Nanotribology

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INM – Leibniz Insitute for New Materials
Nanotribology group

I

- Introduction to tribology
- Atomic force microscopy

II

- Materials and recent experiments in nanotribology

What is Nanotribology?

Tribo- → rubbing
-logy → speaking

Science of wear and friction

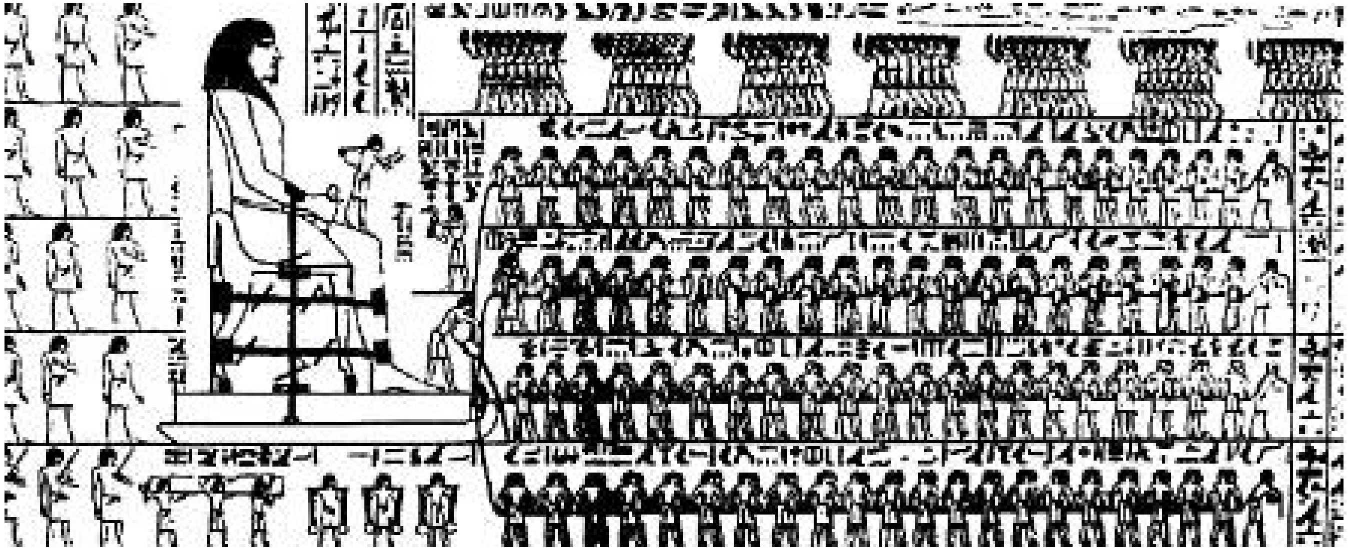
Types of friction:

- Dry friction
- Fluid friction (viscosity)
- Lubricated friction
- Internal friction (plastic deformation, bulk solids)
- Skin friction (drag, velocity dependence)

Scales of friction:

- Macro (movement of bodies)
- Meso (Stress, strain, wear, fracture)
- Micro/ Nano (Origin of friction, AFM, MEMS)

The first tribologist

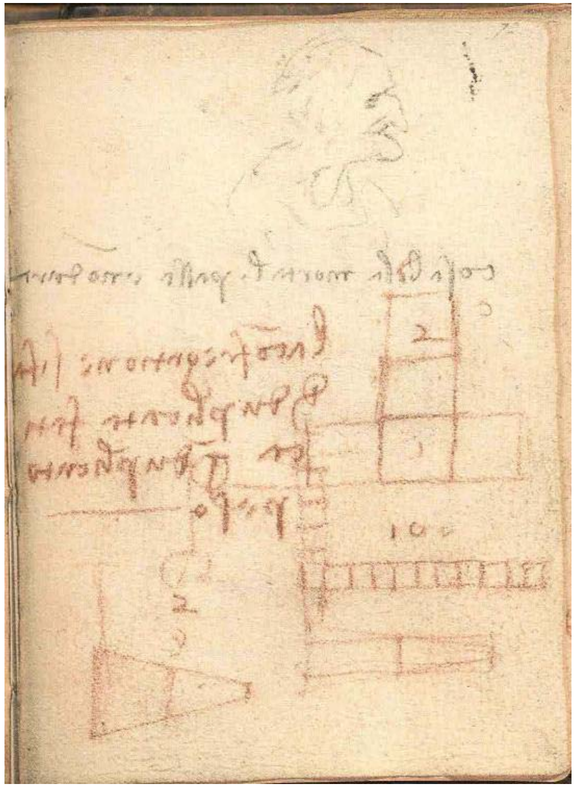


Transport of an Egyptian statue to the grave of Tehuti-Hetep, El-Bersheh around 1880 B.C. The caption indicates that water was used as a lubricant, while an inscription accompanying the picture mentions olive oil as a lubricant.

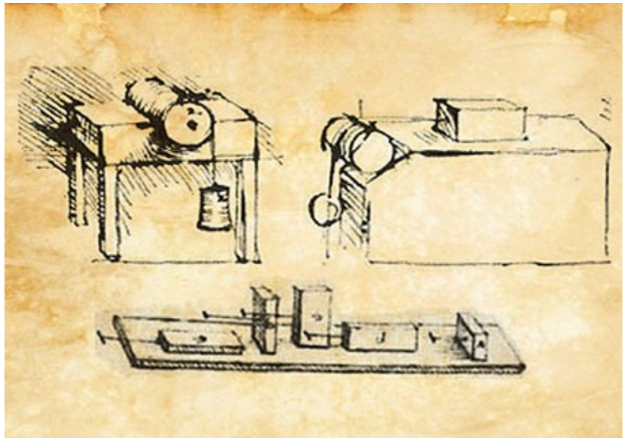
Three classical laws of friction

Unpublished results by da Vinci

Described again 1699 by Amontons full description by Coulomb



First note and sketches relating to the laws of friction (probably 1493)

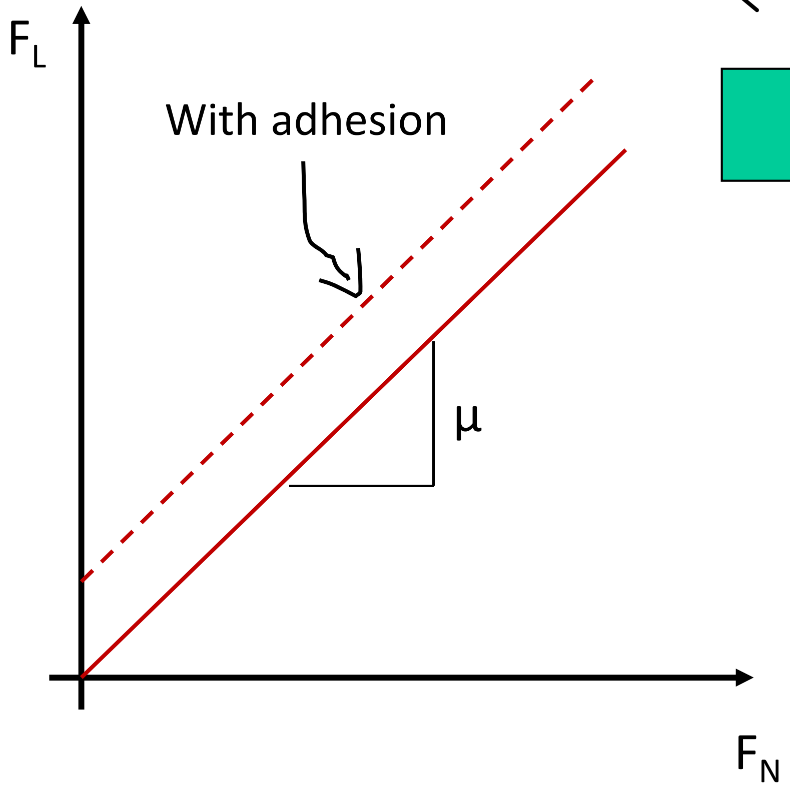


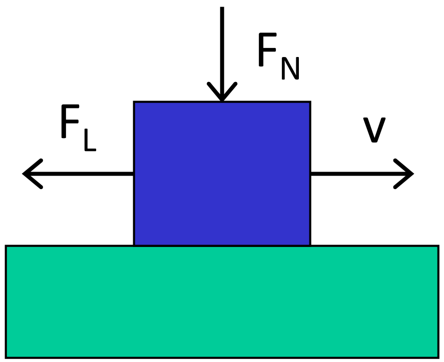
Sketches from two different notebooks (1500-1508)

Charles-Augustin de Coulomb

Classical laws of friction (1/3)

Load dependence





Slope μ – Friction coefficient

$$\mu = \frac{F_L}{F_N}$$

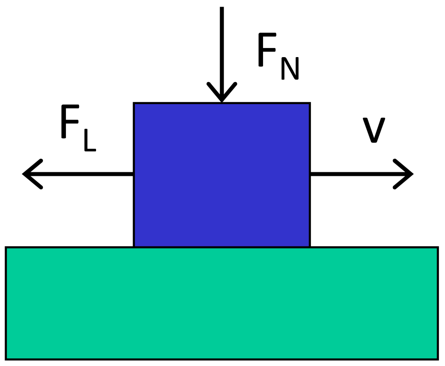
Question

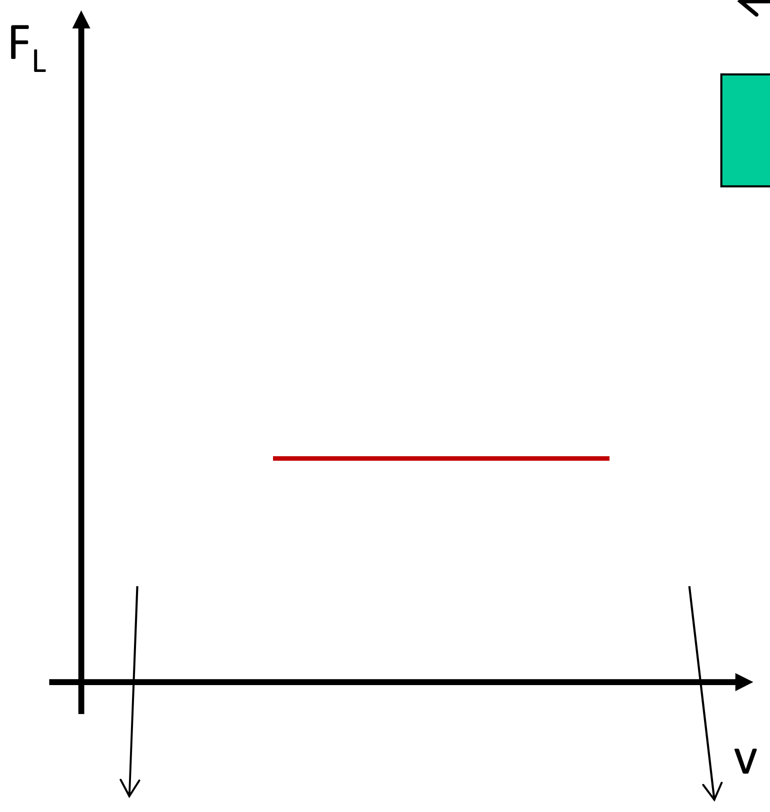
What are typical friction coefficients ?

