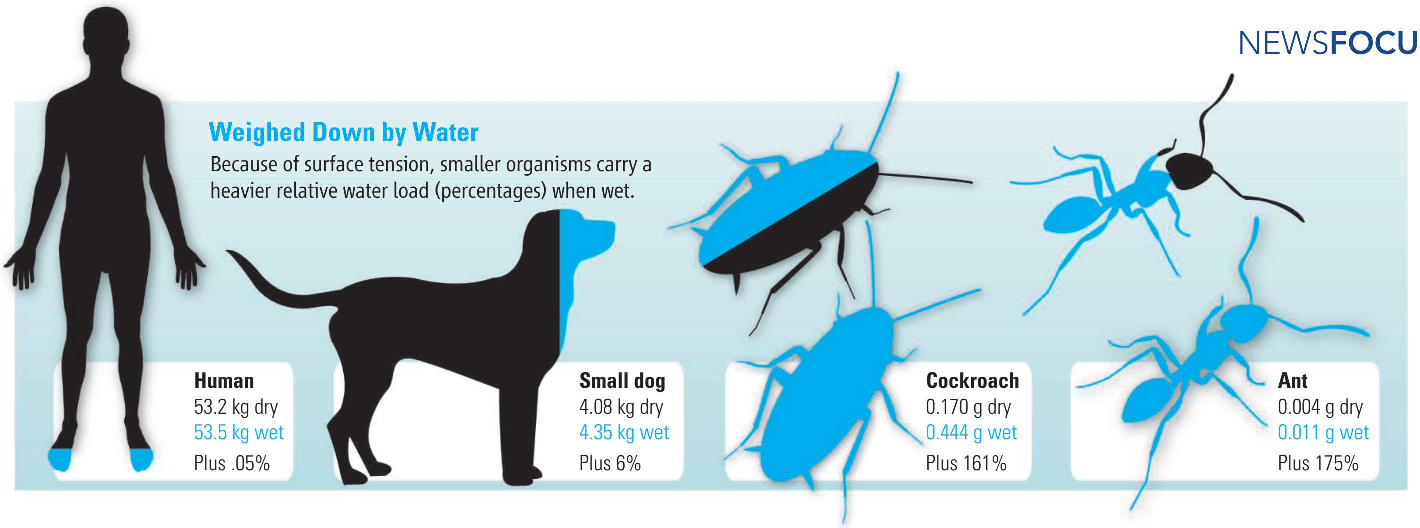


ate swirls that help propel them forward, all without rupturing the water surface. "That work was the trigger of academic interest in surface tension in biology," says Ho-Young Kim, a mechanical engineer at Seoul National University.

Hu has since looked at other phenomena involving air-water interfaces—how dogs shake to dry off, how mosquitoes cope with rain (*Science*, 8 June 2012, p. 1216), and how animals pee—disparate phenomena "linked by common equations and modeling ideas," he says. Since then, other researchers have recognized the power of surface tension to explain form and behavior on the small scale. And while humans, unlike ants, don't have to worry about being trapped because of surface tension, it's still relevant to our lives. For example, our lungs secrete a chemical inside their air-filled sacs to lower the surface tension there, which allows us to breathe without the sacs collapsing when we exhale. Surface tension also allows human and agricultural pathogens to travel long distances in tiny, lightweight droplets.

Some of the most eye-catching new findings were on display at "Shaking, dripping and drinking: surface-tension phenomena in organismal biology," a symposium that Hu helped organize at the annual meeting of the Society for Integrative and Comparative Biology in Austin in January. "The sheer dazzling diversity of biological phenomena to which surface tension is relevant is mind-blowing," says Steven Vogel, a biomechanist at Duke University in Durham, North Carolina.

Giving plants "muscles"

Plants lack muscles, but findings presented at the symposium showed that for some, surface tension can substitute. "When there's a change in surface tension, you get motion," explains Rachel Levy, a mathematician at Harvey Mudd College in Claremont, California. "It creates motion in ways you don't expect."

