

From contact mechanics to wear

J.F. Molinari (LSMS, EPFL, Switzerland)

Outline

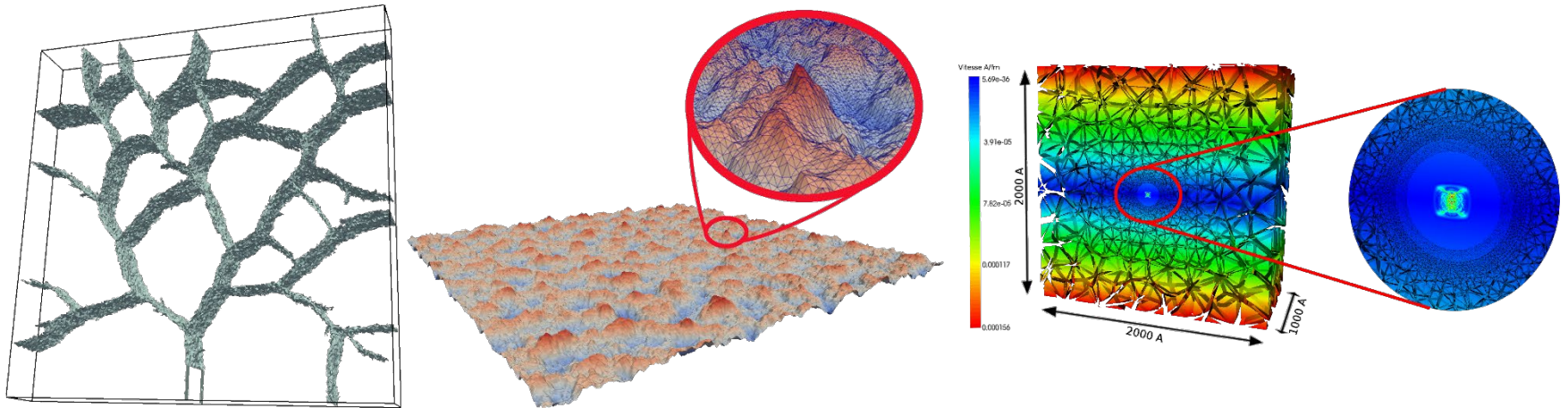
https://c4science.ch/source/Tribology_Course_nb/

- Lecture 1
 - Introduction of lecturer and laboratory LSMS (lsms.epfl.ch)
 - Introduction to tribology (my vision)
 - From da Vinci to rate and state friction laws
- Exercise 1 (optional HW): Some fundamental solutions in mechanics of solids
- Lecture 2
 - Surface roughness, self-affine roughness
 - Single asperity contact: Hertz contact theory
 - Multiple asperities contact, rough contact mechanics
- Exercise 2 (optional HW)
 - Generation with open-source software Tamaas of rough surfaces
 - Resolution of Hertz contact with Tamaas
- Lecture 3: From friction to wear
- Exercise 3 (optional HW): Resolution of rough contact mechanics with Tamaas

Theory and simulations

And a bit of experiments, JF Molinari, lsms.epfl.ch

- Interdisciplinary research: Mechanical and Civil Engng, Mat. Science, Scientific Computing
- Development of novel numerical methods, from atoms to macroscopic scales, including: discrete (MD, DEM) and continuum approaches (FE, BEM); multiscale coupling
- High-Performance Computing
- Open data, open source, easy maintenance (shared developments, manuals, tutorials); <https://akantu.ch> and others



Damage and fracture mechanics

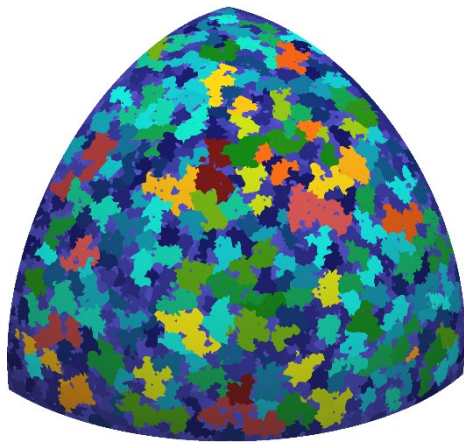
Materials and structures in extreme environments

Context: Extreme environments (explosions, impact, crash, high speed machining,...); Ageing of materials and structures (corrosion, ASR,...)

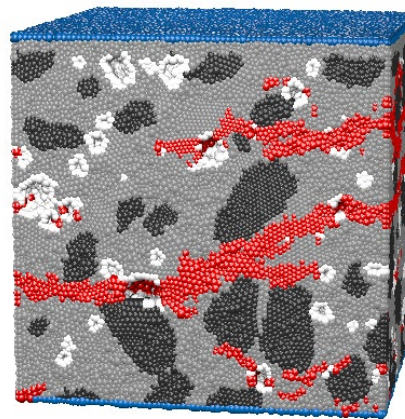
Objective: predict damage and crack network time evolution, in brittle and ductile materials

A few open questions: Onset of damage; Influence of material defects; Instabilities; Damage clustering; Damage mitigation; Energy absorption capacity

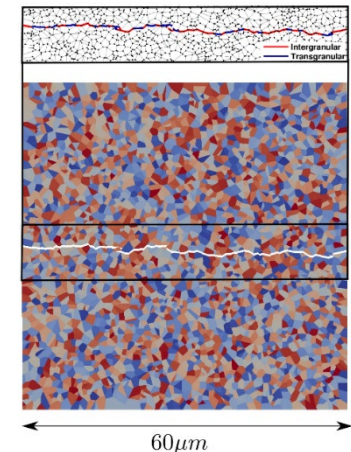
Methods: Massively parallel simulations, cohesive and continuum damage models



Dynamic fragmentation of a brittle shell
(colors represent fragments)



3D Damage evolution in concrete
(dark=hard inclusions; white=voids)



Transgranular and intergranular
cracking in a Si₃N₄ microstructure
(colors represent grains)

Tribology

Uncovering the origins of friction and wear; design of novel interfaces

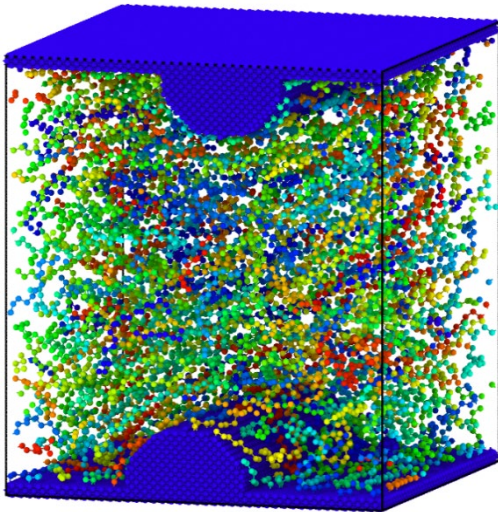
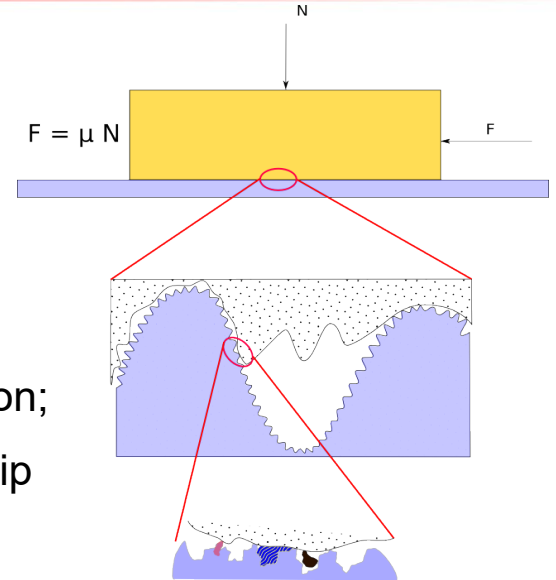
Challenge: multiscale nature of contact

