Adhesion and Detachment Characteristics of “Soft” Adhesive Systems: from pressure-sensitive adhesive tapes to gecko hairy foot pads

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IPR 2009 Symposium, May 1

Adhesion is a Fundamental Phenomenon in Nature

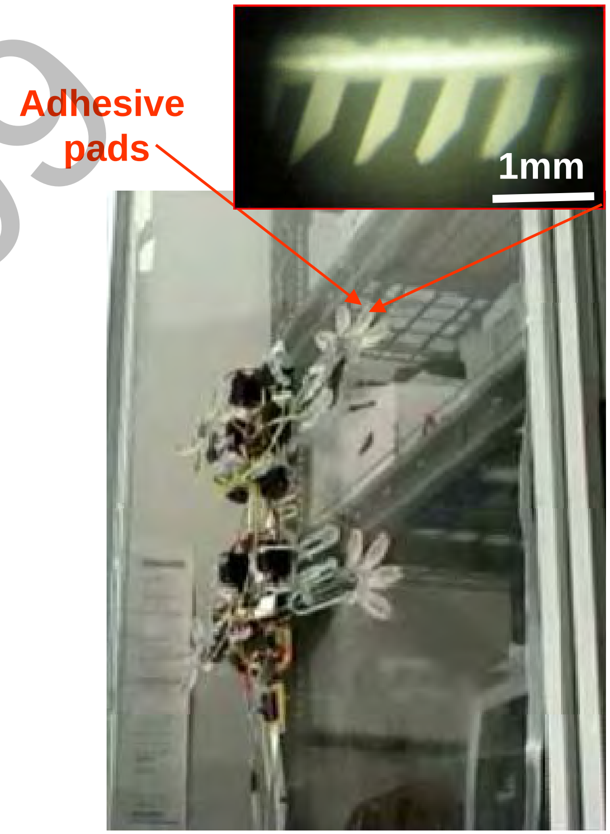
Gecko climbing on bamboo surfaces

Dew drops adhering to a spider web

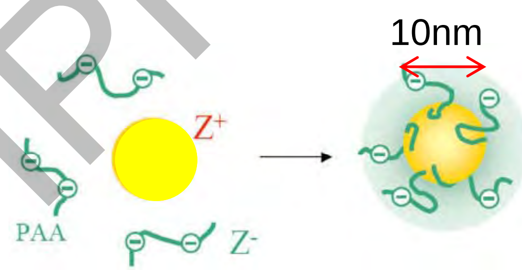
Adhesion is also Essential to Engineering and Future Innovations

Adhesive tapes & labels

Paper – fiber network



Polymer adhesive shield



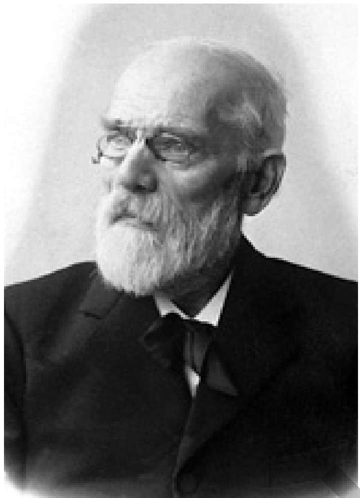
Mico/nano particles

***StickyBot*, Stanford Univ, 2006**

Polymers are Good Adhesives

Molecular Adhesion is Universal

Intermolecular attractive Interaction
(Van der Waals forces)

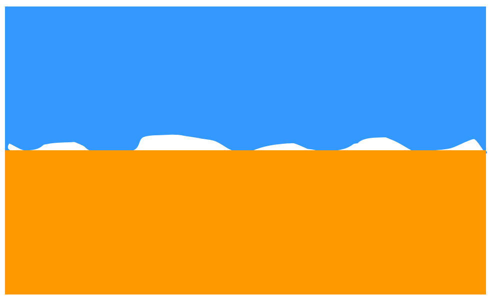


Johannes Diderik van der Waals
The Nobel Prize in Physics 1910

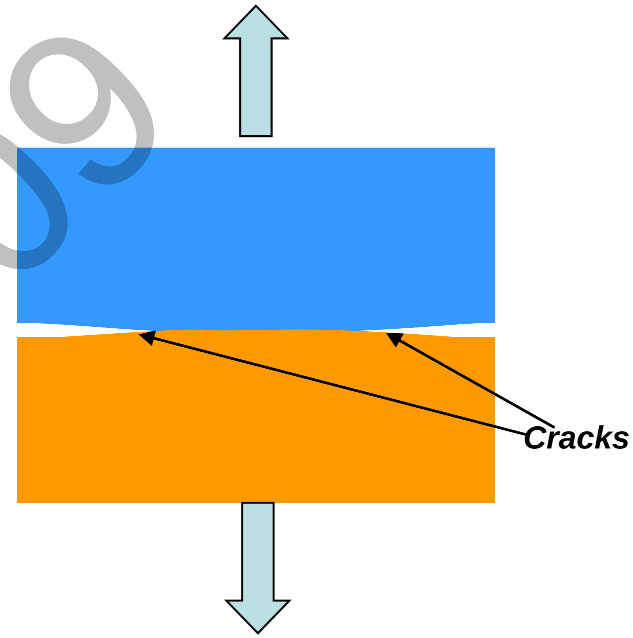
Two smooth surfaces leap into contact at nanometer (10^{-9}m**) distance**

Human hair ~ 100 micrometer in diameter

Practical Adhesion is Complex



Surface roughness reduces adhesion

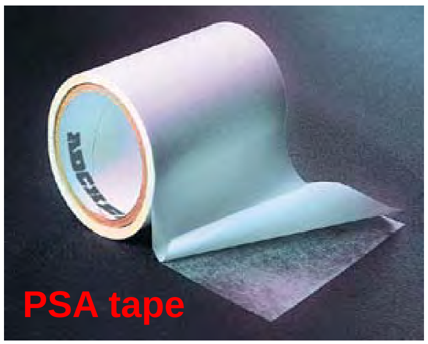


Surface deformation in detachment

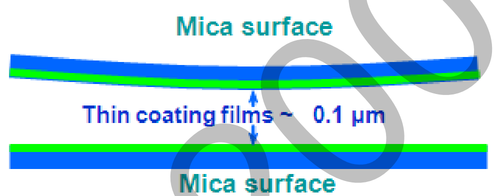
The adhesion and detachment mechanisms matter

Outline

Recent research



The adhesives/paper interactions



Viscoelastic thin coating films

Gecko adhesive system

Future Research

Biomimetic or Bio-inspired Adhesion and Smart Adhesives

Overall Objectives

- ❖ To identify and characterize the behaviors of “soft” (synthetic and biological) adhesive surfaces and associated micromechanical properties
- ❖ To develop new concepts, approaches and techniques to tune adhesion and make smart adhesives .

Today: to highlight key research findings

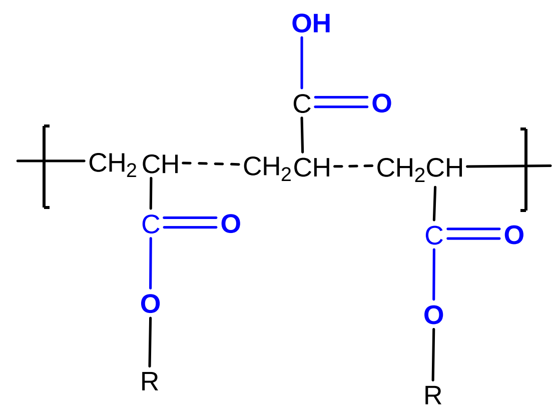
Pressure-sensitive Adhesives/Paper Interactions

What are Pressure-sensitive Adhesives ?

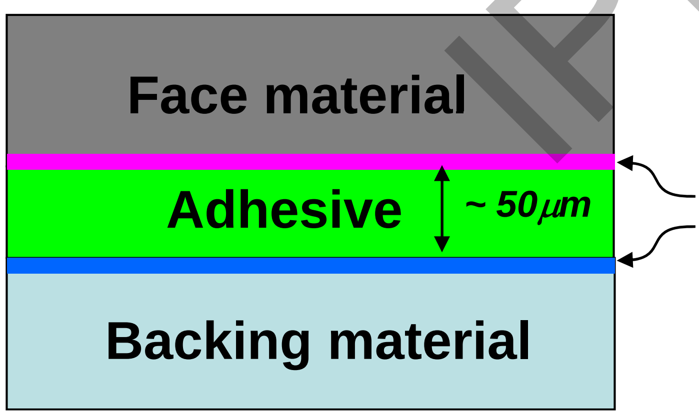
PSAs are materials which adhere under a light pressure.

PSAs are polymeric and have a property called viscoelastic.

They behave like liquid in bonding while fracture like solid in debonding.



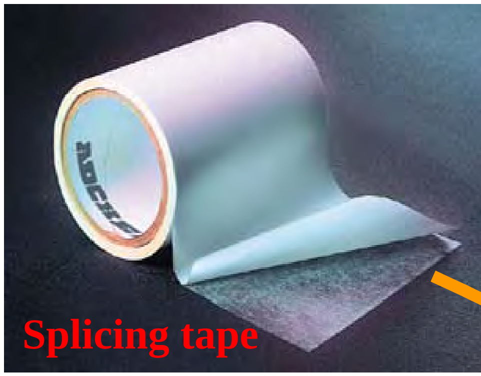
Acrylic PSA

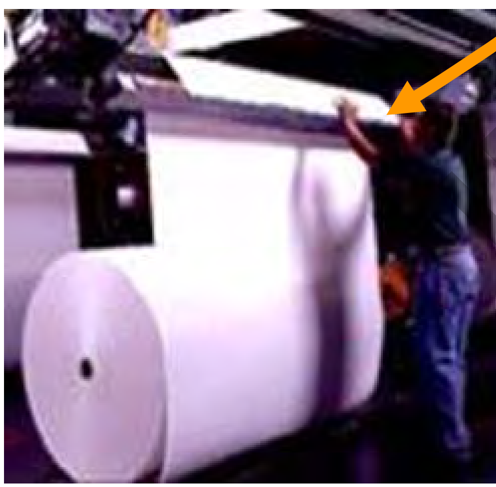


Coating layers

(Release / bonding Agent)

PSAs Used in Papermaking





Performance requirements:

(1) Instant adhesion
(2) Strong joint strength for
survival in further processing
at ~ 60km/hr
(3) Repulpable in recycling

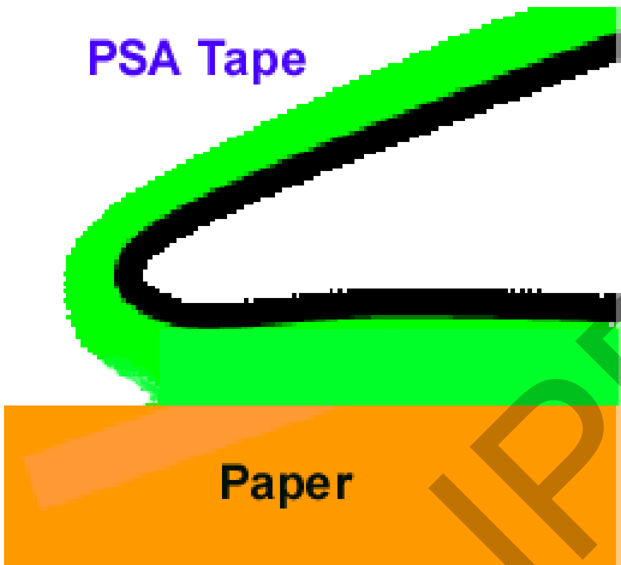
Occasional Failure costs millions $$$

Research questions:

What are the fracture mechanisms?
How to make stronger adhesive bonds?