Consider *Erodium*, a group of flowers whose fruit resemble a bird beak. Inside that beak, each seed develops a centimeter-long awn—a rodlike "tail" that serves two purposes. Initially, inside the fruit, the awn is stretched out. When the fruit dries and cracks open, the freed awn spontaneously coils, releasing its stored energy and sending the seed a half-meter from the parent plant. After the seed lands, the awn winds up during the day and unwinds at night, screwing the seed into the ground bit by bit—a millimeter or so a day.

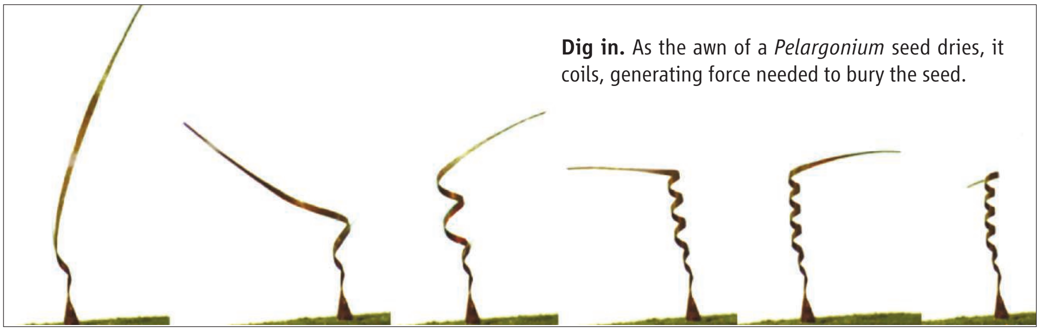
Kim has found that surface tension drives the process. Normally, surface tension causes water droplets to ball up to minimize the air-water interface, he explains. But when those droplets meet a surface that has a greater attraction for the molecules of water than water itself, they will spread out and wet it. He found that the awns of *Erodium* and of *Pelargonium*, another group of plants with self-burying seeds, consist mostly of fibers of lignin and pectin, both water-loving molecules. At times of day when humidity is high, the fibers quickly absorb moisture. "The wet tissues swell and become straight from [an] initially dry, coiled configuration," Kim explains. When humidity drops, the fibers dry out, the tissues shrink, and the awn coils up again.

Kim mounted seeds from both groups of plants onto a force sensor and increased the humidity to measure the force they generated as they tried to uncoil. He also tested the burying potential of the force by watching awns drive their seeds into "soils" of glass beads of different sizes. The force "is just enough to dig into the soil," Kim reported in January.

It might also be enough to propel a microrobot. Today's microrobots all require electrical tethers, because no battery is both sufficiently powerful and small enough to be carried on board. Eventually Kim wants to equip robots with humidity-driven "muscles" that won't require external power. "But first we need to know how the biology works," he says.

A raincoat for a leaf

A floating fern, *Salvinia molesta*, forms meter-thick beds at the surface of ponds and slow-moving rivers. Native to South America, it's become invasive around the world, clogging waterways and disrupting aquatic ecosystems. But what attracted Wilhelm Barthlott to this prolific plant was its ability to keep submerged leaves coated with a thin layer of air. The film of air gives the leaves a silvery sheen and enables the plant to carry out photosynthesis and gas exchange underwater. It also makes the fern buoyant, so it will quickly bob to the surface if an opening appears, filling in any gaps before other species can get established.



Dig in. As the awn of a *Pelargonium* seed dries, it coils, generating force needed to bury the seed.