Objective: direct predictions of friction and wear

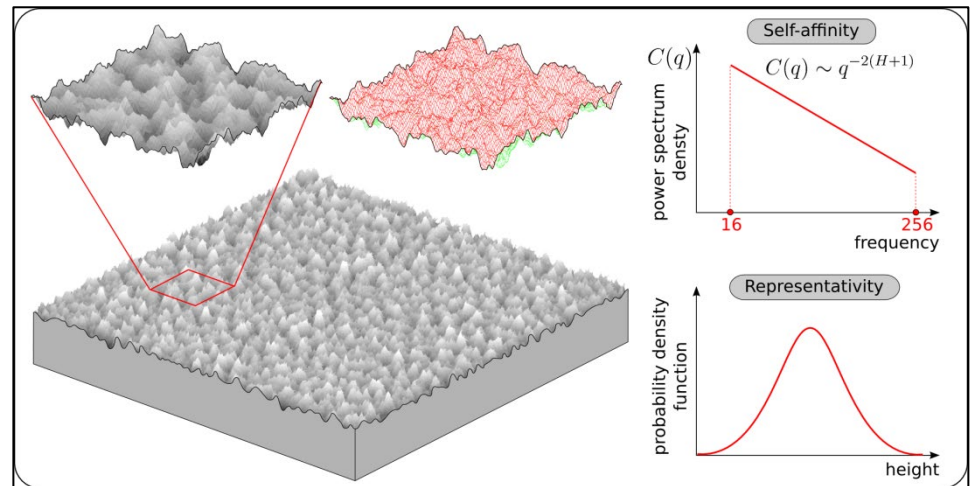
A few open questions:

Sealing pressure (percolation); Role of roughness; Mixed lubrication;
Plasticity at contacting asperities; Third bodies creation; Stick slip

Methods: Spectral methods, FE, MD



Direct computation of friction of a polymeric lubricant in presence of roughness



Representative rough surfaces

Tribology; what is friction?

An old science, but friction still unexplained

Maugis 1982, *“It is incredible that, all properties being known (surface energy, elastic properties, loss properties), a friction coefficient cannot be found by an a priori calculation”*.

Dowson 1979, *“... If an understanding of the nature of surfaces calls for such sophisticated physical, chemical, mathematical, materials and engineering studies in both macro and molecular terms, how much more challenging is the subject of ... interacting surfaces in relative motion*

Table 4.2 Early Table of Friction Coefficient Values Compiled by Rankin (1926) from the Results of Morin (1833)

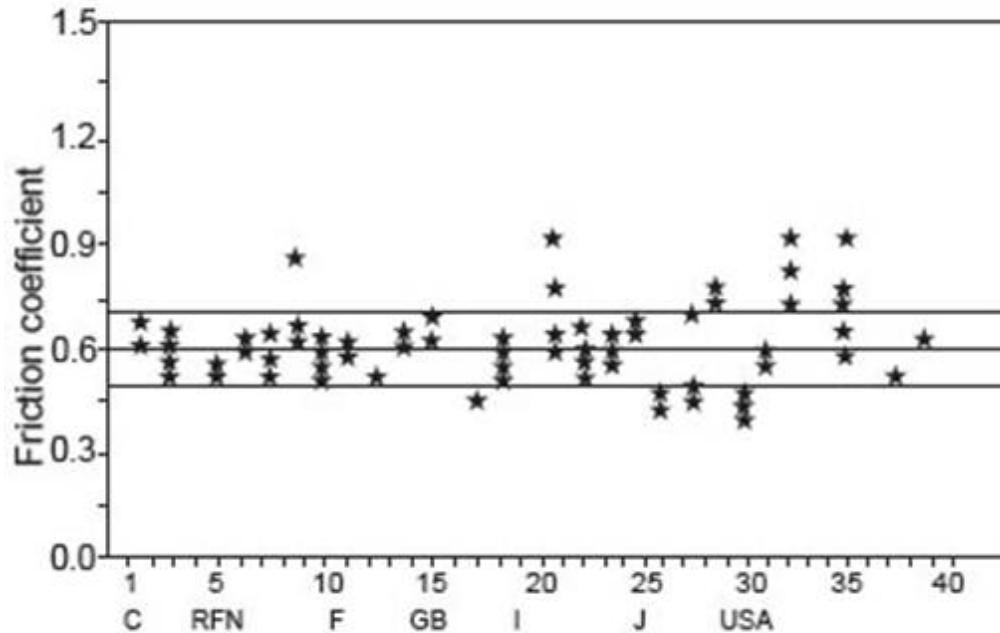
Material	f
Wood on wood, dry	0.25–0.50
Wood on wood, soapy	0.20
Metals on oak, dry	0.50–0.60
Metals on oak, wet	0.24–0.26
Metals on oak, soapy	0.20
Metals on elm, dry	0.20–0.25
Hemp on oak, dry	0.53
Hemp on oak, wet	0.33
Leather on oak	0.27–0.38
Leather on metals, dry	0.56
Leather on metals, wet	0.36
Leather on metals, greasy	0.23
Leather on metals, oily	0.15
Metals on metals, dry	0.15–0.20
Metals on metals, wet	0.30
Smooth surfaces, occasionally greased	0.07–0.08
Smooth surfaces, continually greased	0.05
Smooth surfaces, best results	0.03–0.036
Steel on agate, dry	0.20
Steel on agate, oiled	0.107
Iron on stone	0.30–0.70
Wood on stone	About 0.40
Masonry on brick work, dry	0.60–0.70
Masonry on brick work, damp mortar	0.74
Masonry on dry clay	0.51
Masonry on moist clay	0.33

Tribology; what is friction?

And how do you measure it?

VAMAS report. Vamas.org

“...the friction between identical steel and the aluminum oxide samples was tested in various labs in the world (VAMAS) ...surfaces of samples had the same roughness parameters, the ambient of every test was similar (special air conditioned rooms); the load applied on samples (pressures) and sliding speed were the same”.

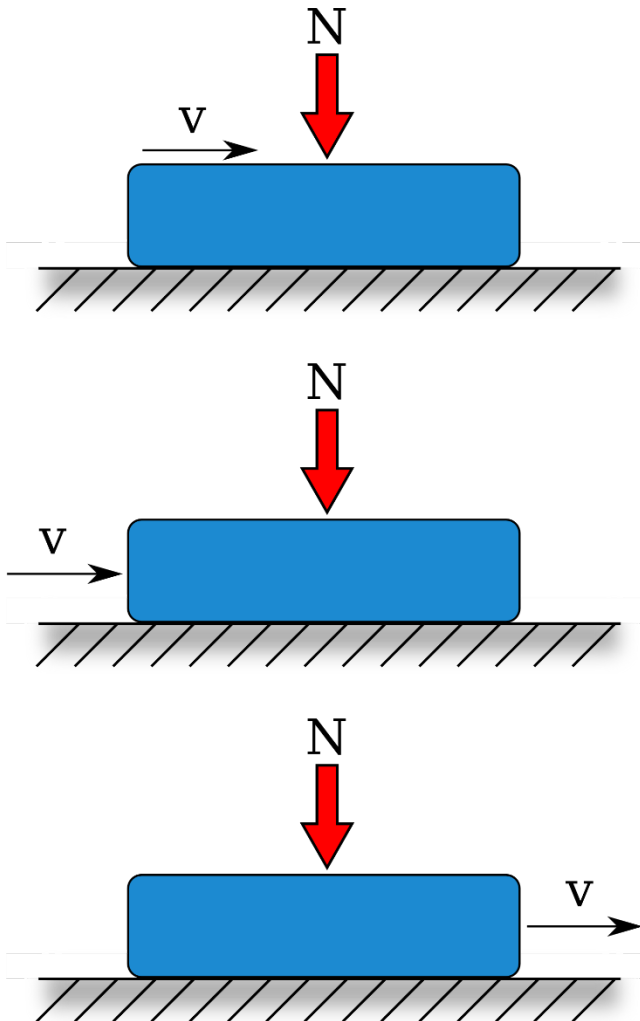


Jan van de Snepscheut: “In theory, there is no difference between theory and practice. But, in practice, there is.”

