Friction Mechanisms: Atomic to Macroscopic

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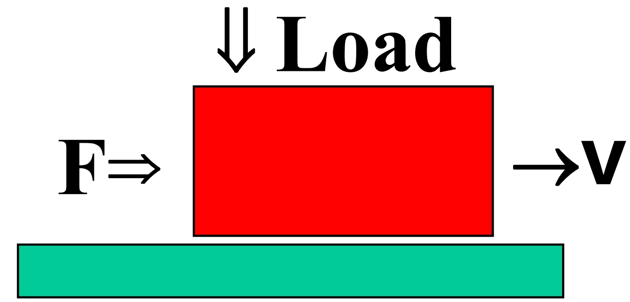
Questions:

- Where do surfaces contact?
- How is friction produced in contacts?
- How do static and kinetic friction differ and age?
- How does concept of contact depend on scale?
- Do similar mechanisms of frictional locking, stick-slip, fracture, … operate at different scales?
- Can studies of mechanisms at small scales provide essential input for modeling larger scales?
- Can large scale experiments test small scale models?

Typical measurement of friction ➔



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 μ=F/Load.
- Friction force independent of the apparent contact area A_{app}.

But: Amontons coated all surfaces with pork fat

Friction at zero and negative loads ∝ A_{app}

Friction depends on history

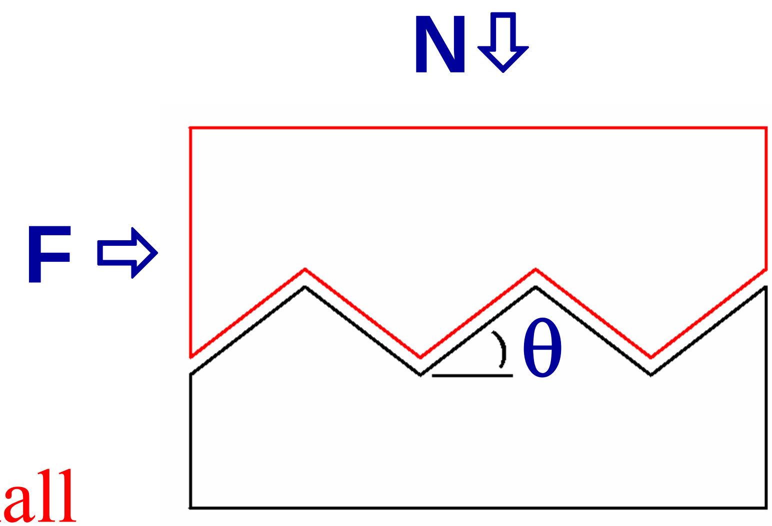
Why Friction $\propto$ Load, Independent of Apparent Area?

Geometric explanation (Amontons,Parents,Euler,Coulomb)

→ Surfaces are rough

→ Friction = force to lift up ramp
formed by bottom surface

→ F=N tanθ ⇒ μ=tan θ



Problems:

→ Most surfaces can't mesh, A/A_0 small
(Müser, Wenning, Robbins, PRL 86, 1295 (2001))

→ Roughening can reduce μ (hard disks)

→ Monolayer of grease changes μ not roughness

→ Once over peak, load favors sliding ⇒ kinetic friction=0

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?

Surfaces Often Rough on Many Scales ⇒ Self-Affine

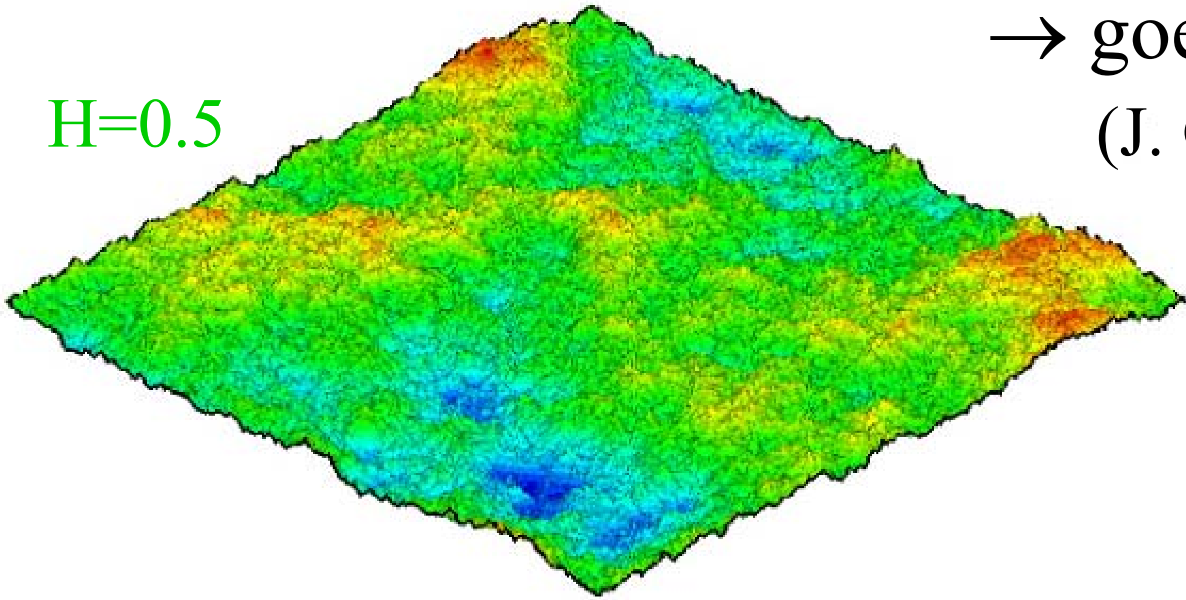
Height variation Δh over length $\ell \rightarrow \Delta h \propto \ell^{H}$ $H<1$

Average slope $\Delta h / \ell \propto \ell^{H-1} \rightarrow$ diverges as scale ℓ decreases

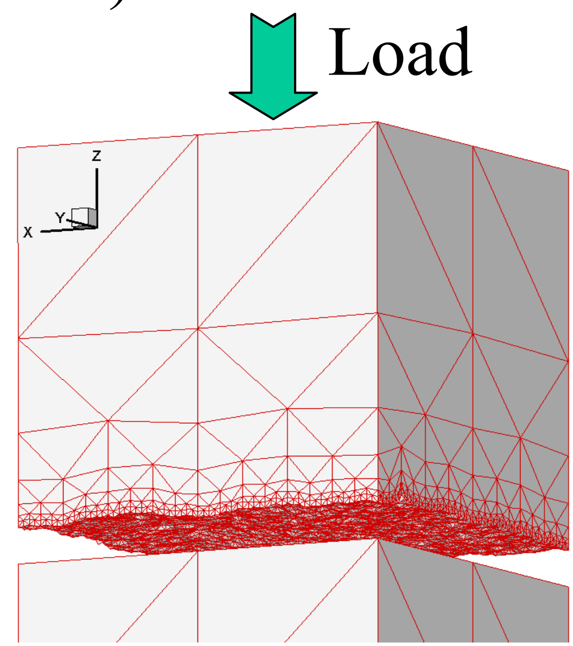
$\rightarrow$ goes to zero as ℓ increases

(J. Greenwood)

H=0.5



Load



Finite-element calculation

Rough surface on rigid flat (maps to 2 rough)

Elastic or J2 isotropic plastic constitutive law

Periodic boundary conditions, L=512 nodes per edge

Full range of H and roughness amplitudes

Hyun, Pei, Molinari, & Robbins, *Phys. Rev. E* **70**, 026117, 2004; J. Mech. Phys. Solids in press.

Area ∝ load N for nonadhesive contact

Constant mean pressure in contact ‹ p › =N/A at low N

Controlled by rms local slope, Δ, not total roughness

Elastic: $\langle p \rangle / E' = \Delta/\kappa$

$E' = E/(1-\nu^2)$

=effective modulus

$$\Delta \equiv \sqrt{\left\langle \left| \nabla h \right|^2 \right\rangle}$$

=rms surface slope

$\kappa(H,\nu)$ from1.8 to 2.2

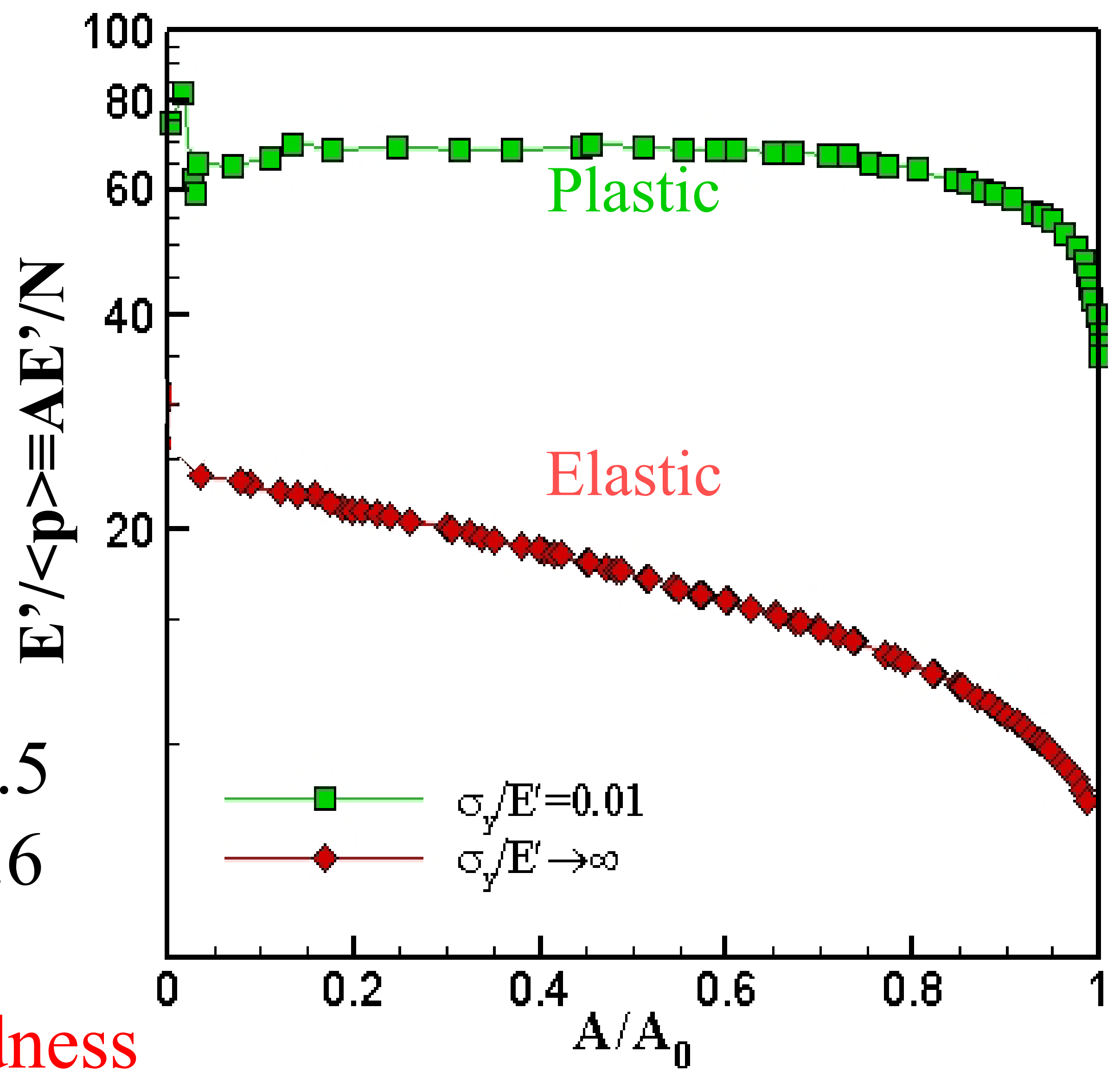
Analytic predictions:

Bush et al., $\kappa=(2\pi)^{1/2}\approx 2.5$

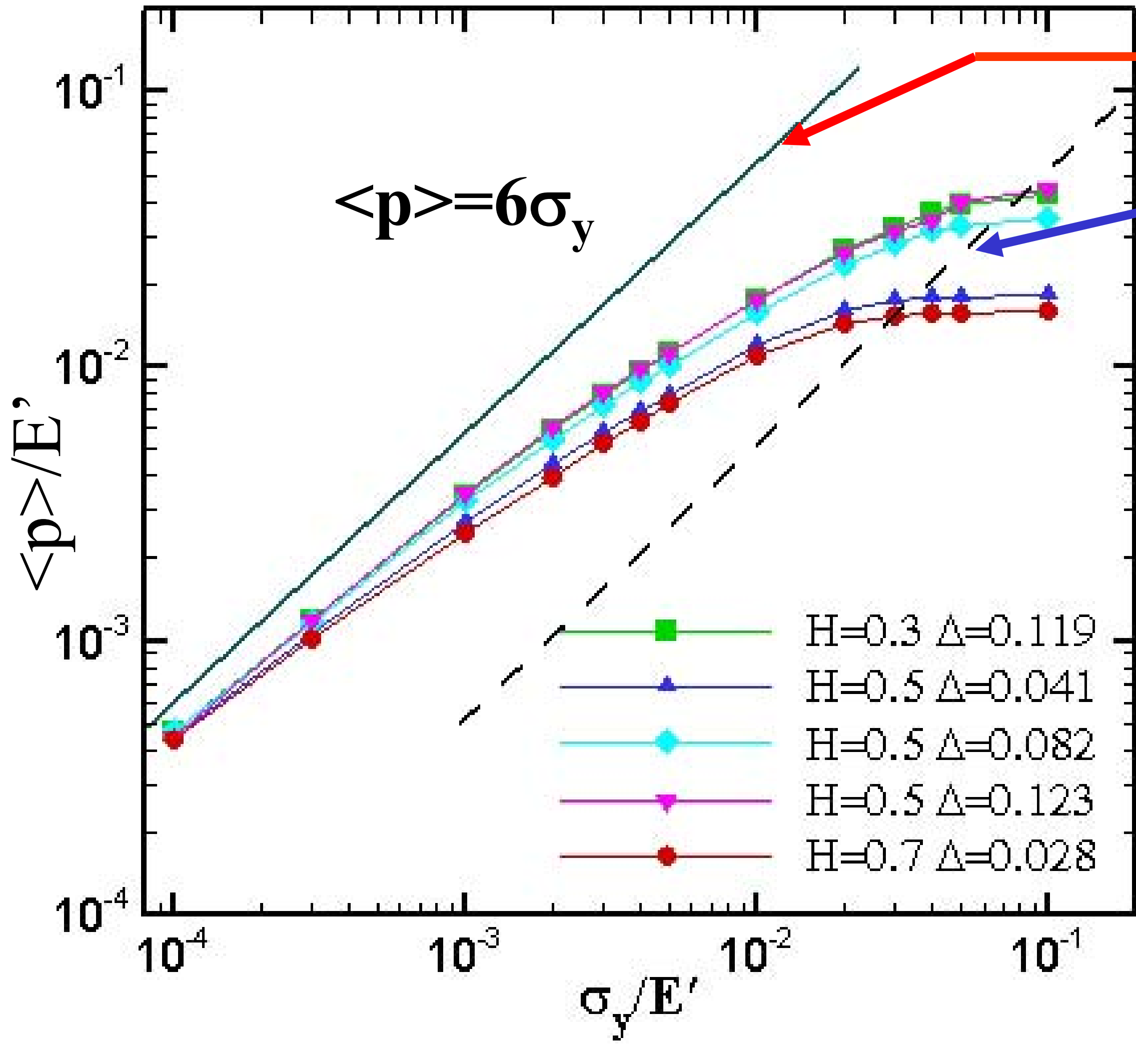
Persson $\kappa=(8/\pi)^{1/2}\approx 1.6$

Plastic: $\langle p \rangle \neq 3\sigma_y$

$3\sigma_y$=single-asperity hardness



Unexpected Dependence of <p> on Yield Stress σ_y



Only elastic for $\langle p\rangle < \sigma_y/2$

$\langle p\rangle / E' \sim \Delta/\kappa$

Bowden and Tabor:

$\langle p\rangle \approx 3\sigma_y$

= single-asperity hardness

For small σ_y/E', <p> is about twice this value. (Gao &Bower)

Power law regime $\langle p\rangle \propto \sigma_y^x$, $x \approx 2/3$ for typical σ_y/E'.

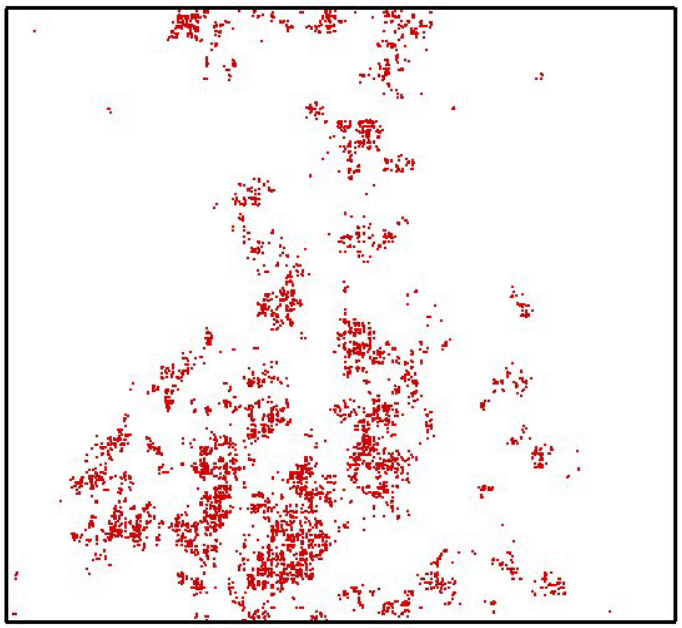
- High strength steel 6×10^{-3}
- Titanium 9×10^{-3}
- Bone 7×10^{-3}
- Silicon 3×10^{-2}
- Amorphous metal 2-5 $\times10^{-2}$

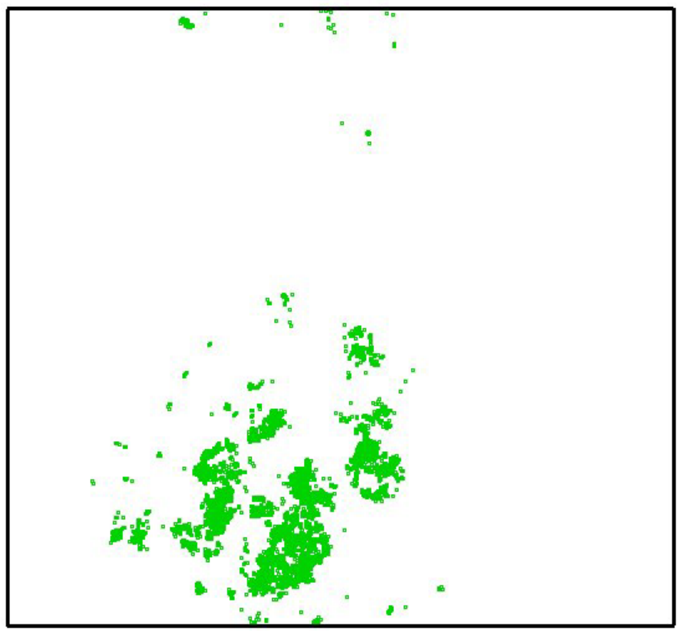
Complex Morphology Varies with Constitutive Law

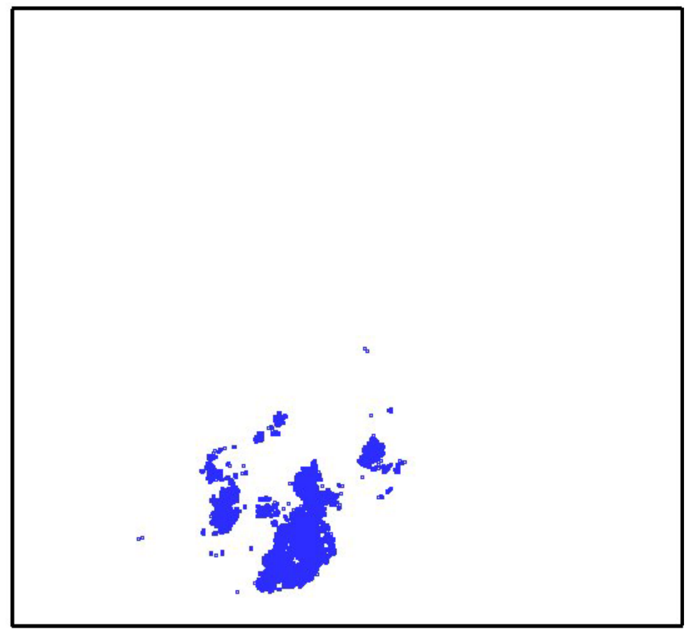
Power law distribution of connected areas a_c: $P(a_c) \propto a_c^{-\tau}$

Connected regions are fractal $a_c \propto r^{Df}$

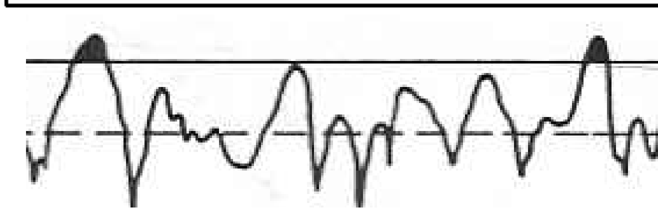
Ideal Elastic	Perfectly Plastic	Overlap Model
$\tau > 2$, $D_f = 1.6$	$\tau \approx 2$, $D_f = 1.8$	$\tau = (2 - H/2)$, $D_f = 2$
Spread evenly		Near highest peak







All results for same surface, 0.015% in contact.



Conclusions of Continuum Studies of Non-Adhesive Contact

- Area proportional to load → <p> = constant
  Elastic: $\langle p \rangle / E' = \Delta/\kappa$ Plastic: $\langle p \rangle \propto \sigma_y^{2/3}$
- Constitutive law changes:
  Power law distribution of contact sizes
  Fractal dimension of contact areas
- Ignoring interactions between asperities gives qualitatively wrong spatial distribution of contacts
- Most contacts at smallest scale
  → results dominated by small scale cutoff
  → continuum mechanics may fail even
  though total area is very large
  → reason kT remains important at macroscale?

What are limits of Continuum Theory?

Continuum theories: Hertz, Johnson-Kendall-Roberts

Assume: 1) continuous displacements, bulk elastic const.

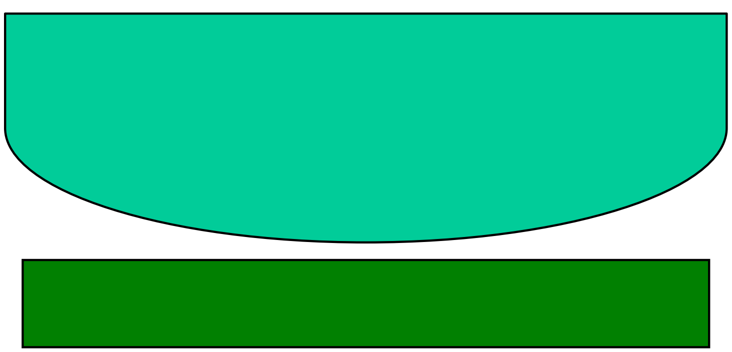
2) smooth surface (often spherical) at small scales

Only tested for atomically flat mica bent into cylinders and elastomers with liquid behavior on small scales

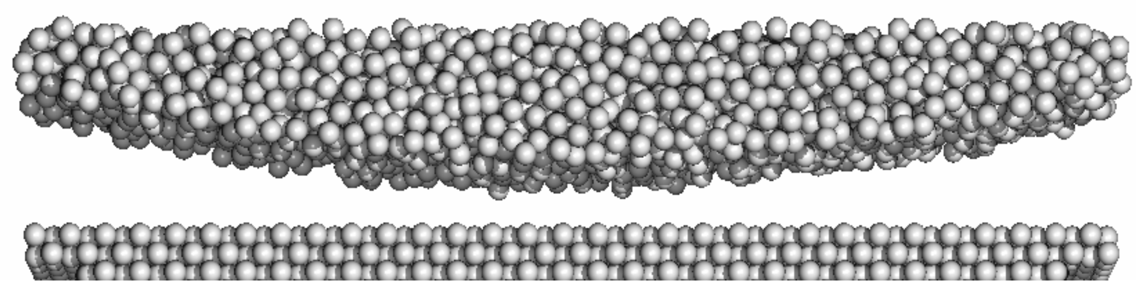
Find (1) valid down to a few atomic diameters, but atomic scale roughness causes failure of continuum theories.

