Propulsion à petits nombres de Reynolds

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ESPCI-ParisTech

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  - interactions avec une paroi, pompes biologiques microscopiques
- systèmes artificiels
    - viscosité et élasticité
    - micronageurs magnétiques

Collaborateurs

Nageur microscopique

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Marcus Roper

Howard Stone (Princeton)

Jérome Bibette (LCMD ESPCI)

Cils artificiels

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Naïs Coq

Olivia du Roure

Denis Bartolo (ENS Lyon)

Dynamique des filaments élastiques

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Anke Lindner

Olivia du Roure

Nawal Quennouz

Microsystèmes magnétiques

Joseph Tavacoli

Julien Heuvingh

Olivia du Roure

Kenny Breuer (Brown)

Références générales

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E. Lauga & T. Powers, *The hydrodynamics of swimming microorganisms*, Rep. Prog. Phys. **72** 096601 (2009)

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C. Brennen & H. Winet, *Fluid mechanics of propulsion by cilia and flagella,* Ann. Rev. Fluid Mech. **9** 339 (1977)

T. Jahn & J. Votta , *Locomotion of protozoa,* Ann. Rev. Fluid Mech. **4** 93 (1972)

J Elgeti, R G Winkler & G Gompper, *Physics of microswimmers—single particle motion and collective behavior: a review*, Rep. Prog. Phys. **78** 056601 (2015)

D. Bray, *Cell movements : from molecules to motility,* Garland Publishing (2001)

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Dans un monde sans inertie

$1\mu m$ $10\mu m$ $100\mu m$ 1mm 1cm 1m 10 m L

1pN 10pN 0,1N 1MN F

10^{-9} 10^{-2} 10^{2} 10^{8} Re

$$F \propto \eta U L$$

$$F \propto \rho U^2 L^2$$

$$\eta \Delta \mathbf{u} = \nabla p$$

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Un monde de petites forces

$$Re = \frac{\rho U L}{\eta}$$

$$Re = 1 \rightarrow UL = \frac{\eta}{\rho} \qquad F \propto \eta U L$$

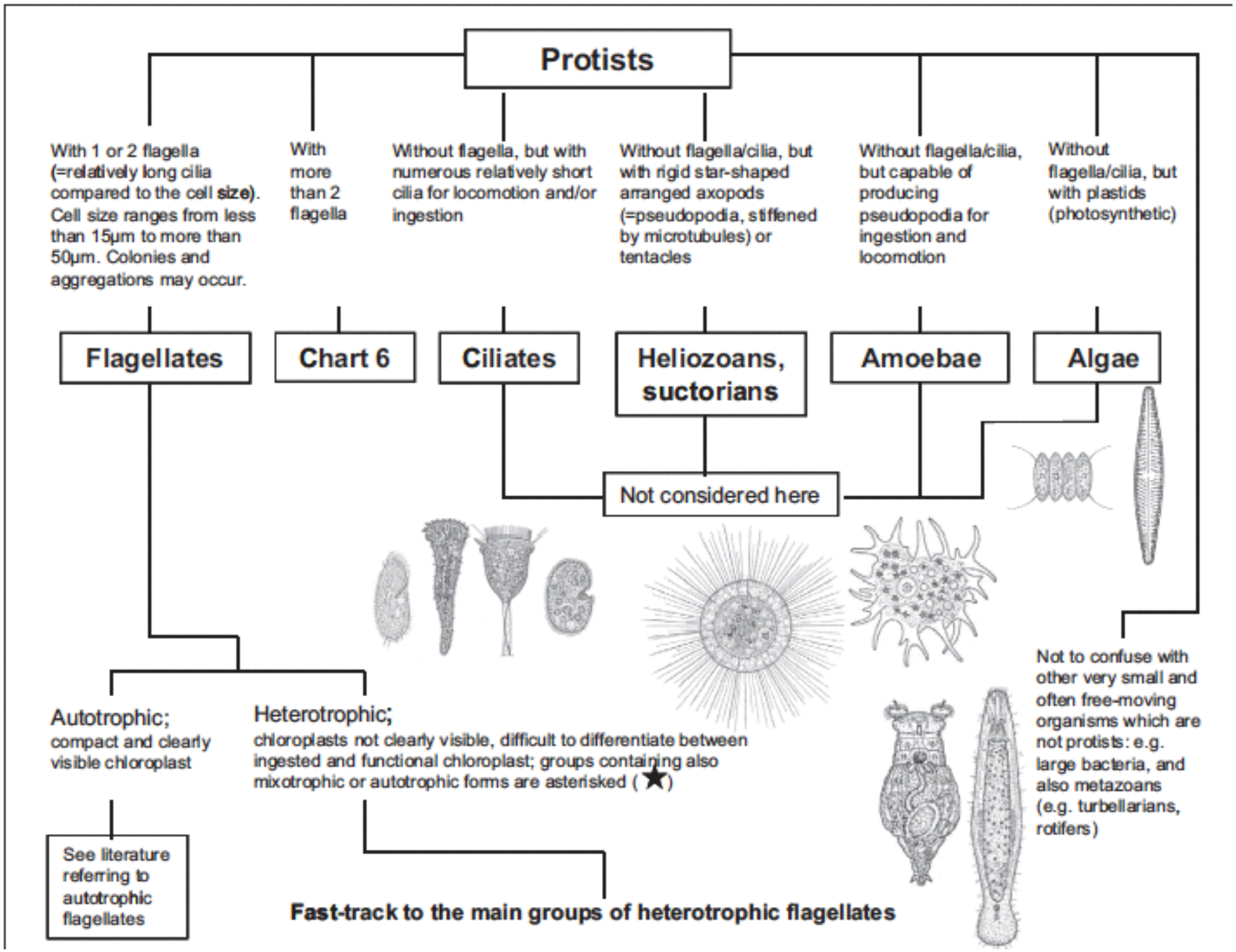
$$F_{Re=1} = \frac{\eta^2}{\rho}$$

1 pN dans l'eau

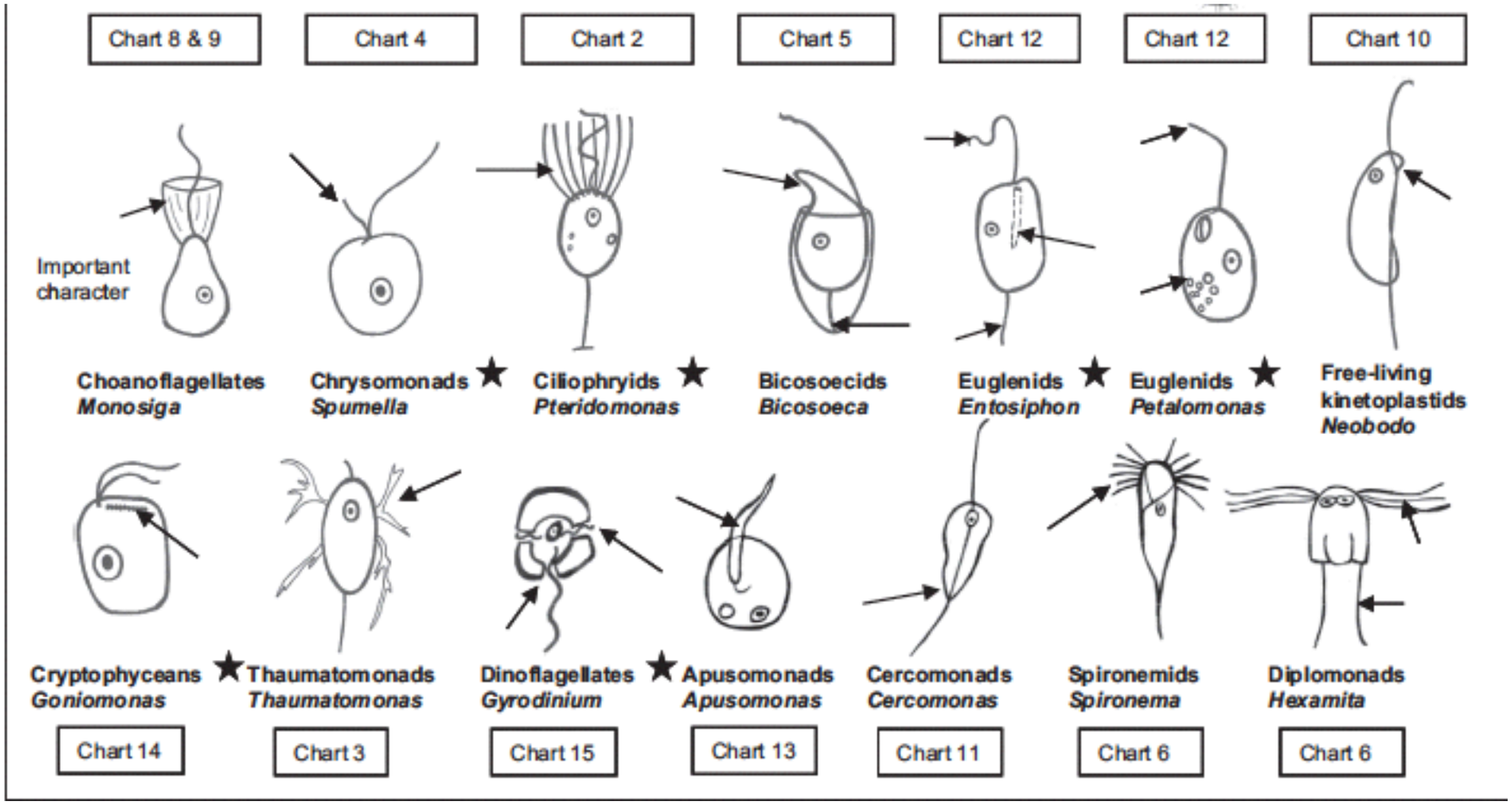
Qulelques microorganismes ….