- Clean metal – clean metal	0.4 – 0.6
- Rubber – rubber	1
- Metal – metal in oil	0.01
- Metal – DLC	0.01
- Synovial fluid	0.003 – 0.01

Classical laws of friction (2/3)

Velocity dependence

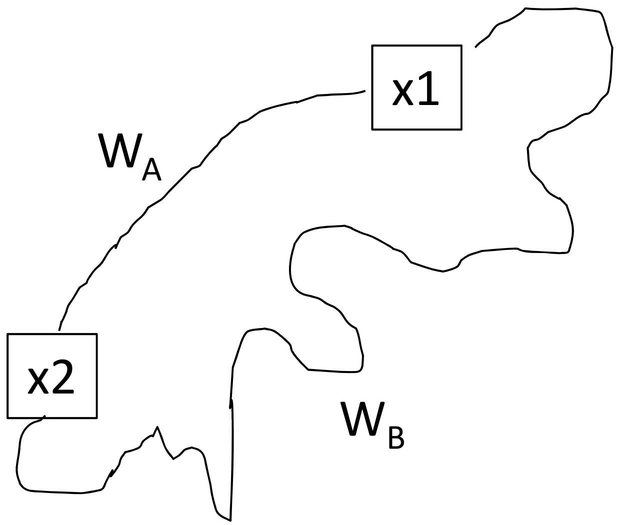




Friction is independent of velocity (for dry fiction)

Work done against friction

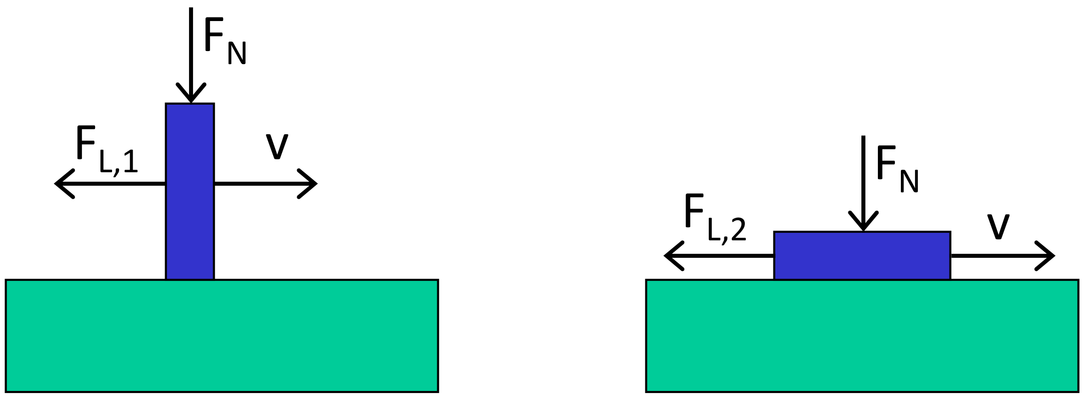
$$W = \int_{x1}^{x2} F_L \, dx$$



$W_A \neq W_B$

Classical laws of friciton (3/3)

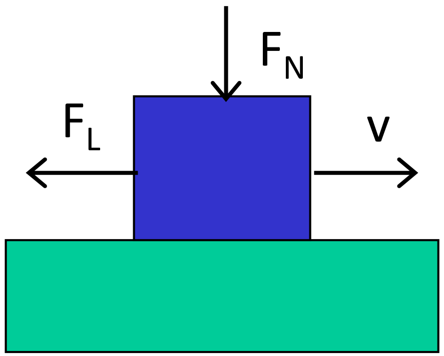
Dependence on contact area

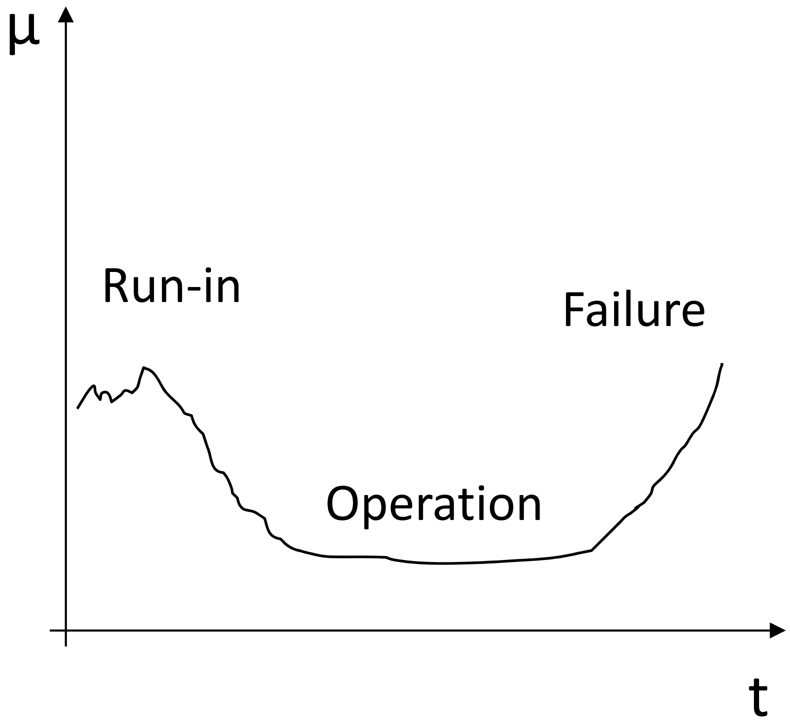


$$F_{L,1} = F_{L,2}$$

Not dependent on geometric area of contact

Experimental tribology



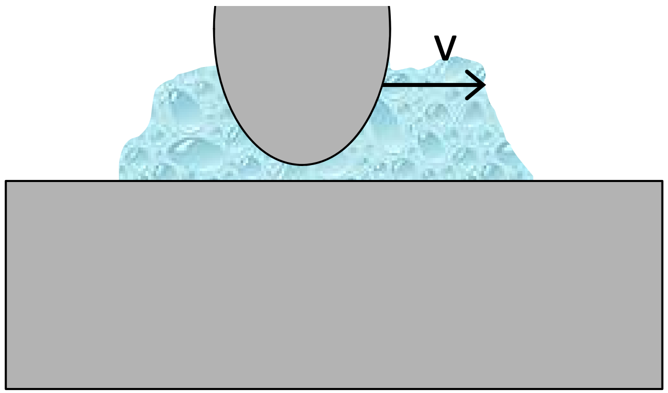


If we consider a real situation with bearings, lubricants and additives, relative motion and wear debris, we see a very complicated and messy problem.

John Ferrante, Tribology Theory Versus Experiment. NASA Technical Memorandum 100198 (1987)

Excursion 1: Lubrication

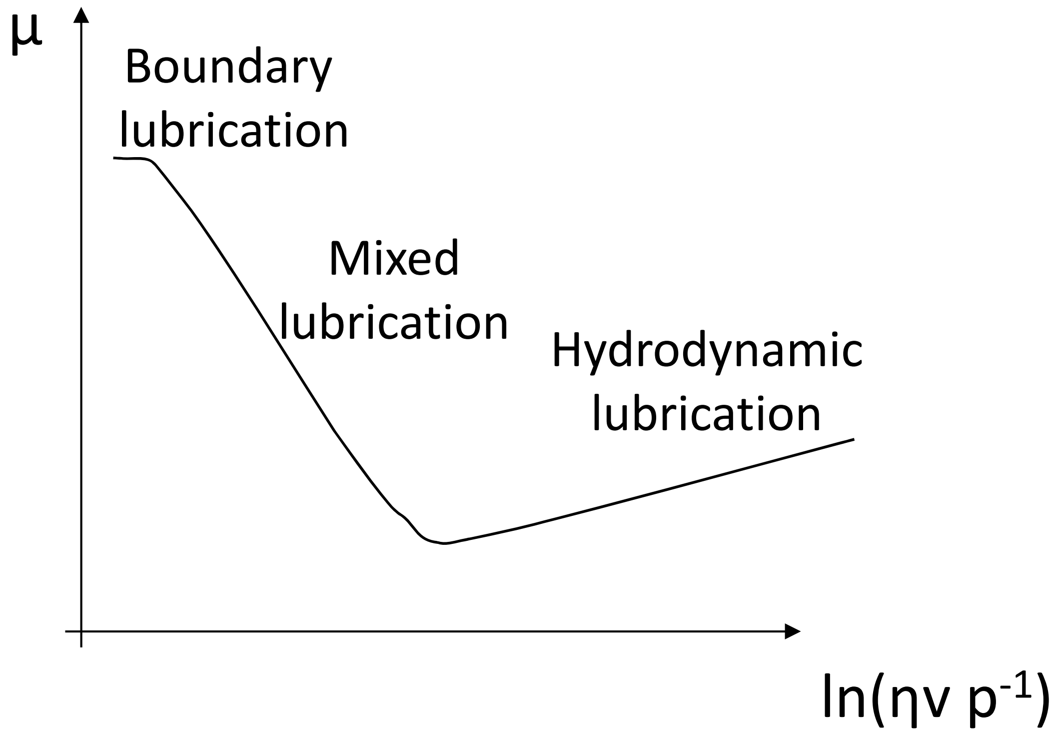
Addition of third material to avoid direct contact between sliding surfaces



Why oil and not water for surface lubrication?

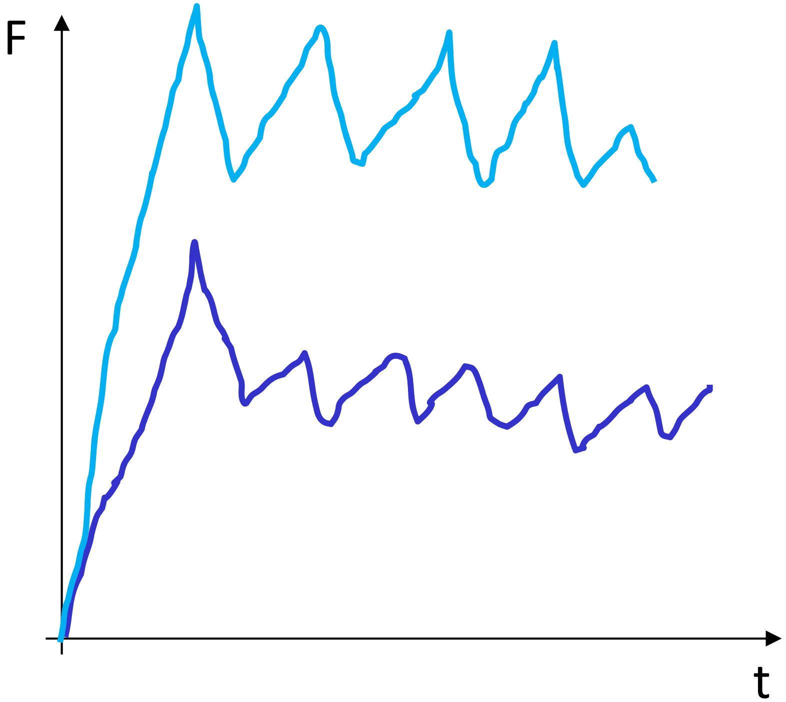
Excursion1: Stribeck curve

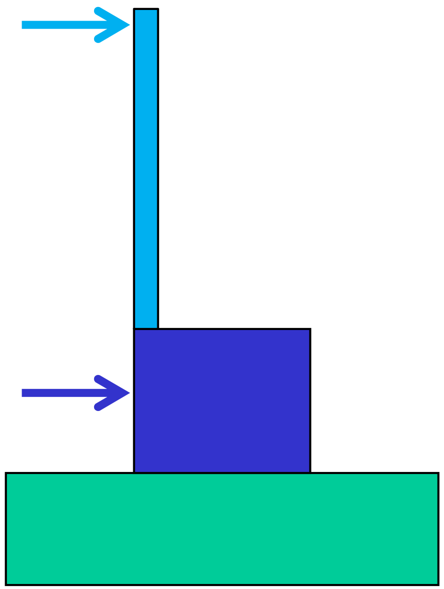
For lubricated contacts



η – Viscosity
p – Normal pressure
v – Velocity

Excursion 2: Construction





Frictional resistance is sum of ploughing and shearing

Adhesion is part of shearing

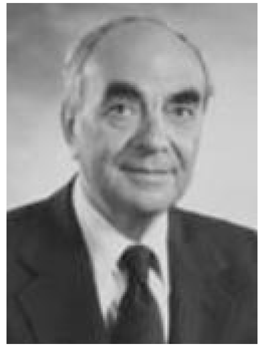
Excursion 3: Ploughing and friction

One material is harder than the other
Amount of friction force required often exceeds the adhesive strength

e.g. hard wedge with opening angle α is sliding over a soft flat surface:

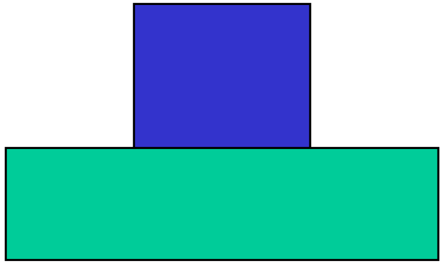
$$\mu_{pl} = \cot\alpha$$

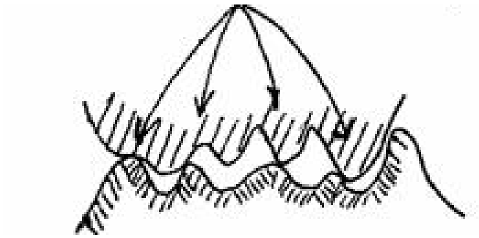
Description by Bowden and Tabor



Adhesion theory of friction

- Contact on small asperities
- Force is high enough to cause plastic deformation
- Plastic flow increases contact area





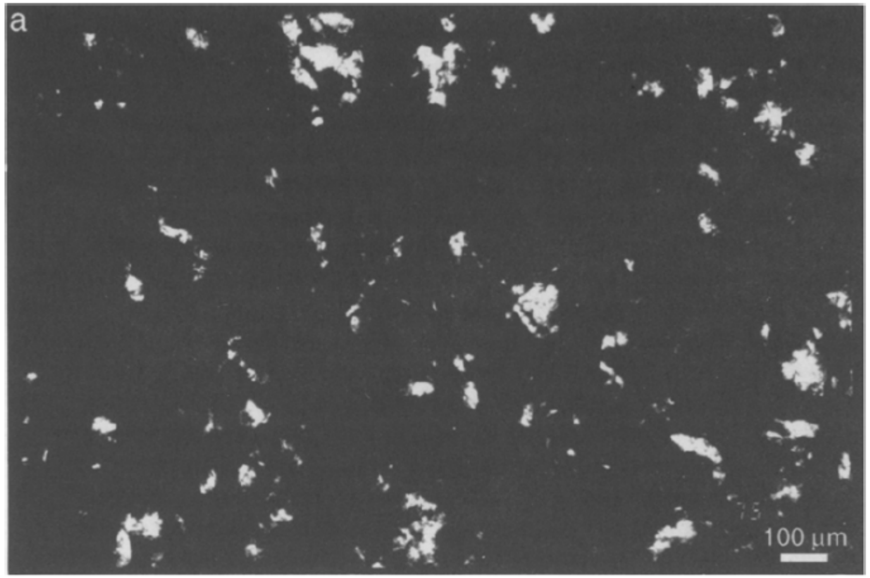
$A_{real} \ll A_{geometric}$

$F_L = \tau \cdot A$ τ – Shear strength

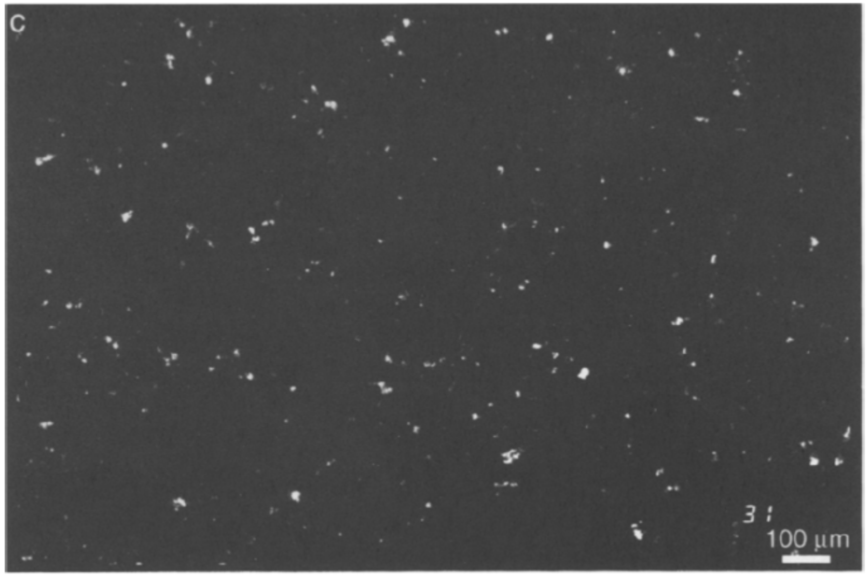
$\tau = \tau_0 + \alpha \frac{F_N}{A}$ Weak dependence on normal pressure

A – Function of normal load $F_L \propto A \propto F_N$

Direct observation of contact area – acrylic plastic



#60 abrasive



#240 abrasive

Typical ratio $A / A_{geometric}$?

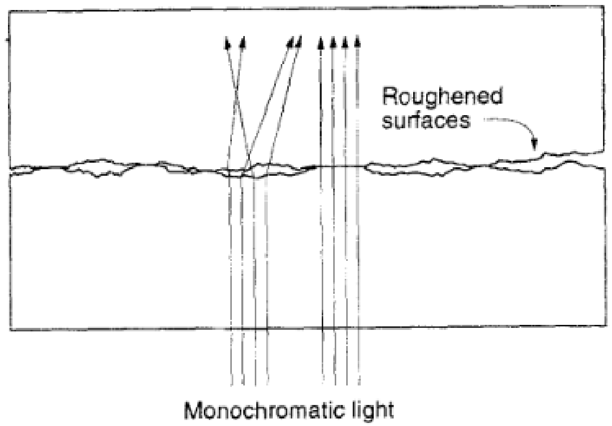
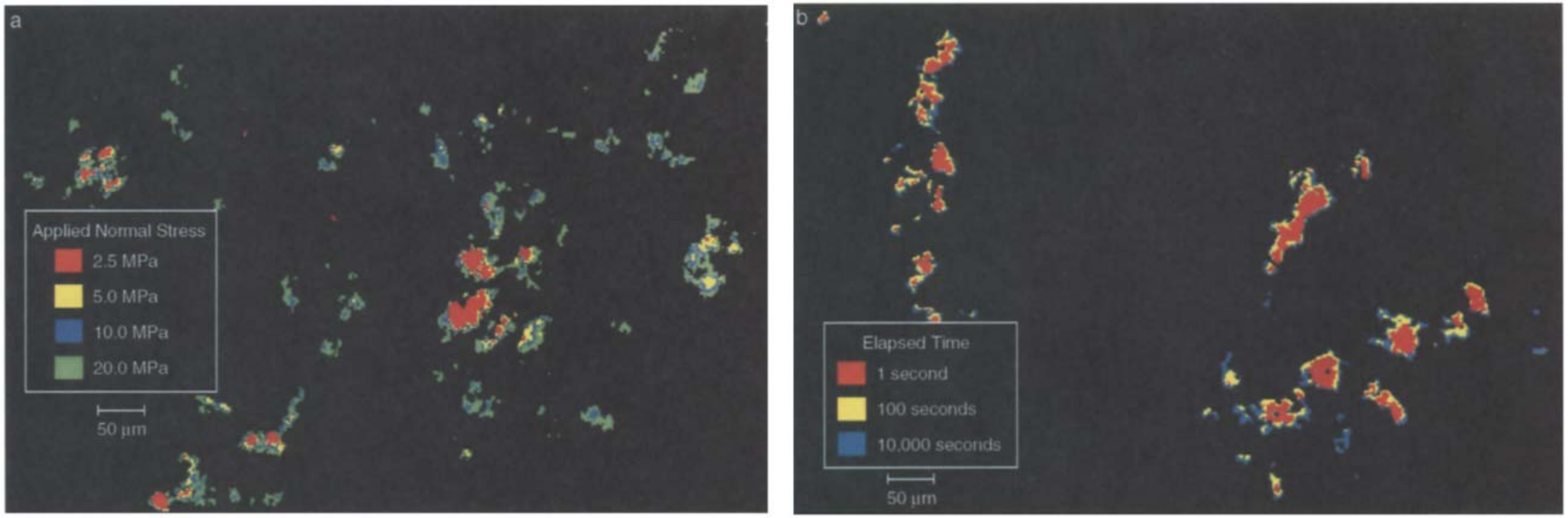


Figure 2
Schematic representation of roughened sliding surfaces. Light transmitted through the sliding blocks is scattered except at contacts.

Kilgore et al., Pure and Applied Geophysics 143 (1994) 283

Direct observation of contact area – acrylic plastic



Kilgore et al., Pure and Applied Geophysics 143 (1994) 283

Shearing, plastic deformation, and friction

$$A = \frac{F_N}{y}$$

$$F_L = \tau \cdot A$$

y – Yield strength
τ – Shear strength

$$\mu = \frac{F_L}{F_N} = \frac{\tau \cdot \frac{F_N}{y}}{F_N} = \frac{\tau}{y}$$

