Understanding the movements of metal whiskers

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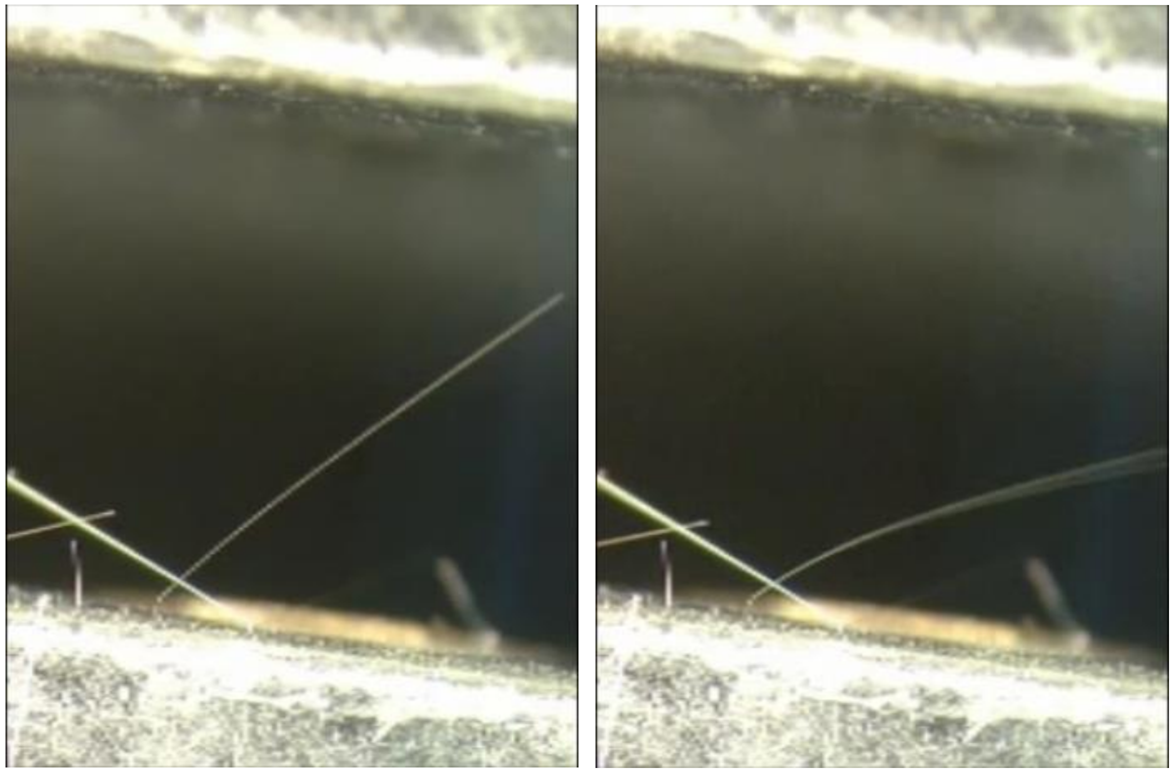
Outline

- Motivation
- Approach
- Whisker mechanics in elastic beam model
- 5 potential mechanisms of movements
  - Air flow effects
  - Brownian movements
  - Mechanical vibrations
  - Garden hose instability
  - Electric instabilities: ionic diffusion and nonequilibrium charges
- Conclusions

Motivation: observations by many

- Examples of movies
  - https://nepp.nasa.gov/whisker/video/index.html
  - https://www.youtube.com/watch?v=HbWRPAVzdmc
- Movies imply whisker movement due to minute air flows (expiration towards whiskers, etc.;), thanks Jay B for explanations
- Anecdotal evidence by many: whiskers move spontaneously, without any intended stimuli (thanks to the discussions during one of the recent teleconferences).
- I saw spontaneous movements myself with a flashlight and a magnifying glass on huge zinc whiskers (thanks Jay B)
- But was it spontaneous? Could it be documented?
- Did others see spontaneous whisker movements?
- **My contribution here: what is possible theoretically?**

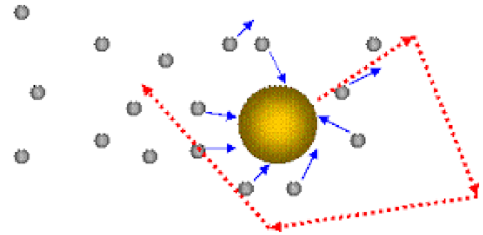
Note:
these are high amplitude movements



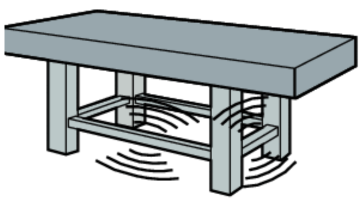
- with characteristic times of 0.1 – 0.01 s
- often, nearest neighbors move incoherently

Proposed mechanisms of metal whisker movements

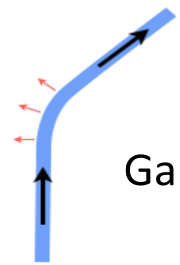
Air flow (NASA team)



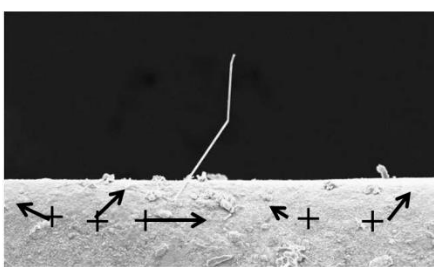
Brownian movements (G. Davy)



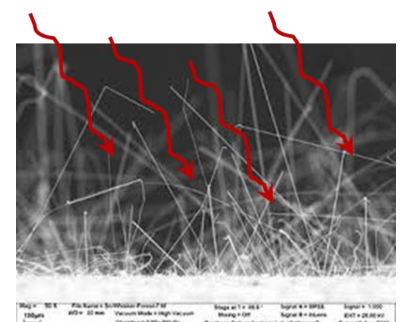
External mechanical vibrations (B. Rollins)



Garden hose instability (VK)



Random electric fields due to ionic diffusion (VK)



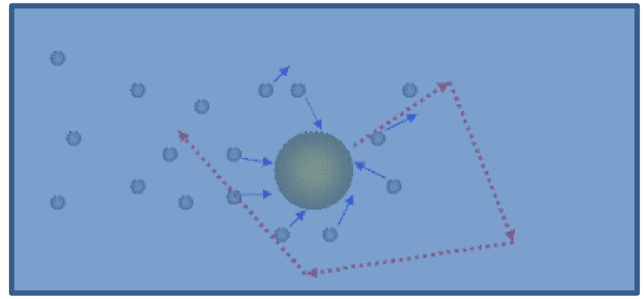
Random electric fields due to light induced recharging (VK)

Announcing final results (in case you do not have time)

Certainly possible

Air flow (NASA team)

unlikely



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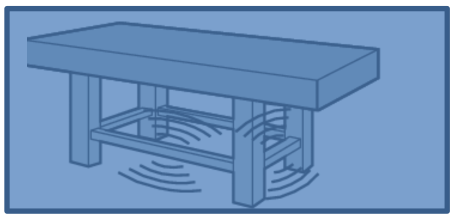