Flying-splice in papermaking mills

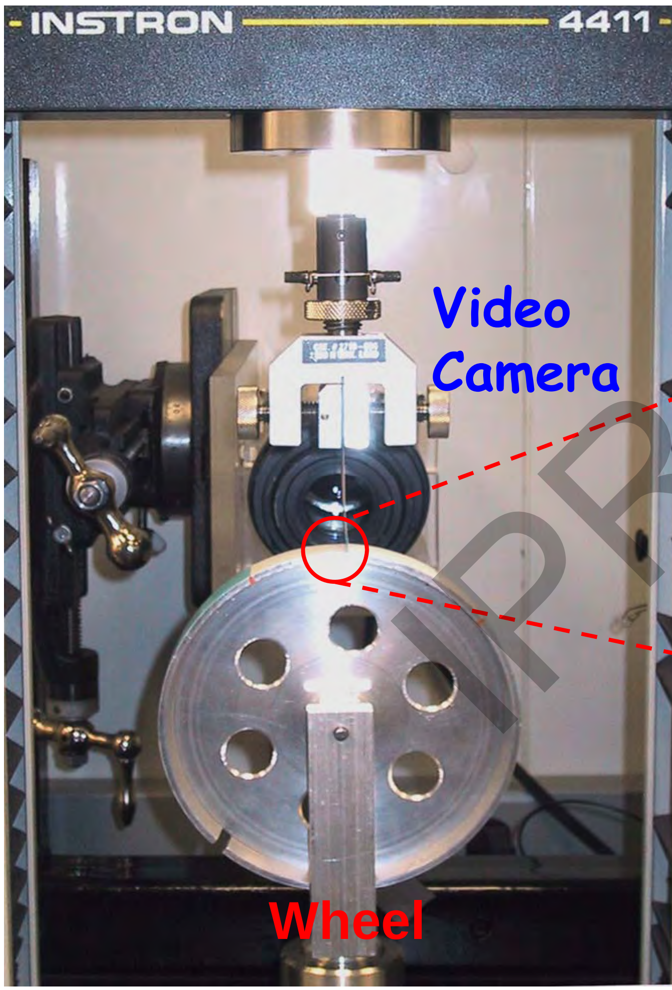
Peeling Adhesion Analysis



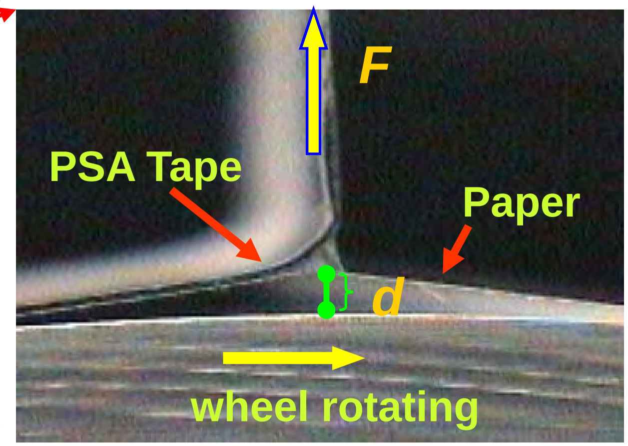
- Easy to perform
- Providing information on both paper and adhesive tape

- It involves complex mechanical effects
  - Peeling angle
  - Bending curvature

Wheel – Peeling Tester



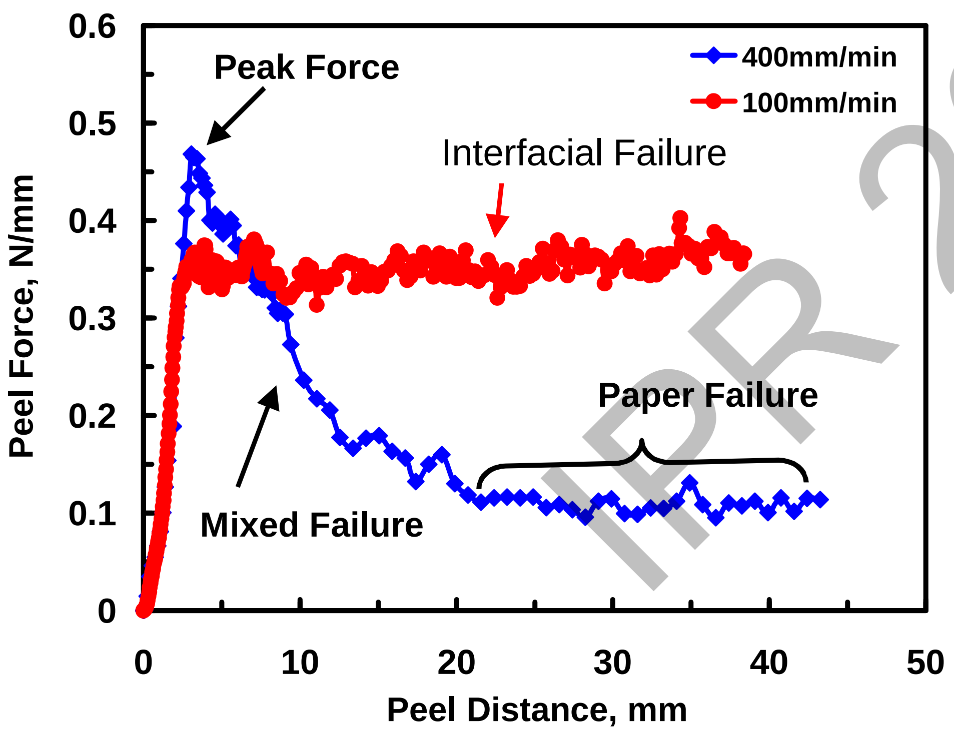
Constant peeling angle
θ = 90°



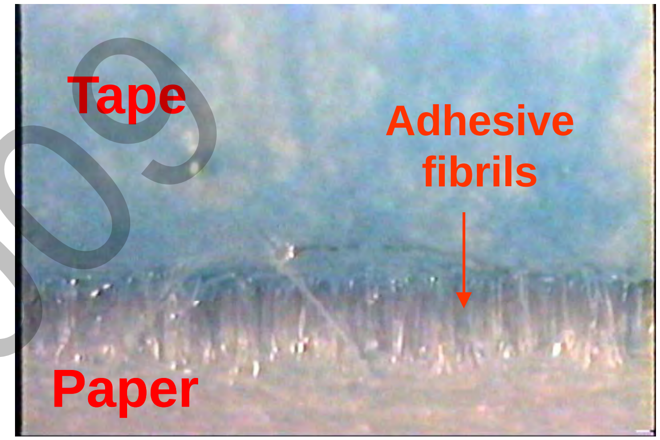
We fixed d = 0 in most of our measurements

Peel Forces and Interfacial Phenomena

Typical peeling curves



Interfacial failure

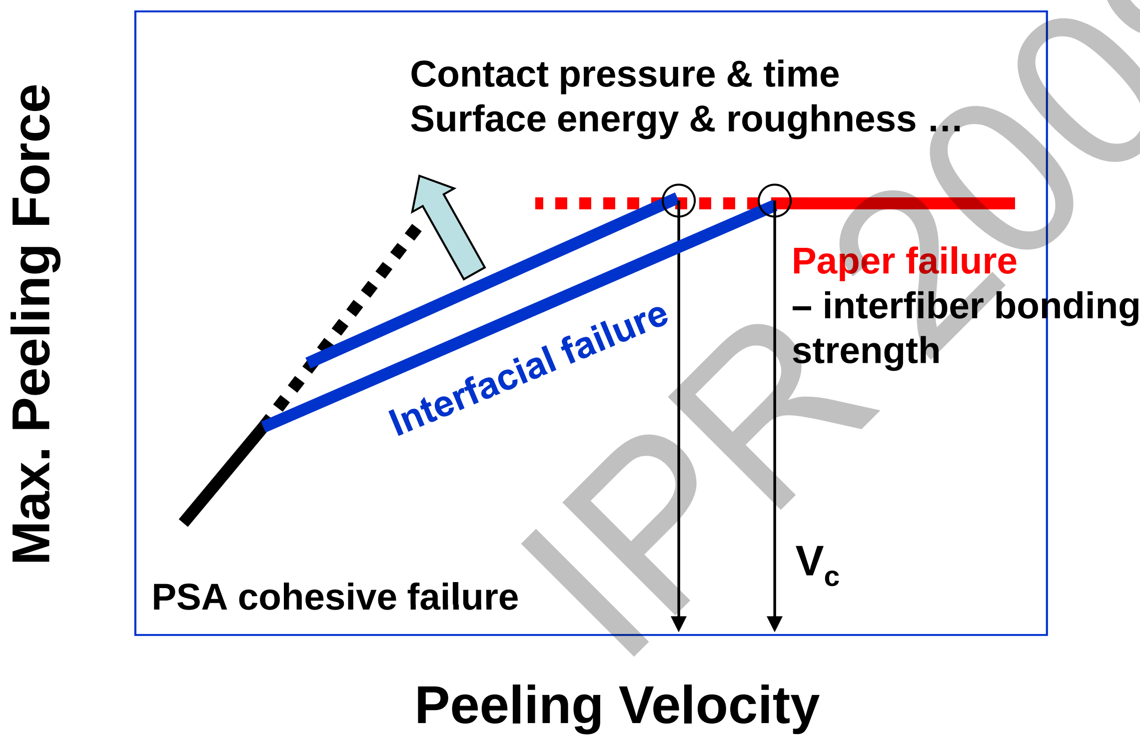


Paper failure

Fibers do not break in delamination.

Both Adhesion Forces and Failure Modes are Functions of Velocity

In logarithmic scales



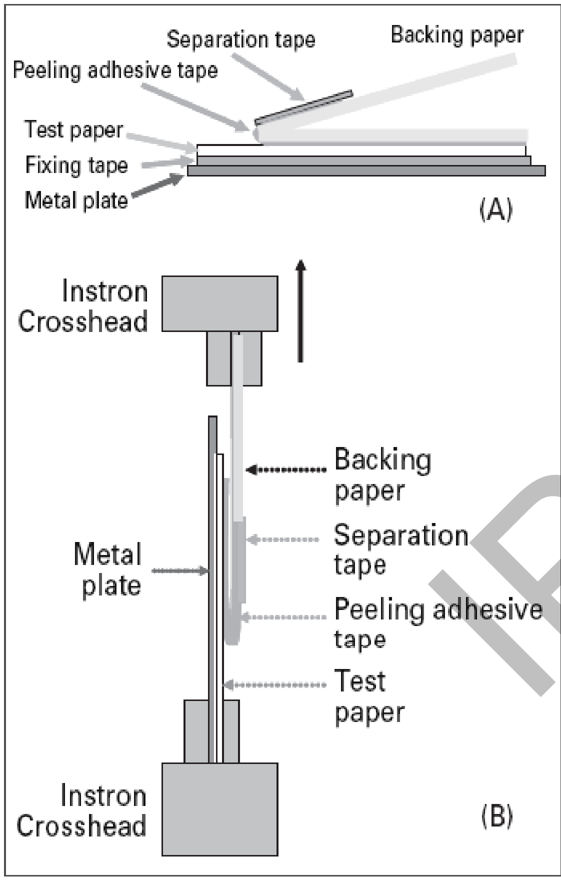
Identified a critical velocity, V_c for the transition of failure modes

Established the link between paper, tape properties, and adhesion performance.

