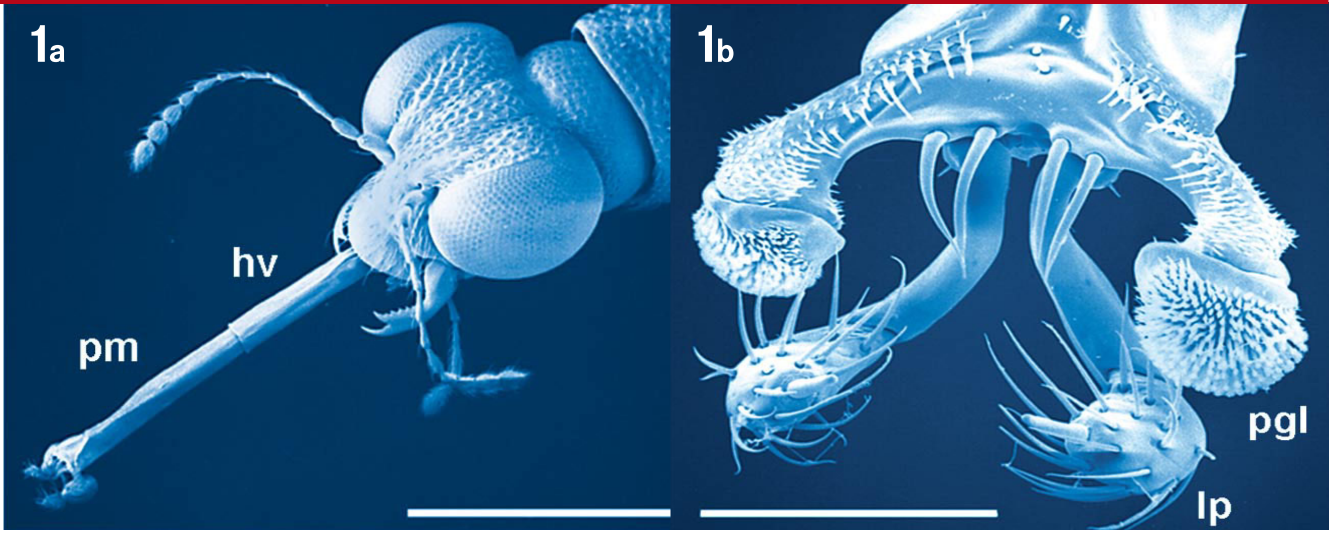
LEARNING FROM NATURE

An insect's tongue as the model for two-phase viscous adhesives?

The first stage in developing two-phase biomimetic adhesives is to analyse the key biomechanical data. One possible biological model is the apparatus which rove beetles use to trap the animals that they feed on. The beetles' extended, rod-shaped lower lips have two sticky pads and shoot out like a catapult to capture potential prey.



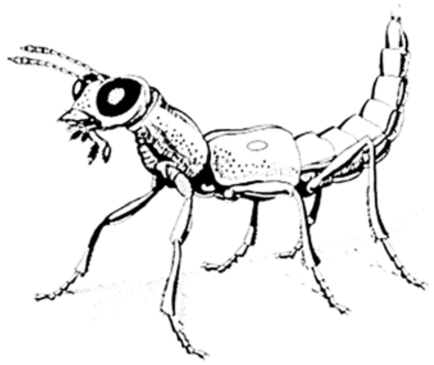
Oliver Betz, Lars Koerner, Stanislav Gorb

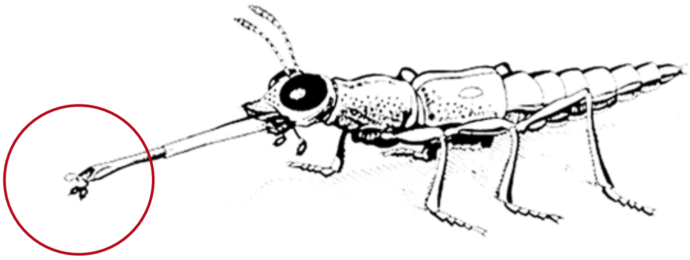
The gecko has long been a biological model for adhesive applications. A less well-known example from the world of nature is the adhesive capture apparatus of rove beetles of the genus *Stenus*, which have a rod-shaped lower lip (labium) with two sticky pads (the paraglossae) that shoots out like a catapult to capture potential prey, Figure 1. The sticky pads adhere to the prey and are then pulled back with the lower lip towards the beetle's upper jaw. The adhesive function is provided by a secretion produced in glands in the beetle's head which passes through the extended labium to the surface of the sticky pads.

