

American Scientist

MARCH-APRIL 2006

THE MAGAZINE OF SIGMA XI, THE SCIENTIFIC RESEARCH SOCIETY



How Gecko Toes Stick

The powerful, fantastic adhesive used by geckos is made of nanoscale hairs that engage tiny forces, inspiring envy among human imitators

Kellar Autumn

Geckos can run up a wall or across a ceiling with ease because of their remarkable toes. But gecko toes aren't sticky in the usual way, like duct tape or Post-it notes. Instead, gecko toes bear a hierarchy of structures that acts together as a smarter adhesive.

The pad of a gecko toe is crossed by ridges covered with hair-like stalks called *setae*, which branch into hundreds of tiny endings. Gecko toes stick to nearly every material under nearly any conditions (even underwater or in a vacuum), and neither stay dirty nor stick to one another. Geckos can attach and detach their adhesive toes in milliseconds while running on smooth vertical and inverted surfaces, a feat no conventional adhesive can match. And unlike sticky pressure-sensitive adhesives, gecko toes don't degrade, foul or attach accidentally to the wrong spot. My colleagues and I have been studying these remarkable animals for over a decade, and these are some of our latest results.

Sticky Fingers

The ability of geckos to stick to surfaces has attracted scientific scrutiny since the time of Aristotle, but the microscopic *setae* on gecko toe pads were only docu-

mented in the 1870s. The underside of a gecko toe typically bears a series of ridges, or *scansors*, which are covered with uniform ranks of *setae*. By the early 1900s, scientists using light microscopes observed that the *setae* themselves had branches. It took the development of electron microscopy in the 1950s to reveal hundreds of split ends and flat tips called *spatulae* on each seta.

A single seta of the tokay gecko (*Gekko gekko*) is roughly 110 micrometers long and 4.2 micrometers wide. Each of a seta's branches ends in a thin, triangular spatula connected at its apex. The end is about 0.2 micrometer long and 0.2 micrometer wide.

Although the tokay gecko is the best studied (and one of the biggest) gecko species, more than a thousand species of geckos encompass a variety of sizes and shapes of spatulae, *setae*, scansors and toes. Some geckos even have *setae* on their tails. Remarkably, similar structures have evolved independently in certain iguanian lizards (genus *Anolis*) and scincid lizards (genus *Prasinohaema*).

In the laboratory, a tokay's two front feet with a pad area of 227 square millimeters (smaller than a dime) were able to withstand 20.1 newtons (about 4.5 pounds) of force parallel to the surface, according to the work of Duncan J. Irschick at Tulane University and his colleagues. There are about 14,400 *setae* per square millimeter on the foot of a tokay gecko. However, in isolation, single *setae* proved to be much less—and much more—sticky than predicted, depending on test conditions. The fact that their stickiness can be so variable led me and my coworkers to conclude that control of attachment and detachment is mechanical rather than chemical.

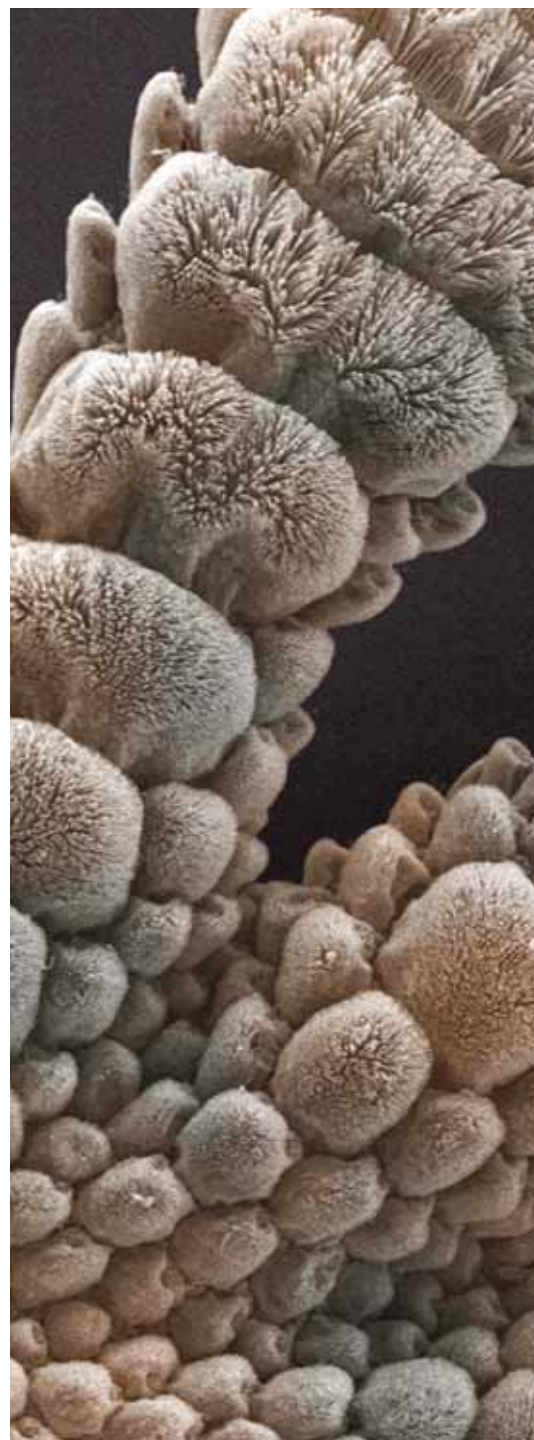


Figure 1. Gecko toe pads operate under perhaps the most severe conditions of any adhesive. The underside of a gecko toe is striped

In 2000, I published the results of a collaborative study with Robert J. Full and Ronald Fearing at the University of California, Berkeley, and Thomas W. Kenny at Stanford University. The study used a newly developed micro-sensor to measure the adhesive force (which resists pulling) and shear force

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with ridges covered with rows of microscopic, hair-like stalks, as shown in this colored scanning electron micrograph. The stalks end in hundreds of tips, each just 200 nanometers wide, which make intimate contact with the surface. The functional properties of gecko feet are as extraordinary as their structure, enabling geckos to run up walls and across ceilings with seeming indifference to gravity. Shown at 30× magnification.