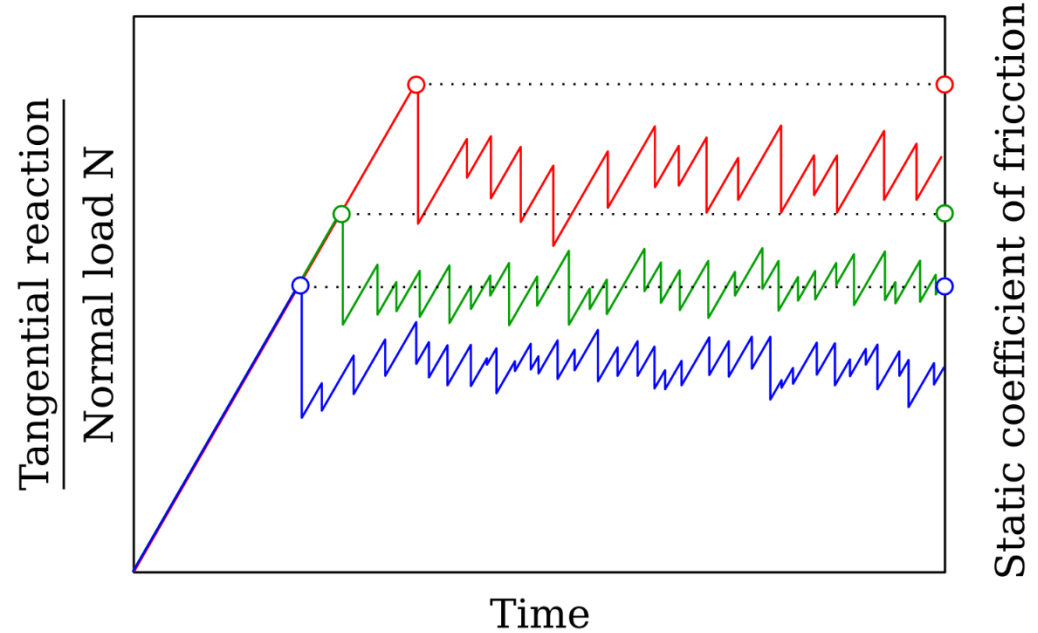
How to measure friction?

Friction as a system property; friction explained with LEFM

Experimental set-up



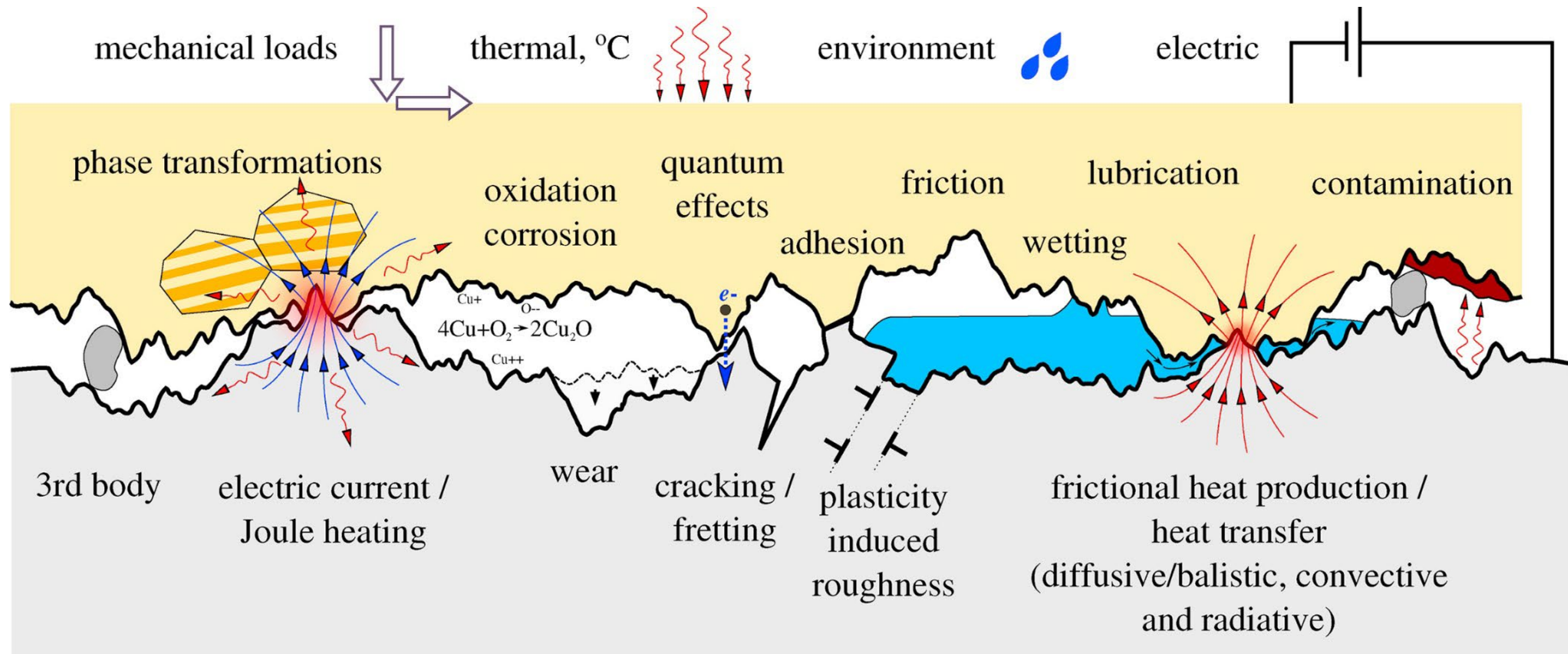
Measurements



Friction is a system property (materials, plus Boundary Value Problem)