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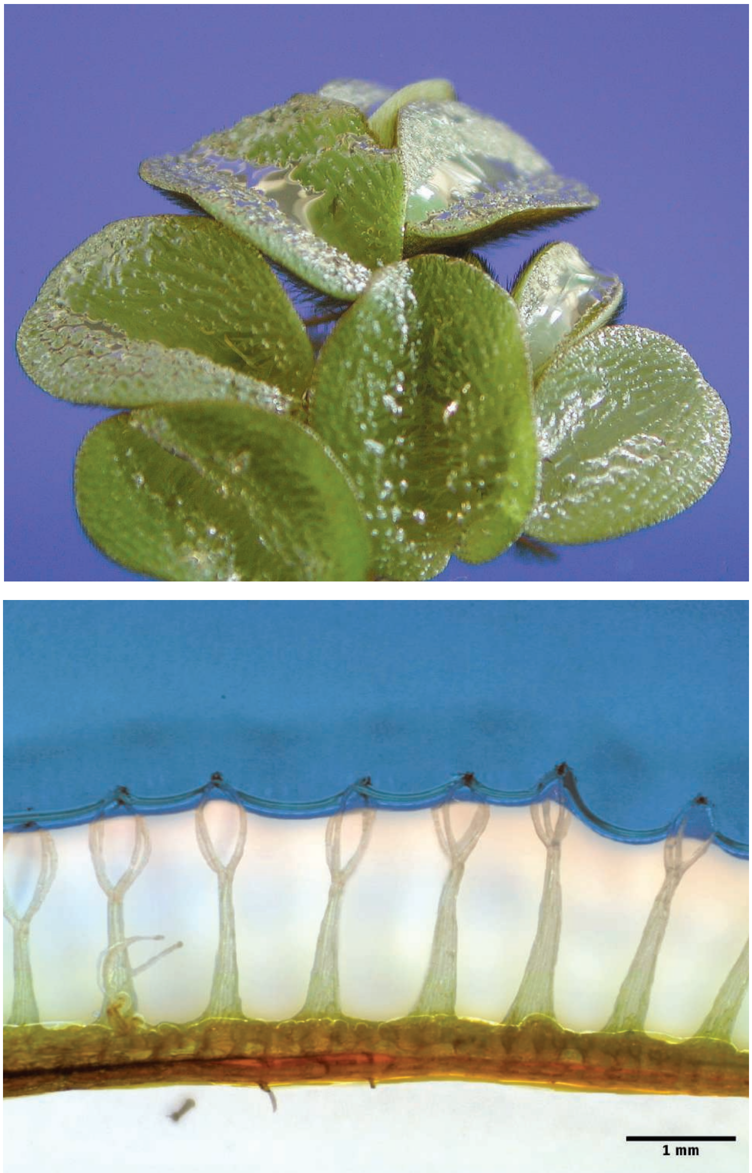
Engineers want to create similar air layers on the hulls of ships to reduce drag and fuel consumption. But to date, they have not been able to generate a layer that lasts. So Barthlott, a biologist emeritus at the University of Bonn in Germany, and his colleagues decided to see how *Salvinia* does it. Studying the microscopic structure of the leaf surface, they discovered hundreds of regularly spaced clumps of 2-millimeter-long hairs, four per clump. The clumps resemble eggbeaters: The hairs in each clump flare out midway up but reconnect at their tips. Along most of their length, the hairs are coated with hydrophobic, or water-repellent, wax, while the tips are waxless and hydrophilic—they attract water. Surface tension pins the air-water interface to the tips so that the air layer resists disruption by turbulence in water. The interface is "a bit like a tent where the hairs are the poles," said Matthias Mayser, a biologist with an engineering background at the University of Liège in Belgium who worked with Barthlott. "The water stays on top of the air."

The plant also repels rain, Mayser explained. "It would be impossible to establish an air layer upon submergence if the room in between the hairs was already filled by water from rain." By filming drops falling on the *Salvinia* leaf surface, he observed that "the [drop's] surface tension keeps the drop in a spherical form and prevents water from penetrating" between the hairs. That keeps the leaf's silvery sheath of air intact.



Airtight. Hairs that keep water suspended above a layer of air (*lower image*) help give a floating fern its silvery sheen.