J. Lighthill SIAM Rev. **18** 161 (1976)

Protozoaires

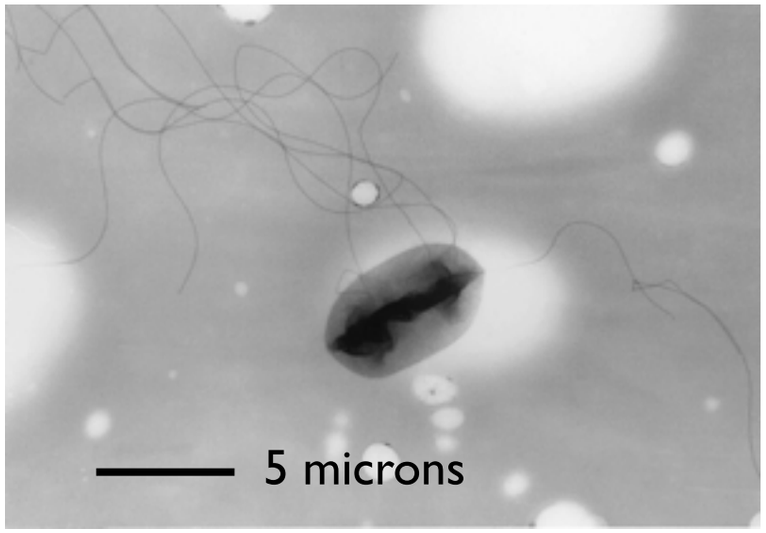


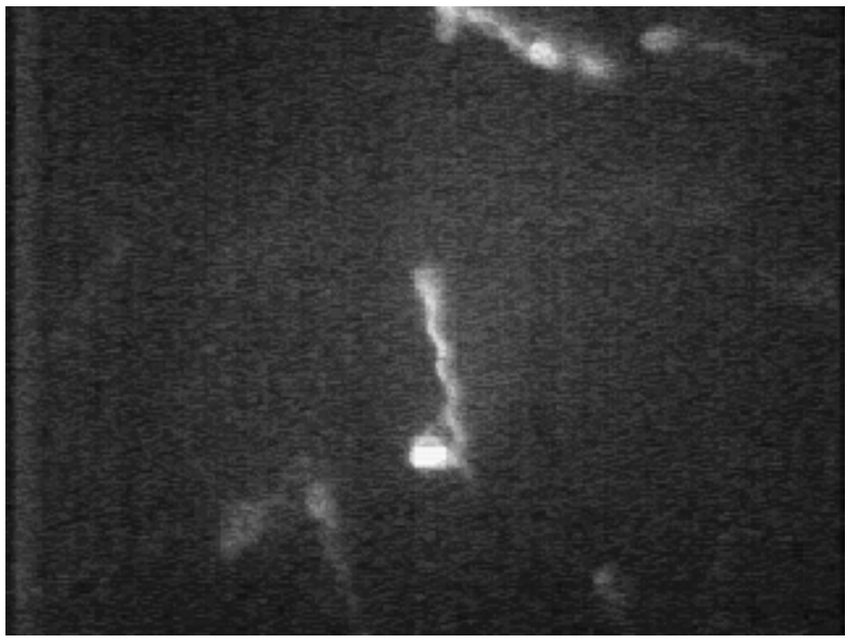
A. Jeuck et H Arndt, Protist, **164** 842 (2013)

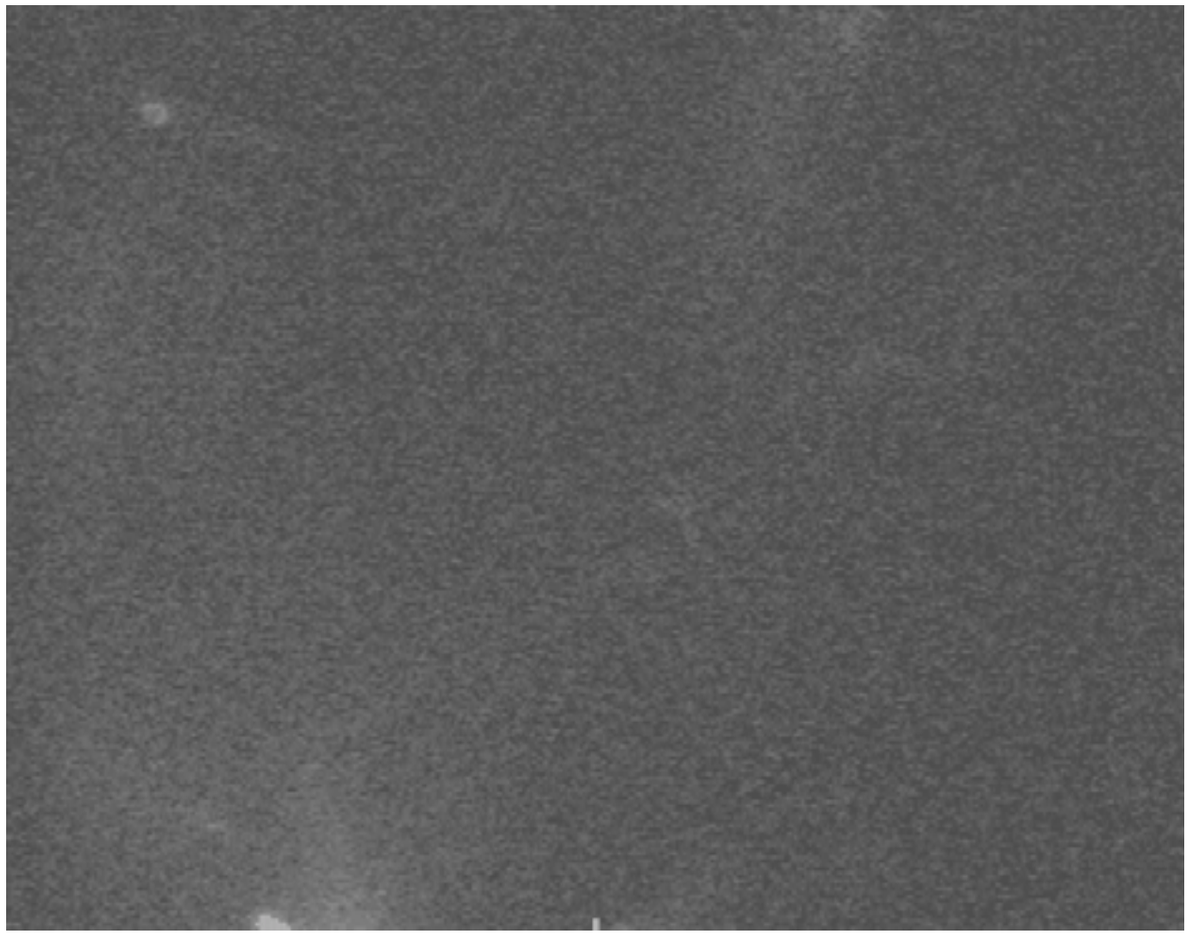


A. Jeuck et H. Arndt, Protist, **164** 842 (2013)

Une bactérie : Escherichia Coli







Films Howard Berg, Harvard

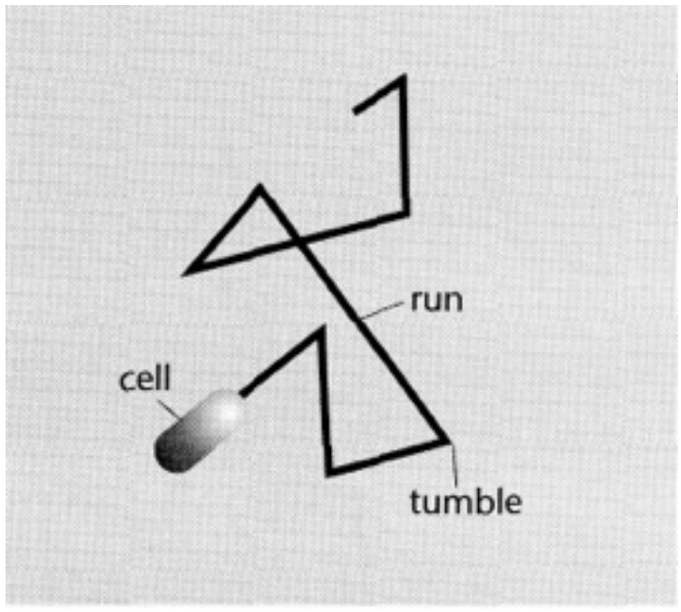
Berg, H.C. (2000) Motile behavior of bacteria. Physics Today **53** (1), 24-29.

Howard Berg. The marvels of bacterial behavior. YouTube

Berg, H.C. E coli in Motion. New York: Springer-Verlag. 2003

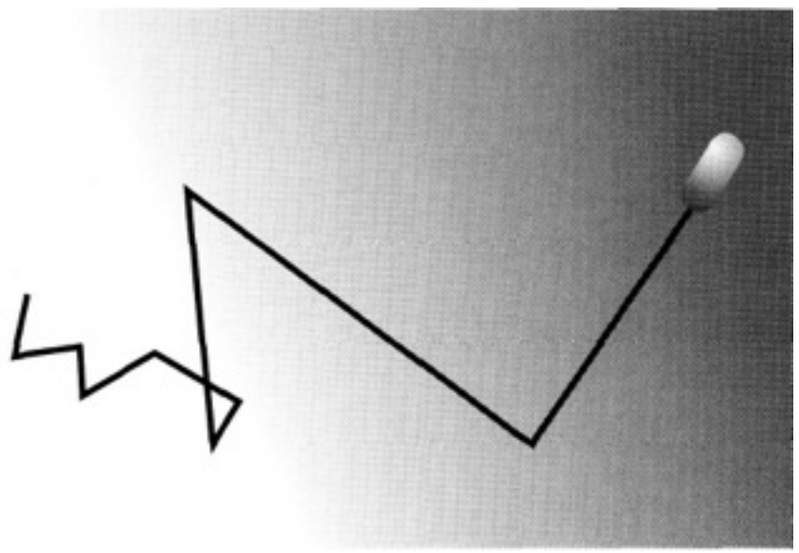
« run and tumble »

100 microns



en l'absence de gradient de nutriment

The algorithm is: if things are getting better don't stop so soon.



avec de gradient de nutriment

Des avantages de la mobilité

Stirring vs. Diffusion

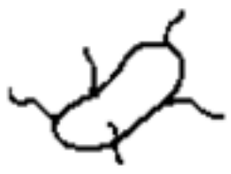
time for transport by stirring: $\frac{\ell}{v}$

time for transport by diffusion: $\frac{\ell^2}{D}$

stirring works if $\frac{\ell v}{D} > 1$

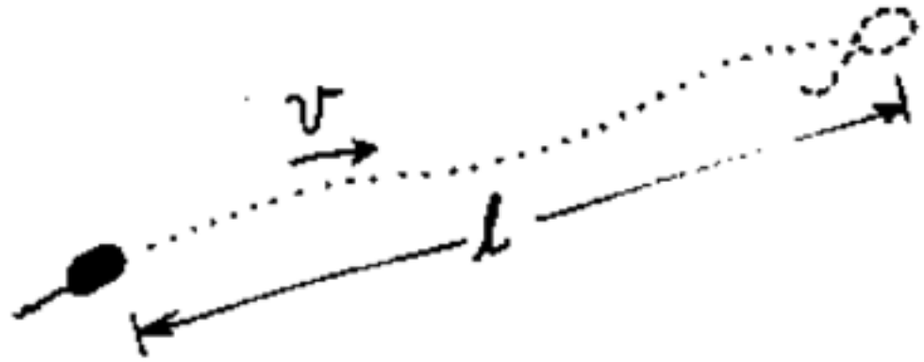
"ℓ" $= \frac{\ell v}{D}$ $\quad$ $\left[R = \frac{\ell v}{\nu} \right]$

$< 10^{-5}$ cm^2/sec $\quad$ $< 10^{-2}$ cm^2/sec



$\ell \approx 10^{-2}$

local stirring accomplishes nothing



to out-swim diffusion:

$\ell \geq D/v$

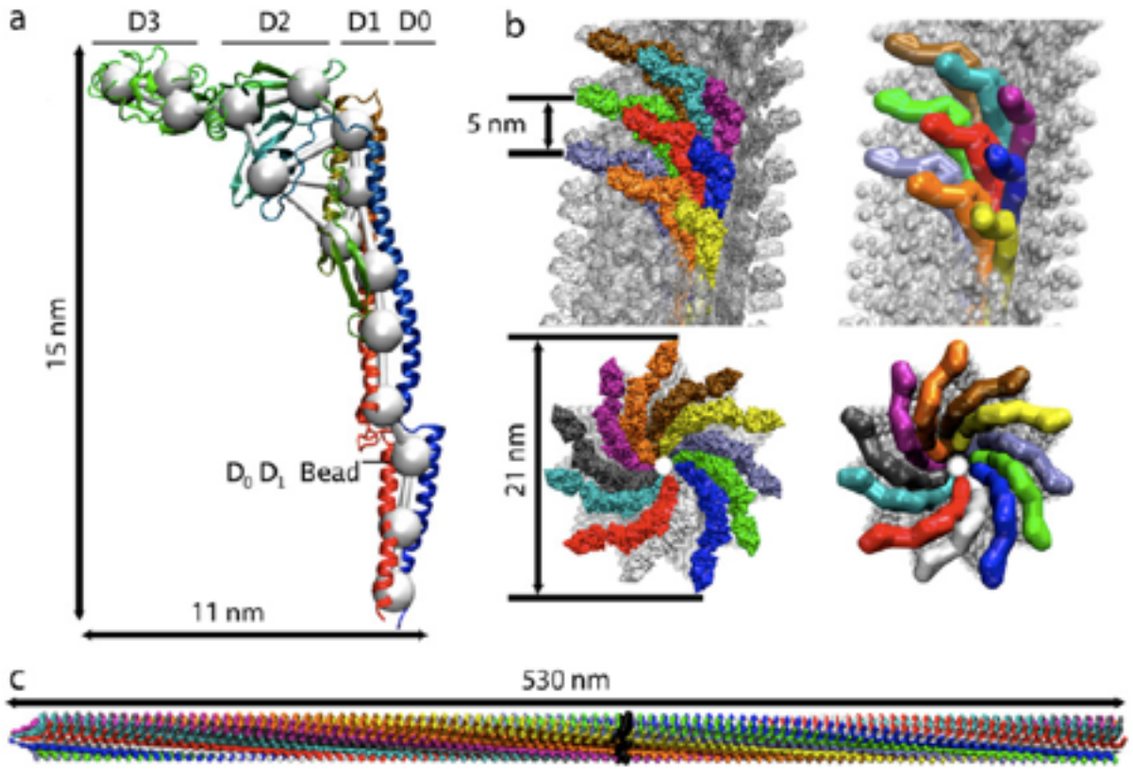
if $D = 10^{-5}$ cm^2/sec, $v = .003$ cm/sec

$\ell \geq 30\ \mu$

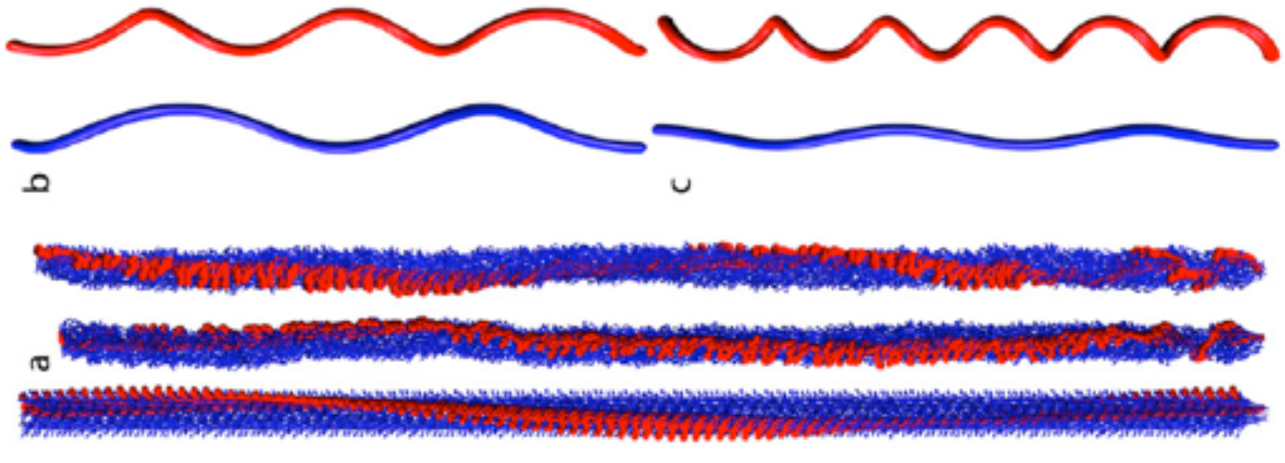
"If you don't swim that far you haven't gone anywhere."