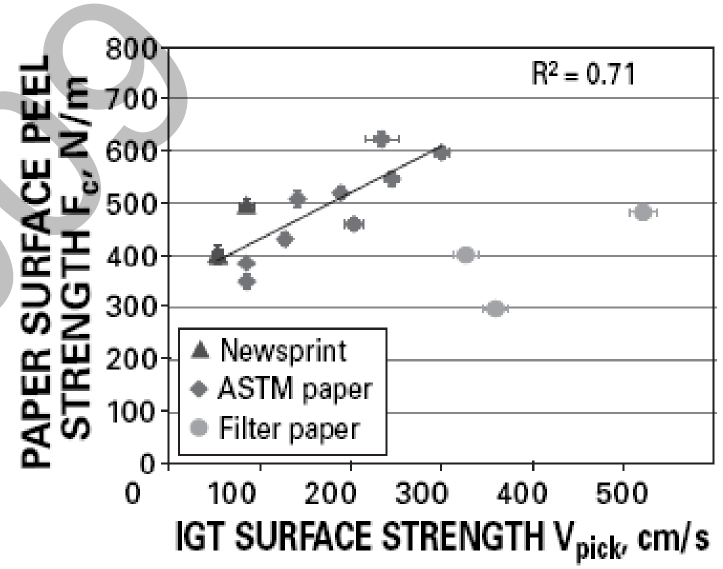
Surface energy is determined by surface chemistry

Zhao, Pelton, *Tappi*, 2004
Zhao, Anderson, Banks, Pelton, *J. Adhesion Sci. Technol*. 2003, 2004

Using Tape-peeling as a Measure of Paper Surface Strength



The peeling method

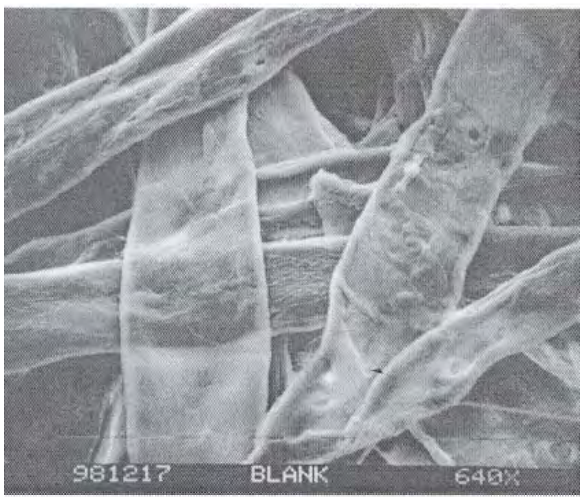


Industrial standard method

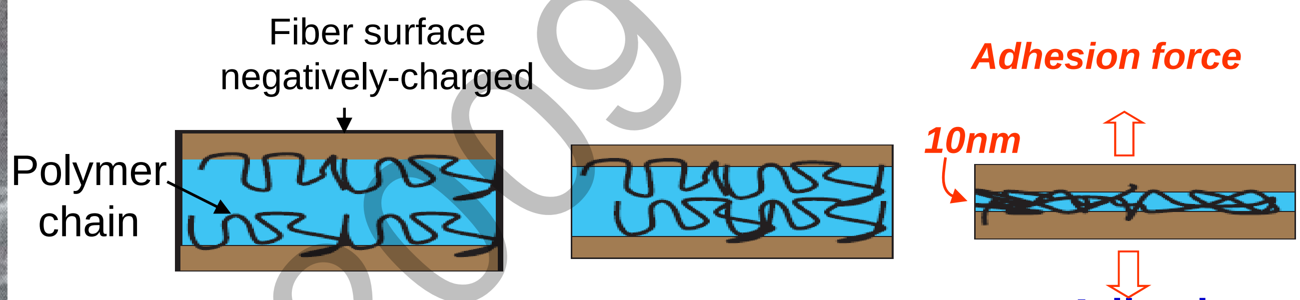
This method cost less than industrial methods; it is adopted by the Australian Pulp and Paper Institute.

Zhao and Pelton, Tappi, 2004

Adding Polyelectrolytes (PE) to Tune Interfiber Adhesion Strength



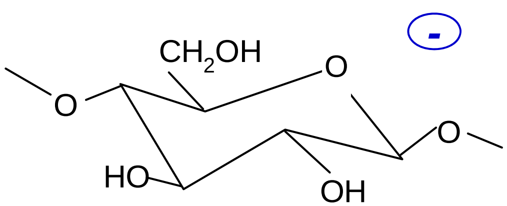
Interfiber-bonds



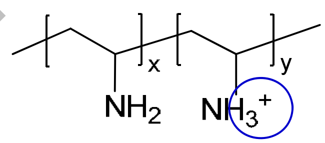
Adsorption

Water removal

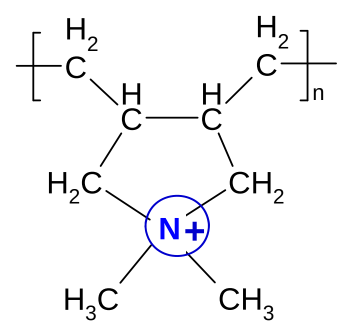
Adhesion



Hydrophilic cellulose
negative charged



Hydrophilic PE
to enhance adhesion



Hydrophobic PE
to reduce adhesion

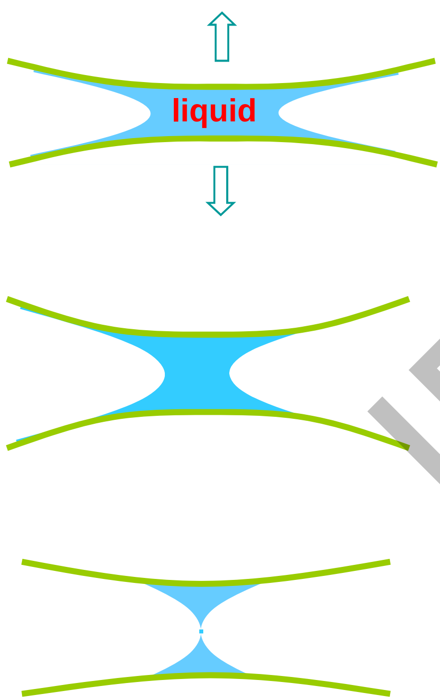
Summary

- Adhesives are highly deformed and form fibrils.
- The adhesion forces increase and failure modes change as peeling velocity increases.
- The max adhesive/paper joint strength is determined by paper surface strength. This finding resulted in a simple approach to measure paper surface strength.
- Interfiber adhesion strength can be tuned by adding polyelectrolytes.

Dynamic Adhesion and Fracture of Thin Coating Films: Solid- and Liquid-like Failure

Failure Mechanisms - Two Extreme Scenarios

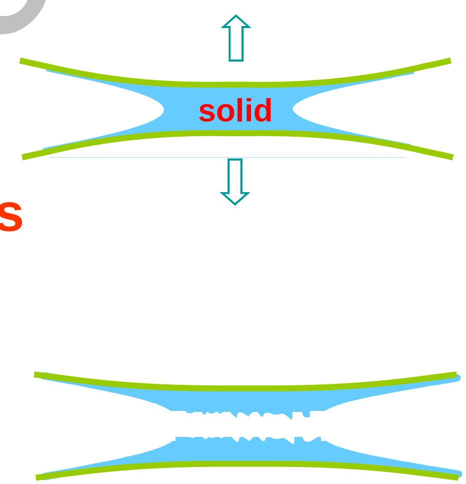
Snapping of a liquid bridge



e.g. water, viscosity of 10^{-3} Pa. S

Behaviors of "soft" materials is far less understood

Brittle fracture of solid

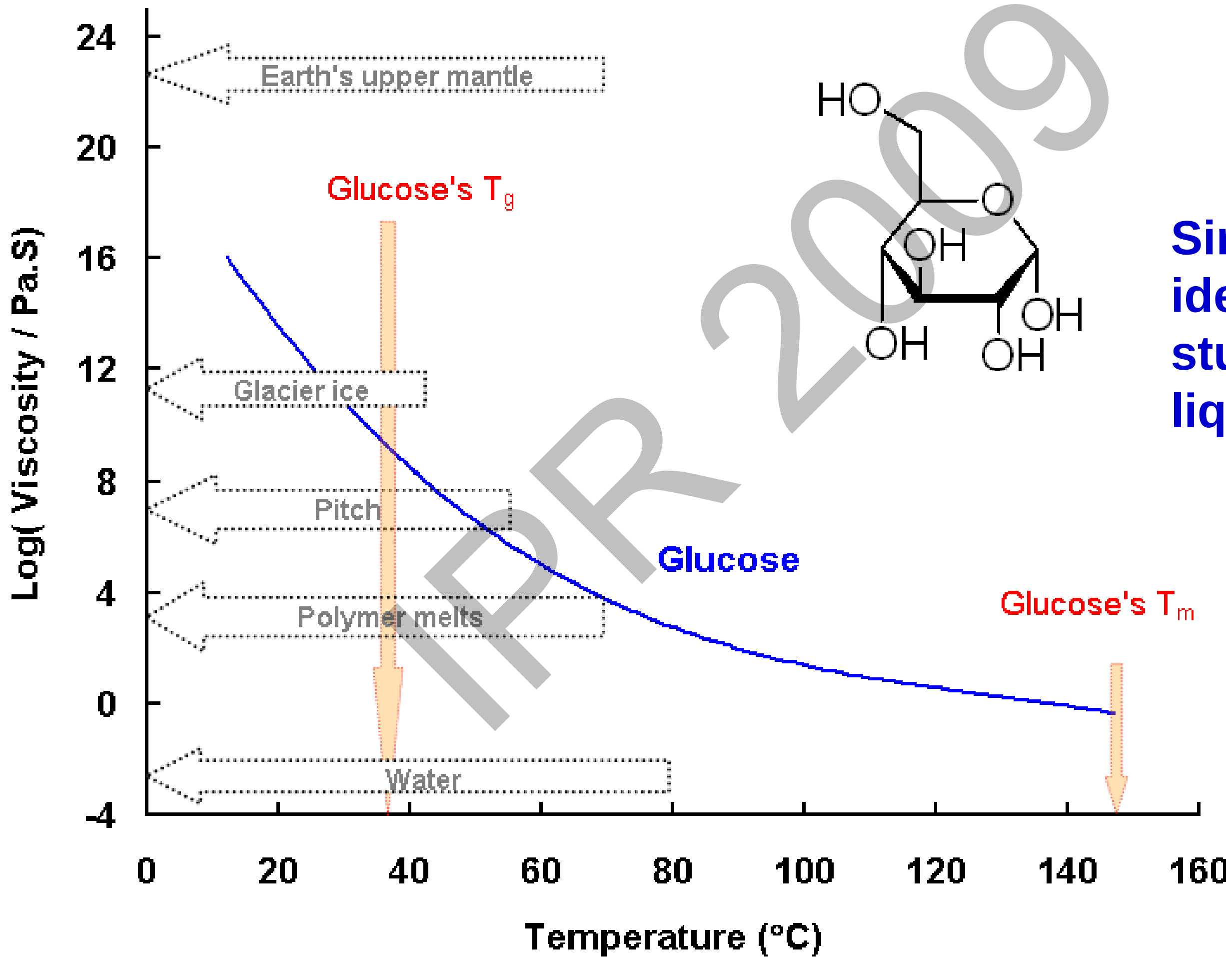


e.g. ice, viscosity of 10^{11}Pa.S

Research Objectives

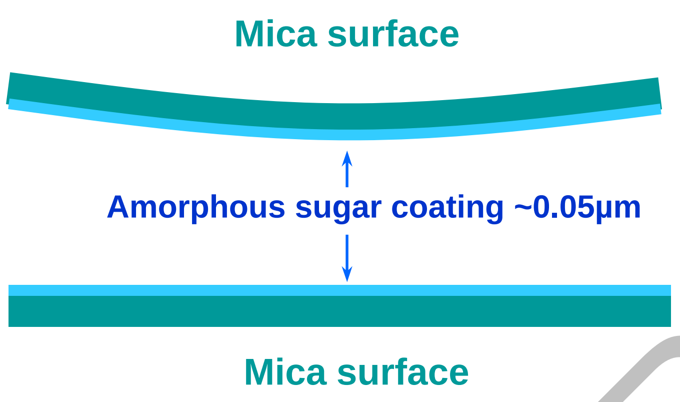
- To identify and characterize:
  - the differences between liquid- and solid-like failure mechanisms of micro/nano thin films
  - Molecular interaction, surface deformation and instabilities in adhesion and subsequent separation

Sugar Viscosity as a Function of Temperature



Simples sugars are ideal materials to study the solid- and liquid-like behaviors

Sugar Films Coated onto Mica Surfaces



Three typical experimental temperatures in N_2 atmospheres

- Glassy state at 23°C
- Viscoelastic state at 40°C
- Viscous fluid state at 75°C

AFM imaging of sugar surface

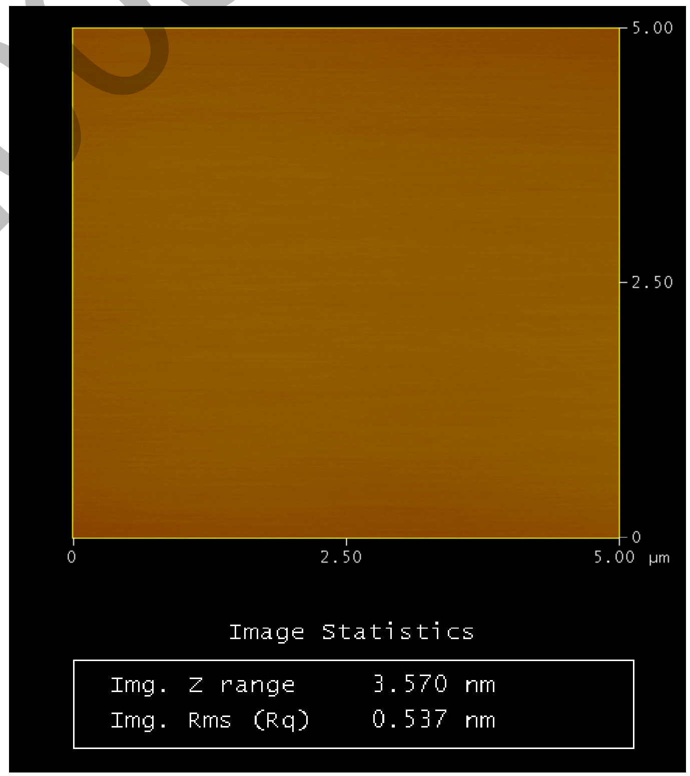
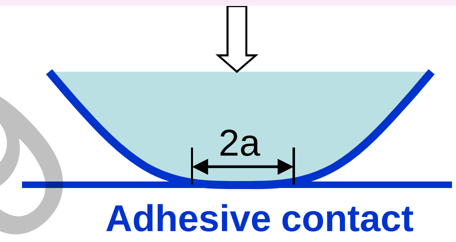