(which resists sliding) of an isolated gecko seta. When we first tried to measure these forces we kept coming up with very small numbers—the resistance to sliding was no more than what we expected from plain friction. It wasn't until we oriented the seta correctly that we discovered the im-

portance of specific motions in getting the seta to stick. The best mechanics mimicked the way gecko legs move during climbing. Slightly pressing the seta against the surface (what we call a normal preload force) yielded a shear force of about 40 micronewtons—six times the force predicted by whole-

animal measurements. Combining the preload with 5 micrometers of rearward displacement (drag) gave an even larger shear force of 200 micronewtons—32 times more than whole-animal measurements and 100 times more than the friction of backward-facing spatulae.

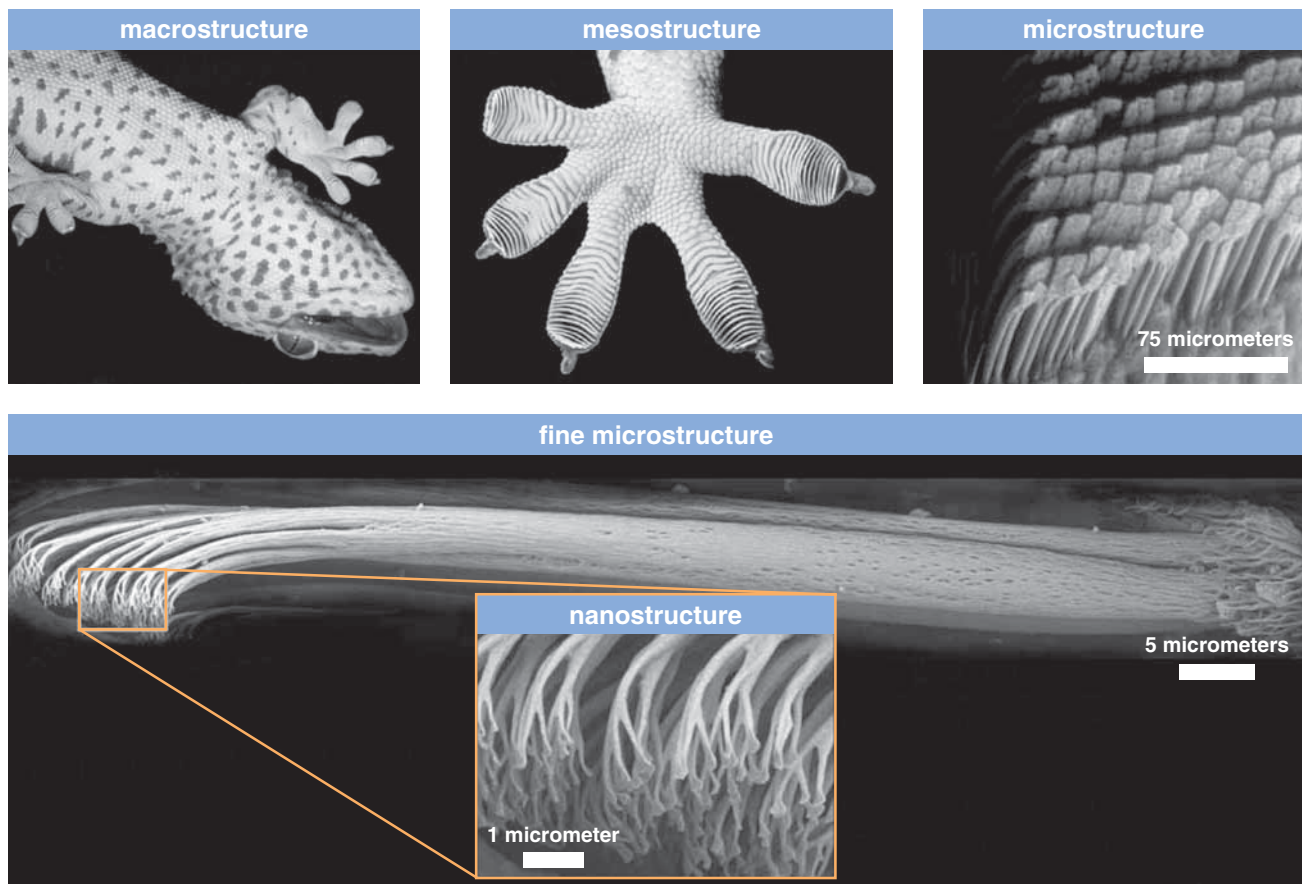


Figure 2. The structural hierarchy of the gecko adhesive system reveals different features at each scale. At the macro-level, a naked-eye view from behind a vertical glass window shows the tokay gecko (*Gekko gecko*) navigating that smooth surface with ease. A closer view of the bottom of the foot shows many ridges crossing each toe. The microstructure of a ridge reveals that it is covered with densely packed projections called setae, which are ordered in a neat, grid-like pattern. Each diamond-shaped structure is the branched end of a cluster of four setae. The fine microstructure of a single gecko seta shows individual fibrils of β -keratin, which comprise the shaft, and extensive branching at the end. The branched filaments form a nano-scale array of hundreds of flattened tips. (Photographs courtesy of Mark Moffett; electron micrographs courtesy of Stas Gorb and the author.)

