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Gecko climbs a wall using van der Waals force

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Abstract

Geckos are lizards who have evolved one of the most effective adhesives known. By using millions of microscopic hairs on their feet they adhere to walls and ceilings because of van der Waals forces. Because van der Waals forces are of very short range, gecko's hairs have to come very close to the surface to adhere using that mechanism. Gecko's hairs are 30-130 μm long that end with hundreds of even tinier hairs of radius 0.2-0.5 μm. Because of these hairs gecko is capable of holding it's weight with only one toe of one foot.

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1 Introduction

In the 4th century B.C., Aristotle observed the ability of the Gecko to run up and down a tree in any way, even with the head downwards [1]. More than two millennia later, the secrets of how geckos use millions of tiny foot-hairs to adhere to even molecularly smooth surfaces, are uncovered. Gecko is up to 35 cm long lizard covered with scales. It is active mostly at night and it makes sounds that are similar to word 'gecko'. That's where it got it's name from. This lizard has an outstanding ability to climb even on moleculary smooth surfaces. For a very long time it was not known whether capillary forces or van der Waals forces are the cause of that adhesion. In year 2002 it was finally confirmed by an experiment that gecko sticks to the wall using van der Waals forces [2].

Figure 1: Gecko and it's setal tips [3]

As seen in Figure 1, gecko has microscopic hairs all over his feet. By using these microscopic hairs ($\approx$ 500.000 per foot) that can adhere to smooth surfaces, geckos are able to support their entire body weight with a single toe. This hairs are called setae (pronounced see' tee). Each of these seta splits on the end into 100 - 1000 even smaller pads, called spatulae (Figure 2), and these are the key to this strong adhesive force. As gecko climbs a wall, it rolls these spatulae onto the surface and them peels them off like tape. Gecko can race up a polished glass at a meter per second using that technique and is nature's supreme climber. And although gecko's feet stick to everything it can race over the sand and then immediately climb a wall.

As we can see there are still some questions to be answered in the future.

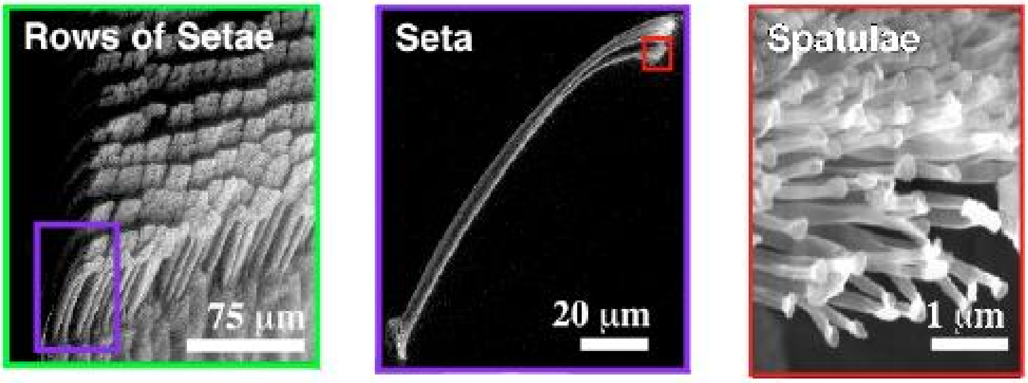

Figure 2: Setae and spatulae [3]

So to understand how gecko climbs the wall we must look at van der Waals adhesion in more details.

2 Measurements

Measurements of adhesion force were made for a single, isolated seta using a micromachined, dual-axis, piezoresistive cantilever [4](Figure 3a, 3b).