Important for small contacts between rough surfaces and ideal single asperities: scanning probe or nanoindenter

Macro View



Molecular View

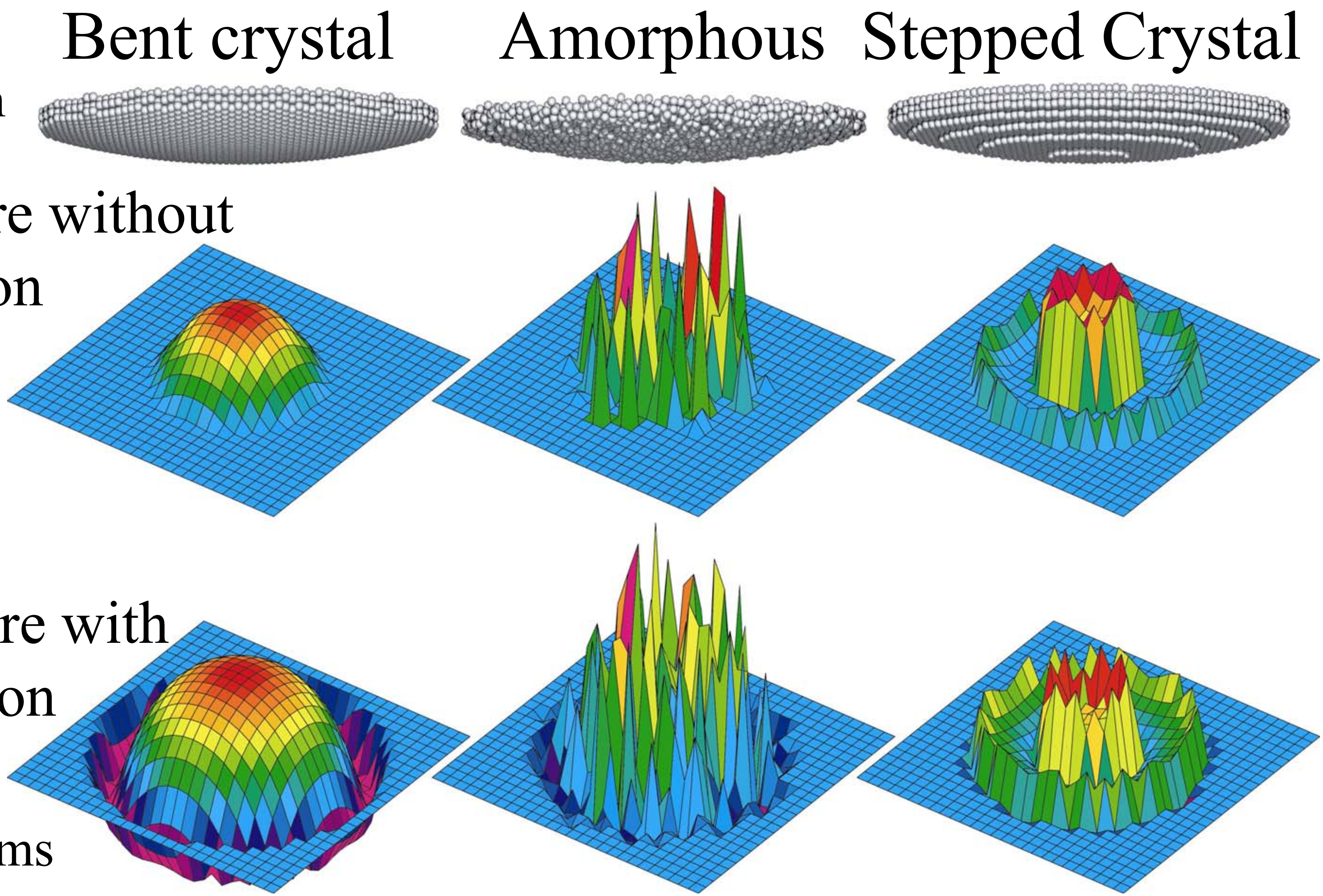


Luan & Robbins, Nature 435, 929 (2005)

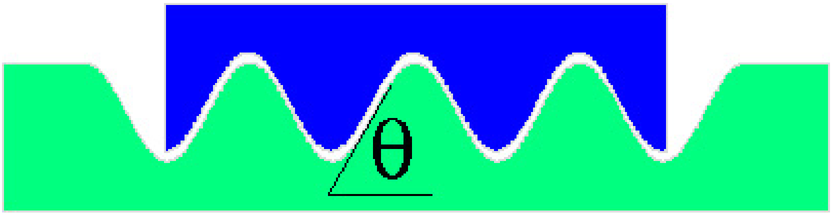
Pressure distribution for sphere on flat

Atomic scale roughness qualitatively changes pressure, yield

Bent crystal agrees with Hertz/JKR, more realistic tips do not



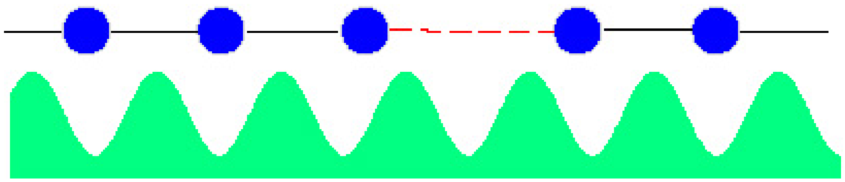
Friction Mechanisms in Contacts



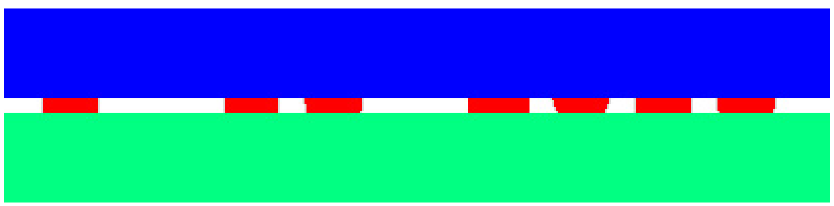
Geometrical Interlocking: $F=N \tan \theta$

Unlikely to mesh, F goes up as smooth

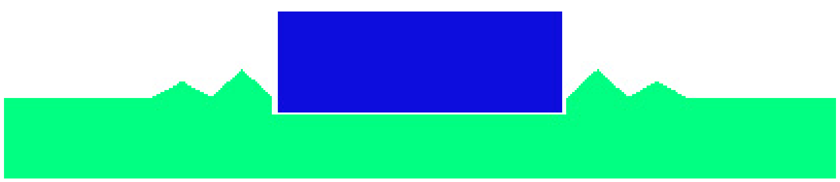
Kinetic friction vanishes



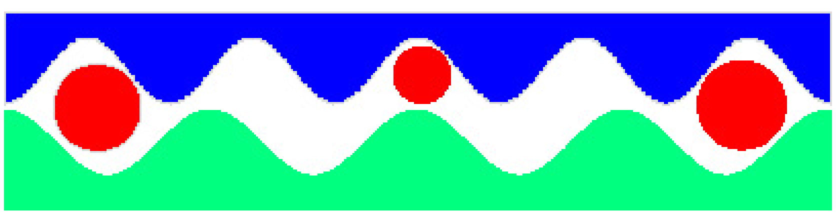
Elastic Metastability:



Mixing or Cold-Welding



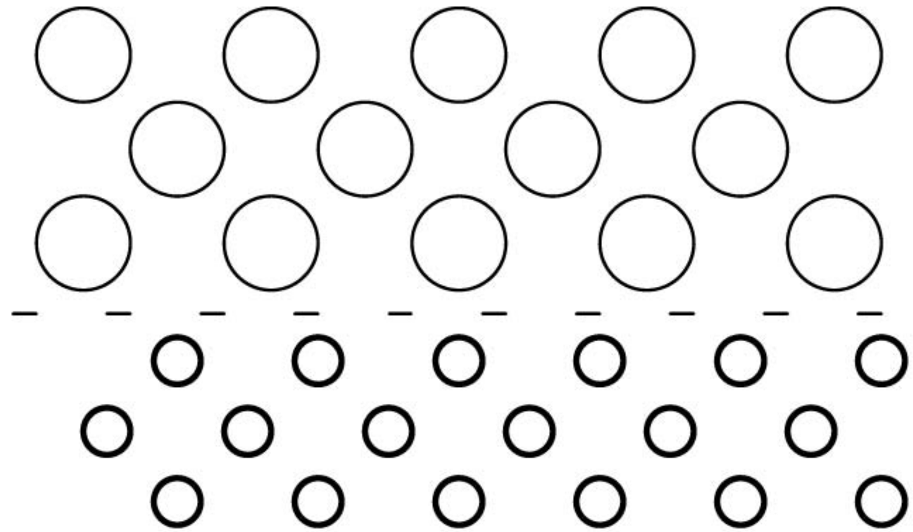
Plastic Deformation (plowing)



Mobile third bodies – hydrocarbons, wear debris, gouge, …

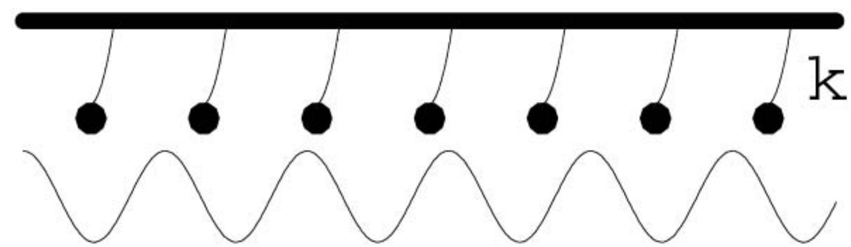
Simple Models of Friction

Two flat crystalline surfaces generally have different periods
⇒ incommensurate

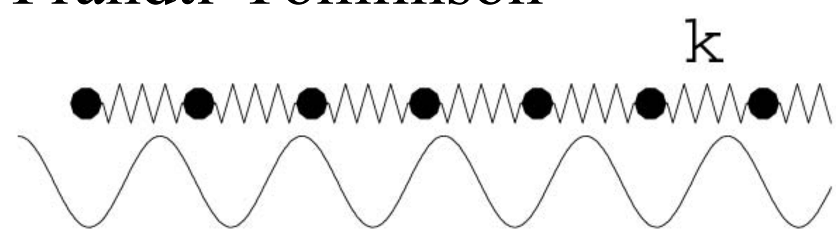


⇒Elastic metastability gives non-zero F_s when interfacial interactions strong compared to internal stiffness

⇒Dissipate energy in pops between metastable states that remain rapid even as mean velocity goes to zero: $F_k \approx F_s$



Prandtl-Tomlinson



Frenkel-Kontorova

Problem: Metastability unlikely
⇒ Expect τ_s=0 almost always

Müser, Urbakh, Robbins, Adv. Chem. Phys. 126, 187 (2003)

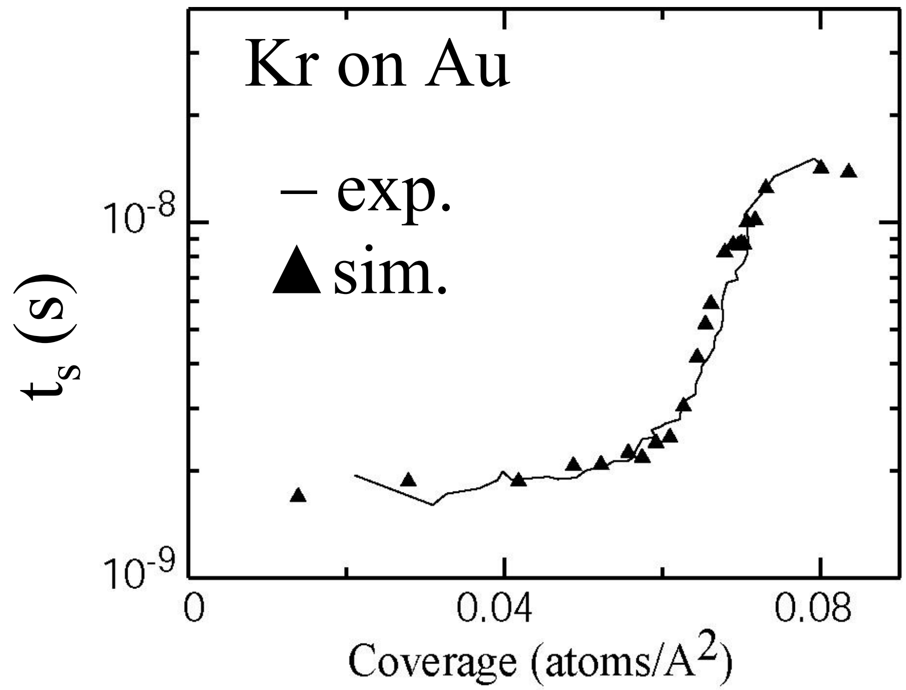
Quartz Crystal Microbalance – Krim et al.

Fluid or incommensurate layers on substrate → no static friction

$F = - v\, M/t_s$

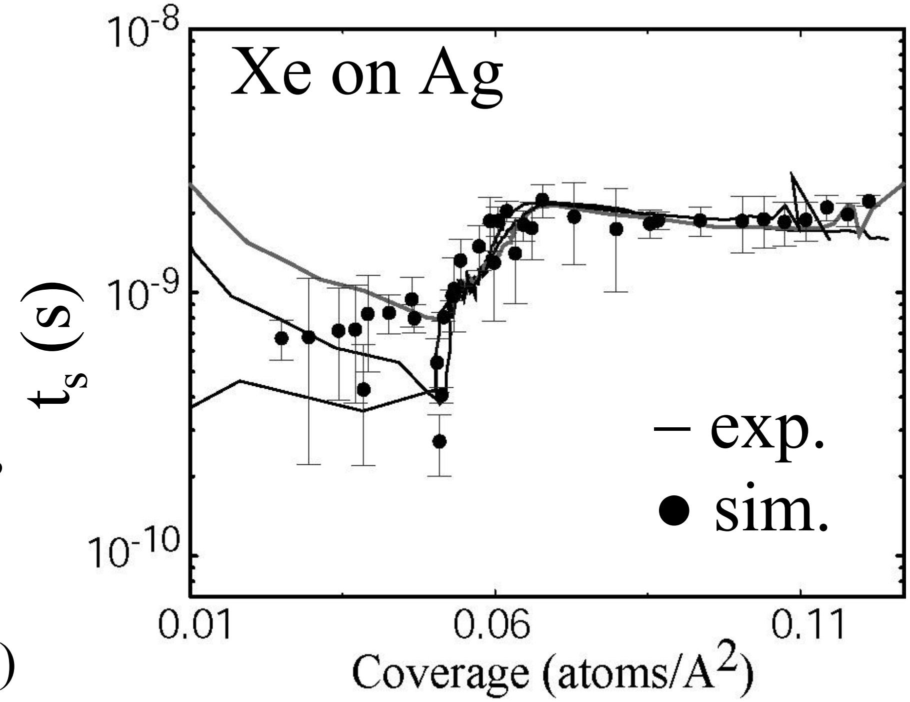
v=velocity relative to substrate

Increase coverage → film solidifies
t_s increases → friction goes down!



