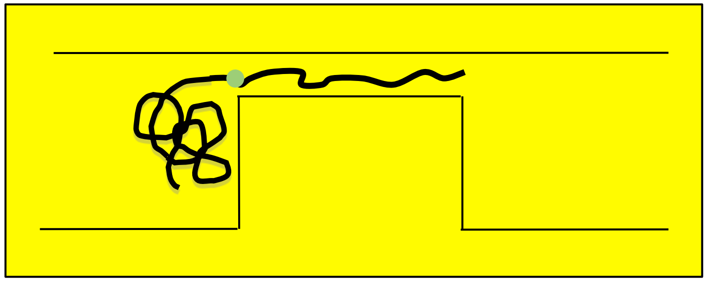
Entropy, temperature, free energy, and entropic forces

Chia-Fu Chou@2009

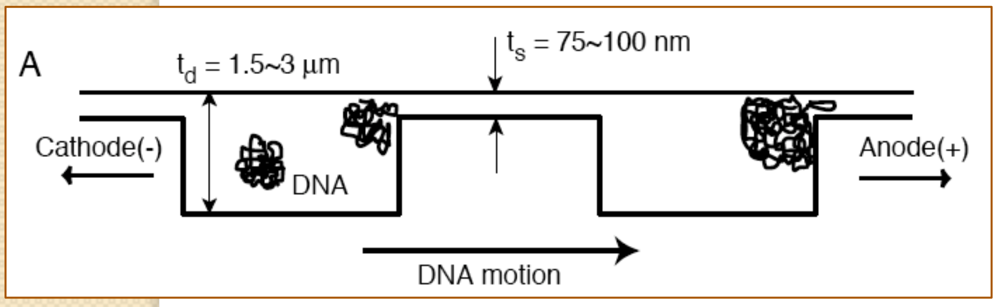
Micro- to Nanofluidic Interface

...A wonderland...

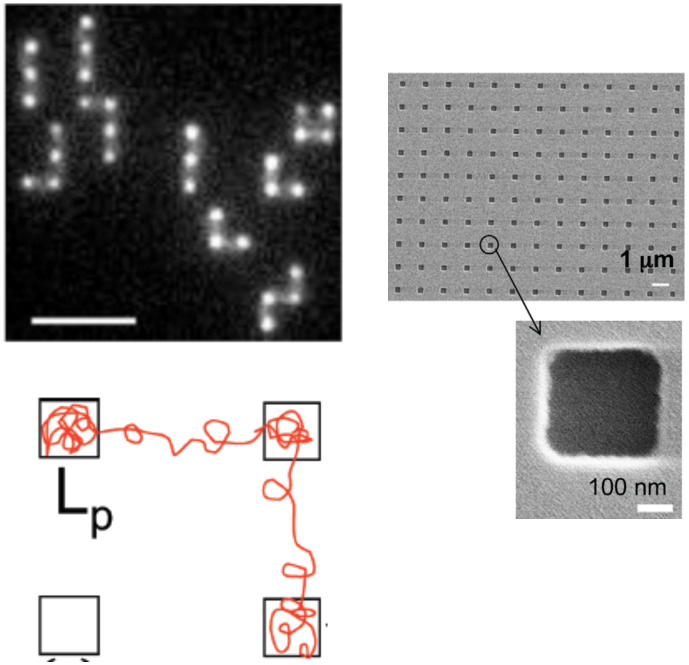
(1) Entropic barrier



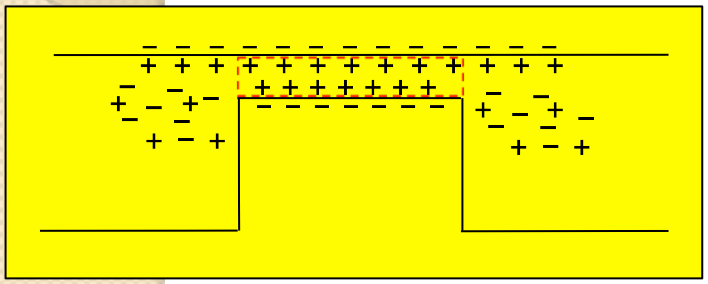
Nanoseparators
J. Han et al., Science 2000

