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Instabilities and solid friction: from linear response to Coulomb friction

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Instabilities and solid friction:
From viscous friction to Coulomb friction

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Background:
Description of a simple tribo contact

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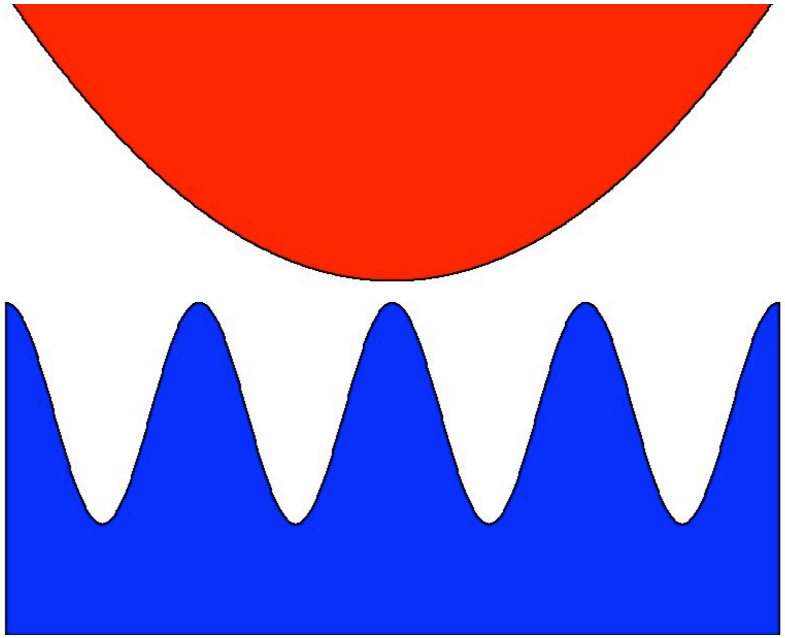

simple tribo contact:
- no third bodies
- no plastic deformation

strong interactions:
- within solids

weak interactions:
- between substrate & slider

x relative displacement of slider & substrate
any other *explicitly* kept variable

u internal degrees of freedom (e.g. phonons)

Background:
Formal theory for simple tribo contact

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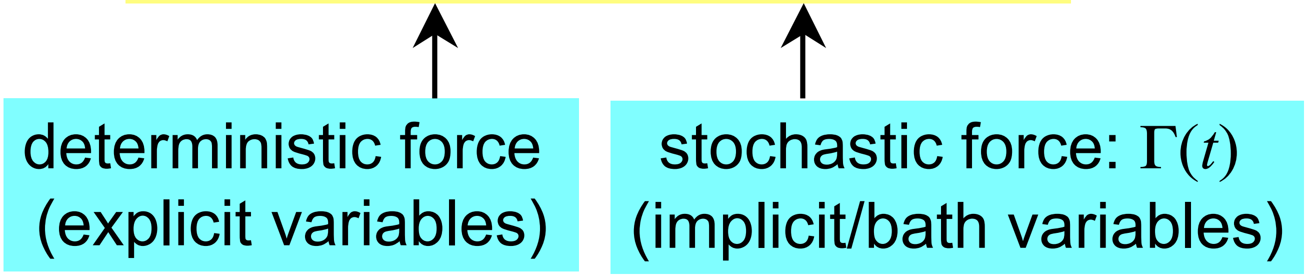
expand: $V(x,u)$ around reference point x_{ref} and $u_{\text{ref}} = 0$

$$V = V(x,0) + V_u(x_{\text{ref}},0)\cdot u + V_{xu}(x_{\text{ref}},0)\cdot(x\text{-}x_{\text{ref}})\cdot u + \ldots$$

$$\Rightarrow F = F(x,0) - V_{xu}(x_{\text{ref}},0)\cdot u(t)$$



deterministic force
(explicit variables)

stochastic force: $\Gamma(t)$
(implicit/bath variables)

assume: x moves slowly compared to u
phonons “equilibrate” at each value of x
$\Rightarrow$ $\Gamma(t)$ satisfies fluctuation-dissipation theorem

