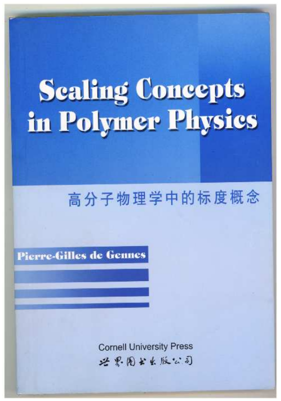
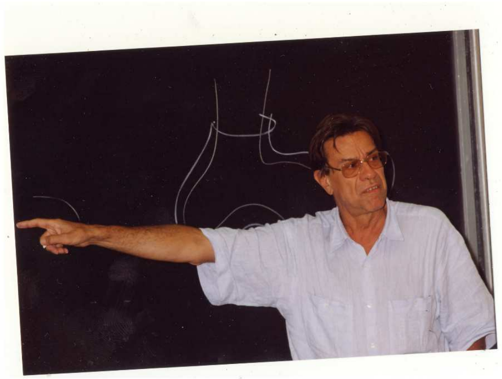
institut Curie
Ensemble, prenons le cancer de vitesse.

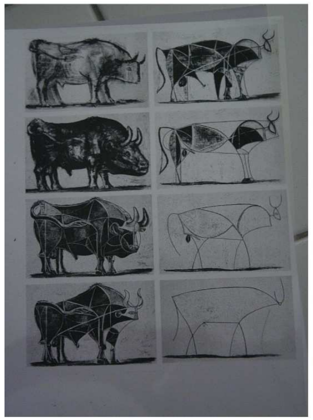
Polymers in confined geometries

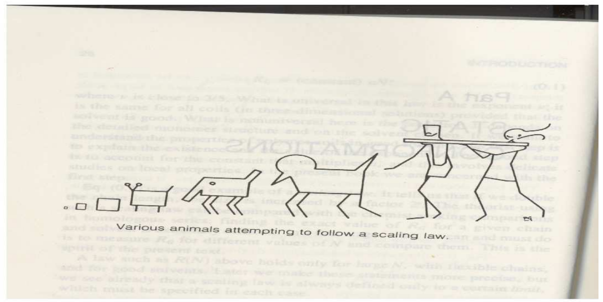
Françoise Brochard

Université Paris 6, Inst. Curie







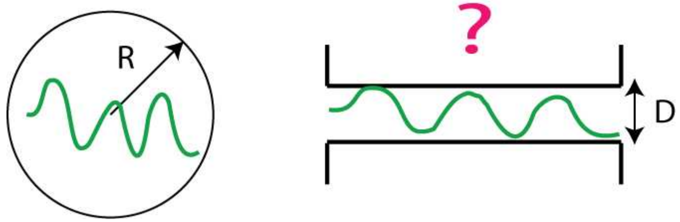


What Pierre-Gilles did all along his career, with the elegance of an artist was to draw white lines for science in large strokes, astonishingly simple, yet so pioneering.