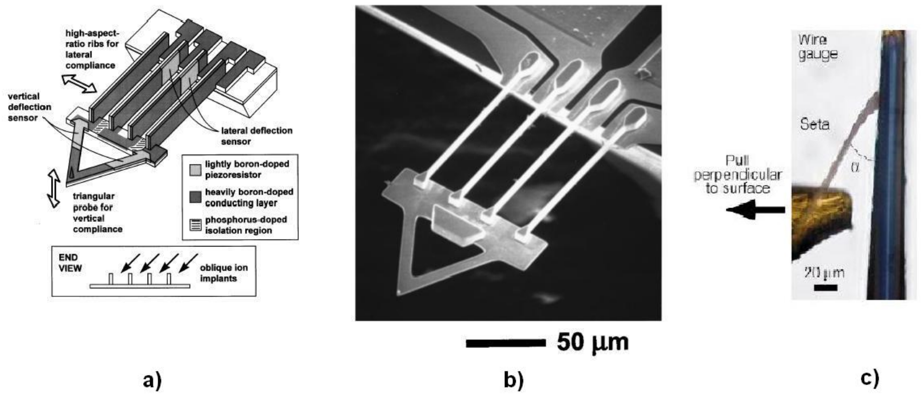

Figure 3: a), b) dual-axis piezoresistive cantilever [10], c) seta attached on a cantilever [3]

To determine how setal force should be measured, the gecko's unusually complex behaviour of toe uncurling during attachment was considered. Uncurling during attachment is much like blowing up an inflating party favour, and toe peeling during detachment is analogous to removing a piece of tape from a surface.

Seta has to be initially pushed toward the surface (perpendicular preload) and then parallel force can be measured. In experiment setal adhesive force parallel to the surface increased until the seta began to slide of the sensor. Setal force parallel to the surface increased linearly with the perpendicular preloading force and was substantially greater than the force produced by the inactive, non-spatular region at all preloads (Figure 4).

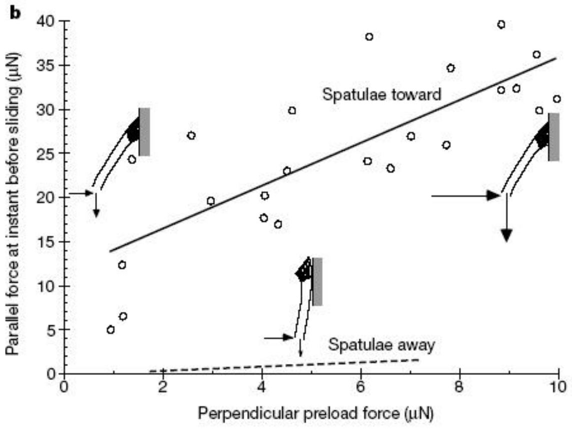

Figure 4: Setal force parallel to the surface during attachment as a function of perpendicular preload force [4]

Experiments in which setae were pulled away from the surface (Figure 3c) demonstrated that perpendicular preload alone is insuficient for effective setal attachment. Setae that were first pushed into the surface and then pulled parallel to it developed over ten times the force $(13.6 \pm 2.6 \mu N)$ upon being pulled away from the surface than those having only a perpendicular preload $(0.6 \pm 0.7 \mu N)$. The largest parallel forces were observed only if the seta was allowed to slide approximately 5 μm along the sensor's surface (Figure 5). The maximum adhesive force of single seta averaged $194 \pm 25 \mu N$.

The orientation of the setae is also important in detachment. It was found that setae all detach at a similar angle $(\alpha = 30.6 \pm 1.8^\circ)$ when pulled away from the wire sensor's surface. Change in the orientation of the setae and perhaps even the geometry of spatulae may help detachment. It is still unclear how that mechanism of peeling foot of the substrate works. One explanation is that only small fraction of the setae detach at any moment and so the force needed to detach them is small. But there is much more to it and animal as a whole must be studied.

