Electrokinetic assembly and manipulation II

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Outline

- Electroosmosis in particle manipulation
- Micro/nano fluidics with an electric field
- Size exclusive capture using nanoneedles

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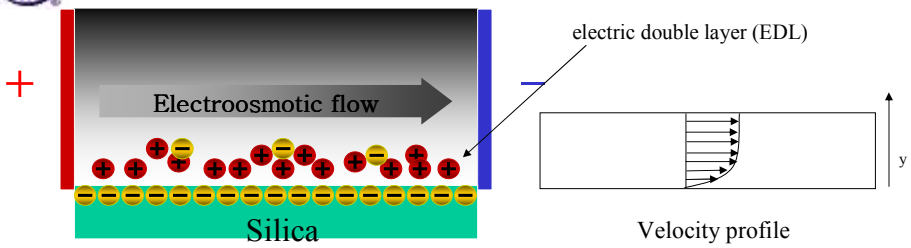
Electroosmosis in particle manipulation

Electroosmosis



Patankar et al., Analytical chemistry, 1998

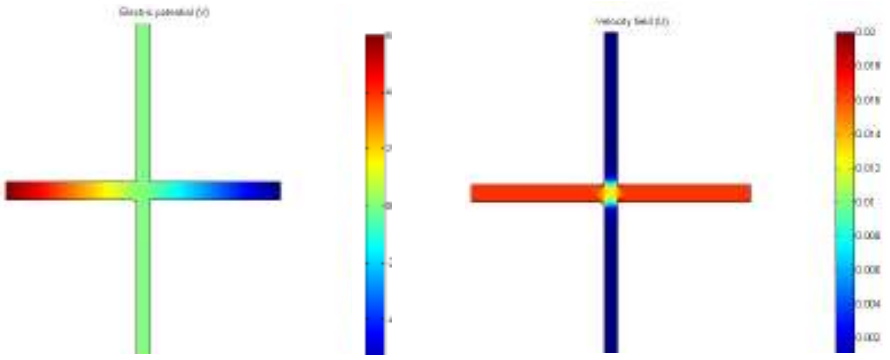
$$\rho\dot{\mathbf{v}} = -\nabla p + \mu\nabla^2\mathbf{v} + \rho_E\mathbf{E}$$

$$\nabla^2\phi = -\rho_E/\varepsilon \Rightarrow \nabla^2\phi = \kappa^2\phi$$

EDL is very thin (a few nm), a slip boundary can be used at the electrode surface:

$$u_s = -\frac{\varepsilon\psi_0 E_x}{\mu}$$

Electroosmotic flow



the distribution of electric field potential flow velocity in the channel

- Simulation of electroosmotic flow in a cross-sectional fluid channel

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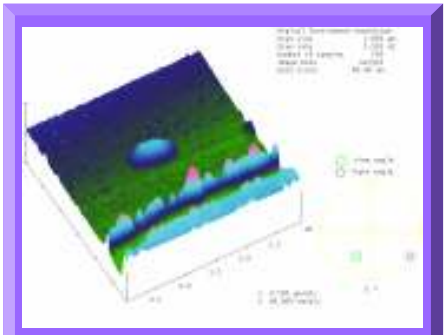
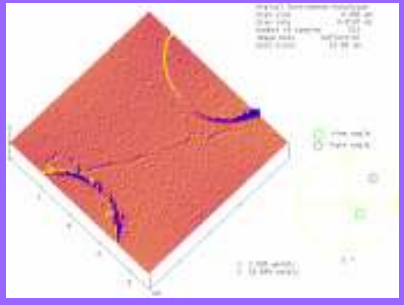
Electroosomotic flow



AC e-field



CEGA

- DNA under an AC field and a composite field.
- Electroosmostic flow by the DC field stretches DNA.
- Deposition at 100ºC from 1aM solution (about 70 molecules in 150μL.)