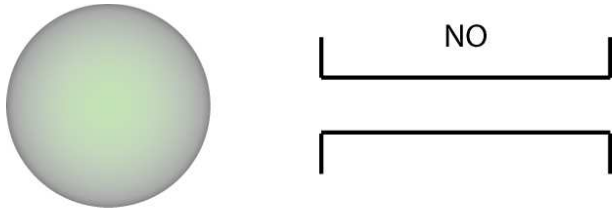
March 13, 2008

Three classes of polymers

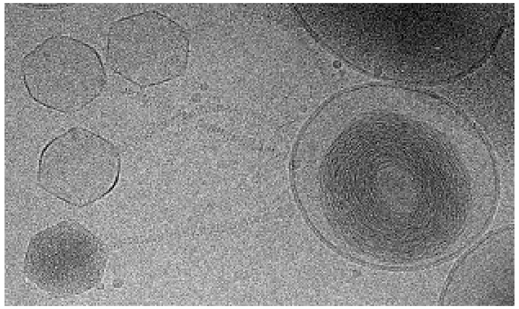
Flexible



Rigid: proteins, colloids



Semi-flexible: DNA

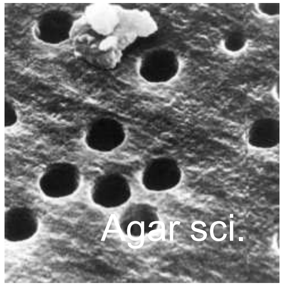


Transfer of T5 genome into proteoliposomes

O. Lambert et al, PNAS 2000, 97

d=1
Rigid tubes

10 nm < D < 1 μm



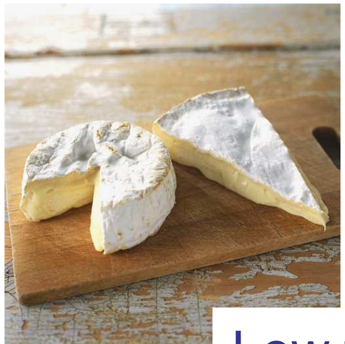
Nuclepore membrane filters
(pioneered by GE 1976)

Radiation-etching of polycarbonate films
(Guillot et al, J. Appl. Phys. 52, 1981)

Filters used in fabrication of cheese and low fat milk

- Porous rocks
- Oil recovery
- Xanthans

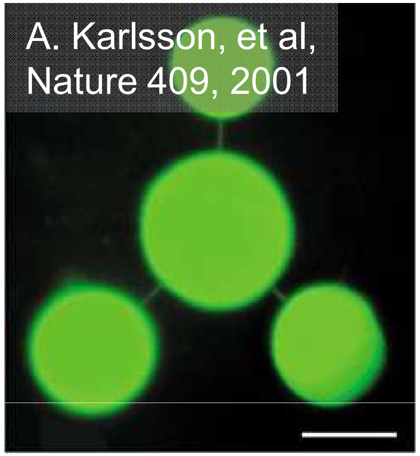
(Saffman Taylor)



Low fat milk producing cow?!

d=1
Soft lipidic tubes

N. Borghi, K. Guevorkian, S. Kremer



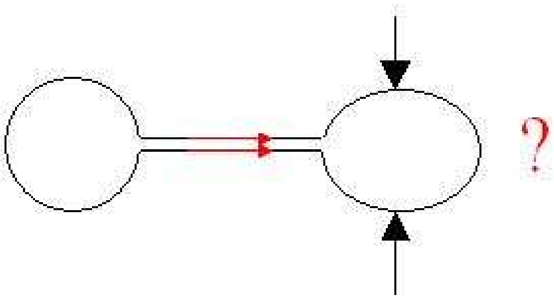
Vesicle networks

QuickTime?and a
Microsoft Video 1 decompressor
are needed to see this picture.

Hydrodynamic tether extrusion

P. G. Dommersnes, et al., EPL, 70 (2005)

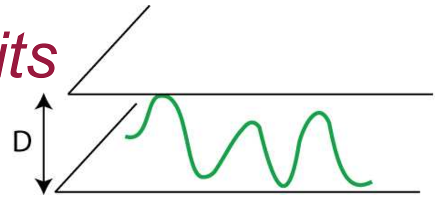
Flows in soft lipidic tubes



QuickTime?and a
decompressor
are needed to see this picture.

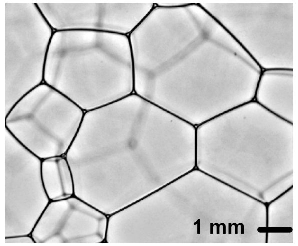
d=2 confinement

Rigid: slits



Soft: soap films

D. Langevin, A.C.I.S, 89 (1989



Polymers in foams → Stabilizing

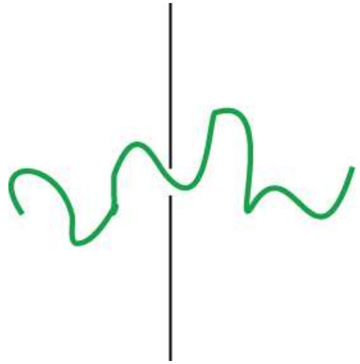
Polymers in foams → Spreading (fluorinated foams)

P. G. de Gennes, C. R. Acad. Sc. 289 (1979)

d=0, "nano holes"

Holes:

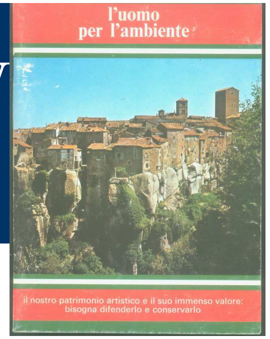
- Protein pores: α-Hemolysin
- Nano fabricated pores



Translocation of polymer through a narrow hole under an electric field.

www.apmaths.uwo.ca/~mkarttu/

Flexible polymers in confined geometry
Statics



Flory: Swollen chain $R=N^{\nu}a$ Ideal chain $R_0=N^{1/2}a$

$$\frac{F_{ch}}{kT} = \frac{R^2}{R_0^2} + N\text{v}C \quad \text{where } \text{v} = a^d \qquad C = \frac{N}{R^d}$$

$$\frac{\partial F_{ch}}{\partial R} = 0 \qquad R = N^{\frac{3}{d+2}}a$$

$$\frac{\text{v}N^2}{R_0{}^d} \sim N^{2-\frac{d}{2}},$$

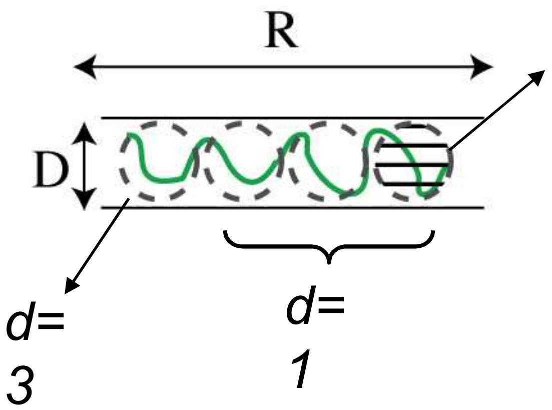
$$d_c = 4$$

d	3	2	1
ν	3/5	3/4	1

d □ ν □

Excluded volume effects increases in confined geometries

PGG: "Blobs"



g monomers

$$R = \frac{N}{g}D = Na\left(\frac{a}{D}\right)^{2/3} \qquad D = g^{3/5}a$$

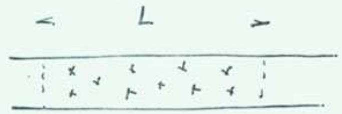
$$F_{conf} \sim \frac{N}{g}kT \sim R\frac{kT}{D} \qquad f_c = \frac{kT}{D}$$

III. MOBILITÉ DANS UN PORE

4

1) APPROX. DEBYE

CHAINE = MILIEU POREUX HOMOGÈNE

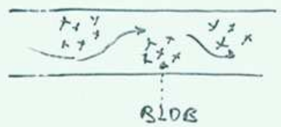


ICI : PAS DE BACK FLOW

$\frac{F}{V} = \mu = \frac{1}{N\eta_s}$ INCORRECT !

2. LOI D'ECHELLE   F. BROCHARD

FLUCTUATIONS IMPORTANTES



$F \simeq \nu \; 6\pi\eta D \; V$

NB BLOBS (ν)   STOKES ($6\pi\eta D$)

$\mu \simeq \frac{g_D}{N\eta D}$

$$\boxed{\mu = \frac{1}{N\eta_0 a}\left(\frac{D}{a}\right)^{2/3}}$$

3) COEFFICIENT DE DIFFUSION $D_c = \mu kT$

PERMEABILITÉ DE MEMBRANE $K = \frac{J_{12}}{c_1 - c_2}$

$K = n_p D^2 \; f \; \frac{D_c}{E_R}$ $f = \frac{C_{pore}}{C} = e^{-N/g}$ DEP. EN P DOMINANTE QUAL. OBSERVÉE

FRACTION TROUS (n_p)   COEFF. PARTAGE (f)   EPAISSEUR MEMBRANE (E_R)