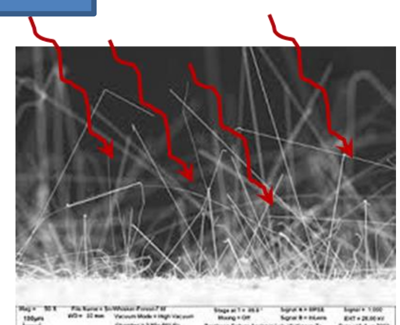
External mechanical vibrations (B. Rollins)

impossible

Garden hose instability (VK)

impossible

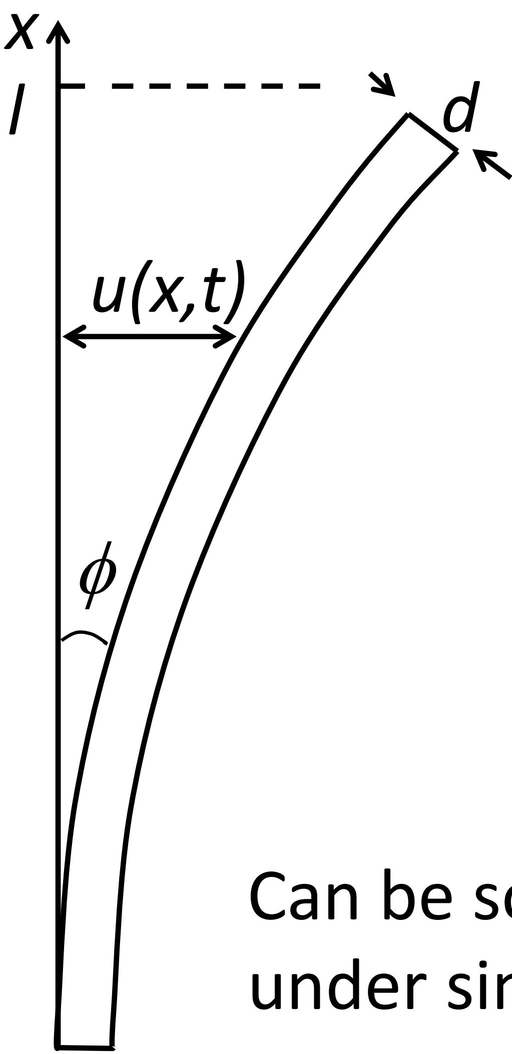
Random electric fields due to ionic diffusion (VK)



plausible

Random electric fields due to light induced recharging (VK)

Elastic beam model for whiskers



Movements reversible – elasticity

Euler-Bernoulli equation

$$YI\frac{\partial^4 u}{\partial x^4}+\rho A\frac{\partial^2 u}{\partial t^2}+B\frac{\partial u}{\partial t}=f(x,t)$$

u – deflection, *t* – time, *Y*-Young's moduli, *I*-area moment of inertia, ρ-material density, *A*-area, *B*-friction coefficient, *f*-force at point x on the beam

Can be solved exactly for cantilever beams under simple forces; otherwise -- useless

Order-of-magnitude approximations

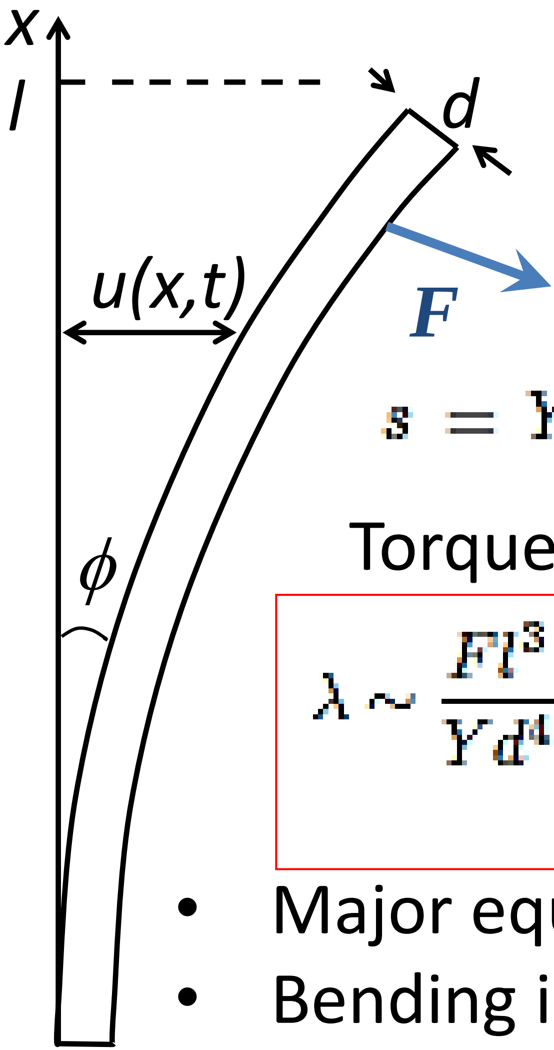
- Phenomena are versatile and parameters unknown→ approximations necessary, exact models excessive
- Neglect all numerical multipliers
  - Example: area of a circle ~ d^2 instead of $\pi(d/2)^2$
- Including even integrals and derivatives
  - Example:

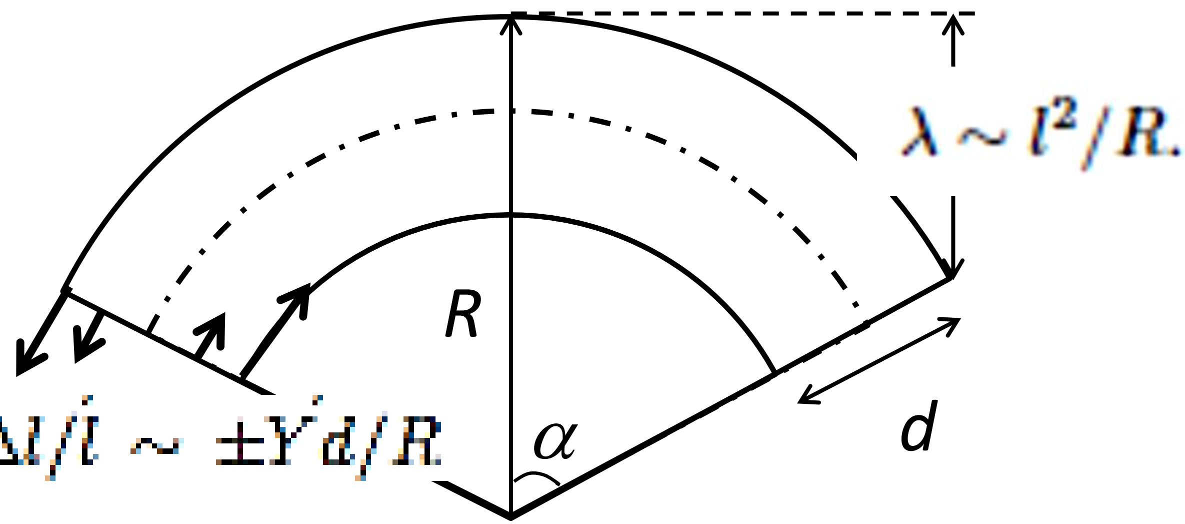
$$\int_0^1 x^2 dx \sim \langle x^2 \rangle \bullet \Delta x = \left(\frac{1}{2}\right)^2 \bullet 1 = \frac{1}{4} \text{ instead of } \frac{1}{3}$$

$$\frac{d(x^2)}{dx} \sim \frac{x^2}{x} = x \text{ instead of } 2x$$

- It works! Errors mostly cancel each other to the accuracy of insignificant multipliers similar to cancelations of random displacements in diffusion
- = 'Errors propagate by diffusion' (attributed to Einstein)
- It is efficient, fast, inexpensive... and almost forgotten