$$\mu = \frac{shear\ strength}{yield\ strength}$$

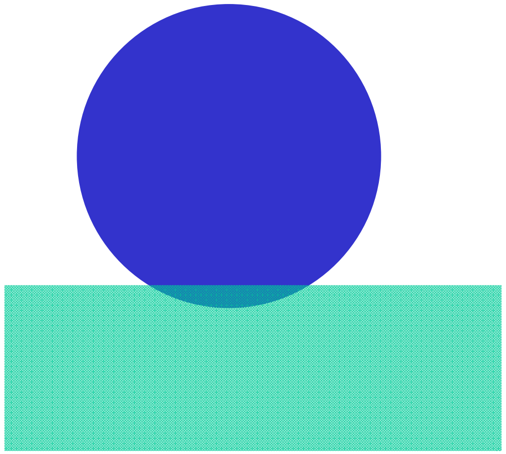
Metals: μ = 0.4 – 0.6

Shearing, elastic deformation, and friction

Elastic deformation described by contact mechanics

Hertz model

- sphere on flat
- no adhesion

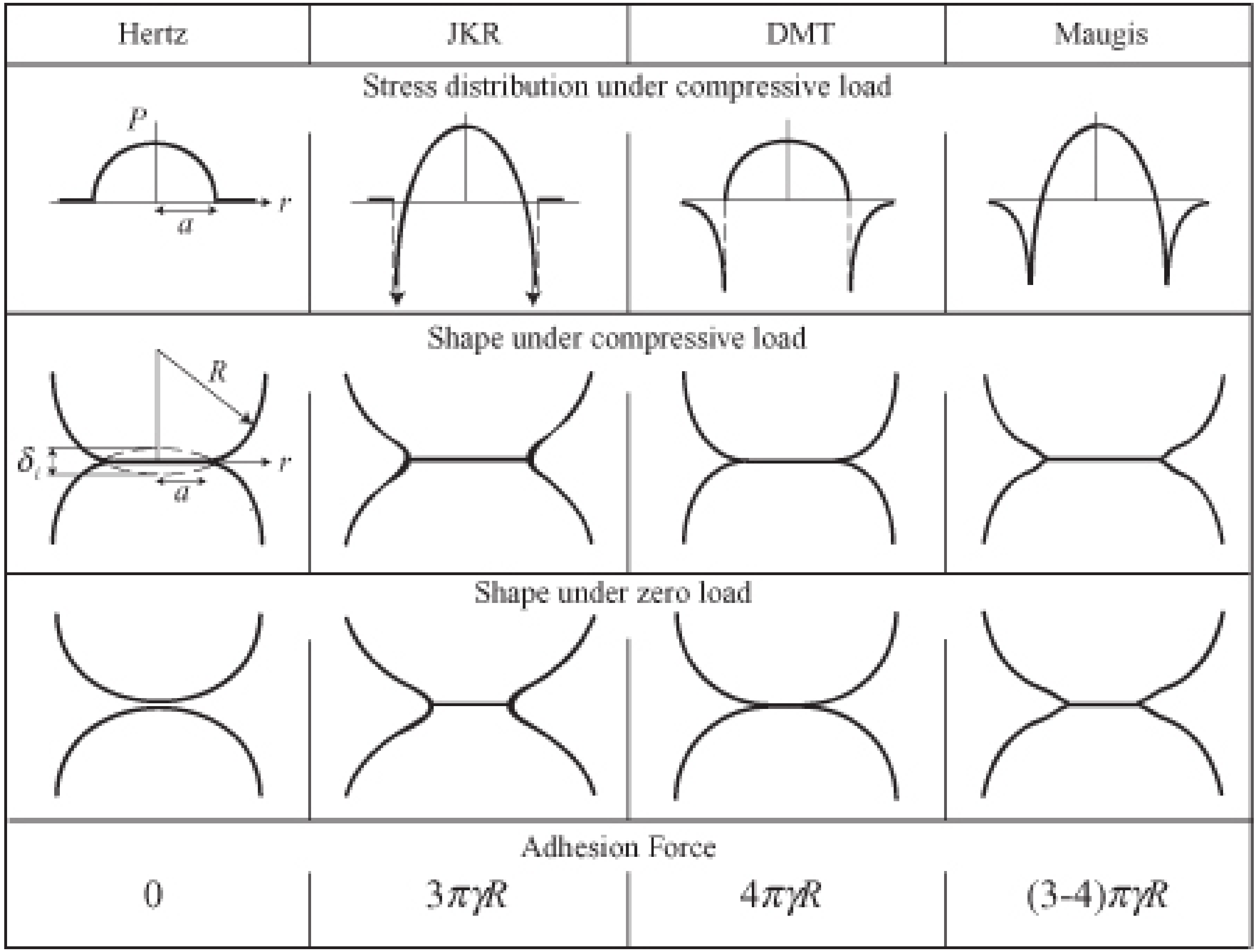


$$A = \pi \left(\frac{3}{4}\frac{R}{E^*}\right)^{2/3} F_N^{\,2/3}$$

E* - Effective modulus of both materials

$$\boxed{F_L \propto F_N^{\,2/3}}$$

Description of contacts



Polymer adhesion, friction, and lubrication / edited by Hongbo Zeng, University of Alberta, Edmonton, AB, Canada. Wiley 2013.
ISBN 978-0-470-91627-8

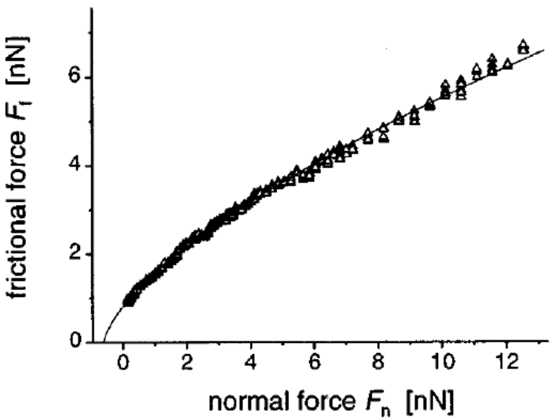
Contact mechanics with adhesion

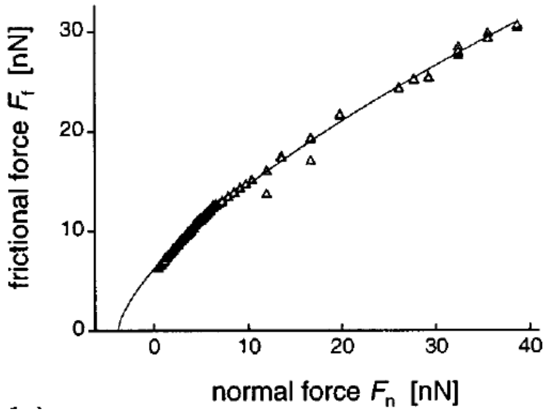
JKR-model

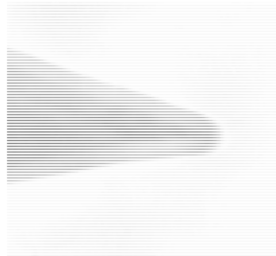
$$A = \pi \left(\frac{3}{4}\frac{R}{E^*}\right)^{2/3} \left(F_N + 3\Delta f R + \cdots\right)^{2/3}$$

Δf – work of adhesion

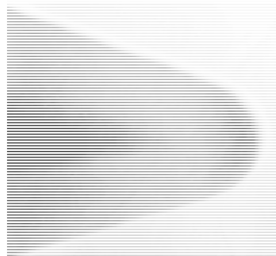
Conflicts with classical friction law



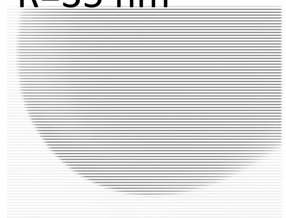




R=21 nm



R=35 nm

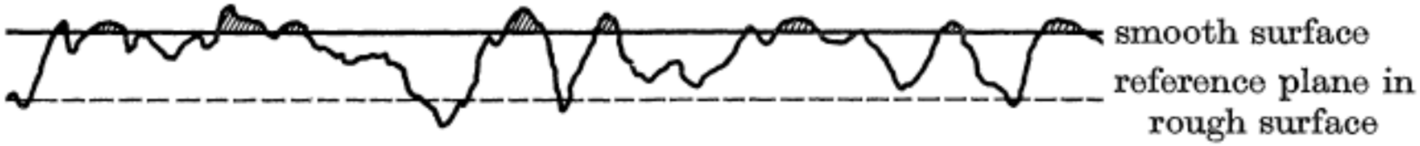


R=112 nm

Schwarz et al., Phys. Rev. B 56 (1997) 6987

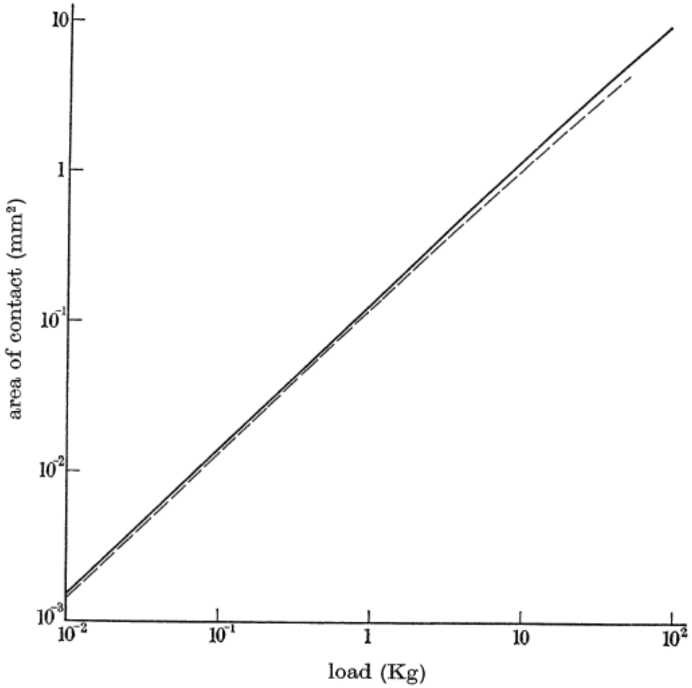
Contact of nominally flat surfaces

By J. A. Greenwood and J. B. P. Williamson



Gaussian distribution of asperity heights

The experimental results which follow show that for many surfaces the height distribution is Gaussian to a very good approximation. We have, therefore,

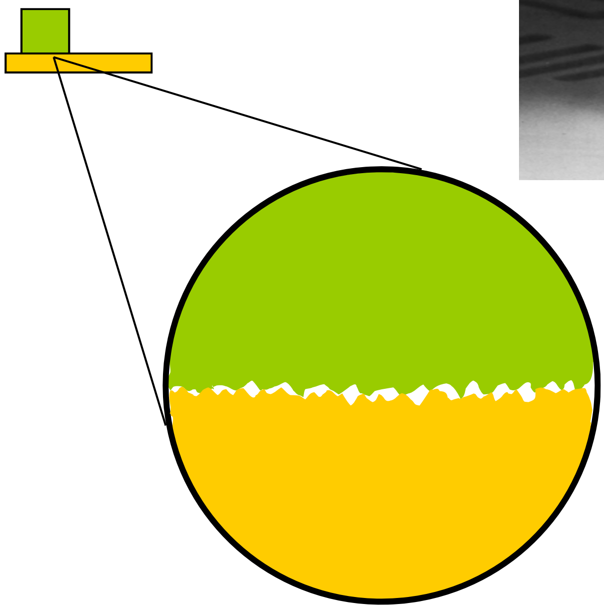


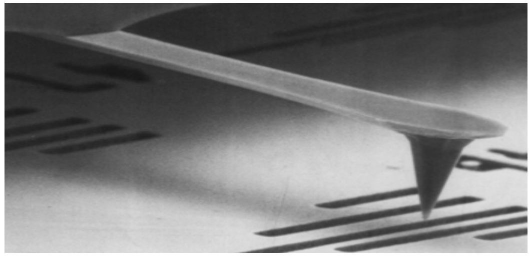
For single asperities: $F_L \propto {F_N}^{2/3}$

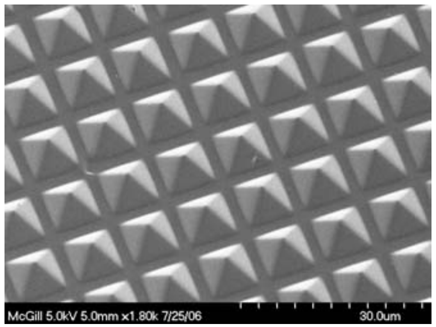
Classical friction law: $F_L \propto {F_N}^{1}$

Problem solved by regarding contact surfaces as Gaussian distribution

Nanotribology - Reducing complexity







- o **Experiments**:
  Scanning Force Microscopy
  Multi-scale Tribometry

- o **Control of Material**:
  Surface Science
  Electrochemistry
  Micro-structuring

