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

Outline :

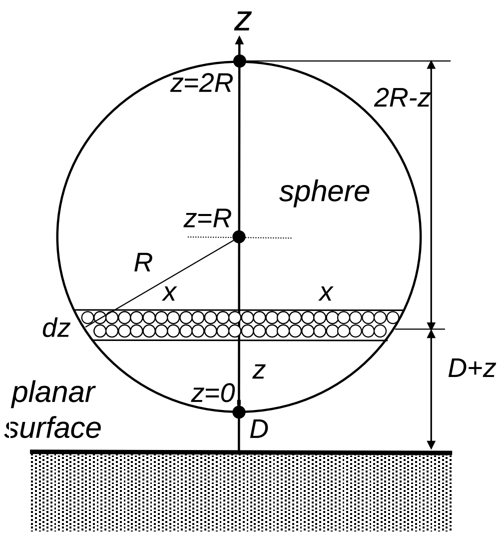
Objectives: To understand how weak van der Waals force can lead to enormous, reversible adhesion

Readings: K. Autumn, *American Scientist*, 94 124 **2006** and Tian, et al. *PNAS* **2006** 103, 51, 19320.

Multimedia : K. Autumn, Discovery Channel movie.

COLLOIDS AND INTERPARTICLE FORCES

-**Definitions**; Colloids, colloidal dispersion, colloidal inks; percolation



$$W(D)_{SPHERE\text{-}SFC} = \frac{-4\pi^2 A\rho^2 R}{(n-2)(n-3)(n-4)(n-5)D^{n-5}}$$

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

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

"Hamaker Constant" :

$\mathbf{A} = \pi^2 A\rho^2$ *(interactions between the same material)*

$\mathbf{A} = \pi^2 A\rho_1\rho_2$ *(interactions between different materials)*

$\mathbf{A} \sim 10^{-19}$ J

$$W(D)_{SPHERE\text{-}SFC}(VDW, n=6) = \frac{-\mathbf{A}R}{6D}$$

$$F(D)_{SPHERE\text{-}SFC}(VDW, n=6) = -\frac{\partial W(D)}{\partial D} = \frac{-\mathbf{A}R}{6D^2}$$