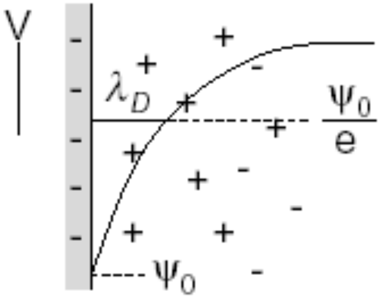


Digital DNA
Reisner et al., PNAS 2009



(2) Debye layer overlapping



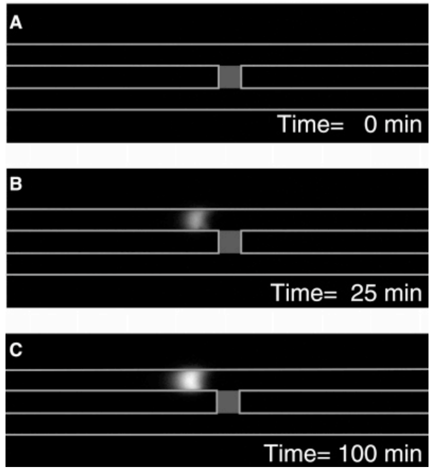


$$\lambda_D = \sqrt{\frac{\varepsilon RT}{2F^2 c}}$$

Conc / M	λ_D / nm
10^{-5}	100
10^{-4}	30
10^{-3}	10
10^{-2}	3
10^{-1}	1

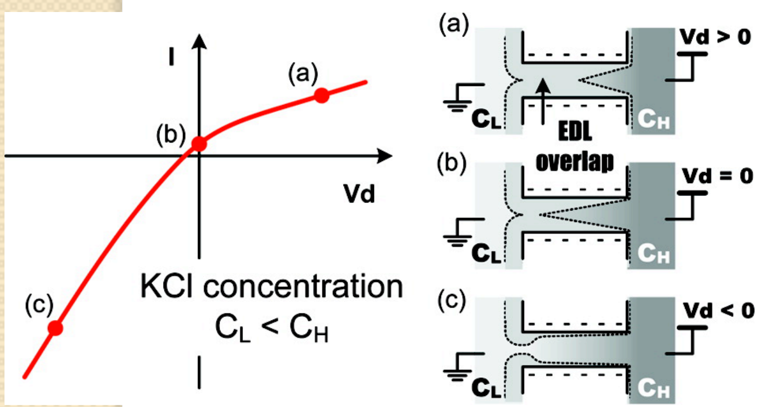
Nanoconcentrators

Wang et al., Anal. Chem. 2005



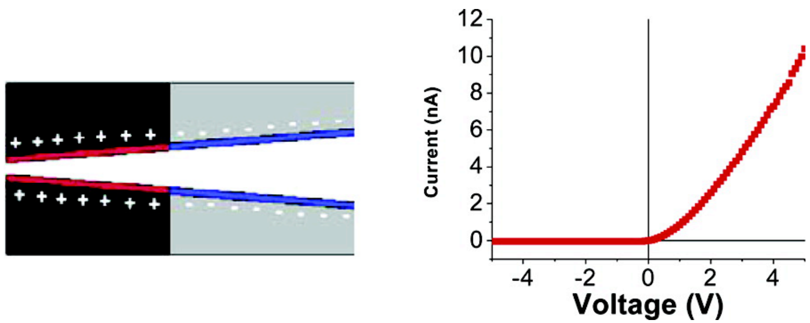
Rectified Ion Transport

Cheng & Guo, Nano Lett. 2007



Nanofluidic diode

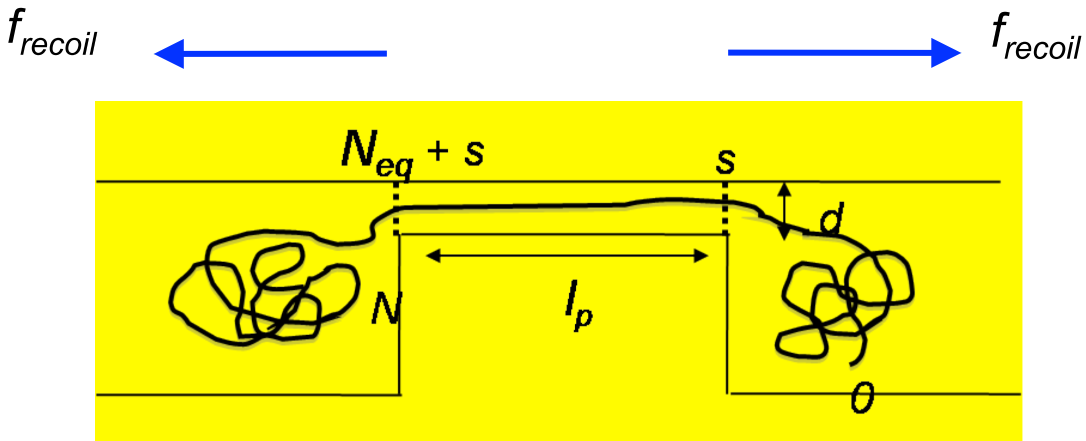
Vlassiouk and Siwy, Nano Lett. 2007



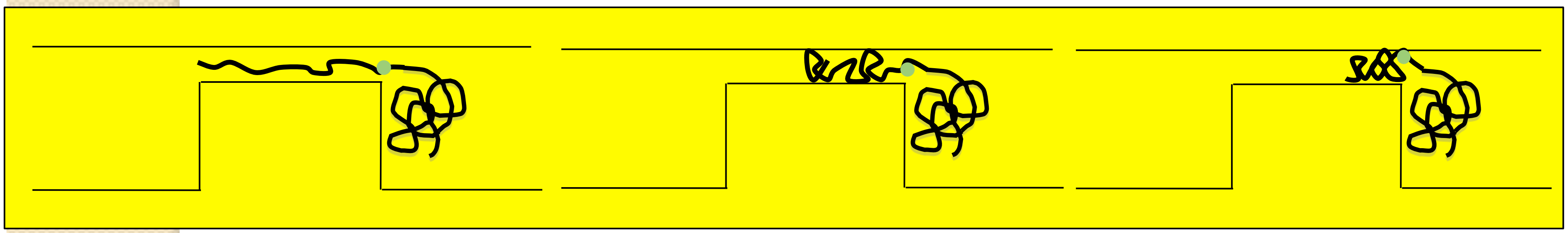
Single molecule tug-of-war of DNA

Understanding the entropic forces acting on the DNA

$$F = U - TS;\ f = -grad(F) = T\ grad(S)$$

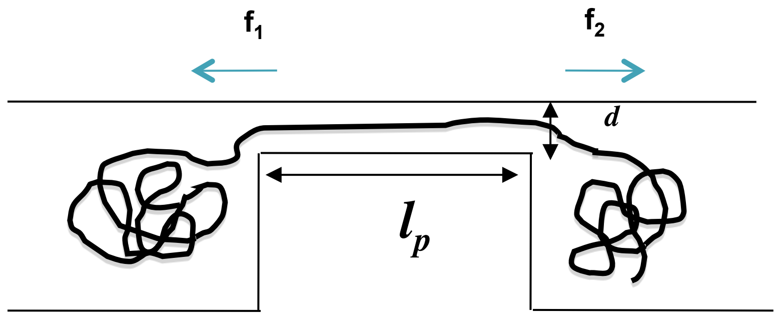


DNA retraction by entropic recoiling from nano- to microchannel



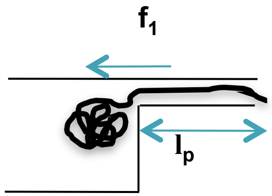
Motivation

(1)



F	Free energy
l_p	projected length of polymer inside the channel
f	force

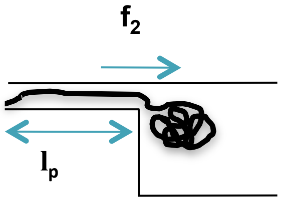
❖ **What do we expect?**



$$F(l_p) \propto l_p$$

(Burkhardt et al., J.Phys A, 1997)

(cylindrical tube diameter (D) << persistence length (P))



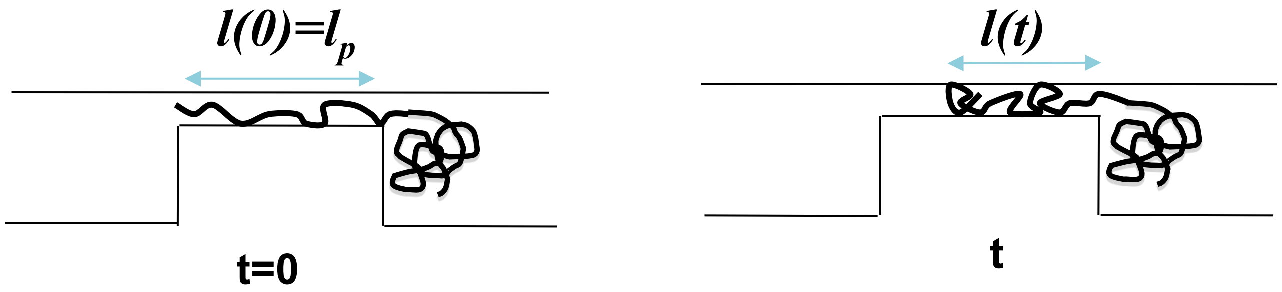
Recoiling force $f = {dF}/{dl}$

is l_p independence $f_1 \cong f_2$

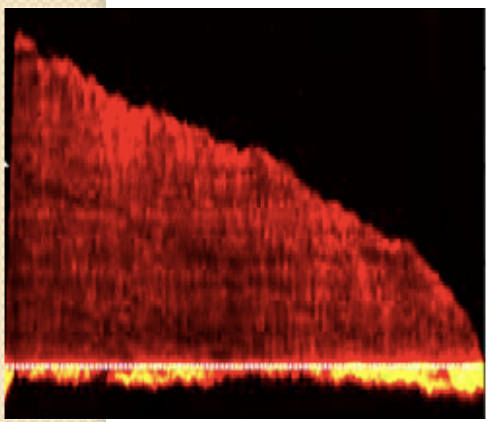
(Turner et al., PRL 2002)

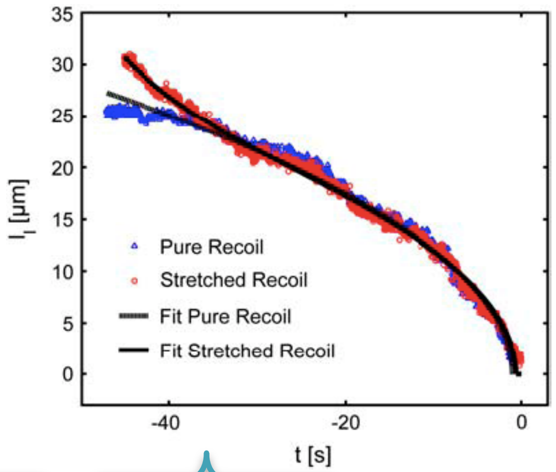
Motivation

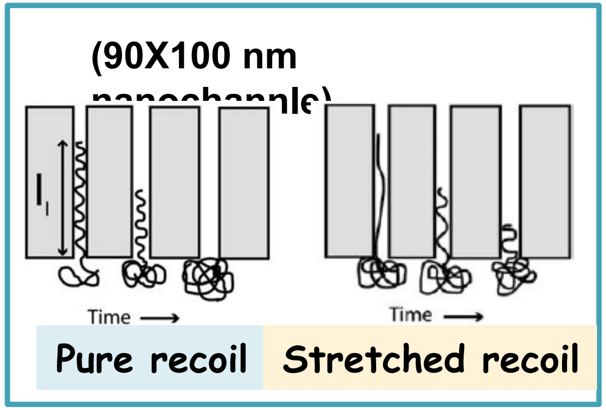
(2)



❖ What do we expect?







$$l(t) = \left[1 + \left(l_p\sqrt{\frac{\rho}{2 f t_f}} - 1\right)e^{-t/\tau}\right]\sqrt{-\frac{2f}{\rho}\left(t - t_f\right)}$$

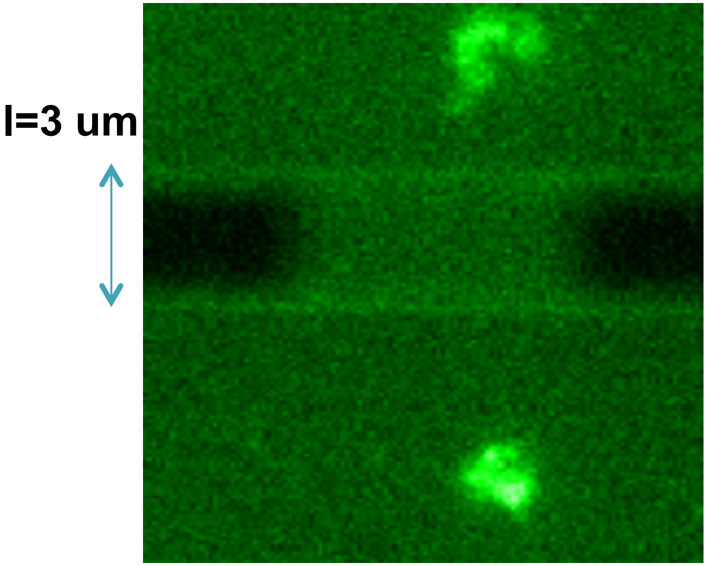
~ phenomenological formula.