Basics of whisker bending





$$s = Y\Delta l/l \sim \pm Y d/R$$

Torque *sAd* by stresses ~ Torque Fl by force *F*

$$\boxed{\lambda \sim \frac{Fl^3}{Yd^4} \sim \frac{F}{K}\left(\frac{l}{d}\right)^2 \equiv \frac{F}{K_b}.}$$

K is compressive spring constant, $K_b = K(d/l)^2$ is bending spring constant

- Major equation: deflection vs. force/geometry
- Bending is easier than compressing
- Very sensitive to whisker geometry

Useful consequences

Frequency of harmonic oscillator

$$\omega_b \sim \sqrt{\frac{K_b}{m}} \sim \frac{d}{l^2}\sqrt{\frac{Y}{\rho}} \sim \frac{d}{l^2} v_s$$

Transversal vibrational frequency depends on whisker geometry and speed of sound in its material

$$F \sim m\frac{\lambda}{\tau_b^2} \quad \Rightarrow \quad \tau_b \sim \frac{1}{\omega_b}$$

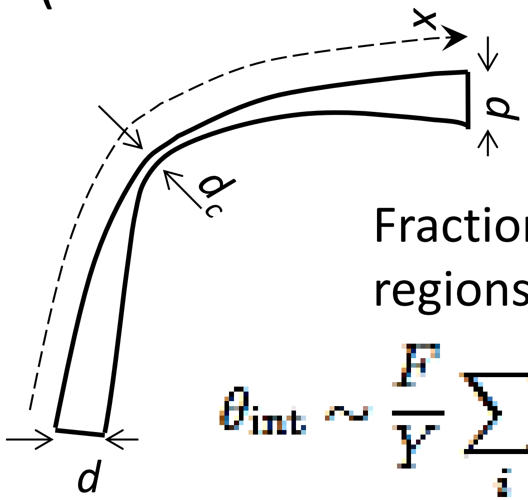
Newton's second law

Time of whisker bending is reciprocal of the above frequency

Typical times on the order of 1-100 ms consistent with observations

Some other applications

Whisker with constriction (not sure how realistic)



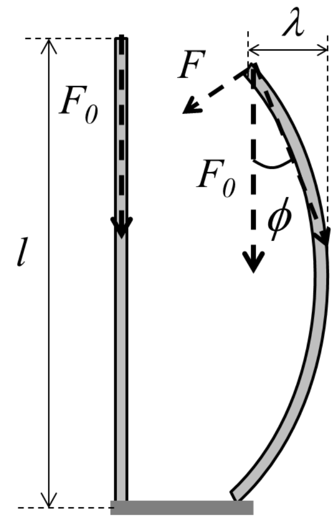
Fraction of constricted regions

$$\theta_{\rm int} \sim \frac{F}{Y}\sum_i \frac{p_i}{d_i^2}$$

Significant lowering of vibrational frequency

$$\omega_{bc} \sim \omega_b\sqrt{\frac{l d_c^2}{d^3}}K_b \ll \omega_b,$$

Buckling instability



Critical compressive force

$$F_0 = F_{0c} \sim Y d^4/l^2.$$

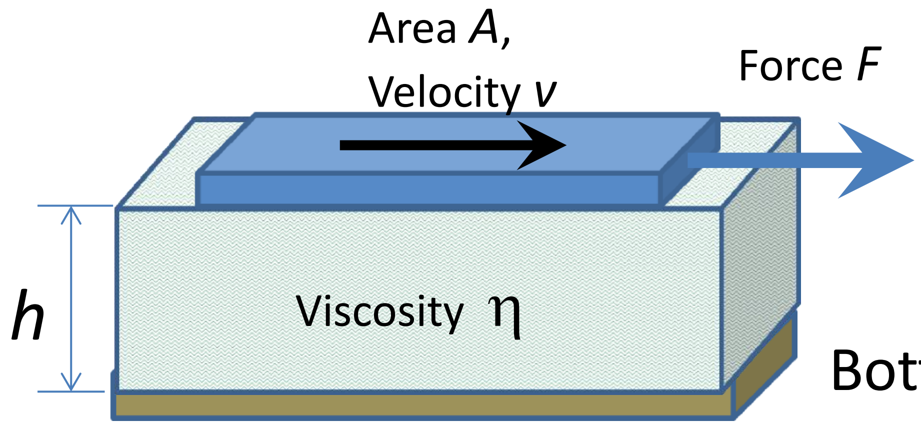
or critical whisker length

$$l_c = \sqrt{Y d^4/F_0}.$$

above which buckling begins

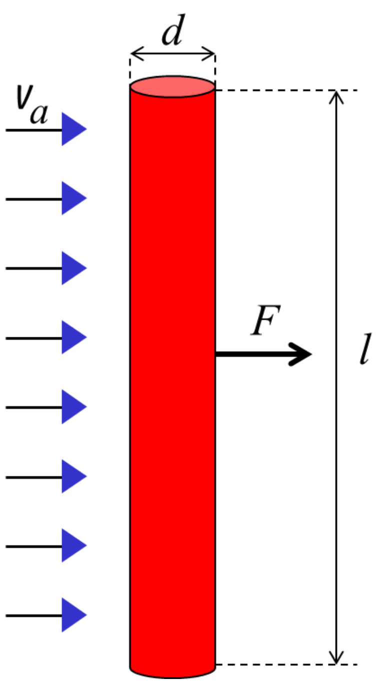
Viscous drag on a whisker

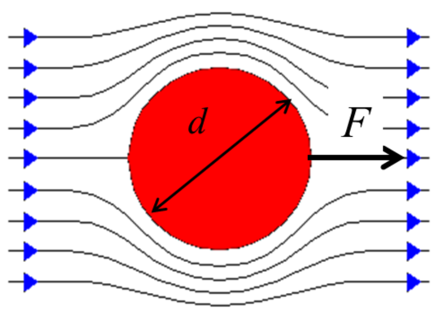
Recalling the concept of viscosity



$$F = \eta \frac{Av}{h}$$

Bottom at rest





$$\boxed{F \sim \eta v_a l}$$

The only length across which the velocity field can change

$$h \rightarrow d$$

Side surface of a cylinder

$$A \rightarrow ld$$

6 mechanisms of whisker movements

Relevant material parameters Sn (Zn)

Parameter	Value	Ref.
density ρ g/cm^3	7.4 (7.1)^a	35
Young's modulus Y GPa	50 (108)	35
sound velocity, v_s,10^5 cm/s	2.7 (3.9)	35
diameter,^{b} d μm	0.1-20	2,3,36–38
length, l	10μm-25 mm	2,3,36–38
dynamic air viscosity, η g/cm-s	$2 \cdot 10^{-4}$	39
kinematic air viscosity, η/ρ_a, cm^2/s	0.15	39
patch size, d_0 μm	0.1-10	7,8
electric charge density, n e/cm^2	$10^{10} - 10^{12}$	7,8
near surface field, E_0 V/cm,	$10^4 - 10^6$	7,8
ion diffusion coefficient D_i, cm^2/s,	10^{-16}	40
electron mobility μ_e, cm^2/V-s,	1000	41