Flying low among the lilies

Galerucella nymphaeae, or water lily beetles, spend most of their time munching water lily leaves. But as Manu Prakash watched them on a Massachusetts pond one day, he noticed a strange behavior. Flying from leaf to leaf, the beetles skimmed the water surface, never lifting off. Prakash, a physicist at Stanford University in California, wondered whether surface tension plays a role in this peculiar flight mode.

He and his graduate student Haripriya Mukundarajan filmed water lily beetles as they flew and took a close look at their anatomy with an electron microscope. They saw that each apple seed–sized beetle was covered with hairs. Further tests showed that the hairs made the insect superhydrophobic. Only the claws at the end of each leg were hairless and hydrophilic. Prakash suspected that the beetle's body and legs would be repelled from the water surface, but the claws would tend to stick to the water.

The film revealed that as the beetle flies, it drags the claws of four of its six legs in the water, raising only the middle two legs. "If there was no surface tension, the moment the wings generate lift, the beetle would pop off the water," Prakash explained at the meeting. But the claws tether the beetle to the water, while the rest of its body is repelled by the water surface. "So the beetle bounces up and down," he said.

Although erratic, skimming the water is a more efficient way for the beetle to travel from leaf to leaf than full-fledged flight would be. To take off into the air would be a waste of time and energy. The only downside is that if the beetle goes too fast—it normally flies about 0.5 meters per second—it catches up with the ripples it creates as it moves, which slows it down. But Prakash thinks the beetles, like water striders, are a textbook example of how evolution has put surface tension to work. "There's so much stuff that you see when you are sitting on a pond."

Germs go airborne

Surface tension may keep some beetles water-bound, but it also helps pathogens take flight. Each cough or sneeze launches bacteria and viruses skyward in a cloud of droplets whose sizes are determined in part by surface tension, says Lydia Bourouiba. Through high-speed video, mathematical modeling, and lab experiments, this applied mathematician from the Massachusetts Institute of Technology in Cambridge is working out details of such airborne pathogens with an eye toward curbing the spread of disease.

Some researchers believe respiratory viruses generally don't travel far after a cough or sneeze, arguing that they are mostly carried in large droplets that land within a meter or two. Others contend that it's the smaller droplets, which are airborne for much longer, that underlie transmission. But very few researchers have studied how pathogens are actually transported from place to place, says James Hughes, a medical epidemiologist at Emory University in Atlanta. "Even the sizes of the droplets emitted remain debated," Bourouiba says. Surface tension, by governing the shapes and sizes of drops and bubbles, as well as how quickly they burst, influences how far they travel.

CREDITS (TOP TO BOTTOM): MATTHIAS MAYSER AND WILHELM BARTHLOTT; ERIK SCHNEIDER, MATTHIAS MAYSER, AND WILHELM BARTHLOTT

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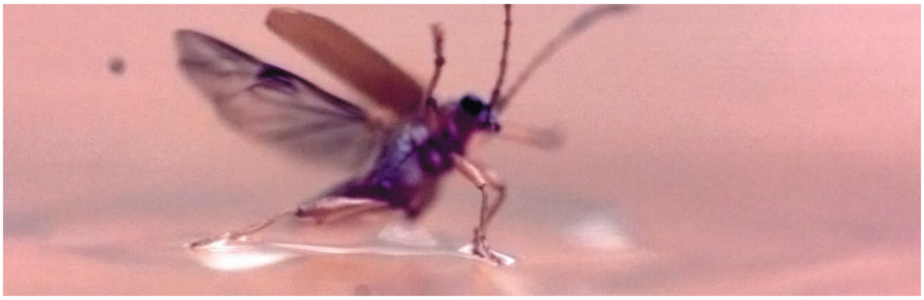

Skimming low. This water lily beetle remains tethered to the water surface as it flies to a new leaf.