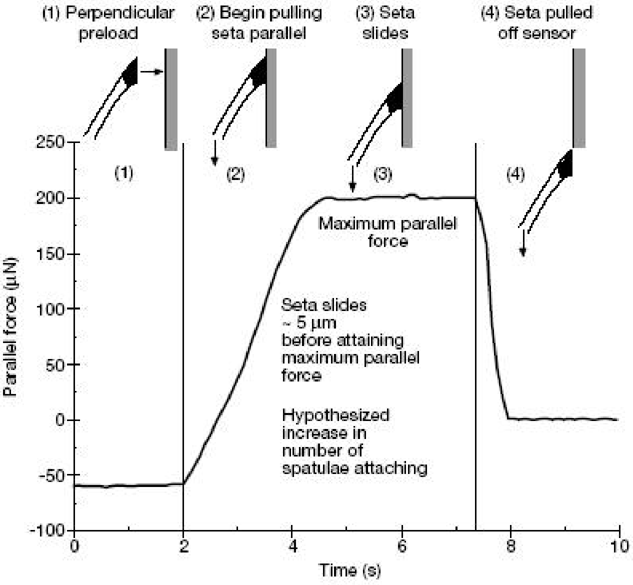

Figure 5: Maximal force after a maximum preload of a single seta parallel to the surface as a function of time [4]

3 About van der Waals adhesion

In physics and chemistry, the term van der Waals force originally referred to all forms of intermolecular forces; however, in modern usage it tends to refer to intermolecular forces that deal with forces due to the polarization of molecules. Van der Waals interactions are observed in noble gases which are very stable and tend not to interact. This is why it is difficult to condense them into liquids. However, the larger the atom of the noble gas (the more electrons it has), the easier it is to condense the gas into a liquid. This happens because when the electron cloud surrounding the gas atom gets large, it does not form a perfect sphere around the nucleus. Rather, it's only spherical if averaged over longer times and generally forms an oval, which has a slight negative charge on one side and a slight positive charge on the other. The atom becomes a temporary dipole. This induces the same shift in neighboring atoms and spreads from one atom to the next. Unlike charges attract and the induced dipoles are held together by dispersion force (or van der Waals force)[5].

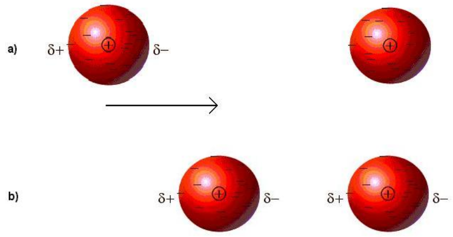

Figure 6: Polar atom induces dipole in neighbouring atom

There are three types of van der Waals forces: orientation, induction and dispersion. All of them contribute to van der Waals force, but usually dispersion bond is the strongest.

3.1 Induction force

Forces between polar molecule and nonpolar molecule are called induction forces. Polar molecules can polarize nonpolar molecules inducing dipole in nonpolar molecule (Figure 7).

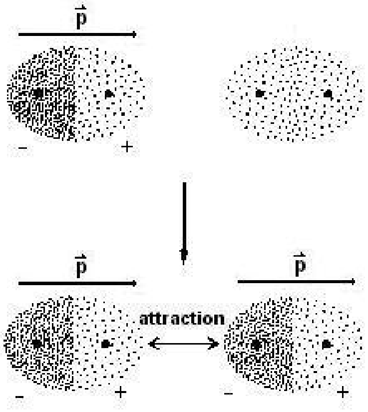

Figure 7: Polar molecule induces dipole in a nonpolar molecule

Stronger the dipole of polar molecule easier the dipole is induced in nonpolar molecule. Nonpolar molecule is also easier polarized if it has more electrons. How sensitive is the shape of electron cloud of an atom for applied electric field tells us electron polarizability (α). Higher α means that a relatively weak electric field causes greater changes in electron distribution around an atom.

For applied electric field E on a nonpolar molecule induces dipole $p_{ind} = \alpha E$, where α is polarizability of a molecule. Energy of an induced dipole in applied electric filed E is $W = -\frac{1}{2}\alpha E^2$.

Now we will look what happens in a case when a nonpolar molecule is in an electric field caused by permanent neighbouring dipoles.