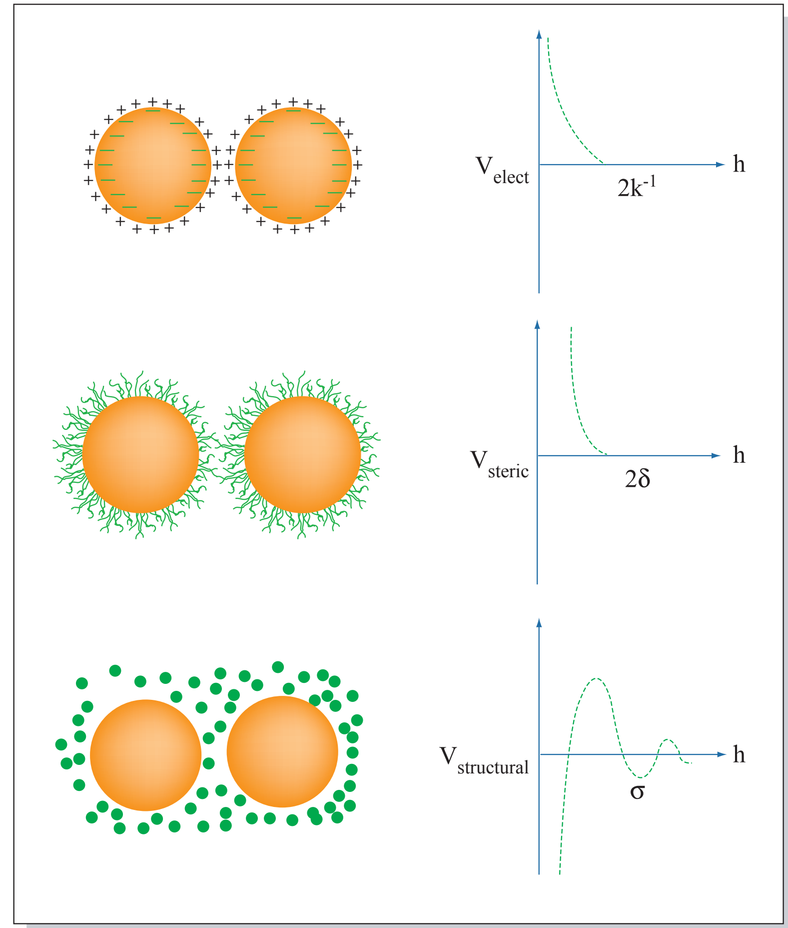


Figure by MIT OCW.
After Lewis. *J Am Ceram Soc* 83 no. 10 (2000): 2341-59.

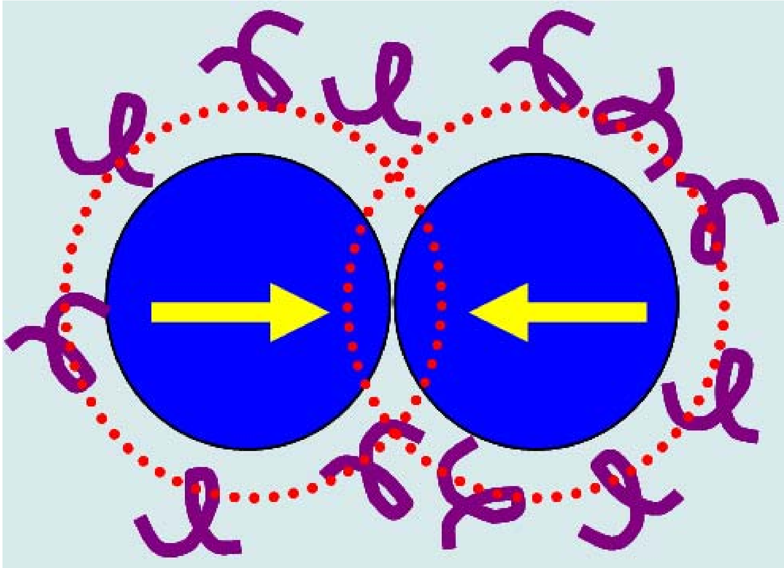
-Analytical formulas for VDW interactions for other geometries

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

$$W(D) = \underbrace{W(D)_{VDW} + W(D)_{ELECTROSTATIC}}_{DLVO\ Theory} + W(D)_{STERIC} + W(D)_{STRUCTURAL} - W(D)_{DEPLETION}$$

COLLOIDAL STABILITY: EFFECT ON DISPERSION

"**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_BT
Weakly Flocculated : well depth ~ 2-20 k_BT
Strongly Flocculated : deep primary minimum