By filming coughs, sneezes, and bursting bubbles and closely examining the cloud of droplets emitted, she has characterized their sizes and the flight distances. She used these observations to help come up with a mathematical model that assesses how buoyancy and momentum interact to determine how far the droplet cloud launched by a cough or sneeze can travel. The model shows that coughing can spread pathogens 200 times farther than other models had predicted, she reported at the meeting. Smaller droplets can waft up to 6 meters.

Temperature and humidity should also influence droplets' lifetimes, and Bourouiba says her model can account for their effects as well. That could prove useful for understanding what environmental conditions promote a pathogen's spread. "Here's somebody that comes from a totally different background and discipline who is applying her expertise and know-how to an important public health issue," Hughes says.

Bourouiba and her colleagues have put their approach to work to understand the spread of *Clostridium difficile*, which can cause severe and persistent diarrhea. The bacterial infection affects about a half-million people a year, particularly in hospitals or long-term care facilities. Outbreaks can be hard to stop because the bacterium produces spores that last for months, and hospitals find it everywhere, including suspended in the air. But how does it get airborne? High-pressure flush toilets, Bourouiba reported at the meeting and in a paper posted to the arXiv preprint server in October.

She mounted a camera to the sides of toilet seats; with special lighting, filming at up to 2000 frames per second, she was able to visualize water droplets erupting with each flush. While a substantial portion of the airborne droplets were large enough to sink back onto the toilet seat or other nearby surfaces, many were so small that they remained suspended, she said. As with the visualizations of coughs and sneezes, she used these observations to develop another mathematical model, one that predicts the range and spread of droplets spewing from the toilet.

Certain cleaning products actually worsen the problem, she says, by reducing the surface tension of the water in the toilet bowl, which allows more small droplets to escape. "This is important," she said, "because current mitigation strategies in hospitals only focus on bleaching surfaces, thus effectively ignoring the aerosol problem." The modeling may give "us enough information to design intervention strategies," she said, such as increasing surface tension with water additives.

Achoo. Following a sneeze, high-speed video and image processing visualized a waterfall of large droplets (*left*) and a lingering cloud of small droplets (*right*) that can spread pathogens farther.

CREDITS (TOP TO BOTTOM): MANU PRAKASH AND HARIPRIYA MUKUNDARAJAN; LYDIA BOUROUIBA AND JOHN BUSH/MIT

Bourouiba and Tristan Gilet, a fluid dynamics engineer at the University of Liège, are also looking at how the properties of water can spread plant diseases. Agricultural experts have long known that plant diseases flourish after rain, among them wheat leaf rust, which threatens global wheat crops. Bourouiba and Gilet wondered whether the raindrops themselves help disperse the pathogens living on leaves. They again enlisted high-speed video, studying natural and artificial leaves with a range of sizes and other properties.

Because leaves are somewhat hydrophobic, an impacting raindrop tends to form a discrete puddle instead of a thin film. That standing water can absorb pathogens. The videos showed that when another raindrop lands right next to a puddle, it splashes, launching part or all of the puddle from the leaf, Gilet reported at the meeting. "The second raindrop expels [the first] in a very efficient way." How far that water travels depends on the size and flexibility, or compliance, of the leaf. Small leaves, like a tomato's, bend and absorb the impact of the raindrop, dampening any splash. Big leaves resist the impact, so the splash can travel much farther, he said.

"The idea of rain generating disease in plants is pretty new," Hu says. "It spreads [pathogens] in a way the pathogen couldn't do itself." The importance of the effect will vary depending on the concentration of pathogens and the size of the ejected drop. But the research suggests that a wider spacing between plants could slow the spread of some diseases.

From insect locomotion to a strategy for boosting global crop yields: A simple physical phenomenon lets us not only understand the world of the very small; it may also help us cope better with the world at large. And that's what appeals to Hu. "I love that when I study surface tension dynamics I can draw on ideas from many disciplines: mathematics, biology, chemistry, physics, computer science, and engineering," he says. "We need all of these perspectives to understand the many ways surface tension impacts the world."

–ELIZABETH PENNISI

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