E. Purcell, *Life at low Reynolds number* , Am. J. Phys. **45** 3 (1977)

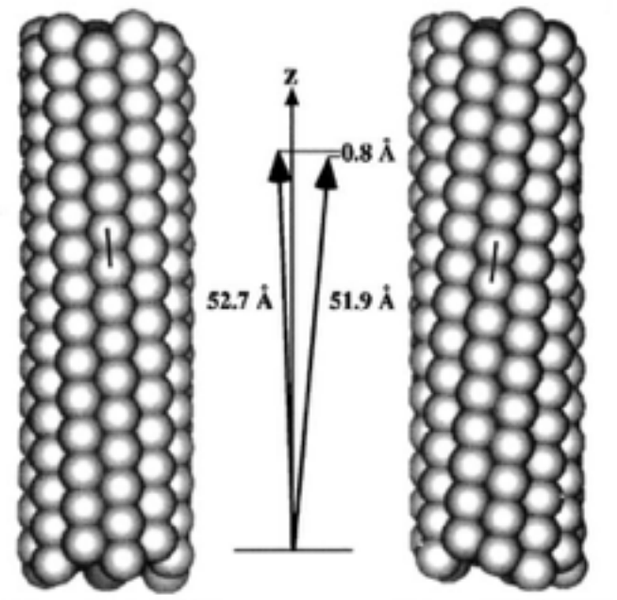
Flagelle bactérien : une hélice passive



Flagelline



A. Arkhipov et al., Biophysical Journal 2006

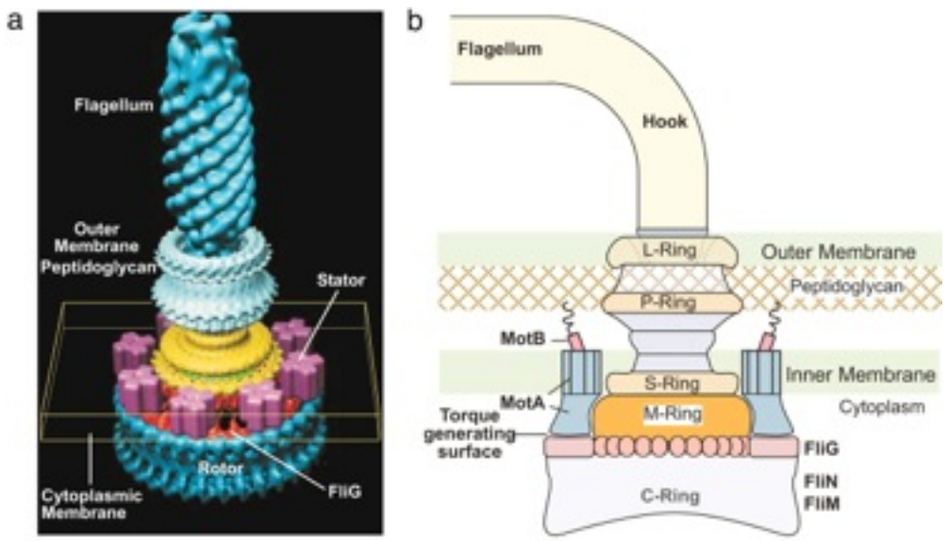


Filaments droits avec les deux types de flagelline L et R

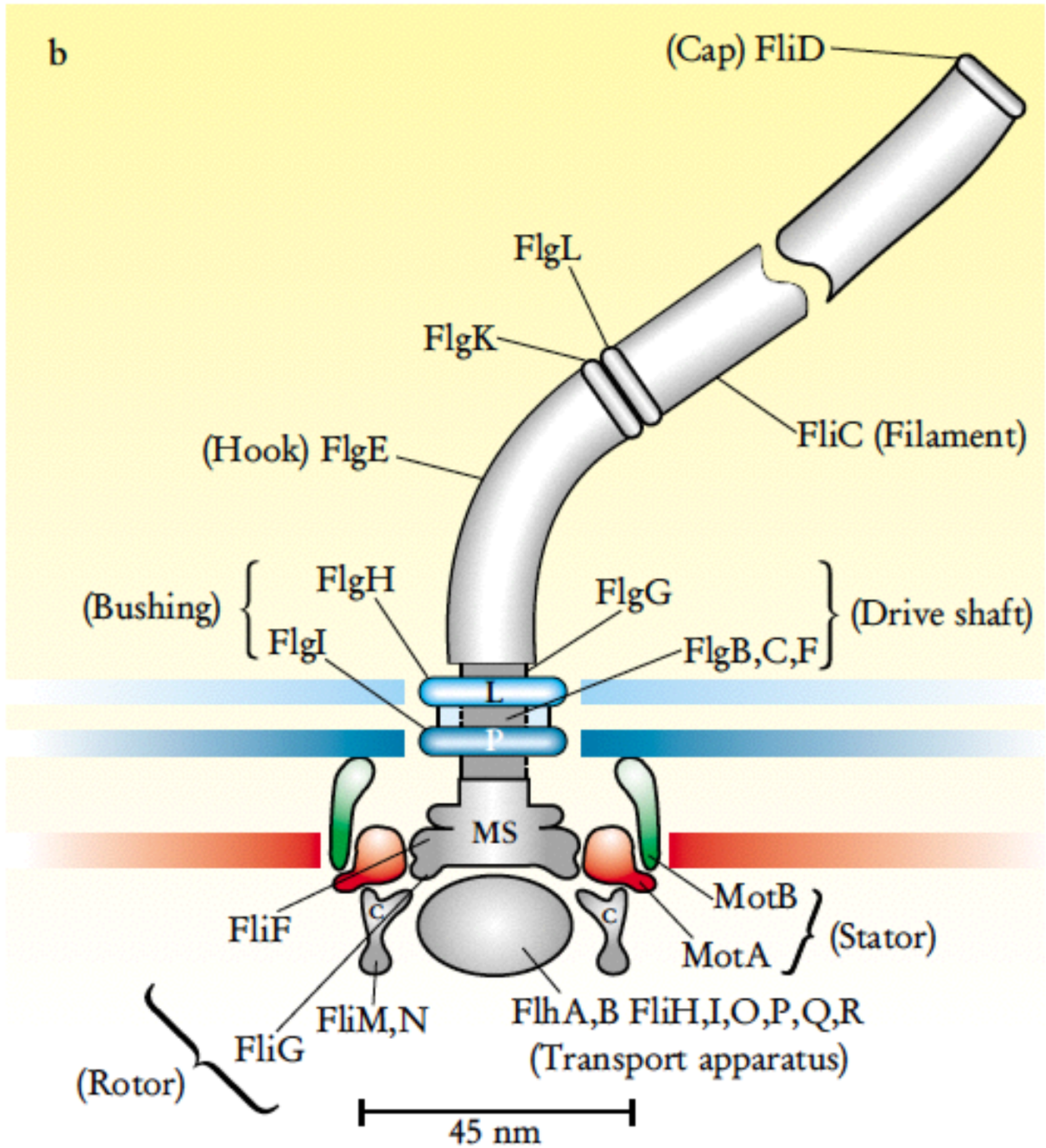
R+L : filaments hélicoïdaux

H. Berg, Ann. Rev. Biophys. **72**, 19 (2003)

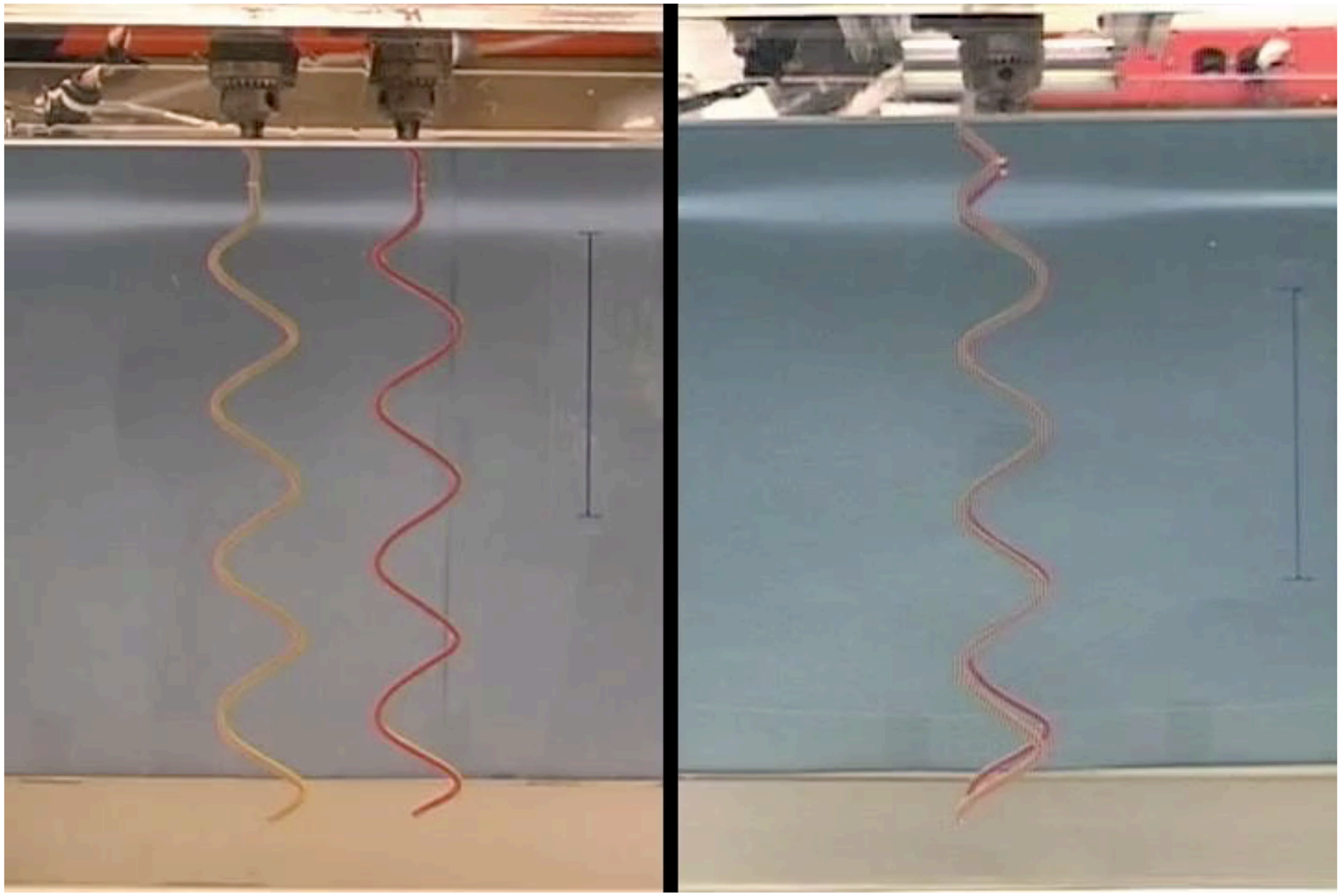
Le moteur d'E. Coli



Moteur moléculaire à gradient de protons

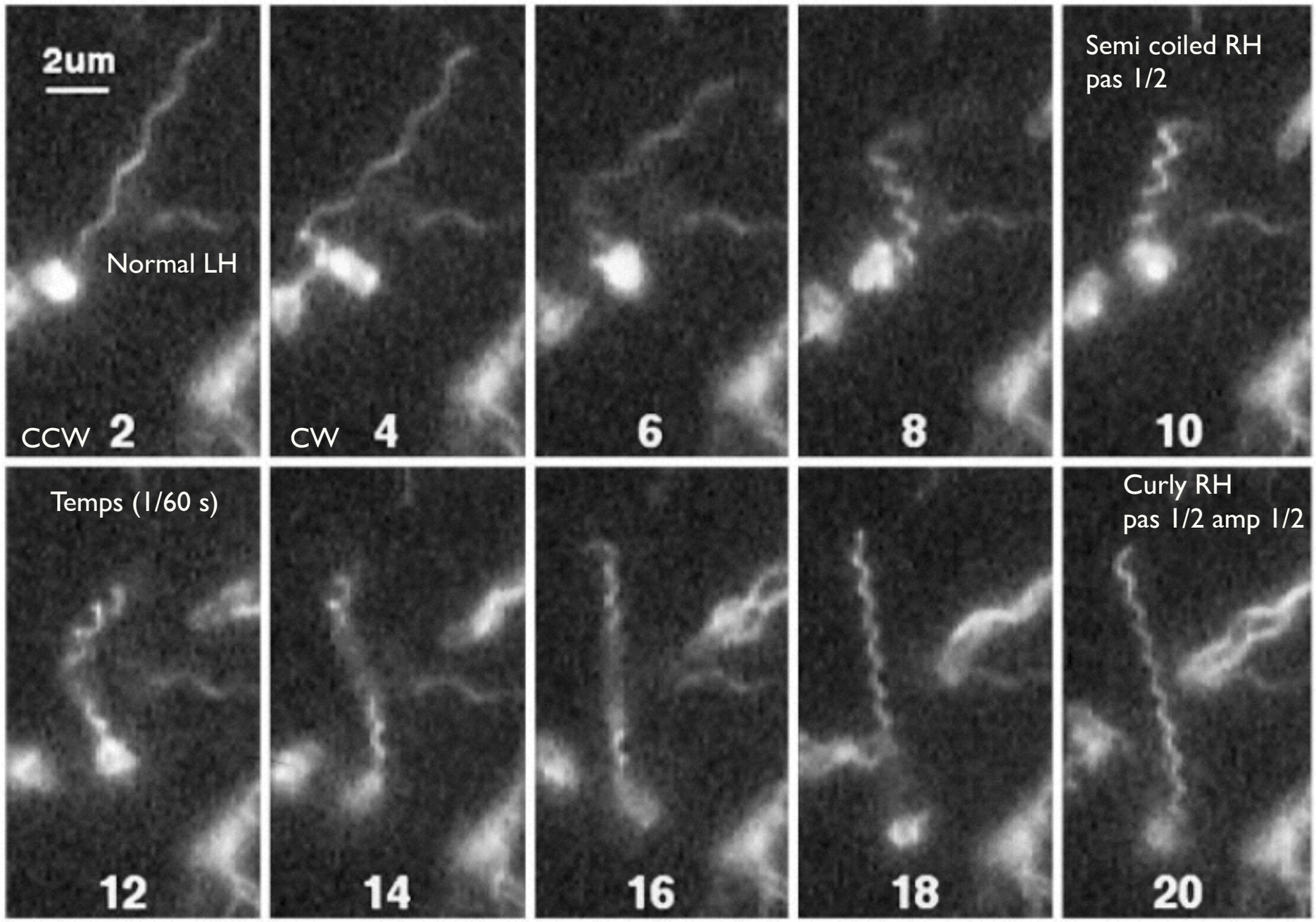


Comment les flagelles s'apparient en faisceau



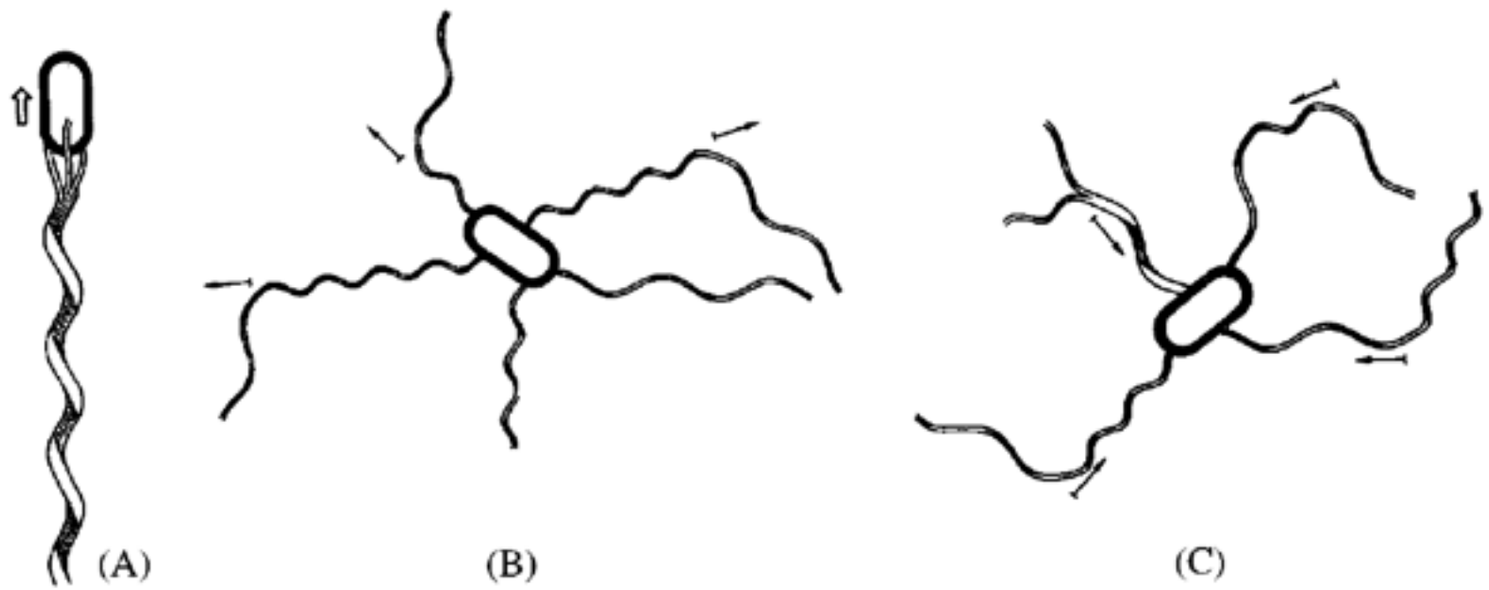
vidéo : groupe de Kenny Breuer, Brown Univ.