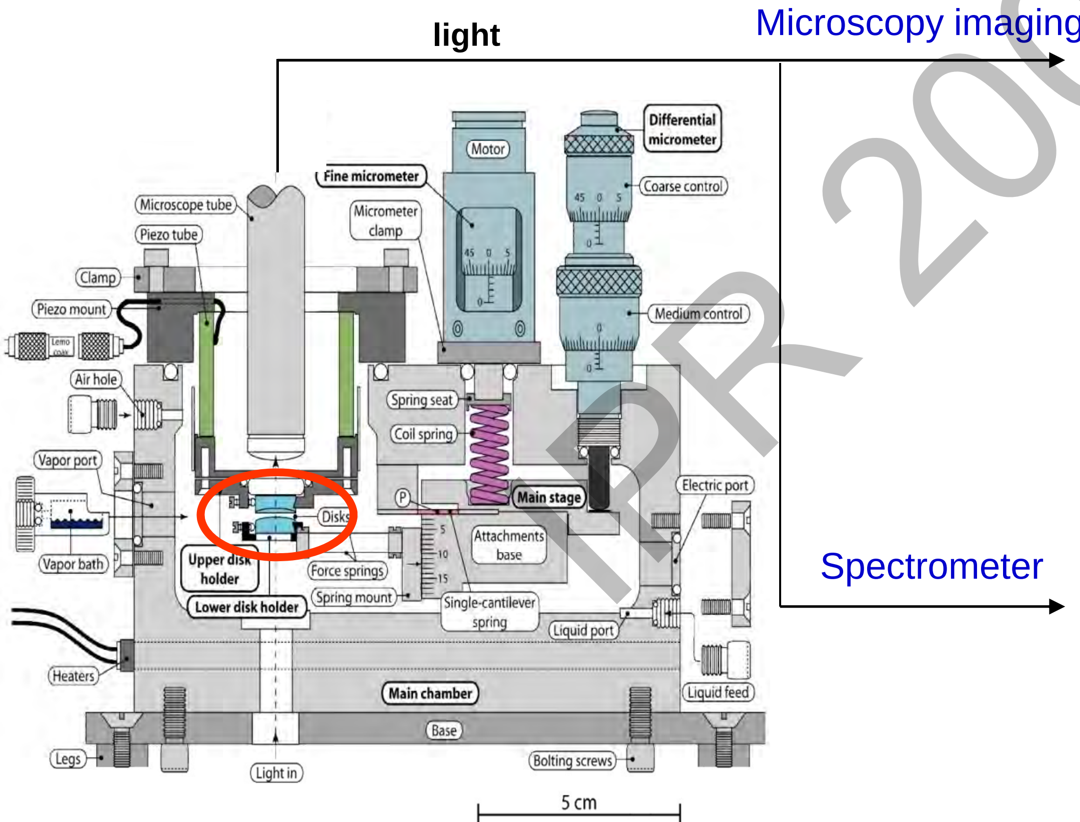
Image RMS = 0.537nm

Using SFA and FECO to Study Adhesion Failure Mechanisms

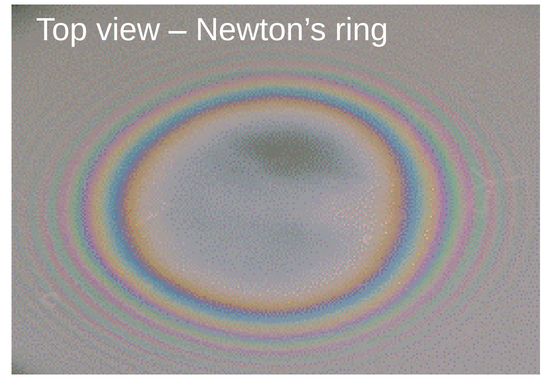
SFA: Surface Forces Apparatus

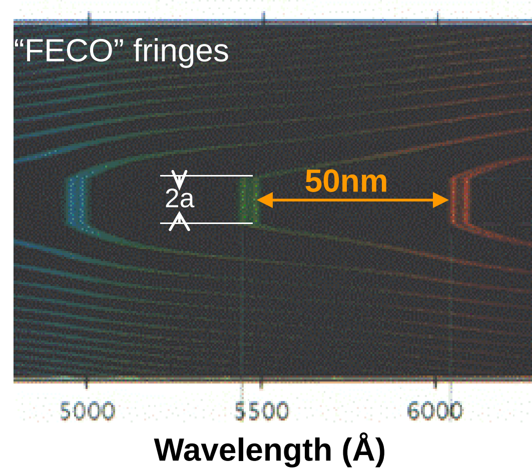
FECO: "Fringes of Equal Chromatic Order" - thin film interference patterns





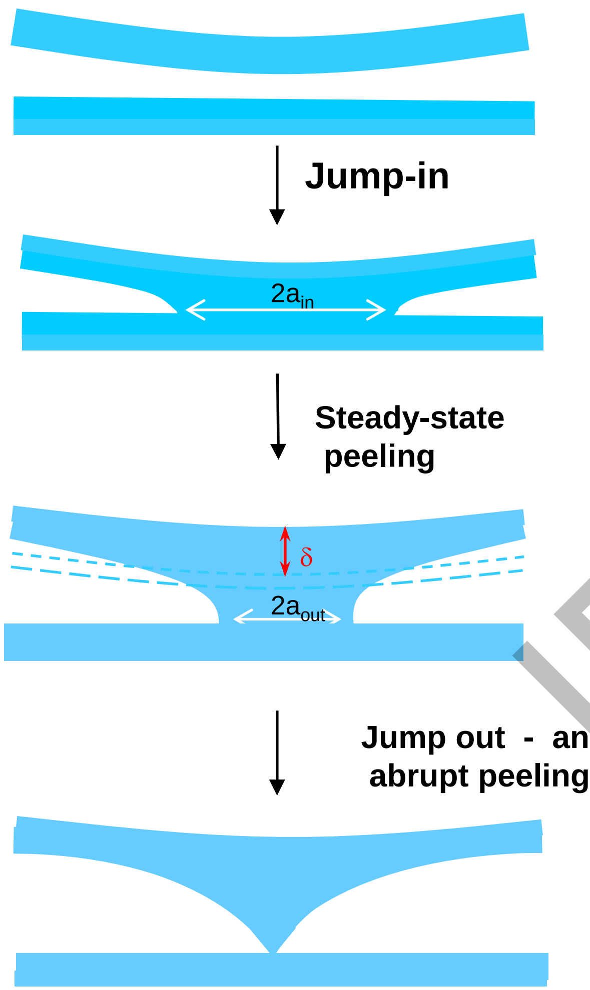
SFA 2000



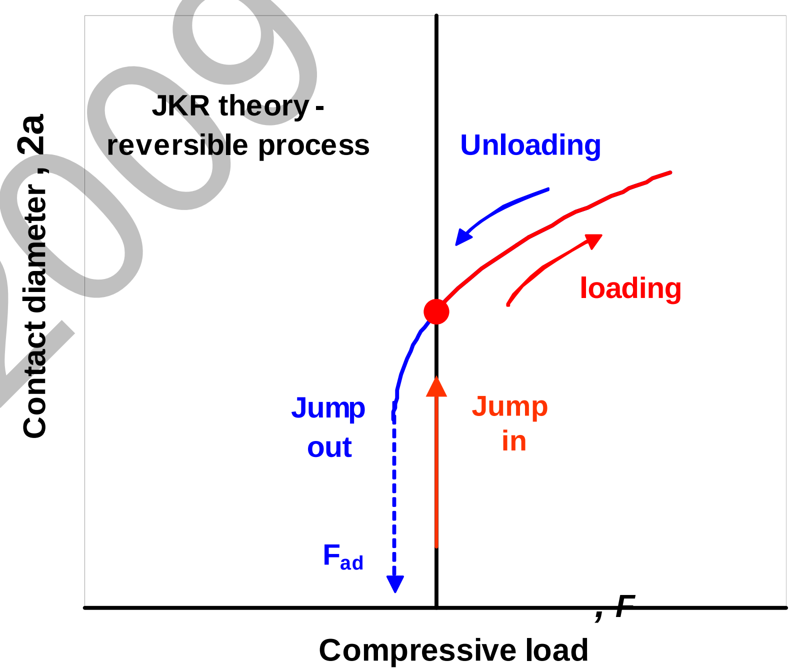


Tabor, Winterton, Israelachvili,1970

Using the JKR-theory as An Analytical Tool



JKR - plot



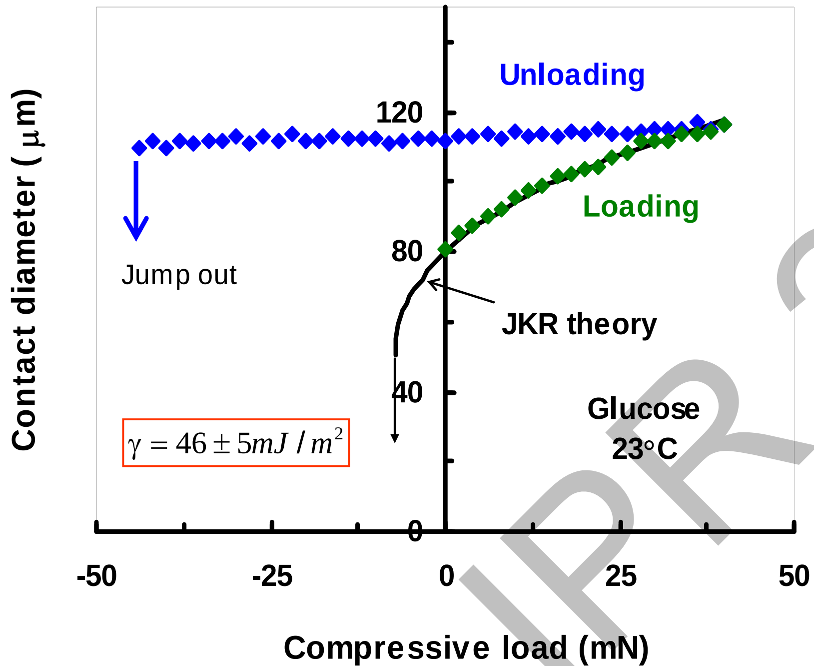
Classic adhesion theory (equilibrium and elastic system)

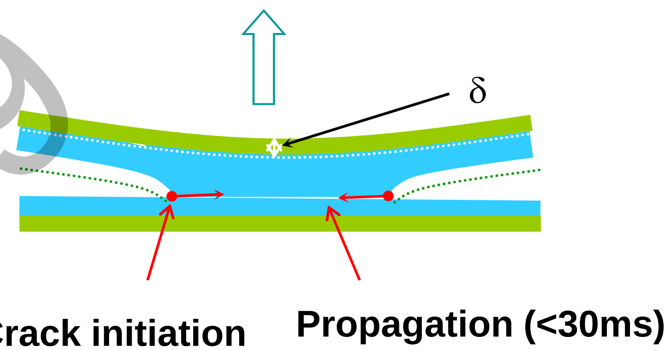
$$F_{ad} = 3\pi R\gamma$$

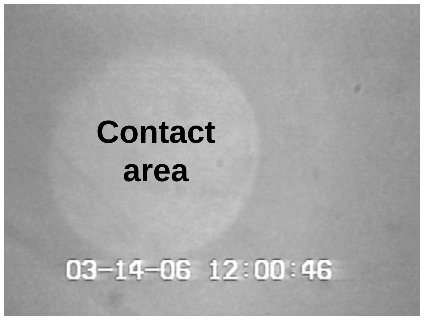
Surface energy

Johnson, Kendall, Roberts (1971) *Proc R Soc London Ser A* 324:301–313.

