A Rough View of Friction and Adhesion

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QUARKNET, JHU, July 27, 2016

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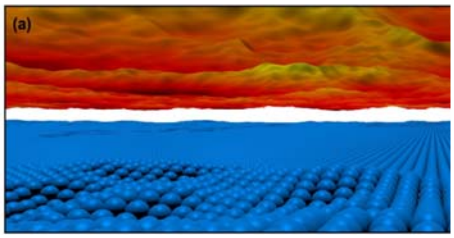
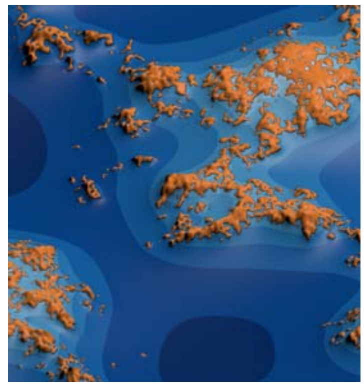




Supported by NSF, AFOSR, European Commission

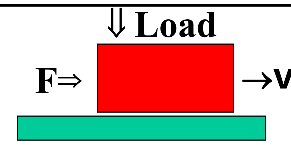
Friction and Every Day Life

- ☞ **Allows us to walk and drive**
- ☞ **Holds thread, nails, screws, bolts, bricks, …**
- ☞ **Holds fabric and knots together**
- ☞ **Determines how things feel, texture of food**
- ☞ **Wastes energy → ~20% in car engine**
- ☞ **Produces wear → abrades material**
  → destroys lubricants

- ☞ **Central to earthquake triggering, dynamics**

Economic cost of poor friction control more than 2% of GNP

Friction Laws ?



Static friction F_s

→ minimum force needed to initiate sliding.

Kinetic friction $F_k(v)$

→ force to keep sliding at velocity v.

Typically, $F_k(v)$ varies only as log(v) and $F_s > F_k(v)$ at low v

Amontons' Laws (1699):

- Friction ∝ load → constant $\mu = F/\text{Load}$.
- Friction force independent of apparent contact area A_{app}.

But: Amontons coated all surfaces with pork fat

$F \propto A_{app}$ for soft, flat solids, polymers, tape

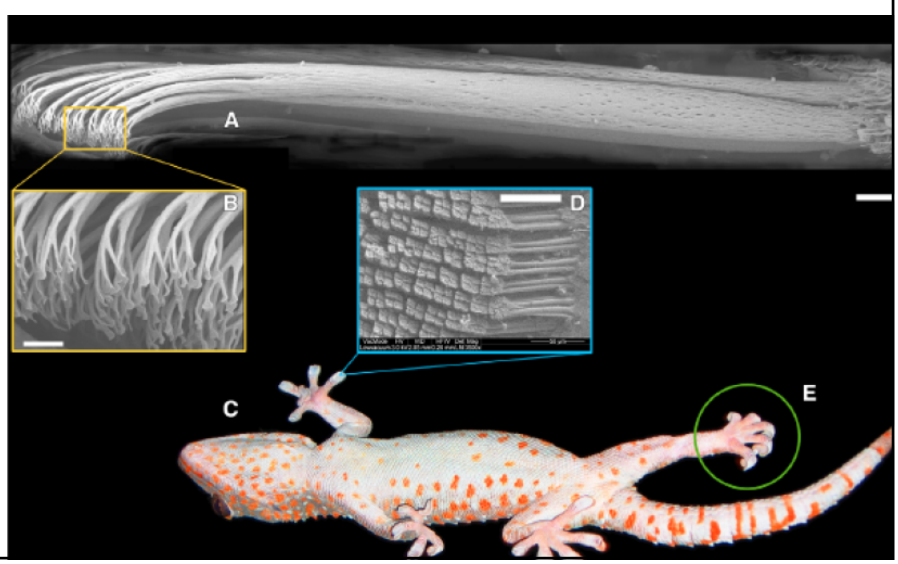
μ often changes with load ⇒ friction for load ≤ 0

Friction depends on history (rate-state models)

Laws violated in nanoscale experiments & simulations

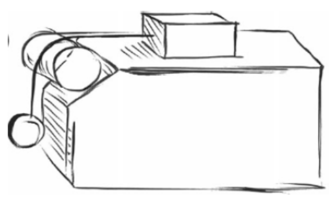
⇒ solids slide like fluids, fluids stick like solids

Many Systems Have Friction with Load ≤ 0
Geckos, tape, putty, … stick on walls or ceilings



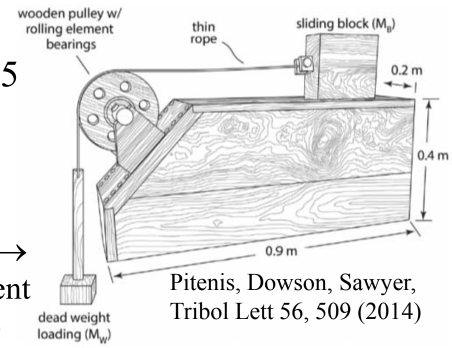
Friction Laws ?

Davinci's Experiments → μ=0.25

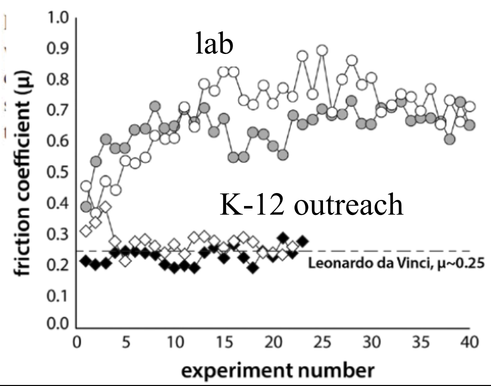


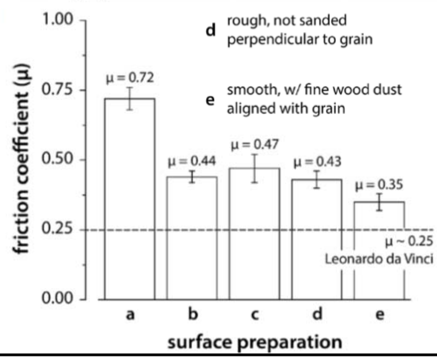
←DaVinci sketch

Modern → experiment



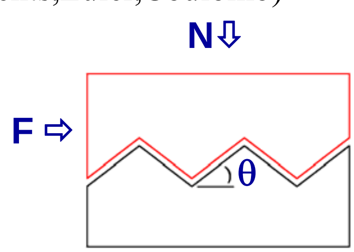
Pitenis, Dowson, Sawyer, Tribol Lett 56, 509 (2014)





Why Friction ∝ Load & Independent of Apparent Area?

Geometric explanation (Amontons,Parents,Euler,Coulomb)
→ Surfaces are rough
→ Friction = force to lift up ramp formed by bottom surface
→ $F=N \tan\theta \Rightarrow \mu=\tan\theta$



Problems:
→ Most surfaces can't mesh
→ Roughening can reduce μ (hard disks)
→ Monolayer of grease changes μ not roughness
→ Once over peak, load favors sliding ⇒ kinetic friction=0
→ Friction proportional to apparent area not load in some cases

Static friction ⇨ Force to escape metastable state
How can two surfaces always lock together?
Kinetic friction ⇨ Energy dissipation as slide
Why is this correlated to static friction? Why does T matter?