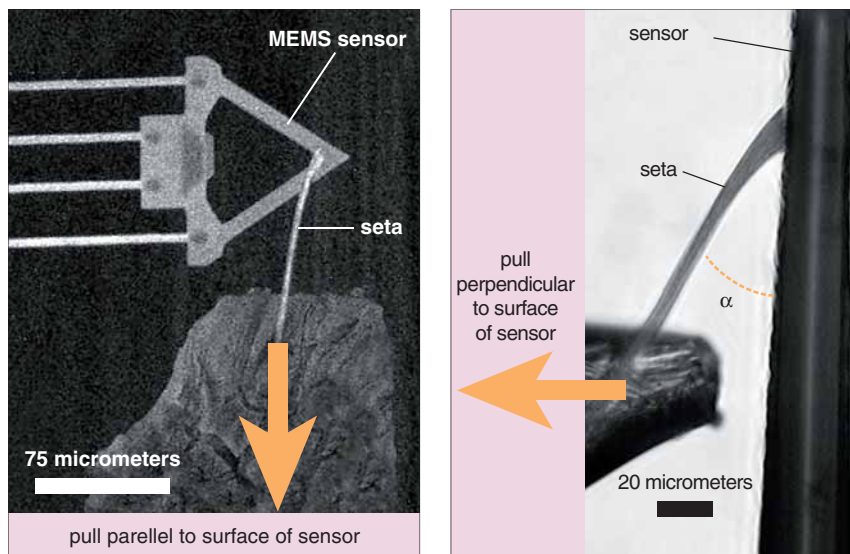


Figure 3. The author used a micro-electromechanical system (MEMS) cantilever to measure the shear force (parallel to the surface) generated by a single seta (left). A thin wire measured the attachment force of a single seta. The angle between the setal stalk and the wire, α , is critical to determining this force. Arrows show the pulling direction for each experiment. (Photographs courtesy of the author.)

Theoretically, the 6.5 million setae on a tokay gecko could generate 1,300 newtons of shear force—enough to support the weight of two medium-sized people—based on measurements from single setae. These numbers suggest that a gecko is only attaching 3 percent of its setae in generating the strongest force (20 newtons) measured in whole-animal experiments. Even more surprising, a 50-gram gecko needs less than 0.04 percent of its setae (attached maximally) to support its mass (which requires half a newton of force) on a wall. At first glance, gecko feet seem to be enormously overbuilt by virtue of a safety margin of at least 3,900 percent.

In real life the safety factor is probably not this high because the setae cannot all orient in the same direction at the same time. Moreover, many spatulae are unable to contact the substrate on uneven, dusty or flaking surfaces, particularly those with

roughness on the same scale as the spatulae. But the excess capacity is unlikely to go to waste: Geckos could use it to withstand tropical storms, resist predator attack or recover their grip after a drop.

Indeed, when geckos fall, they can arrest themselves by re-attaching their toes to passing leaves or branches, a recovery that requires much of a gecko's adhesive safety margin. Consider the example of a 50-gram gecko falling from rest. If the gecko falls 10 centimeters before attaching a foot to a vertical surface, then it will be moving at 1.4 meters per second (neglecting air resistance). If the foot is able to produce 5 newtons of friction, the gecko will come to a stop in 15 milliseconds after sliding 1.1 centimeters. In this theoretical example, recovering from a modest fall of 10 centimeters requires 50 percent of the shear capacity of one foot based on whole animal measurements (but still less than 4 percent of the theoretical maximum calculated from single setae).

The surprisingly large forces generated by single setae made us wonder how geckos manage to lift their feet so quickly—in just 15 milliseconds—with no measurable detachment forces. A few years ago, we observed that simply increasing the angle be-

tween the setal shaft and the substrate to 30 degrees causes detachment. As this angle increases, we think that increased stress at the trailing edge of the seta causes the bonds between seta and substrate to break. The seta then returns to an unloaded default state. Thus, gecko adhesive can be thought of as the first known programmable adhesive: Preload and drag steps turn on and modulate stickiness; increasing the shaft angle to 30 degrees turns off stickiness.

Foot Fetish

Although scientists have spent many years documenting the setal structures of geckos, finding out how they stick has been harder. In 1900, Anton Haase of Schleswig, Germany first suggested that geckos stick by intermolecular forces (*adhäsion*). It now appears he was right, but at least seven possible mechanisms for gecko adhesion have been discussed over the past 175 years. Scientists have eliminated glue, friction, suction, electrostatics and micro-interlocking as candidates.

Geckos lack glandular tissue on their toes, so sticky secretions were ruled out early in the study of gecko adhesion. The friction hypothesis was also dismissed quickly because, by definition, friction only acts in shear;

therefore, it cannot in itself explain the adhesive capabilities of geckos on inverted surfaces.

The hypothesis that toe pads act as suction cups proved harder to dispel, despite abundant evidence. Some experts remained convinced of a suction mechanism through the late 1800s and early 1900s, although they had no evidence to prove it. Then in 1934, Wolf-Dietrich Dellit of Gotha, Germany published a paper that described experiments carried out in a vacuum. The gecko toes remained stuck, strongly refuting the suction hypothesis. But the idea has been surprisingly tenacious in the popular literature: It was advocated as recently as 1969 in an article in *Natural History* magazine.

Other scientists proffered electrostatic attraction as a mechanism for adhesion. Dellit also dashed this claim by showing that geckos could still adhere even when the build-up of electrostatic charge was impossible. (He conducted this experiment on a metal surface in air ionized by a stream of x rays.)