Structure of results

Quantity	$d=1\mu m$ $l=1mm$	$d=1\mu m$ $l=10mm$	$d=10\mu m$ $l=1mm$	$d=10\mu m$ $l=10mm$
$v_a$cm/s, Eq. (18) Re[a]	$5\cdot10^2$ 500	0.05 0.5	$5\cdot10^6$ $5\cdot10^6$	$5\cdot10^3$ $5\cdot10^4$
ω_b, s^{-1} Eq. (5)	3000	30	30,000	300
$\Delta\phi$, rad Eq. (24)	10^{-4}	$3\cdot10^{-4}$	10^{-6}	$3\cdot10^{-6}$
$t_{\Delta\phi}$, s Eq. (25)	$2\cdot10^{-4}$	2	$2\cdot10^{-8}$	$2\cdot10^{-4}$
λ/l,Eq. (27) for $w=g$	$2\cdot10^{-3}$	1	$2\cdot10^{-5}$	0.02
λ/l,Eq. (29)	10^{-7}	10^{-5}	10^{-9}	10^{-7}
λ/l,Eq. (30),[b] $\cos\theta\sim1$	$10^{-3}-10$	$0.1-10^3$	$10^{-7}-10^{-3}$	$10-10^5$
$\delta E/E$, Eq. (32)[c]	10^{-9}	10^{-10}	10^{-9}	10^{-10}
$\delta E/E$, Eq. (32)[c] with $\delta n/n=1$	0.4	0.04	0.4	0.04

[a] $Re=lv_a\rho_a/\eta$ denotes the Reynolds number.
[b] The computed ratios $\lambda/l>1$ are formal and must be replaced with 1.
[c] For the observation time $t=1$ s.

Quantity = estimated parameter that can be compared to observations

Neglecting continuous (~lognormal distributions) of whisker lengths and diameters, four reference points are taken:
Thin whiskers d=1 μm
Thick whiskers d=10 μm
Short whiskers l=1 mm
Long whiskers l=10 mm

1. Air flow

Air flow cause	Air flow velocity (cm/s)[a]
Room A/C	400
HVAC Vent	220
Person walking	180
Door opening	120
Expiratory air flow [b]	100
Diffuser vent	25

[a]Data from Ref. 17, except the "expiratory" mode, for which the velocity was estimated assuming the average lungs expiratory volume[18] of ~ 1 L and the lips expiration opening area $\sim 1\ \mathrm{cm}^2$ held for 10 s.

Yes, air flow can be a cause

Quantity	Thin whiskers: $d = 1\mu m$, $l = 1mm$	Thin whiskers: $d = 1\mu m$, $l = 10mm$	Thick whiskers: $d = 10\mu m$, $l = 1mm$	Thick whiskers: $d = 10\mu m$, $l = 10mm$
v_a cm/s, Eq. (18)	$5 \cdot 10^2$	0.05	$5 \cdot 10^6$	$5 \cdot 10^3$
Re^a	500	0.5	$5 \cdot 10^6$	$5 \cdot 10^4$
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[a] $Re = l v_a \rho_a / \eta$ denotes the Reynolds number.

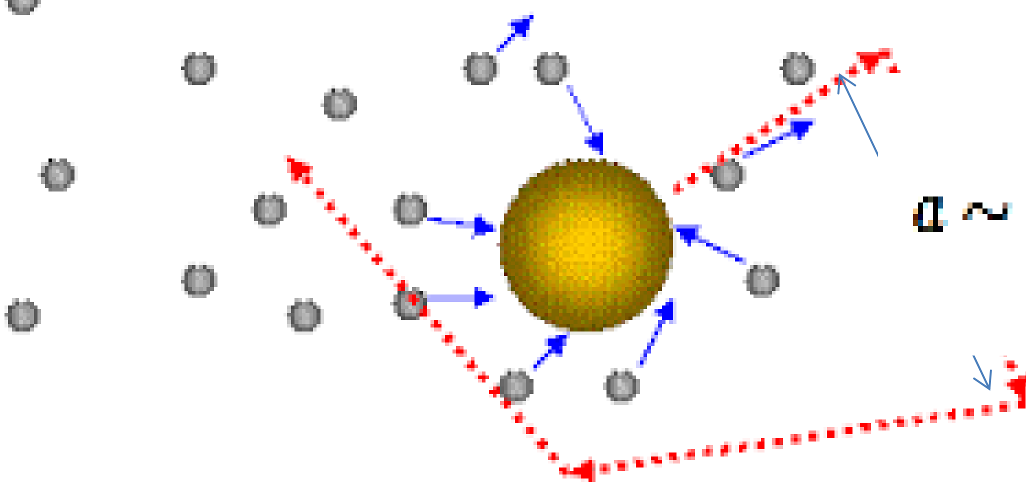
Air velocity that produces deflections comparable to whisker lengths.

Even thick whiskers can be moved under strong enough wind

$$F \sim \eta v_a l,$$
$$\lambda \sim F l^3 / Y d^4$$
$$\lambda \sim l \text{ - citerion}$$

Brownian movements of ‘free’ particles

τ_η - coherency time $\qquad \eta v_T d \sim \dfrac{m v_T}{\tau_\eta}$

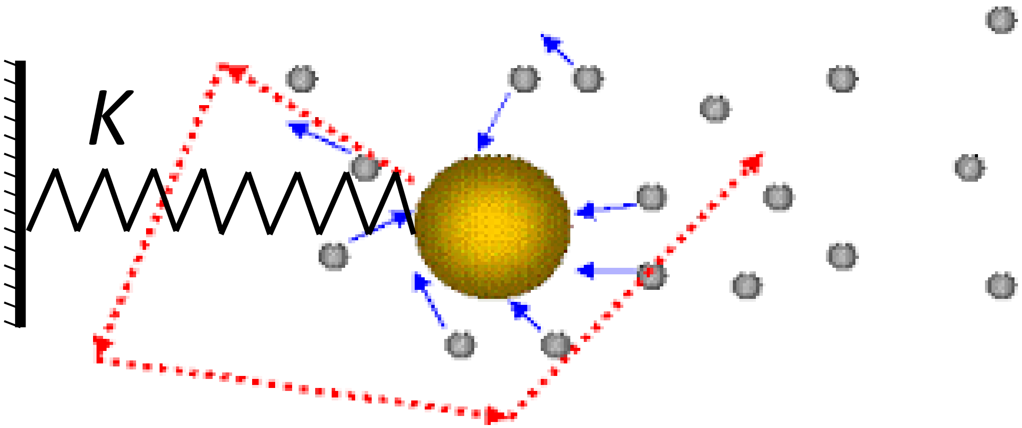


$$a \sim v_T \tau_\eta \sim \sqrt{\frac{k_B T}{m}}\tau_\eta \sim \frac{\sqrt{k_B T \rho d}}{\eta}$$

$$L \sim a\sqrt{\frac{t}{\tau_\eta}} \sim \sqrt{\frac{k_B T}{\eta d}t} \equiv \sqrt{D_d t} \quad \text{with} \quad D_d \sim \frac{k_B T}{\eta d}$$

Typical Brownian displacements are small: ~ 10 μm per 1 s
(It took microscope to discover Brownian movements).

