LECTURE 12: VAN DER WAALS FORCES AT WORK: GECKO FEET ADHESION

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Objectives: To understand how weak van der Waals force can lead to enormous, reversible adhesion


Multimedia: K. Autumn, Discovery Channel movie.

COLLOIDS AND INTERPARTICLE FORCES
-Definitions: Colloids, colloidal dispersion, colloidal inks; percolation
\[
W(D)_{\text{SPHERE-SFC}} = \frac{-4\pi^2 \rho^2 R}{(n-2)(n-3)(n-4)(n-5)D^{n-3}}
\]

\[
W(D)_{\text{SPHERE-SFC}}(\text{VDW}, n = 6) = \frac{-\pi^2 \rho^2 R}{6D}
\]

\[
w(r) = r^{-6}, W(D)_{\text{MOL-SFC}} \sim D^{-3}, W(D)_{\text{SPHERE-SFC}} \sim D^{-1}
\]

"Hamaker Constant":

\[A = \pi^2 A \rho^2 \] (interactions between the same material)

\[A = \pi^2 A \rho_1 \rho_2 \] (interactions between different materials)

\[A \sim 10^{-19} \text{ J} \]

\[
W(D)_{\text{SPHERE-SFC}}(\text{VDW}, n = 6) = \frac{-AR}{6D}
\]

\[
F(D)_{\text{SPHERE-SFC}}(\text{VDW}, n = 6) = -\frac{\partial W(D)}{\partial D} = -\frac{AR}{6D^2}
\]

- Analytical formulas for VDW interactions for other geometries

- Colloidal stability, other long range forces; electrostatic double layer, steric, electrosteric, structural, depletion

\[
W(D) = W(D)_{\text{VDW}} + W(D)_{\text{ELECTROSTATIC}} + W(D)_{\text{STERIC}} + W(D)_{\text{STRUCTURAL}} - W(D)_{\text{DEPLETION}}
\]

Figure by MIT OCW.
"Depletion Interaction": For entropic reasons the chains avoid the space between two close particles, or between a particle and a planar wall, and create an effective attraction among the colloid particles.

**Dispersed state**: repulsive energy barrier $>> k_B T$

**Weakly Flocculated**: well depth $\sim 2-20 k_B T$

**Strongly Flocculated**: deep primary minimum

-e.g. Dispersion of nanotubes

Figure by MIT OCW.

-attach and detach their toes in milliseconds to nearly every material (not Teflon!!)
-run on vertical and inverted, rough and smooth surfaces
-gecko toes don't degrade, foul, or attach accidentally to the wrong spot→ like a pressure sensitive adhesive
-they are self-cleaning and don't stick to each other
-flatten their palm down and then unroll their toes; remove without any measurable force

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Macrostructure → Mesostructure → Microstructure → Fine microstructure → Nanostructure → Nanostructure →

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ADHESIVE FORCE OF A SINGLE GECKO FOOT-HAIR (From K. Autumn et al. Nature, 2000, 681)

-Two front feet of a 50g Gecko can hold 2Kg, 20.1 N, 4.5 lbs

Three images from Autumn et al, Nature 2000, 681
removed due to copyright restrictions.

- Wanted to measure individual seta adhesion to explain macroscopic forces; couldn't get this experiment to work for months, thinking about neural control, chemicals/proteins? started applying the sequence of motions that Gecko's use (mechanical program), perpendicular preload and then small rearward displacement

- Measured force of individual seta 200 μN (can feel this) × 6.5 million setae on all feet = 1200 N, 269 lbs, 2 medium-sized humans!! only 3.5% of total possible adhesion needed to sustain the 2 Kg above, and < 0.04% to sustain body weight or 2000 of 6.5 million setae→overengineered, 3900% safety margin.

- How do Gecko's ever take their feet off surfaces? Hair detaches automatically when angle between setal shaft and substrate is 30 degrees→ adhesive that is under mechanical control.
MOLECULAR ORIGINS OF ADHESION (From Autumn, et al. PNAS 2002 99, 19, 12252)

Theories:
× mechanical interlocking; nanoscale velcro hooking → molecularly smooth Si wafers
× suction cups → experiments done in vacuum
× secretion of a protein adhesive → lack glandular tissue in toes
× capillarity forces due to bridging water meniscus

- van der Waals forces (short range)

experiment hydrophilic (Si wafer) versus hydrophobic surfaces (GaAs, but is also polarizable) → Geckos stuck to both, hence concluded VDW interactions dominate

-More dependent on geometry of structure rather than chemistry

THEORETICAL ASPECTS OF GECKO ADHESION  
(From Tian, et al. PNAS, 2006, 103, 51, 19320)

\[ F_f = \text{Friction force} \]
\[ F_{VDW} = \text{van der Waals force} \]
\[ F(\theta) = \text{peeling force along spatula shaft} \]
\[ F_L = \text{lateral component of peeling force along spatula shaft} \]
\[ F_n = \text{normal component of peeling force along spatula shaft} \]
\[ F_b = \text{resistance to bending} = \text{negligible} \]

(i) **contact regime**, LJ equilibrium, VDW balanced by short range atomic repulsion

(ii) transition "peel zone"; integrated \( F_{VDW} \) balanced by \( F(\theta) \) (part of noncontact regime)

(iii) \( x > x_2 \) \( F_{VDW} \) negligible (part of noncontact regime), \( F = F(\theta) \)

\[ E_x = E_0 \sin \left( \frac{2\pi x}{x_0} \right) \rightarrow F_x = F_f = \frac{2\pi E_0}{x_0} \cos \left( \frac{2\pi x}{x_0} \right) \]

\( x_0 \) = critical spacing related to atomic lattice, molecular or asperity dimensions on the spatula

\[ P(D)_{SFC-SFC} (VDW) = -\frac{A}{6\pi D^3} \]