ρ	Drag coefficient per unit extended length
t_f	translocation time

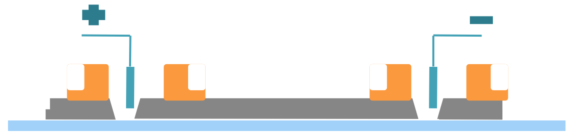
Estimated recoiling force ~ 200 fN

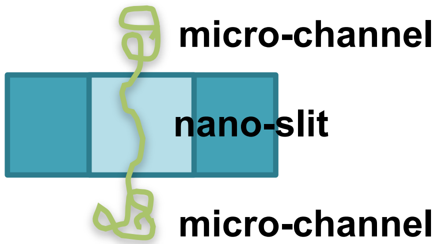
(Mannion et al, Biophys. J.,90,4538 2006)

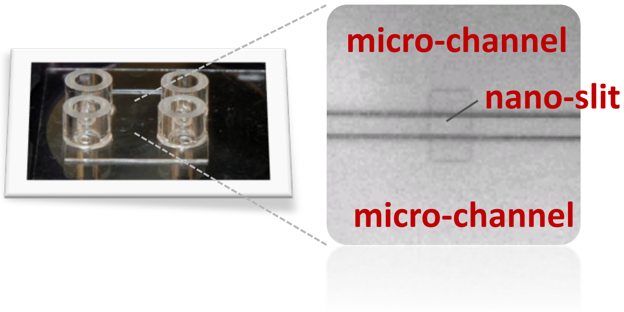
DNA tug-of-war through Nanoslits

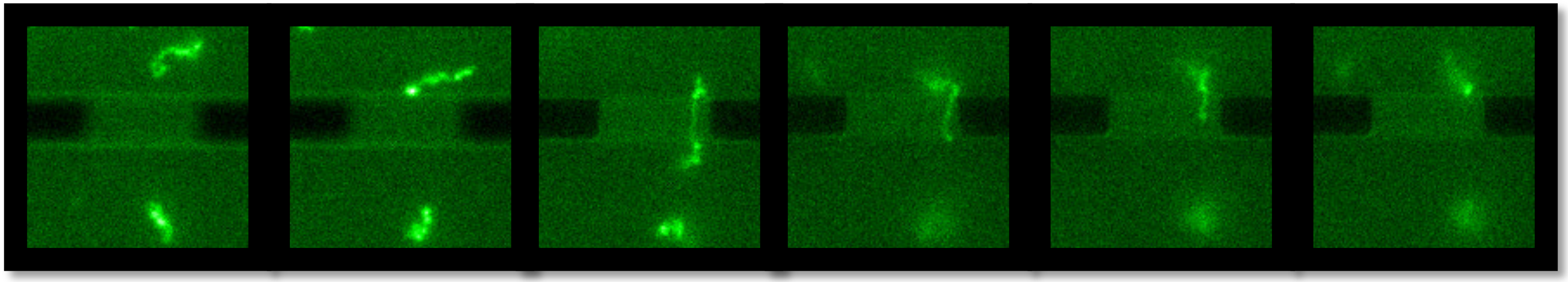


(size of nanoslits is 100 nm depth, and 3 μm length)









(a) DNA in Microchannel

(b) Drive in

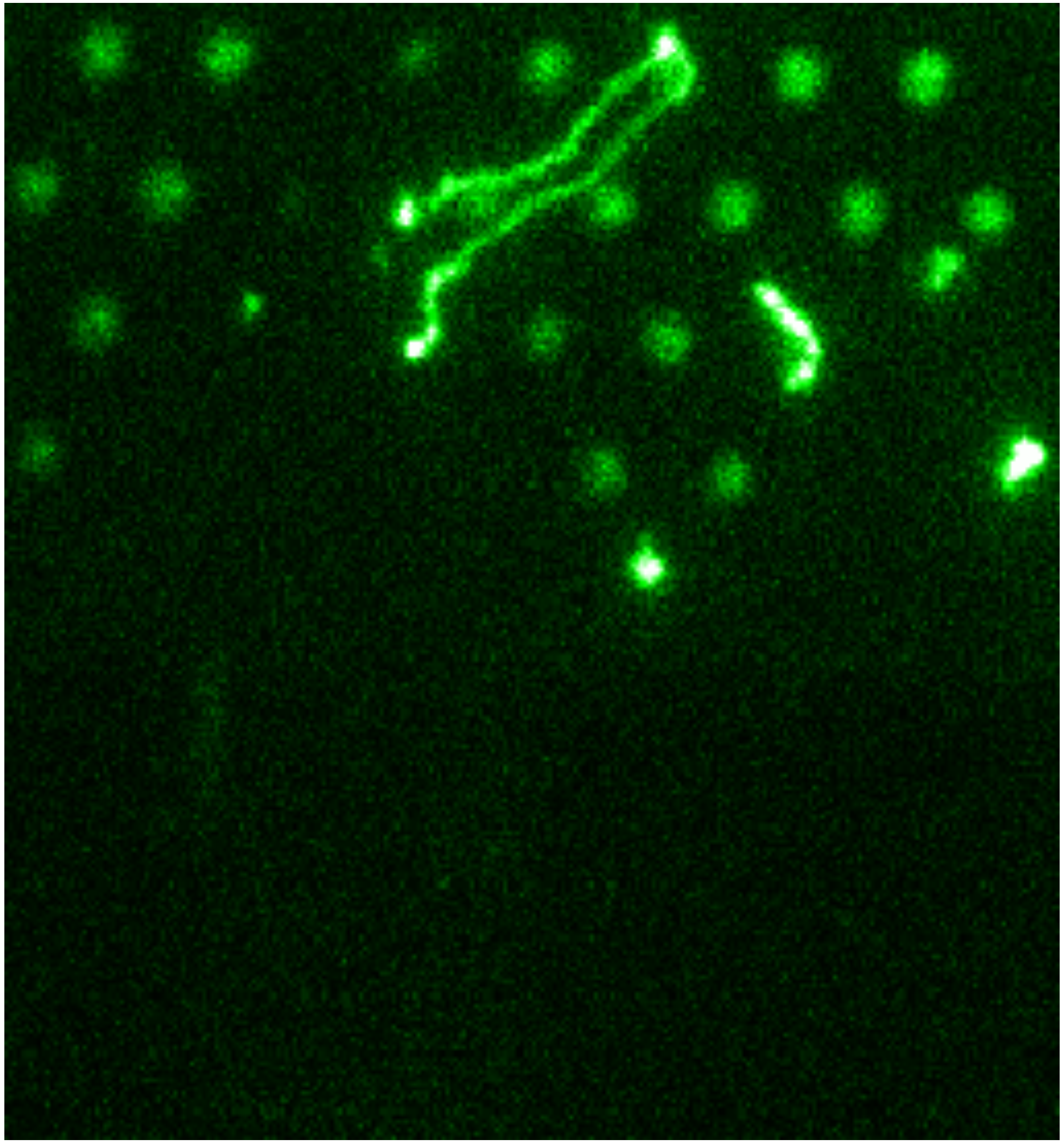
(c) Tug of war (sec~min)

(d) DNA retraction, t=0

(e) DNA retraction, t=t*

(f) Retracting from Nanoslit

DNA tug-of-war through Nanoslits

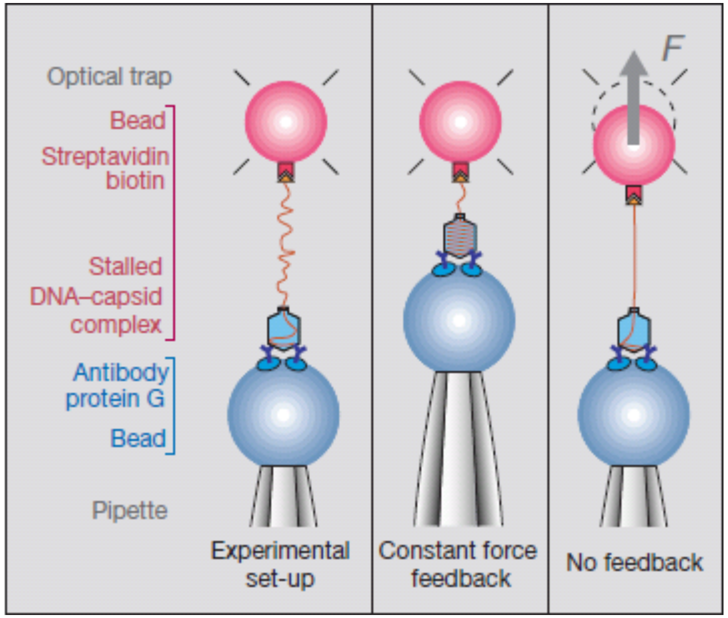


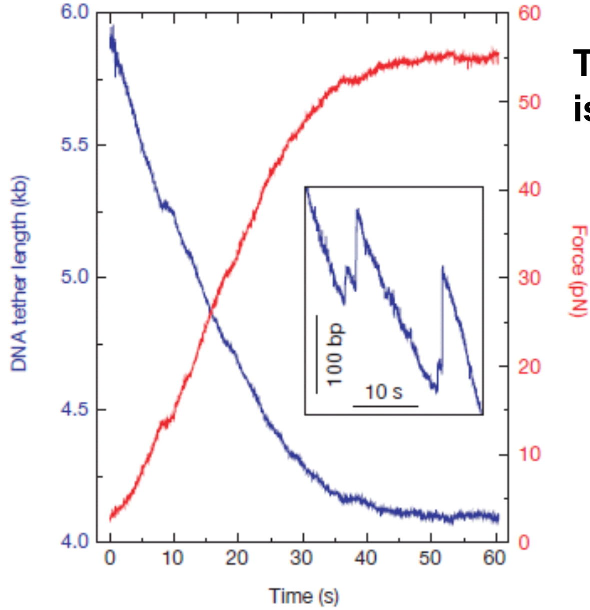
3x speed

Nanoslit:
100 nm depth
20 μm length

Discussion

Bacteriophage φ29 packages its 6.6 μm long, double-stranded DNA into 42 X 54 nm capsid.





The highest force is 55 pN.

There are *entropic*, *electrostatic* and *bending* energies of DNA which need to be overcomed to package the DNA to near-crystalline density.

Comparing to our results, the entropic recoiling force of 50 nm nanoslits is around 1 pN.