Modification: Brownian movements of a harmonic oscillator



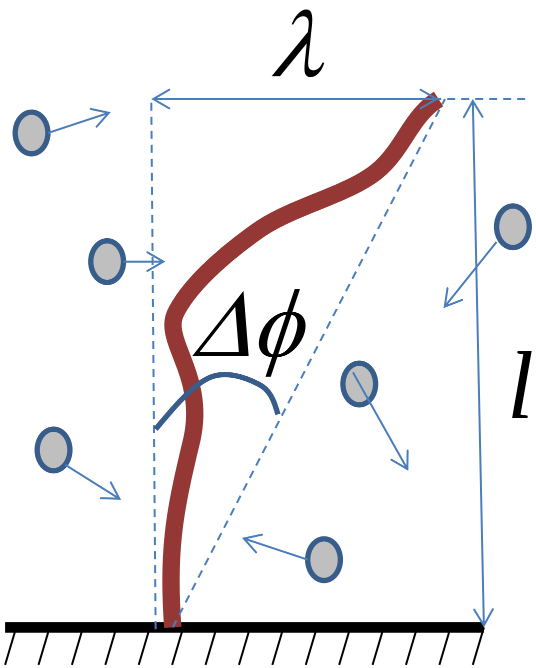
The spring limits Brownian displacements to that of equipartition theorem

$$\frac{KL_{\max}^2}{2} = \frac{k_B T}{2}$$

The 'free' particle Brownian model works for $L<L_{max}$
Brownian diffusion confined

Brownian movements of elastic beams

Limiting deflection is determined by bending elasticity K_b and thermal energy k_BT



$$\frac{K_b\lambda^2}{2} = \frac{k_BT}{2}$$

$$\Delta\phi \sim \sqrt{\frac{k_BTl}{Yd^4}}.$$

$$t_{\Delta\phi} \sim \frac{\eta}{Y}\left(\frac{l}{d}\right)^4$$

This theory is consistent with the known results for bending fluctuations of long molecules

Brownian movements of metal whiskers is unlikely

Quantity	Thin whiskers $d=1\mu m$, $l=1mm$	Thin whiskers $d=1\mu m$, $l=10mm$	Thick whiskers $d=10\mu m$, $l=1mm$	Thick whiskers $d=10\mu m$, $l=10mm$
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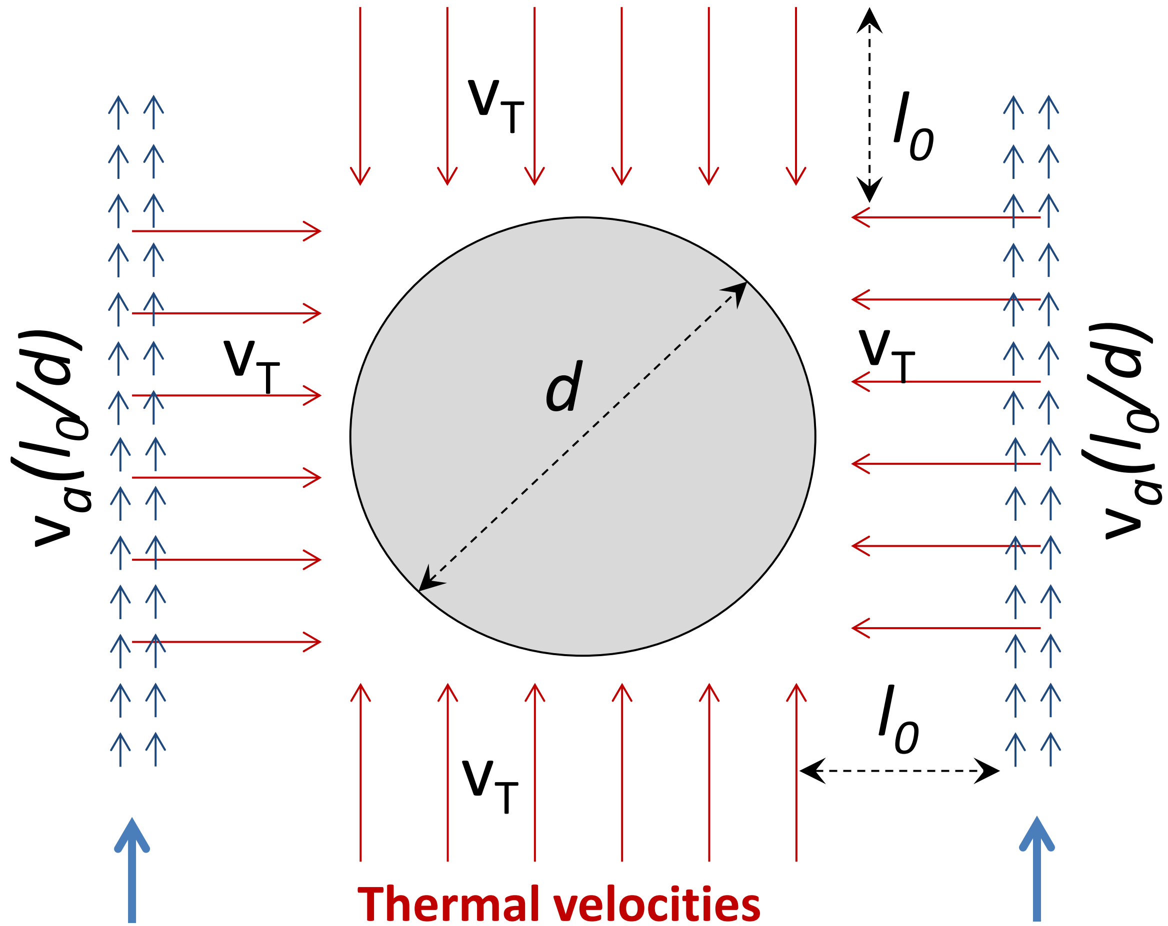
$^a Re = l v_a \rho_a/\eta$ denotes the Reynolds number.

Predicted angles are too small... maybe OK for severely constricted whiskers

Even though predicted time scales can be realistic

Brownian movements vs. viscous drag: what is so different?



Vertical air flow has a certain direction: momenta from both sides add

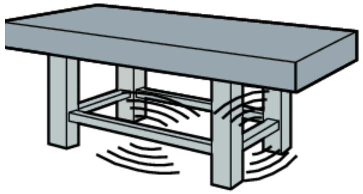
Brownian random momenta don't have preferential direction and mutually cancel