Changements de conformation des flagelles



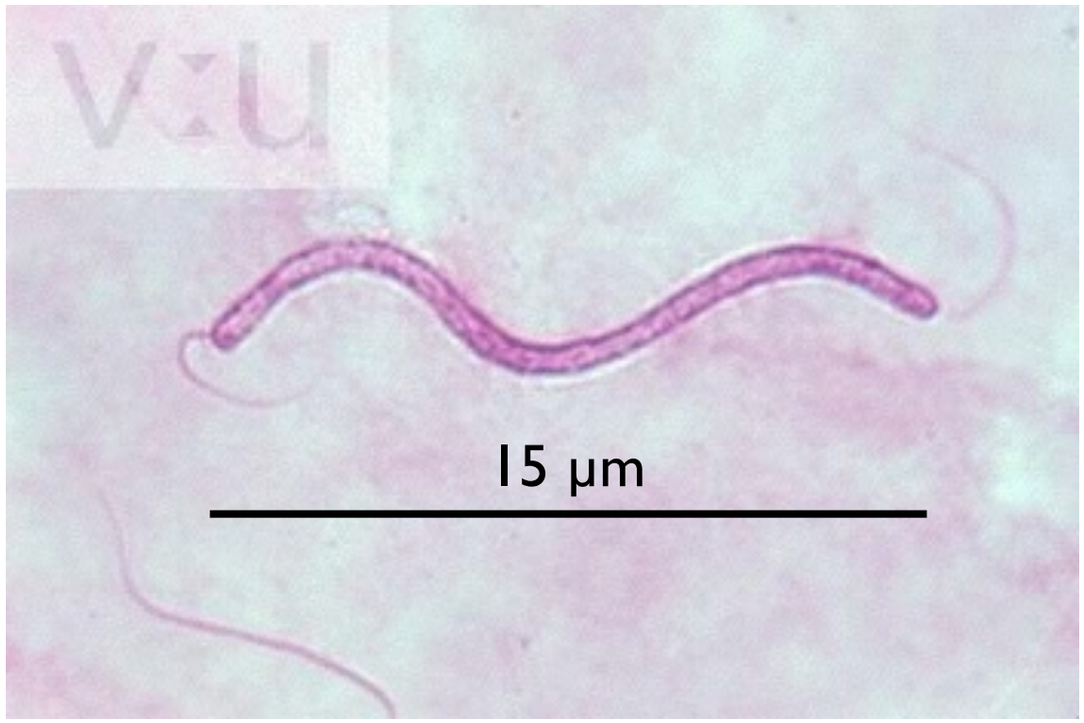
H. Berg, Ann. Rev. Biophys. **72**, 19 (2003)

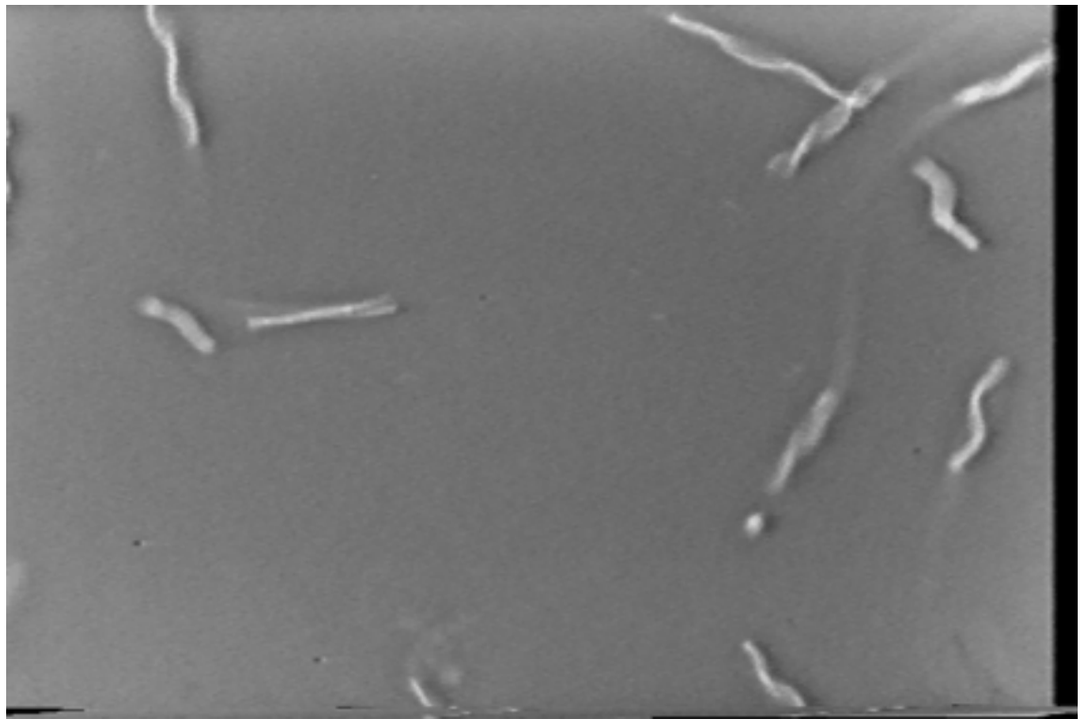
Changements de conformation des flagelles



Salmonella

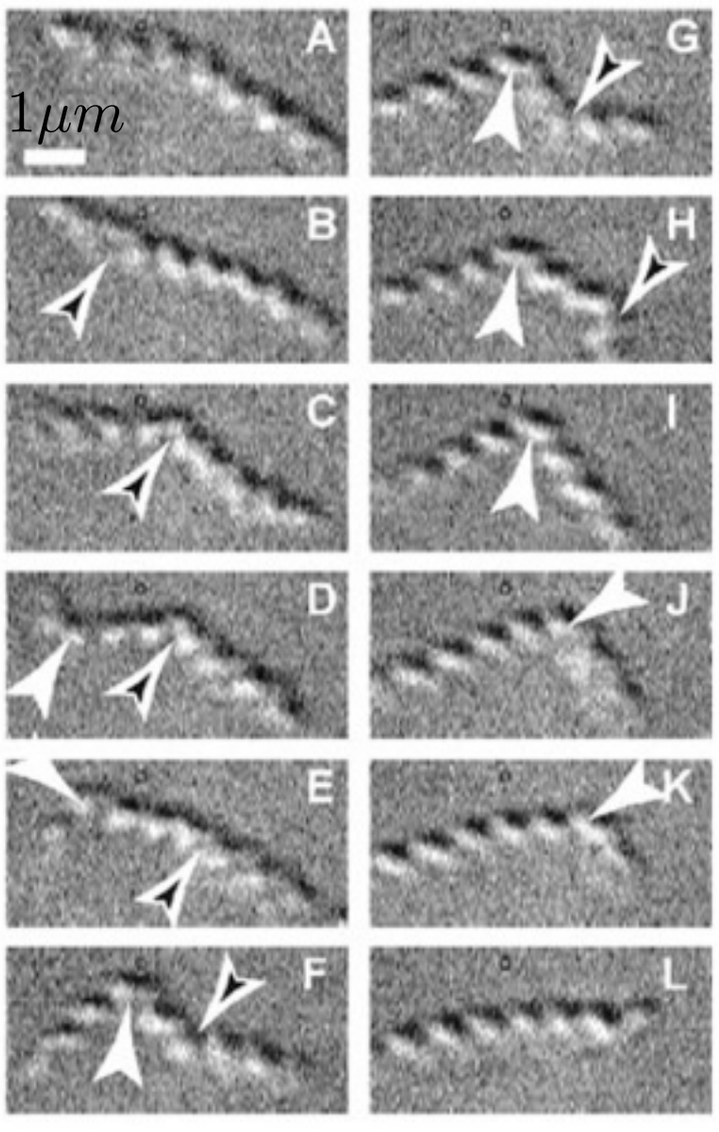
D. Bray & T. Duke, Ann. Rev. Biophys. Biomol. Struct. 33, 53 (2004)