Smith *et al.*, Nature 413, 748 (2001)

Theory and simulations of DNA dynamics in micro- to nano-confinement

Goals: **Develop theory and simulations to help exploit the balances of forces in strong confinement in order to manipulate DNA molecules and proteins for nanopore detection**

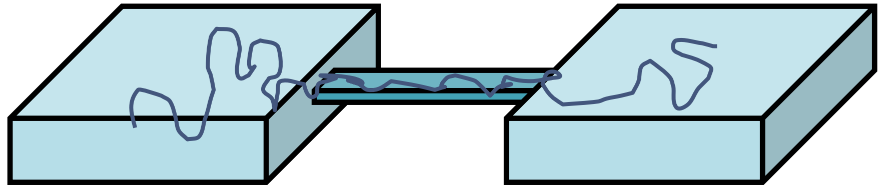
Macromolecule conformation and dynamics in micro- and nano-channels are controlled by

Thermal/Entropic forces

Electrostatic forces

Steric (Excluded volume) forces

Fluid / Hydrodynamic forces



Micro → Nano :

Polymer conformational freedom is restricted : Entropy ↓

Debye length / channel height ↑ : Electrostatics ↑

Diffusion length / channel height ↓ : Hydrodynamics screened

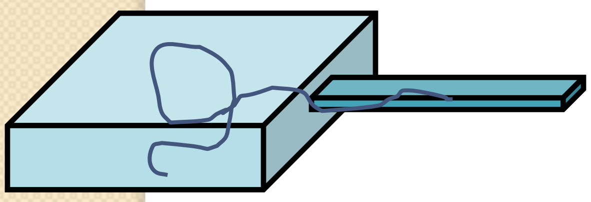
Courtesy Dr. YL Chen

Problems

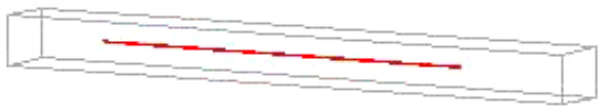
Chain dynamics in < 100nm channels is not well understood

Hybrid lattice-Boltzmann/Brownian dynamics simulations to capture DNA dynamics and interactions with the fluid

- **Translocation micro- to nano-channel**



- **Inside the nanochannel**

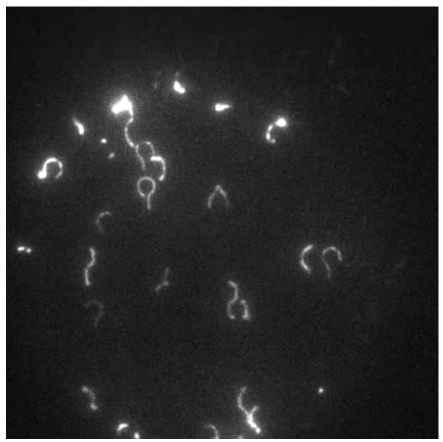


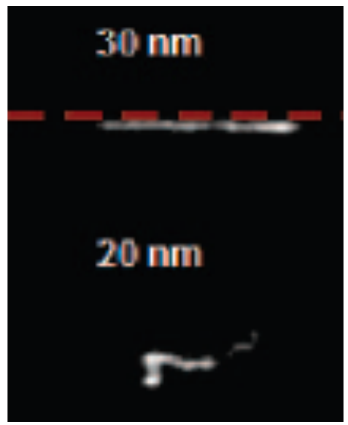
- **Collision with microposts and stretching**

Electrostatic interactions in strong confinement

As the nano-channel size approach the Debye length (5-20 nm), electrostatic interactions are *comparable or stronger* than the entropic and fluid forces

Develop coarse-grained simulations that fully captures DNA/Protein/Ion interactions in nanochannels





Courtesy Dr. YL Chen

Nanopore Single-molecule sequencing

Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 13770–13773, November 1996
Biophysics

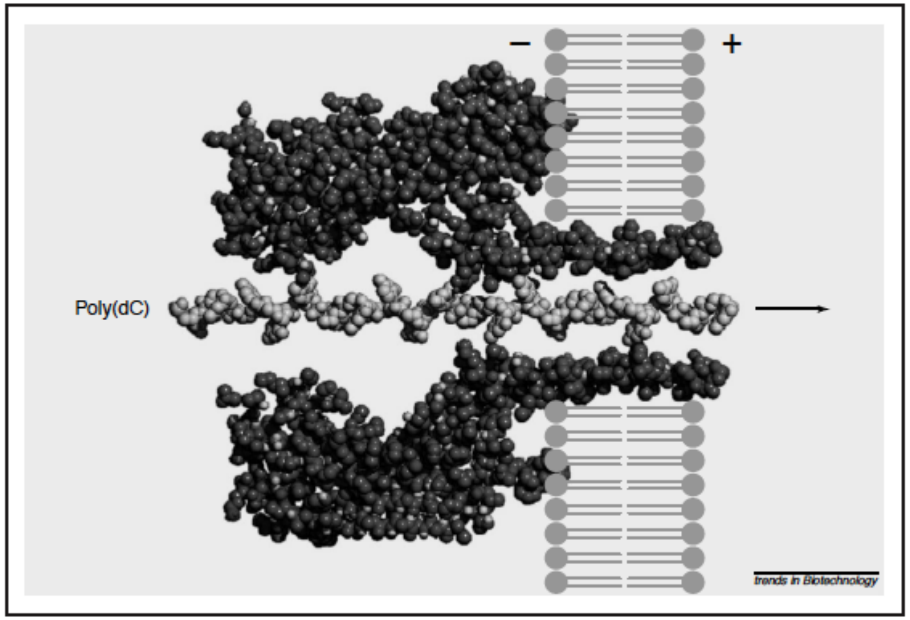
Characterization of individual polynucleotide molecules using a membrane channel

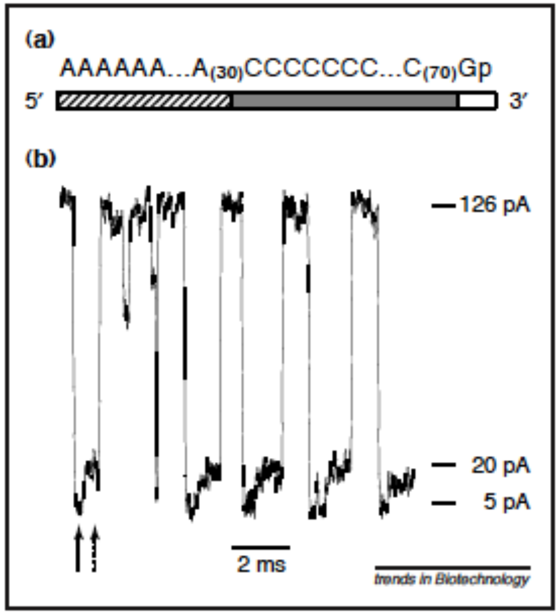
John J. Kasianowicz*, Eric Brandin†, Daniel Branton†‡, and David W. Deamer§

*Biotechnology Division, National Institute of Science and Technology, 222/A353, Gaithersburg, MD 20899; †Department of Molecular and Cellular Biology, Harvard University, 16 Divinity Avenue, Cambridge, MA 02138; and §Department of Chemistry and Biochemistry, University of California, Santa Cruz, CA 95064

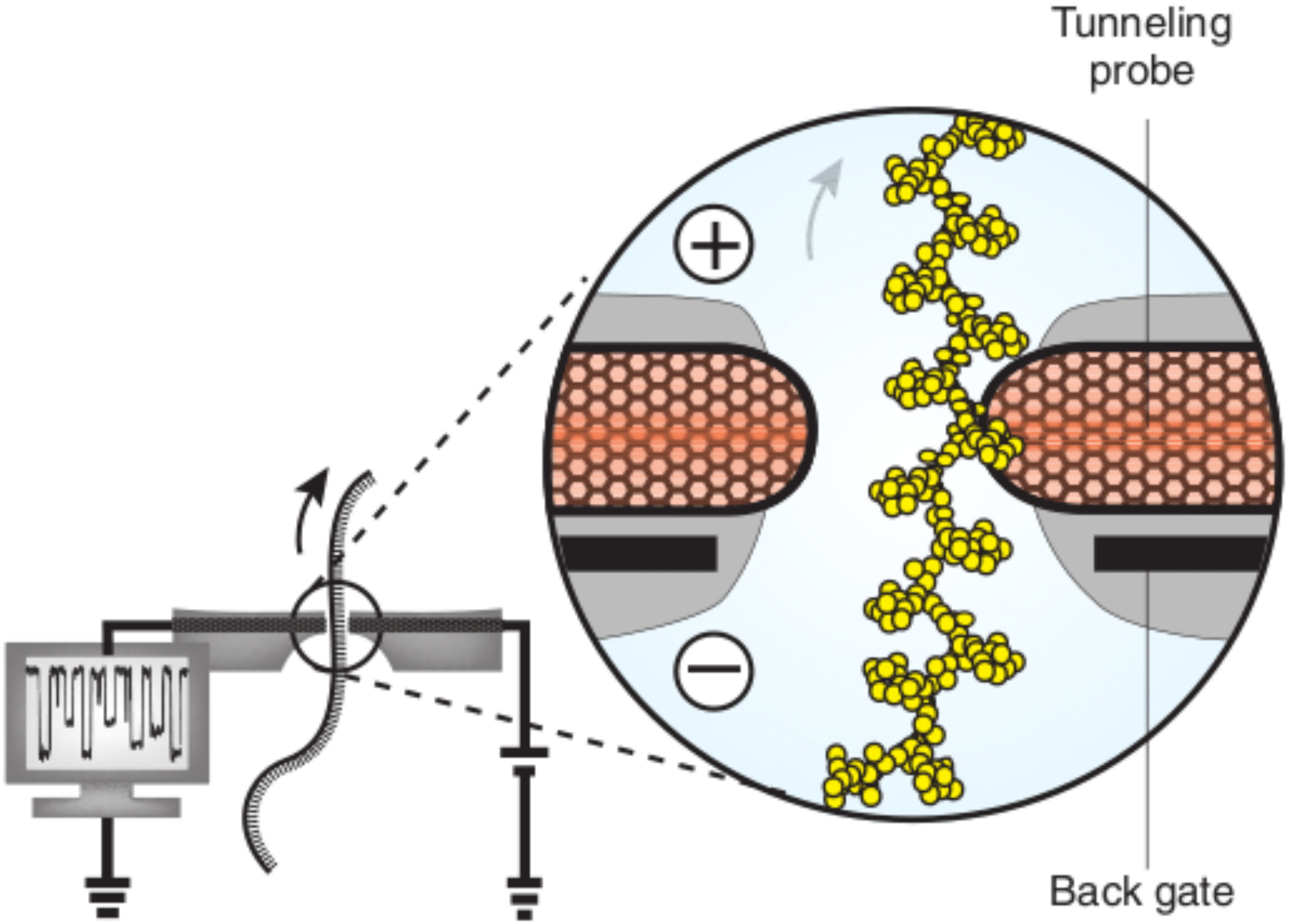
Contributed by Daniel Branton, September 5, 1996