Background
Eliminating “bath modes” in contacts

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$$m\ddot{x}(t) = F(x) - m\int_{-\infty}^{t} dt'\gamma'(t-t')\dot{x}(t') + \Gamma(t) \quad + F_{\mathrm{ext}}(t)$$

$$\gamma'(\Delta t) = \frac{1}{2k_B T m}\langle \Gamma(t)\Gamma(t+\Delta t)\rangle_x$$

in our tribo system: $\Gamma(t) = V_{xu}(x_{\mathrm{ref}},0)\cdot u(t)$

$$\gamma'(x,\Delta t) = \sum_u \frac{|V_{xu}|^2}{2k_B T m}\langle u^*(\Delta t)u(0)\rangle_x$$

assuming time scale separation → $\approx \gamma(x)\cdot\delta(\Delta t)$

white noise $\quad \gamma(x) = \int d\Delta t\, \gamma'(x,\Delta t)$ ← inverse slip time $<< \omega_{\mathrm{Debye}}$

see, e.g., Smith, Cieplak, Robbins, Phys. Rev. B **54**, 8252 (1996)

Friction on adsorbed monolayers, u = internal modes of layer

Background
Eliminating "bath modes" in contacts

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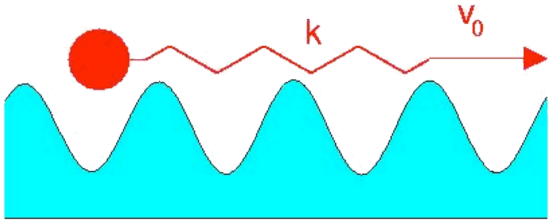
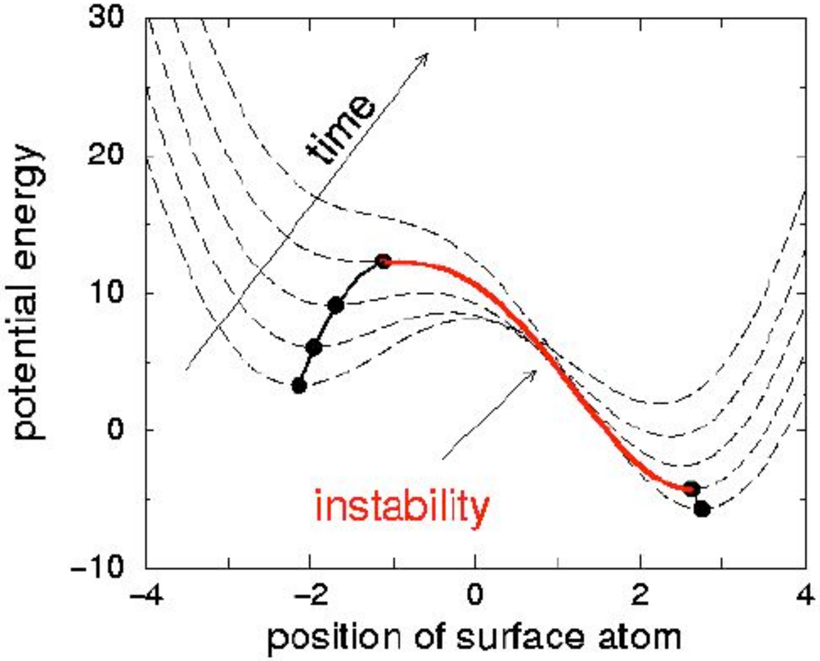
$$m\ddot{x} = F - m\gamma(x)\dot{x} - F_{\text{ext}}(x,t) + \Gamma(x,t)$$

$$\text{e.g. } m\ddot{x} = V_0 \sin x - m\gamma\dot{x} - k\cdot(x - vt) + \Gamma(t)$$