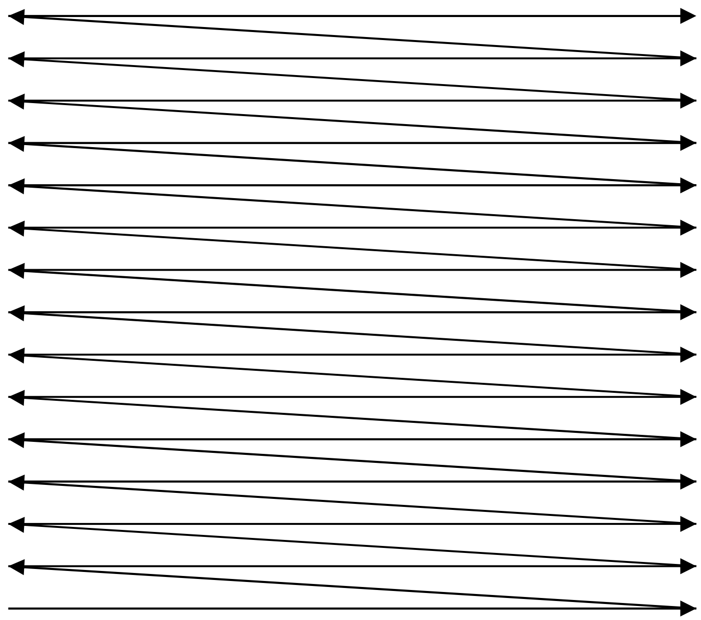
- o **Modelling:**
  Molecular dynamics
  Multiscale approaches

Scanning force microscopy

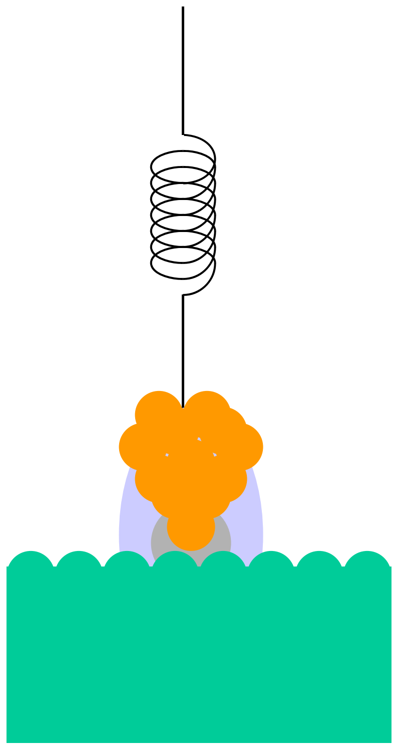
usually known as AFM
(atomic force microscopy)

Scanning …

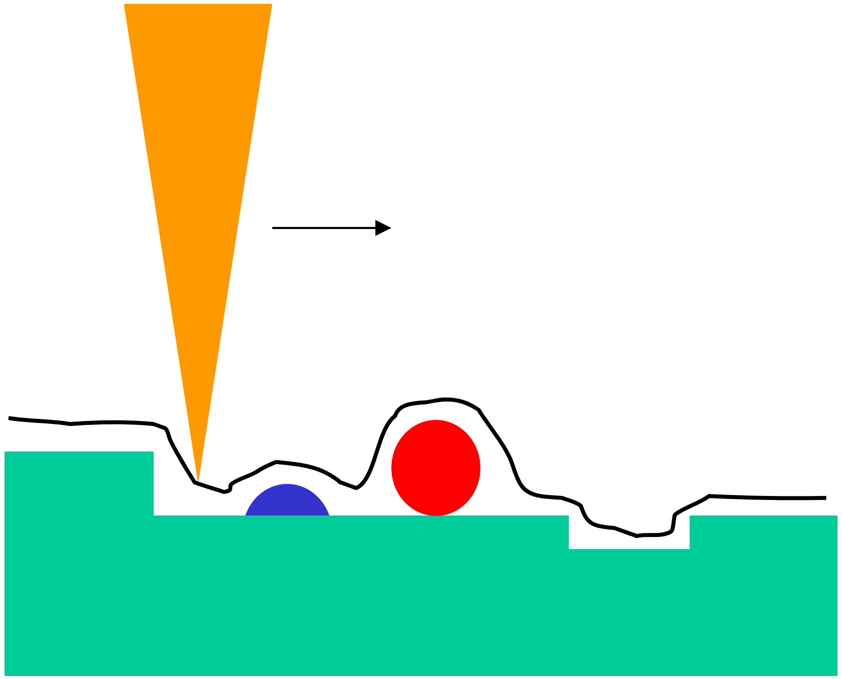
Probe is moved along scan lines over a sample surface



… Force …

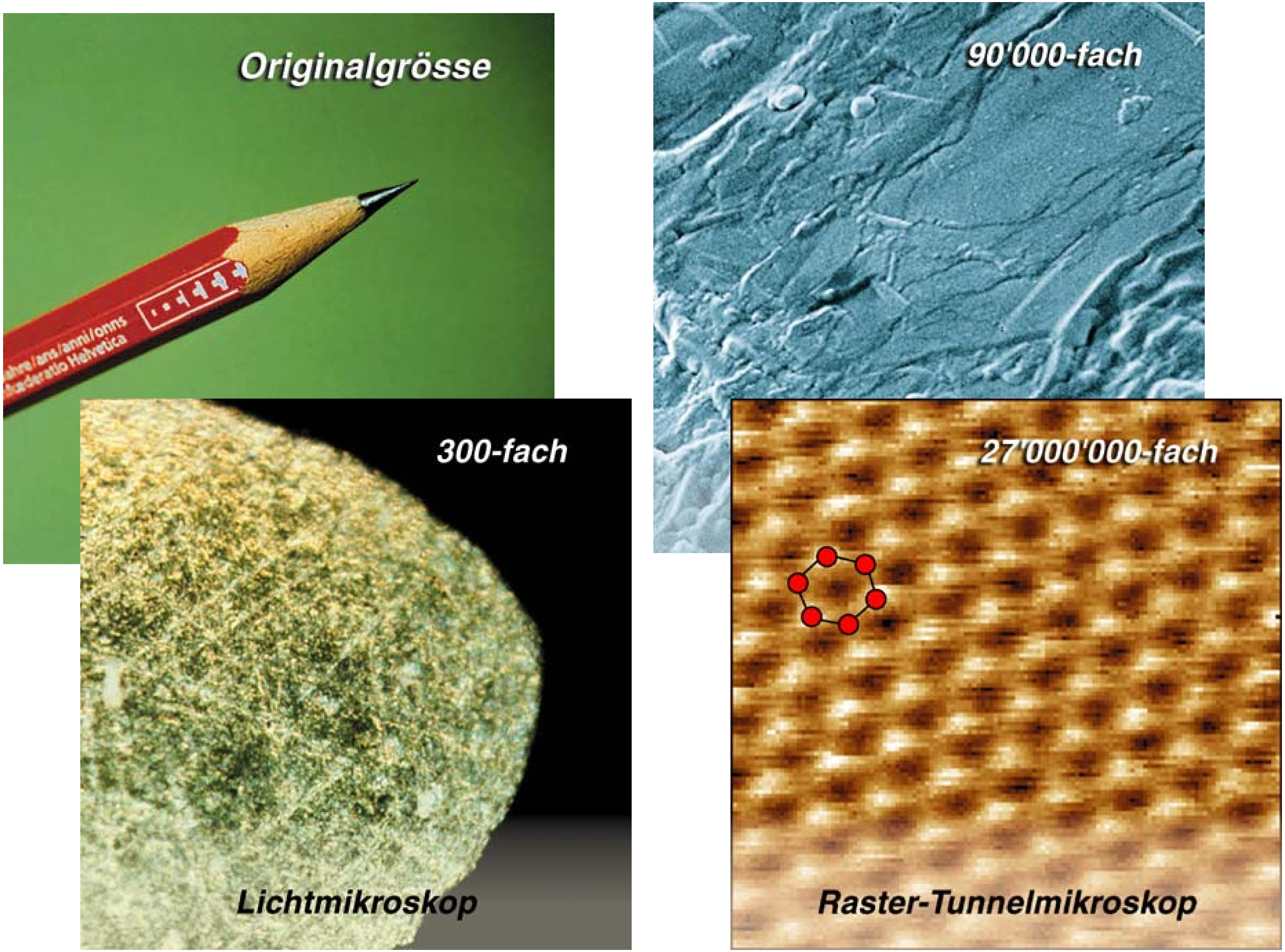


… Microscopy

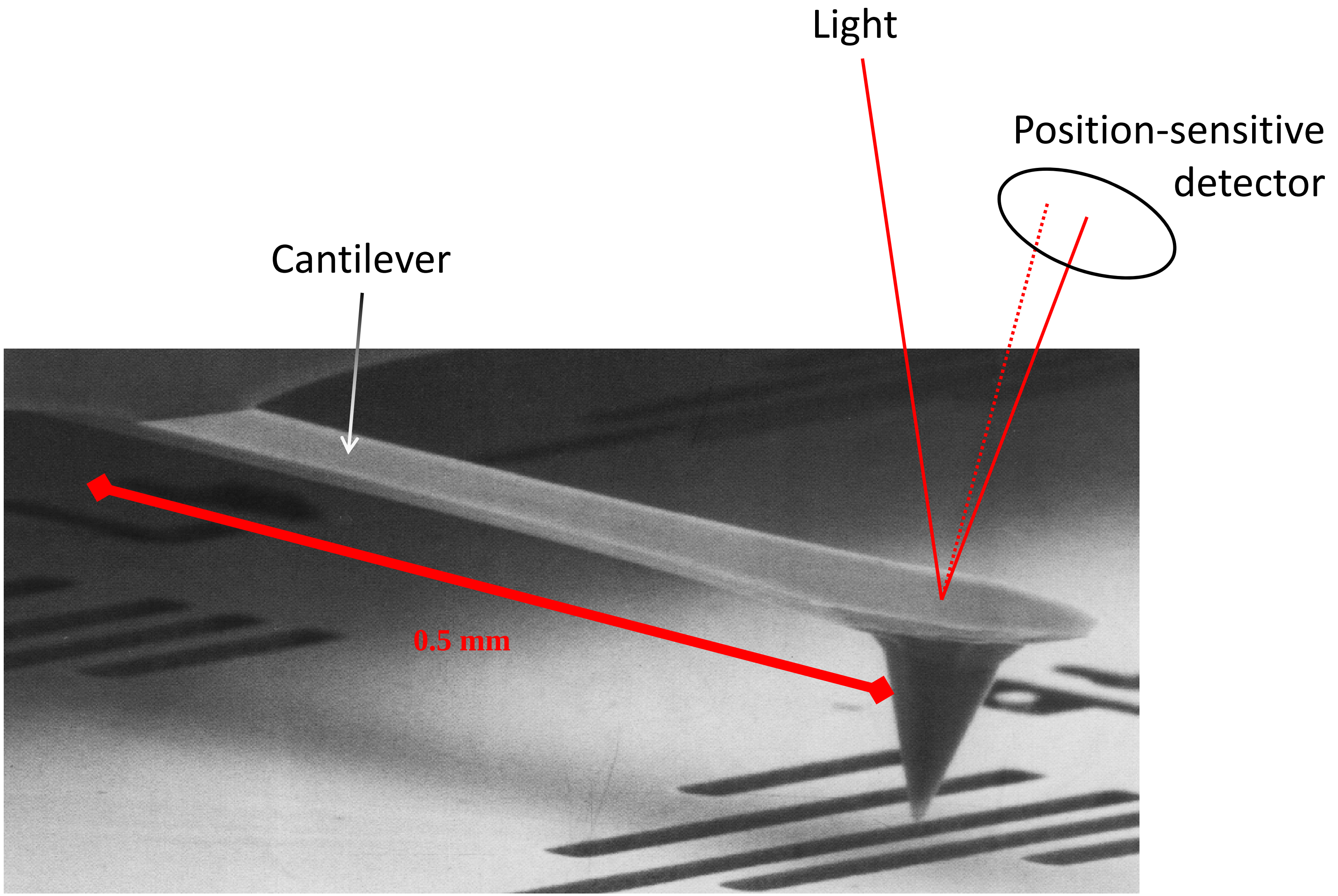


Data are recorded as a function of lateral position.