Contact Behavior of Sugar Surfaces at 23°C, Viscosity of 10^{14} Pa.S



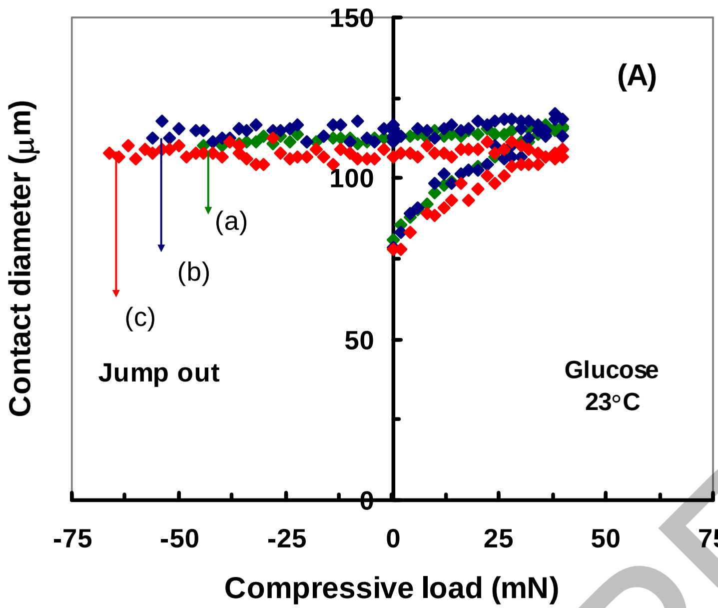


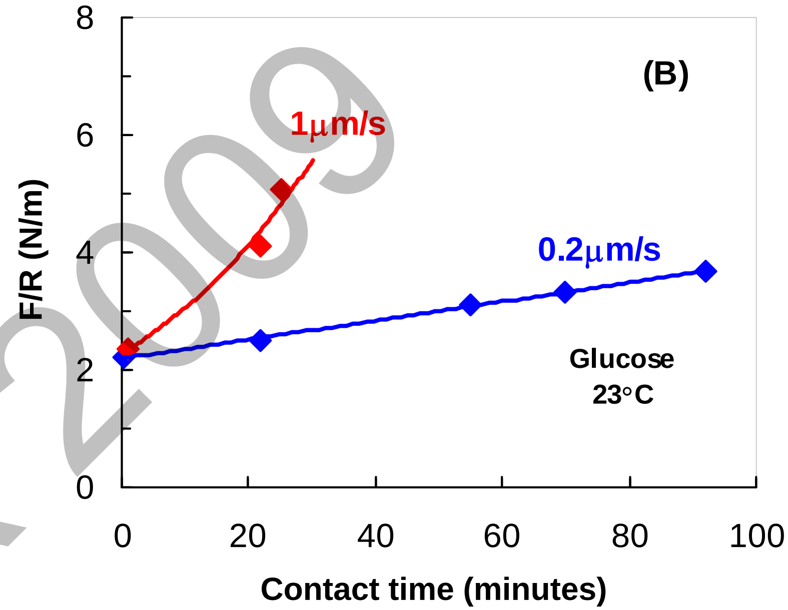


Adhesion Hysteresis - time effects

Brittle fracture/cracking

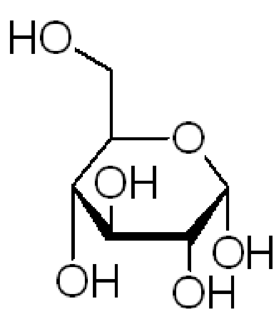
Time Effects

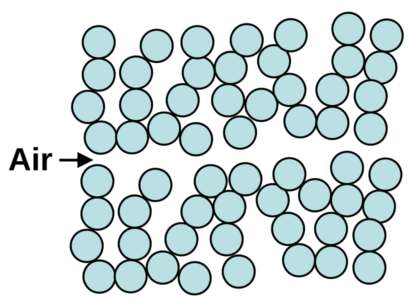




Contact time: a < b < c

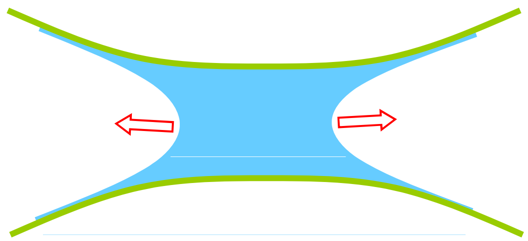
Separation velocity

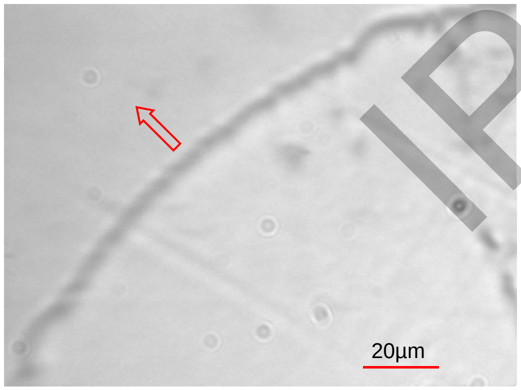




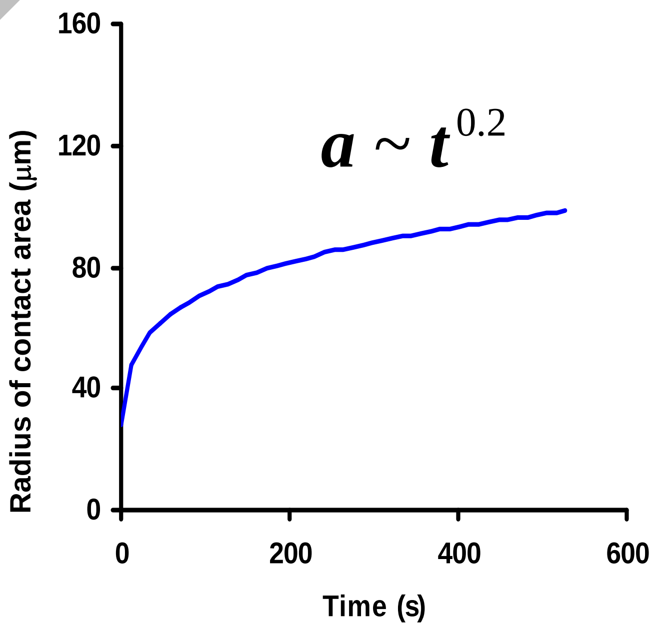
Glucose molecules rearrangements at the interface - a dynamic process

Adhesion and Coalescence of Viscous Fluid Surfaces at 75° C(10^3Pa.S)





- Coalescence occurs right after adhesive contact
- Contact area scales with time

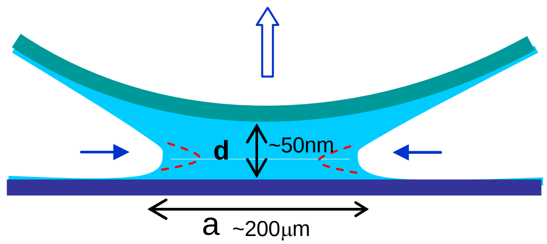


Transient surface patterns during fluid-fluid coalescence

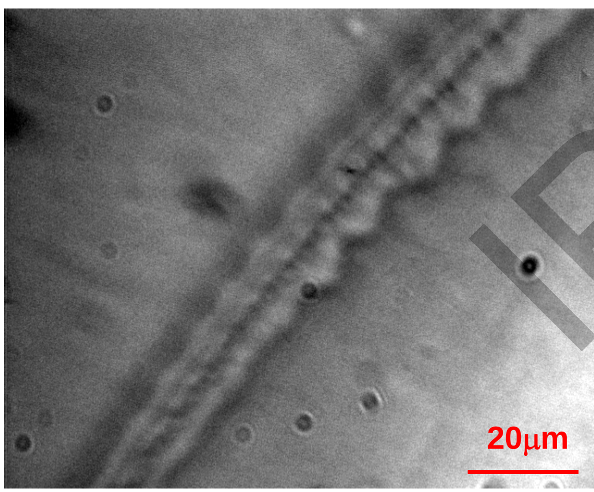
Zeng, **Zhao**, Tian, Tirrell, Leal and Israelachvili, 2006

Detachment of Viscous Sugar Surfaces

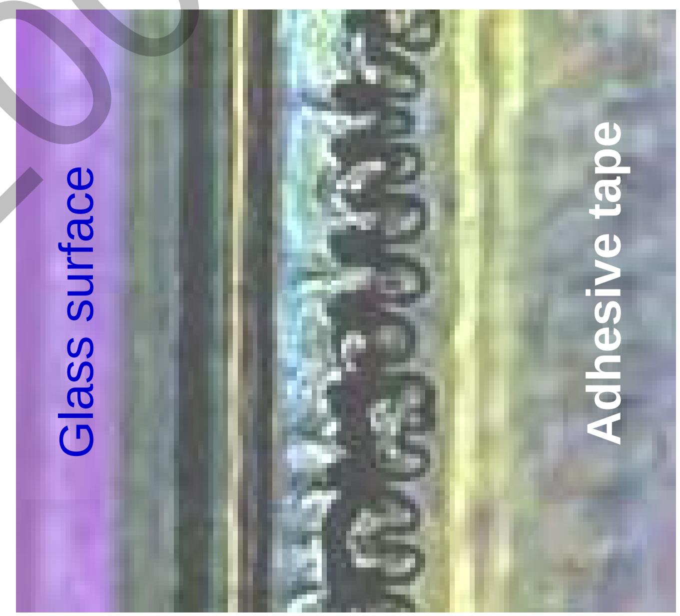
Viscous fingerings due to the Saffman-Taylor instability



$$\frac{a}{d} = 4000$$



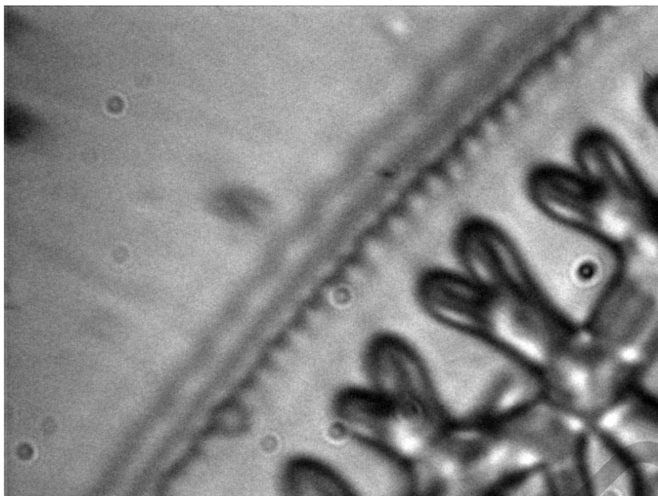
Instability during the peeling of adhesive tape

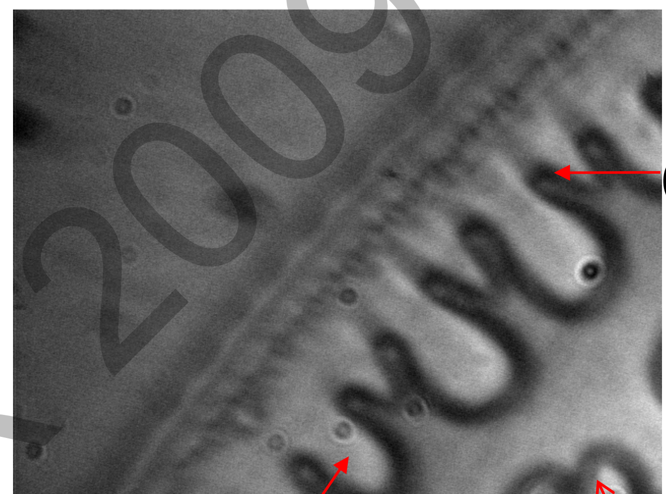


F. Frankel, G. M. Whitesides, On the Surface of Things, 1997

Viscous fingerings consume a large amount of energy, giving a strong adhesive bond.

Evolution of Interface Ripples/waves in Detachment





- video demo – a slow-down process

This may be due to the lateral acceleration of fluid during its normal separation.