-e.g. Dispersion of nanotubes

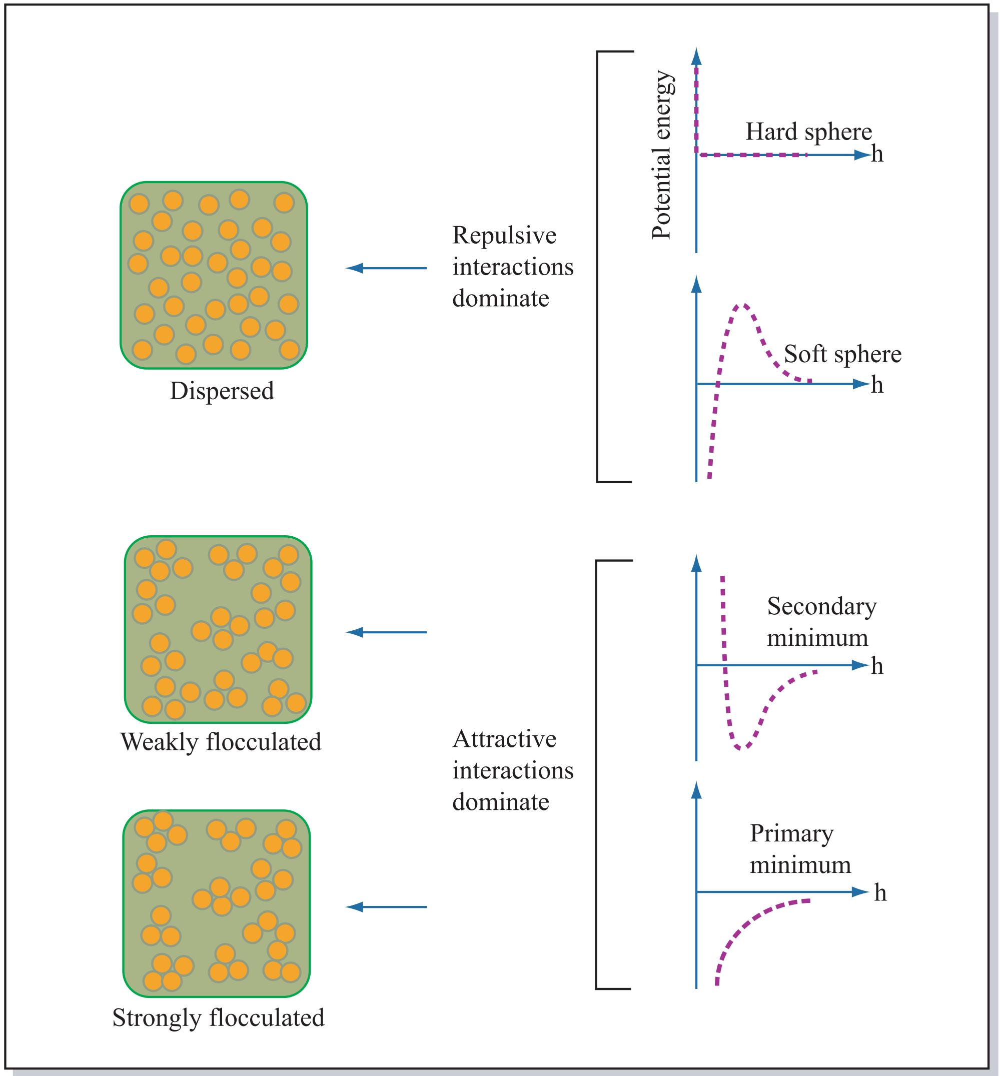
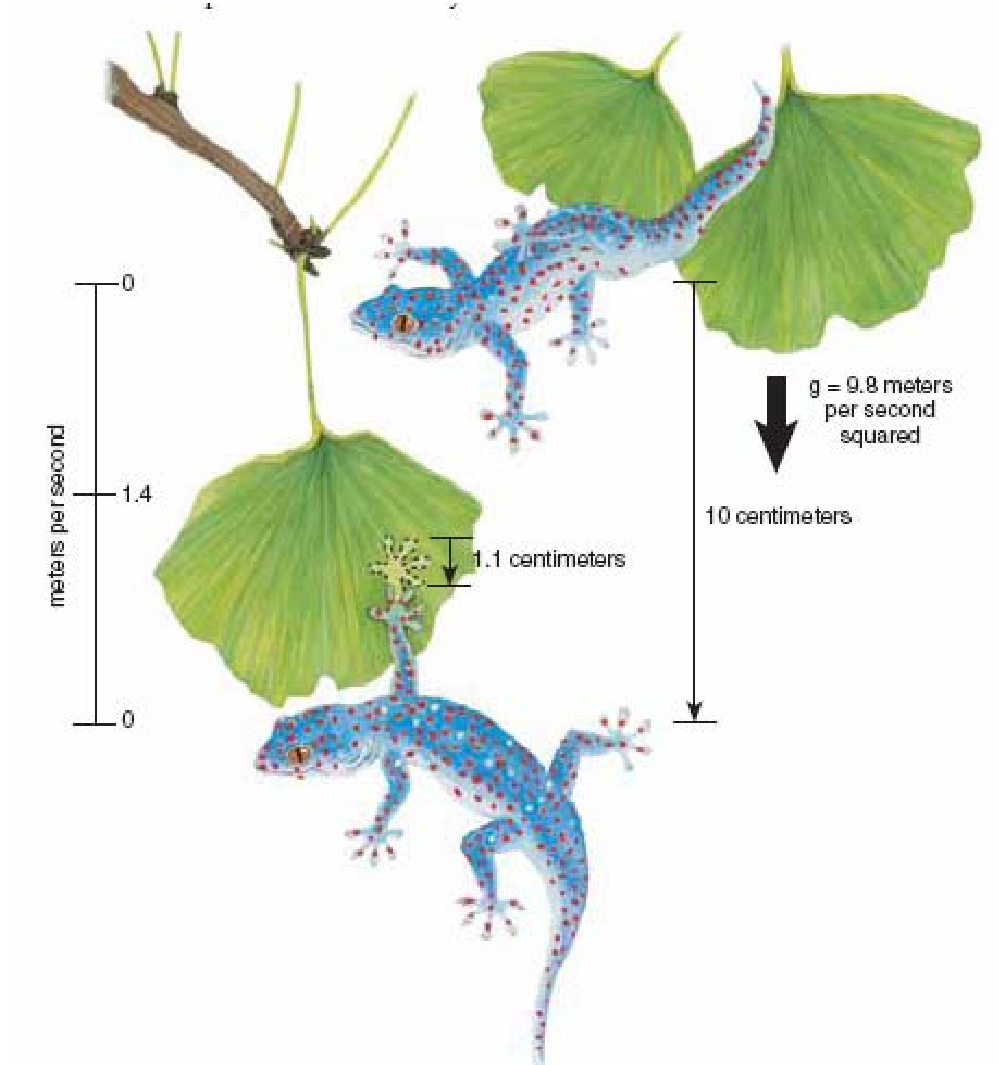