Prandtl-Tomlinson model



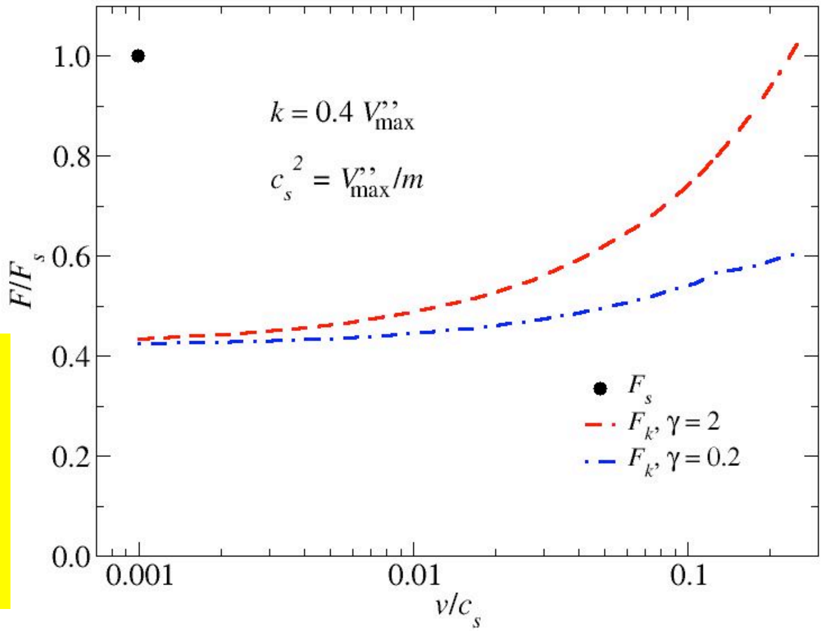
if V'' exceeds k

$\Rightarrow F_k$ is finite and relatively independent of γ

$$F_k = \Delta E / \Delta a$$

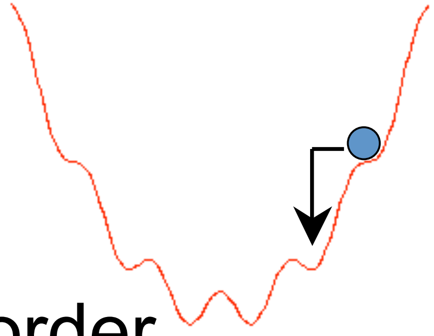
Prandtl Tomlinson model
Role of damping

For *bi-stable* potentials:
F_k barely depends on γ
(at "relevant" velocities v)



Prandtl (1928)
$\sim$ const + $T \ln v$ (v large, T small)
$\sim v \cdot \exp(E/k_B T)$ (v small, T large)

For *multi-stable* potentials:
F_k can depend on γ
- (always) discontinuous in both γ and v
- (usually) non-monotonic in both γ and v
- dependence reduced/eliminated by disorder



Origin of solid friction

What is the nature/magnitude of the dissipation?

- usually irrelevant
  unless significant heating, adsorbed layers,
  superlubric or other viscous systems

What is the nature of the instabilities?

- dislocation motion / plastic deformation
- third bodies (boundary lubricants)
- chemical reactions including hybridization changes
- phase transformations
- elastic instabilities (incommensurations)

Damping vs. instabilities (1)

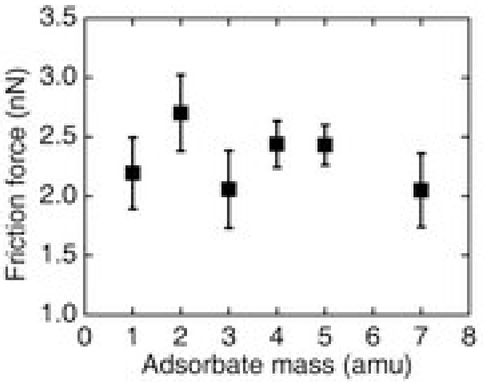
R. J. Cannara et al., Science **318**, 780 (2007):
We compared H- and D-terminated single-crystal diamond and silicon surfaces, and in all cases the hydrogenated surface exhibited higher friction. [~30%]

What does linear response say about m-dependance of γ?

- attempt frequency $\sim 1/\sqrt{m}$
- momentum exchange $\sim m$

$\}\ \gamma \sim \sqrt{m}$

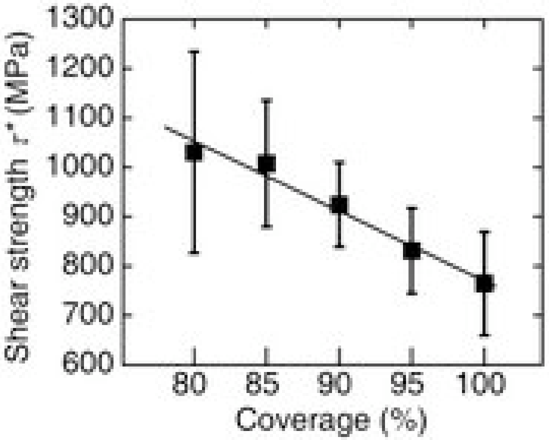
How can small damping lead to large friction?



if nothing but isotope mass is changed

Easier H desorption
- small ΔE
- large ν

Mo, Müser, Szulfarska, Phys Rev B (in press)



Damping vs. instabilities (2)