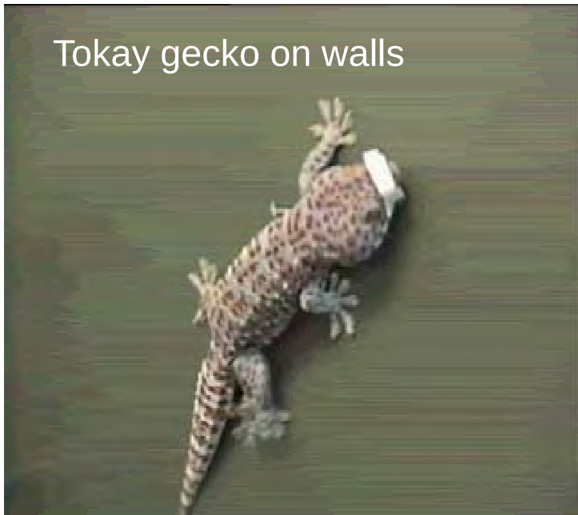
Co-existence of sharp tips and round fingers were observed for the first time, suggesting a unifying theory.

Summary

- The fracture of two adhered surface was manifested by crack nucleation and propagation at one extreme and the snapping of a liquid bridge at the other
- The fracture of two adhered viscoelastic surfaces was manifested by rounded fingers
- Practical Implications
  – Cavitations and fingerings consume a large amount of energy, resulting in a strong adhesive bond.
  – Adhesion can tuned by adjusting material viscosity.

Understanding Gecko Adhesive System –
learn from nature

Gecko – a Super Climber


Tokay gecko on walls


House gecko on ceilings
John Bokma @2007


Marbled Gecko
Photo Courtesy Ben Moulton

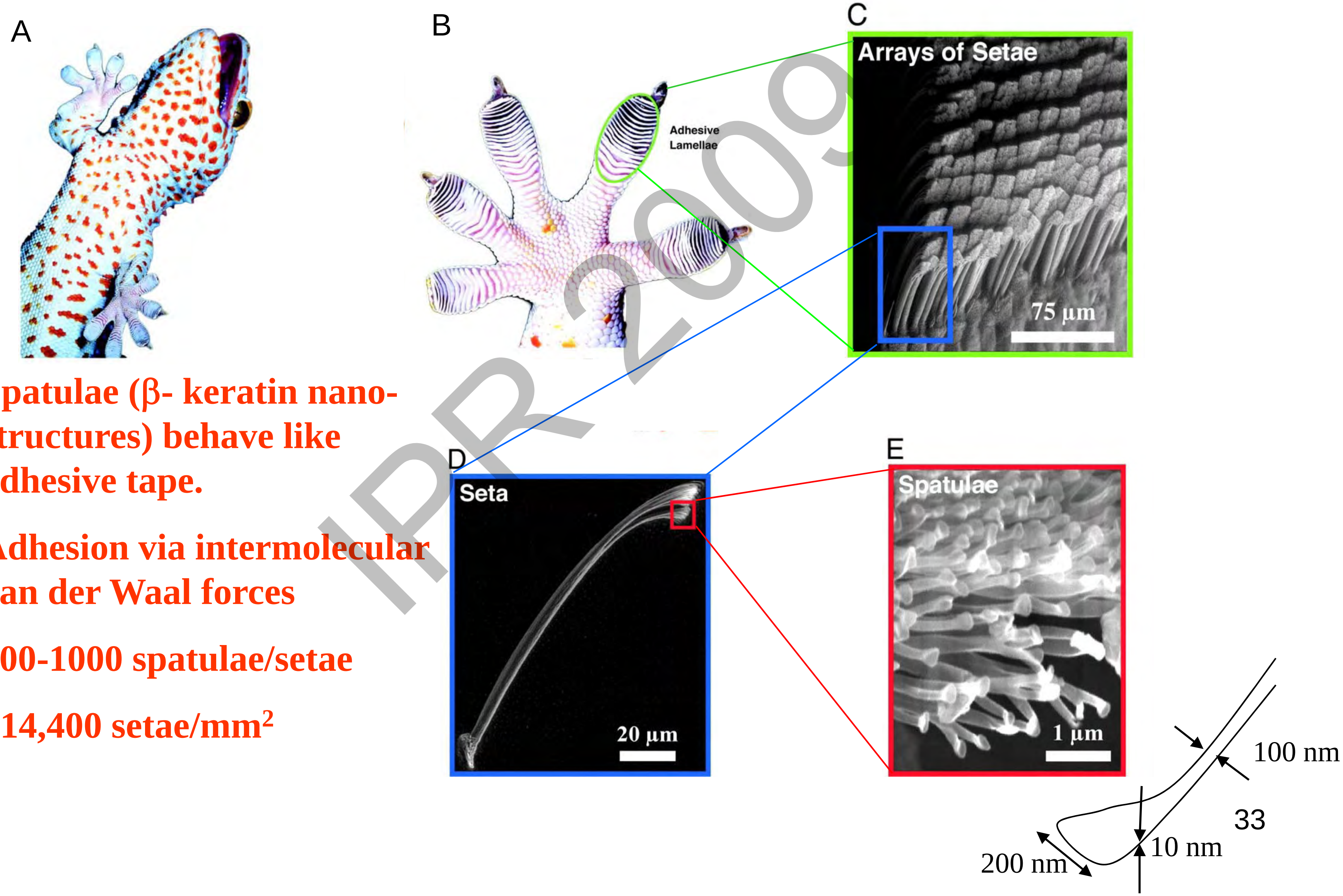

St Croix, US Virgin Islands

There are about 850 gecko species.

We focus on Tokay gecko, the largest species


Hawaiian Gecko
Quincy Dein Photography

What is Known about Gecko Adhesion



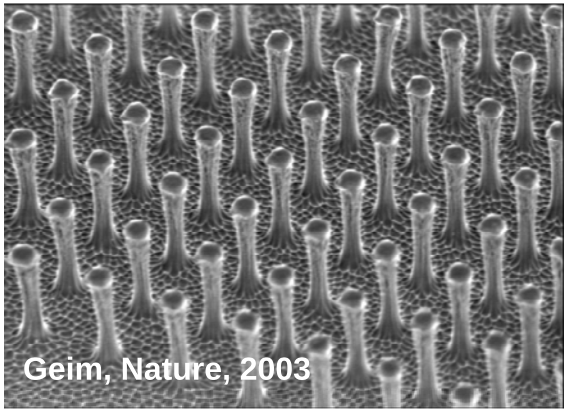
Spatulae (β- keratin nano-structures) behave like adhesive tape.

Adhesion via intermolecular van der Waal forces

100-1000 spatulae/setae

~14,400 setae/mm^2

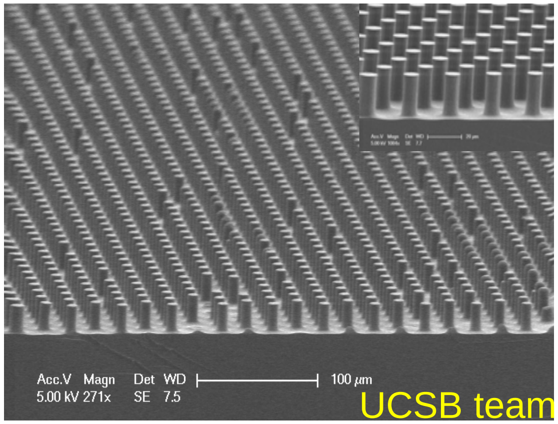
Recent Research and Challenges



Many research on the fibrillar surfaces (varied aspect-ratio, shape)

Physical characterization of gecko attachment and detachment.

Design of '**responsive**' surfaces for smart adhesives and robotic applications

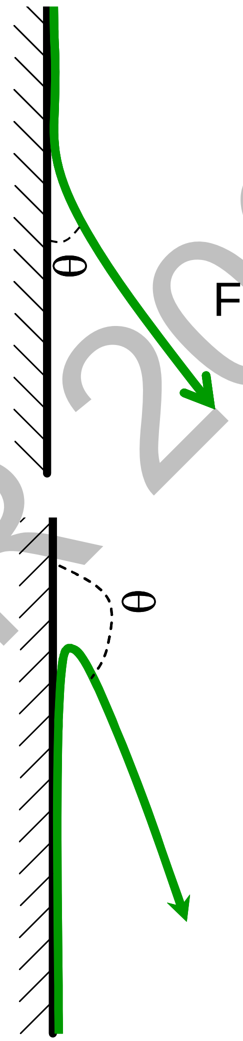


StickyBot, Stanford Univ, 2006

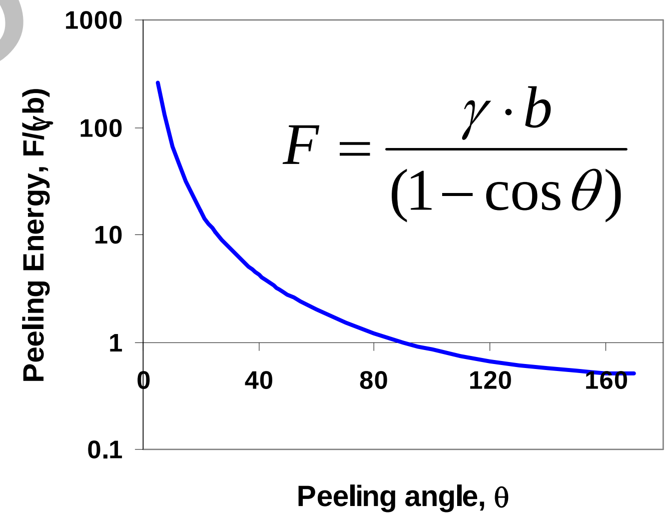
Gecko Attachment and Detachment - Peeling Mechanism

Walking gecko on walls

Detaching gecko foot



Gecko engages attachment at small pulling angles while detachment at large angles

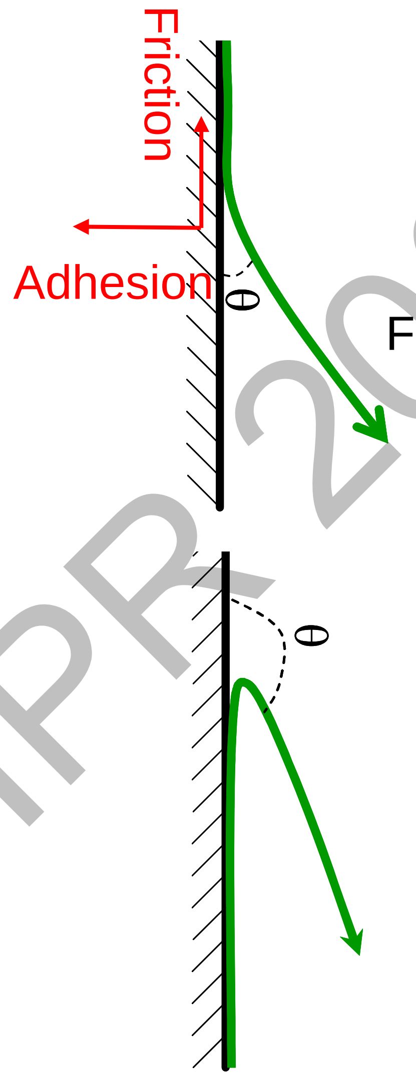


$$F = \frac{\gamma \cdot b}{(1 - \cos\theta)}$$

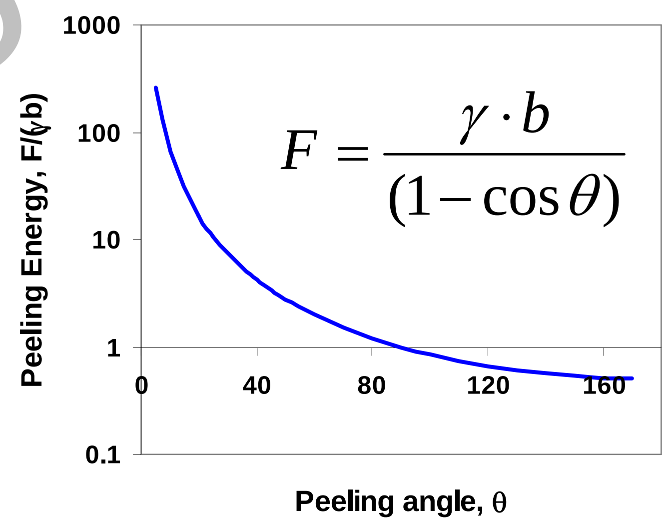
Gecko Attachment and Detachment - Peeling Mechanism