Figure by MIT OCW.
After Lewis. *J Am Ceram Soc* 83 no. 10 (2000): 2341-59.

GECKO ADHESION - "STICKY FEET" (From K. Autumn, et al. *American Scientist*, **2006**, 124)



-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

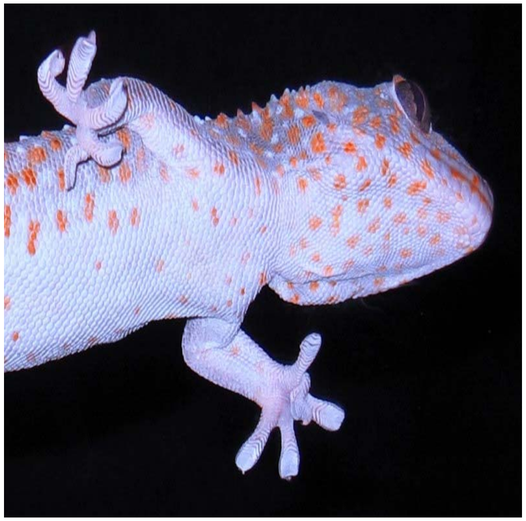
-they are self-cleaning and don't stick to each other

-flatten their palm down and then unroll their toes; remove without any measurable force

Reprinted by permission of American Scientist, magazine of Sigma Xi, The Scientific Research Society.

HIERACHICAL STRUCTURE OF GECKO FEET (From K. Autumn, et al. *American Scientist*, **2006**, 124)