First I calculate electric filed caused by a permanent dipole p_1:

$$\Phi_1 = \frac{\vec{p_1} \cdot \vec{r}}{4\pi\epsilon\epsilon_0 r^3} \qquad \vec{E_1} = -\nabla\Phi_1$$

$$\begin{aligned}
\vec{E_1} &= -\frac{1}{4\pi\epsilon\epsilon_0}\nabla\frac{\vec{p_1} \cdot \vec{r}}{r^3} = -\frac{1}{4\pi\epsilon\epsilon_0}\Big((\vec{p_1} \cdot \vec{r})\nabla(\frac{1}{r^3}) + (\frac{1}{r^3})\nabla(\vec{p_1} \cdot \vec{r})\Big) = \\
&= -\frac{1}{4\pi\epsilon\epsilon_0}\Big(-3(\vec{p_1} \cdot \vec{r})\frac{\vec{r}}{r^5} + \frac{1}{r^3}\vec{p_1}\Big) = \\
&= -\frac{1}{4\pi\epsilon\epsilon_0}\Big(\frac{\vec{p_1}}{r^3} - \frac{3(\vec{p_1} \cdot \vec{r})\vec{r}}{r^5}\Big)
\end{aligned}$$

or

$$\vec{E_1} = \frac{p_1}{4\pi\epsilon\epsilon_0 r^3}\Big(3\cos\theta\sin\theta, 3\cos^2\theta - 1\Big) \tag{1}$$

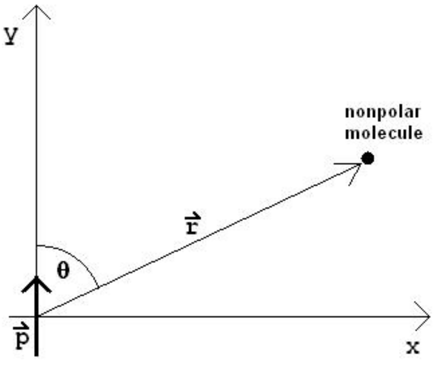

Figure 8: Electric field of a dipole

Now I can calculate interaction potential between polar and nonpolar molecule, called **Debye** energy:

$$\begin{aligned} W(r,\theta) &= -\frac{1}{2}\alpha E_1^2 = \\ &= -\frac{1}{2}\frac{\alpha p_1^2}{(4\pi\epsilon\epsilon_0)^2 r^6}\Big(3\cos^2\theta + 1\Big) \end{aligned} \tag{2}$$

and

$$W_{Debye}(r) = \int_0^\pi W(r,\theta)d\theta = -\frac{\alpha p_1^2}{(4\pi\epsilon\epsilon_0)^2 r^6} \tag{3}$$

3.2 Orientation force

Forces between polar molecules are called orientation forces. Stronger the polarity stronger the force between molecules. In general dipoles have random orientations with $< p >= 0$ but if we apply external electric field E dipoles partially align $\Rightarrow < p > \neq 0$. We presume Boltzman distribution of molecules:

$$< p >= \frac{\int p_0 \cos\theta \; e^{p_0 E \cos\theta / k_B T} dV}{\int e^{p_0 E \cos\theta / k_B T} dV} \approx \frac{p_0^2}{3k_B T}E = \alpha_{el.st.}E, \tag{4}$$

where p_0 is dipole momentum of one molecule and $\alpha_{el.st.}$ is electrostatic polarizability.

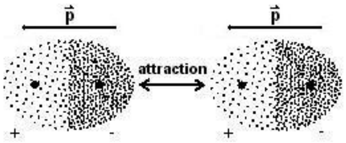

Figure 9: Electrostatic forces

Now we have similar problem as in **3.1** except our dipoles are fluctuating around equilibrium position caused by temperature. If we use Boltzman distribution we can change α with $\alpha_{el.st.}$ (defined in (4)) and put it in equation (3). We get **Keesom** energy:

$$W_{Keesom}(r) = -\frac{p_1^2 p_2^2}{3k_B T(4\pi\epsilon\epsilon_0)^2 r^6} \tag{5}$$

3.3 Dispersion force

If both of the molecules are nonpolar the dispersion force is the only possible between them. In atoms electrons move unorganized and so temporary dipole is created. This induces the same shift in neighboring atoms and spreads from one atom to the next. So the attraction between nonpolar molecules can be achieved (Figure 10).