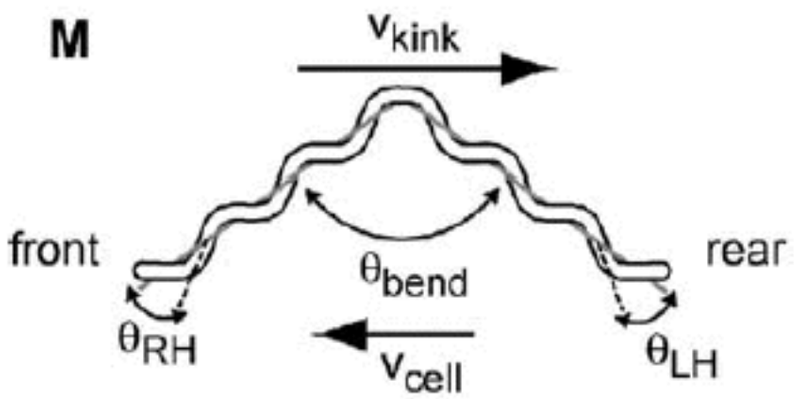




Spirillum volutans

Nage par changement d'hélicité

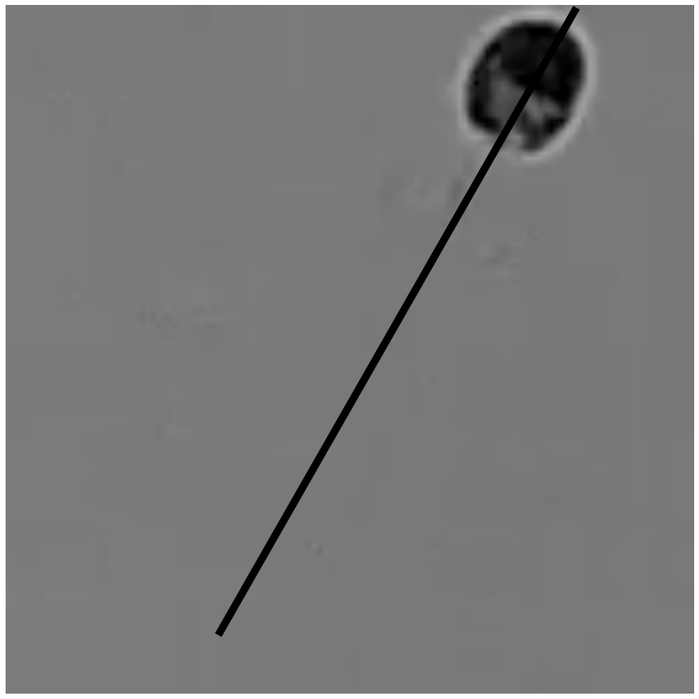


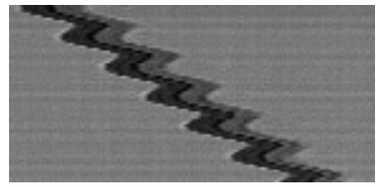


Spiroplasma

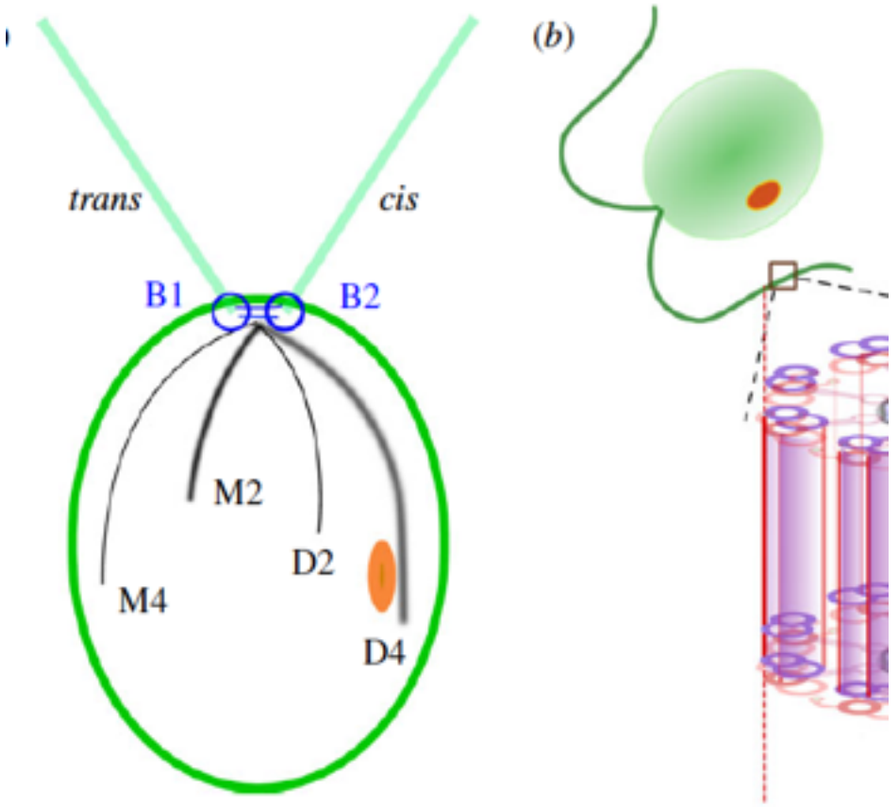
J. Shaevitz et al., Cell 2005

Une algue verte : Chlamydomonas

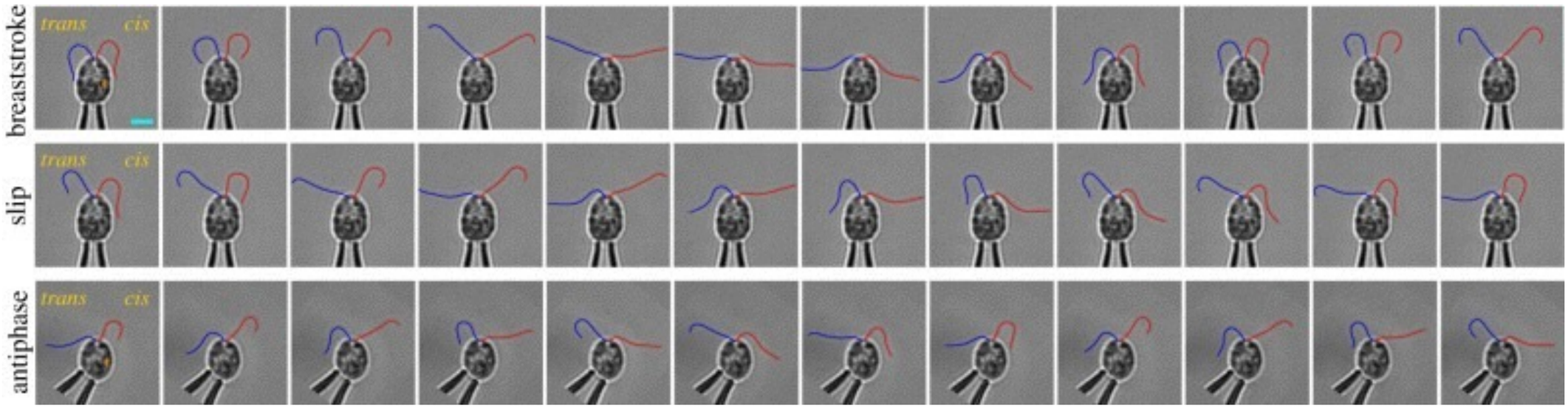




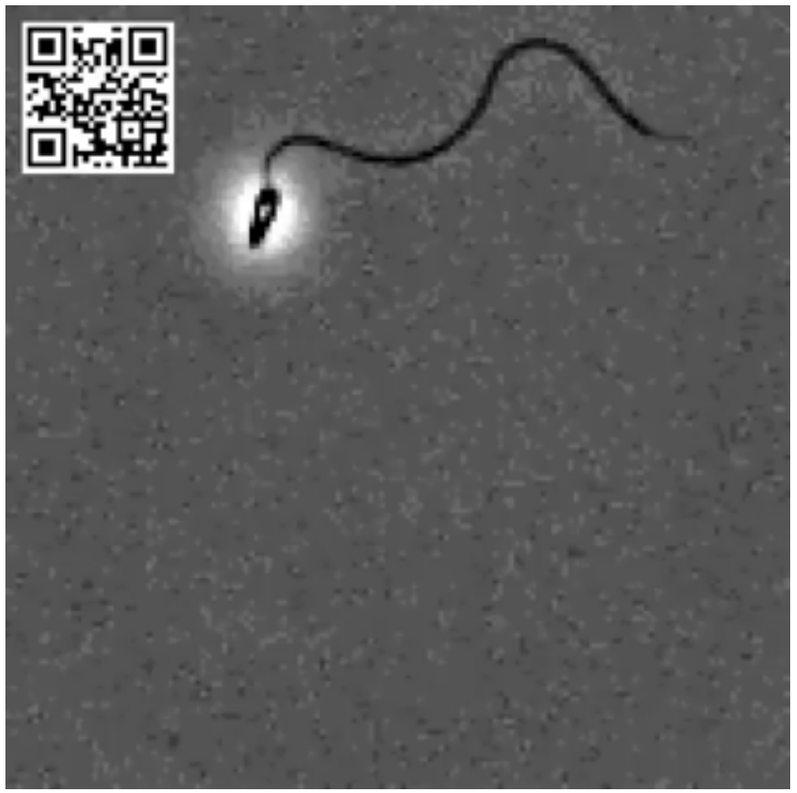
Différents modes de nage de Chlamydomonas



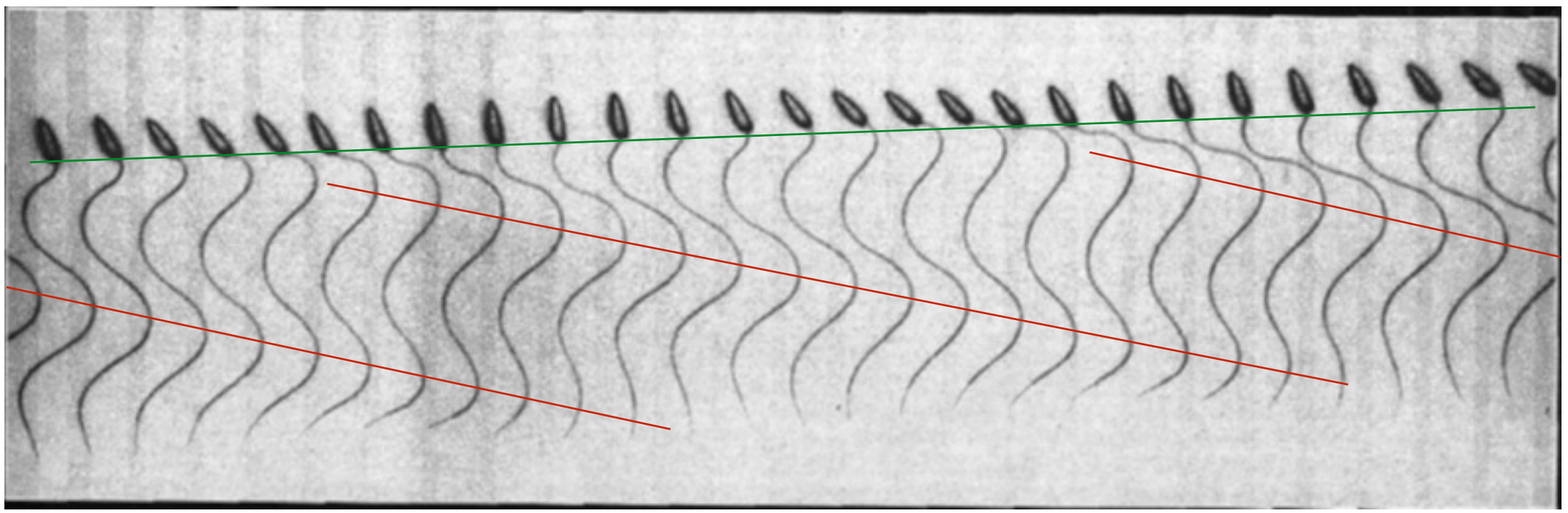
Wan KY, Leptos KC, Goldstein RE. 2014 Lag, lock, sync, slip: the many 'phases' of coupled flagella. J. R. Soc. Interface 11: 20131160.



Spermatozoïde : propulsion par onde progressive

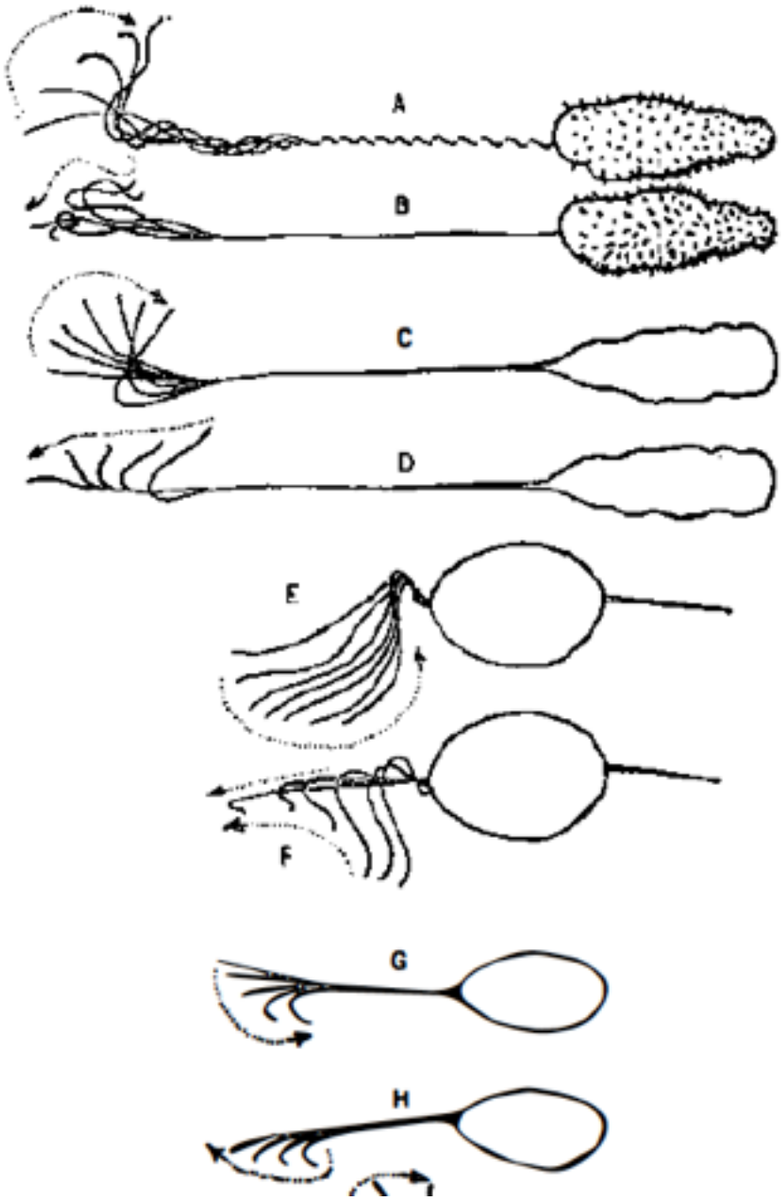


Vidéo J. Guasto



Chronophotographie C. Brokaw

Variations sur les flagelles



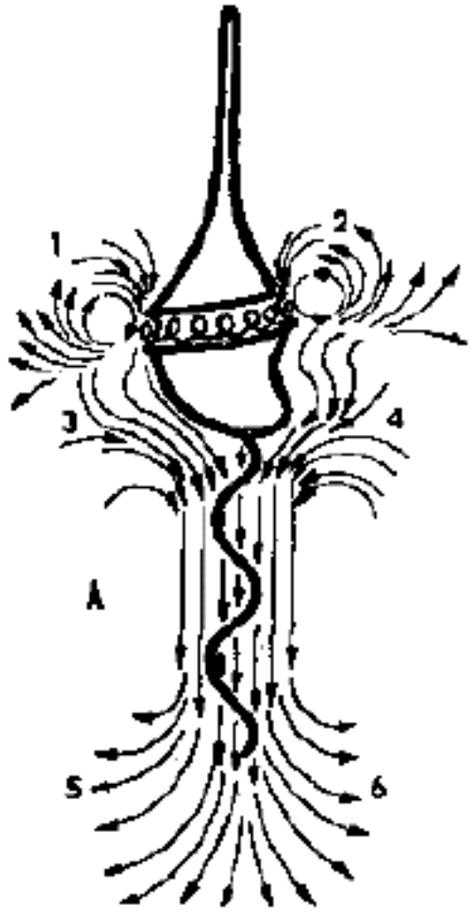
Mastigamoeba setosa

Peranema trichophorum

Entosiphon silcatum

Petalomas sp.