A single α-hemolysin channel (Ø =2.5 nm) embedded in a lipid bilayer



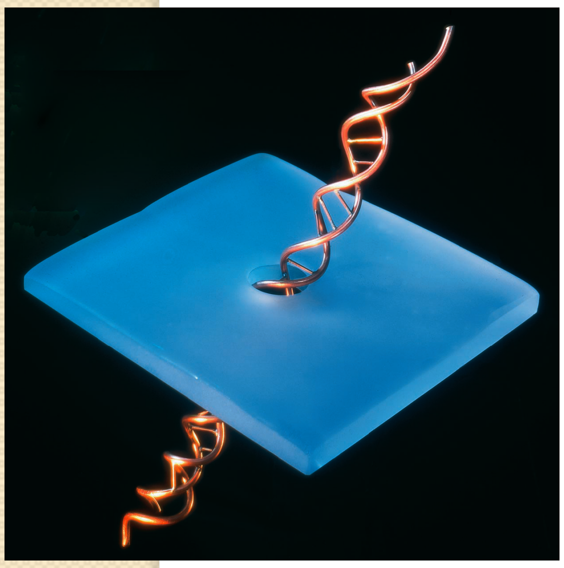


Solid State Nanopore DNA Sequencing

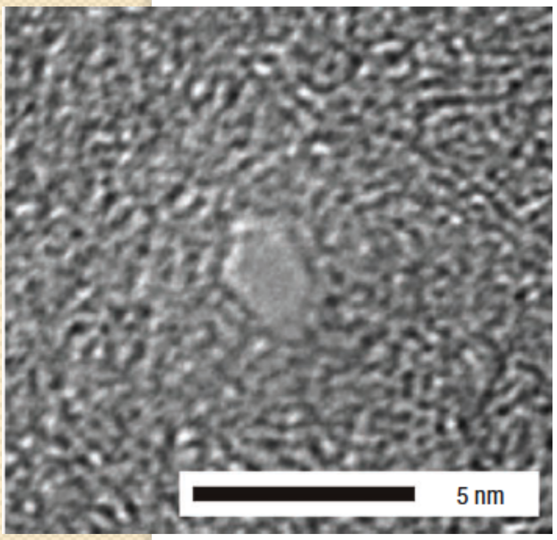


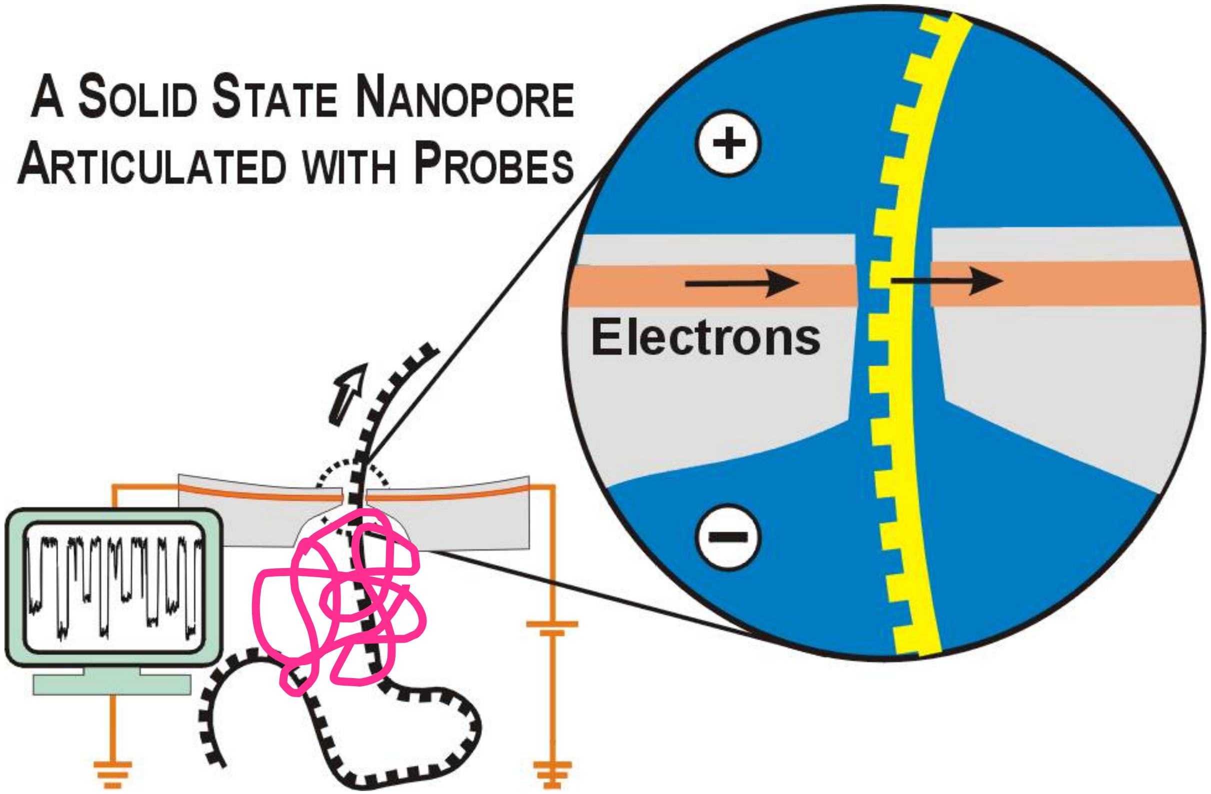
Nature Biotechnology 10, 1145 (2008)