Dellit himself came to favor the mechanism of microinterlocking to explain gecko adhesion. The curved tips of setae could act as micro- or nanoscale hooks that catch on surface irregularities—much like organic, microscale Velcro or the crampons on

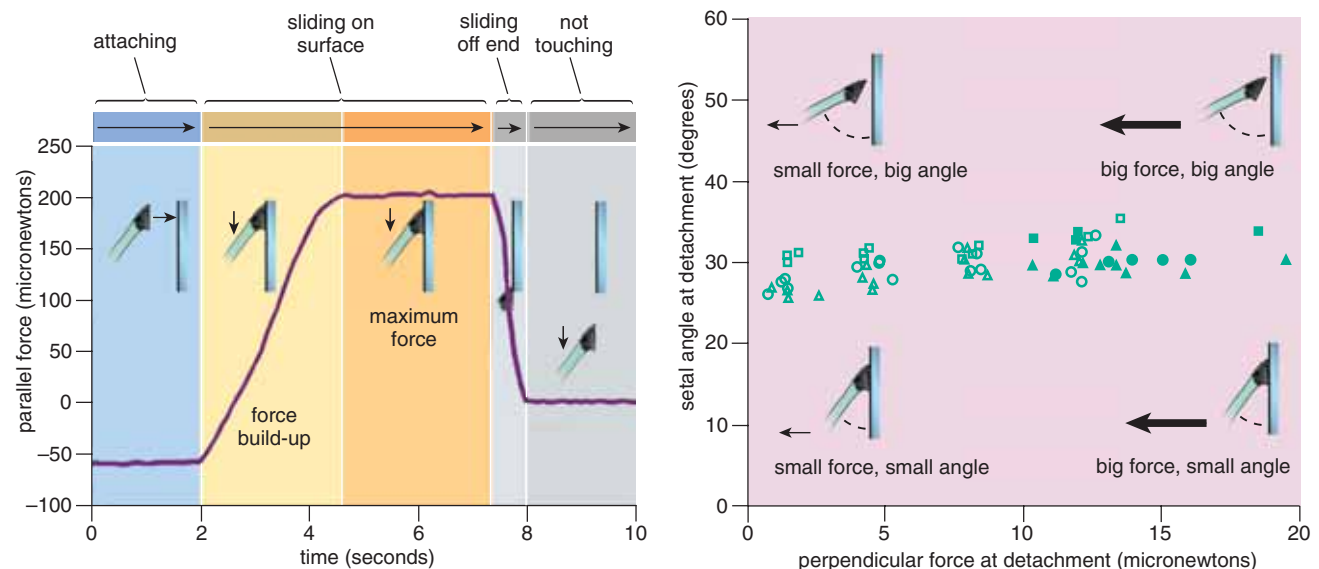


Figure 4. The author measured the shear force (*left*) of a single seta by pressing it against a microsensor, then pulling perpendicular to the surface of the sensor. These data report the resulting force as a function of time. Inset diagrams show the relative positions of seta and sensor at different points in the experiment, with arrows to indicate the direction of force applied to the seta. The maximum observed force of 200 micronewtons was 32 times greater than the predicted value from animal experiments. At right, the author plotted attachment forces exerted by single setae as a function of the angle between the setal shaft and the surface. The results of two different types of experiments are shown: Filled symbols represent setae pulled away from the surface until they released; open symbols indicate setae held at a constant force as the angle increased. Each symbol shape represents a different seta. The data reveal a consistent angle of detachment—about 30 degrees—over the entire range of pulling forces.

a mountaineer's boot. However, the ability of geckos to adhere upside-down on polished glass challenged this proposition. Microinterlocking could play a secondary role under some conditions, but the fact that geckos generate large adhesive forces on the molecularly smooth surface of a silicon dioxide-coated wafer (a finding that we published a few years ago) shows that a rough surface is not necessary for adhesion.

The hypothesis that geckos adhere by intermolecular forces was proposed by Rodolfo Ruibal and Valerie Ernst at the University of California, Riverside, who first described the spatular structures at the tips of setae in 1965 using electron microscopy. They concluded that spatulae were unlikely to

function like the spikes on climbing boots and postulated that the spatulae lie flat against the substrate—thereby increasing contact area—when the seta is engaged. Thus, gecko adhesion was almost certainly the result of molecular interactions rather than mechanical interlocking.

The turning point in the study of gecko adhesion came with a series of experiments by Uwe Hiller at the University of Münster in the late 1960s and early 1970s. Hiller concluded that the chemical properties of the substrate, rather than its texture, determined the strength of attachment. These observations provided the first direct evidence that intermolecular forces are responsible for attachment in geckos. But which forces?

Several forces exist between molecules. Many insects, amphibians and mammals take advantage of intermolecular *capillary forces* (which exist between solids and liquids) to stick to surfaces. And although geckos lack secretory glands on their feet, capillary adhesion could still exist because water molecules are commonly present on polar, hydrophilic surfaces at ambient humidities. Hiller's observation that geckos cannot adhere to polytetrafluoroethylene (PTFE, also known as Teflon) could be explained by the capillary hypothesis, since Teflon is strongly nonpolar and hydrophobic, and would not harbor stray water molecules. Indeed, the inverse correlation between adhesive force and hydrophobicity suggested that the surface polarity might determine the strength of adhesion.

Another possibility is the *van der Waals force*, named after Dutchman Johannes Diderik van der Waals who won the 1910 Nobel Prize in physics. The force that carries his name is strongly dependent on the distance between surfaces; it also increases with the *polarizability* of the two surfaces (in other words, the ease with which their electron clouds are temporarily distorted) but is not related directly to surface *polarity* (the intrinsic, unequal sharing of electrons in a molecule that generates tiny poles of positive and negative charge). Teflon, for example, is not very polarizable. It is also extremely nonpolar. Thus, the gecko's inability to cling to Teflon could be explained either by the van der Waals or capillary hypotheses.