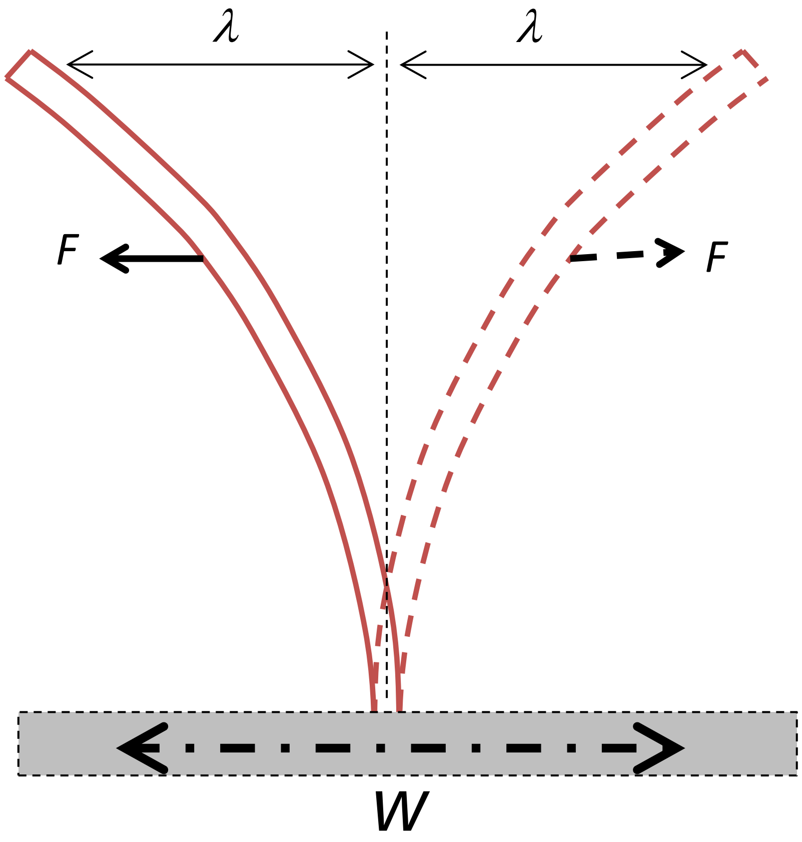
$$Nv_a\frac{l_0}{d} > \sqrt{N}v_T$$

$$N \sim d^2 l_0 n >> 1 \ \ (!),$$

n – atomic concentration

External vibrations





Inertia force $F = -mw$

deflection $\lambda = \dfrac{Fl^3}{Yd^4}$

truck on a rural road $w \leq g$

standard lab $w < 0.01g$

External vibrations unlikely to move metal whiskers

	Thin whiskers		Thick whiskers	
Quantity	$d = 1\mu m$ $l = 1mm$	$d = 1\mu m$ $l = 10mm$	$d = 10\mu m$ $l = 1mm$	$d = 10\mu m$ $l = 10mm$
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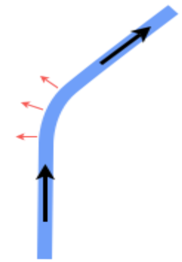
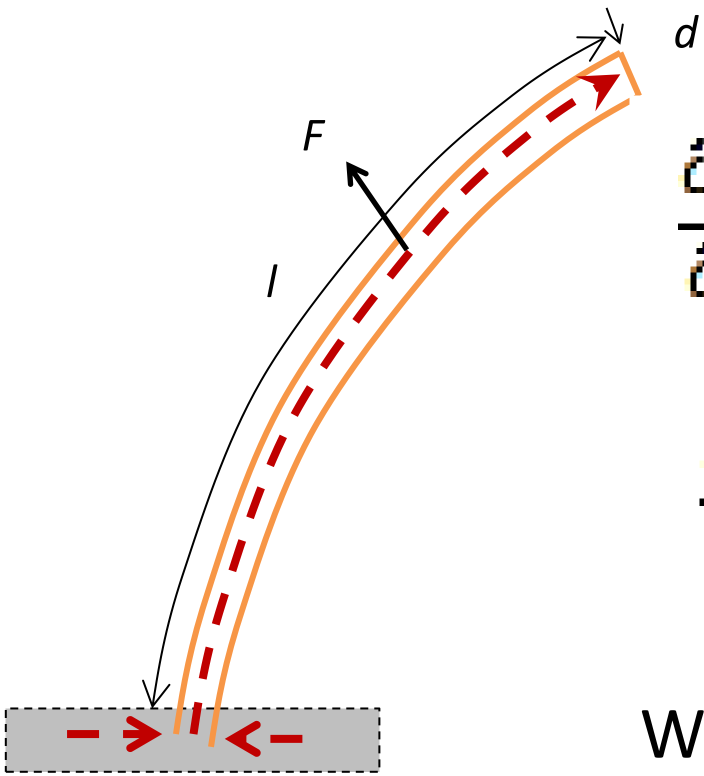
Displacements small, except maybe severely constricted whiskers

Garden hose instability





$$\frac{\partial p}{\partial t} = v_w \frac{\partial m}{\partial t} \sim v_w \rho d^2 \frac{\partial l}{\partial t} = \rho v_w^2 d^2.$$

$$\frac{\lambda}{l} \sim \left(\frac{v_w}{v_s}\right)^2 \left(\frac{l}{d}\right)^2$$

Whisker growth velocity v_w~ 1A/s is so much smaller than the speed of sound v_s~ 10^5 cm/s that this effect is strictly impossible

Garden hose instability irrelevant

	Thin whiskers		Thick whiskers	
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Random electric fields due to ionic diffusion

Diffusion can be represented as appearance of random dipoles

$$p^2 = e^2 D_i t,$$

$$(\delta E)^2 \sim \frac{(nl^2)e^2 D_i t}{l^6}$$

D_i – ion diffusion coefficient

n – ionic concentration per area

l – whisker length, t - time

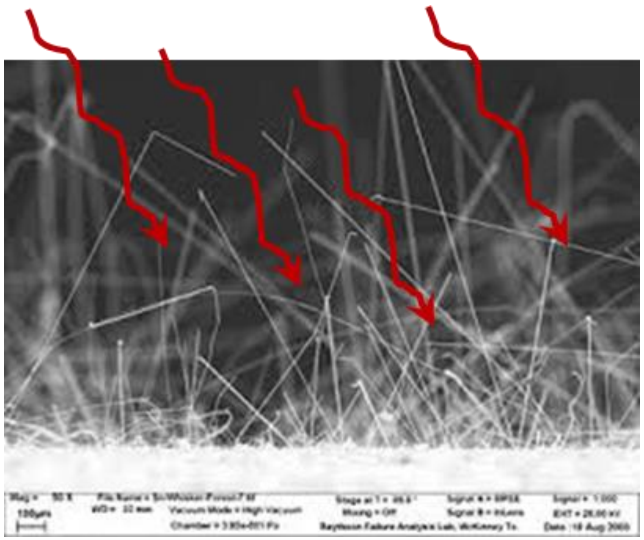
Ionic diffusion is too slow

Quantity	Thin whiskers: $d=1\mu m$, $l=1mm$	Thin whiskers: $d=1\mu m$, $l=10mm$	Thick whiskers: $d=10\mu m$, $l=1mm$	Thick whiskers: $d=10\mu m$, $l=10mm$
u_s, cm/s, Eq. (18)	$5\cdot 10^2$	0.05	$5\cdot 10^5$	$5\cdot 10^3$
Re^a	500	0.5	$5\cdot 10^6$	$5\cdot 10^4$
ω_0, s^{-1} Eq. (5)	3000	30	30,000	300
$\Delta\phi$, rad Eq. (24)	10^{-4}	$3\cdot 10^{-4}$	10^{-6}	$3\cdot 10^{-6}$
$t_{\Delta\phi}$, s Eq. (25)	$2\cdot 10^{-4}$	2	$2\cdot 10^{-6}$	$2\cdot 10^{-4}$
λ/l, Eq. (27) for $w=g$	$2\cdot 10^{-3}$	1	$2\cdot 10^{-5}$	0.02
λ/l, Eq. (29)	10^{-7}	10^{-5}	10^{-9}	10^{-7}
λ/l, Eq. (30),[b] $\cos\theta\sim 1$	$10^{-3}-10$	$0.1-10^3$	$10^{-7}-10^{-3}$	$10-10^5$
$\delta E/E$, Eq. (32)[c]	10^{-9}	10^{-10}	10^{-9}	10^{-10}
$\delta E/E$, Eq. (33)[c] with $\delta n/n=1$	0.4	0.04	0.4	0.04