Nanopore single-molecule sequencing



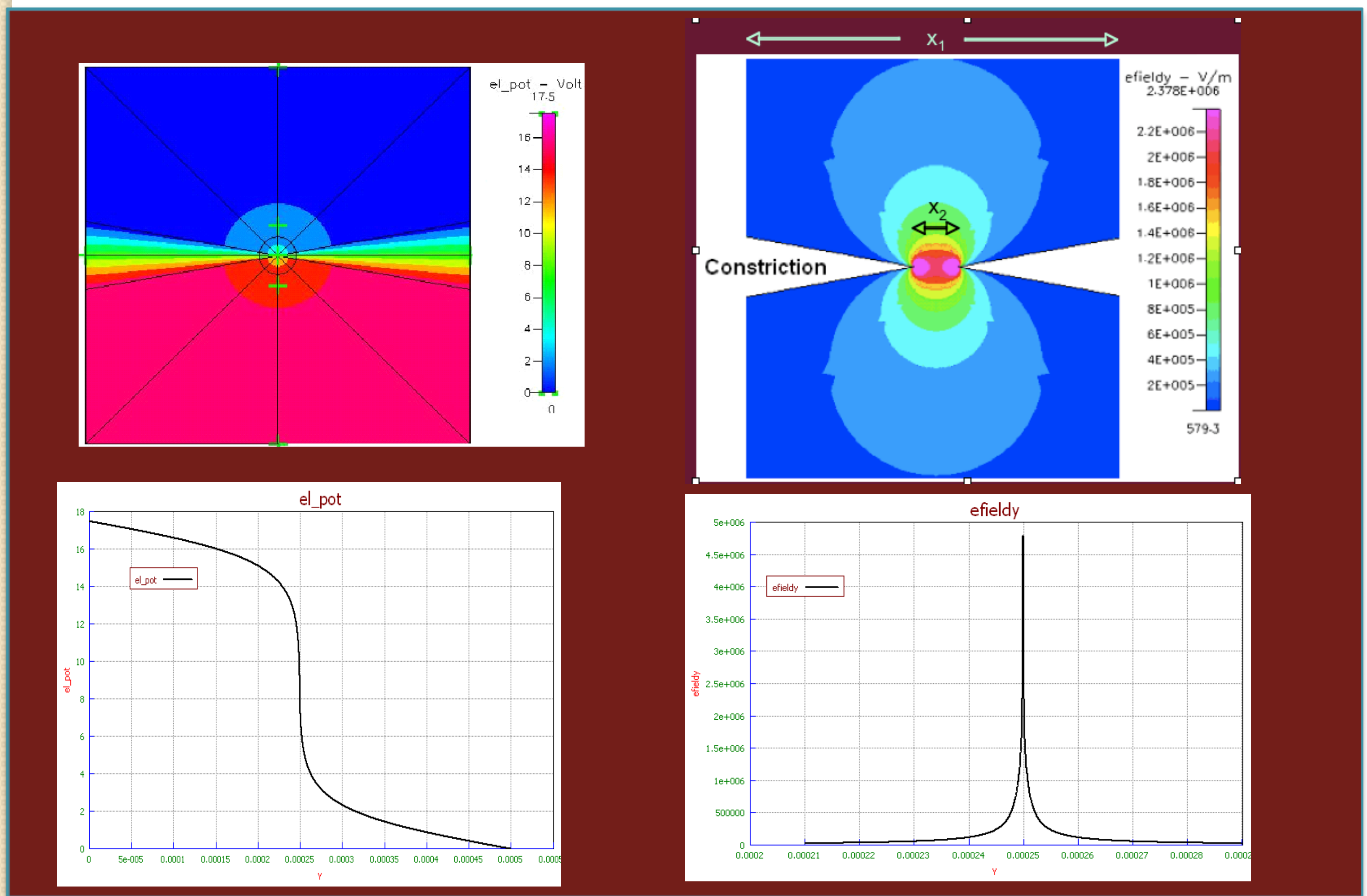
Dekker group, Nat. Mater. 2003





D. Branton, J. Golovchenko, Harvard

Electric Potential/Field Distribution



Potential drop and field focusing mostly occurs at the nanopore!

Spatial Localization - Nanopore

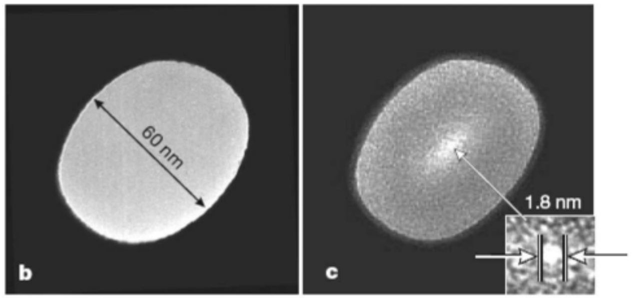
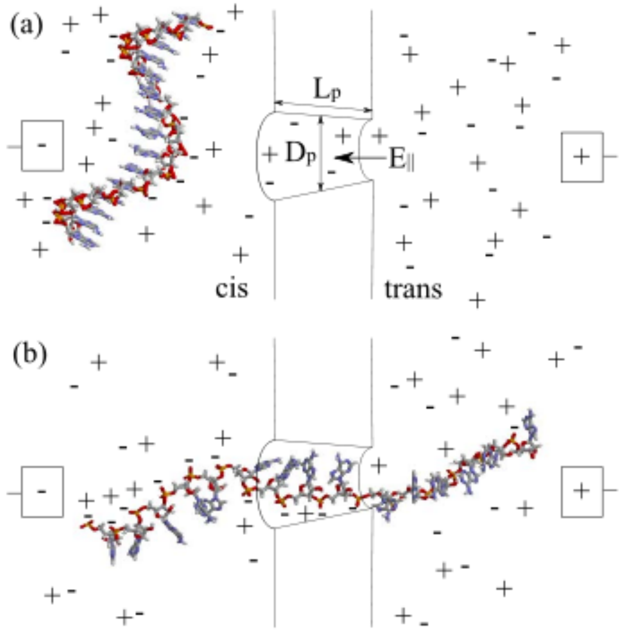


FIG. 12. Fabrication technique of Li *et al.* (2001) for creating nanoscale solid-state pores: a Si_3N_4 membrane with a large pore is first created (b). An ion beam is then focused at this large pore, activating a diffusion process that closes the hole (c). The current of Ar^+ decreases as the pore shrinks (a), the monitoring of which can be used to control pore size. From Li *et al.*, 2001.



Localize DNA for Measurement

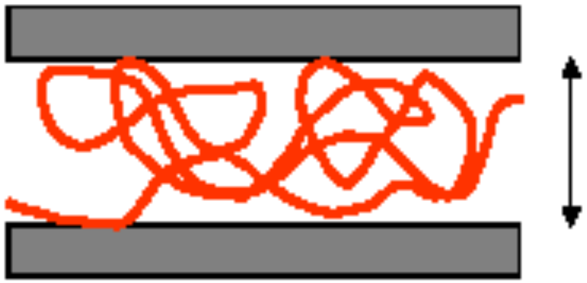
Controlled Propagation for Precision

Nanotechnology 20 (2009) 185101

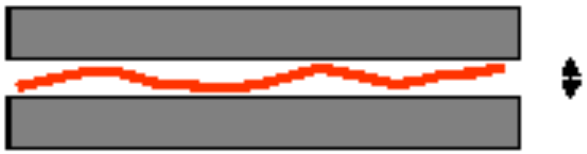
Polymer dynamics in confined nanoenvironment

DNA is stretched in small channels because the energy to form a loop is greater than kT

$$W_{loop} = \pi k_B T \frac{L_p}{R}$$



$2R = 2\mu m \quad W_{loop} \approx 0.15 k_B T < k_B T$



$2R = 0.1\mu m \quad W_{loop} \approx 3 k_B T > k_B T$

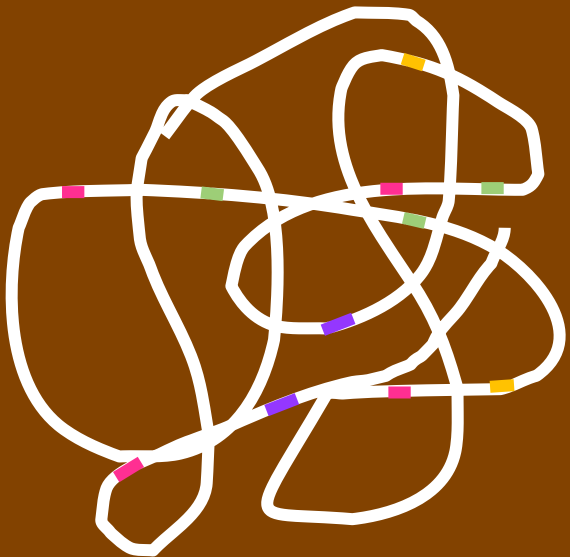
For DNA the persistence length L_p=50nm

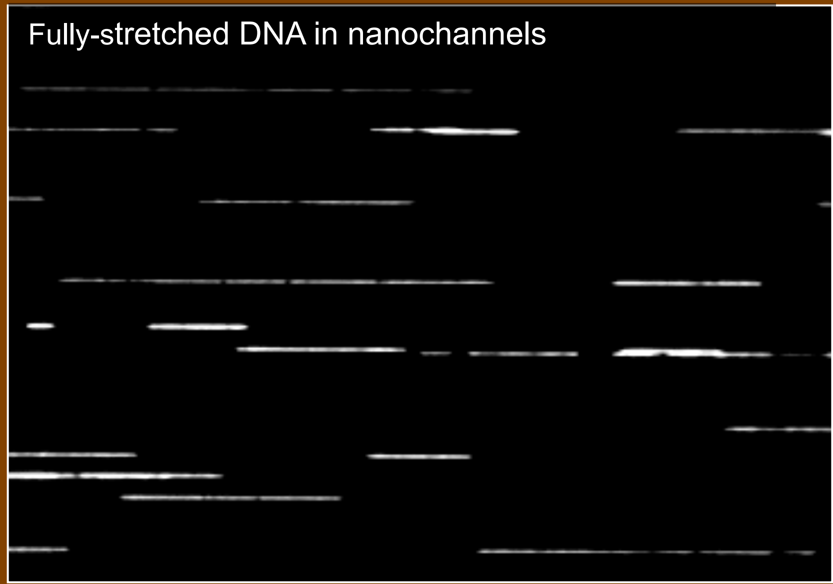
J. Tegenfeldt

Transcriptional factor (TF) mapping/ Identify protein binding sites

(AS Nano program)