Many Mysteries Remain About Friction's Origins

Friction determined by processes on wide range of scales

•Friction comes from interactions between atoms in repulsive contact < nm → sensitive to exact chemistry, atomic geometry, … that is often unknown

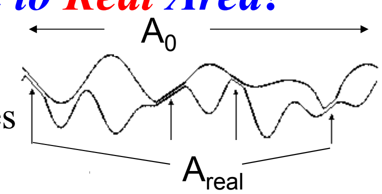
•Surfaces rough on nm to mm scales
Area and geometry of contacting regions determined by roughness and long-range elastic and plastic deformation.

•Adhesion typically ignored in determining contact & friction

No general theory for behavior far from equilibrium
  Equilibrium ⇒ stable state minimizes free energy
  Far from equilibrium ⇒ must solve dynamical equations

Computer simulations allow controlled "experiments"
  Explore trends, discover unanticipated mechanisms

Is Friction Proportional to Real Area?



Common view since mid 1900's
Surfaces rough on many length scales
  and usually find $A_{real} << A_0$

Measurements and theory ⇒ $A_{real} \propto$ Load in many cases
  ⇒ get Amontons' laws if constant shear stress τ_{shear}
    friction = $A_{real}\ \tau_{shear} \propto$ Load

Also explains many exceptions to Amontons' laws
  Adhesion ⇒ A_{real} nonzero at zero load, still have friction
  Friction $\propto A_0$ for soft materials because $A_{real} \approx A_0$
  Friction $\propto A_{real}$ predicted by continuum theory for
    single asperities with radii from nm to mm
    $\propto N^{2/3}$ for non-adhesive solids (Hertz theory)
    Bowden & Tabor – hard sphere on polymer

Surfaces Often Rough on Many Scales ⇒ Self-Affine

Artificial landscape – computer generated self-affine fractal

http://thornyissues2.blogspot.com/2014/06/beauty-in-nature-fractals_21.html

Surfaces Often Rough on Many Scales ⇒ Self-Affine

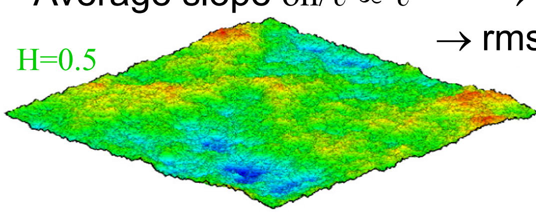
Height variation δh over length $\ell \rightarrow \delta h \propto \ell^{H}$ $0<H<1$

for wavelengths $\lambda_s < \ell < \lambda_L$ - range can matter

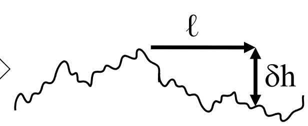
Total height variation: $h_{rms} \sim \lambda_L^{H}$

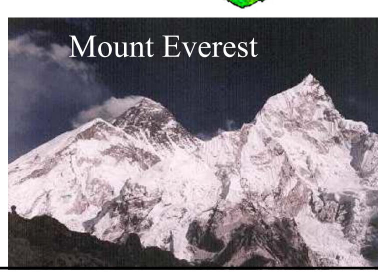
Average slope $\delta h/\ell \propto \ell^{-(1-H)} \rightarrow 0$ as ℓ increases

$\rightarrow$ rms slope $h'_{rms} \sim \lambda_s^{-(1-H)}$

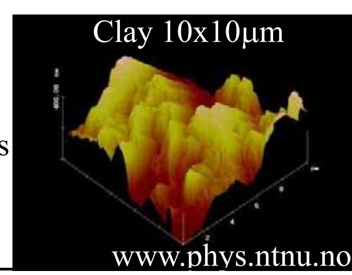


⇨





Examples with H=0.8



Surfaces Often Rough on Many Scales $\Rightarrow$ Self-Affine

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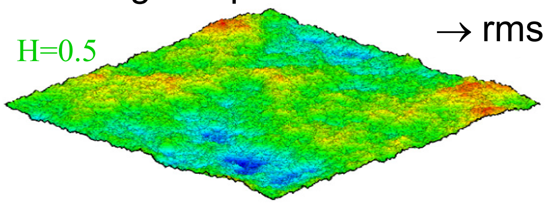
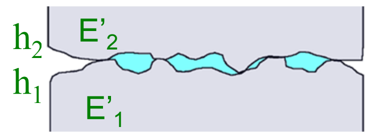
H=0.5





Continuum theory (contact not friction):

2 rough elastic solids $\Rightarrow$ rough rigid and elastic flat

heights h_1, h_2 $\Rightarrow$ $h=h_2-h_1$

Moduli E'_1, E'_2 $\Rightarrow$ $E'=1/(1/E'_1+1/E'_2)$

$E'=E/(1-\nu^2)$; E=Young's modulus, ν=Poisson ratio

Surfaces Often Rough on Many Scales $\Rightarrow$ Self-Affine

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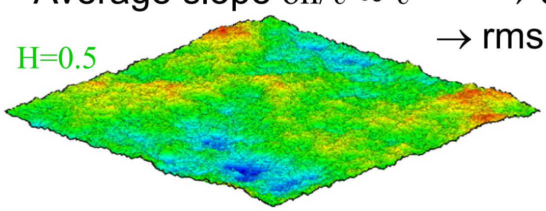
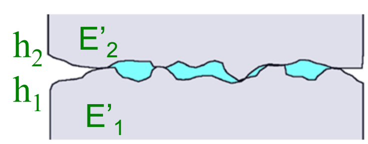




Finite-element method for wide range of H, etc..

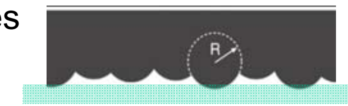
Hyun, Pei, Molinari, & Robbins, PRE70, 026117, '04; JMPS 53, 2385, '05; Trib Int. 40, 1413, '07

Atomistic molecular dynamics (MD) or Greens function

Akarapu, Sharp & Robbins, PRL 106, 001504301 (2011), Pastewka & Robbins, PNAS, 111(9), 3298 (2014).

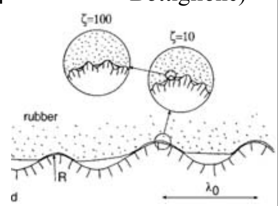
Nonadhesive Elastic Contact of Rough Surfaces

- Hertz - Single spherical contact $A_{real} \propto N^{2/3}$, N=normal load
- Many spheres, different heights-Greenwood & Williamson
  Contact where undeformed surfaces overlap (Bearing area model)
  N ⇒force to flatten each asperity
  →Predicts $A_{real} \propto N$, *explains friction* $\propto$*N?*
  BUT $A_{real} \propto N$ only at very small $A_{real}/A_{app} < 10^{-4}$
  Wrong long-range correlations.