Forced penetration

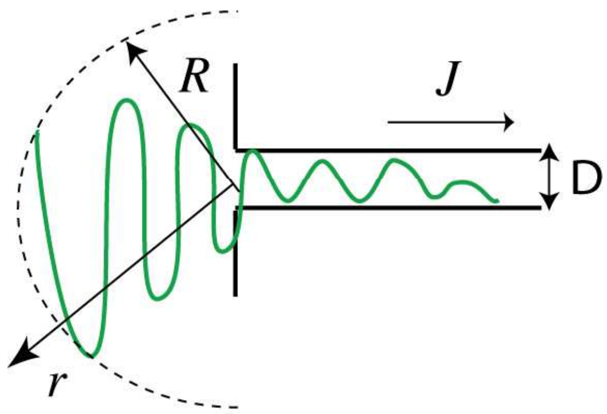
Hydrodynamic analysis

S. Daoudi and F. Brochard, Macromolecules, (11) 1978

$$\dot{\gamma} > \frac{1}{\tau_z}$$

$$\frac{J}{r^3} \qquad \frac{kT}{\eta R^3}$$

$$r^* = R\left(\frac{J}{kT/\eta}\right)^{1/3}$$



Affine deformation

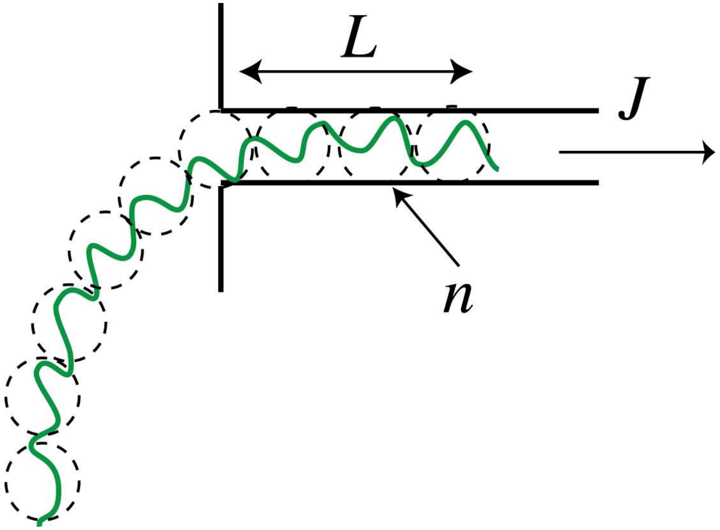
$$\frac{R_\perp}{R} = \frac{r}{r^*}$$

$$R_\perp = r = D \to r^* = R \to \boxed{J_C = \frac{kT}{\eta}}$$

Forced penetration

Role of fluctuations = suction model

P. G. de Gennes, 1984

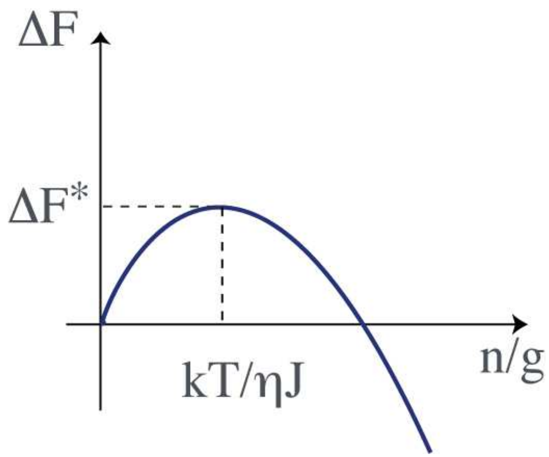


Force on a blob: $\eta V D = \eta J / D$

Aspiration energy: $\Delta F_A = -\frac{n}{g} \eta \frac{J}{D} L$

$$\Delta F = \Delta F_c + \Delta F_a = kT \left[\frac{n}{g} - \eta \frac{J}{kT} \left(\frac{n}{g} \right)^2 \right]$$

$\rightarrow J_c = \frac{kT}{\eta}$ Penetration of first blob

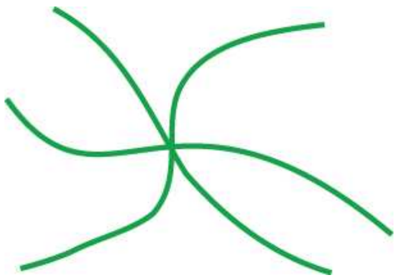


J_c does not depend on chain length, *N*

Role of topology

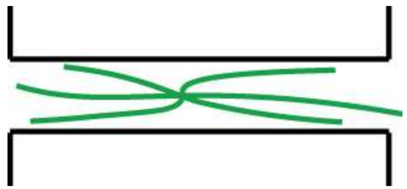
F. Brochard & P.G. de Gennes, CRAS Paris 323 (1996)