Walking gecko on walls

Detaching gecko foot

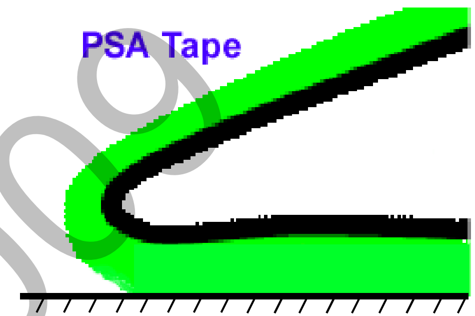


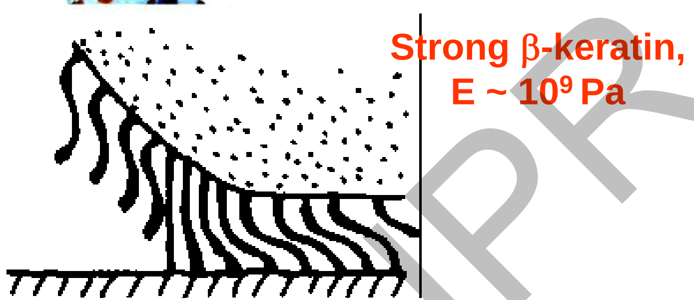
Gecko engages attachment at small pulling angles while detachment at large angles

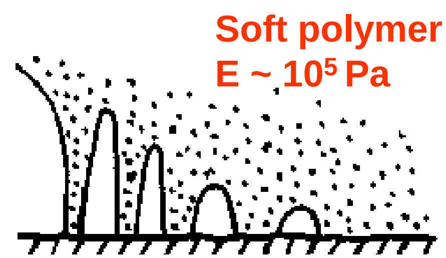


Surface features of the gecko setal arrays

Gecko Foot Pad vs Adhesive Tape





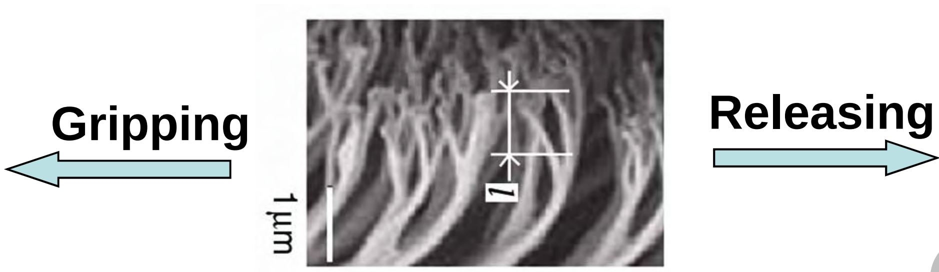


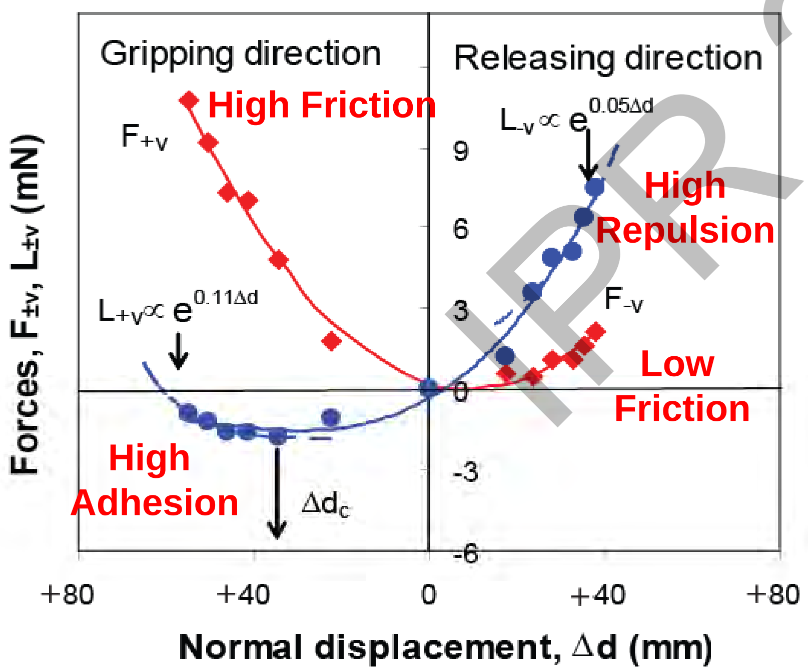
Build-in micro/nano fibrillar structures

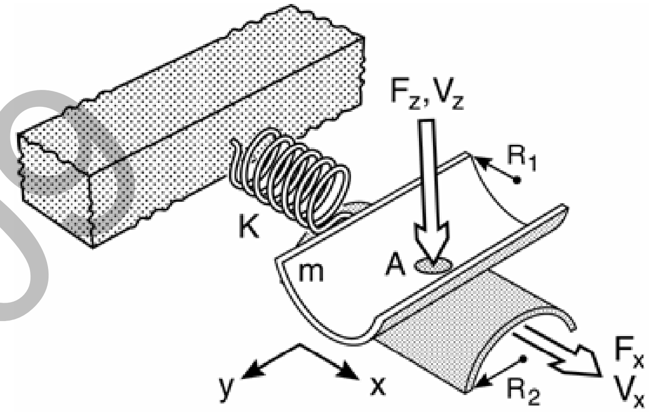
Stress-induced adhesive fibrills

Fibrillar structures consume a large amount energy in detachment, resulting in high adhesion strength

Contact Dynamics (Adhesion and Friction) Measurements

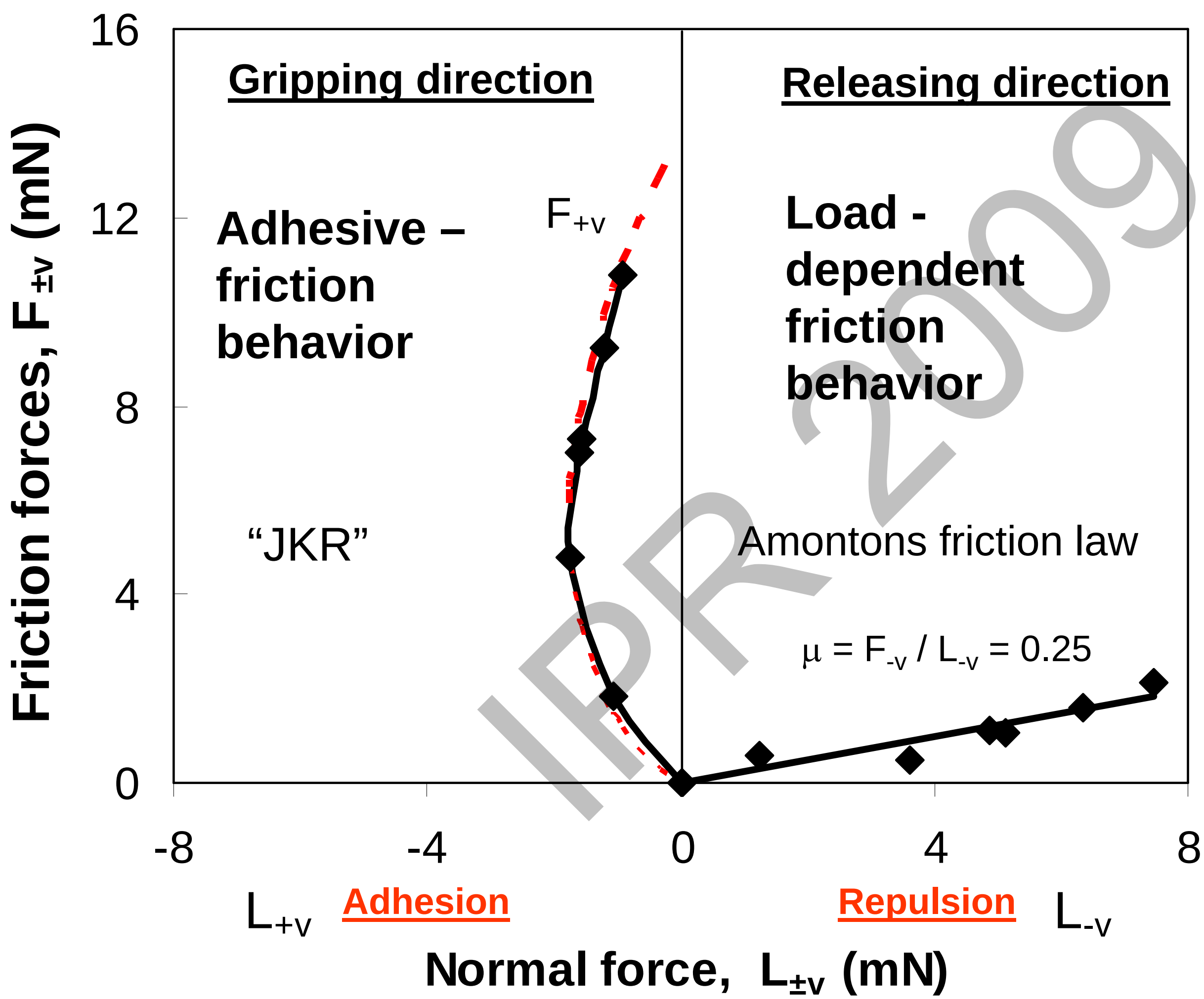






Surface Forces Apparatus

Gecko setal arrays are structurally anisotropic, exhibiting strong **directional adhesion and friction properties**.



To mimic gecko adhesive pads and functionalities, anisotropic curved structure is essential.

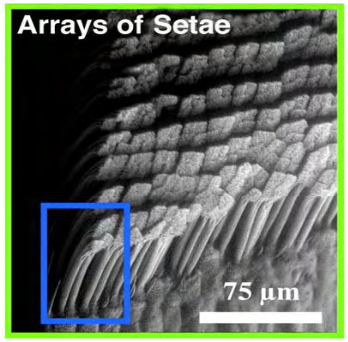
Zhao, Israelachvili, et al., *Langmuir*, 2007

Summary

Gecko foot pads behave like adhesive tape while its robust and responsive adhesion arises from the build-in micro/nano-sized fibrillar structures.

Many things are still unknown, e.g., the formation of gecko fibrils.

This suggests a new strategy to design and tune adhesion by surface patterning.



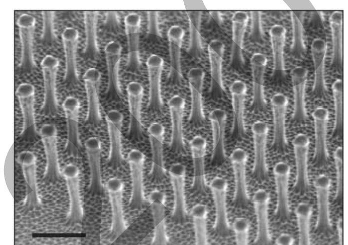
Current and Future Research

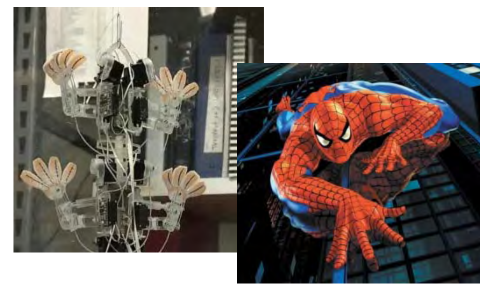
Biomimetic Adhesion and Smart (responsive, adaptable) Adhesive Devices

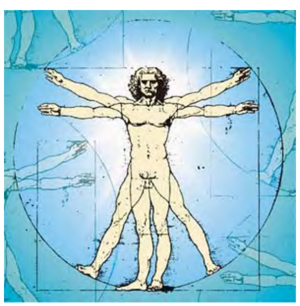
Biomimetic studies for responsive and adaptable materials

Nature ***Science*** ***Fabrication*** ***Application***

?