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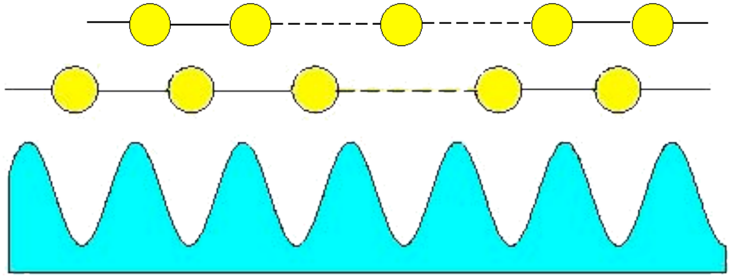
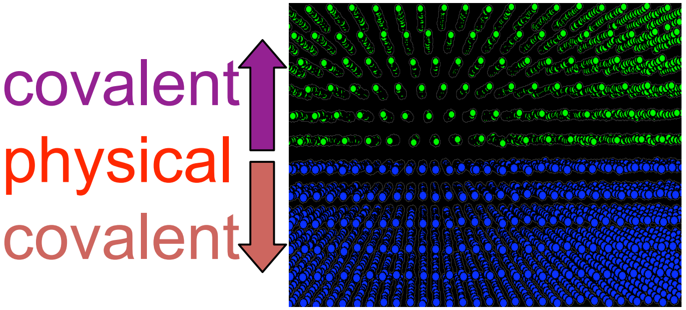
T. Filleter et al., Phys. Rev. Lett. **102**, 086102 (2009):
The friction on SiC is greatly reduced by a single layer of graphene and reduced by another factor of 2 on bilayer graphene.

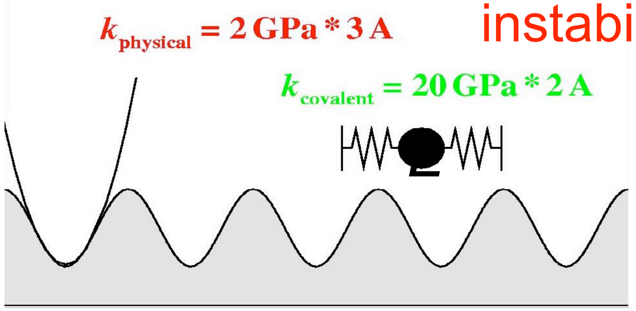
If slip / pinning occurs at the substrate, then single layer likely to be "deformed" & second layer changes energetics of instability



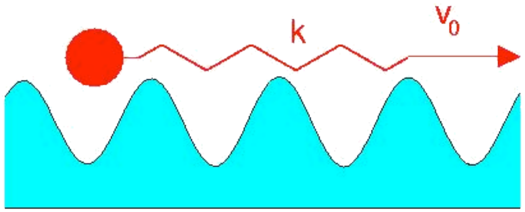
There is an effect of dimensionality of object on pinning (friction)
Müser, Europhys Lett **66**, 97 (2001)

Elastic instabilities and dimensionality





instabilities only if $k < \partial^2 V / \partial x^2$

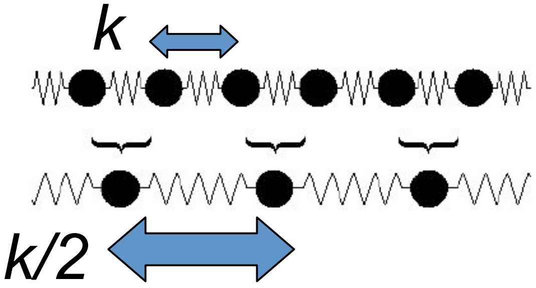


If on local scale: $k_{\text{bulk}} > k_{\text{interf}}$ then on large scale: $k'_{\text{bulk}} < k'_{\text{interf}}$?

Need to analyze how k changes with size:

1*d* linear chain

$$\boxed{k_L = \frac{L_{\text{atomic}}}{L} k_{\text{atomic}}}$$



2*d* elastic sheet: $k_L = k_{\text{atomic}}$ (no resistance to bending)

3*d* solid: $k_L = L^{1/2} k_{\text{atomic}}$

MHM, Europhys. Lett. **66**, 97 (2004)

Origin of solid friction (cont'd)

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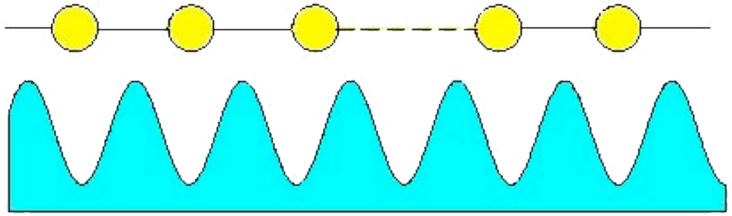
What is the nature/magnitude of the dissipation?