Stars



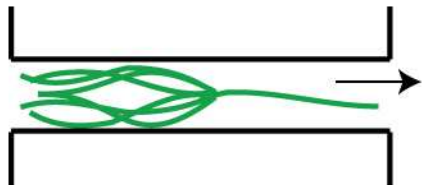
Symmetric

$$J_c^* = J_c f^2$$



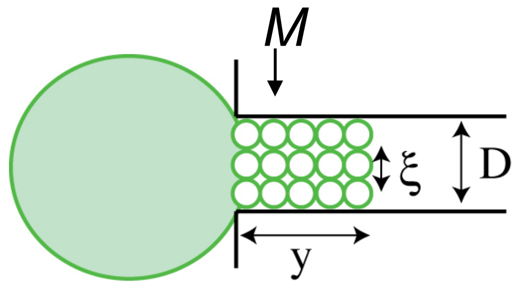
Asymmetric

$$J_{c1} = J_c^* \frac{D}{N a f^{1/2}}$$



Branched Polymers

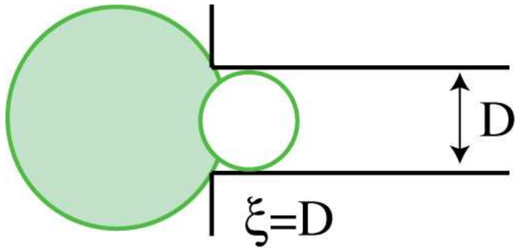
$\left(\gamma = \frac{1}{4}\right)$



C. Gay et al, Macromolecules, (29) 1996

$$\xi = \frac{D^{4/3}}{a^{1/3} M^{1/6}}$$

$$J = J_c \frac{D^4}{\xi^4} \qquad f = \frac{D^2}{\xi^2}$$



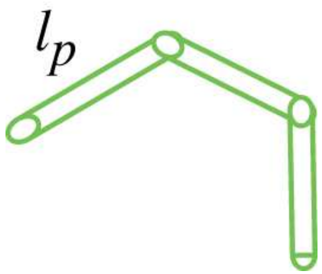
T. Sakaue, et al., EPL, (72) 2005

$$J_c = \frac{kT}{\eta} \quad !$$

f_V □ f_c $\quad$ f_V increased faster than f_c

Penetration of first blob (ξ=D) limits the penetration

DNA: semi-rigid polymers



$$v_B \sim l_p^2 a$$

$$g = \frac{l_p}{a}$$

F. Brochard, et al, Langmuir (21) 2005

$$R_0 = N_D^{1/2} l_p = \sqrt{N a l_p}$$

$$\frac{F_{ch}}{kT} = \frac{R^2}{R_0^2} + \frac{F_{ve}}{kT}$$

d=3 $$\frac{F_{ve}}{kT} < 1 \text{ if } N < N_{c3} = \left(\frac{l_p}{a}\right)^3 \sim 10^6 \quad !$$

d=1 $$\frac{F_{ve}}{kT} = \left(\frac{N}{g}\right)^2 \frac{l_p^2 a}{R^2 D} < 1 \text{ if } N < N^* = \left(\frac{l_p}{a}\right)^{1/3} \left(\frac{D}{a}\right)^{4/3} \sim 10^3$$

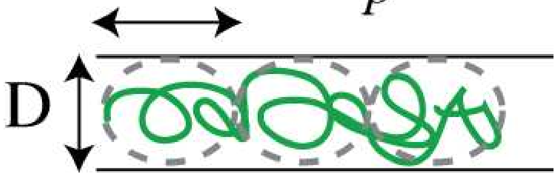
Long DNA is ideal in 3d but swollen in nanotubes

$D > l_p$

$D < l_p$

Reisner, et al., PRL 94 2005

$L^* = (N^* a l_p)^{1/2}$



$$L = \frac{N}{N^*} L^*$$

$$F_{conf} = \frac{N}{N^*} \Delta F^* \qquad \frac{\Delta F^*}{kT} = \frac{N^* a l_p}{D^2}$$

$$f_c = \frac{F_{conf}}{L} = \frac{\Delta F^*}{L} \approx \left(\frac{N^* a l_p}{D^2} \right)^{1/2} kT$$