Modeling friction across scales

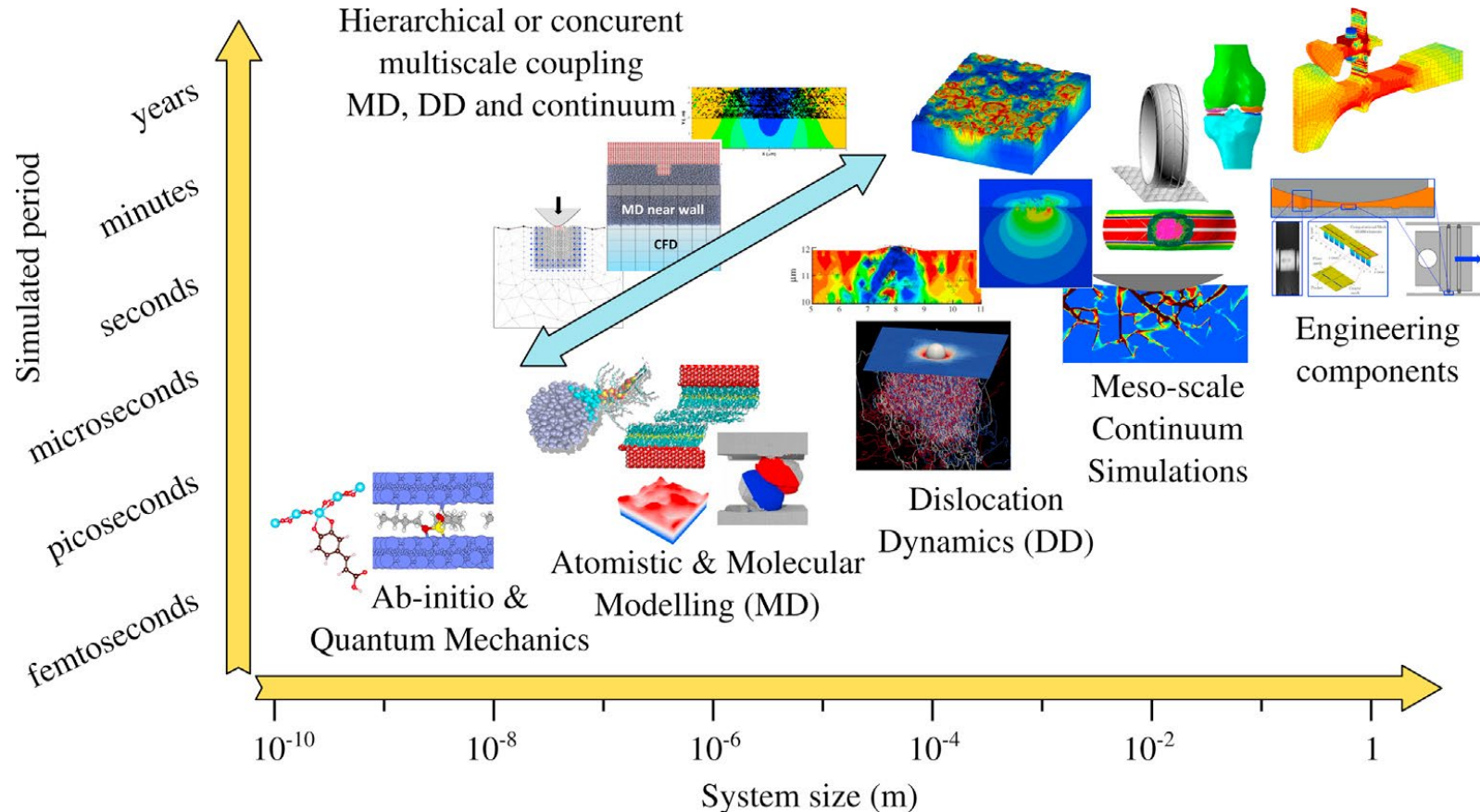
Many parameters to account for



Review paper: Vakis et al., Tribology International, 2018

Modeling friction across scales

A variety of techniques



Review paper: Vakis et al., *Tribology International*, 2018

Rough division: macroscale, mesoscale, nanoscale

A brief history of tribology

Slow progress over time...

- **Leonardo da Vinci** (1452-1519)
Unpublished manuscripts



- **Guillaume Amontons** (1663-1705)
Published basic friction law (1699)



- **Charles-Augustin de Coulomb** (1736-1806)
Confirmed Amontons basic friction law (1785)



- **Bowden & Tabor** (20th century)
Physics and chemistry of solids lab
at Cambridge in 1946
Founding fathers of Tribology



Basic friction laws

Inheritance of da Vinci

Amontons-Coulomb Laws:

- I. Friction force F proportional to applied load W
- II. Friction force F independent of apparent area of contact
- III. Friction force F independent of velocity for ordinary sliding speeds

Second law counterintuitive!

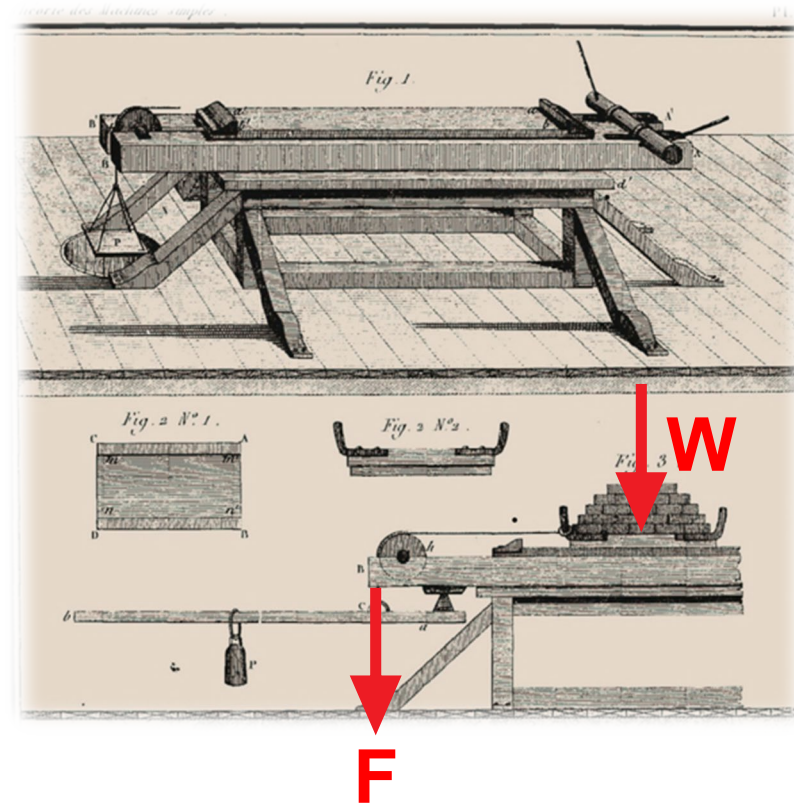
– Friction coefficient $\mu = \frac{F}{W}$

– But really $F = \mu W + F_{adh}$

Two viewpoints:

J.N. Israelachvili, in “Intermolecular and surface forces”: “These are three laws of friction that are all wrong and are also attributed to the wrong person”.

E. Popova, V.L. Popov, “The research works of Coulomb and Amontons and generalized laws of friction”.

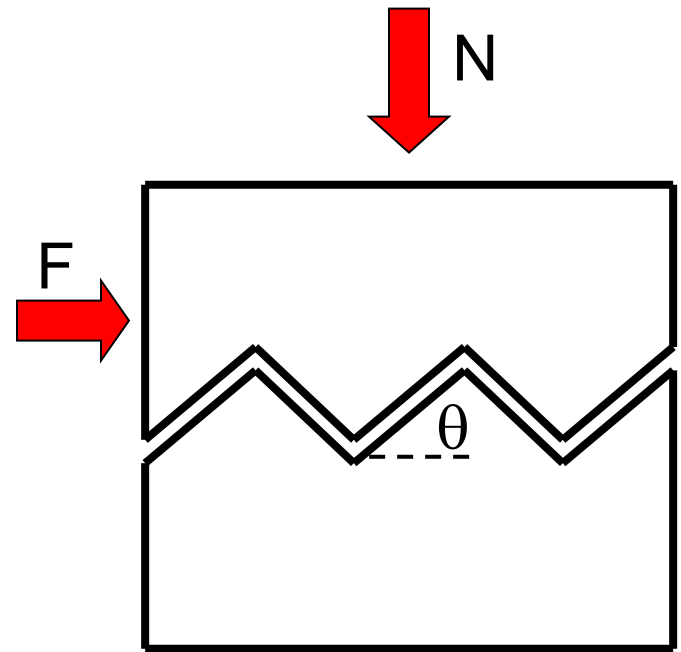


Can we predict friction?

A simple geometrical model

Geometric model (Amontons, Parents, Euler, Coulomb)

- Surfaces are rough
- Friction = force to lift up ramp formed by bottom surface
- $F = N \tan \theta \Rightarrow \mu = \tan \theta$
- But model has several problems...
 - 0 to infinite friction
 - Opposite to experimental data in presence of adhesion



An explanation
for friction ?