- Scaling Theory: Persson 2001
  Area & pressure as increase resolution
  Gives $A_{real} \propto N$, right spatial correlations

(Carbone & Bottiglione)



- Finite-element continuum for wide range of H, etc.. Hyun, Pei, Molinari, & Robbins, PRE70, 026117, '04; JMPS 53, 2385, '05; Trib Int. 40, 1413, '07
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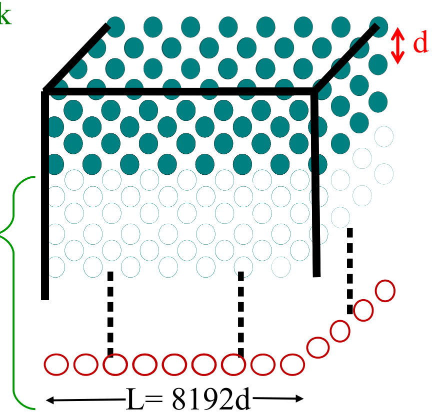
Molecular Dynamics up to Micrometer Scales

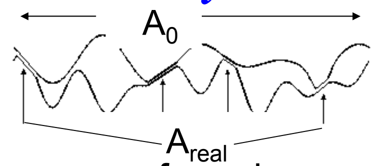
Challenge: elastic interactions - long-range →need cube of size L^3
Use multiscale approach for L~ 3 μm ~10^{12} atoms

At surface - molecular dynamics (MD) simulations of ~10^8 atoms
At depth where displacements are small only need linear response
→Use atomic Greens function in bulk
Seamless boundary conditions
Similar to Campana & Muser
Extended to long range interactions, analytic GF, multibody potentials
EAM, Stillinger-Weber, …
Periodic boundaries or semi-infinite



Campaña, Müser, *Phys. Rev. B* 74, 075420 (2006); Pastewka, Sharp, Robbins, *Phys. Rev. B*86, 075459 (2012)

Area ∝ Load ⇒ Dimensional Analysis



Only material property is
contact modulus $E' = E/(1-\nu^2)$

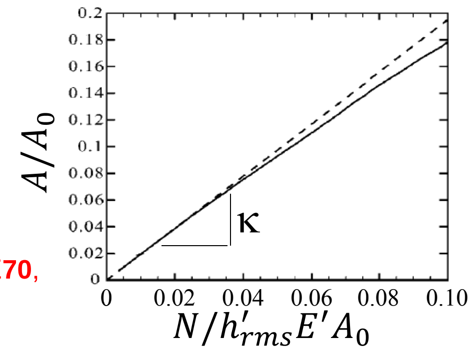
$A_{real}\, E'/\text{Load}$ is dimensionless

rms slope h'_{rms} – dimensionless measure of roughness

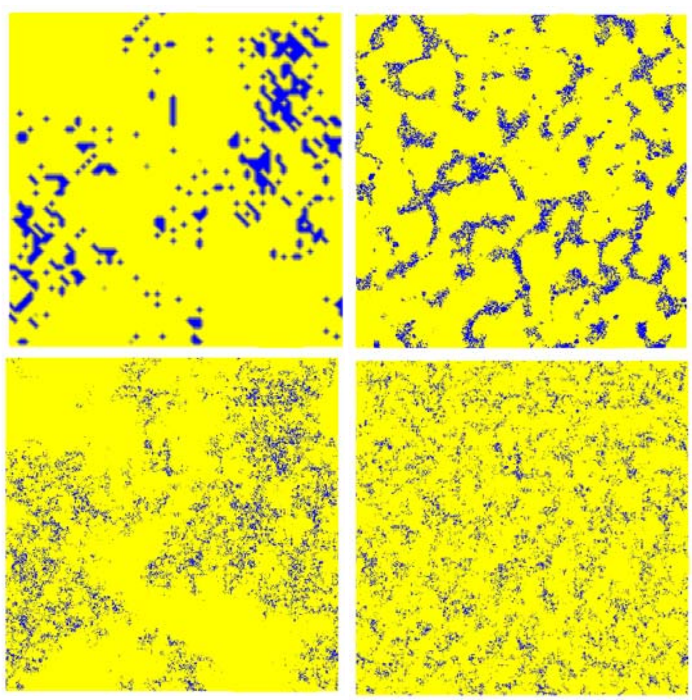
$A_{real} = \kappa\, \text{Load}/ E'\, h'_{rms}$ - steeper → less area
→ independent of λ_L, h_{rms}, system size

Numerical solution:
$\kappa \sim 2$ for all H, h'_{rms}, ν, …

Fixed pressure in contact
$p_{rep} = E'\, h'_{rms}/\kappa$



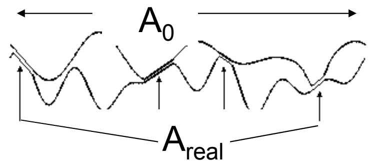
Hyun, Pei, Molinari, & Robbins, PRE **70**, 026117, '04; JMPS **53**, 2385, '05; Trib Int. **40**, 1413, '07



Very different surface roughness profiles give same κ=2.0

Results for different synthetic & experimental surfaces at $A/A_0 \sim 0.1$

Dimensional Analysis- Elastic, No Adhesion



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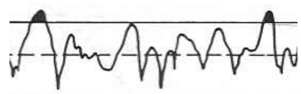
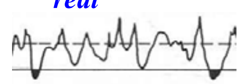
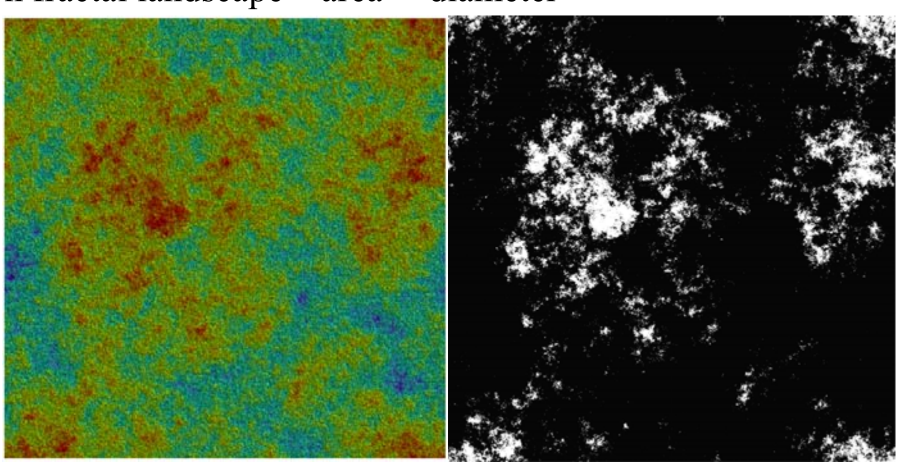
→ independent of λ_L, h_{rms}, system size
Numerical solution: $\kappa \sim 2$ for all H, h'_{rms}, ν, …
Very different analytic models→predict similar κ
Bearing area – Greenwood-Williamson $\kappa = (2\pi)^{1/2} \approx 2.5$
Persson's scaling theory $\kappa = (8/\pi)^{1/2} \approx 1.6$
Bearing area – contact where undeformed surfaces overlap⟶ no asperity interactions
→wrong spatial structure



Models Predict Very Different Contact Geometry For Same Rough Surface and A_{real}

Bearing area model ⟹ Contacts like lakes on fractal landscape – area ∝ diameter^2

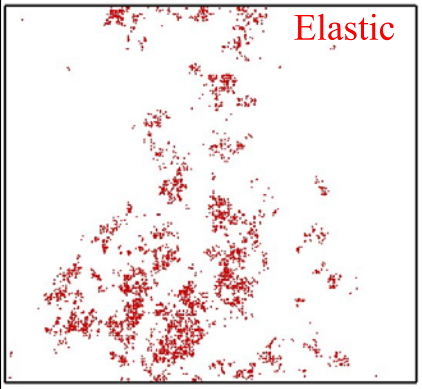


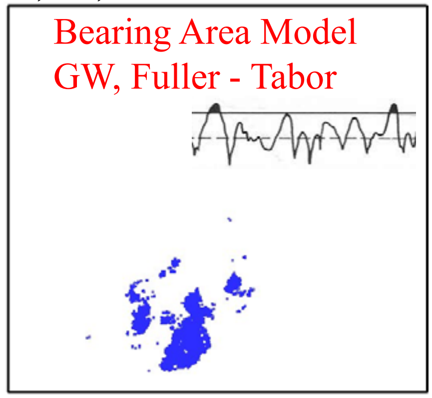


Red higher, blue lower   White regions contacts=lakes

Models Predict Very Different Contact Geometry For Same Rough Surface and A_{real}