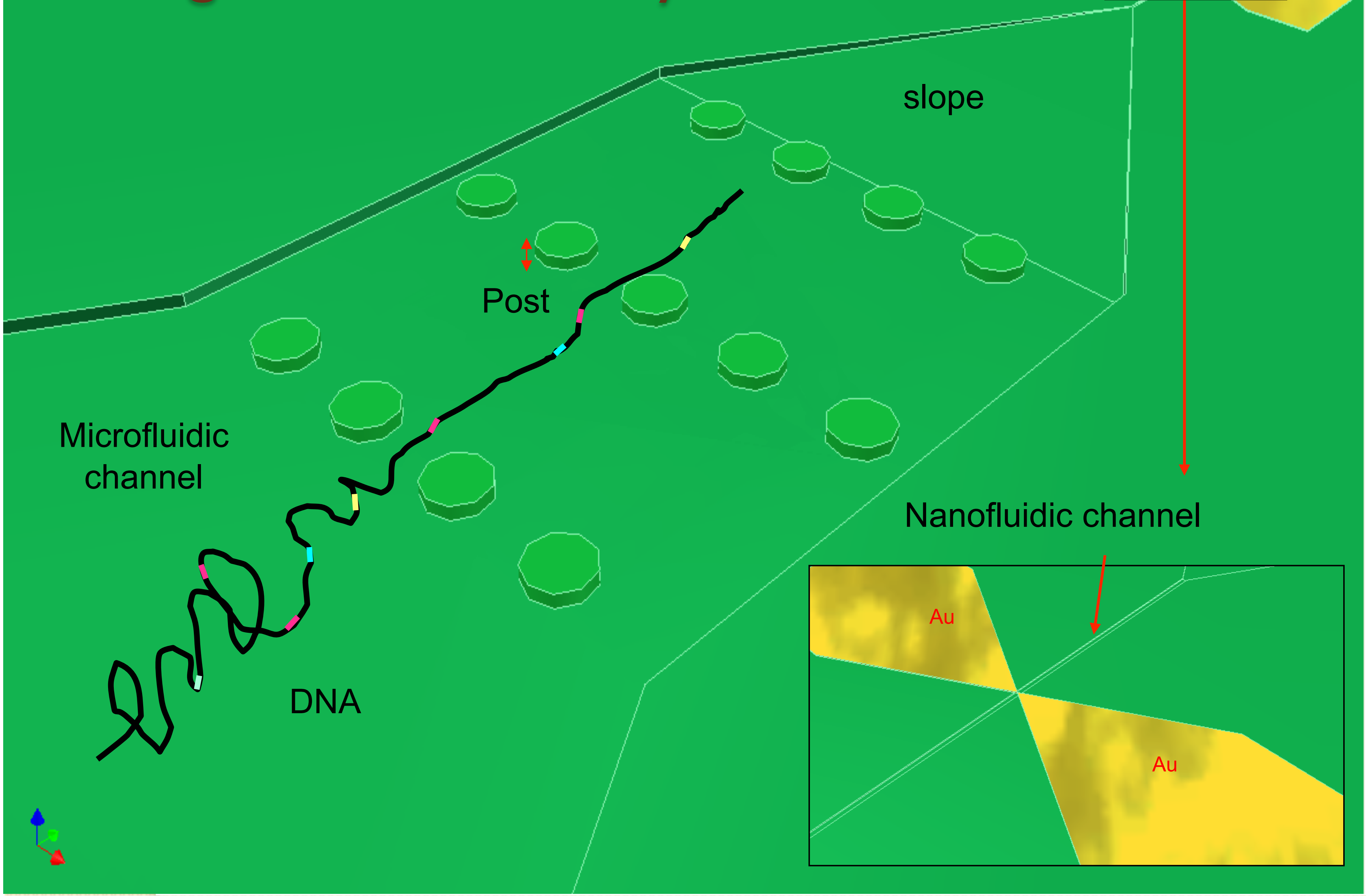
Coiled protein-binding DNA



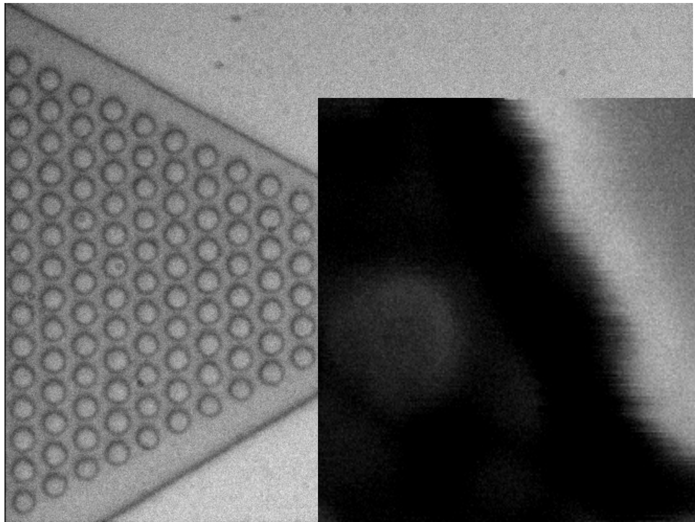


TF mapping → Barcode reading

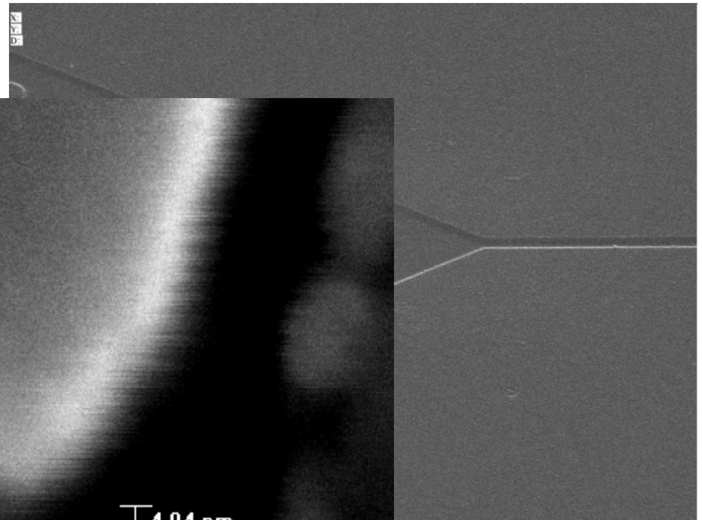
Single molecule analysis device

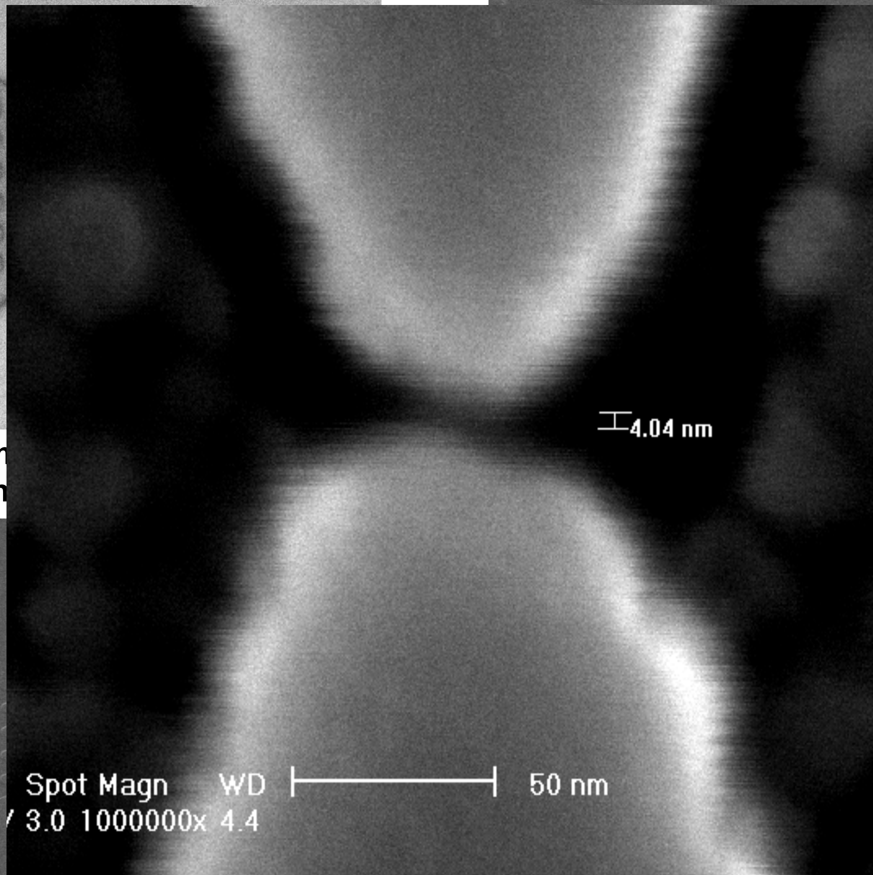


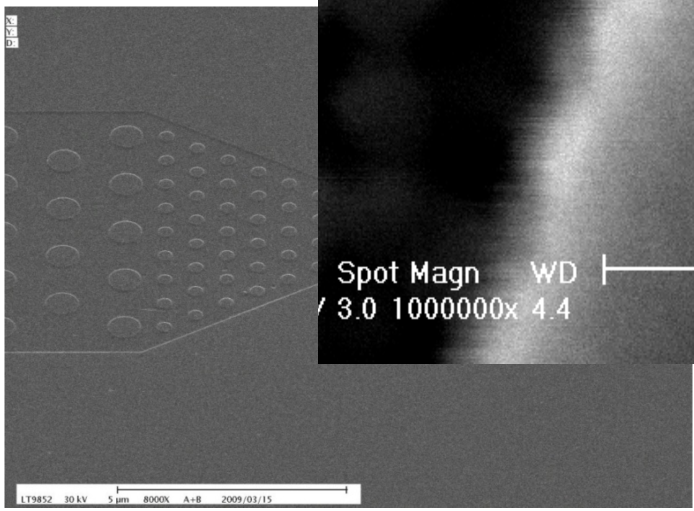
Nanochannel Fabrication – Fused Silica



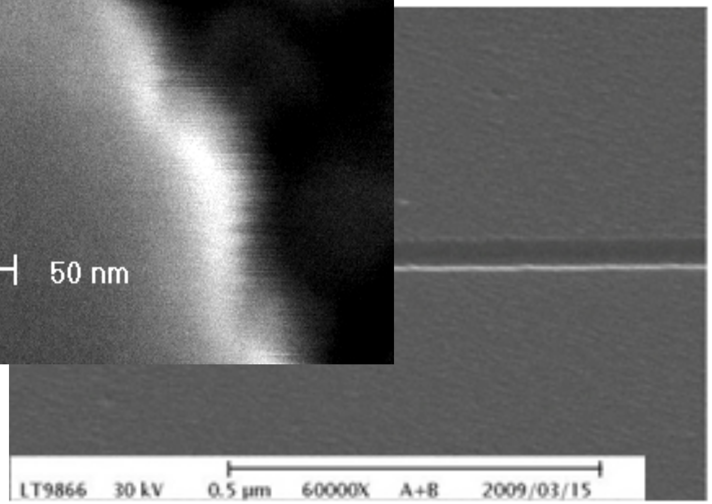
Bright Field In
and Nan







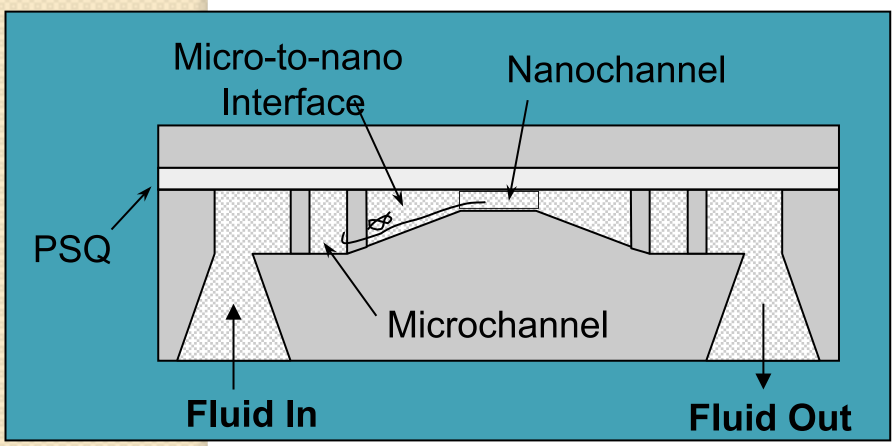
SEM Image of Etched Nanoslit
and Nanochannels