Forced penetration

- Electric field E: $f_E = qEN = f_c \to E^* = E_1^* \frac{N^*}{N}$

  passage $qE > \left(\frac{a l_p}{N^*} \right)^{1/2} \frac{kT}{D^2}$

  Barrier 1st blob

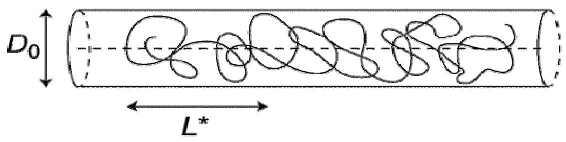
- Flow: ideal blobs

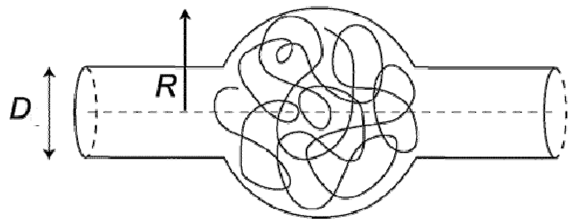
  $$f_v = \frac{N}{N^*} \eta V R^* \left(\frac{R^*}{D} \right)^2 = \frac{N}{N^*} f_v^*$$

  Sponge $\xi = D^2/R^*$

  passage $f_v^* = f_c \Rightarrow J_c^{SR} = \frac{kT}{\eta} \left(\frac{D}{R^*} \right)^2 = J_c \left(\frac{D}{l_p} \right)^{2/3} \left(\frac{a}{l_p} \right)^{2/3}$

Soft tubes
Snake vs Globule





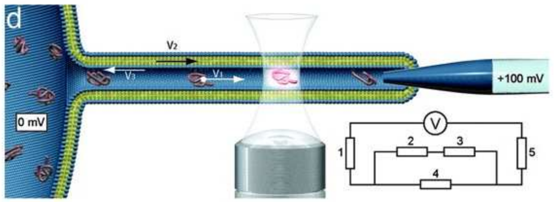
$D > l_p$

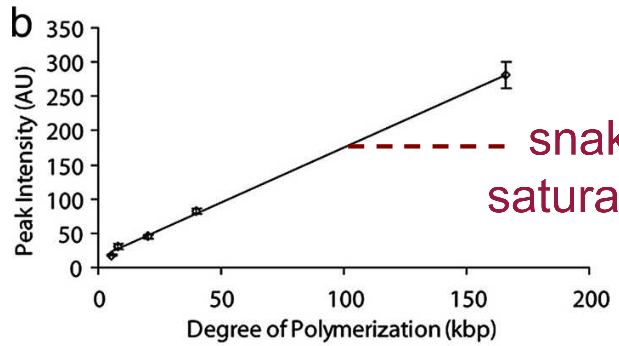
$$F_{snake} = \frac{Nal_p}{D^2} kT$$

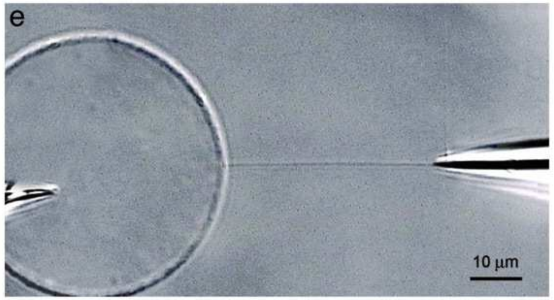
$$F_{Globule} = \sigma R^2 + \frac{N^2 a^3 kT}{R^3}$$

F. Brochard, et al., LANGMUIR 21 (2005)
M. Tokarz, et al, PNAS 102 (2006)

$$F_{snake} = F_{Globule} \qquad N_c = \frac{aD^4}{l_p^5}\left(\frac{\kappa}{kT}\right)^3$$





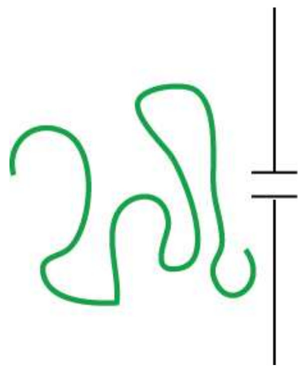


Holes = passage of polymers

Neutral polymers: (POE)