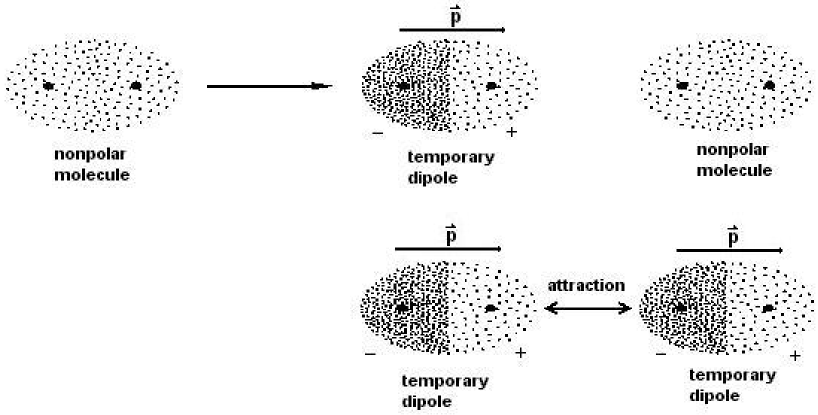

Figure 10: Concept of dispersion forces

Both energies considered until now can be calculated in a classical way. Unfortunately they do not completely explain the interaction between molecules, e.g. the attraction between two nonpolar molecules. This interaction can be understood only in the context of quantum mechanics. The static dipole moment, which occurs in the equation of the Debye energy, is replaced by a fluctuating dipole moment in quantum mechanics. The reason for this fluctuation is the uncertainty principle. The fluctuating dipole polarizes neighbouring molecules, leading to an attraction.

The energy between two molecules with the ionization energies $h\nu_1$ and $h\nu_2$ amounts to **London** energy[6]:

$$W_{London}(r) = -\frac{3}{2}\frac{\alpha_{01}\alpha_{02}}{(4\pi\epsilon\epsilon_0)^2}\frac{h\nu_1\nu_2}{(\nu_1+\nu_2)}\frac{1}{r^6} \tag{6}$$

and is a bit simplified if both molecules are the same:

$$W_{London}(r) = -\frac{3}{4}\frac{\alpha_0^2 h\nu}{(4\pi\epsilon\epsilon_0)^2}\frac{1}{r^6} \tag{7}$$

where ν is electric absorption's frequency and α_0 is electron polarizability.

As already mentioned all of these forces contribute to van der Waals force, but usually dispersion bond is the strongest:

$$W_{vdW}(r) = W_{Debye}(r) + W_{Keesom}(r) + W_{London}(r) = \frac{-A}{r^6} \tag{8}$$

4 Van der Waals energy between macroscopic bodies

Using the above results we would now like to calculate the adhesion force of gecko's feet.

4.1 Lifshitz theory

We should mention there also exists another way of computing attraction force between two macroscopic bodies using Lifshitz theory. With Lifshitz theory we get the same results as with sumation of $1/r^6$ interactions and much more. We also get retardation effects which are consequence of finite speed of light. These retardation effects cause the interaction between macroscopic bodies to change from $1/r^x$ regime to $1/r^{x+1}$ regime at certain distance. This boundary distance is nontrivial and is dependent of dielectric spectrum ($\epsilon(\omega)$)of both interacting bodies. Qualitatively this distance is:

$$l = \frac{c}{\nu_{abs}} \tag{9}$$

As a consequence, for distances greater than 10 - 100 nm [9] the vdW energy drops more rapidly as for smaller distances. In our calculations we will not use the retarded potentials bacause our distances are shorter as we will see.