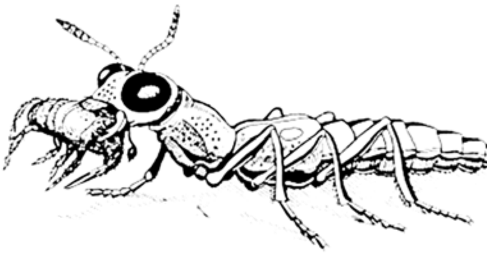
The "sticky harpoon" of the *Stenus* beetles has a number of interesting properties from a biomimetic perspective. However, before possible technical applications of the system can be considered, a better understanding of its structural, chemical and physicochemical characteristics is essential. This can be achieved by analysing the microstructure of the sticky pad, the histochemistry of the adhesive secretion and the adhesive performance of the entire capture apparatus on synthetic surfaces.

Structure of the adhesive pads

The adhesive pads consist of five functional elements which work together synergistically during the process of capturing the prey. The network of soft endocuticular fibres shown in the lower scanning electron microscope image in Figure 2 stabilises the interior of the pad and ensures that the entire structure is flexible and elastic /1, 2/, so that it can adapt closely to specific shapes and surface irregularities of the prey insect. Before the beetle strikes, this loose network of fibres is expanded by the haemolymph which flows in among the fibres. As a result, the sticky pads increase signifi-







1c

Figure 1c consists of sketches of the process of catching prey. After the beetle has moved to a critical distance away from the prey (top), the capture apparatus shoots rapidly out (centre) and is then pulled back to the beetle's upper jaw, together with the prey which adheres to it (bottom).
(Picture credit: /9/ courtesy of Springer Verlag Heidelberg).
Abbreviations: hv = connecting membrane, lp = labial feelers, pgl = paraglossae, pm = prementum.

Figures 1a und 1b:
The adhesive capture apparatus of the rove beetle *Stenus comma*.
A is a scanning electron microscope image of the head with the protruding lower lip (labium); scale = 1 mm.
B is a scanning electron microscope image of the tip of the labium with the adhesive pads; scale = 100 μm.

Figures A and B courtesy of Dr. W. Arens (Hersfeld)

cantly in size before they hit the prey, Figure 3 C. The impulse which results from the pads hitting the prey compresses them and causes them to return to their original form /2/. The dense network of cuticular fibres provides mechanical support for the adhesive surface, which is not smooth, but is made up of numerous hair-like outgrowths (2 in Figure 2). These excrescences are arranged in a hexagonal pattern (3 in Figure 2). Their length ranges from 20 to 25 μm, their radius is around 1.3 μm and their aspect ratio is 10 (terminal branches (see below): length 1.4 to 1.6 μm, radius 0.1 μm and aspect ratio 8). The distance between the hair-like excrescences is around 2 to 5 μm. The end of each outgrowth divides into between 9 and 30 branches (4 in Figure 2). In comparison with hairs without branches, this type of terminal branching structure generally allows the smaller terminal branches to be packed more densely. The overall number of adhesive contacts therefore amounts to several thousand for each of the beetle's adhesive pads /1, 3/. In addition, the terminal branches presumably prevent the neighbouring hair-like outgrowths from becoming stuck together and improve their tolerance to rough surfaces /4/. Electron microscope and cryo-scanning electron microscope images have shown that these hair-like excrescences are deeply immersed in the adhesive secretion (5 in Figure 2) and only the outermost branches stick out /7/. The use of adhesive secretions in natural adhesive systems generally has a number of advantages. These include the possibility of bonding different materials, improved load distribution over the contact area and the enlargement of the actual contact surface, because small irregularities on the surface are smoothed out /5/. "Wet" adhesion systems of other kind are also effective in allowing insects to walk vertically up and down different natural surfaces. However, in this case much smaller quantities and-other chemical properties of the secretion are involved and the adhesion mechanism relies primarily on capillary forces.