Force: chemical potential $\Delta\mu$

A. Oukhaled, et al, PRL, 98, 2007
P. Merzylak, et al., Biophys. J., 77, 1999
L. Movleanu, et al.,Biophys. J., 84, 2003

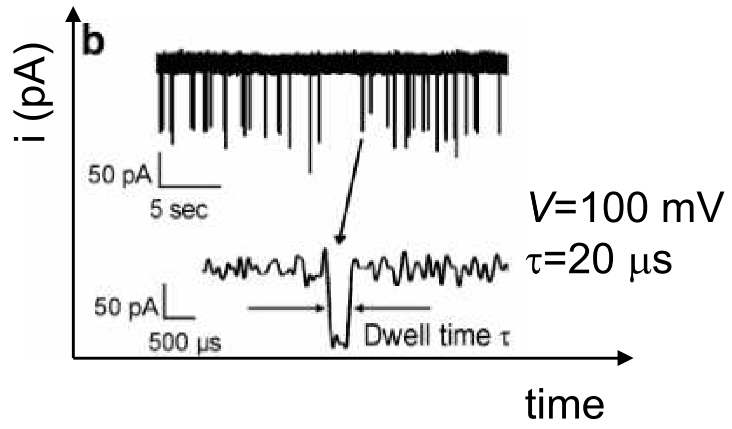


Charged polymers: (DNA - Polyelectrolytes)

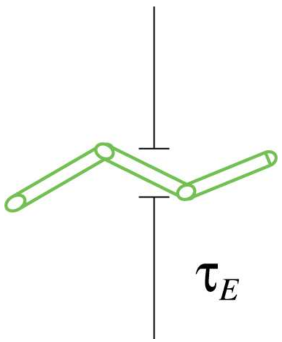
Force: Electric field

Observation: Blockade of the pore

M. Bates et al, Biophys. J. 84, 2003
J. Storm et al, Nanoletters, 5, 2005



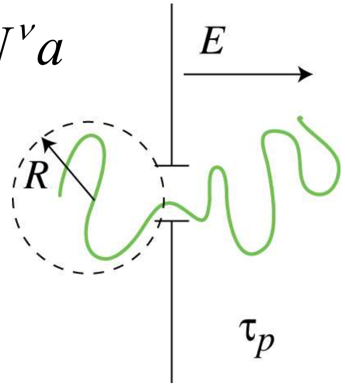
Problems of DNA entering a cell



$$\eta l_p V = \frac{\Delta\mu}{a}$$

$$\tau_E = \frac{r_p}{V} \sim 10^{-4}\ \text{s}$$

$$R \sim N^{\nu} a$$



$$\eta R\dot{R} = f(\sim eV/a)$$

$$\tau_p \sim \frac{\eta}{f} R^2$$

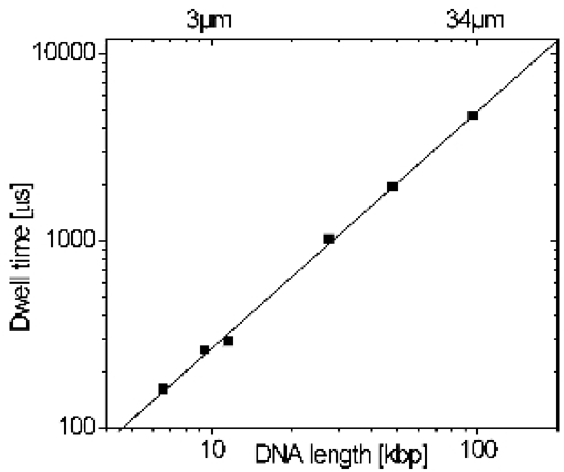
$$\tau_p \sim N \quad \text{DNA}$$

$$\tau_p \sim N^{1.2} \quad \text{swollen polymer}$$

$$\tau_{transfection} = \frac{\tau_E}{n}\ ,\ n = \frac{C}{N} r_p^3 \quad \sim \quad \text{hours!}$$

www.ks.uiuc.edu

PGG Physica A 274 (1999)
PGG PNAS 96 (1999)



Fast DNA translocation

$$\tau_p \sim R^2 \sim N^{1.27}$$

J. Storm et al, Nanoletters, 5, 2005

QuickTime?and a decompressor are needed to see this picture.