Pei, Hyun, Molinari, & Robbins, *J. Mech. Phys. Sol. 53*, 2385, '05



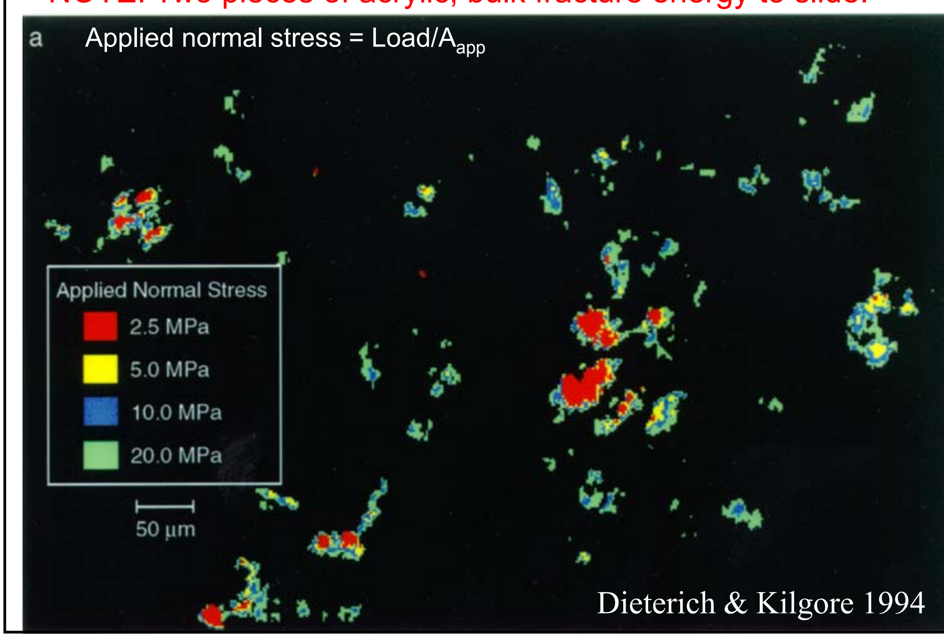


Connected regions fractal	non-fractal
Area $a_c \propto r^{D_f}$ with $D_f \approx 1.6$	$D_f = 2$
Most area in smallest a_c	Most area in largest a_c

Dramatic change in conductance, stiffness, adhesion,…

Contact area ∝ Load Even with Adhesion!

NOTE: Two pieces of acrylic, bulk fracture energy to slide!



Why aren't all surfaces sticky?

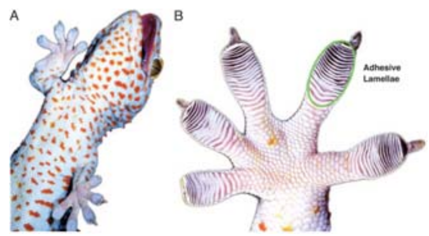
Adhesion Paradox (Kendall)

At atomic scales – surfaces feel van der Waals attraction

⟶ ~10MPa → $1cm^2$ supports 100kg

At macroscopic scales – surfaces not sticky

⟶ no force to separate, contact theories ignore adhesion

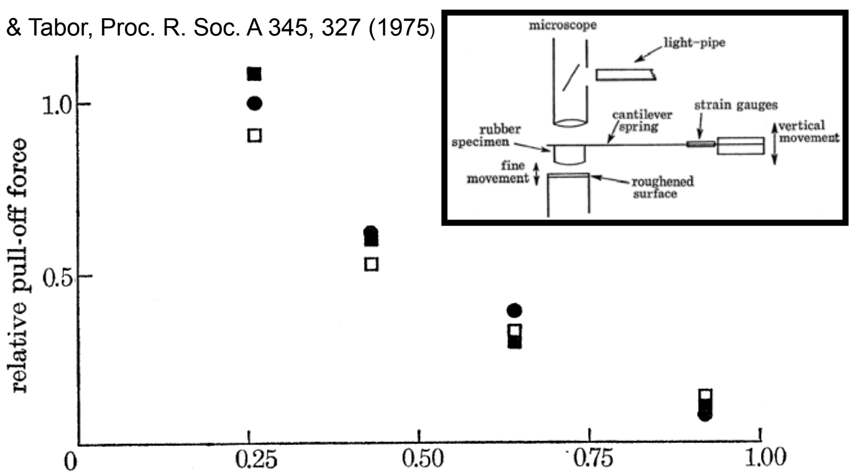


Hansen, Autumn, PNAS 102, 385 (2005)

Jeong, Suh, Nano Today 4, 335 (2009)

Roughness Eliminates Adhesion

Fuller & Tabor, Proc. R. Soc. A 345, 327 (1975)



Roughness – center line average in μm

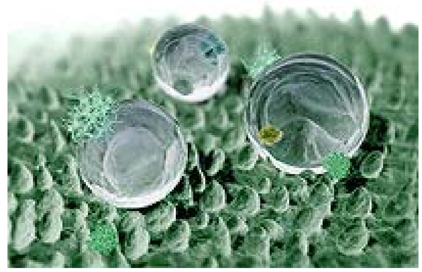
Roughness lowers area close enough to adhere

Only see adhesion here because use soft material, rubber

Past theories – qualitatively wrong ⇒ h' not h_{rms}

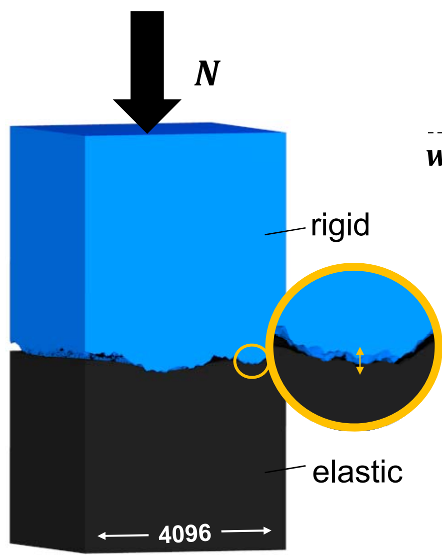
Roughness and Superhydrophobicity

Roughness also limits spreading of liquid on solid,
but need very high surface slope >1 to make nonwetting