Nature of the adhesive secretion

The adhesive secretion emerges through lateral openings on the outer edge of the sticky pad (Figure 2: top right). From here it must spread across the entire surface of the sticky pad without contaminating the side areas below, which do not come into direct contact with the prey. The spread of the secretion is probably controlled by powerful capillary forces which arise from the gap between the shafts and the terminal branches of the hairs.

According to studies carried out by Gregor Kölsch, the secretion consists of two non-miscible phases /7/.

Ultrastructural images show that droplets of a fat-like substance emulsify in a larger aqueous protein fraction. Additional histochemical tests identified water-soluble sugars, proteins and lipids, which means that the secretion is a complex mix of more than one chemical phase, Figure 3. As has been suggested in the case of the attachment pad secretion of locusts /6/, an emulsion of this kind could be beneficial for the effective distribution of the secretion over different types of surfaces (hydrophilic and lipophilic). In addition, coalescing droplets of lipids on the outer edge of the sticky pad could prevent the aqueous protein phase below from drying out. This allows the beetles to keep the sticky pads permanently moist and ready for use.

The large quantity of secretion and the fact that its adhesive effect occurs at high speed lead us to assume that the adhesion mechanism is based on the viscous properties of the secretion as well as on capillary forces /7/. High viscosity was demonstrated in high-speed video recordings which showed the sticky pad being retracted from a surface. As is the case with commercially available adhesives, the secretion elongates and forms long parallel fibres, before finally breaking away from the contact area of the substrate. This observation supports the importance of the cohesive forces which give the secretion a high level of internal strength. In addition, the formation of fibres in the adhesive has the benefit that greater energy is needed to separate it from the surfaces /8/. It is obvious that the viscosity of the adhesive secretion changes very rapidly during the process of trapping the prey. While it is being transported to and distributed over the sticky pads before the capture process starts, it is highly fluid, but after making contact with the prey it becomes increasingly viscous.