What is the nature of the **instabilities**?

- dislocation motion / plastic deformation of bulk
- third bodies
- chemical reactions including hybridization changes
- phase transformations
- **elastic instabilities**

Hammerberg et al., Physica D **123**, 330 (1998)

Frenkel Kontorova model captures early time behavior of friction process & low-dimensional systems (graphene?)



Müser, Tribol. Lett. **10**, 15 (2001)

If interactions in atom-based models are tuned to produce elastic instabilities, irreversible processes such as cold-welding and wear occur.

Elastic wrinkle instabilities
Examples

not for yet for public exposure

Elastic wrinkle instabilities
Preliminary results (1)

not for yet for public exposure

involved student: Hamid Mohammadi, UWO

Elastic wrinkle instabilities
Preliminary results (2)

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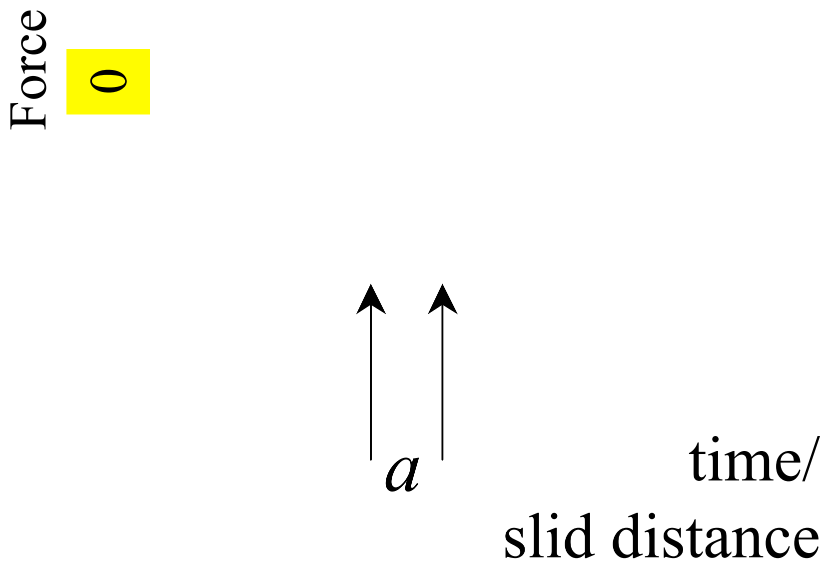

involved student: Hamid Mohammadi, UWO

Elastic <u>wrinkle</u> instabilities
Preliminary results (3)

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involved student: Hamid Mohammadi, UWO

Conclusions

In order to rationalize kinetic (solid/Coulomb) friction, we need to unravel the instabilities in the system.

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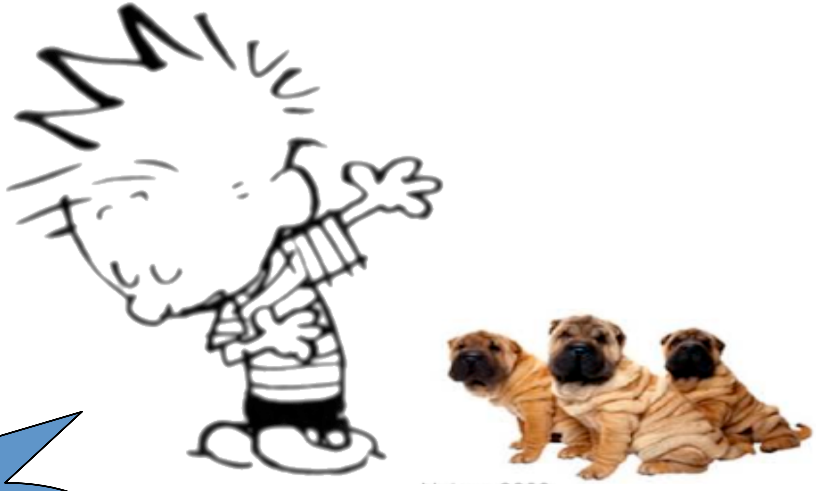
- friction of graphite lamella: stiffness-effect

It's the thickness that matters

- isotope effect in friction due to stability of D atoms?

That’s it.



Thanks for your attention!