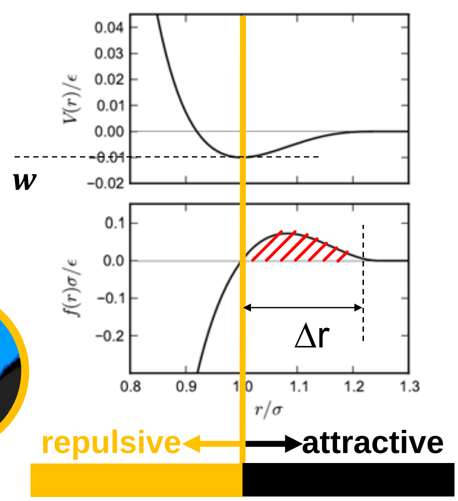


http://en.wikipedia.org/wiki/Lotus_effect

Calculation Methods



Volume $(4096a_0)^3$

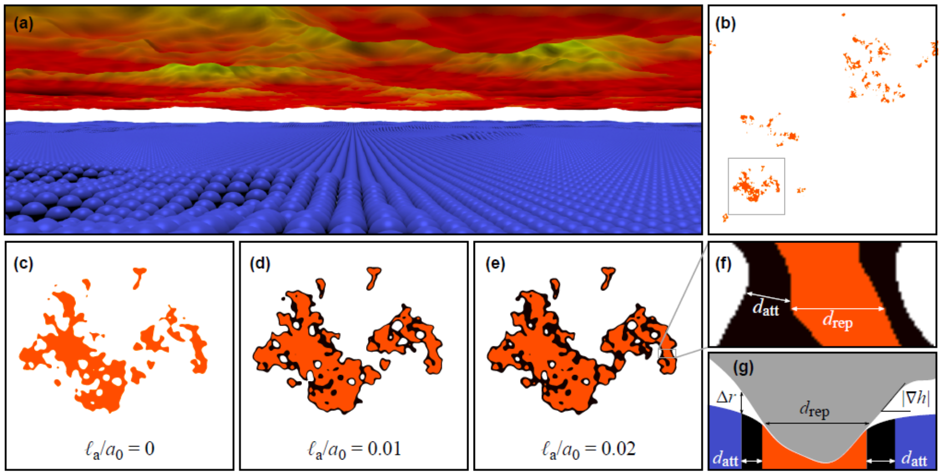


average attractive stress $\frac{w}{\Delta r}$

adhesion length $\ell_a = \frac{w}{E'}$

Contact area = A_{rep} where atoms repel

Geometry ⟶ Analytic prediction for κ



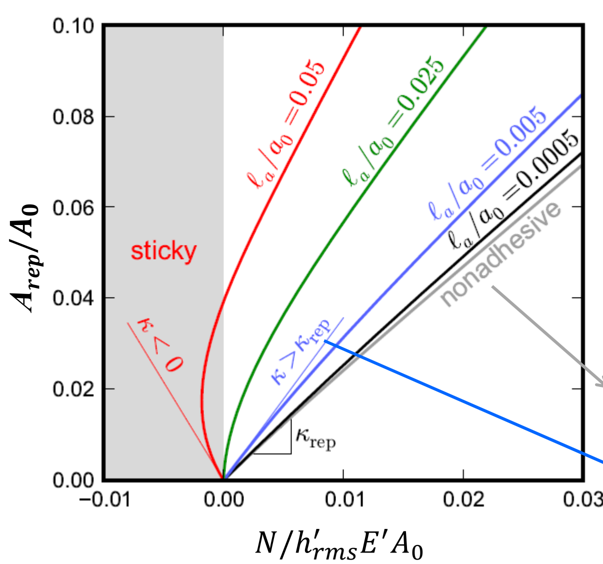
Adhesion doesn't change geometry just adds attraction – DMT limit

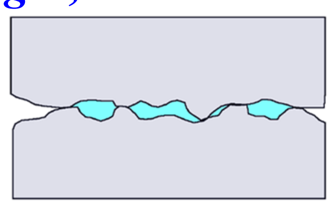
Fix N_{rep} ⟶ A_{rep} indep. of l_a ⟹ $N_{rep}=A_{rep}\,p_{rep}$, $p_{rep} = E'\,h'_{rms}/\kappa_{rep}$

⟶ Attractive area A_{att} (black) spreads around perimeter of A_{rep}

$N_{att}=A_{att}\,p_{att}$, $p_{att} = w/\Delta r$ and $A_{att} \propto A_{rep}$ because fractal

Add Adhesion - First κ changes, then sticks





h'_{rms} - rms slope

E' - contact modulus

$\ell_a = w/E'$

a_0=atomic spacing

$$\kappa_{rep} = \frac{h'_{rms}E'A}{N} \approx 2$$

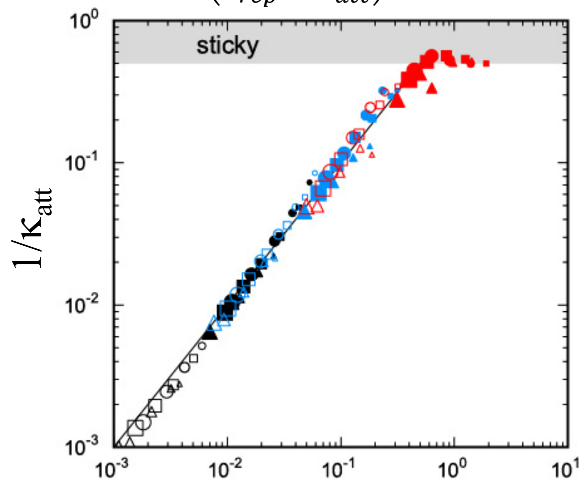
$1/\kappa = 1/\kappa_{rep} - 1/\kappa_{att}$

κ< 0 ⟶ sticky

κ also describes changes in stiffness and conductance

Predicted and Measured κ_{att}

$$N = N_{rep} - N_{att} = \left(\frac{1}{\kappa_{rep}} - \frac{1}{\kappa_{att}}\right) A_{rep} h'_{rms} E'$$



ℓ_a/a_0=0.0005
ℓ_a/a_0=0.005
ℓ_a/a_0=0.05
H=0.3 ▲
H=0.5 ■
H=0.8 •
λ_s/a_0=4, 8, 16, 32, 64 indicated by symbol size
h'_{rms}=0.3 □
h'_{rms}=0.1 ■

Predict $1/\kappa_{att} = \frac{\pi \ell_a}{2h'_{rms}}\left(\frac{2\Delta r}{h'_{rms} d_{rep}}\right)^{\frac{2}{3}}$

Pastewka and Robbins, PNAS, 111(9), 3298-3303 (2014).

Consequences

Necessary condition for atomic surfaces

Ratio of adhesive to repulsive pressure $\frac{w/\Delta r}{E' h'_{rms}/\kappa_{rep}} = \frac{\kappa_{rep}\ell_a}{\Delta r\ h'_{rms}} > 1$

$\Delta r \sim a_0$ – atomic spacing⟶ w/(E'a_0)=ℓ_a/a_0 >0.5 h'_{rms}

- Diamond/diamond bond ℓ_a/a_0 =0.06, LJ ℓ_a/a_0 =0.05
  Adhesion if $h'_{rms} < 0.1$
- Passivated surface – van der Waals at interface
  Reduce ℓ_a/a_0 100-fold
  ⟶Adhesion if $h'_{rms} < 0.001$ (wafer bonding)

Almost none of the surfaces around us show macroscopic adhesion even if nm scale attraction

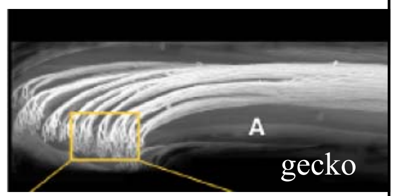
Consequences

Necessary condition for atomic surfaces

Ratio of adhesive to repulsive pressure $\frac{w/\Delta r}{E' h'_{rms}/\kappa_{rep}} = \frac{\kappa_{rep}\ell_a}{\Delta r\ h'_{rms}} > 1$

$\Delta r \sim a_0$ – atomic spacing⟶ $w/(E' a_0) = \ell_a/a_0 > 0.5\ h'_{rms}$

- Animals lower E' in 2 ways – independent stalks or sparse network of beams in compliant shell



- Elastomers – ℓ_a=nm to μm vs. 3pm
  all atoms ⟶ w; E'⟶ stretching between crosslinks
  $\ell_a/a_0 \sim n^3$ with n=# monomers between crosslinks
  Dahlquist criterion E'<0.1MPa not big w

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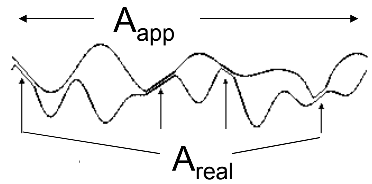
Is Friction Proportional to Real Area?