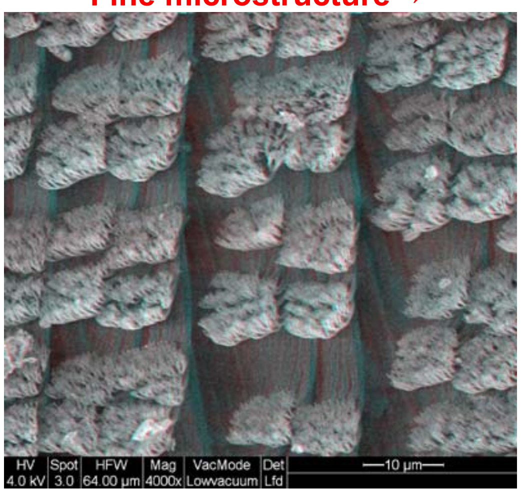
Macrostructure→



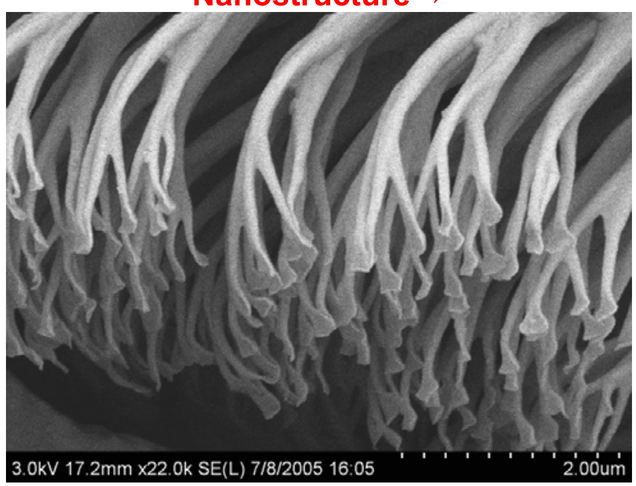
Mesostructure→

Microstructure→

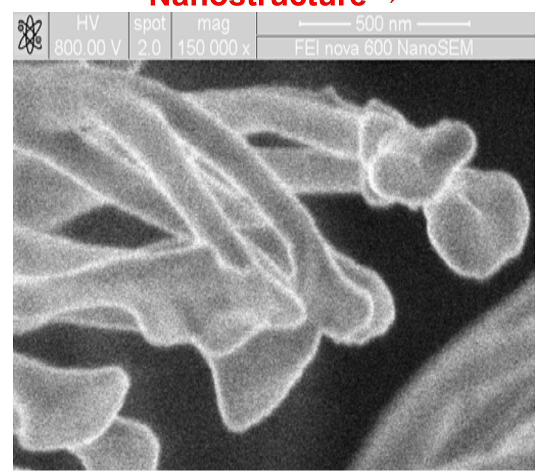
Fine microstructure→



Nanostructure→



Nanostructure→



Reprinted by permission of American Scientist, magazine of Sigma Xi, The Scientific Research Society.

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

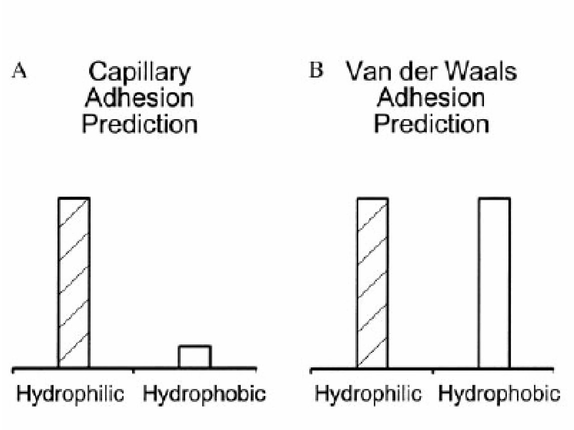
× secretion of a **protein adhesive**→lack glandular tissue in toes

× **capillarity forces** due to bridging water meniscus

-**van der Waals** forces (short range)