Bowden and Tabor (1950s)

Seminal contribution

- Real contact area
(much smaller than apparent area)
 - Sum of microcontacts

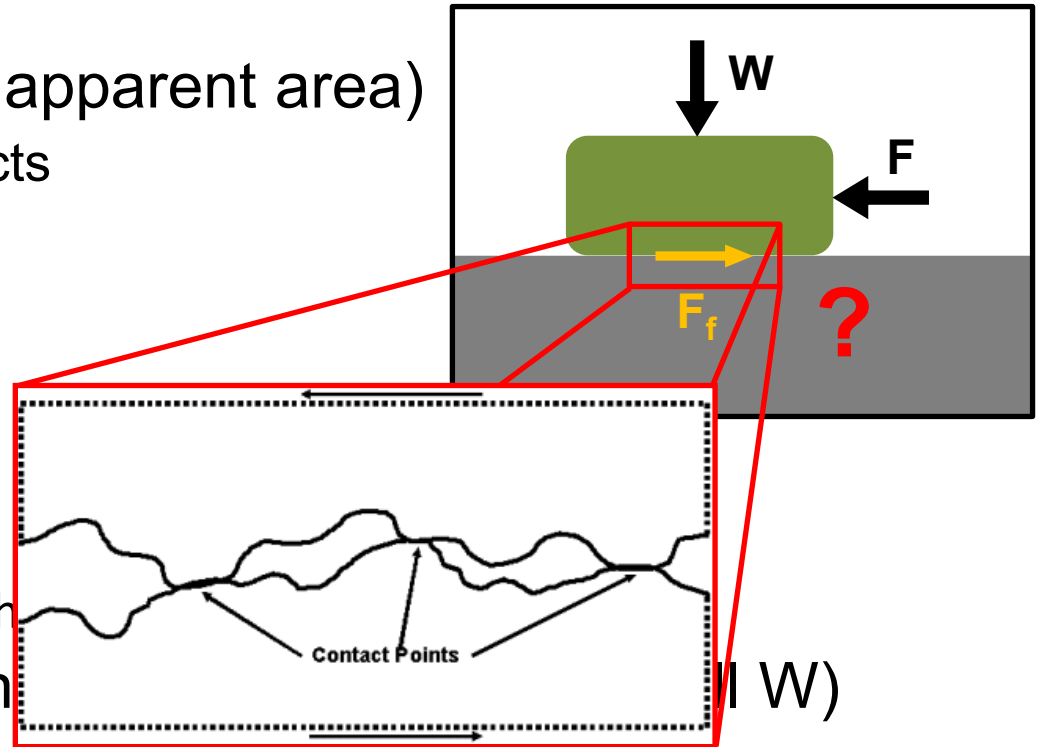
- Friction force

$$F_f = \sigma_s \cdot \Sigma_r$$

- Σ_r real contact area
- σ_s shear strength of the material

W increases $\Rightarrow \Sigma_r$ increases

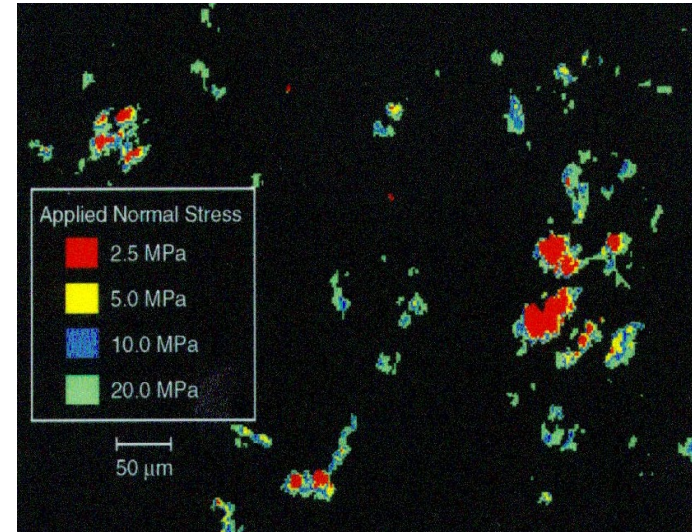
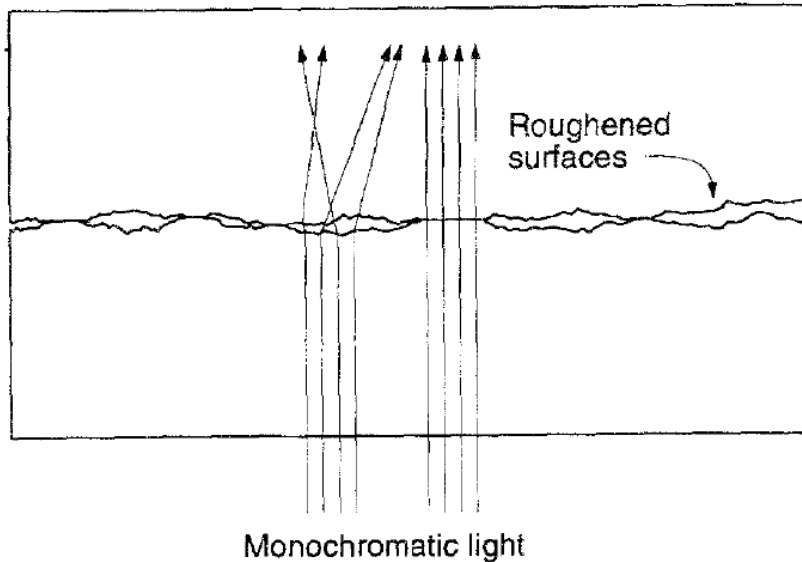
$\Rightarrow$ friction force increases



Micro contacts

Real versus nominal contact area

Micro contacts: seen with optical images, *Dieterich-Kilgore, Tectonophysics, 1994*



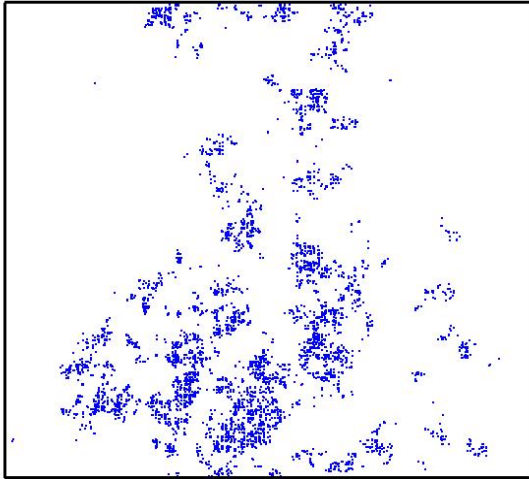
$$A_{real} \ll A_{nominal}$$

- da Vinci (1452-1519), Amontons (1663-1705), Coulomb (1736-1806):
friction coeff μ independent of $A_{nominal}$
- Explained by Bowden and Tabor (1950):

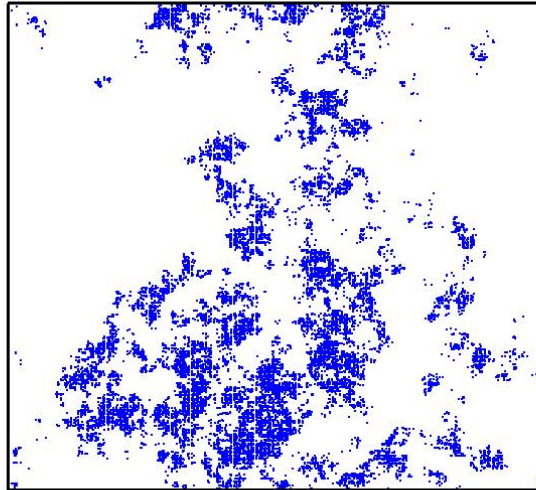
$$F = \sigma_j A_{real} = \mu N$$

Asperity interactions

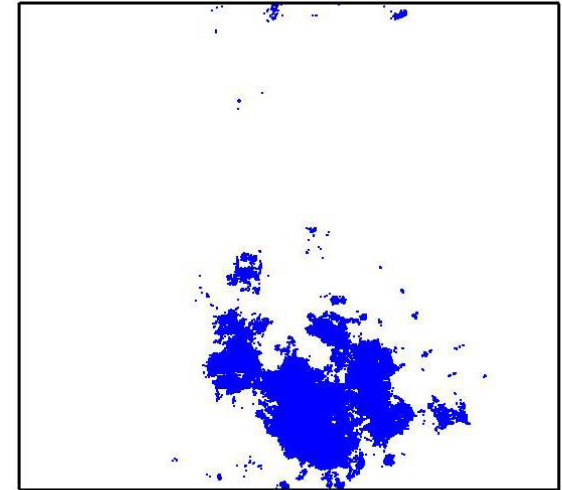
Mechanics matters !