For t = 1s

Too slow diffusion

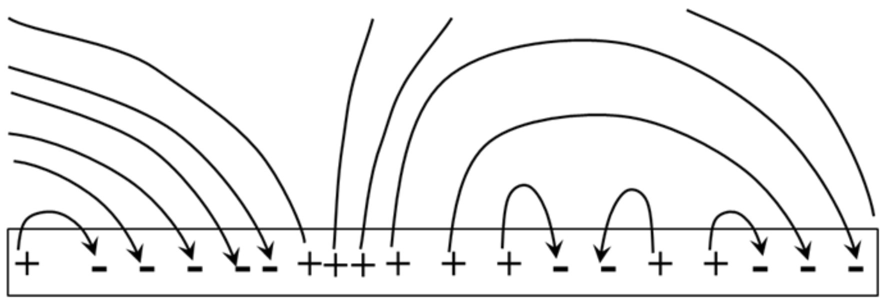
Nonequilibrium electric charges

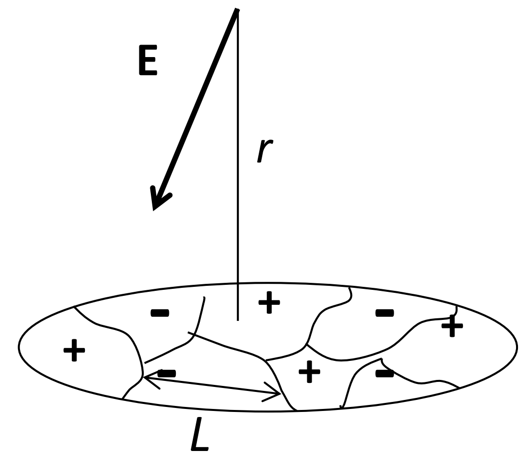


Light or ionizing radiation, or change in ambient ionization create nonequilibrium charge distribution altering electric fields on whiskers

This mechanism is built on the electrostatic theory of metal whiskers implying random charge patches on metal surfaces

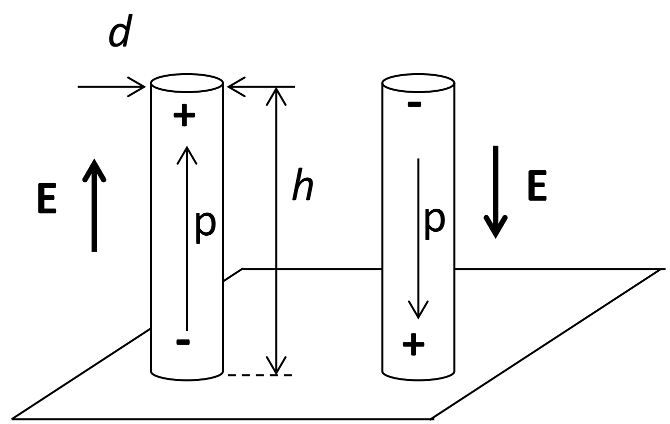
Recalling the electrostatic theory (VK 2014) Charge patches

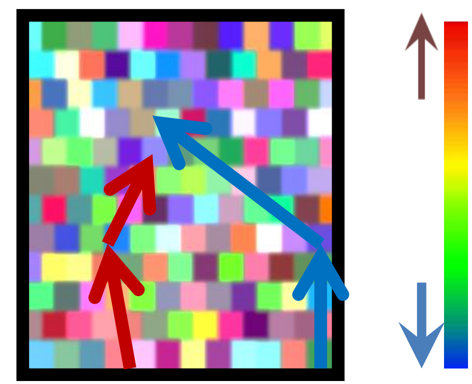




- Random charge patches due to imperfections: grain boundaries, oxides, ion contaminations, local deformations, dislocations, etc.
- Patch size L~ 0.1 -10 μm, field near the surface E_0~10^4-10^6 V/cm
- At distances r>L the field is random and decays, $|E|\sim|E_0|(L/r)$
- E-field theory explains the versatility of whisker triggers (GB, stresses, contaminations, humidity) and their random nature

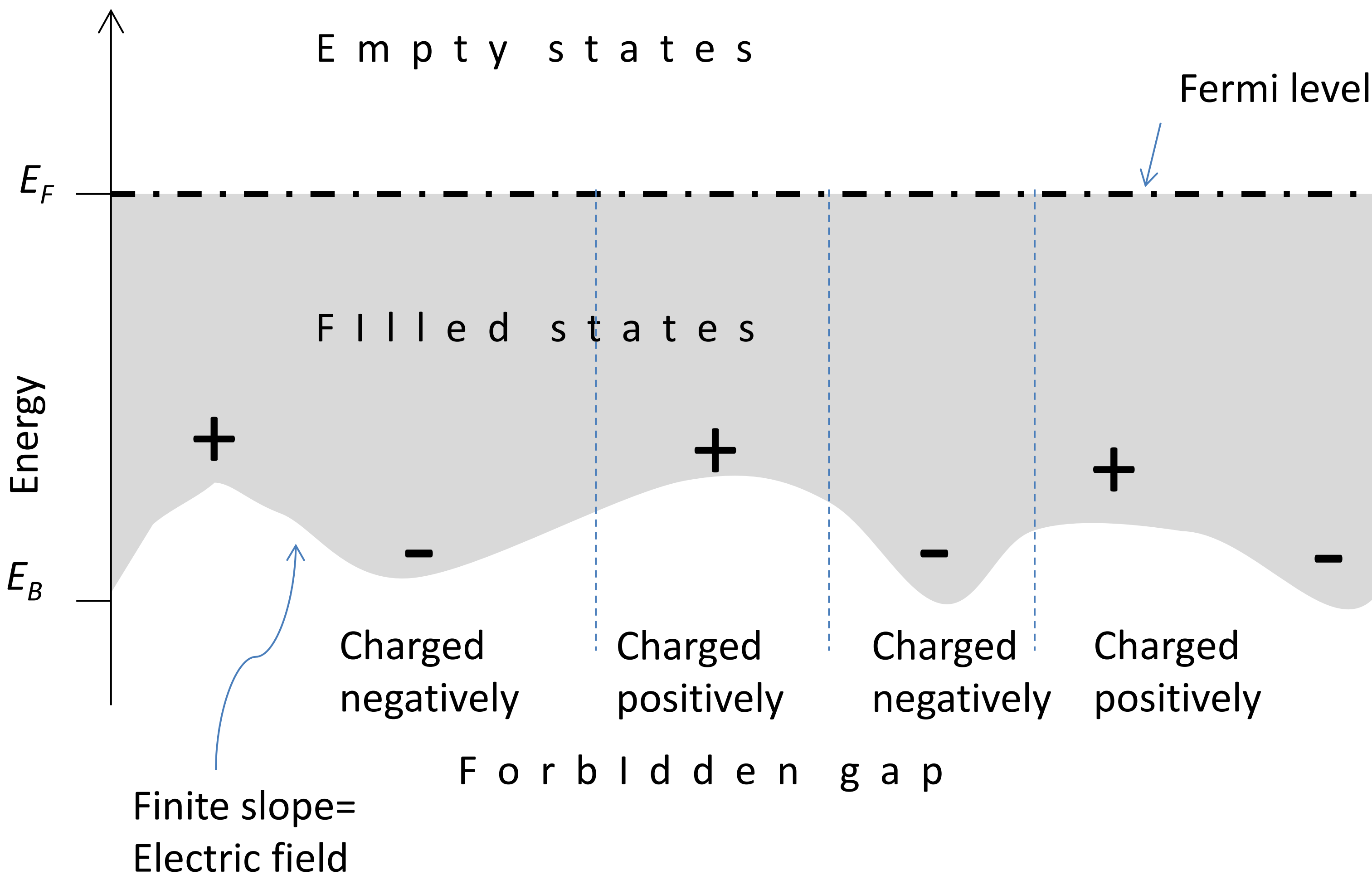
Recalling the electrostatic theory (cont) Whisker development



