examples is almost entirely lacking (*6*).

If bdelloids are asexual, such divergence might be quite stable if the lethality of homozygosis from occasional homogenizing events is offset by the benefit of having two gene copies with divergent function. In that case, heterozygosity might persist even across species and higher taxonomic groups. In addition to firming up the evidence that the two *lea* genes are indeed on allelic segments of separate chromosomes, it could therefore be most informative to study their population genetics. The persistence of both gene copies on separate chromosomes would constitute independent evidence for bdelloid asexuality and, as Pouchkina-Stantcheva *et al*. suggest, such stable heterozygosity may have contributed to the fitness of bdelloid rotifers.

References

1. N. N. Pouchkina-Stantcheva *et al.*, *Science* **318,** 268 (2007).
2. D. B. Mark Welch, M. Meselson, *Science* **288**, 1211 (2000).
3. M. Lynch, *Mol. Biol. Evol.* **23**, 450 (2006).
4. D. B. Mark Welch *et al.*, www.sil2007.org/
5. D. B. Mark Welch, www.nioo.knaw.nl/networks/partner/
6. N. Gemmel, J. Slate, *PLoS ONE* **1**, e125 (2006).

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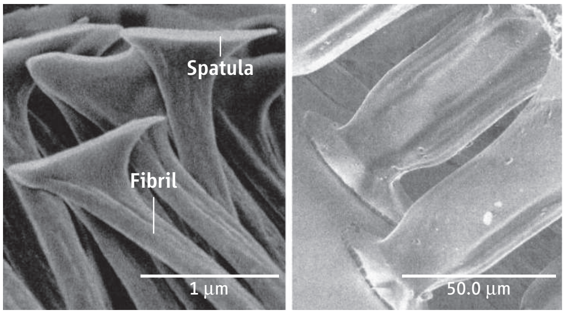
MATERIALS SCIENCE

Biomimetic Solutions to Sticky Problems

In a smart adhesive inspired by biological adhesive structures, subsurface structures dramatically increase adhesive strength.

W. Jon. P. Barnes

Many biological surfaces have remarkable properties, some of which have inspired materials science. For example, Velcro was developed from the interlocking mechanism of the seeds of burdock that readily attach to one's clothes as one walks through the countryside. Similarly, self-cleaning materials have been developed based on the "Lotus effect" (the way in which water drops roll off the superhydrophobic leaves of lotus plants, taking dirt particles away with them).



Of lizards and robots. The spatula-tipped adhesive setae in an anoline lizard (*Anolis*)] (**left**) inspired the structured adhesive used by Daltorio *et al.* (*7*) in the development of climbing robots (**right**).

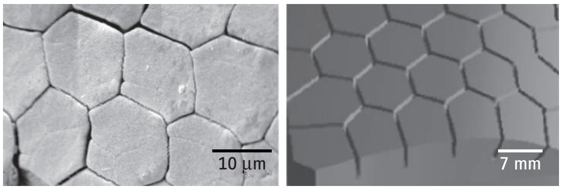
The adhesive mechanisms of climbing animals have also guided materials scientists. An excellent example is provided by Majumder *et al.* (*1*) on page 258 of this issue. Inspired by the complex subsurface structure of the smooth adhesive pads of tree frogs and insects such as grasshoppers and ants, they show that adhesive force can be increased by up to a factor of 30 by subsurface structures such as air- or fluid-filled pockets.

Climbing animals have many abilities that are the envy of materials scientists. First, they have remarkable powers of adhesion. Even a large gecko can run across a ceiling; a tree frog jumping from branch to branch does not fall so long as a single toe pad makes good contact with the tree; ants can carry more than 100 times their own weight while walking upside-down. Second, the adhesive mechanisms are reversible (geckos can walk at more than 10 steps a second), and detachment is effortless. Third, animal adhesive pads can have self-cleaning properties and thus do not get fouled. Finally, the adhesive pads of geckos only stick when required.