Misaligned mica, MoS_2, graphite also show ~no static friction

(Hirano et al. PRL 67, 2642 (1991); Martin et al., Dienwiebel et al. PRL 2004)



Kr on Au: Cieplak, Smith, Robbins, Science **265**, 1209 (1994)

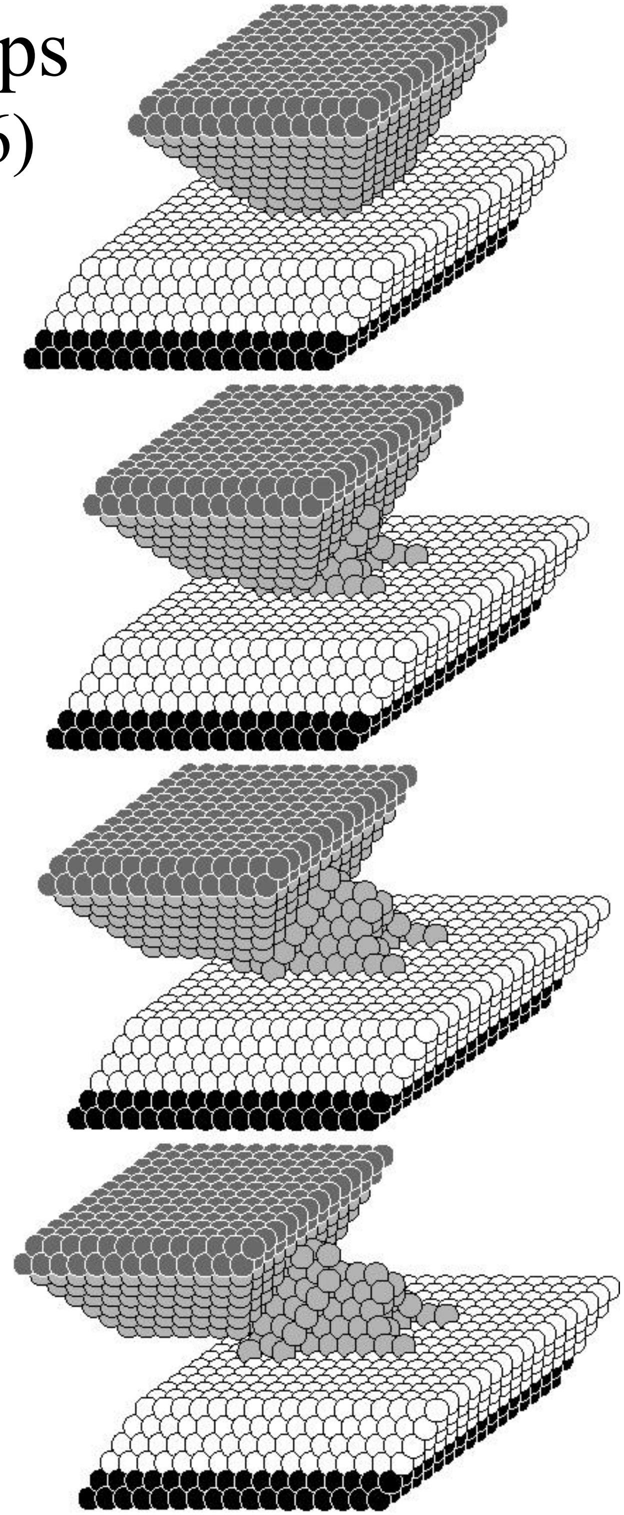
Xe on Ag: Tomassone, Sokoloff, Widom, Krim, PRL **79**, 4798 (1997)

Friction Only for Commensurate (100) Tips

(Sørensen, Jacobsen & Stoltz, Phys. Rev. B 1996)

Copper tip aligned with substrate
⇒ geometrical interlocking and friction
⇒ wear for (100) surfaces not for (111)

Rotate copper tip so incommensurate
⇒ no interlocking, friction, or wear
unless tip is very small (5x5 atoms)



Copper (100) tip on Copper (100) surface slid in (011) direction.

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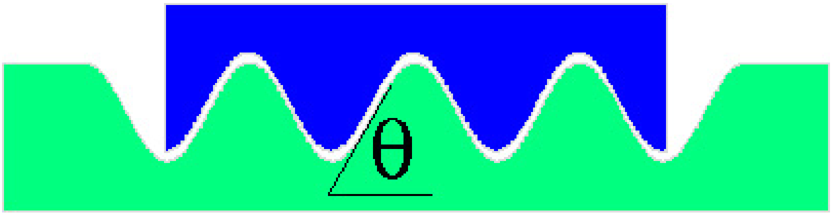

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Unlikely to mesh, F goes up as smooth

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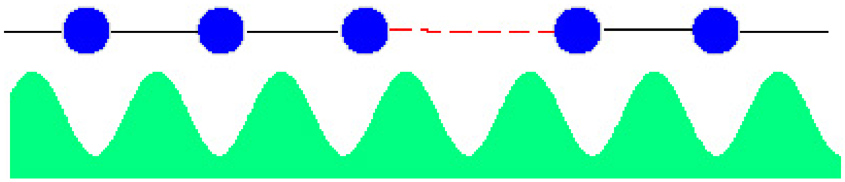
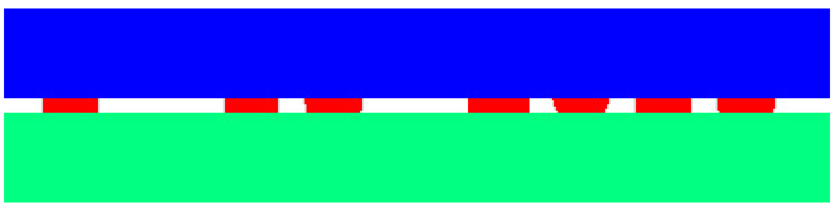


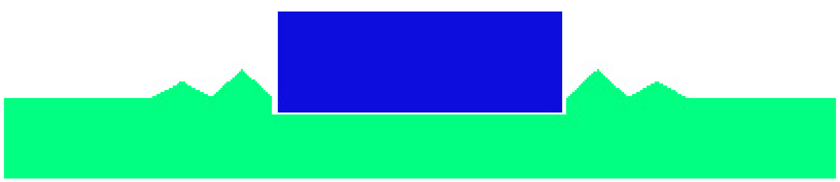
Elastic Metastability:

Intersurface interaction too weak



Mixing or Cold-Welding

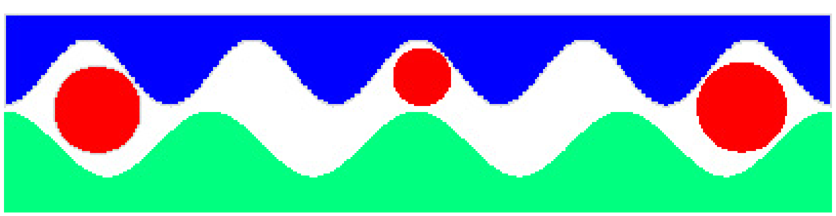
Hard to observe in sims. even with clean, unpassivated surfaces in vacuum



Plastic Deformation (plowing)

Load and roughness dependent

⇒High loads, sharp tips

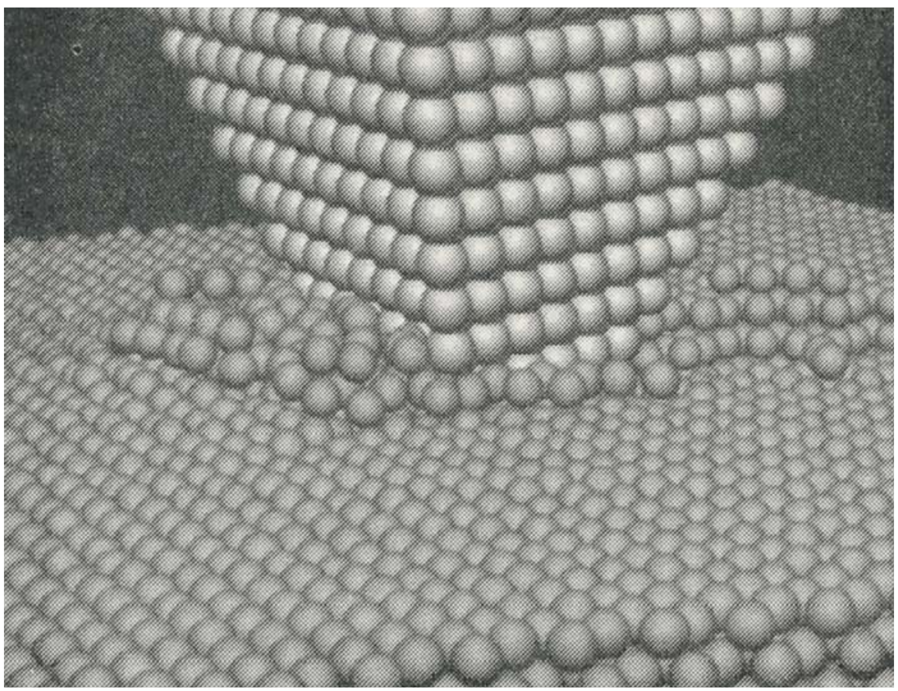


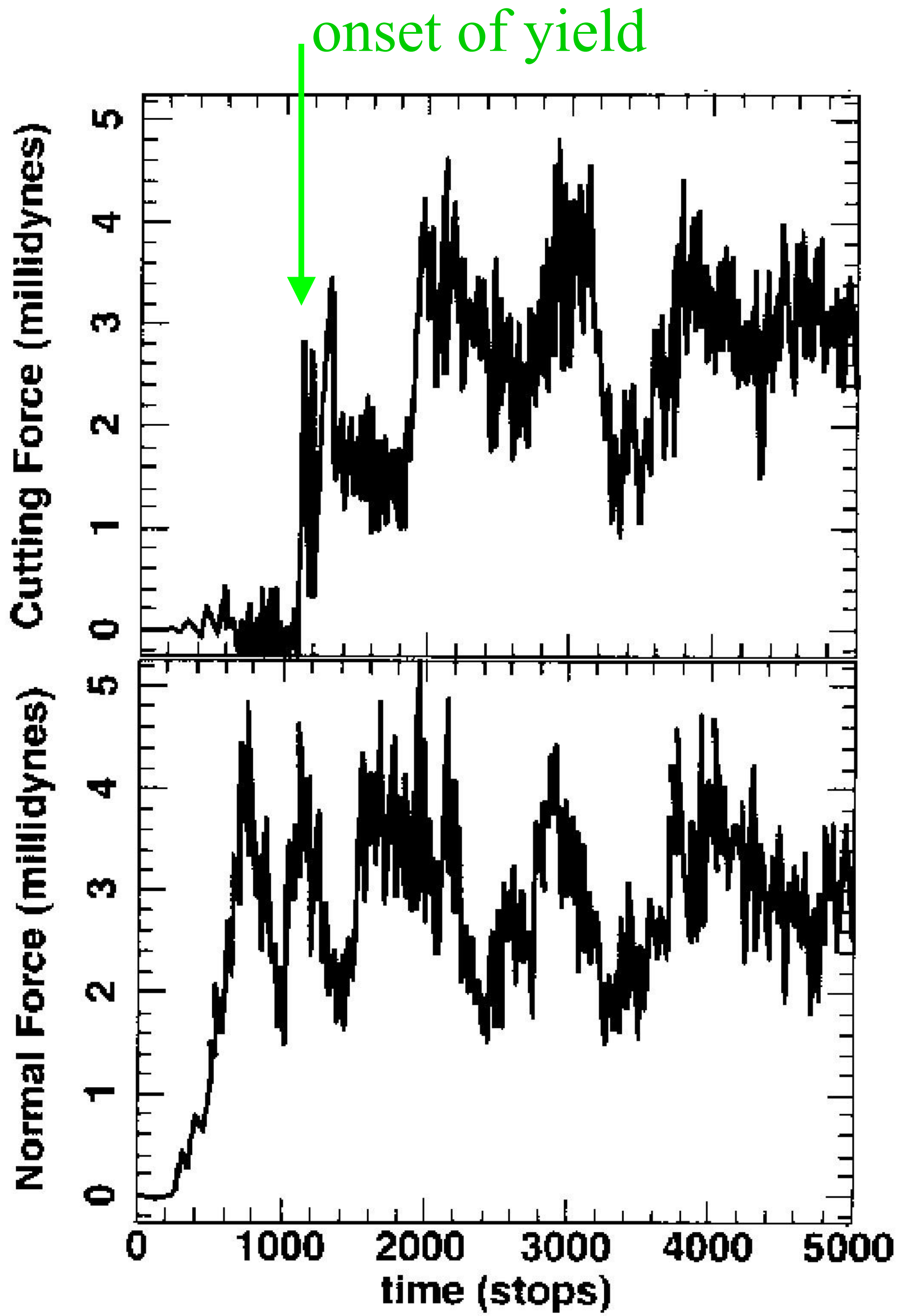
Mobile third bodies – hydrocarbons, wear debris, gouge, …