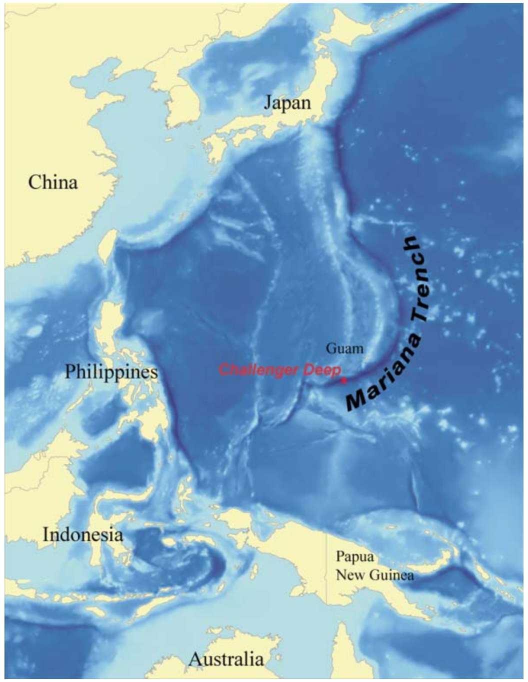
Display and analysis with help of computer.


Originalgrösse
90'000-fach
300-fach
27'000'000-fach
Lichtmikroskop
Raster-Tunnelmikroskop

Essential parts of an AFM



~ 500 kPa



~ 110 MPa

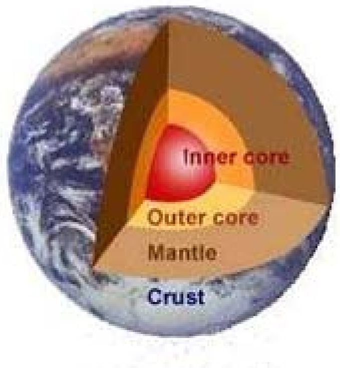
AFM tip on surface

$$P = \frac{F}{A}$$

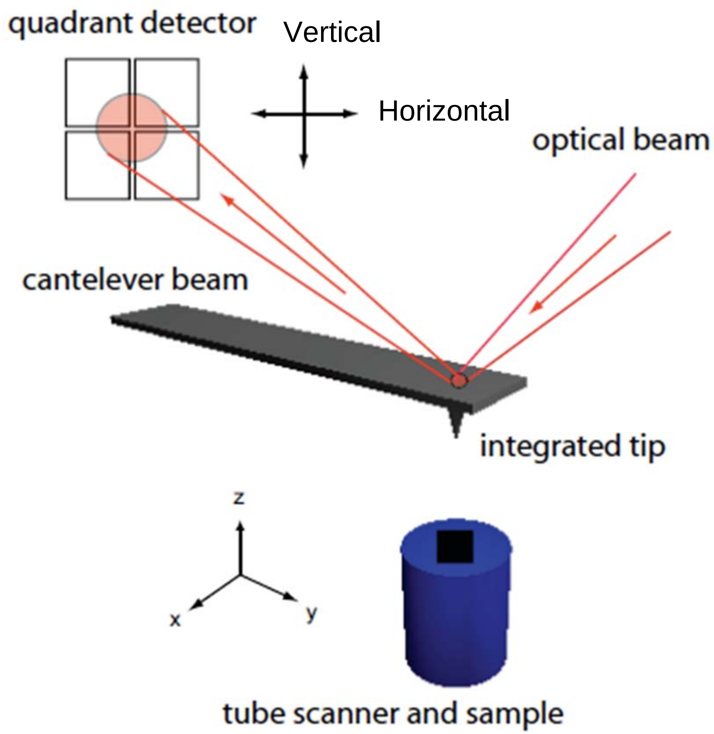
$$P = \frac{10\ nN}{1\ nm^2}$$

$$\boldsymbol{P = 10\ GPa}$$

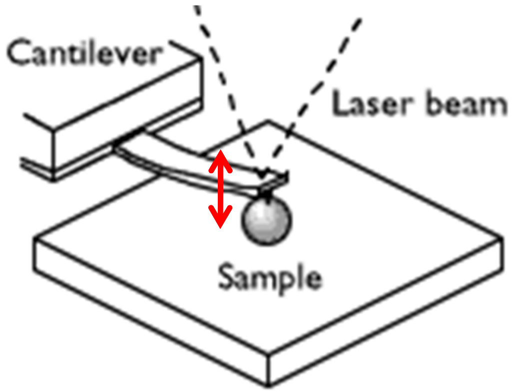
~ 360 GPa



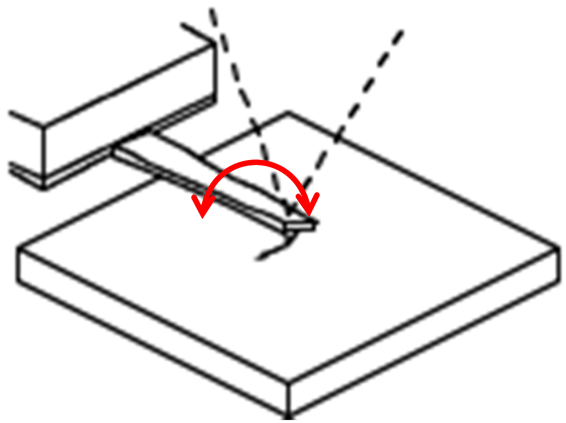
Normal and lateral force measurement



normal deflection



lateral deflection



Meyer, Bennewitz, Hug: *Scanning Probe Microscopy*. Springer-Verlag 2003

Forces

Q: Where in nature do you experience a force of 1 N?

Q: What force (in N) does one measure in an **atomic** force microcope?

What is a NanoNewton?

What is 1 Newton?
A chocolate-oriented unit for force.

Nanoscience of chocolate?
1 bar are 100 cm^3 or 10^{23} nm^3
Weight of 1 nm^3 is 10^{-23} nN (=0)

Binding forces in chocolate
Cross-section 1 cm^2 or 10^{14} nm^2
Weight carried 4 kg
Rupture force 4×10^{-13} N/nm^2

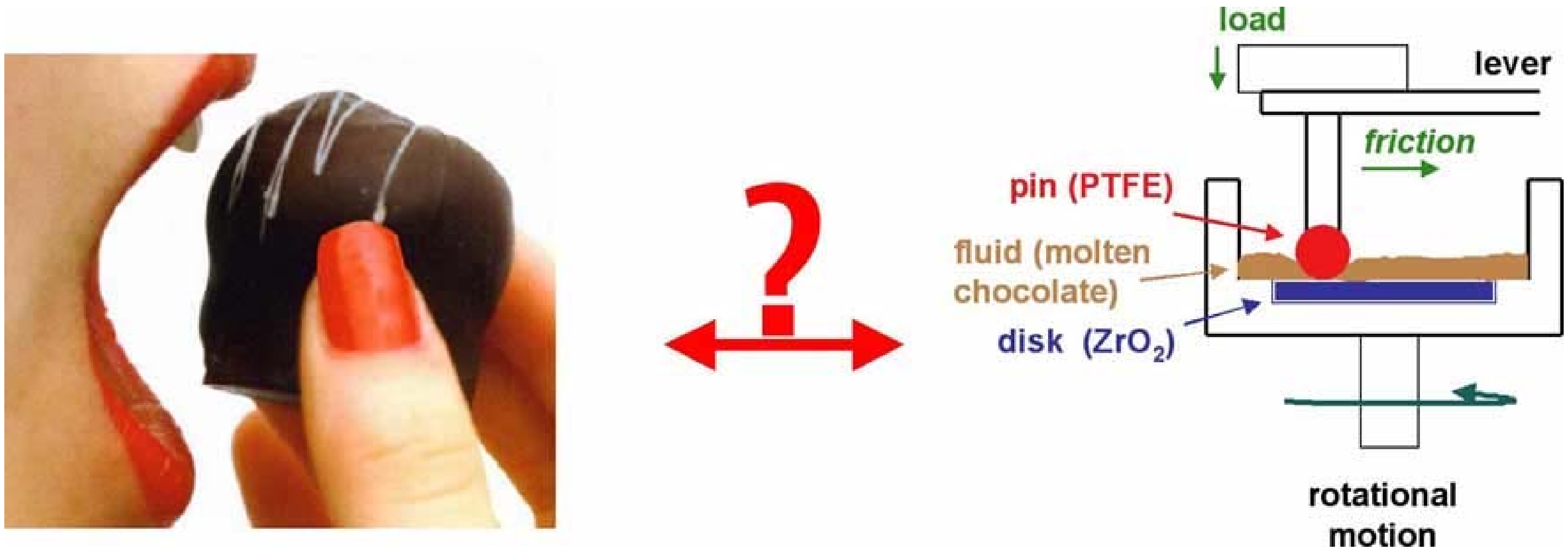
PicoNewton describe molecular forces in softer materials.
NanoNewton describe molecular forces in harder materials

A tribological model for chocolate in the mouth: General implications for slurry-lubricated hard/soft sliding counterfaces

Seunghwan Lee[a], Manfred Heuberger[a], Philippe Rousset[b] and Nicholas D. Spencer[a,*]

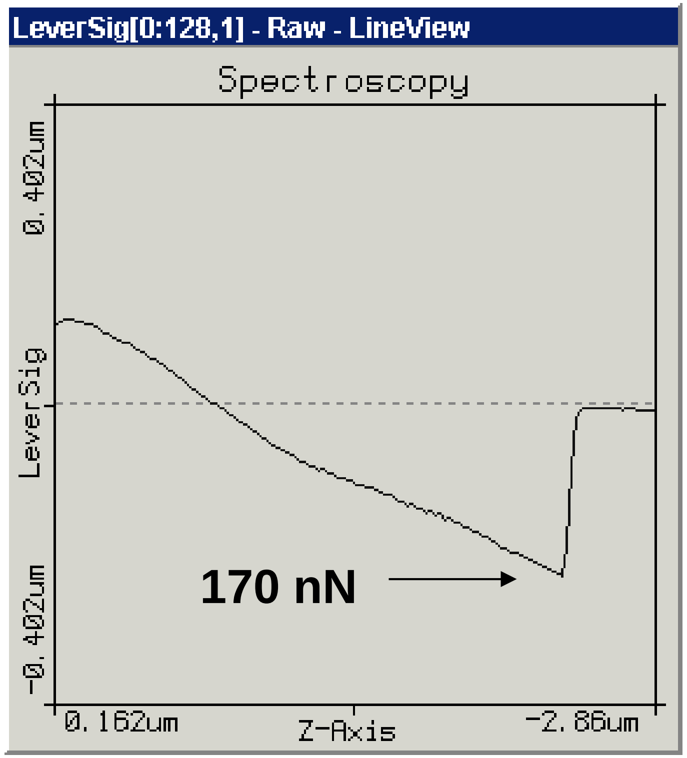
[a] *Laboratory for Surface Science and Technology, Department of Materials, Swiss Federal Institute of Technology (ETH), Zürich, CH-8092, Switzerland*