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AC electroosmosis flow

The charge relaxation time of a liquid: $\tau = \varepsilon / \sigma$

ε, σ are fluid permitivity and conductivity

- If the AC frequency $f < 1/(2\pi\tau)$, charge on electrodes and in EDL alternates according to potential sign change
- The flow direction doesn't change with potential sign change

$$u_s = -\frac{\varepsilon \psi_0 E_x}{\mu}$$

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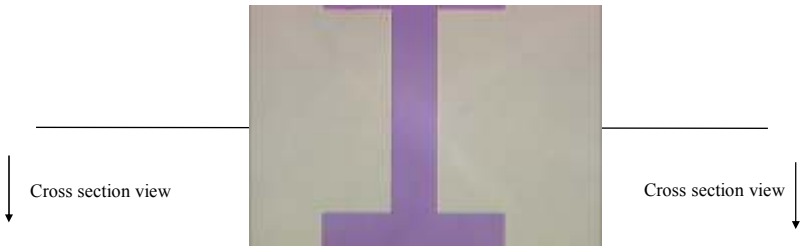
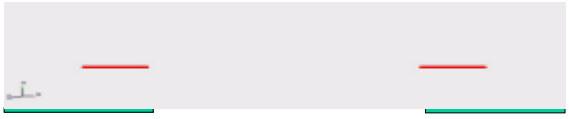
Rotation induced by local electroosmosis flow





2 CNTs

AC field 100 Hz, 0.5v/μm, parallel electrodes gap size: 5 μm
Local electroosmosis flows near the edges of electrodes induce vortices and lead to CNTs rotation

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- **Micro/nano fluidics**
- **with an electric field**

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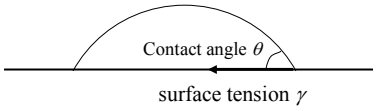
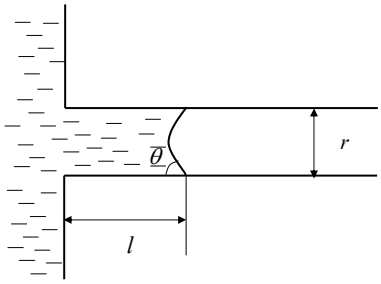
Capillary filling

- Dynamics of capillary filling without ionic effect



Pressure from surface tension $p_c = \frac{2\gamma\cos(\theta)}{r}$



Washburn equation $\frac{dl}{dt} = \frac{(P+P_c)r^2}{8\mu l}$

When external pressure P=0 $l = \sqrt{\frac{\gamma\cos(\theta)r}{2\mu}} \cdot \sqrt{t}$

μ is the liquid viscosity

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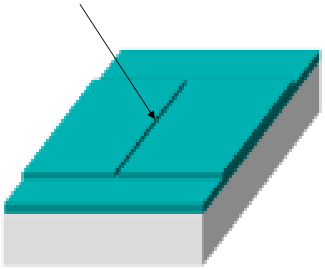
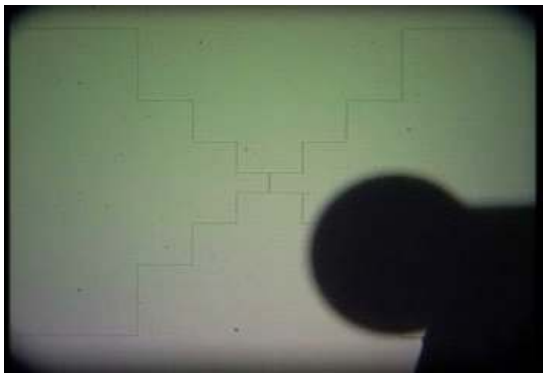
Capillary filling in open microchannel

Microchannel



Microchannel configuration



When a solution including microspheres (6μm in diameter) is placed on microchannel, the solution is introduced by capillary action.

The solution is continuously flowing due to the evaporation at the other side.