Rigid Tip on Clean Cu Surface

(Belak and Stowers, Fundamentals of Friction,1992)

No sliding friction (cutting force) until plastic deformation occurs



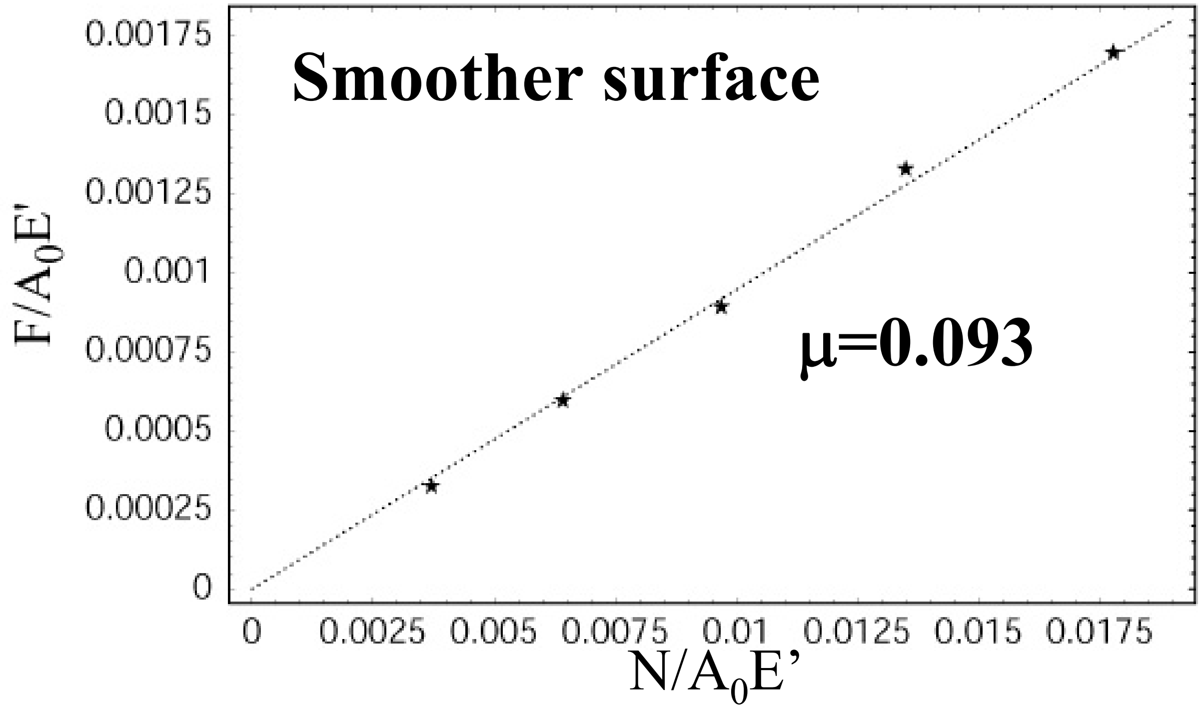


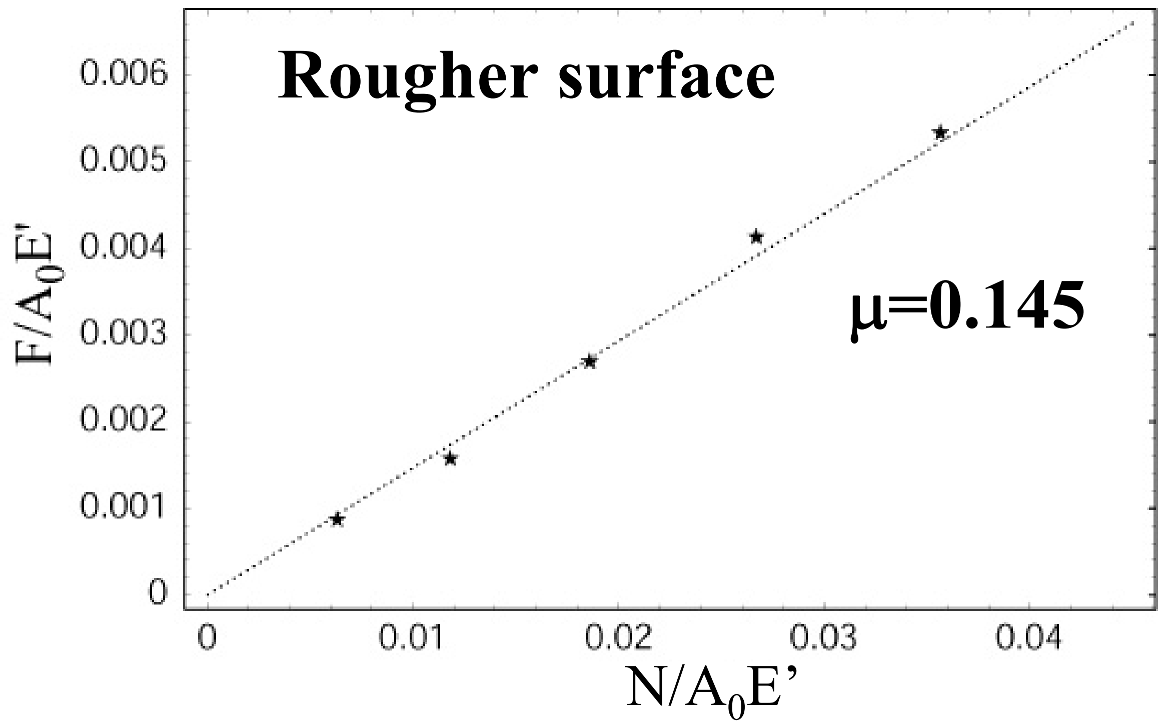
Friction Between Self-Affine Surfaces

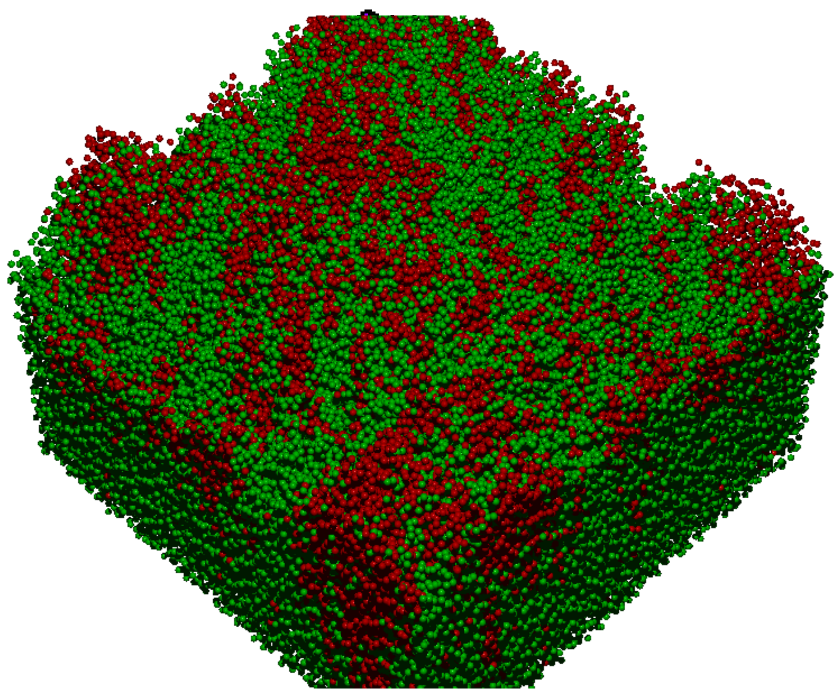
F=μN (N=Load)

∝rate of plasticity

μ ∝ rms roughness







Red atoms: neighbor bond changed > 20%

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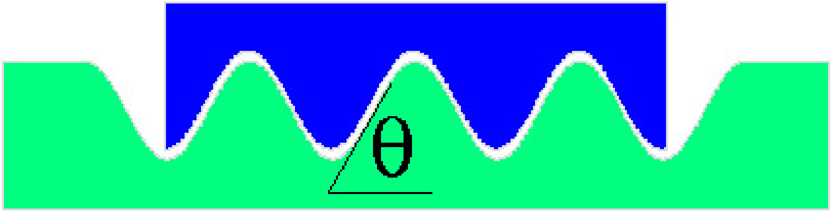

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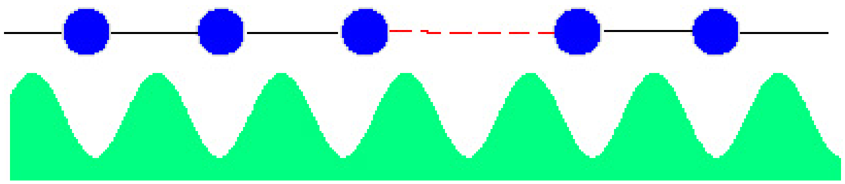

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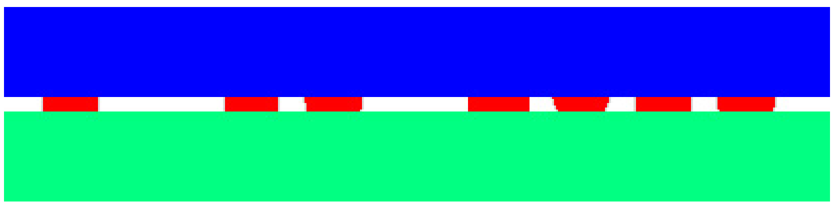

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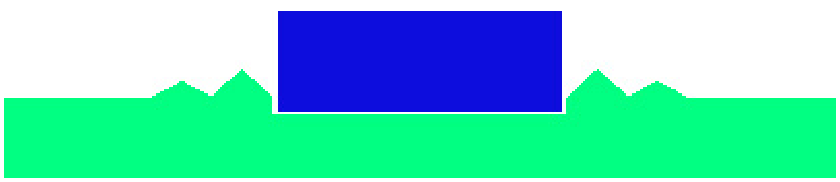

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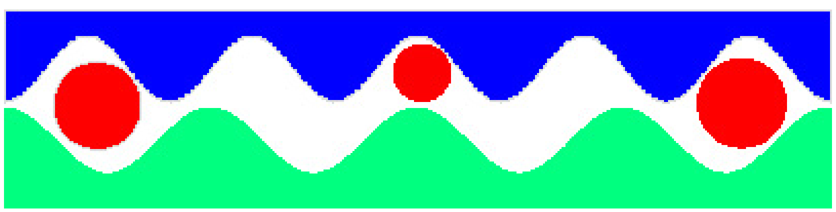


Mobile third bodies → “glassy state”
hydrocarbons, wear debris, gouge, …

Glass seen in Surface Force Apparatus,
Robust friction, Mech. on many scales

Why is friction often proportional to load?

- Not just $A_{real} \propto$ Load and $F \propto A_{real}$ since A_{real} varies with parameters like Δ that have weaker effect on μ
- Friction between clean surfaces very sensitive to local structure, surface orientation, … but measured μ is not

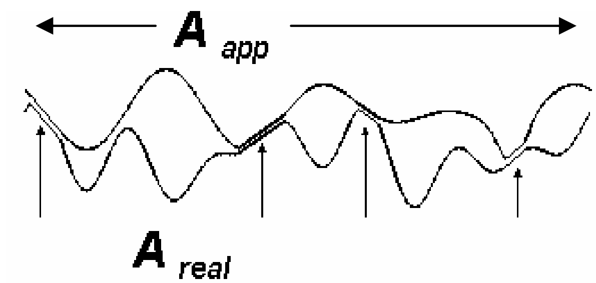
➔ Assume friction from yield stress τ_s of molecular contacts

Glassy systems: τ_s rises linearly with pressure p

If: $F_s = A_{real}\,\tau_s(p)$ with $\tau_s = \tau_0 + \alpha p$ (Briscoe)

Then: $F_s = A_{real}\,\tau_0 + \alpha$ Load

$\mu_s = F_s/\text{Load} = \alpha + \tau_0/\langle p \rangle$



➔ Constant μ if $\langle p \rangle = \text{Load}/A_{real} = \text{const.}$ or $\tau_0 \ll \langle p \rangle$ (Independent of distribution of pressure)

➔ Friction at zero or negative load with adhesion, as observed

$\Rightarrow$ Adsorbed layers give $\tau_s = \tau_0 + \alpha P$ with small τ_0 and α nearly independent of factors not controlled in experiment

Model

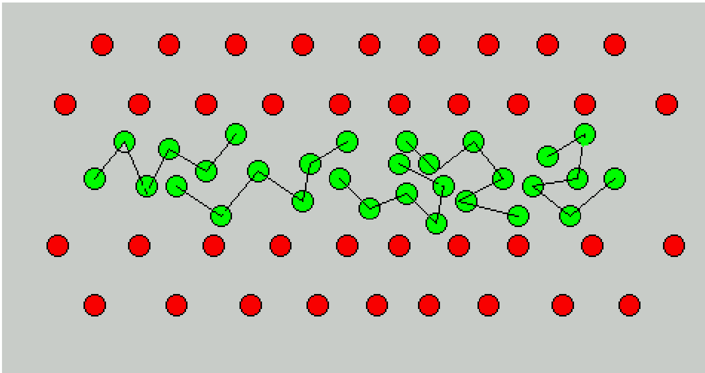
- N chains of n monomers → bead-spring model.