[b] *Nestlé Research Center, Department of Food Science and Process Research, Vers-chez-les-Blanc, 1000 Lausanne 26, Switzerland*

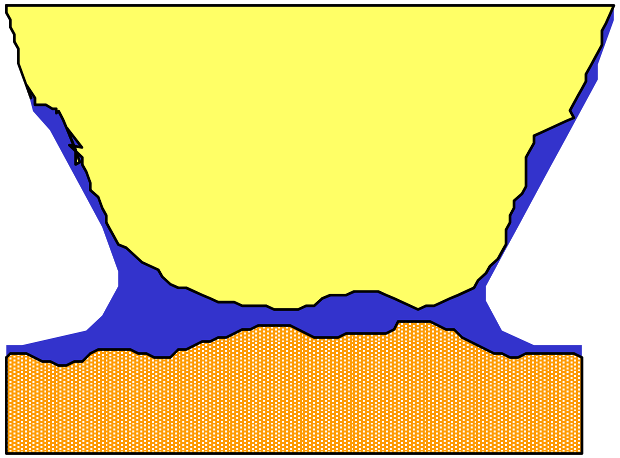


http://www.surface.mat.ethz.ch/research/surface_forces/tribology_and_surface_forces

Adhesion - how water disturbes

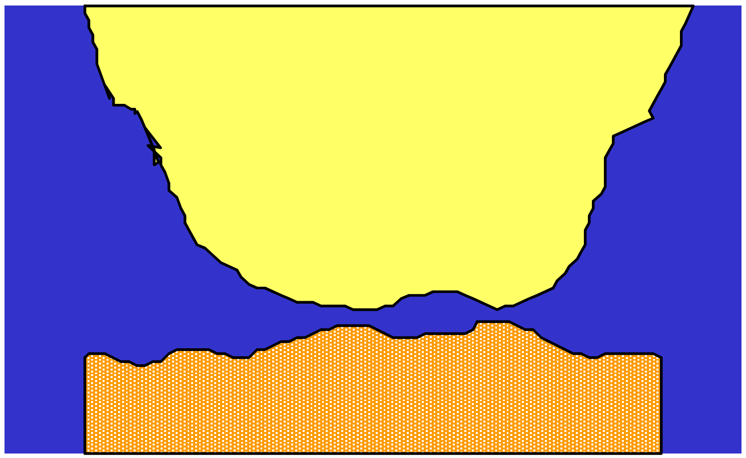


Force vs. distance curve

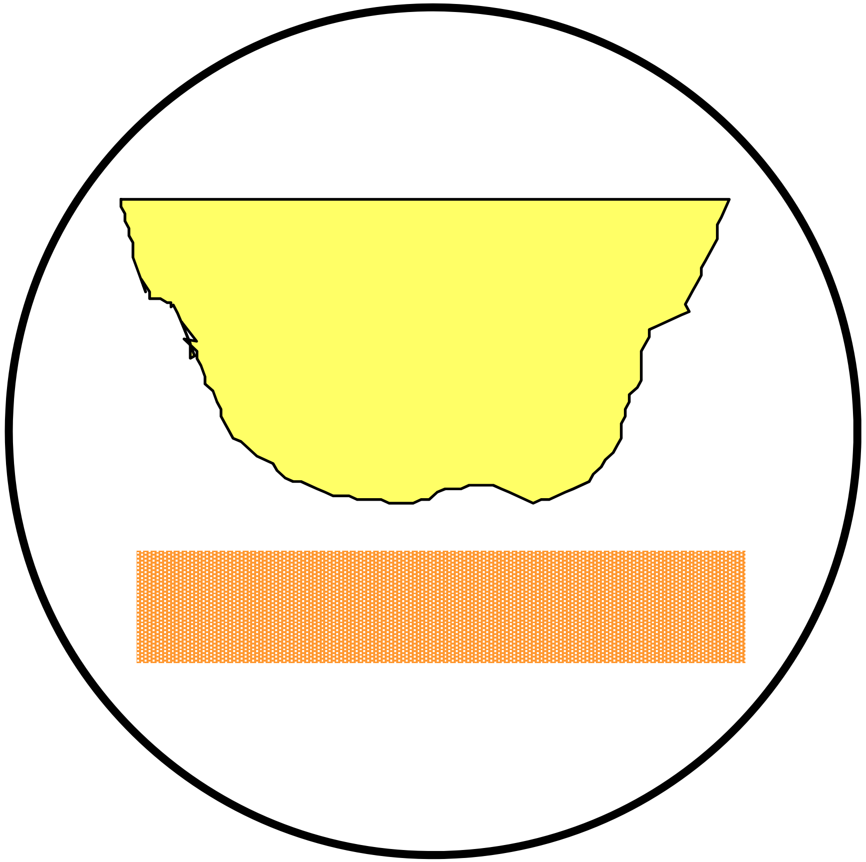


Capillary force

Way out of experimental physics



Measurements in water



... or in vacuum

Relevant forces

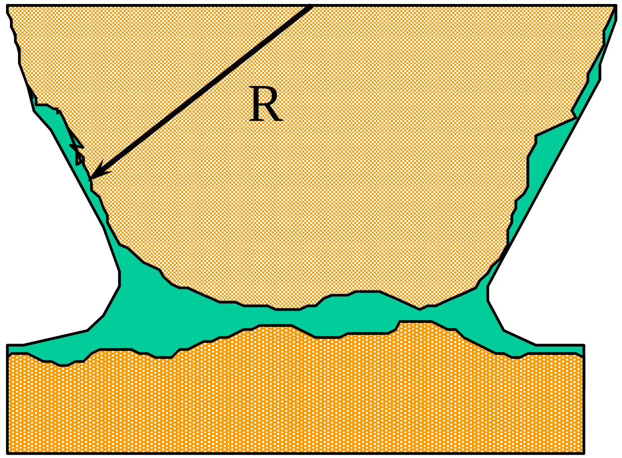
- **short-range repulsive forces (Pauli exclusion) or ionic repulsion forces**
- **short-range chemical binding forces**
- **van der Waals forces (always present, retarded beyond 100 nm)**
- **electrostatic forces (long-ranged)**
- **magnetic forces**

- **interaction in liquids**
  - hydrophobic / hydrophilic forces
  - steric forces
  - solvation forces

Literature:
J. Israelachvili
Intermolecular and Surface Forces with Applications to Colloidal and Biological Systems, **Academic Press (1985)**

Capillary forces

$F_{max} = 4\ \pi\ R\ \gamma\ \cos(\Theta)$

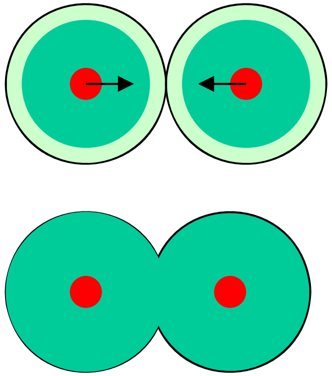


γ (H_2O) = 0.074N/m R=100nm

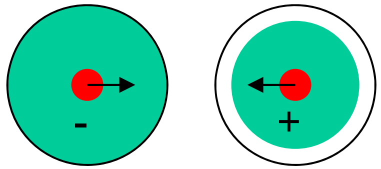
Contact angle for hydrophilic surfaces $\Theta \approx 0°$

$\Rightarrow\ F_{max} = 90nN$

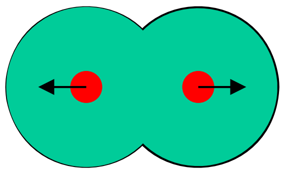
Atomic Forces



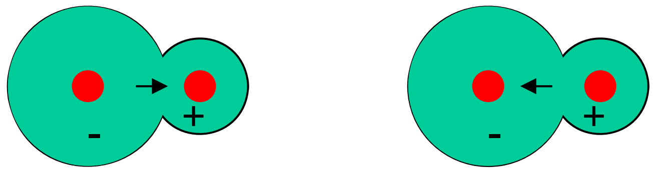
Chemical bond



Ionic attraction

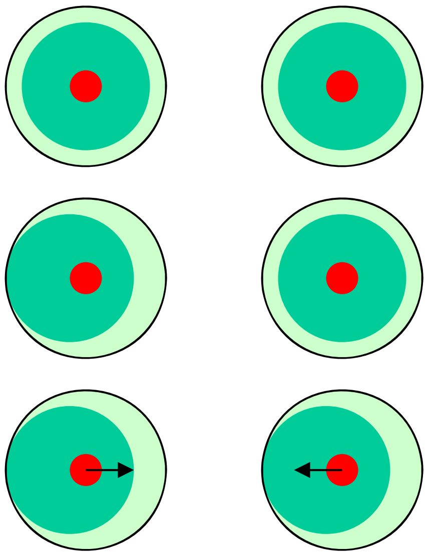


Repulsion upon overlap of electrons



Dipole attraction

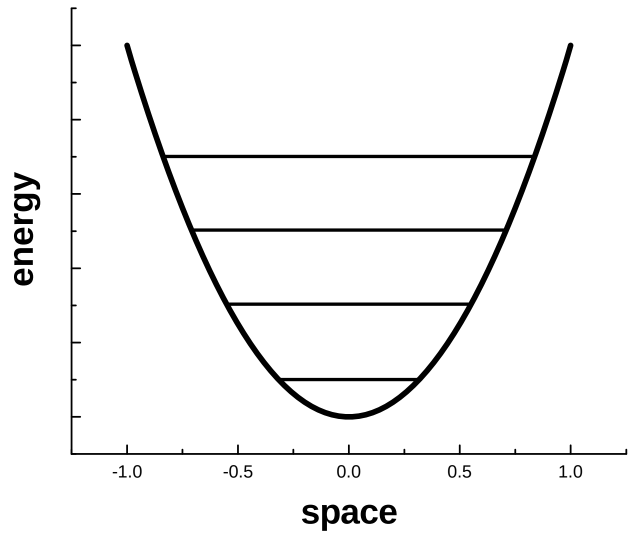
Van der Waals Force



Two neutral atoms

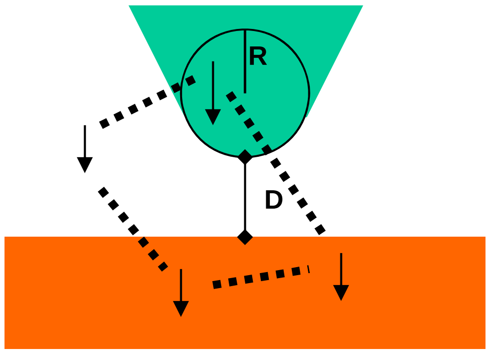
Dipole fluctuation: Unavoidable in quantum mechanics

Induced dipole



Range limited to 10 nm due to retardation effect.