Conclusions

Tubes and slits (citations: 3000, 2003<1200<2008)

- Solid:
  - polymer characterization and separation, oil separation
- Soft:
  - gene therapy, soap films stabilization
  - lipidic tubes: transport, nanoreactors

Holes (citations: 587, 2003<275<2008)

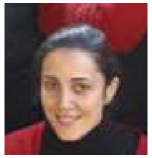
- Detection of polymer length
- Polymer length separation using minute amount of sample

Goal:

- Sequencing of DNA, RNA
- Transfection

Acknowledgments

Former students


Axel Buguin

Pierre Nassoy

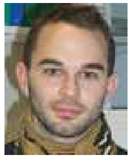
- Biology

J.-P. Thiery

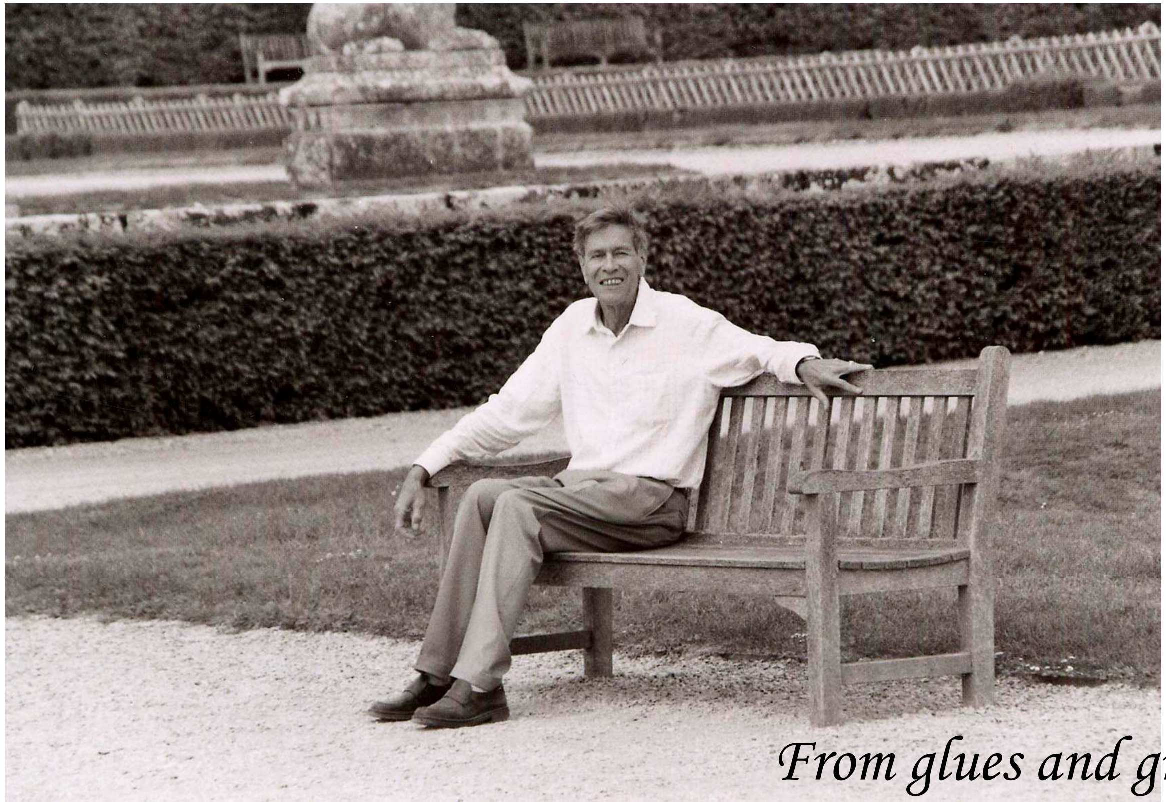
M. Bornens

Y.-S. Chu

M. Théry



Thanks Pierre Gilles for sharing with us your insatiable love for science



From glues and grains to rheology
Using notions of symmetry and analogy
He illuminates the messy
With math not so dressy
But with insights deep from figurology

Mahadevan, Boston 2006