Is F= $A_{real}\ \tau_{shear}$?

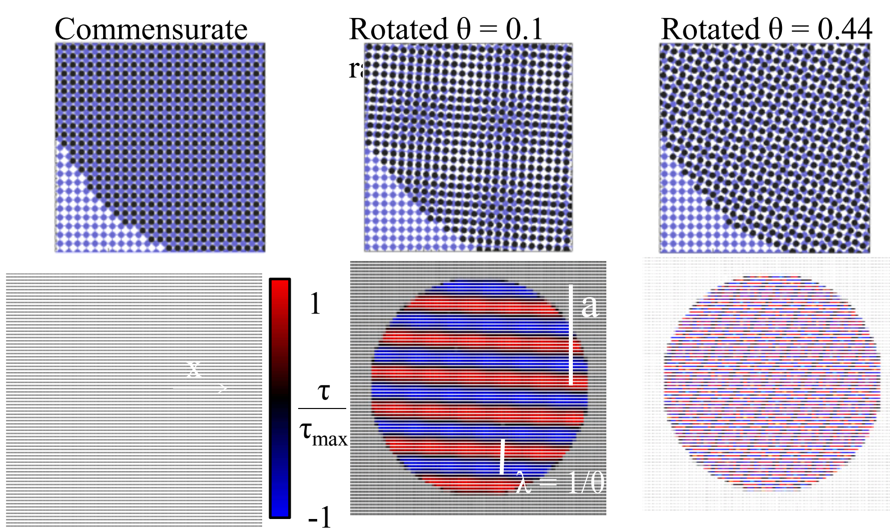
Problems ⇒ What determines τ_{shear}?

Why $\mu \approx$ constant for given materials?

Macroscale ⇒ A_{real}/Load not material property ~$1/h_{rms}$'

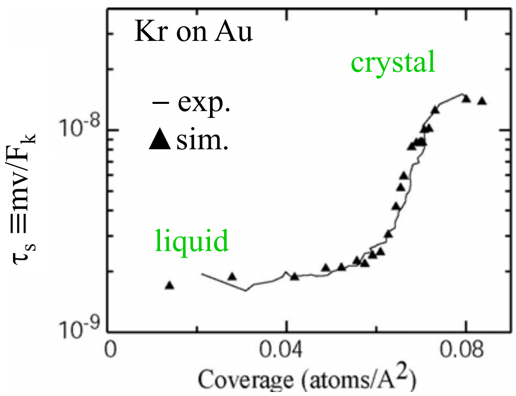
Nanoscale ⇒ A_{real} hard to define, τ_{shear} often zero, depends on pressure, variables not controlled in experiment

What About Shear Stress in A_{real}?
Rigid Incommensurate Surfaces – No Net Friction!



Structural Superlubricity – Rigid Surfaces

Hirano & Shinjo – Contacting crystals typically incommensurate,
⇒No common period → lateral force averages to zero, F_s=0
Even identical surfaces become incommensurate if rotated
Consistent with many experiments & simulations
F_s=0 for incommensurate monolayers on substrate (Krim et al.)
Solids more slippery than fluid of same element

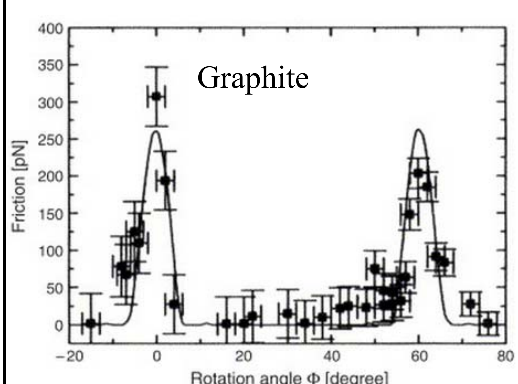


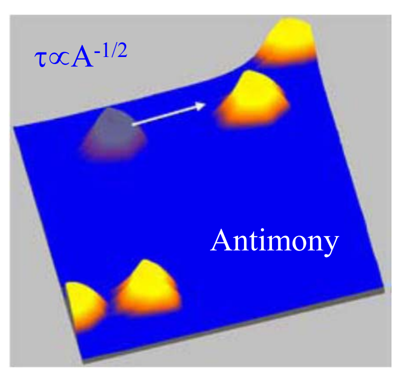
Friction proportional to velocity - F_k=v m/τ_s

Cieplak, Smith, Robbins, Science **265**, 1209 (1994)

Structural Superlubricity – Rigid Surfaces

Hirano & Shinjo – Contacting crystals typically incommensurate,
⇒No common period → lateral force averages to zero, F_s=0
Even identical surfaces become incommensurate if rotated
Consistent with many experiments & simulations *in vacuum*
F_s~0 for misaligned mica, graphite, MoS_2, antimony, adsorbed gas
(Hirano et al. '91, Krim et al., Dienwiebel et al. '04, Martin et al., Dietzl et al. '08)

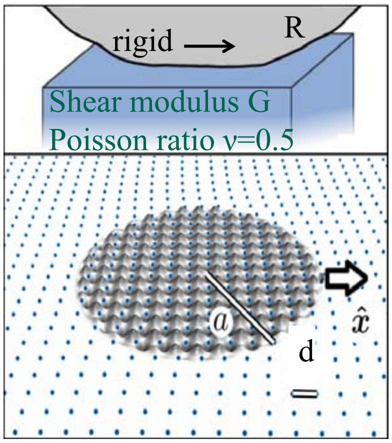




Dienwiebel et al. '04

Dietzel et al. PRL 101, 125505, '08

Elasticity Eliminates Structural Lubricity



Slide corrugation potential quasi-statically, minimize the energy

Vary dislocation core size

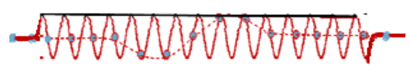
$b_{core} = dG/\tau_{max}$

Represent rigid surface with sinusoidal lateral force

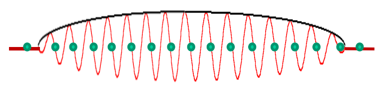
$f_x = f_0 \sin(2\pi x/d)$

$f_y = f_0 \sin(2\pi y/d)$

"Adhesive model" $f_0 = \tau_{max} d^2$



"Non-adhesive" $f = \tau^0_{max} \sqrt{1 - r^2/a^2}$

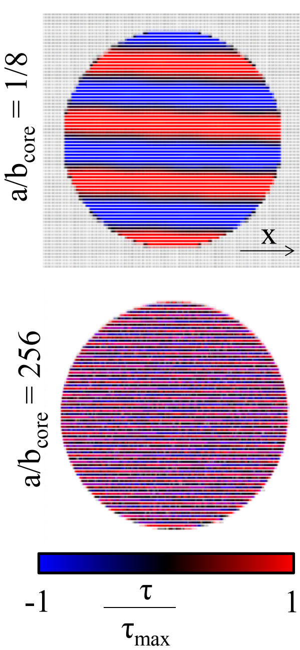


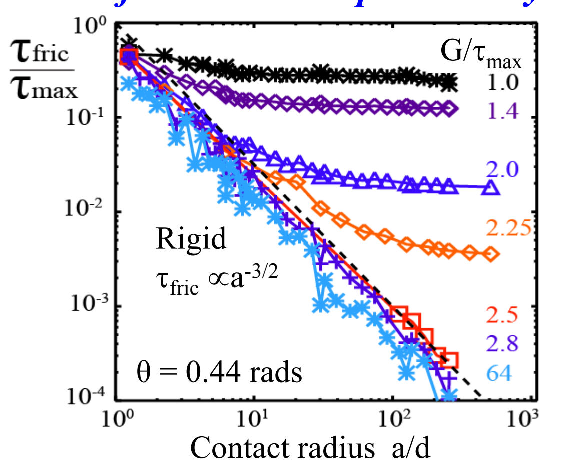
Use $\tau^0_{max} \sim \mu_0 p^0 = \mu_0 Ga/R$ to model pressure variation under sphere