  Lennard-Jones interaction between monomers:

  $V_{LJ}=4\varepsilon\,[(\sigma/r)^{12}-(\sigma/r)^{6}]$ for $r<r_c$

  Neighbors on chain:

  $V_{ch}= -\frac{1}{2} K_o R^2 \ln[1-r^2/R_o^2]$.



- Wall atoms held to sites by springs

  (111) surface of fcc crystal here

Interact with monomers with V_{LJ}, but with ε_w and σ_w.

- Increase force on top wall till slides to find τ_s (static).

  Study diffusion of top wall to test if $\tau_s > 0$

  Move wall at constant velocity v to find τ_k (kinetic).

- Vary → Pressure P

  → Relative orientation and lattice constants d of walls

  → Direction and velocity of sliding

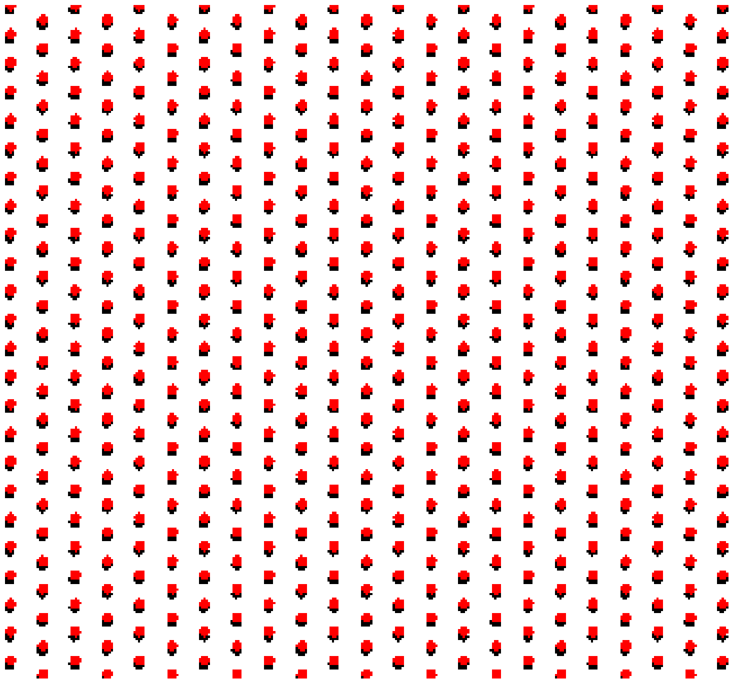
  → Surface density (coverage) of monomers

  → Chain length n

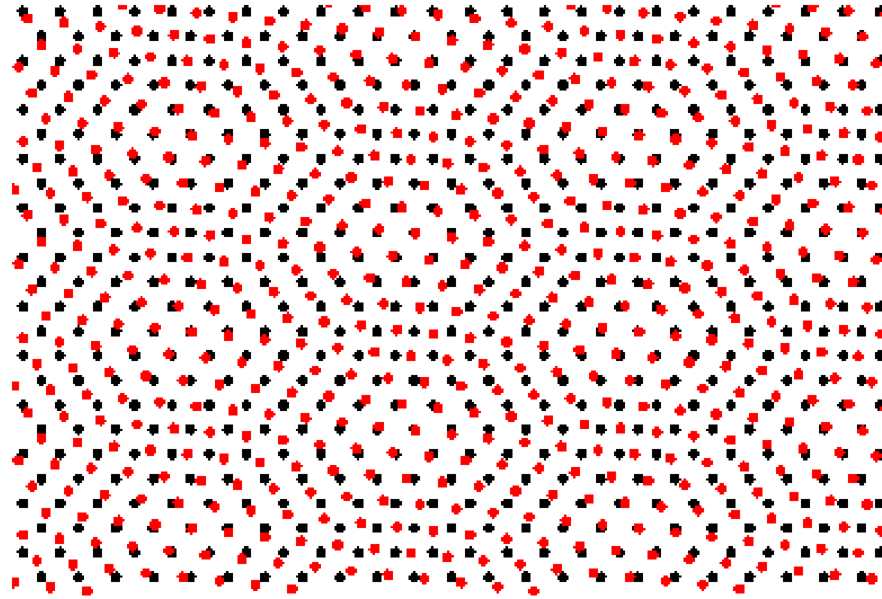
  → Strength ε_w, length σ_w, and range r_c of potential.

Wall Geometries

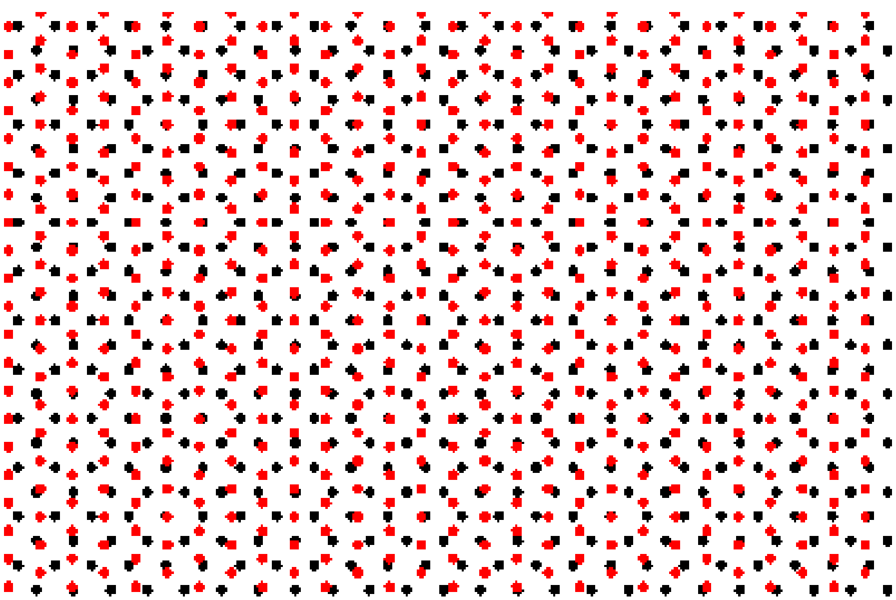
a) 0°



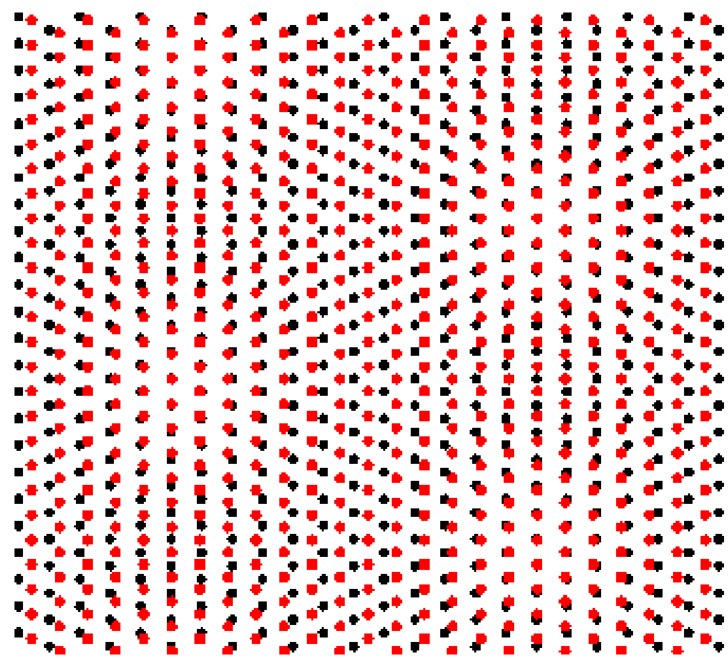
b) 8.2°



c) 90°



d) d_{top}/d_{bot}=13/12

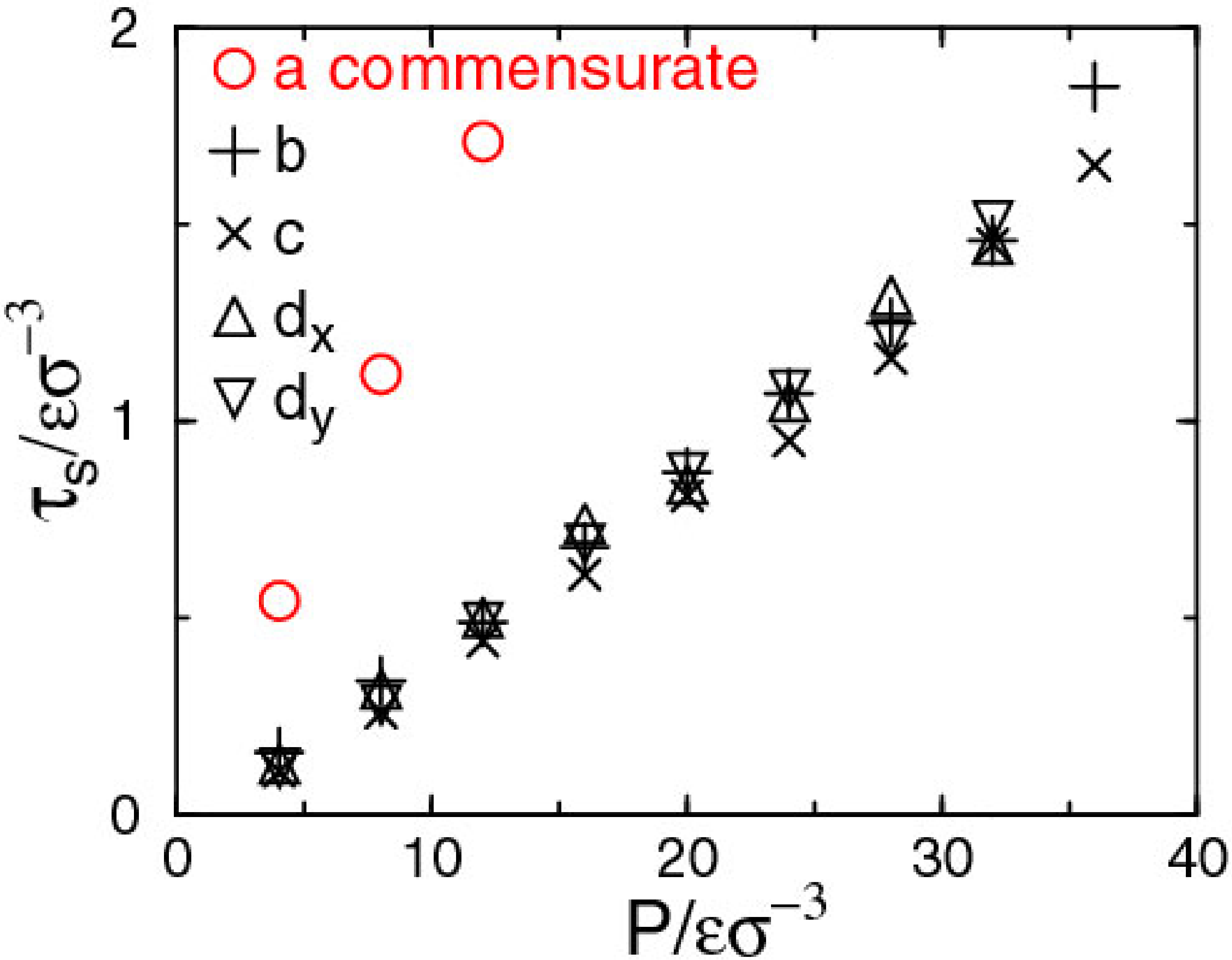


Find: $\tau_s > 0$ for incommensurate walls **with** adsorbed film

All incommensurate walls (b-d) give same τ_s

τ_s independent of sliding direction: x, y, etc.