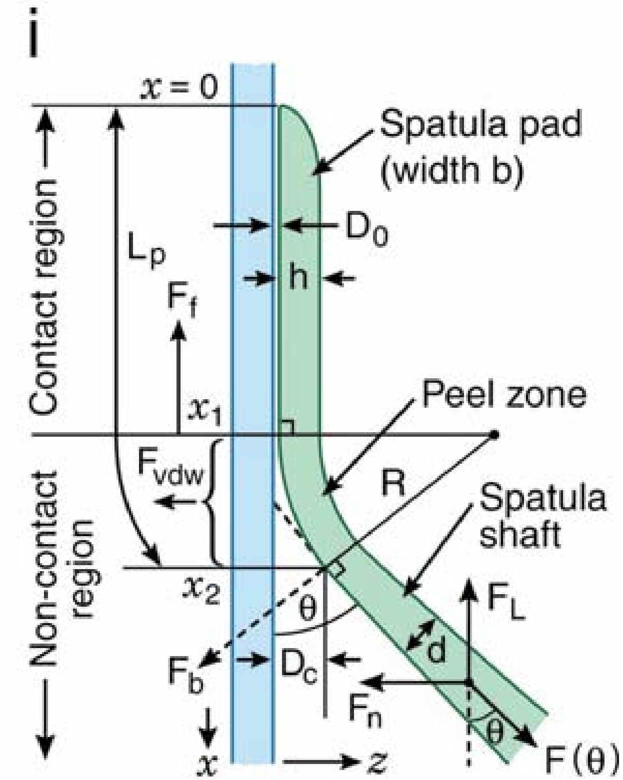
experiment hydrophilic (Si wafer) versus hydrophobic surfaces (GaAs, but is also polarizable) →Geckos stuck to both, **hence concluded VDW interactions dominate**

-**More dependent on geometry of structure rather than chemistry**



Courtesy of National Academy of Sciences, U. S. A. Used with permission. Source: Autumn, K., et al. "Evidence for van der Waals Adhesion in Gecko Setae." *PNAS* 99, no. 19 (September 17, 2002): 12252-12256. © 2002, National Academy of Sciences, U.S.A.

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



F_f= Friction force

F_{VDW}= van der Waals force

F(θ) = peeling force along spatula shaft

F_L= lateral component of peeling force along spatula shaft

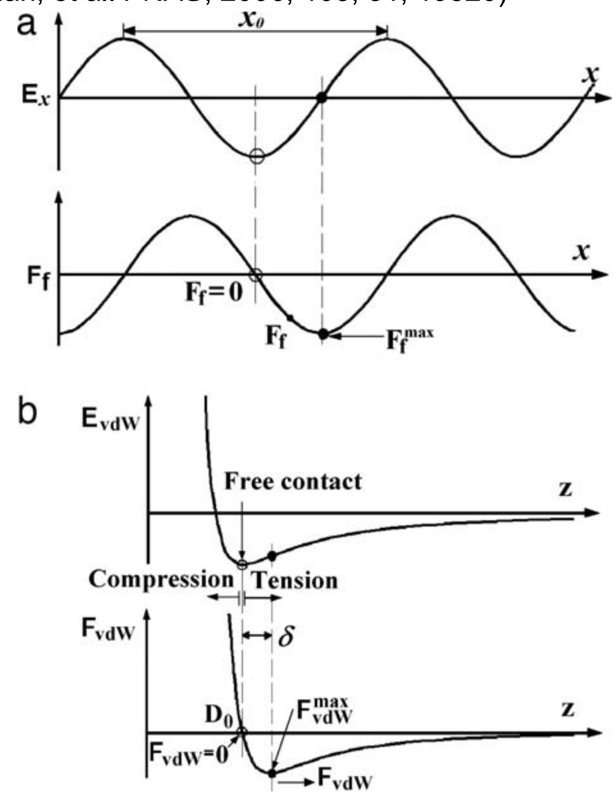
F_n= normal component of peeling force along spatula shaft

F_b=resistance to bending = negligible

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

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

(iii) **$x>x_2$** F_{VDW} negligible (part of noncontact regime), F= F(θ)



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

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

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

Courtesy of National Academy of Sciences, U. S. A. Used with permission. Source: Tian, Y., et al. "Adhesion and Friction in Gecko Toe Attachment and Detachment. " *PNAS* 103, no. 51 (2006): 19320-19325. © 2002, National Academy of Sciences, U.S.A.