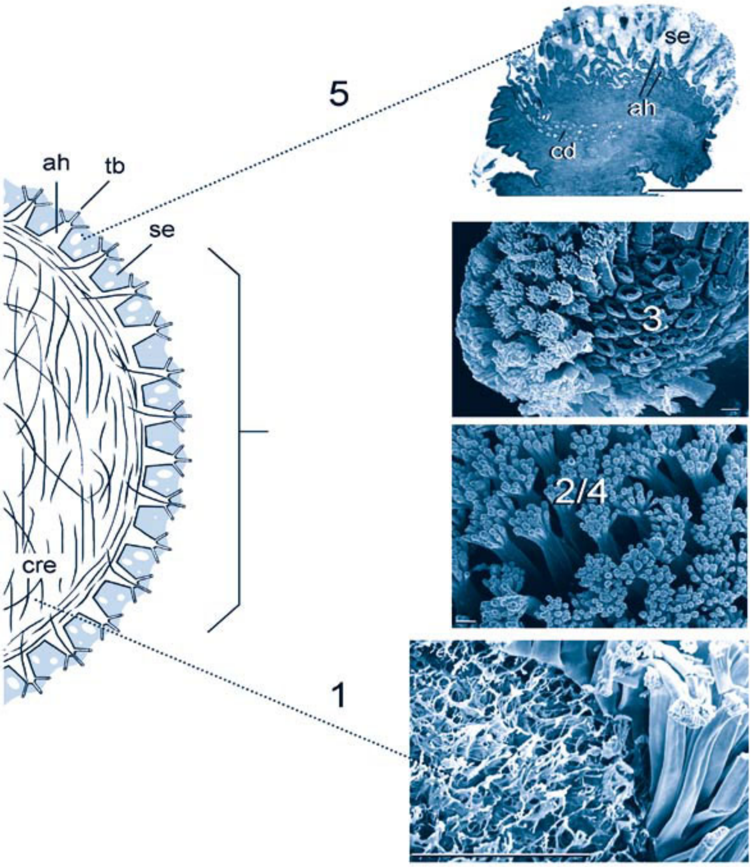


Figure 2: Elements in the hierarchical structure of the adhesive pads of rove beetles of the genus *Stenus*. Left: Cross-section of a sticky pad showing different elements of the system. Right: The equivalent scanning and transmission electron microscope images of these elements: (1) Network of flexible cuticular fibres within the pad (scale = 20 µm); (2) Image of the adhesive hairs which (4) end in multiple branches (scale = 1 µm); (3) The base of the hair shafts with the distal section removed to show the hexagonal packing pattern (scale = 2 µm); (5) Cross-section of a sticky pad showing the two phases of the adhesive secretion (white droplets of secretion in a grey matrix) (scale = 20 µm) /7/.
Abbreviations: ah = adhesive hair, cd = chitinous ducts which bring the secretion to the surface of the pad, cre = network of cuticular fibres, se = secretion, tb = terminal branches.

Adhesive performance of the capture apparatus

While catching the prey insect, the apparatus exerts a specific contact pressure on the insect. This presumably reduces the thickness of the film of fluid between the two surfaces and increases the adhesion. The secretion is also pushed into the surface irregularities of the prey. Using micro force sensors we succeeded in measuring both the contact pressure and the adhesion force exerted when the labium is subsequently retracted. These experiments were carried out with the plastic head of an insect needle which was used as the prey dummy. It became clear that the contact load was relatively low (0.1 to 0.2 mN), while the resulting adhesive forces in the case of some species were as high as 1.2 mN. In relation to the entire surface of the sticky pad, these figures are equivalent to contact pressures of 5 to 25 kPa and a tensile strength of 140 kPa. The performance of the adhesive was the same on all the synthetic surfaces studied (epoxy resin and silane-coated glass), regardless of the surface roughness and energy.

Biomimetic application potential

In summary, the capture apparatus of the *Stenus* beetles can be described as a hierarchical system in which a multi-phase adhesive secretion is combined with the

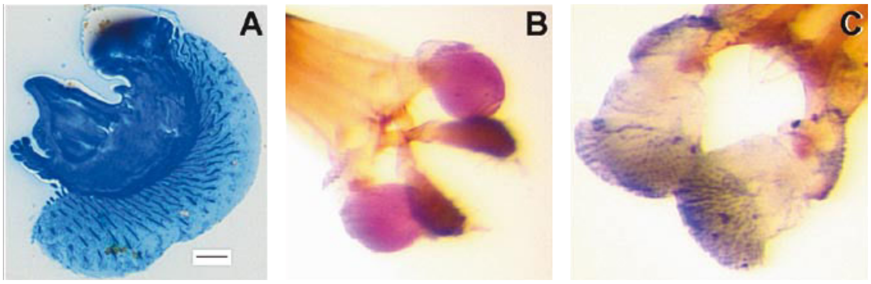
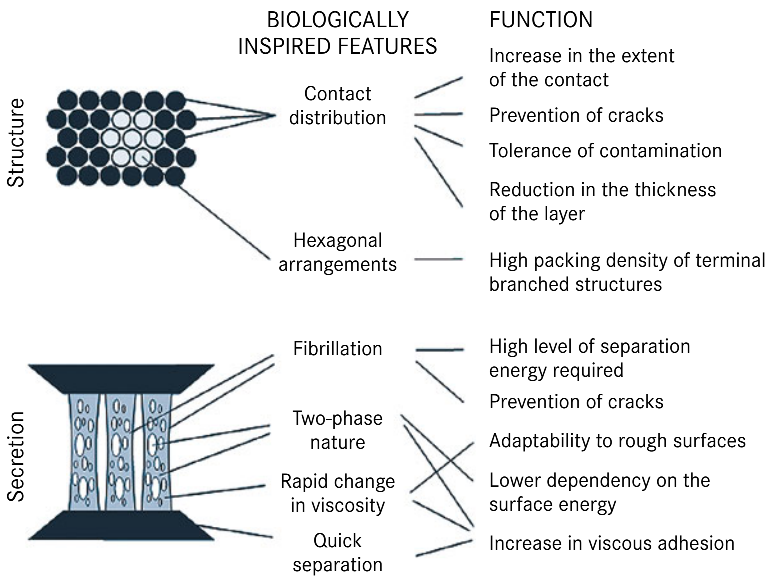


Figure 3, top: Results of the histochemical tests on the nature of the secretion: A Protein (Coomassie Blue), scale = 10 µm, B Carbohydrate (periodic acid, Schiff's reagent (PAS)), C Lipid (Sudan Black B).