4.2 Single molecule and wall

Using equation (8) and Figure 11, we can calculate energy between one molecule at a distance L from the wall and all molecules in the wall.

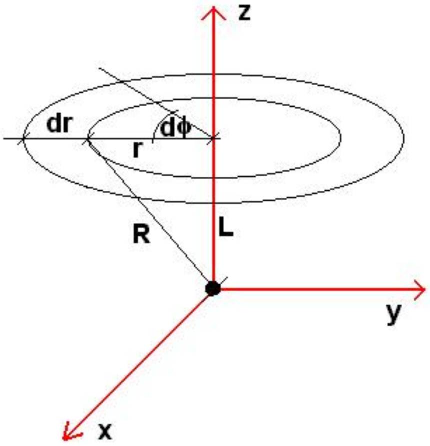

Figure 11: Calculation of interaction between molecule and a wall

At a distance R, we have dN molecules in infinitesimal volume dV of wall according to $dN = \rho dV$ where ρ is molecular density of the wall. We take into account only those molecules which are at least L away from molecule.

Using polar coordinates we get:

$$\begin{aligned} W_{vdW}(L) &= \int_N W_{vdW}(R)dN = -\int_V \frac{A}{R^6}\rho dV = \\ &= -A\rho\int_0^{2\pi} d\phi \int_L^\infty dz \int_0^\infty \frac{rdr}{(r^2+z^2)^3} = \\ &= -\frac{A\rho\pi}{2}\int_L^\infty \frac{dz}{z^4} = \\ &= -\frac{A\rho\pi}{6}\frac{1}{L^3} \end{aligned} \tag{10}$$

Van der Waals energy between molecule and a wall in our case is proportional to L^{-3} and no longer to L^{-6} as between two molecules. Now we can also calculate adhesion force:

$$F_{vdW} = -\frac{\partial W(L)}{\partial L} = -\frac{A\rho\pi}{2L^4} \tag{11}$$

4.3 Adhesion of gecko spatula to the wall

And now we can finally calculate van der Waals energy between gecko spatula and a wall. I will approximate spatula with a spherical cap (Figure 12).

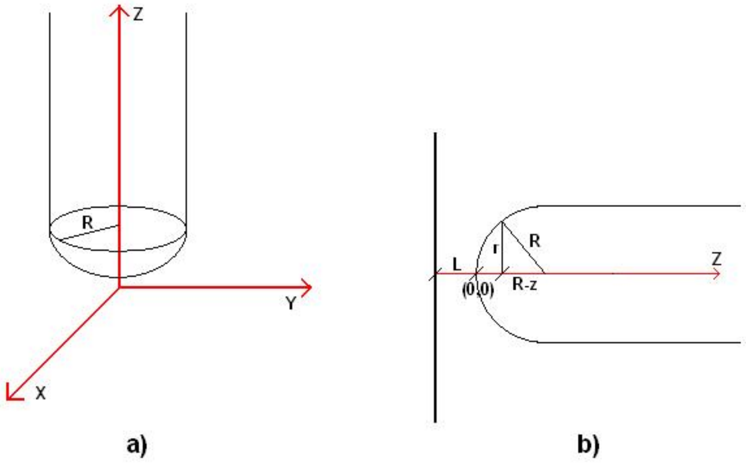

Figure 12: Spatula (infinitely long cylinder with spherical cap) near an infinite wall

Every molecule in the spatula has the energy with the wall according to equation (10). Now all we have to do is count the molecules in the spatula at every distance from the wall. Number of molecules in a volume is $dN = \rho_{spatula} dV$. We use equation (10) to start with, then we calculate number of molecules only for spherical cap as those molecules contribute most of the energy.