Hiller's experiments were groundbreaking because they provided the first direct evidence for adhesion in the strictest sense, but the precise nature of the adhesion remained in question until recently. In 2002, I published a paper with Anne M. Peattie, an undergraduate student (now a Ph.D. student at U.C. Berkeley), in which we reanalyzed Hiller's data to test the hypothesis that van der Waals forces are sufficient for gecko adhesion. We primarily focused on hydrophobicity and a theoretical quantity called *adhesion energy*, which takes geometry and surface chemistry into account when calculating attractive forces. A quantity called *water contact angle*, or θ , is used to measure hydrophobicity, based on the premise that the more hydrophobic a surface is, the more water will

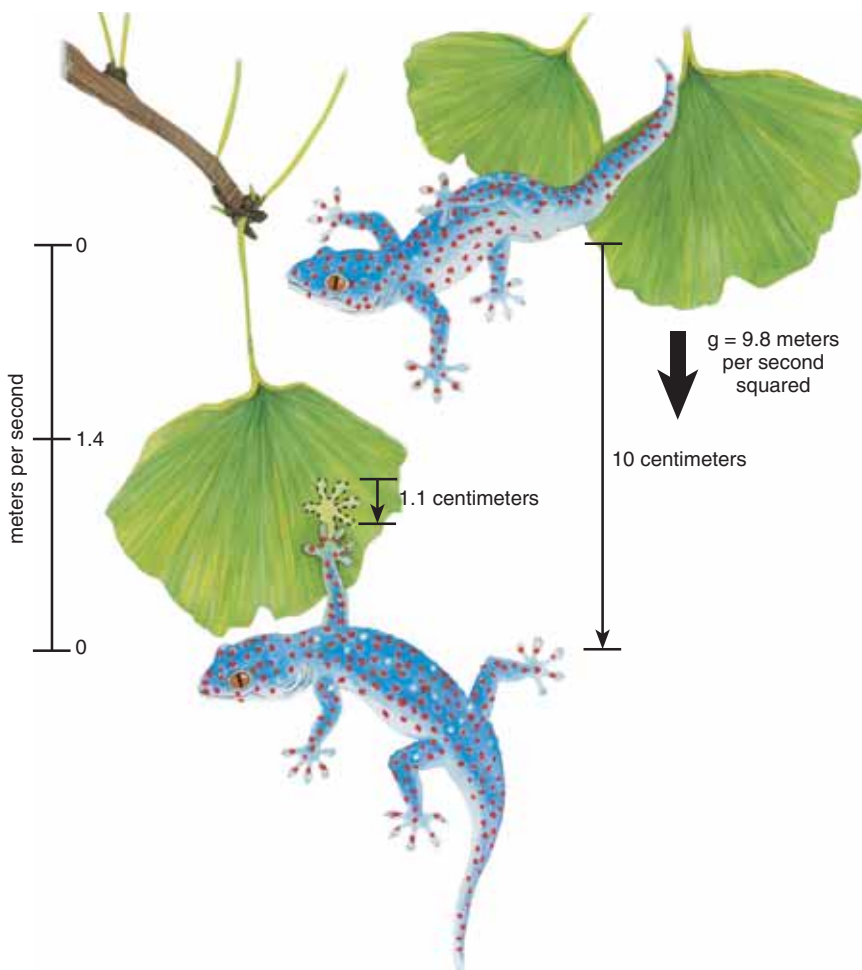


Figure 5. Geckos can recover from a fall by slapping a foot against a passing leaf or branch. This recovery takes advantage of the large adhesive forces that gecko toes are capable of generating. Consider the example of a 50-gram gecko that falls 10 centimeters before attaching a foot to a nearby leaf. During the fall, the gecko accelerates at 9.8 meters per second squared; at the instant it touches the leaf below, it will be moving at 1.4 meters per second. If the foot produces 5 newtons of friction, the gecko will come to a sudden stop (0.015 seconds) after sliding only 1.1 centimeters. This arrest uses 50 percent of the maximum shear capacity of one foot based on whole-animal measurements but less than 4 percent of the theoretical maximum calculated from single setae.



Figure 6. The strong adhesion between the hydrophobic surface of tokay gecko toes and the molecularly smooth, hydrophobic surface of a wafer of gallium arsenide demonstrates that the van der Waals force is a sufficient mechanism of gecko adhesion. (Photograph courtesy of the author.)

bead up on it. Values of θ greater than 90 degrees are considered hydrophobic. Using an approach developed by my colleague Jacob Israelachvili at the University of California, Santa Barbara, Anne and I linearized the relation between hydrophobicity and adhesion energy and showed that adhesive forces do not increase on hydrophilic surfaces, consistent with the van der Waals hypothesis.

Since that time, my lab has made several direct tests to determine whether capillary adhesion or van der Waals force is sufficient to explain adhesion in geckos. In measuring the hydrophobicity of the setal surface, we discovered that tokay gecko setae are ultrahydrophobic ($\theta = 160.9$ degrees), probably because of the hydrophobic amino acids that make up the β -keratin protein of which they are con-

structed. This property suggests that setae interact primarily via van der Waals forces whether water is present or not.

In a collaboration with Bob Full, Ron Fearing, Tom Kenny and Jacob Israelachvili, we also measured adhesion and friction of setae on two polarizable surfaces: gallium arsenide, GaAs, which is strongly hydrophobic, and silicon dioxide, SiO_2 , which is hydrophilic. If capillary adhesion was the dominant force, then gecko toes should stick to the hydrophilic SiO_2 but not to the hydrophobic GaAs. However, if van der Waals forces were sufficient, then geckos should be able to adhere to both GaAs and SiO_2 surfaces. We observed the latter to be true. Using live geckos, we found no significant difference between shear stress on GaAs ($\theta = 110$ degrees) and SiO_2 ($\theta = 0$ degrees). In separate experiments with a single gecko seta, the adhesion on SiO_2 differed by only 2 percent from adhesion on a hydrophobic sensor made of silicon alone.