$\tau_s = \tau_0 + \alpha P$ up to $P > 1$GPa ($\epsilon\sigma^{-3} \sim 40$MPa)

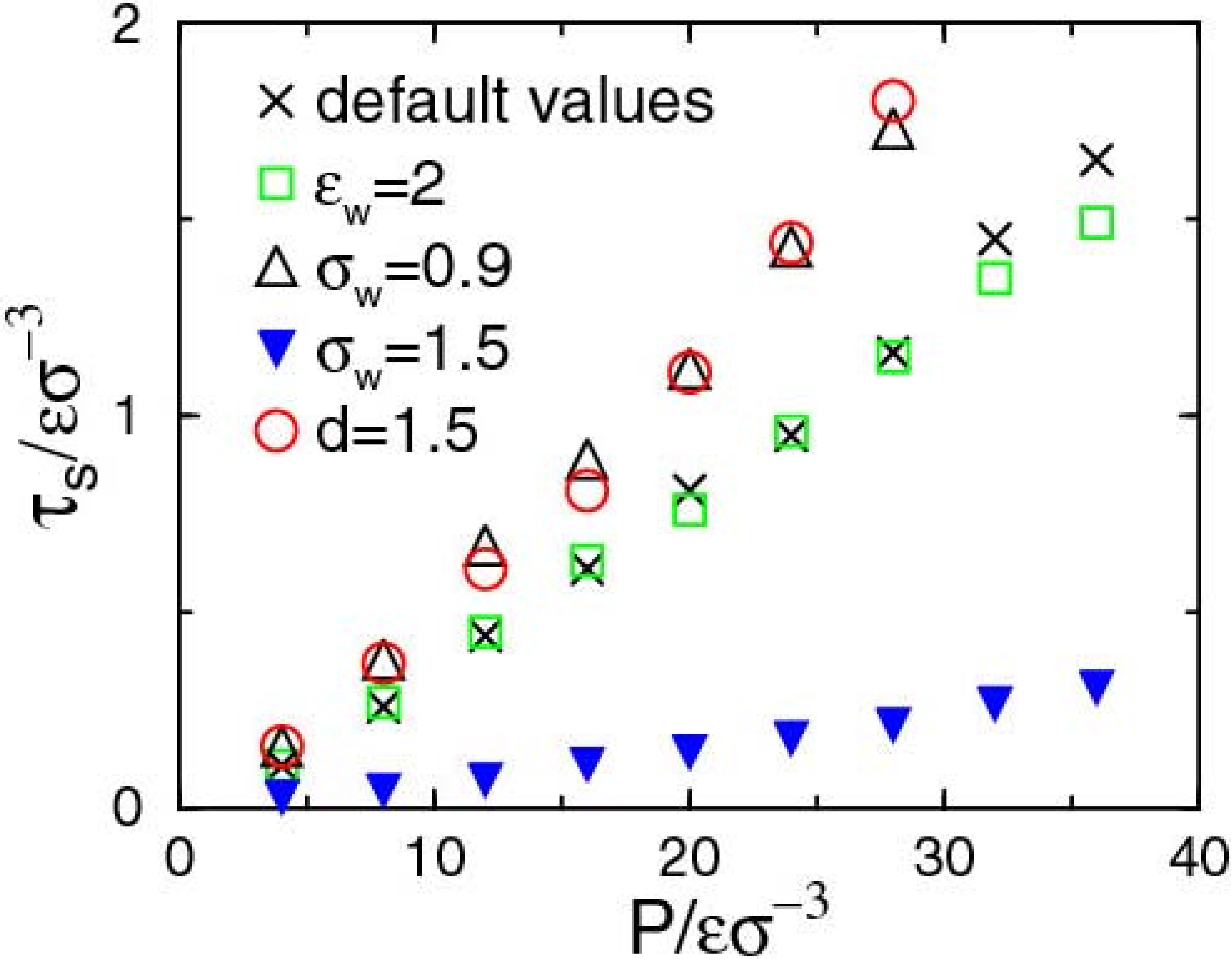


quarter monolayer

Effect of Potential

α independent of coverage, chain length ($n \leq 6$), ε_w or r_c

α increases with $d/\sigma_w \rightarrow$ "rougher" surface



default:
ε_w=1
σ_w=1
d=1.2

$\varepsilon\sigma^{-3} \approx$ 40MPa

Geometric Explanation

If pressure high enough → hard sphere limit

Repulsive force balances pressure

$F \sim P/c \sim 48\,(\varepsilon_w/\sigma_w)(\sigma_w/r)^{13}$ where c=coverage

$\Rightarrow r \sim \sigma_w\,(c\,\varepsilon_w\,/P\,\sigma_w)^{1/13}$

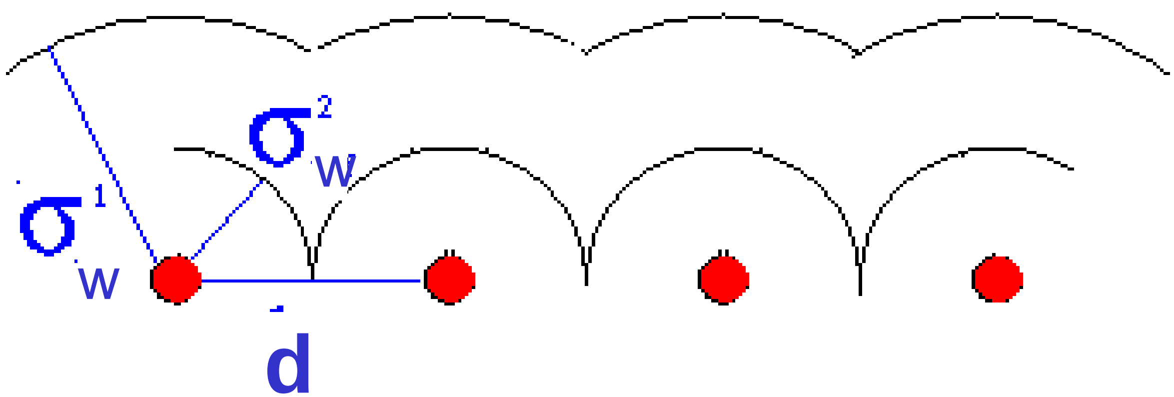
Effective hard-sphere radius: insensitive to c, ε_w ,

P almost linear in σ_w

Surface of closest approach depends on d /σ_w

$\alpha \propto$ maximum slope, increases with d/ σ_w

Similar ideas explain rise in bulk yield stress with p



Analytic theory: Müser, Wenning, Robbins PRL 86, 1295, '01

Airborne hydrocarbon films can explain Amontons' laws

➔ Adsorbed layers (even diffusing) lock surfaces together producing a static friction consistent with macro experiments

✓ ⇒ $\tau_s = \tau_0 + \alpha P$ for P up to ~1GPa

✓ ⇒ α of order 0.1 crystal: $\alpha \rightarrow$ 0.03 to 0.2, amorphous larger

✓ ⇒ τ_0 small compared to typical P $\tau_0 < 10$MPa

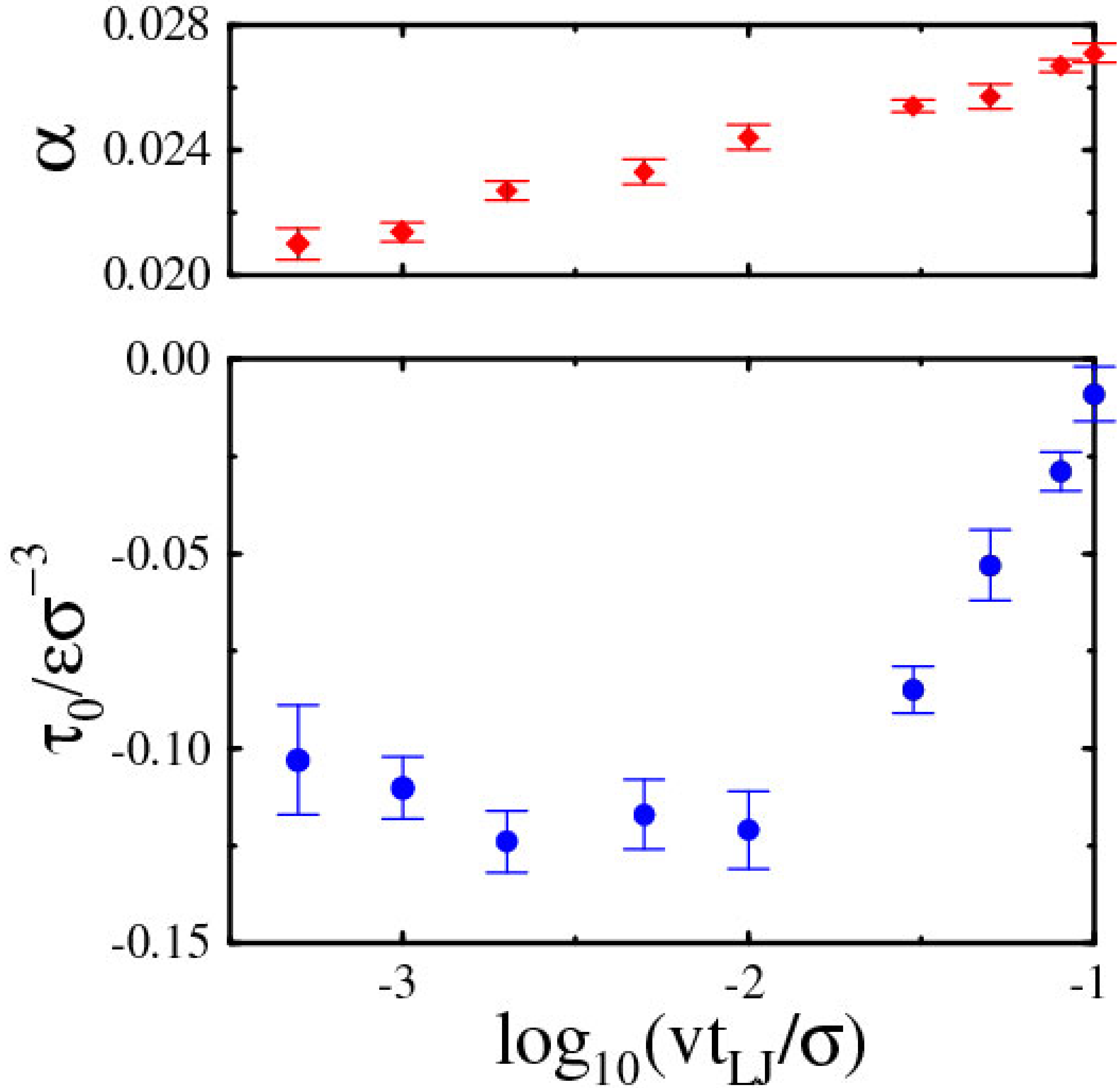
✓ ⇒ $\tau_s \approx$ independent of uncontrolled experimental parameters

- ✓ → sliding direction
- ✓ → wall orientation
- ✓ → thickness of adsorbed film (coverage)
- ✓ → chain length n=1 to 6 (~$C_{20}H_{42}$ and smaller)

➔ α primarily depends on relative size of wall atoms and adsorbed molecules in this simple model

G. He, M. H. Müser & M. O. Robbins, Science 284, 1650 (1999); Phys. Rev. B64, 035413 (2001).

Velocity Dependence of Kinetic Friction



Still linear in P

$\tau_k = \tau_0 + \alpha P$

$\alpha = a + b \log(v)$

τ_0 = const. for $v \leq 10^{-2}\ \sigma/t_{LJ}$

G. He and M. O. Robbins, Tribol. Lett. 10, 7 (2001)

Connection to "Rate-State" Models

For rocks, wood, metals,… (Dieterich,Ruina,Rice,…)