How different these abilities are from the properties of parcel tape! Following contact and mild pressure, parcel tape will adhere quite well, but it does not detach easily and is seldom reusable, because its tacky nature means that it is quickly fouled by adhering material. It also has an uncanny knack of sticking to anything it comes into contact with, making the wrapping of presents a lot less pleasurable than it ought to be.

So how do climbing animals stick? In addition to claws, present in many species but not tree frogs, two rather different adhesive structures have evolved: hairy and smooth adhesive pads. The toe pads of geckos and other lizards are covered with millions of tiny branching hairs, which can get so close to the substrate that intermolecular forces provide excellent adhesion (*2*). In contrast, the smooth adhesive pads of tree frogs, arboreal salamanders, and insects such as ants secrete a fluid so that they adhere by wet adhesion (*3*, *4*). In tree frogs at least, the main force appears to be capillarity, but viscosity and direct molecular contact may also play a role because of the thinness (0 to 35 nm) of the intervening fluid layer (*5*). (The hairy pads of insects also carry tiny amounts of fluid; adhesion is thus also likely to be mainly by capillarity.)

Such mechanisms have inspired materials scientists in a number of ways (*6*). For example, both Daltorio *et al.* (*7*) and Santos and colleagues (*8*) have used microstructured polymer adhesive feet based on the hairy pads of geckos (see the first figure) in the development of robots that can successfully climb a vertical glass sheet. Another particularly successful biomimetic structure—reusable tape that adheres equally well in wet and dry conditions—combines the microstructure of gecko pads with a thin layer of synthetic polymer that mimics the protein glue of mussels (*9*). Also, car tires are in production with a honeycomb tread pattern that closely resembles the surface structure of tree frog toe pads (see the second figure).



From toe pads to tires. Hexagonal toe pad epithelial cells surrounded by mucus-filled channels in the tree frog, *Litoria* (**left**). A similar hexagonal tread pattern is used in a Continental winter tire (**right**).

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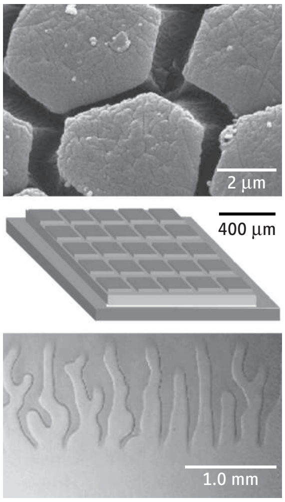
Majumder *et al.* started from the discovery that micropatterned structures resembling the toe pads of tree frogs and crickets can enhance adhesion (see the third figure). Normal adhesive tape detaches when cracks spread into the adhesive from the point of peeling. When all the energy is concentrated at a single crack, peeling occurs readily, but micropatterning can increase the force required to produce peeling by up to a factor of three. Cracks form wherever there is a groove in the pattern; when the energy is spread between many cracks—as is the case in a micropatterned tape—more force is required to produce separation (*10*, *11*).

The authors take this principle a step further. They have investigated the role of subsurface structures such as air- and oil-filled microchannels. The channels have similar crack-arresting properties as some of the patterned surfaces studied in (*10*, *11*), but the effect is much more dramatic.



The power of ridges. The adhesive surface of the smooth adhesive pad of the cricket *Tettigonia* contains a hexagonal pattern of grooves (**top**) (*12*). On an elastic film incised with a related pattern (**middle**), cracks spread differently during peeling (**bottom**) than they would on an unpatterned surface (*10*).

Depending on several factors—such as the thickness of the adhesive layer, the channel diameter, the interchannel spacing, and whether the channel is filled with air or oil—adhesion can be increased by up to a factor of 30. Under different conditions, the adhesive can act as a quick-release coating so that the tape, while sticking well, can be peeled off easily. The adhesive remains elastic and can thus be used again with no reduction in adhesive efficiency.

Future smart adhesives like that reported by Majumder *et al.*, designed to do particular tasks, are also likely to be inspired by the remarkable mechanisms developed by climbing animals over millions of years of evolution. In this area of materials science, biomimetics is certainly coming of age.