$$\begin{aligned} W_{spatula}(L) &= \int W_{vdW} dN = \int W_{vdW} \rho_{spatula} dV = \\ &= -\frac{A\pi \rho_{wall} \rho_{spatula}}{6} \int \frac{1}{z^3} dV = \\ &= -\frac{A\pi^2 \rho_{wall} \rho_{spatula}}{6} \Big(\frac{R}{L} - \frac{1}{2} + \frac{L(L+2R)}{2(L+R)^2} + ln(\frac{L}{L+R}) \Big) \end{aligned}$$

If $R >> L$, which is the case, we can simplify:

$$W_{spatula}(L) \approx -\frac{A\pi^2 \rho_{wall} \rho_{spatula}}{6} \frac{R}{L} \tag{12}$$

and compute adhesion force of one spatula to the wall:

$$F_{spatula-wall}(L) = \frac{\partial W_{spatula}(L)}{\partial L} \approx -\frac{A\pi^2 \rho_{spatula} \rho_{wall}}{6} \frac{R}{L^2} = \frac{H_{spatula-wall} R}{6L^2} \tag{13}$$

where we have introduced material-dependent Hamaker constant defined as $H_{spatula-wall} = A\pi^2\rho_{spatula}\rho_{wall}$.

We can take [4]: $H_{spatula-wall} = 10^{-19}J,\ R = 0.5\mu m\ and\ L = 0.3nm$. Gecko has 2.000.000 setae on all feet and each seta splits into about 500 spatula on the end [4]. Our calculated adhesion force of gecko to the wall is therefore:

$$F_{gecko-wall}(L) \approx 2 \cdot 10^6 \cdot 500 \cdot F_{spatula-wall} = 10^9 \frac{H_{spatula-wall}R}{6L^2} \approx 93N. \quad (14)$$

If we now approximate gecko mass with about $200g$ we can see that gecko can easily hold on to a ceiling even with only one of five fingers on one foot.

5 Conclusion

It has been proven that geckos use van der Waals forces to climb walls and ceilings. But could human climb the wall using same principles? Researchers all over the world are searching for an answer. There are efforts to make so called gecko tape as alternative adhesive tape. Synthetic setae (Figure 13) were already made and adhesion has turned out to be the same as gecko's seta adhesion [2].

It is not so far away when production of van der Waals adhesives will become reality. Possibilities are almost endless: adhesive tape which could be used again and again, adhesives which would work even in vacuum, tires that would better stick to the road, etc.

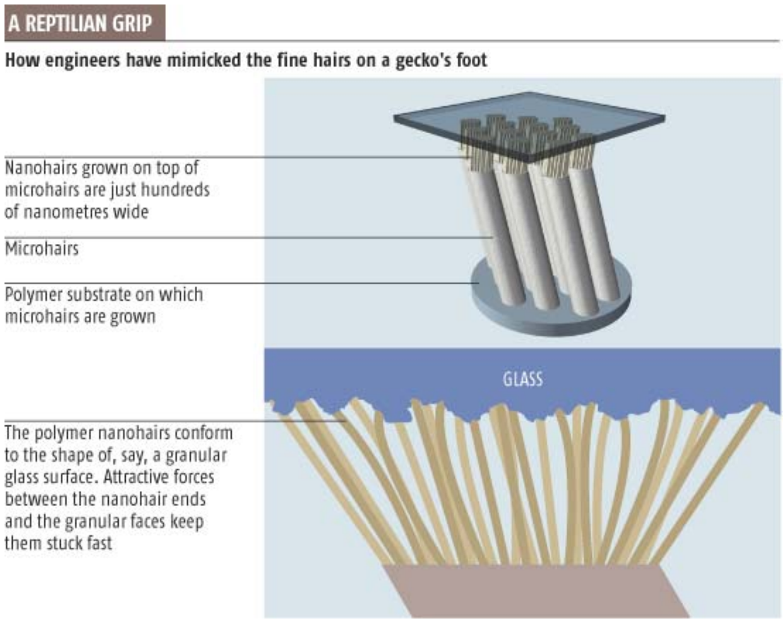

Figure 13: Synthetic seta [11]

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