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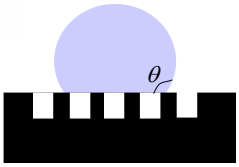
Fluid manipulation at small scale

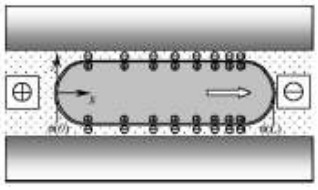
- External pressure
  - Syringe pump

www.syringepump.com/

- Modify surface property
  - Micro-patterned surface
  - Surface coating



- Applying external electric field
  - Electro-wetting



- Change ion concentration

Electrically varied surface tension. Junhoon et al., *J. Microelectromech.*, 2000

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Microchannel vs. nanochannel

- Size matters
  - EDL overlaps when channels shrinks to nano size
  - Reduced electroosmotic mobility
  - Viscosity of liquids in nanochannels is substantially higher than in bulk
  - Surface effect is dominant
- For microchannels, a external voltage is required to generate large enough potential difference to drive flow
- The requirement for nanochannels is much lower due to its small size
- Filling length can be controlled by ion concentration

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Zeta potential

- The potential induced by ions in liquid or charges on wall surface is called zeta potential ϕ
- Based on Debye-Hueckel approximation for charge density, the equilibrium zeta potential

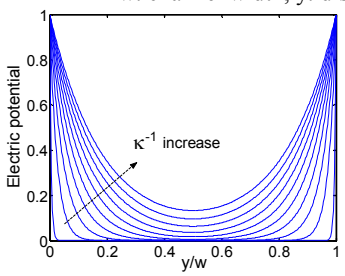
$$\nabla^2\phi = -\rho_E/\varepsilon \quad \Longrightarrow \quad \nabla^2\phi = -\frac{2cze}{\varepsilon_0\varepsilon}\sinh\left(-ze\phi/k_BT\right)$$

ρ_E :free charge density
ε :permitivity

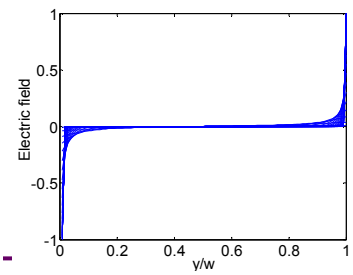
e:charge on a proton, ***z***: valence of ion with concentration ***c***

Assume $ze << k_BT$ $\quad \boxed{\nabla^2\phi = \kappa^2\phi}$ where $\kappa = \sqrt{\frac{2cz^2e^2}{\varepsilon_0\varepsilon k_BT}}$ $\quad \kappa^{-1}$:Debye length

w: channel width, y: distance from the wall.



Zeta potential distribution



E field distribution

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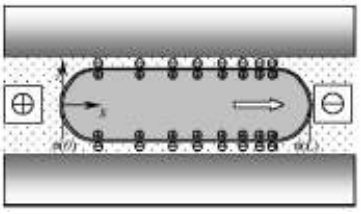
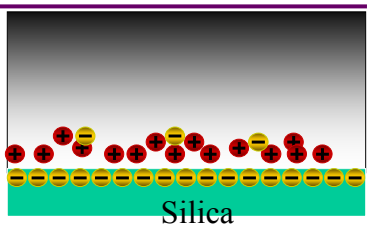
Electro-wetting theory





•Electrowetting: motion of electrolyte drop induced by an applied voltage between electrolyte and wall

$$\gamma_{dw} = \gamma_{dw}^{0} - CV^2/2$$

where γ_{dw} is the total surface tension γ_{dw}^{0} with only chemical components,

$C = \varepsilon_m \varepsilon_0 / h$ interface capacitance for a uniform dielectric of thickness h

V is the potential difference between electrolyte drop and wall

•The contact angle θ is given by the Young-Dupre equation as: $\gamma_{dw} = \gamma_w - \gamma_d \cos(\theta)$

$$\theta = \cos^{-1}\left(\frac{\gamma_w - \gamma_{dw}^{0} + CV^2/2}{\gamma_d}\right)$$