$\mu=\mu_0+A\ \ln(v/v_0) + B\ \ln(\Theta/\Theta_0)$; $d\Theta/dt=1-\Theta v/D_c$

→ A represents change in shear stress with v

→ B change in area of contact with time

Our model has fixed area → only see A

Find: $A \approx 0.001$ vs. 0.005 to 0.015 for rocks,

$A/\mu_0 \approx 0.05$ vs. 0.008 to 0.025 for rocks

$A \propto T$ as in experiments

$\mu \propto T \ln v$ follows from simple activation (Eyring) model

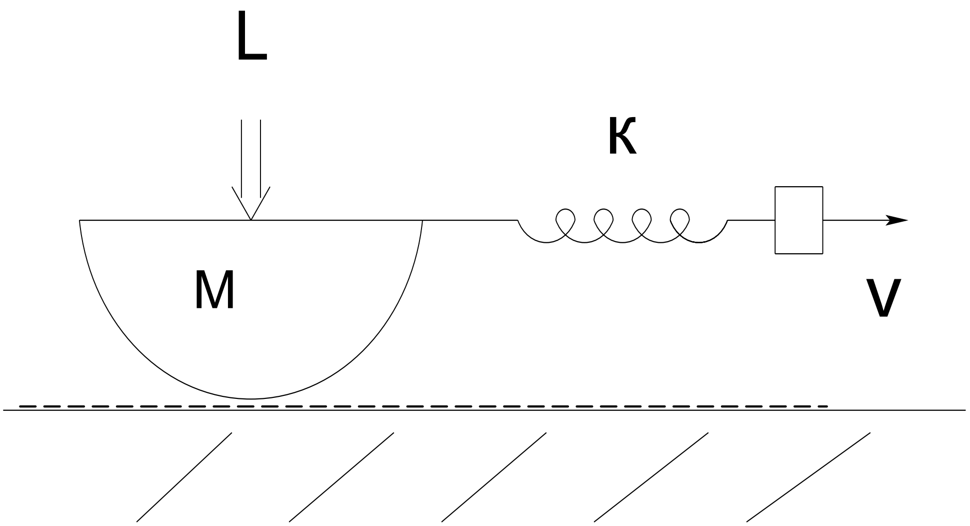
→ most molecules stable at any time

→ resist sliding just as for static friction

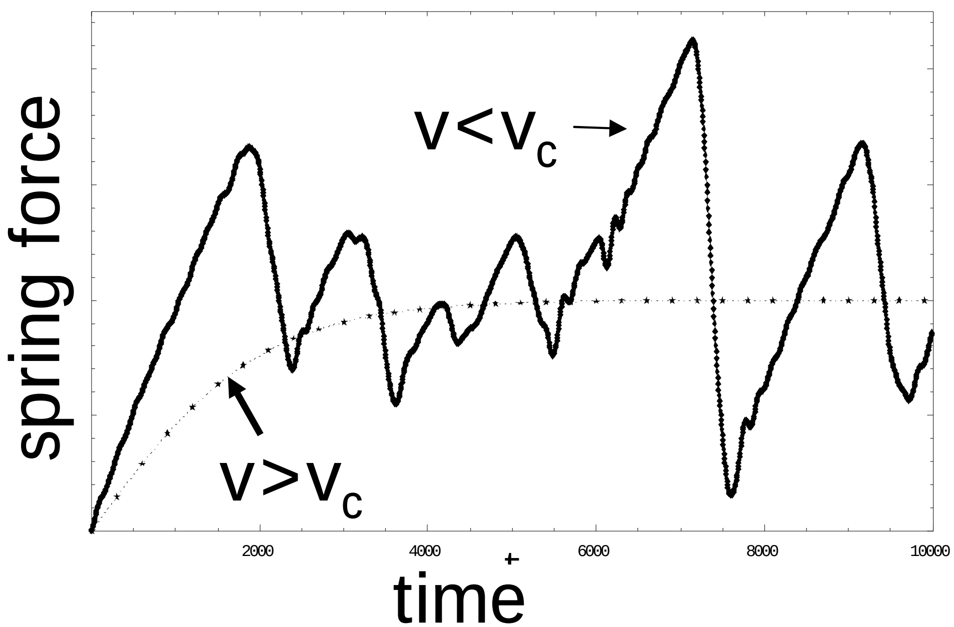
→ thermal activation over barrier reduces F

⇨ lower v, more thermal excitation → $F \propto \log v$

Dilation/Phase change in layer ⇒ stick-slip



Stick-Slip common in daily life: squeaky hinges, sound of violins
Controlled by spring constant κ, velocity v



Stick-Slip usually observed below velocity v_c.

What determines V_c ?

Models for V_c

- Experiments & simulations on confined films suggest stick-slip due to dynamic phase transitions between static solid and molten sliding states
  (Gee et al., J. Chem. Phys. 93:1895, 1990; Thompson & Robbins, Science 250:792,1990)
- Critical velocity then determined by either

1) Time to change phase (T&R 1990, Yoshizawa & Israelachvili, J. Chem. Phys. 97:11300, 1993, Persson & Volokitin, Surf. Sci. 457, 345, 2000)

2) Ability to absorb kinetic energy into potential energy

(Robbins & Thompson, Science 253:916,1991)

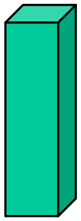
$\frac{1}{2} M v_c^2 \sim F_s \sigma \Rightarrow v_c \propto M^{-1/2}$=slider mass

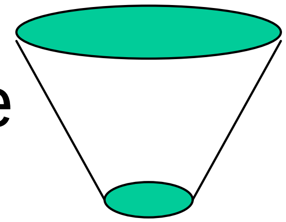
BUT above neglects elasticity of slider,

Persson and Braun argue that V_c stays large.

Find role of elasticity depends on geometry of slider

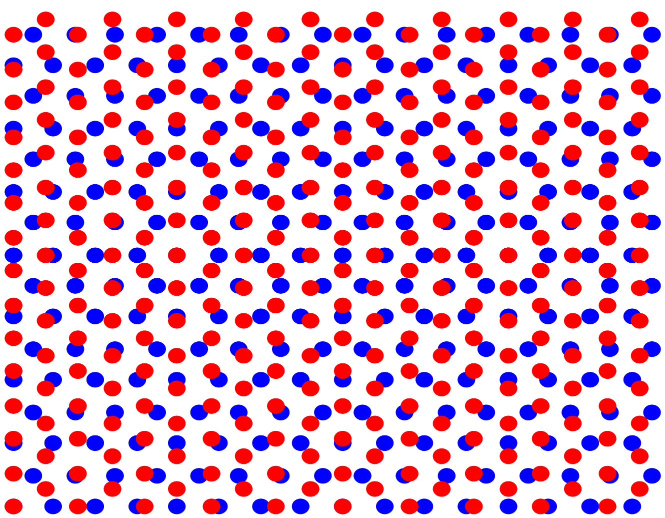
Two Slider Geometries

column  A_i = const, M~H

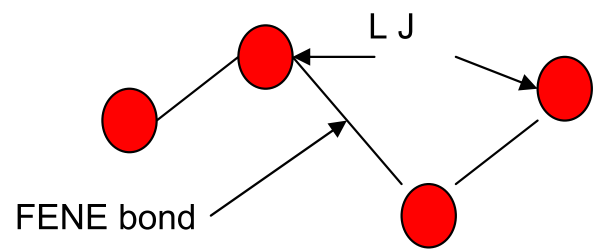
cone  $A_i = \text{const} + c\,i^2$, $M \sim H^3$

Divide slider into L layers, i^{th} coupled by springs to $(i\pm1)^{th}$
Mass M_i and coupling spring k_i proportional to layer area A_i.
Shear velocity $V_s \sim (k_i/M_i)^{1/2} d \sim 10\text{-}20$, d=lattice constant

At interface → Thin film between two incommensurate walls

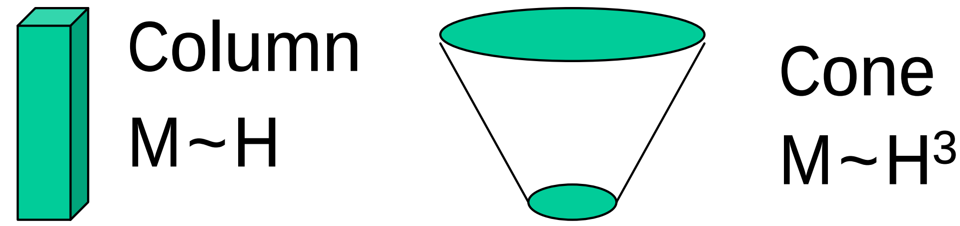


Temperature: T~0.7

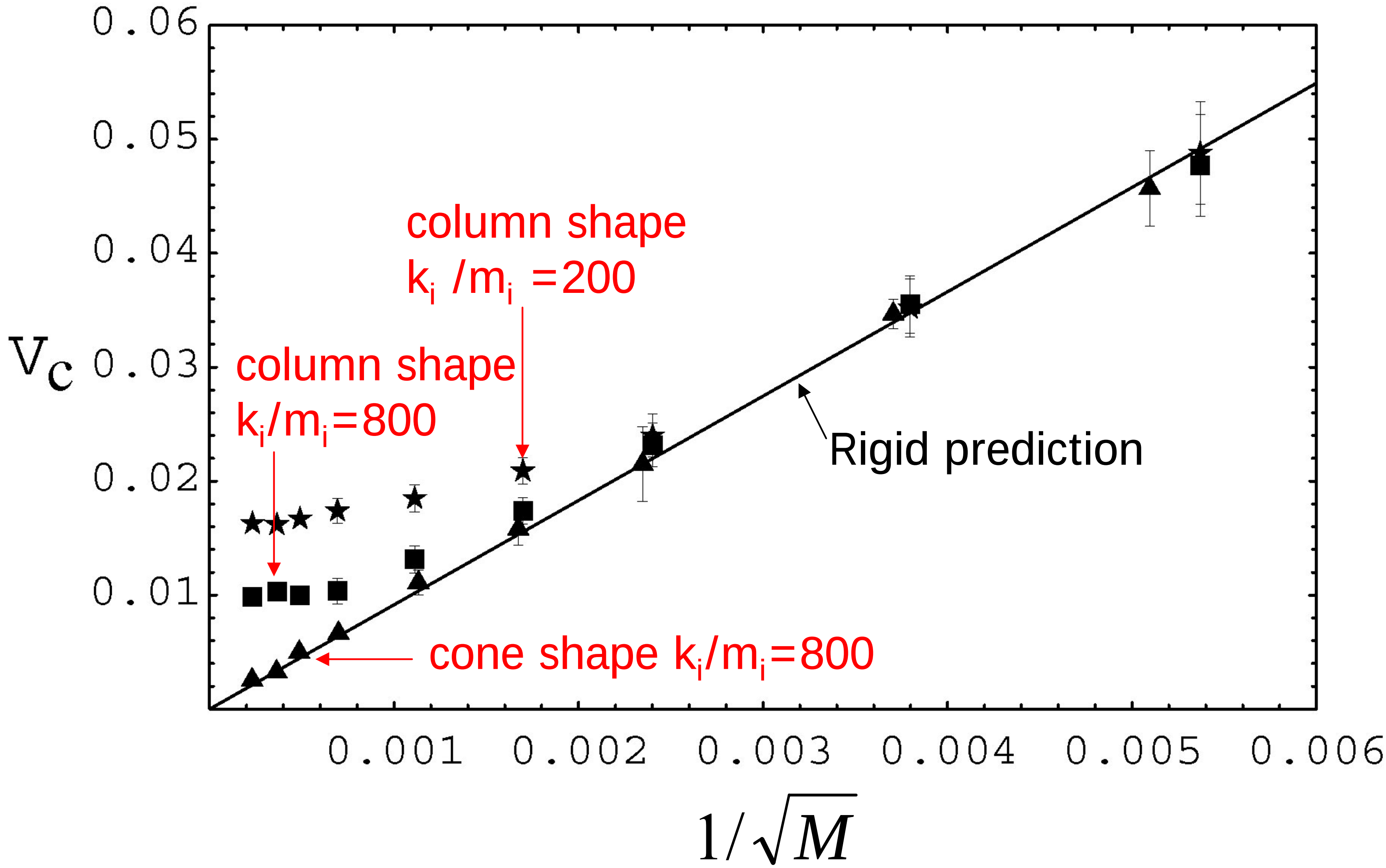


Film → bead-spring chain molecules
Repulsive Lennard-Jones interaction between wall and chain molecules.
All quantities in LJ units

Results for V_c



Find V_c from minimum constant force where slider keeps sliding (weak pulling spring limit)



Theoretical explanation

Two key time scales:

1. Time for slider to stop: $t_d \sim d/V_c$
2. Time for elastic wave to propagate over the height H of slider: $t_s = H/V_s$

Slider acts like rigid object when $t_s << t_d \rightarrow V_c \sim M^{-1/2}$

Check scaling of times with H assuming $V_c \sim M^{-1/2}$

Column shape: $M \sim H \rightarrow t_d \sim H^{1/2} \rightarrow t_d << t_s$, if H large

Cone shape: $M \sim H^3 \rightarrow t_d \sim H^{3/2} \rightarrow t_d >> t_s$, if H large

$\Rightarrow$ As $H \rightarrow \infty$, cone is rigid but column is not

$\Rightarrow$ Surface force apparatus like cone, but earthquake more like column?

Adsorbed layers explain many experiments

➔ **Lock surfaces together** (even when diffusing)

⇒ $\tau_s = \tau_0 + \alpha P$ for P up to ~1GPa

⇒ $\tau_s \approx$ independent of uncontrolled experimental parameters

α primarily depends on relative atomic sizes in our model

➔ **Kinetic friction also linear:** $\tau_k = \tau_0 + \alpha P$

⇒ α, τ_0 follow same trends as for τ_s

→ At low v, α is 10 to 20% smaller than for static case

→ α shows $k_B T$ log v dependence seen in experiment

→ Most molecules stable at any time, resist sliding just as for static friction, each pops and dissipates separately

Biggest contribution to friction from those close to popping

⇨ As v decreases, more thermal excitation, $F \propto \log v$

Pedagogical intro. to friction mechanisms and illustrating simulations
J. Ringlein and M. O. Robbins, Am. J. Phys. 72, 884-891 (2004)

Friction Mechanisms: Atomic to Macroscopic

Questions:

- Where do surfaces contact?
- How is friction produced in contacts?
- How do static and kinetic friction differ and age?
- How does concept of contact depend on scale?
- Do similar mechanisms of frictional locking, stick-slip, fracture, … operate at different scales?
- Can studies of mechanisms at small scales provide essential input for modeling larger scales?
- Can large scale experiments test small scale models?

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