Figure 4, right: Summary of the functional principles with biomimetic potential in the system under investigation.



specific structure of micro-pillars with terminal branches. This adhesive system has numerous properties which are potentially of biomimetic interest. For example, the system is environmentally friendly because it is based on proteins and carbohydrates. Another interesting factor is the rapid development of the adhesive contact at high speed. The contact is also highly stable and, at the same time, reversible. In addition, the secretion can easily spread over the surface, but is highly resistant to drying out, as long as it remains in contact with the pads. Furthermore, it appears that the viscosity of the secretion can be modified within a period of only a few milliseconds. The contact pressure needed is relatively low in relation to the resulting tensile strength. Finally, the adhesive performance of the system is not particularly sensitive to unpredictable surface roughness and energy. The specific functional principles associated with the system are summarised in Figure 4.

Before these principles can be used in potential technical applications, further basic research is needed, which could be carried out in cooperation with partners from industry. The first step involves the chemical characterisation of the main components of the secretion, including the proteins, which could have specific adhesive properties. After this, the adhesive must be reproduced in the laboratory so that it can be tested in combination with bioinspired, artificial, microstructured surfaces in accordance with DIN/ISO standards, in order to identify potential product applications.

Acknowledgement

This pilot study was funded by the German Federal Ministry of Education and Research (bionics competition, BNK 2-052). ■

The Authors
References

Prof. Dr. Oliver Betz (Phone: +49(0)70 71.2 97 29 95, Fax: +49 (0)70 71.29 46 34, oliver.betz@uni-tuebingen.de) is the head of the Department of Evolutionary Biology of Invertebrates at the University of Tübingen, Lars Koerner (larskoerner3@hotmail.com) is his doctoral student.
Dr. Stanislav Gorb (sgorb@zoologie.uni-kiel.de) is chair and director at Zoological Institute in Kiel, Germany.

/1/ Betz, O. 1996. Function and evolution of the adhesion-capture apparatus of *Stenus* species (Coleoptera, Staphylinidae). Zoomorphology 116: pages 15 – 34.
/2/ Kölsch, G. & Betz, O. 1998. Ultrastructure and function of the adhesion-capture apparatus of *Stenus* species (Coleoptera, Staphylinidae). Zoomorphology 118: page 263 Zoomorphology 118: pages 263 – 272.
/3/ Bauer, T., Pfeiffer, M. 1991. "Shooting" springtails with a sticky rod: the flexible hunting behaviour of *Stenus* comma (Coleoptera; Staphylinidae) and the counter-strategies of its prey. Animal Behavior 41: pages 819 – 828.
/4/ Jagota, A. & Bennison, S. J. 2002. Mechanics of adhesion through a fibrillar microstructure. Integrative and Comparative Biology 42: pages 1140 – 1145.
/5/ Gorb, S. N. 2008. Biological attachment devices: exploring nature's diversity for biomimetic. Philosophical Transactions of the Royal Society A: (10.1098 rsta.2007.2172).
/6/ Vötsch, W., Nicholson, G., Müller, R., Stierhof, Y.-D., Gorb, S. & Schwarz, U. 2002. Chemical composition of the attachment pad secretion of the locust *Locusta migratoria*. Insect Biochemistry and Molecular Biology 32: pages 1605 – 1613.
/7/ Kölsch, G. 2000. The ultrastructure of glands and the production and function of the secretion in the adhesive capture apparatus of *Stenus* species (Coleoptera: Staphylinidae). Canadian Journal of Zoology 78: pages 465 – 475.
/8/ Creton, C. 2003 Pressure-sensitive adhesives: an introductory course. MRS Bulletin 2003: pages 434 – 439.
/9/ Weinreich, E. 1968. Über den Klebfangapparat der Imagines von *Stenus* Latreille (Coleoptera: Staphylinidae) mit einem Beitrag zur Kenntnis der Jugendstadien dieser Gattung. (The adhesive capture apparatus of the imagines of *Stenus* Latreille (Coleoptera: Staphylinidae) with a contribution to the knowledge of the young stages of this genus.) Zeitschrift für Morphologie und Ökologie der Tiere 62: pages 162 – 210.