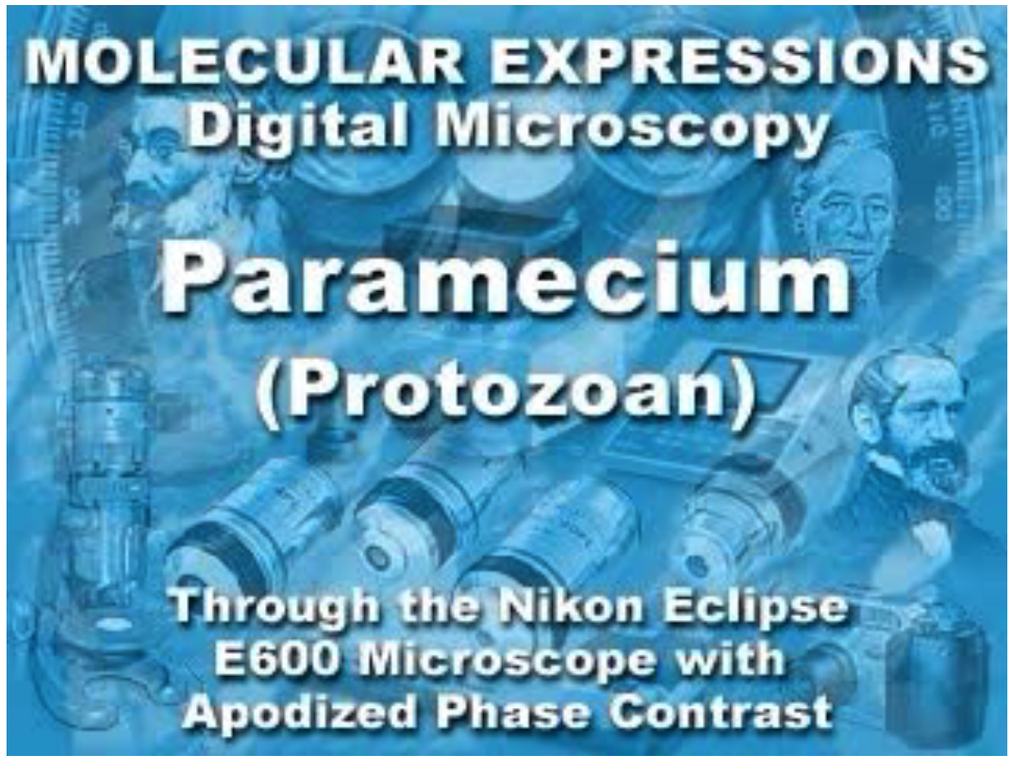
Ochromonas

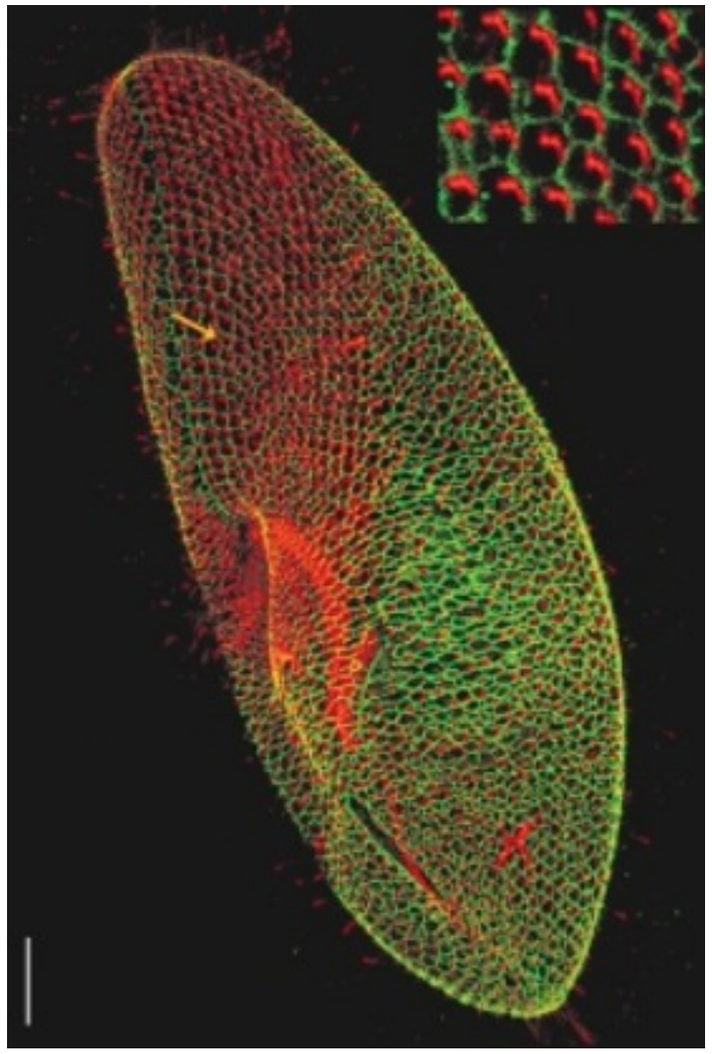


Ceratium

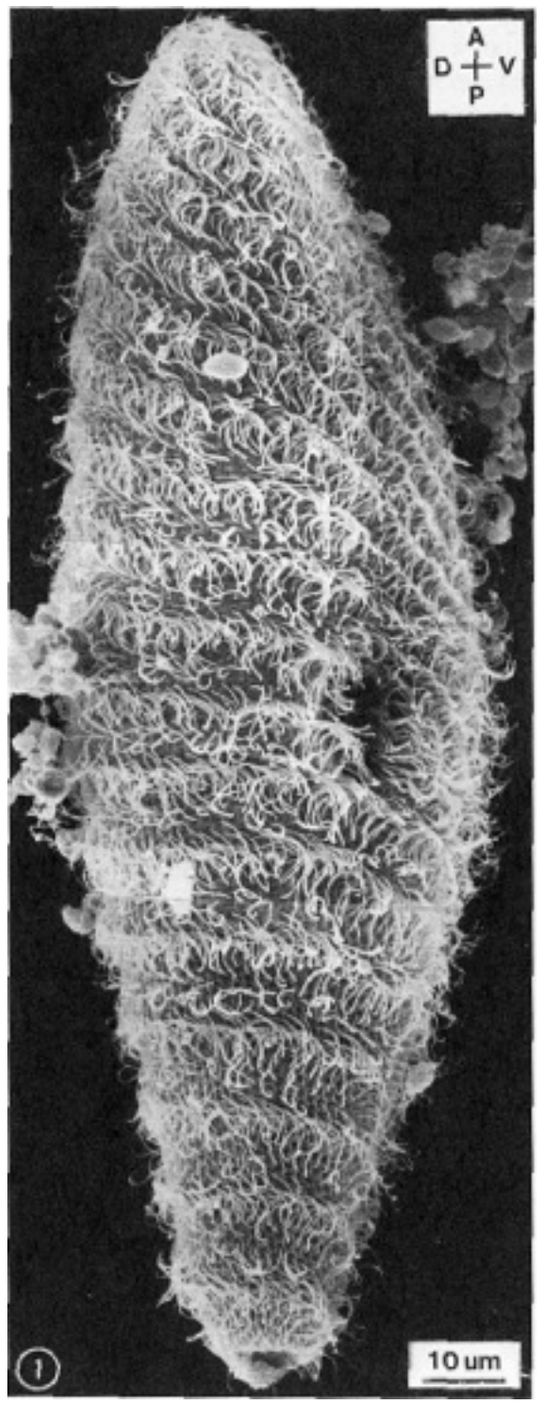
T. Jahn & J. Votta , *Locomotion of protozoa,*
Ann. Rev. Fluid Mech. 4 93 (1972)