Elastic contact with $A=0.0125$

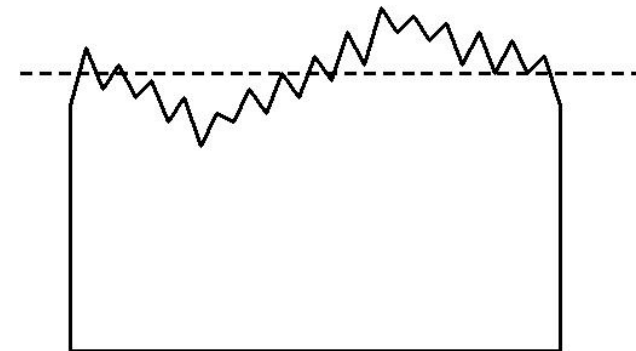


Elasto-plastic contact,
 $A=0.0335$
Perfectly plastic



Overlap or cut-off model,
 $A=0.03$

- Hyun et al., "Finite-element analysis of contact between **elastic** self-affine surfaces", *Phys. Rev. E*, 2004
- Pei et al., "Finite-element analysis of contact between **elasto-plastic** self-affine surfaces", *JMPS*, 2006

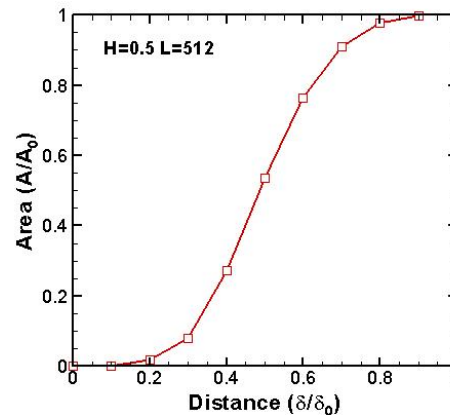
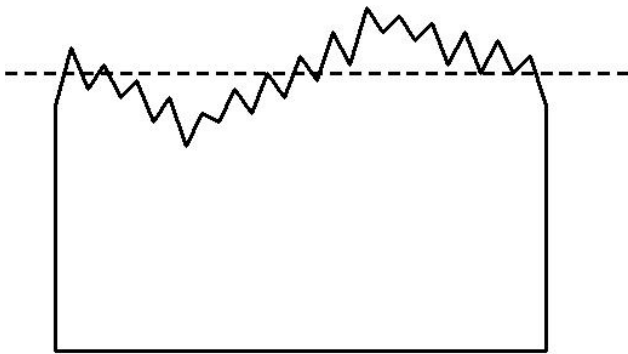


Theoretical models

Real contact area proportional to normal load

Hertz: elastic contact of elastic sphere $\Sigma_r \propto W^{\frac{2}{3}}$
(no friction, no adhesion)

Simplest model for roughness: the overlap (or cutoff) model (no mechanics)



Overlap model fails to capture linearity

Linearity captured (many asperities of various heights + mechanics):

- Greenwood and Williamson, 1966 (distribution of heights of spheres);
- Bush et al., 1975 (distribution of radii and aspherical asperities);
- Persson, 2001 (self-affine surfaces);
- Borri-Brunetto et al., 2001, Hyun, Pei, Molinari, Robbins, many others...

Connection with material prop.

Prediction of friction ?

- Fully plastic contact
 - Bowden & Tabor:
 - Plastic Greenwood and Williamson model (1966):

$$F_f = \sigma_s \cdot \Sigma_r$$

$$\Sigma_r = \frac{W}{H}$$



- Friction coefficient

$$\mu = \frac{F_f}{W} = \frac{\sigma_s \cdot \Sigma_r}{H \cdot \Sigma_r} = \frac{\sigma_s}{H} = \frac{\sigma_s}{p}$$

- But this models has also very limited predictive ability

Static and dynamic friction

Friction revisited

Advances in Physics,
Vol. 55, Nos. 3–4, May–June 2006, 279–348



Review paper: T. Baumberger, C. Caroli, 2006

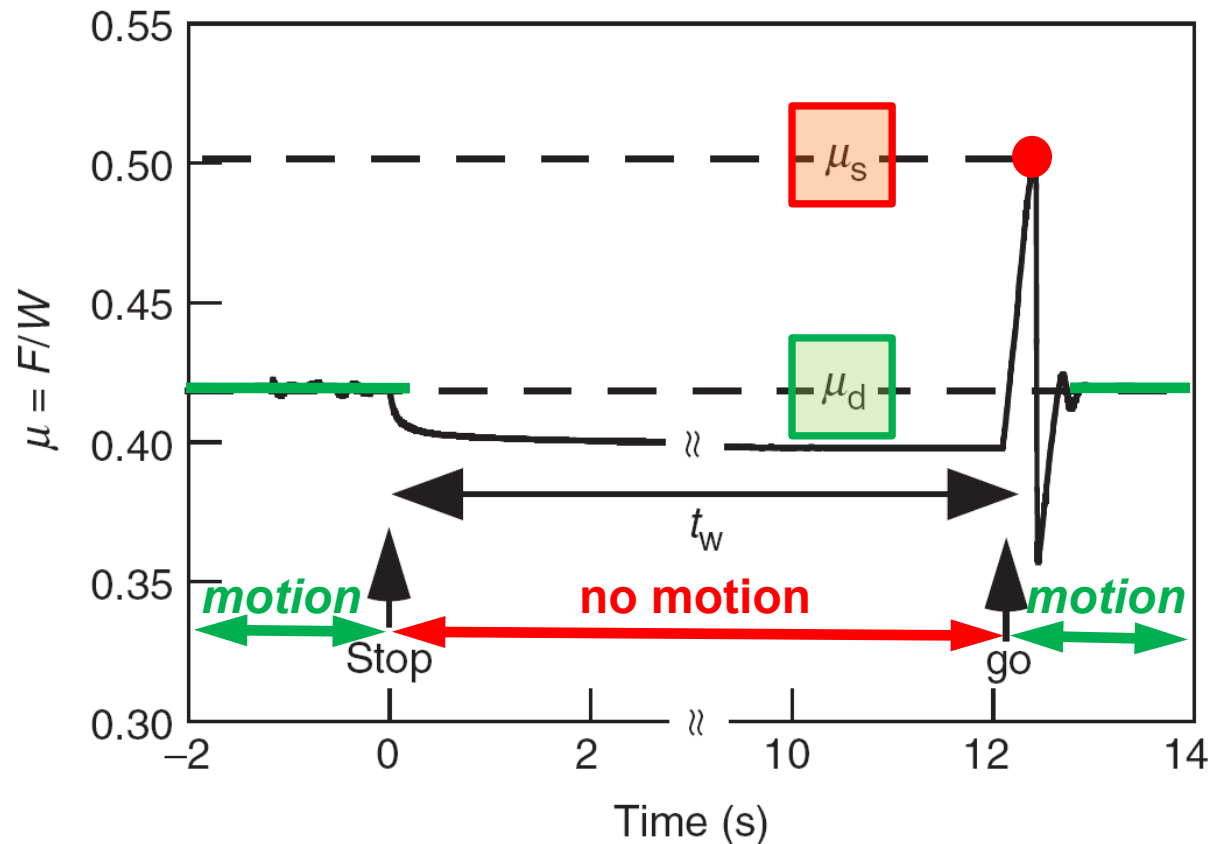
Solid friction from stick–slip down to pinning and aging

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Institut des Nano-Sciences de Paris, Université Pierre et Marie Curie-Paris 6,
Université Denis Diderot-Paris 7, CNRS, UMR 7588
Campus Bouicaut, 140 rue de Loumel, 75015 Paris, France