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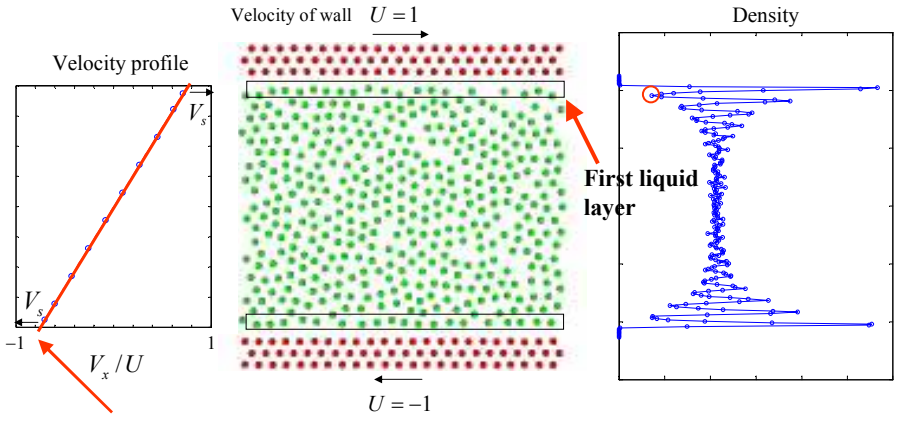
Dynamics of liquid flow in nanochannel



All slip occurs at the first liquid layer

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Multiscale modeling

Continuum Fluid Dynamics

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Fluid velocity
Pressure
Species concentration
Flux

Molecular Dynamics

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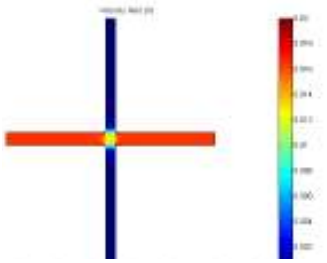
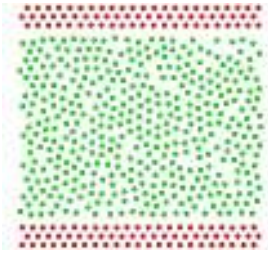
Mobility
Diffusivity
Viscosity
Slip BC
Contact angle





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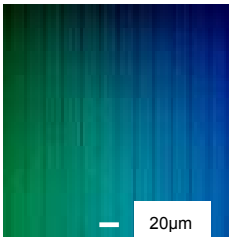
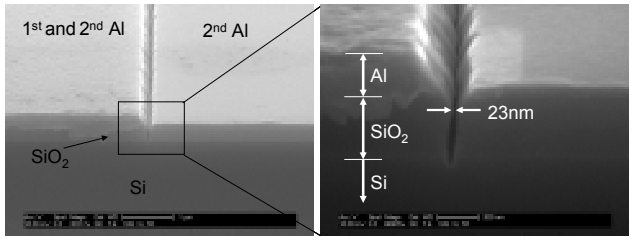
Diffusion experiment





Fabricated nanochannels by the shadow edge nanolithography
Fabrication process is discussed in the next lecture.

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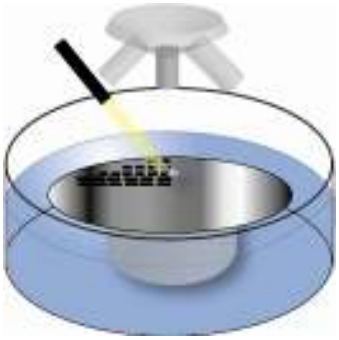
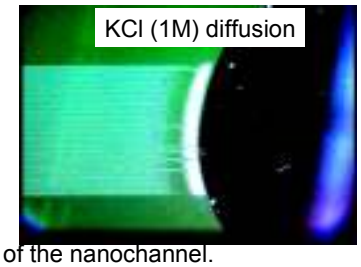
Diffusion experiment in open nanochannels



Nanochannel without solution



- Ionic solution is introduced at one side of the nanochannel.
- It is observed through microscope.
- The diffusion experiment is recorded by computer and analyzed by software.