Because the van der Waals force is the only mechanism that can cause two hydrophobic surfaces to adhere in air, the experiments with GaAs and silicon provide direct evidence that van der Waals force is sufficient for adhesion in gecko setae. Water-based capillary forces are not required. Setal adhesion is strong on polar and nonpolar surfaces, perhaps because setae are so hydrophobic themselves, and certainly because of the very large contact area of the spatular nanoarray. Gecko setae thus have the property of material independence: They can

adhere strongly to a wide range of materials with little regard for surface chemistry.

This independence does not preclude an effect of water on gecko adhesion under some conditions. Water probably alters contact geometry and adhesion energies between hydrophobic and hydrophilic surfaces (for example, between spatulae and glass). But it is exceedingly difficult to predict what the effect of water would be because the system is so complex.

Last year a group of scientists led by Pavel Neuzil from the Institute of Bioengineering and Nanotechnology in Singapore published results showing that gecko spatulae adhered more strongly in a wet atmosphere than in a dry one. The authors concluded that capillary adhesion must dominate under most conditions. However, this interpretation is difficult to reconcile with the extreme hydrophobicity of gecko setae.

New results from the research team headed by Eduard Arzt at the Max Planck Institute in Stuttgart resolve this dilemma. They found strong adhesion at very low humidity and, like the Singapore group, measured increased adhesion with increasing humidity. However, they found that capillary bridges, which mediate capillary forces, do not form. Even at very high humidity, no more than two layers of water molecules were present—far too few to form a capillary bridge. Thus, Arzt's group rejected "true" capillary forces under all conditions and surmised that the water

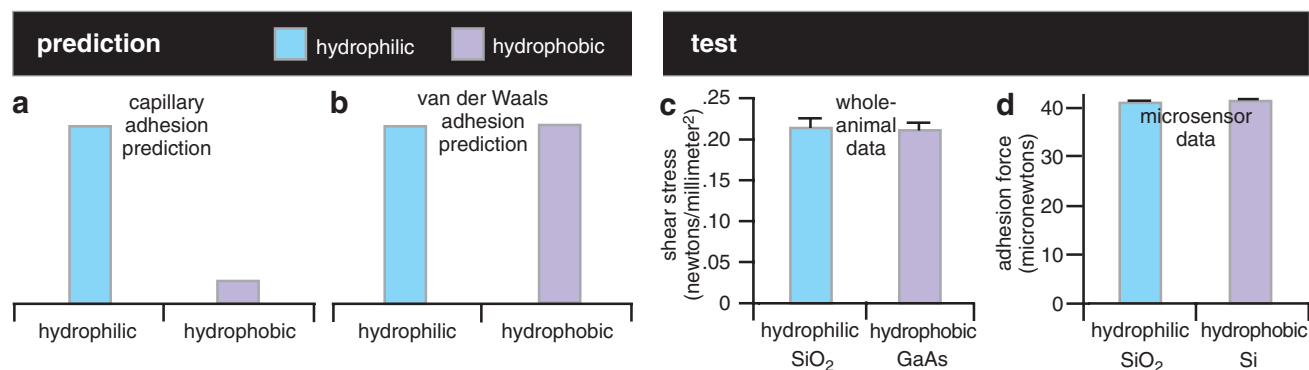


Figure 7. The difference between polar surfaces and polarizable surfaces can be used to test the capillary and van der Waals hypotheses of gecko adhesion. For highly polarizable surfaces such as gallium arsenide (GaAs) and silicon dioxide (SiO_2), the capillary hypothesis (a) predicts that geckos will adhere strongly to the hydrophilic (polar) SiO_2 but not the hydrophobic (nonpolar) GaAs. The van der Waals hypothesis (b) predicts that the adhesive forces will be similarly large for both. Experiments that tested the adhesive force with whole animals on GaAs and SiO_2 surfaces (c) and with single setae on SiO_2 and silicon microensors (d) showed comparable adhesion forces for both types of surfaces. These data match the predictions of the van der Waals hypothesis.

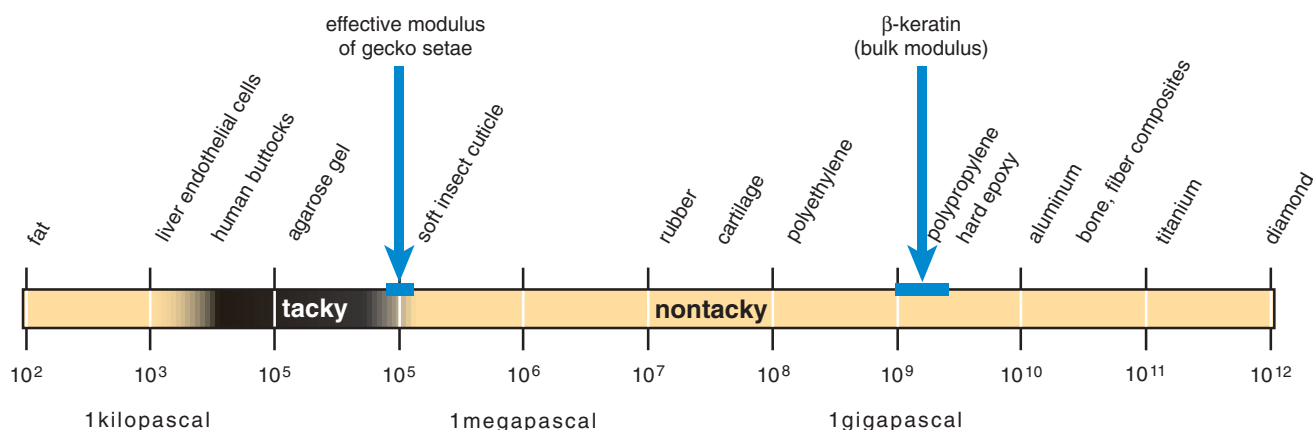


Figure 8. Young's modulus is a quantity that describes how deformable or rigid a substance is. Although the bulk modulus (a related quantity) for β -keratin is around 2 gigapascals, the effective modulus for setal arrays is orders of magnitude lower—near 100 kilopascals—which is the upper limit for “tack” or stickiness. This value probably represents a compromise between strong, rapid adhesion and the avoidance of spontaneous or inappropriate attachment.

molecules must increase the number of van der Waals bonds that are made. The data support our conclusion that geckos stick by van der Waals forces alone—even at high humidity.