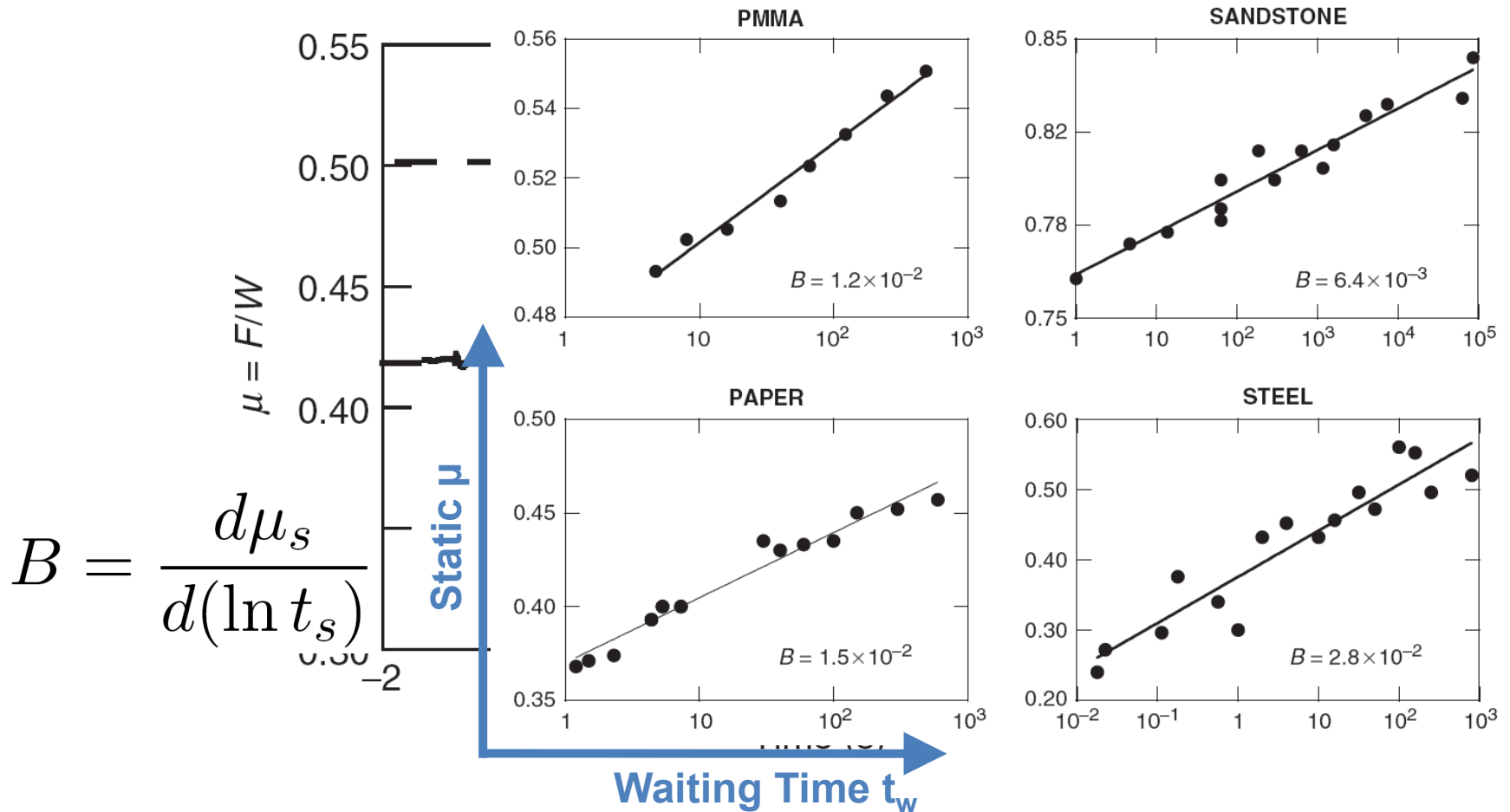
(Received 16 June 2005; revision received 30 March 2006;
accepted in revised form 31 March 2006)

Experiments show that



Rate and state friction

Aging of microcontacts, state variable



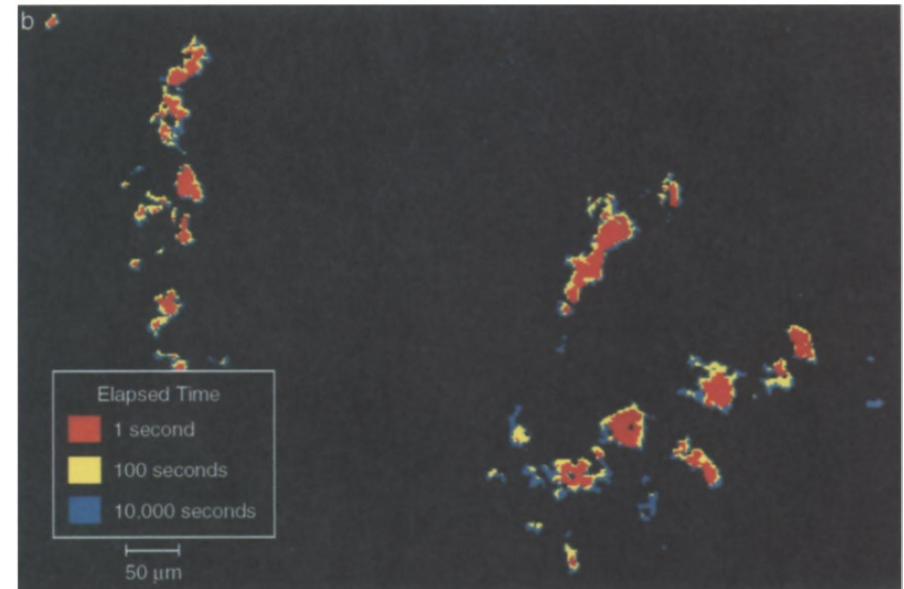
MCI state variable

Static friction

Bowden & Tabor Formulation

What could be a function of time?

$$F_f = \sigma_s \cdot \Sigma_r$$



GW: plastic mode

Plastic creep = increasing real contact area

Chemistry

Dieterich &
Kilgore (1994)

MCI state variable

Dynamic friction

Geometric aging:

- Phenomenologically:
(most simple equ.)
 D_0 : lengthscale

$$\phi(t) = \int_{t_0}^t \exp\left[-\frac{x(t) - x(t_1)}{D_0}\right] dt_1$$



- Non-linear differential equation:

$$\dot{\phi} = 1 - \frac{\dot{x}\phi}{D_0}$$

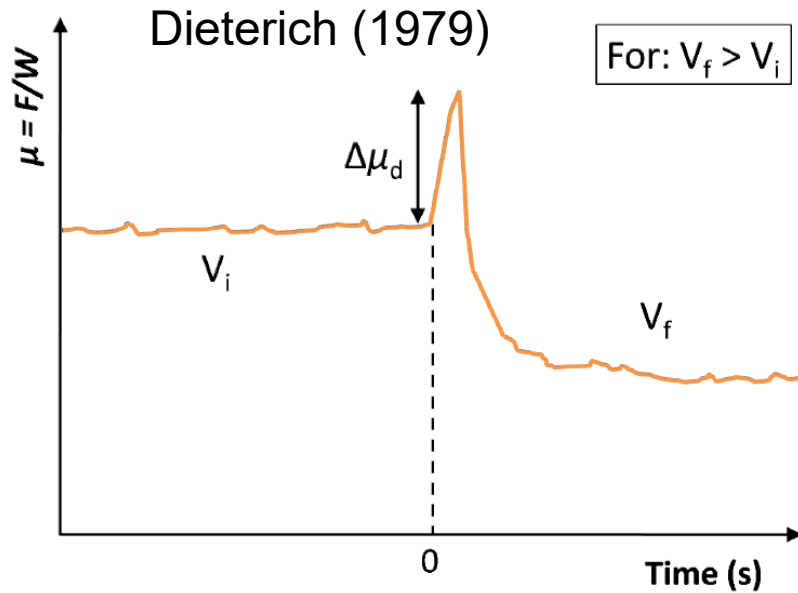
- State Variable



$$F = \sigma_s \cdot \Sigma_r(\phi)$$

MCI rate variable

Dependence on sliding velocity



Here velocity weakening, but evidence of velocity weakening and then strengthening behavior

$$\Delta\mu_d(V_i \rightarrow V_f) = A \cdot \ln\left(\frac{V_f}{V_i}\right)$$



$$\sigma_s(\dot{x}) = \sigma_{s0} \left[1 + \alpha \ln \frac{\dot{x}}{V_0} + O(\ln^2) \right]$$