Van der Waals forces between tip and sample



Integration of mutual interactions

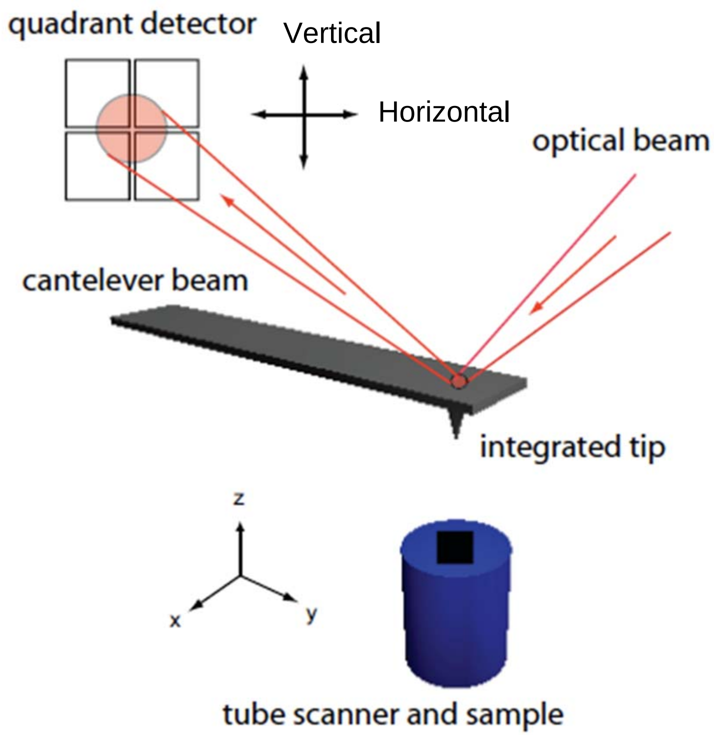
Force between the tip and surface can be approximated as force between a ball of radius R and a surface at distance D:

$$F = -\frac{AR}{6D^2}$$

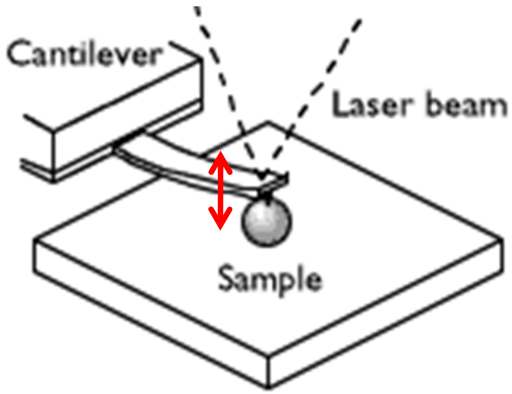
Hamaker constant A is material dependent and of the order of 10^{-19} J.

J. Israelachvili, *Intermolecular and surface forces*, chap. 11

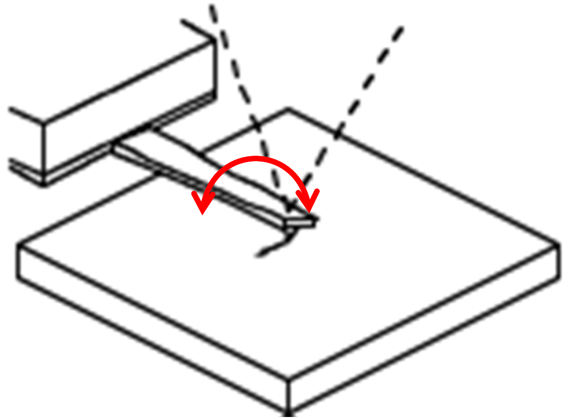
Friction force microscopy
Lateral force microscopy



normal deflection



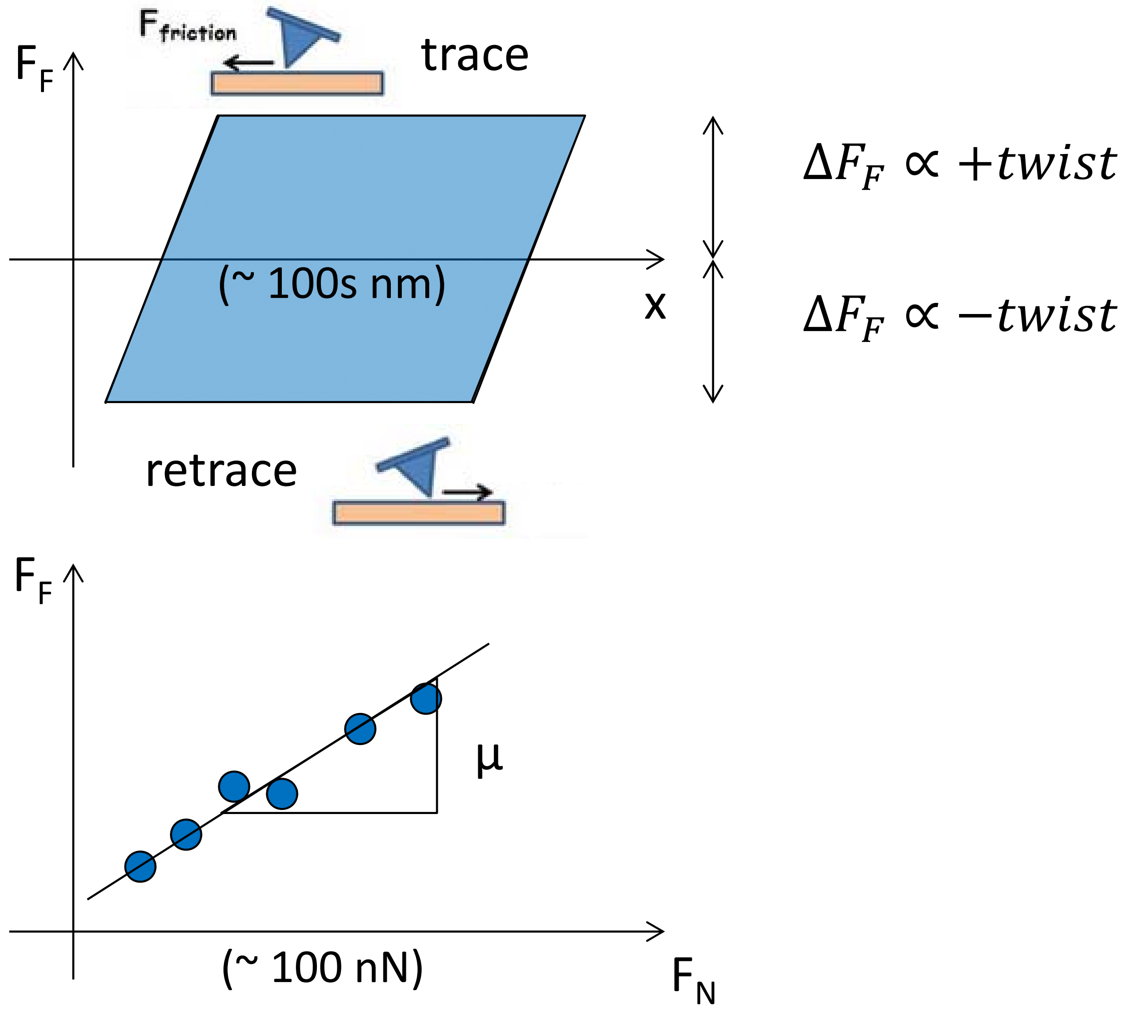
lateral deflection



Meyer, Bennewitz, Hug: Scanning Probe Microscopy, Springer-Verlag 2003

Friction loop

For a preset loading force F_N



Friction Force Microscopy

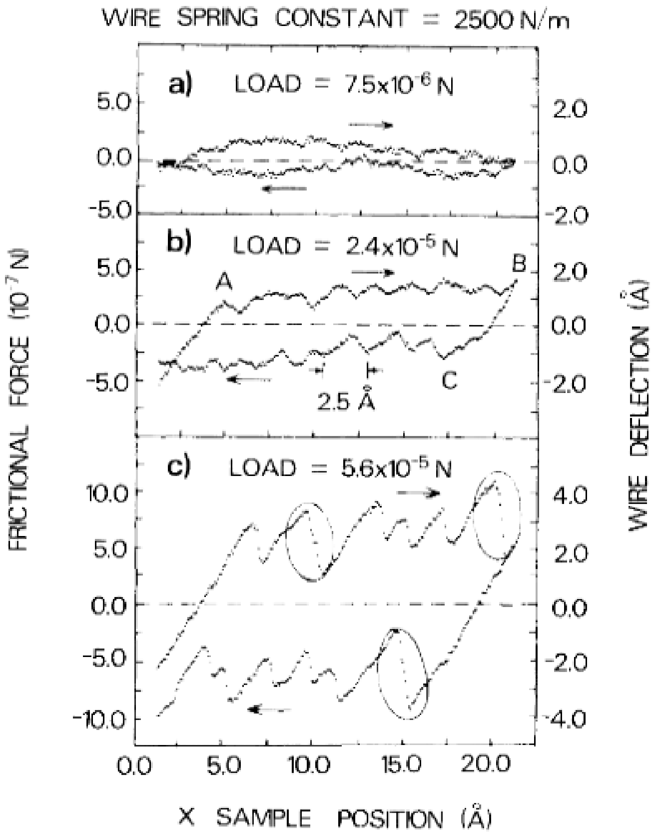


FIG. 2. The wire deflection parallel to the surface and the corresponding frictional force on the tip as a function of sample position for three different loads. The circled sections in (c) indicate where double slips occur.

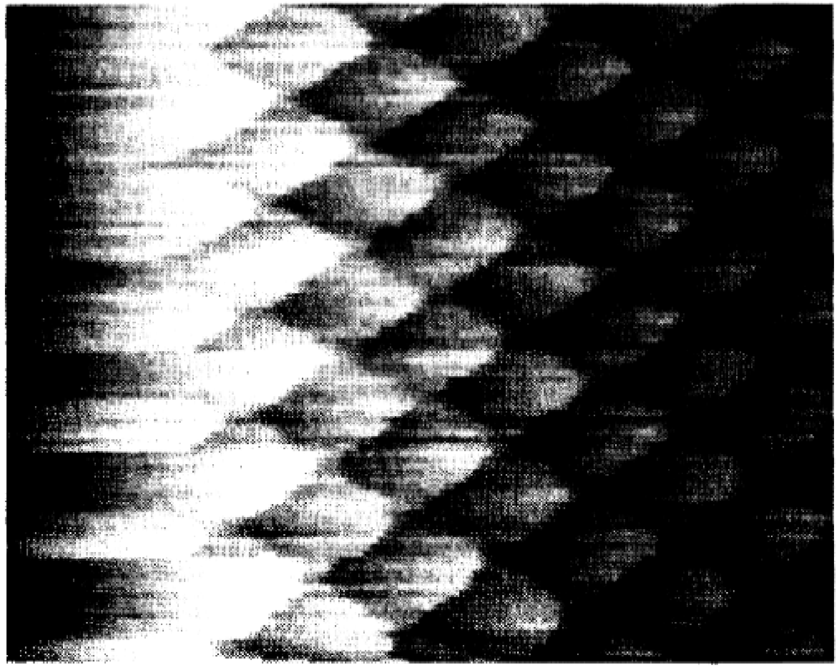


FIG. 3. The frictional force in the x direction as a function of x and y. The intensity of the image is scaled to the frictional force with the bright areas corresponding to a high force. The full-scale change from dark to bright corresponds to 1.8×10^{-6} N. Only scans in left-to-right direction are shown. The size of the image is 20 by 20 Å,[2] with no correction for distortion from the piezoelectric scanners. The load on the tip is 5.6×10^{-5} N, and the wire spring constant is 2500 N/m.

First observation of atomic stick slip: Mate CM et al., Phys Rev Lett 59 (1987) 1942

Friction Force Microscopy