Nonstick Surface

Paradoxical as it may seem, there is growing evidence that gecko setae are themselves strongly anti-adhesive. Setae do not stick spontaneously to surfaces, but instead require a mechanical program for attachment. And unlike adhesive tapes, gecko setae do not self-adhere: Pushing the setal surfaces of a gecko's feet together does not cause them to stick. Furthermore, gecko setae do not seem to stay dirty.

How is it that sticky gecko feet remain quite clean around everyday contaminants such as sand, dust, leaf litter, pollen and plant waxes? Insects, which face similar challenges, must

restore soiled adhesive pads to normal function by spending much of their time grooming. By contrast, geckos do not groom their feet. Although some plant and animal surfaces self-clean (with water droplets), no self-cleaning adhesive had ever been shown until we documented it in geckos in a paper published last year.

With undergraduate Wendy Hansen (who now is also working towards a Ph.D. at U.C. Berkeley), I studied the phenomenon of self-cleaning by applying 2.5-micrometer-radius microspheres to the feet of tokay geckos. We found that the microspheres did diminish a gecko's adhesive capacities, but the animal needed only four simulated steps on a clean glass surface to recover enough setal function to support its body weight by a single toe. The debris stuck to the glass, not the setae.

The key to this phenomenon seems to be adhesion energy. Wendy and I developed mathematical models of self-cleaning that suggested that in order to shed debris, the adhesion energy of all spatulae adhering to a dirt particle must be equal to or less than the adhesion energy between the same particle and the surface. Perhaps this is why spatulae have to be made of a hydrophobic, anti-adhesive material: Although the adhesion energy of each spatula is low, the adhesion of the array as a whole is higher by maximizing the number of uncontaminated spatulae. If the adhesion energy were higher (perhaps because of polar forces or hydrogen bonding), then the self-cleaning and anti-self-adhering properties would probably be lost. Thus, the evolution of extremely sticky toes that are also self-cleaning probably represents a sweet spot in the design space for adhesive nanostructures.

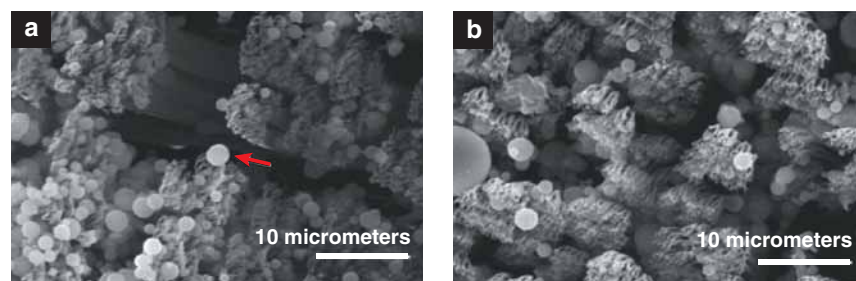
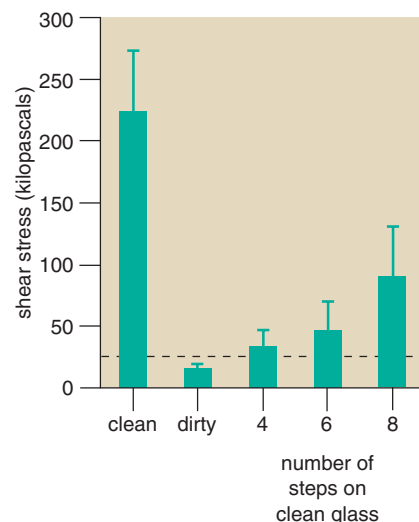


Figure 9. The author tested the self-cleaning properties of gecko setae by dusting gecko feet with 2.5-micrometer-radius microspheres. The images from a scanning electron microscope show setal arrays after the initial dirtying with microspheres (a). The red arrow indicates a microsphere adhering to several spatulae. After five simulated steps on clean glass, the spatulae have shed most of the debris (b). The graph at far right shows the average shear stress exerted by clean, dirty and self-cleaned gecko digits. The dotted line indicates the minimum force required to support one gecko's body weight (43 grams) by a single toe (an area of 0.19 square centimeters). (Micrographs courtesy of the author.)



The shape of a seta also helps it resist indiscriminate sticking. In their resting state, setal stalks are curved in toward the body and the spatulae are disorganized. In a paper soon to be published, Wendy and I hypothesize that this arrangement explains why the default, unloaded state for gecko toes is not sticky. When the foot is planted, the setae flatten and their tips point out, thereby bringing the spatulae uniformly flush with the substrate and maximizing their area of contact—and adhesion. We conclude that gecko setae are probably nonsticky by default because only a small contact fraction is possible unless the setal array is mechanically deformed by a preload force.

The deformation of a substance is dictated by its stiffness or elasticity, which is reflected in a quantity called *Young's modulus*, measured in pascals (newtons per square meter). High values correspond to extremely rigid materials such as diamond (10^{12} pascals or 1 terapascal); fat cells have some of the lowest values (100 pascals). Bulk β -keratin is fairly hard, with a Young's modulus ranging from 1.3 to 2.5 gigapascals in bird claws and feathers (the values for β -keratin in lizards remain unknown).