Rate Variable



$$F = \sigma_s(\dot{x}) \cdot \Sigma_r(\phi)$$

Putting it together

Example of Rice and Ruina friction

$$\mu_d(\phi, \dot{x}) = \mu_d(V_0) + B \ln\left(\frac{\phi V_0}{D_0}\right) + A \ln\left(\frac{\dot{x}}{V_0}\right)$$

$$\dot{\phi} = 1 - \frac{\dot{x}\phi}{D_0}$$

- **Rate and state friction laws:**
- **Rice & Ruina (1983)**, Dieterich (1979, 1981), Ruina (1983), Rice (1983):
- Static Friction

$$\mu(t, 0) = \mu_d(V_0) + A \ln\left(\frac{0}{V_0}\right) + B \ln\left(\frac{V_0}{D_0} \cdot t\right)$$

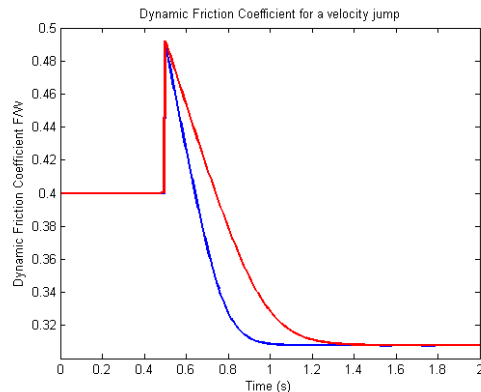
Rate and state friction

A

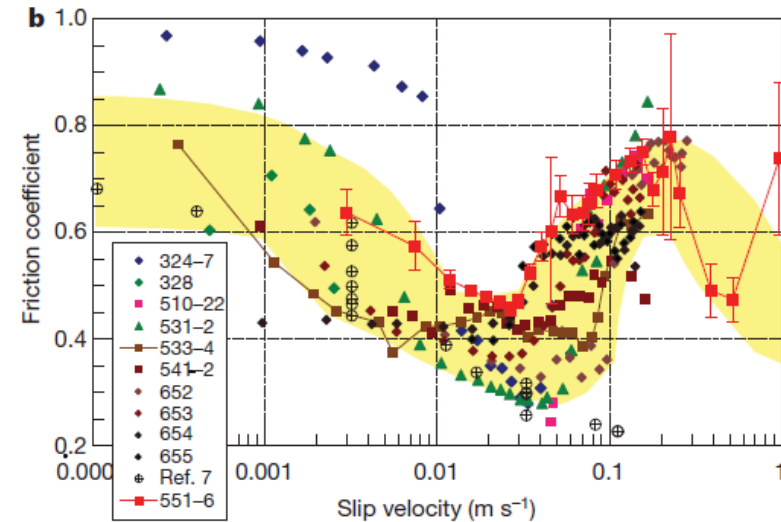
Generally **A** and **B** of the order of $\sim 10^{-3}$ - 10^{-2} and **D₀** is of the order of 1-100 μm (size of microcontacts)

If **A-B** > 0, friction is rate-strengthening

If **A-B** < 0, friction is rate-weakening



Parameter **D₀** increased (red curve)



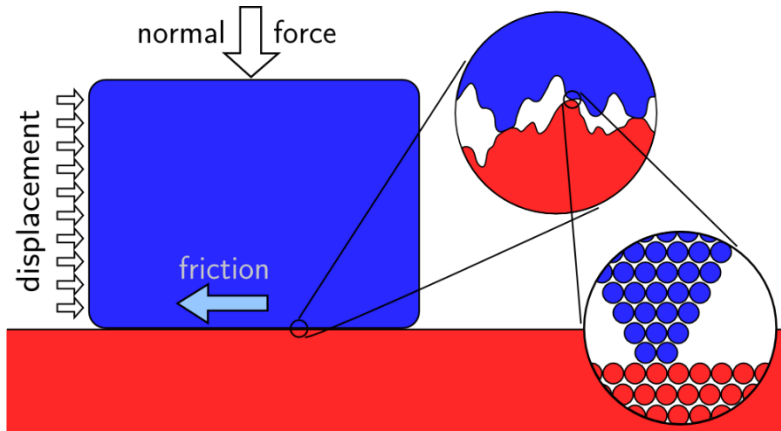
Friction coeff for granite
Reches and Lockner (2010)

Rate and state laws remain
phenomenological models

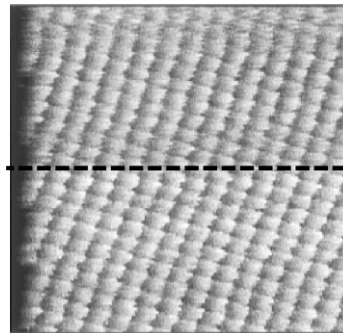
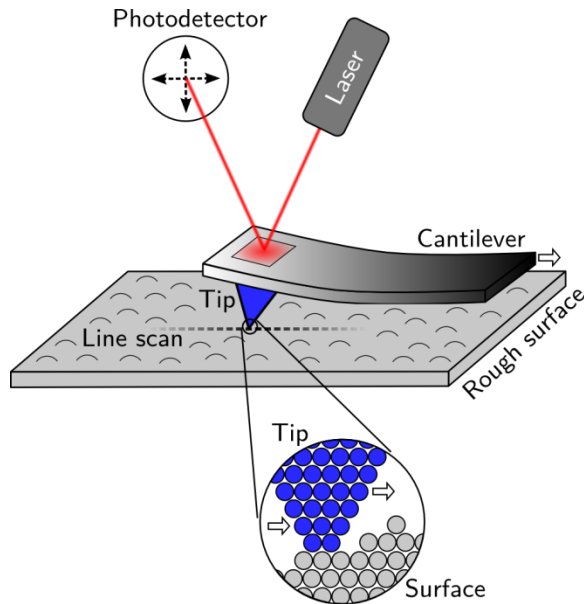
What is **D₀** lengthscale? and **A, B** ?...
Microscopic origins?

Nanotribology

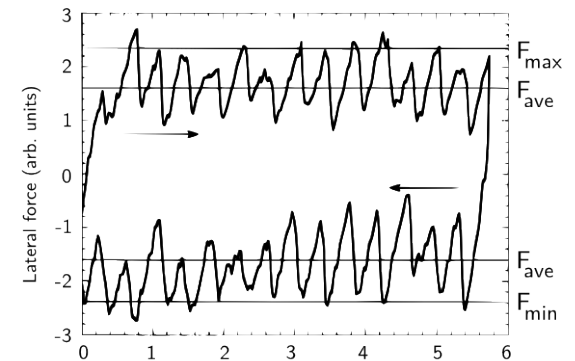
1990's onward



- Magnification until atomic level (AFM)
- Domain of nanotribology (nanoscience, nanotechnology)
- Possibility to elucidate molecular origins of friction
- Hope to control friction at the most intimate level (i.e. hard disk success story)
- Atomistic simulations to get insights



Lateral force image (6x6 nm)



Friction loop (line scan)

Summary

- Tribology is an old science with many open mysteries :
We still do not have predictive models for friction,
and experiments are not trivial,
and yet friction/wear crucial in so many applications...
- Ultimately friction emerges from what happens at microcontacts (real contact area is much smaller than nominal contact area)
- Static friction: Amontons-Coulomb (beware of adhesion)
- Dynamic friction; rate and state friction laws
- Mechanics matters