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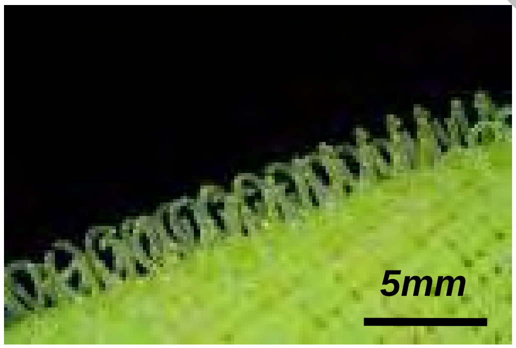
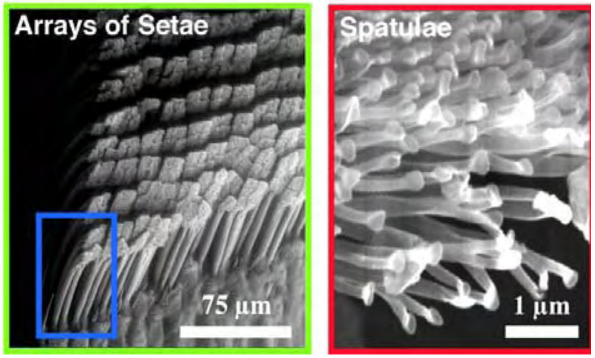
Responsive and adaptable to external , both chemical and mechanical, stresses

NON-Responsive surface

Climbing Velcro man
Video demo



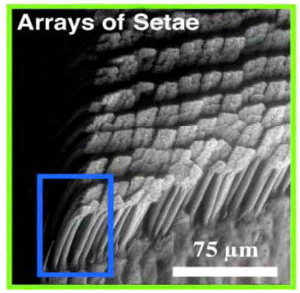


Overall Research Objectives

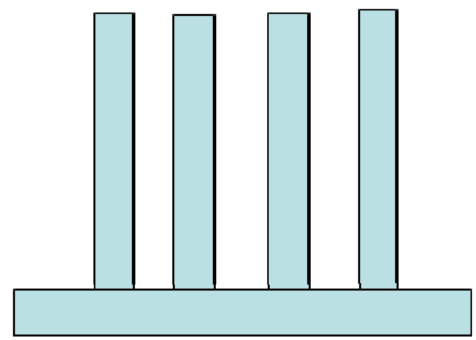
As future technological innovations gear towards miniaturizing machines and maximizing performance density, our challenges as engineers and scientists become our ability to build micro- and nano-machines and understand phenomena at a scale we normally do not deal with.

Focus on polymeric materials for both mechanical and biological applications.

Biological Fibrillar Adhesive Structures

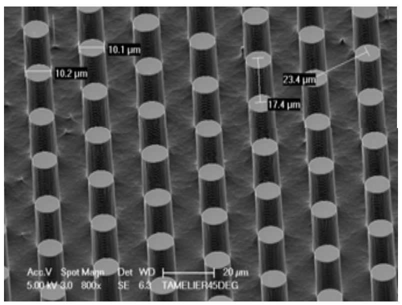


Fibrillar micro/nano structures is characteristic of biological attachment devices, which are natural Post-it Note

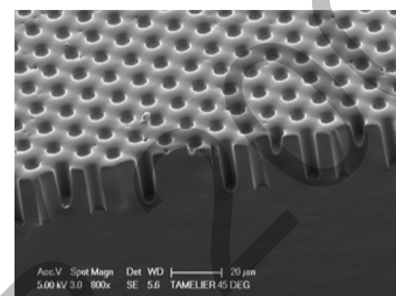


(Materials Today, 2004)

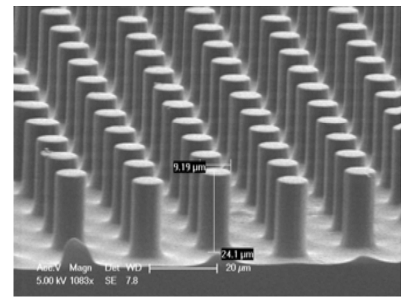
Fabrication of micro polymer pillars



(i) Microfabrication of silicon masters for molding



(ii) PDMS mold fabricated using silicon masters

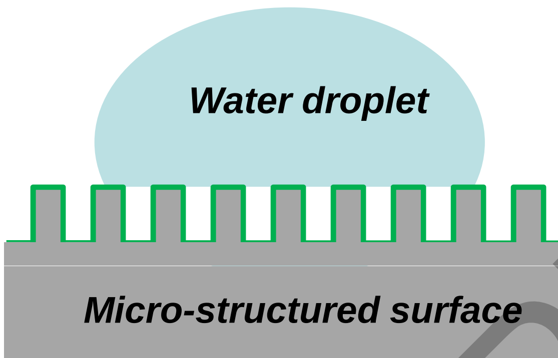


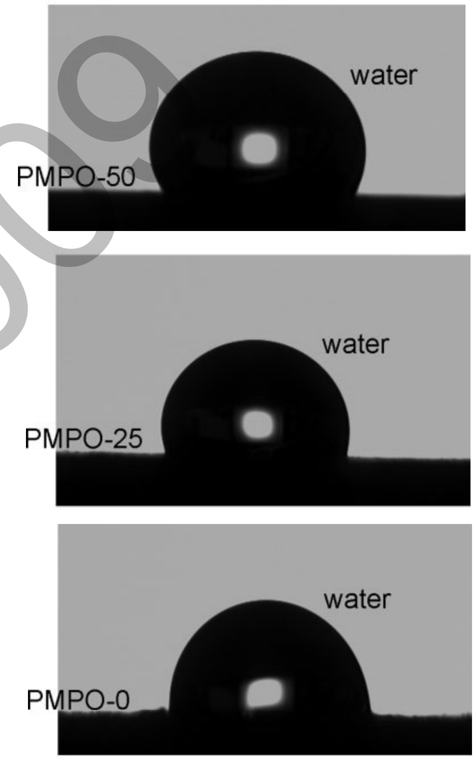
(iii) Polymer micro-pillar structures fabricated using PDMS mold

- Key design factors: Number density, Aspect ratio, Mechanical strength, Surface chemistry

In collaboration with Dr. Israelachvili and Dr. Turner group at UCSB

Fabrication of micro polymer pillars with “tailored” properties





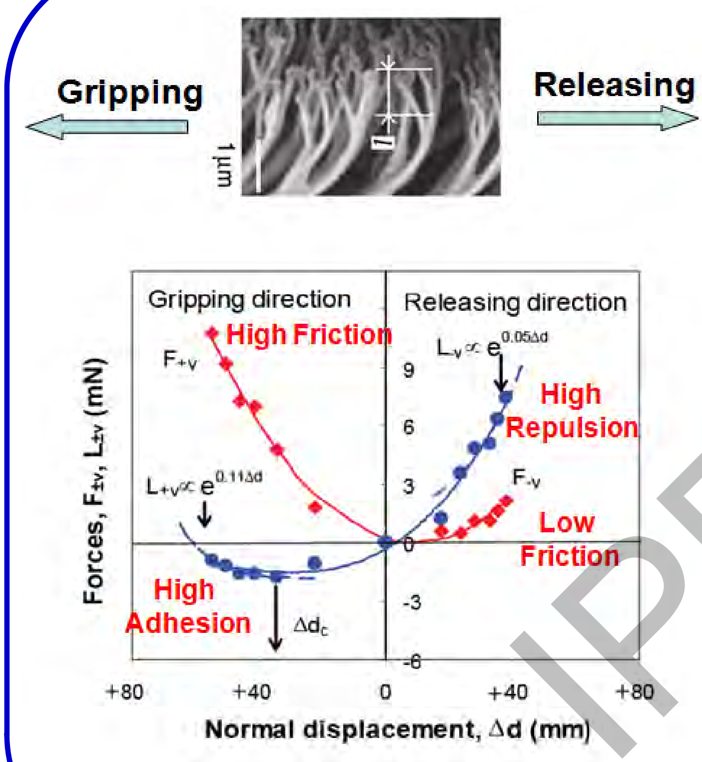
In collaboration with Dr. Alex Penlidis and Dr. Neil McManus

TABLE 3. The surface properties of PMPO at different PDMS contents.

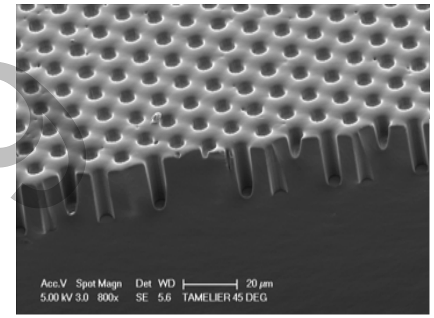
Sample	PMPO-0	PMPO-25	PMPO-50
Contact angle (°) (water)	79 ± 2.1	93.4 ± 1.3	99.6 ± 2.3
Surface free energy (mJ/m^2)	71.7 ± 2.3	68.1 ± 1.6	54.0 ± 2.1

S.-H. Zhu, N.T. McManus, C. Tzoganakis, A. Penlidis, 2007

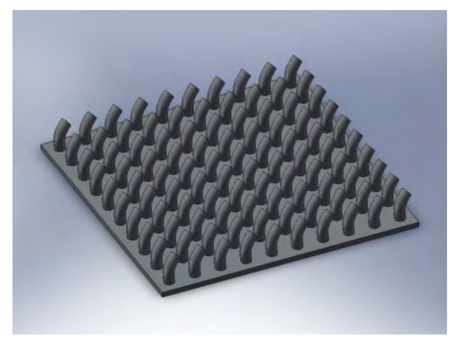
Fabricating Curved Structures



Gecko directional adhesion



Tilted PDMS mold

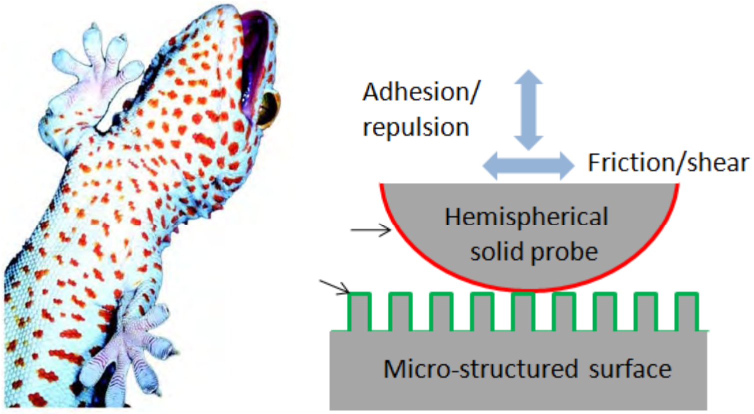


Curved micro-pillars

To mimic this properties, we fabricate curved pillars.

In collaboration with Dr. Turner group at UCSB and Dr. Pesika group at Tulane University

Summary

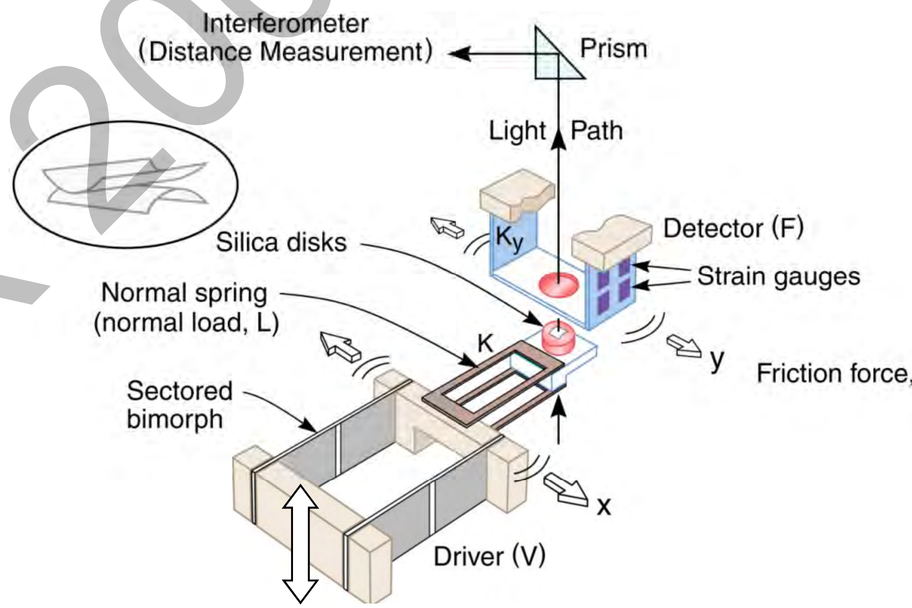


Gecko-like micro/nano structured materials

Micro/nano porous hydrogels , artificial cartilage, and joint lubrication

FABRICATION OF BIOMIMETIC STRUCTURES AT SMALL SCALES FOR RESPONSIVE AND ADAPTABLE MATERIALS APPLICATIONS

PROF. BOXIN ZHAO
CHEMICAL ENGINEERING, U WATERLOO



Surface forces and micro/nano tirbological studies

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  Dr. Gary Leal

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  Dr. Kim Turner (Mechanical Department, UCSB)

- McMaster University

  Dr. Robert Pelton

  Dr. Shiping Zhu

  Dr. John MacGregor

  Dr. Honglu Yu

  Dr. An-chang Shi