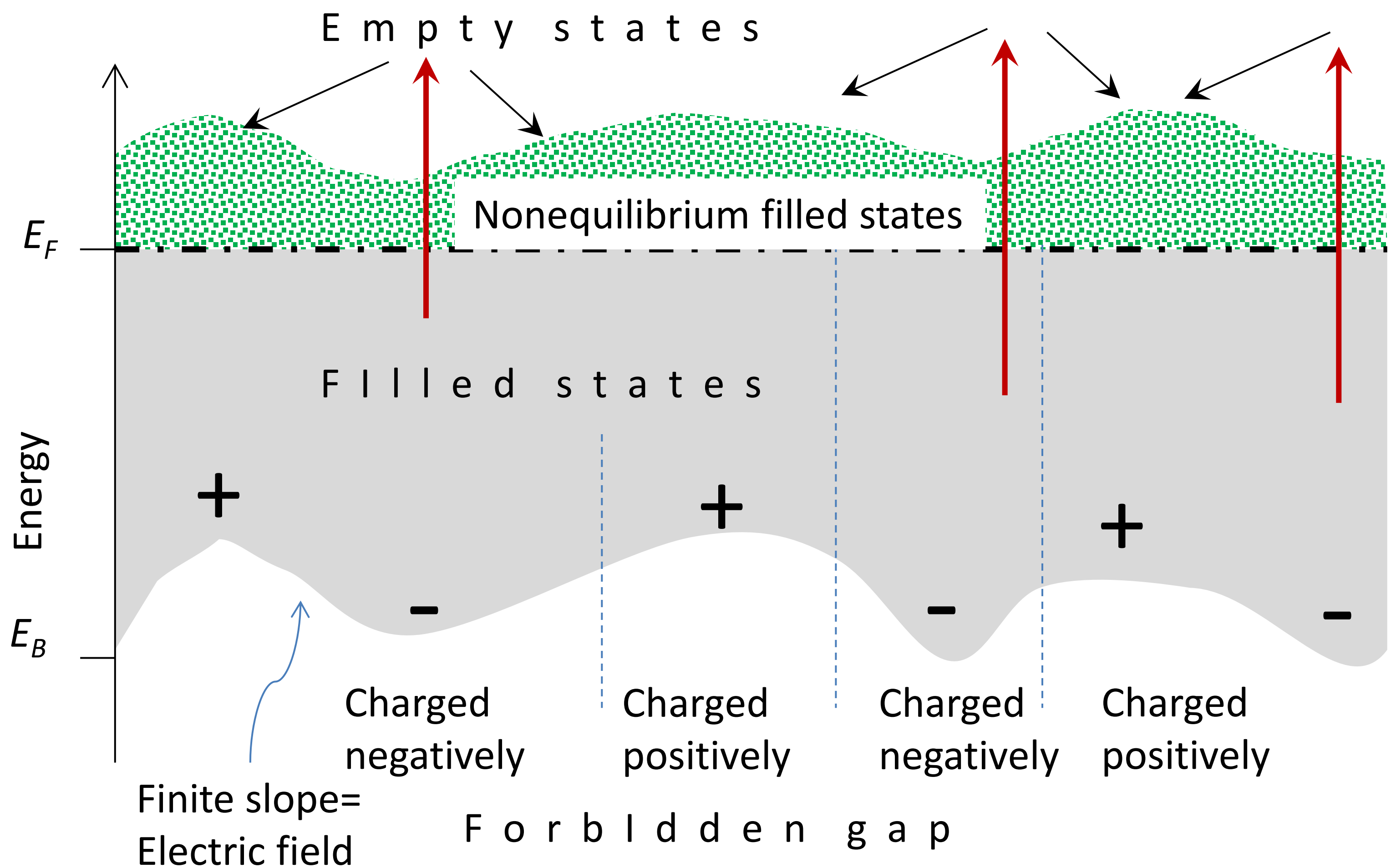


- Nucleation and growth of metal whiskers decreases system free energy because whiskers are polarized in the field
- High aspect ratios of up to ~ 10,000 naturally explained
- Growth kinetics: dormant period followed by constant growth rate
- Growth along pathways of not too different polarization (up or down)
- Random points of growth arrest determine the whisker length statistics: close to lognormal
- Quantitative estimates (for the first time) consistent with data

Equilibrium energy diagram



Nonequilibrium energy diagram



Photoinduced transitions level out the field (electrons are moved to screen the existing fields)

Nonequilibrium charge features

- Previously unknown with metals
- Well known in many polycrystalline semiconductors
- Relaxation times up to months vary by many orders of magnitude between different materials and different samples, (trapping-detrapping, charging-recharging)
- Assuming the same true with metals could explain:

  (a) possibility of ‘spontaneous’ whisker movements

  (b) its unpredictable nature depending on sample recipe, light intensity and ambient, i. e.

  (c) why some researchers observed ‘spontaneous’ whisker movements, while others didn’t

Nonequilibrium charge effect

Similar to ionic diffusion and using Einstein relation between electron diffusivity and mobility μ,

$$\frac{\delta E}{E} \sim \frac{\delta n}{n}\sqrt{\frac{k_B T \mu_e t}{nel^2 d_0^2}}.$$

This effect can be very strong even for nonequilibrium charge density comparable to the original charge density (moderate photoconductivity)

Nonequilibrium charges: estimate

Quantity	$d=1\mu m$ $l=1mm$	$d=1\mu m$ $l=10mm$	$d=10\mu m$ $l=1mm$	$d=10\mu m$ $l=10mm$
v_d, cm/s, Eq. (18)	$5\cdot10^{2}$	0.05	$5\cdot10^{6}$	$5\cdot10^{3}$
Re[a]	500	0.5	$5\cdot10^{6}$	$5\cdot10^{4}$
ω_0, s^{-1} Eq. (5)	3000	30	30,000	300
$\Delta\phi$, rad Eq. (24)	10^{-4}	$3\cdot10^{-4}$	10^{-6}	$3\cdot10^{-6}$
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Effect potentially strong,
Not easily predictable

Conclusions

- Air flow, even minute, can certainly be a cause of whisker movements
- Redistributing electrons in metal surface by light or other external agent can be a cause of whisker movements as well, although remains very sensitive to sample recipes and environment
- Metal whiskers can and should be systematically understood at a quantitative level – it is possible, and we do not even need computers for that