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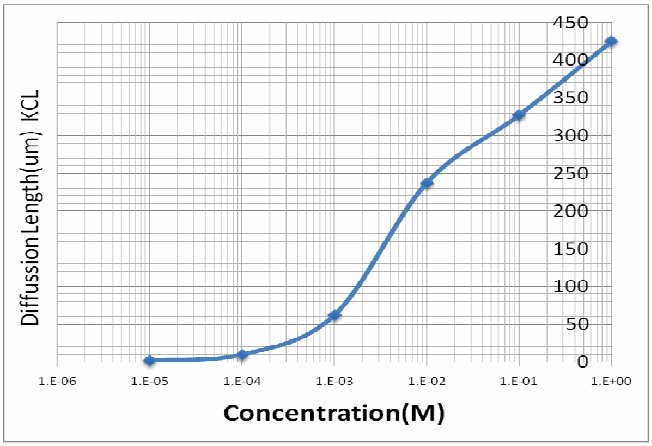
Diffusion length at different ion concentration



Diffusion length of KCl at different concentration

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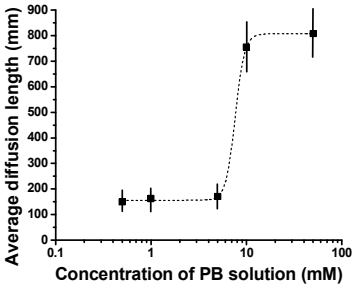
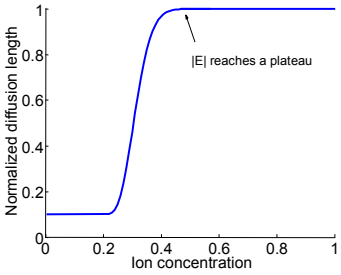
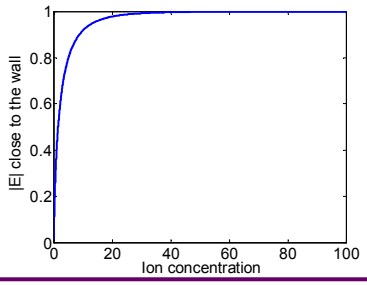
Diffusion length at different ion concentration



Three distinct regimes





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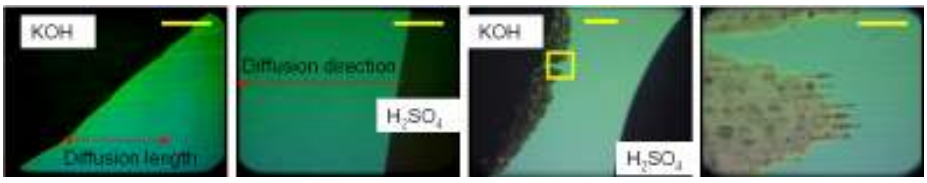
Diffusion and reaction in nanochannels



- KOH solution on the left side and H_2SO_4 on the right.
- Depending on the charge of both solutions, a larger diffusion length is observed for H_2SO_4.

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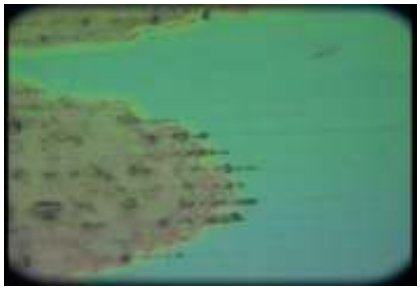
Diffusion and reaction in nanochannels

KOH H_2SO_4



Salt generated during the reaction.