References

1. A. Majumder, A. Ghatak, A. Sharma, *Science* **318**, 258 (2007).
2. K. Autumn *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **99**, 12252 (2002).
3. W. J. P. Barnes, C. Oines, J. M. Smith, *J. Comp. Physiol. A* **192**, 1179 (2006).
4. W. Federle *et al.*, *Integr. Comp. Physiol*. **42**, 1100 (2002).
5. W. Federle *et al.*, *J. R. Soc. Interface* **3**, 689 (2006).
6. C. Creton, S. Gorb, Eds., *MRS Bull.* **32(6)** (2007).
7. K. A. Daltorio *et al.*, *MRS Bull.* **32**, 504 (2007).
8. D. Santos *et al.*, *Proceedings of the IEEE International Conference on Robotics and Automation*, Rome, Italy, 10 to 14 April 2007, pp. 1262–1267.
9. H. Lee, B. P. Lee, P. B. Messersmith, *Nature* **448**, 338 (2007).
10. A. Ghatak *et al.*, *Proc. R. Soc. Lond. A* **460**, 2725 (2004).
11. J. Y. Chung, M. K. Chaudhury, *J. R. Soc. Interface* **2**, 55 (2005).
12. S.N. Gorb, M. Scherge, *Proc. R. Soc. Lond. B* **267**, 1239 (2000).

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ATMOSPHERE

Monsoon Mysteries

Jagadish Shukla

Today's climate models cannot adequately predict the mean intensity and the seasonal variations of the Asian summer monsoon.

The Asian summer monsoon, manifested in all its glory and fury over the Indian subcontinent, is the largest seasonal abnormality of the global climate system: During the monsoon, the equatorial region is colder than the regions to the north. The summer monsoon rains that result are critical for food production, water supply, and the economic well-being of the Asian society. There is thus great interest in predicting the waxing and waning of the Asian monsoon.

What are the prospects for predicting monsoon rainfall over India and the surrounding regions? Why has the accuracy (or "skill") of monsoon forecasts been so low? What are the projected impacts of global warming on the Asian summer monsoon? In July of this year, a conference at the Indian Institute of Sciences, in Bangalore, addressed some of these questions (*1*).

A review of the current status of short-range (1 to 10 days) forecasting presented at the conference shows that the weather prediction centers in the world have made steady progress in improving the skill of 5-day forecasts. But India somehow missed the revolution in numerical weather prediction. According to A. K. Bohra and S. C. Kar (*1*), there has been no improvement in the accuracy of the 5-day forecasts over India for many years.

Monsoon forecasting has a long history in India. After the subcontinent had experienced a devastating drought and famine in 1877, the British Government asked the recently established India Meteorological Department (IMD) to forecast monsoon rainfall. The earliest methods of forecasting the summer monsoon were based on the snowfall in the preceding winter in the Himalayan region (*2*). In the early 20th century, Sir Gilbert Walker—an applied mathematician at the University of Cambridge who became director-general of observatories in India in 1904—identified empirical relationships between the monsoon rainfall and global circulation features in data from other British colonies around the world. He devised a forecasting methodology using a linear regression model with past data (*3*).

Normand showed over 50 years ago that the forecasts made by Walker had no skill (*4*). (A forecast has no skill if it is no better than forecasting each year's rainfall to be the same as the long-term average rainfall.) Yet, the IMD continues to forecast monsoon rainfall over India using the same basic methodology as Walker did. Verification of forecasts for seasonal mean rainfall over India for the recent 1990 to 2006 period also shows that there is no skill (*5*). The problem is that the IMD uses too many nonindependent predictors, giving artificial skill in explaining the past data and poor skill in actual forecasts (*6*).

What determines the predictability of monsoon rainfall? More than 25 years ago, Charney and I proposed (*7*) that seasonal mean monsoon rainfall is influenced by the slowly varying boundary conditions of sea surface temperature (SST), soil wetness, and snow cover. Many global climate models have since been used to test the validity of this hypothesis, but none have been successful in making skillful predictions of Indian monsoon rainfall. It remains an open question

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