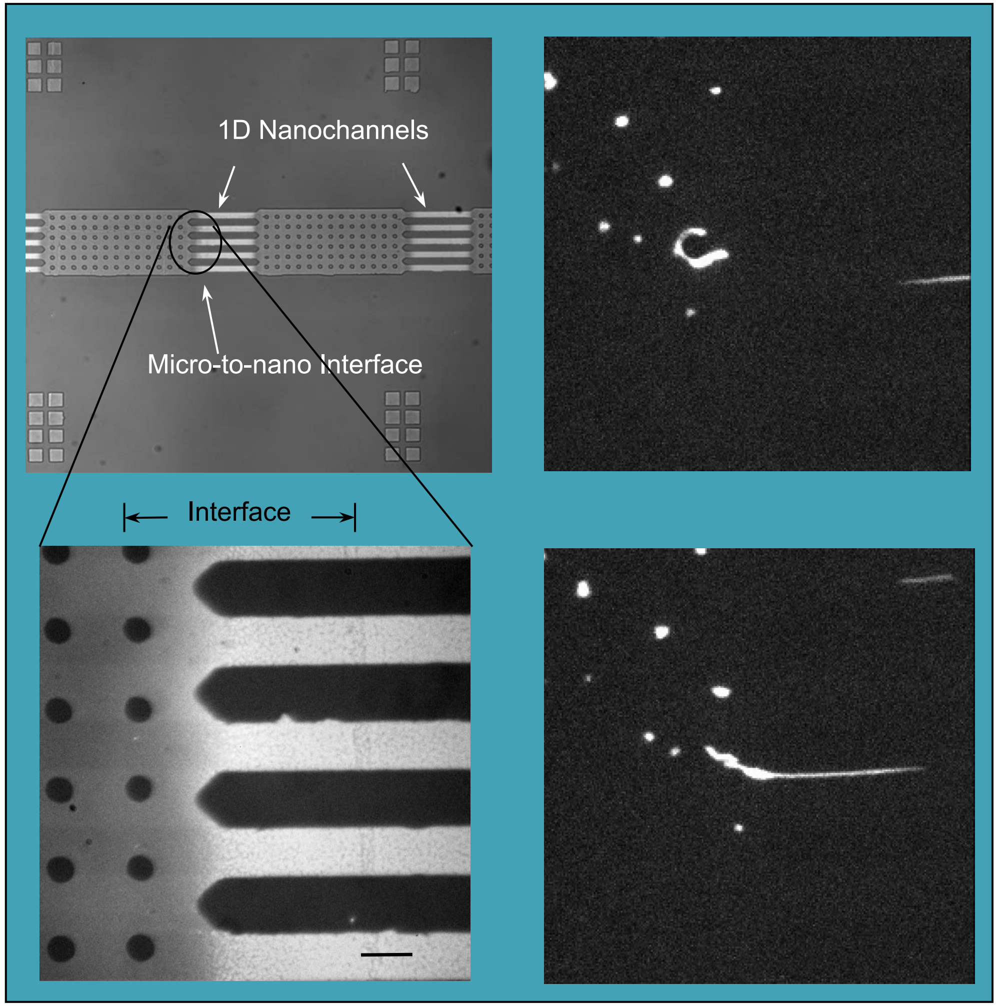
More Closer Look at The Nanochannels

World-micro-nano interfacing

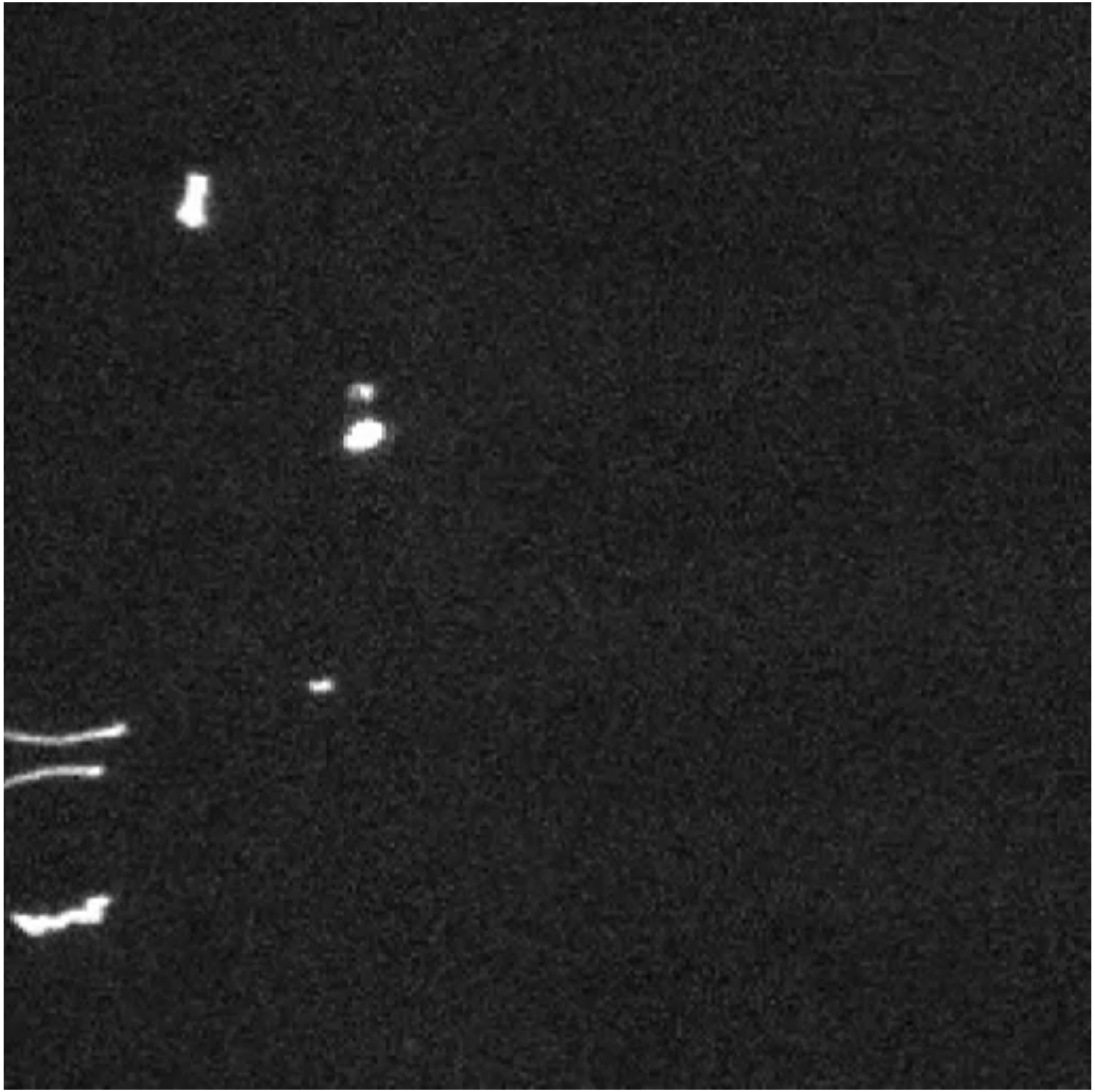
→ Continuous reduction of entropy



Gu, Gupta, Chou *et al. Lab Chip*, 7, 1198 (2007)



DNA strands going up the ramp in the interfaced area (movie)



Exercise 2

- In entropic recoiling at a micro-nanofluidic interface, how does one derive the retraction length with a sqrt(t) dependence?

(Turner, Craighead et al., PRL 2002)

(Mannion et al, Biophys. J.,90,4538 2006)