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DNA chip using nanochannels

Array of Nanochannels

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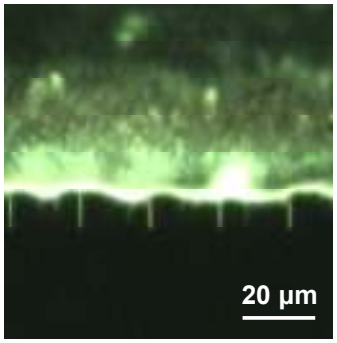
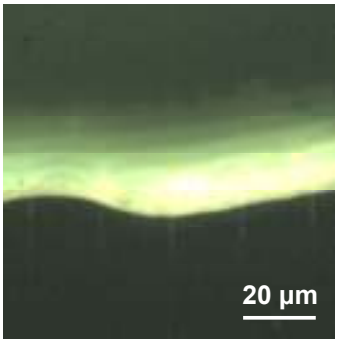
Diffusion Experiment in Nanochannels



λ-DNA molecules (1 μg/mL) treated with PicoGreen dye and TE buffer



Fluorescein particles at 100 μg/mL (0.3 mM)

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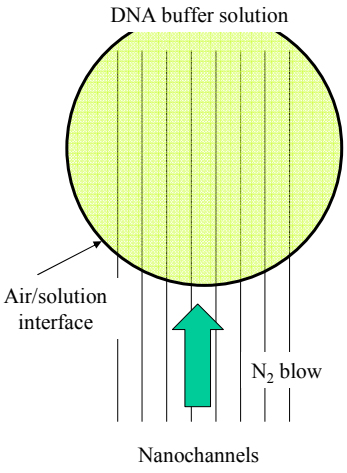
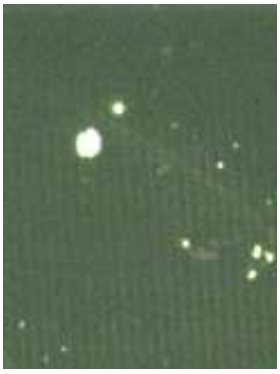
DNA Fluorescence Images





100 pg/mL DNA concentration (1/10000 X reagent)
(about 20,000 DNA molecules in ~4 μL drop)

Since DNA is negatively charged, it is not introduced by capillary action in nanochannels.
External pressure was used for introducing DNA.

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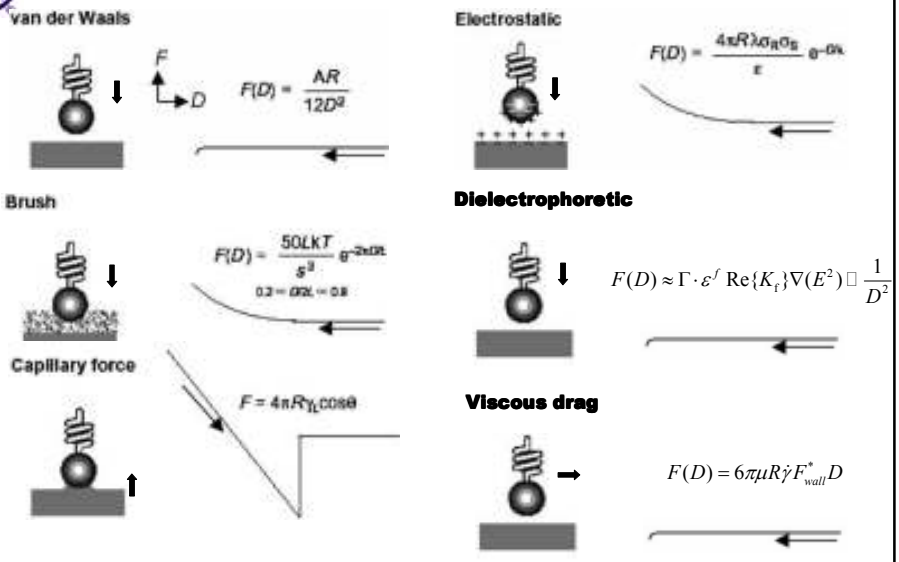
Summary of physics involved in two lectures



Expanded/revised from Heinz and Hoh, *Trends Biotechnology*, 1999

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Size-exclusive capture using nano needles (Fishing DNA in fluid)

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Reference

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