Agrees with full sphere calculation

Linear response not influenced by curvature

Elasticity → Breakdown of Structural Superlubricity





τ_{fric} – Static friction force per area

τ_{max} – max traction parameter, d – atomic size

$b_{core} = dG/\tau_{max}$ – dislocation core size

Large a/d, $\tau_{fric} = \tau_{Peierls} \propto G \exp[-2\pi G/\tau_{max}]$

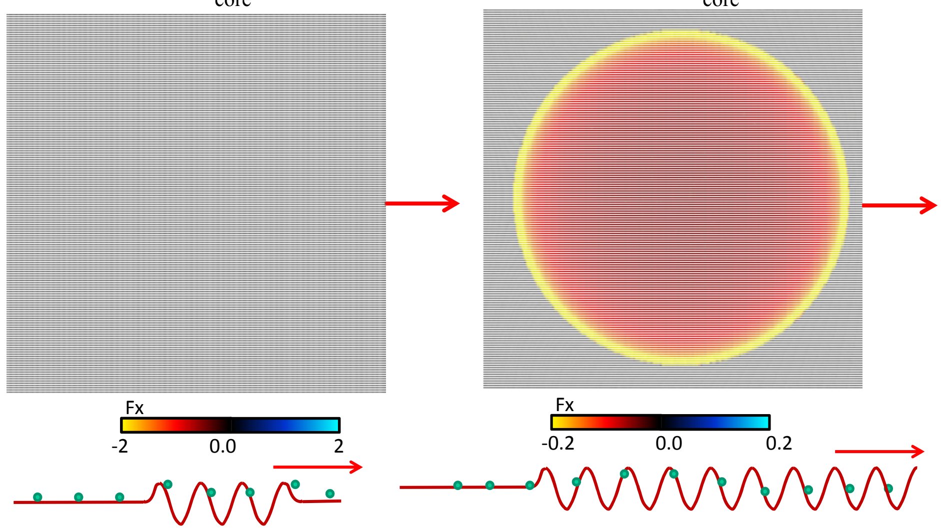
Commensurate Slides via Dislocations at Large a/bcore

Small – coherent

$a = 30\ d$ $b_{core} = 128\ d$

Large – dislocation assisted

$a = 126\ d$ $b_{core} = 1\ d$



Precursors, scale dependent friction like that of Fineberg

Commensurate Adhesive Case: Three Friction Regimes

τ_{fric} – Total static friction per area

τ_{max} – Local yield

a – contact radius

b_{core} – core size

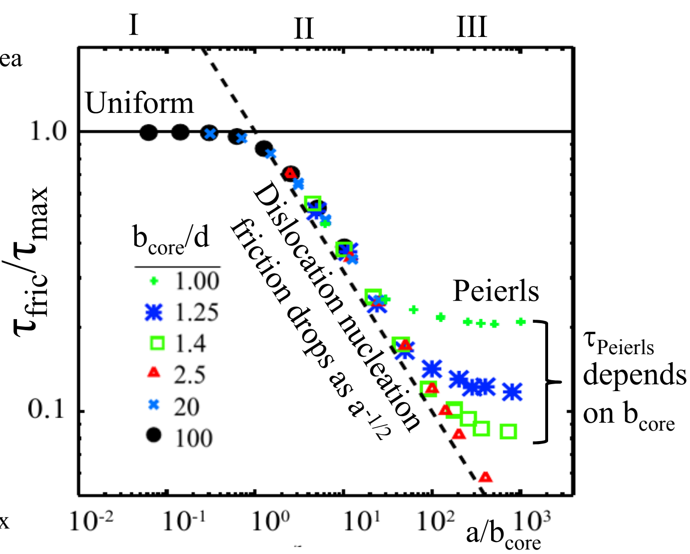
d – atomic spacing

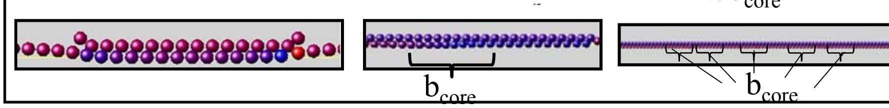
G – shear modulus

Agrees with scaling of Hurtado, J. A. & Kim, K.-S. 1999 *Proc. R. Soc. Lond* A **455**, 3363–3384.

Like precursors of Rubinstein & Fineberg

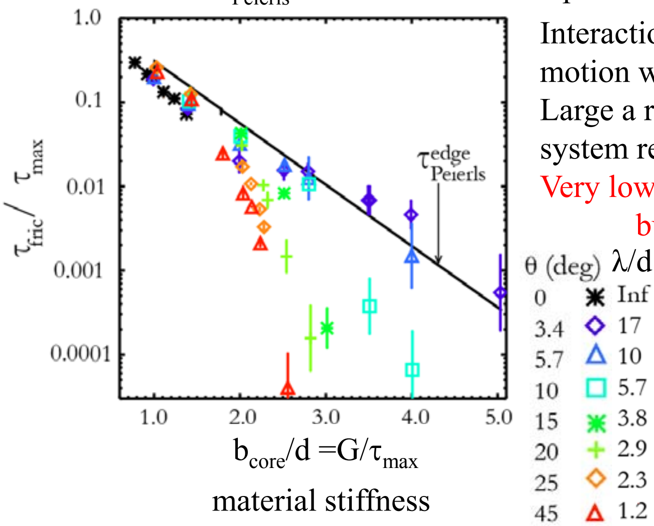
$b_{core} \equiv dG/\tau_{max}$





Static friction → Peierls Stress as $a/b_{core} \rightarrow \infty$

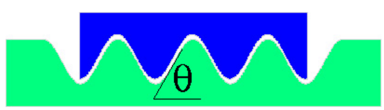
Single dislocation $\tau^{edge}_{Peierls} \propto G \exp[-2\pi b_{core}/d]$ measured separately
Friction near $\tau^{edge}_{Peierls}$ when dislocations separated ($b_{core} < \lambda \equiv 1/\theta$)



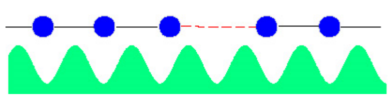
←commensurate
←incommensurate

Interactions lower stress for motion when $b_{core} > \lambda$
Large a results track periodic system results for same angle
Very low friction for large b_{core}
but finite, not zero