By contrast, a pressure-sensitive adhesive, like that used in masking tape, is made from a soft, viscoelastic material that is *tacky*—it spontaneously deforms to increase the area of surface contact and has a Young's modulus of below 100 kilopascals at 1 hertz, according to the so-called Dahlquist criterion. (Carl A. Dahlquist was a pioneering adhesives scientist at 3M.) Such adhesives can be attached and detached repeatedly without leaving a residue because they work primarily through weak intermolecular forces. However, they are prone to creep, degradation, self-adhesion and fouling.

Structures made of β -keratin—such as gecko setae—should be too stiff to work like a pressure-sensitive adhesive. How can setae function as an adhesive if they are made of something so rigid? The answer lies in the micro- and nanostructure of the seta, according to a mathematical model developed in Ron Fearing's laboratory. His model represents setae as tiny cantilever beams that act as springs with an *effective* Young's modulus much lower than the gigapascal-hard β -keratin they are made of. The most recent experiments from my lab observed an effective modulus of about 100 kilopascals in isolated arrays from

tokay geckos—remarkably close to the upper limit of the Dahlquist criterion. The unique hierarchy of structures on the gecko toe results in a low effective modulus, which causes gecko adhesive to have some of the same properties as properly tacky materials without the drawbacks. The combination of strength (at the level of the keratin protein) and ease of deformation (at the level of the spatulae and setae) may enable gecko adhesive to tolerate heavy, repeated use without creep or degradation. And because setae have a nonsticky default state and require mechanical deformation in order to adhere, they don't stick to each other or become fouled. The adhesion of gecko setae is programmable, direction-dependent and possesses a built-in release mechanism.

The Gecko Muse

With such remarkable properties, it is unsurprising that materials scientists are trying to create artificial, geckolike adhesives. Using a nanostructure to create an adhesive is a novel and bizarre concept. It is possible that had it not evolved, humans never would have invented it. For the booming nanotechnology industry, such products would be valuable for picking up, moving and aligning ultraminiature circuits, sensors or motors. For bigger applications, such as robots that could explore the wreckage of a fallen building or the surface of another planet, artificial gecko setae would endow the machines with unprecedented freedom of movement. Be-

cause a geckolike nanostructure could be applied directly to the surface of a product, such adhesives could replace screws, glues and interlocking tabs in manufactured goods. More whimsically, they might enable fumble-free football gloves or revolutionary rock-climbing aids. (This last idea is not new. Shivaji, a legendary Hindu ruler of 17th-century India, reportedly used adhesive lizards as grappling devices to scale a sheer cliff and mount a surprise attack on his enemies.)

Several groups of scientists have made good progress toward fabricating synthetic spatulae in the years since our team published the first such effort in 2002. However, by gecko standards, today's best synthetic setae are still primitive. Two materials, one by Andre K. Geim and colleagues at the University of Manchester, the other by Michael T. Northern and Kimberly L. Turner at the University of California, Santa Barbara, have adhesion coefficients (a ratio of adhesive force to preload force) that are about half a percent and one percent, respectively, of real gecko setae. In late 2005, Ali Dhinojwala and others from the University of Akron and Rensselaer Polytechnic Institute published their description of a carbon-nanotube carpet that generated adhesive force even greater than that of gecko setae. However, the product only works at a nanometer scale, rather than the centimeter scale of real gecko toes. Clearly, better designs will require deeper exploration of real gecko setae. And as technology

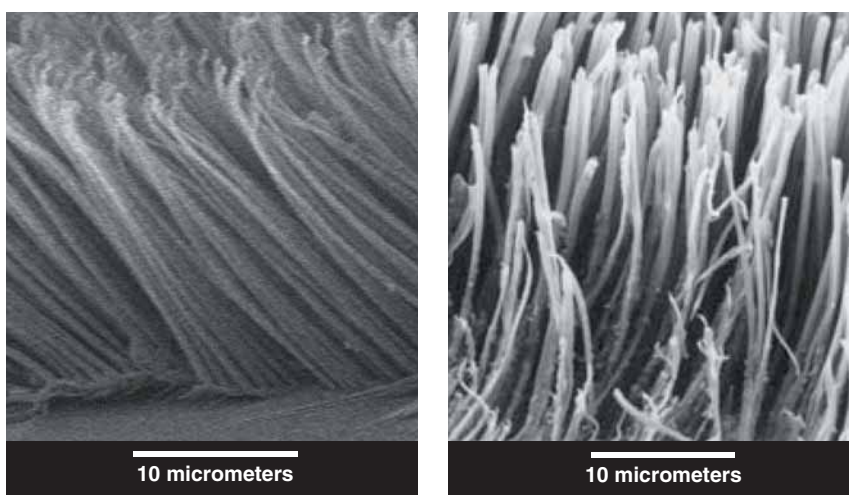


Figure 10. Some artificial nanoscale adhesives closely match the length and thickness of biological counterparts. The setae of the knight anole (*Anolis equestris*, left) are unbranched with spatular tips. The polyimide fiber array developed by the author and his collaborators (right) has similar proportions. (Anole micrograph courtesy of Anne Peattie. Polyimide fiber micrograph courtesy of Ronald Fearing.)

and the science of gecko adhesion advance, it may even become possible to tune the design to create completely new properties.

Many questions remain for scientists who study mechanisms of gecko adhesion. What is the effect of surface roughness on friction and adhesion? How can scientists better model the hierarchical contributions of spatulae, setae, scansors, toes and legs? How do spatulae and setae work in more than a thousand other gecko species (assuming they don't go extinct before scientists can study them)? What is the molecular structure of setae? Answers to these basic biological questions are key to the development of bio-inspired adhesives that may someday rival their natural counterparts. Then maybe we will be able to scamper across the ceiling too.

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