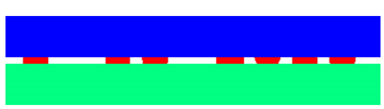
Friction Mechanisms in Contacts



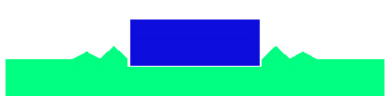
Geometrical Interlocking: F=N tan θ
Unlikely to mesh, F goes up as smooth
Kinetic friction vanishes



Elastic Metastability:
Marginal dimension - exponentially weak in disorder or lateral coupling



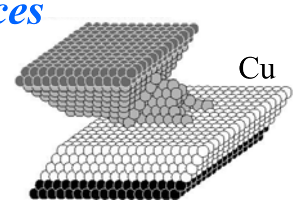
Mixing or Cold-Welding
Most likely for clean, unpassivated surfaces in vacuum



Plastic Deformation (plowing)
Load and roughness dependent
⇒High loads, sharp tips

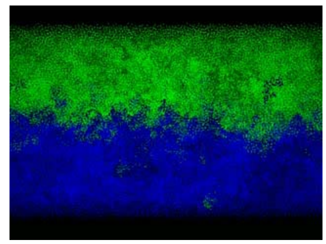
Mobile third bodies → "glassy state"
hydrocarbons, wear debris, gouge, …
Glass seen in Surface Force Apparatus,
Robust friction mech. on many scales

Welding at Interfaces



Metals weld in vacuum conditions
- Scale, orientation dependence

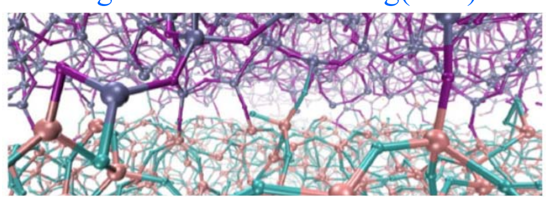
Sørensen, Jacobsen & Stoltz, Phys. Rev. B 1996
Bowden and Tabor for many metal pairs
Landman, Fujita, Matsukawa, …



PMMA in Fineberg experiments
– energy release ~ fracture energy

Strength of polymer weld depends on contact time and pressure
Ge, Pierce, Perahia, Grest, Robbins
PRL 110, 098301 (2013)

Thermally activated covalent bonding of silica: friction ~log(time)



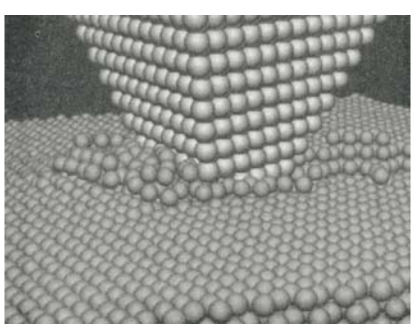
Li, Liu, Szlufarska,
Trib. Lett. 56: 481 (2014)
Li, Tullis, Goldsby, Carpick
Nature 480, 233 (2011)

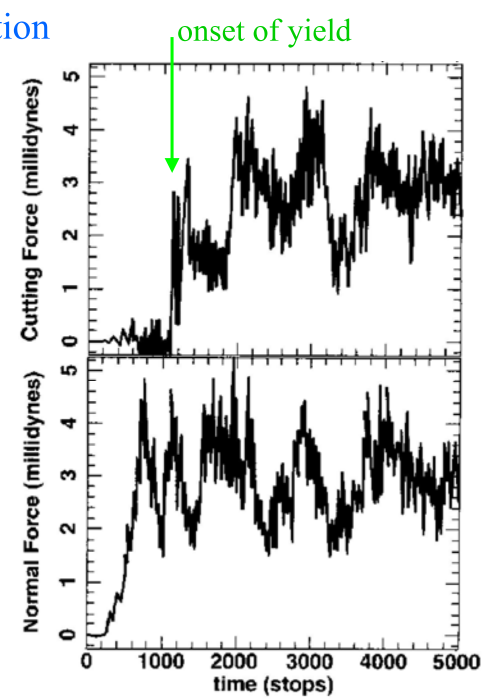
Friction from Plastic Deformation

Belak and Stowers, Fundamentals of Friction,1992
Many other examples at meeting
Molinari, Szlufarska, …

No sliding friction (cutting force) until plastic deformation occurs

Geometry dependent





“Dirt” Leads to Static Friction

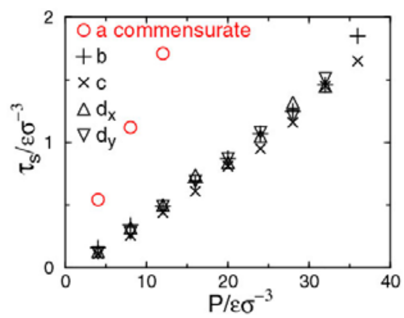
Molecules adsorbed from air, wear debris, elastomer segments,
and other mobile “third bodies” lock surfaces together, $F_s \neq 0$

Find $\tau_s=\tau_0 + \alpha\, p \Rightarrow F_s=\tau_0\, A_{real} + \alpha\, N$ (He, Müser, Robbins, Science ‘99)

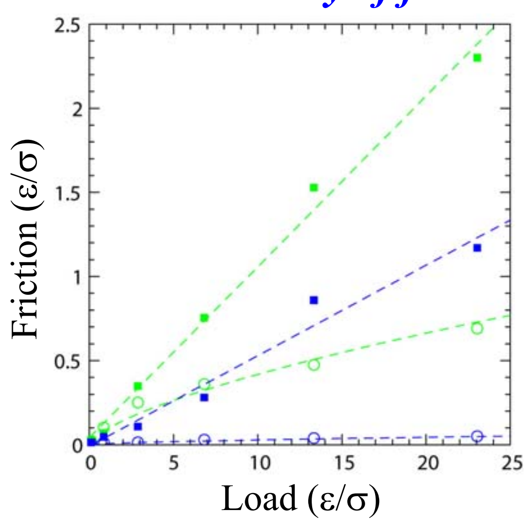
$\Rightarrow$ can explain Amontons’s laws without a constant τ_{shear}

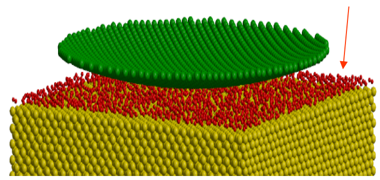
$\Rightarrow$ $\alpha \sim \mu$ is indep. of many parameters not controlled in experiment
Reflects slope of ramp formed by adsorbed molecules
$\Rightarrow$ Ramp keeps rearranging so always uphill

$\Rightarrow$ Thermal activation model explains why kinetic friction near static and rises like $(k_BT/V^*)\log(v)$ with atomic scale volume V^*



Adsorbed layers give $F \propto$ load for AFM tips and decrease variability of friction with tip geometry





Conclusions

- Have analytic understanding of relation between contact area and load: $p_{rep}=N/A=E'/\kappa_{rep}h'$ ⇐*please measure*
- Parameter-free theory for onset of adhesion
  Adhesion rare, typical $w/E' \equiv l_a$ << atomic spacing
- Parameter-free theory for sphere on flat contact
- Proportionality between area and load is not enough to explain Amontons' laws even in nonadhesive case
  → Is h' a material parameter?
  → Clean surfaces - friction exponentially weak
  → Plowing, wear, … geometry changes τ
  → Welding may give constant τ for polymers?
- Third bodies give $\tau_s=\tau_0+\alpha p$, material property of body
  $\alpha \Rightarrow \mu$ independent of uncontrolled exp. parameters
  gives rate state behavior with right energy scale