Paramécies



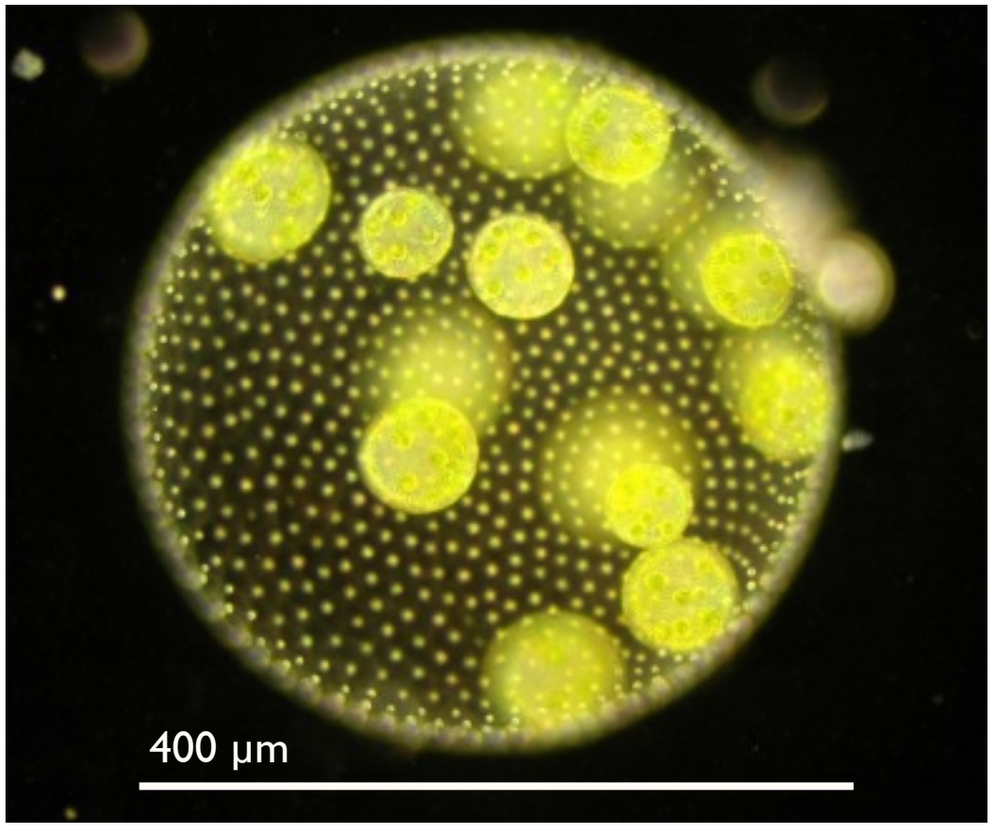


Réseau infraciliaire



Ondes métachronales

Volvocales



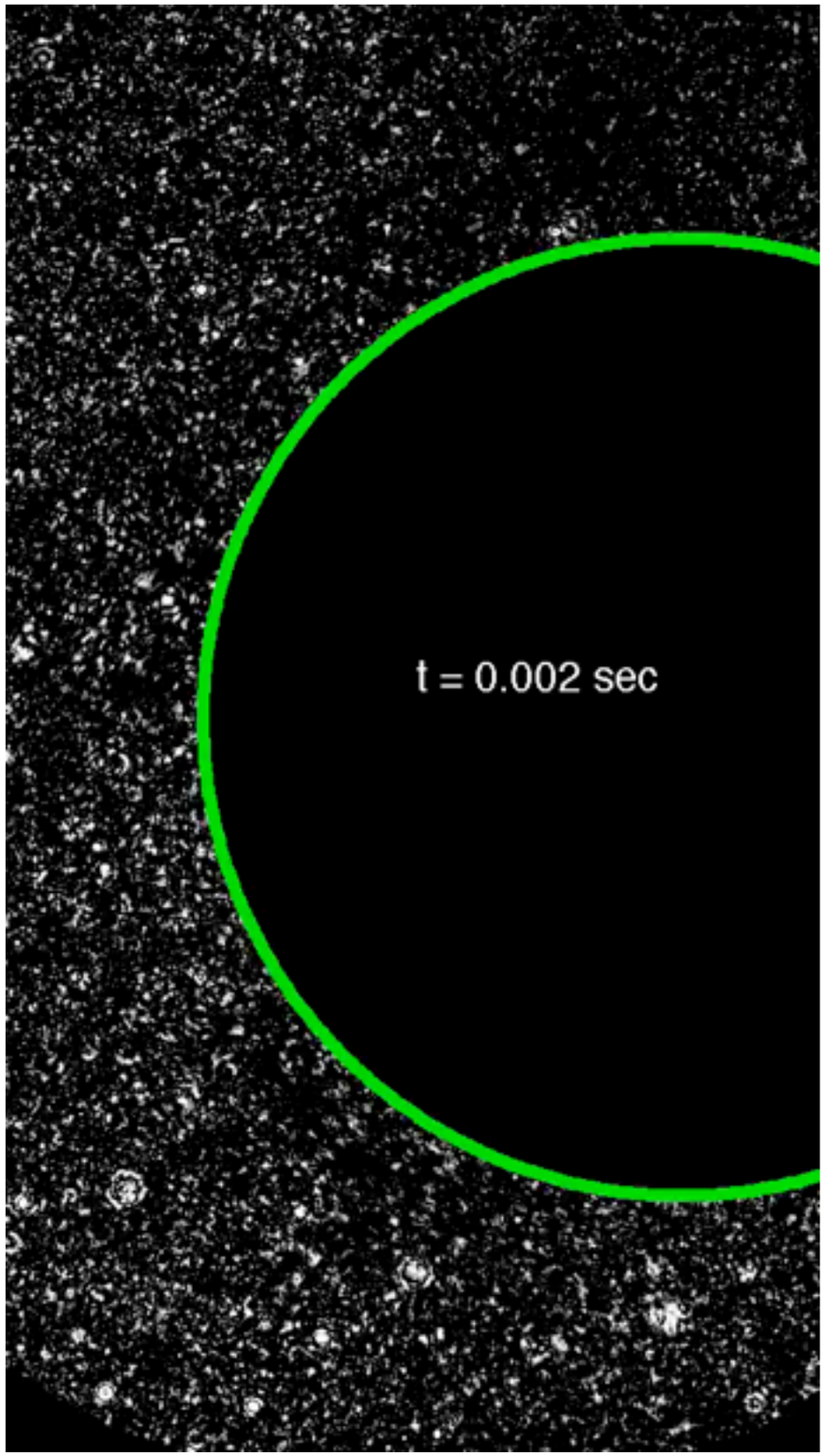
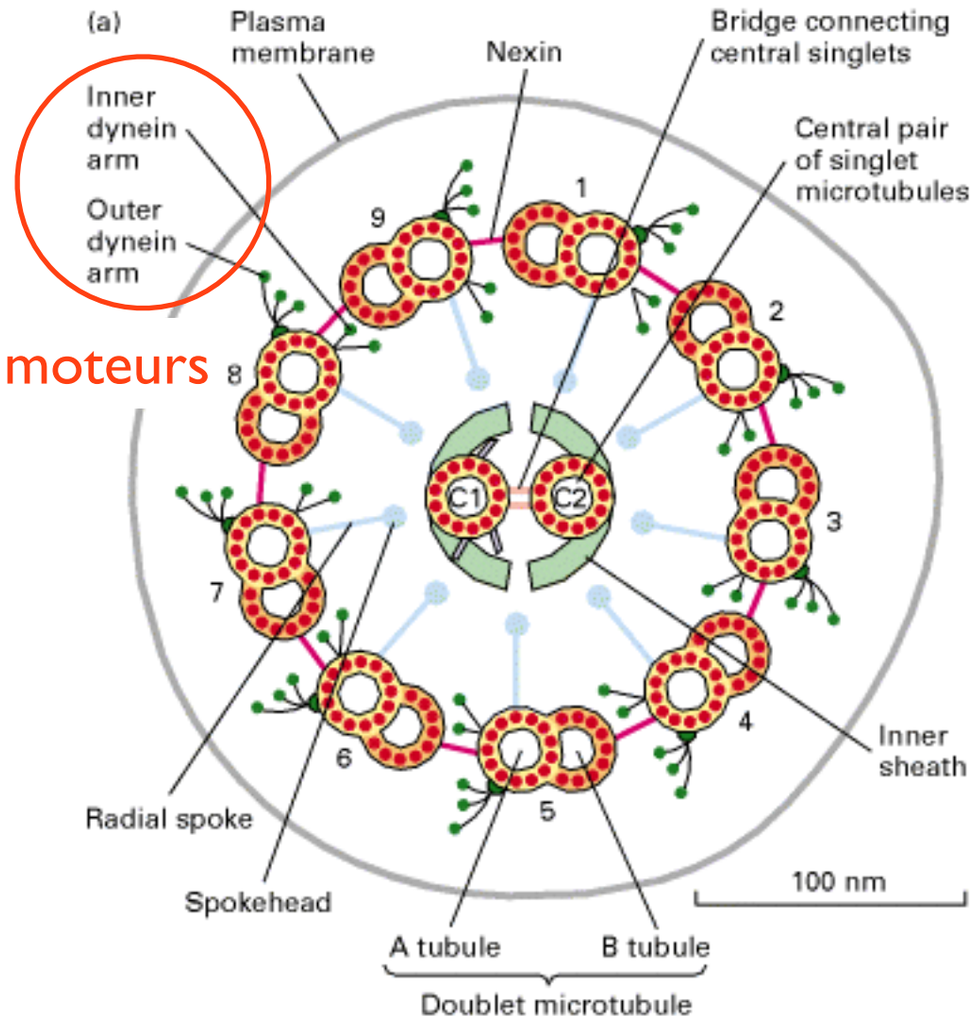
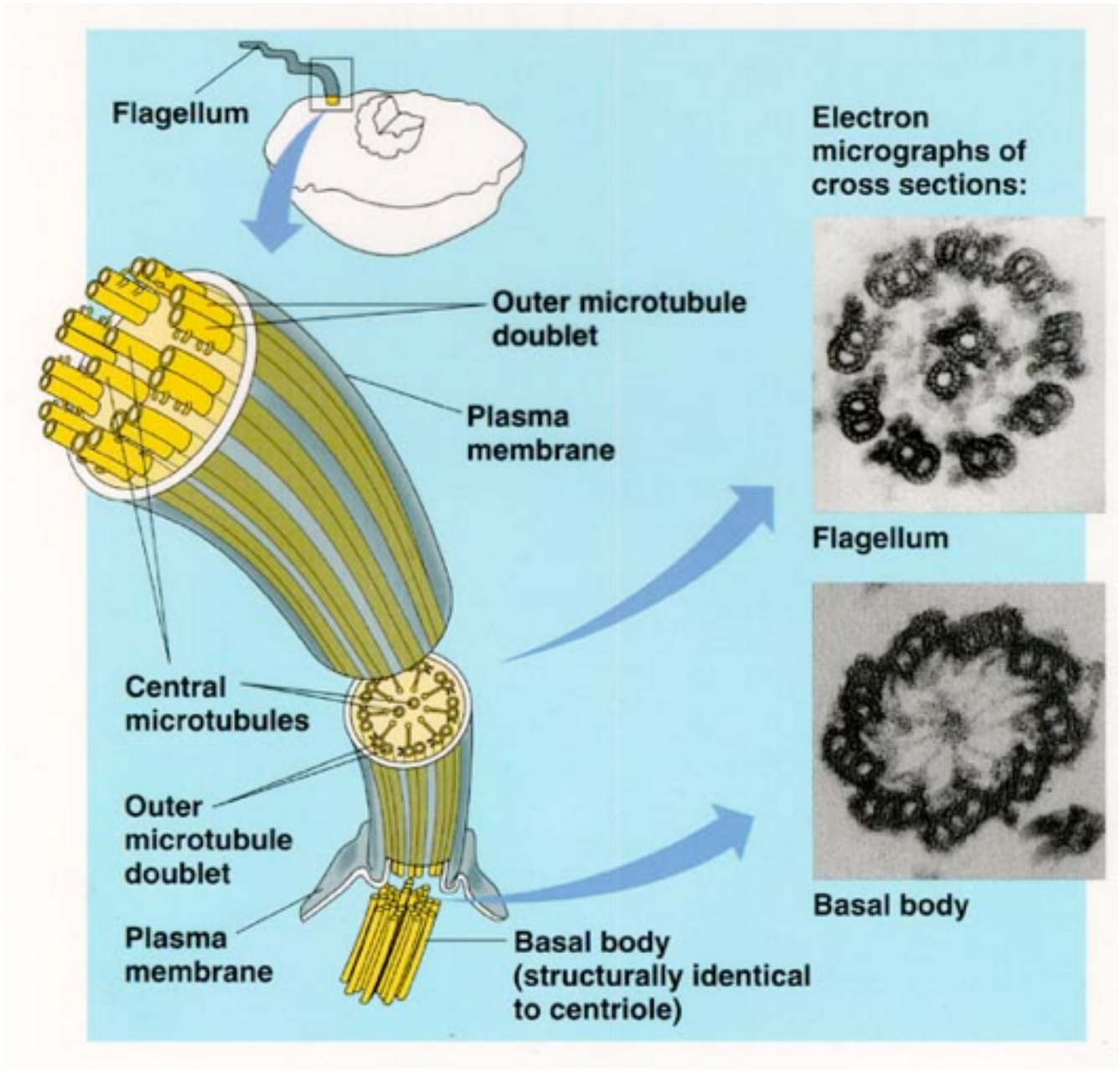


Image et vidéo : groupe de Ray Goldstein, DAMTP, Cambridge

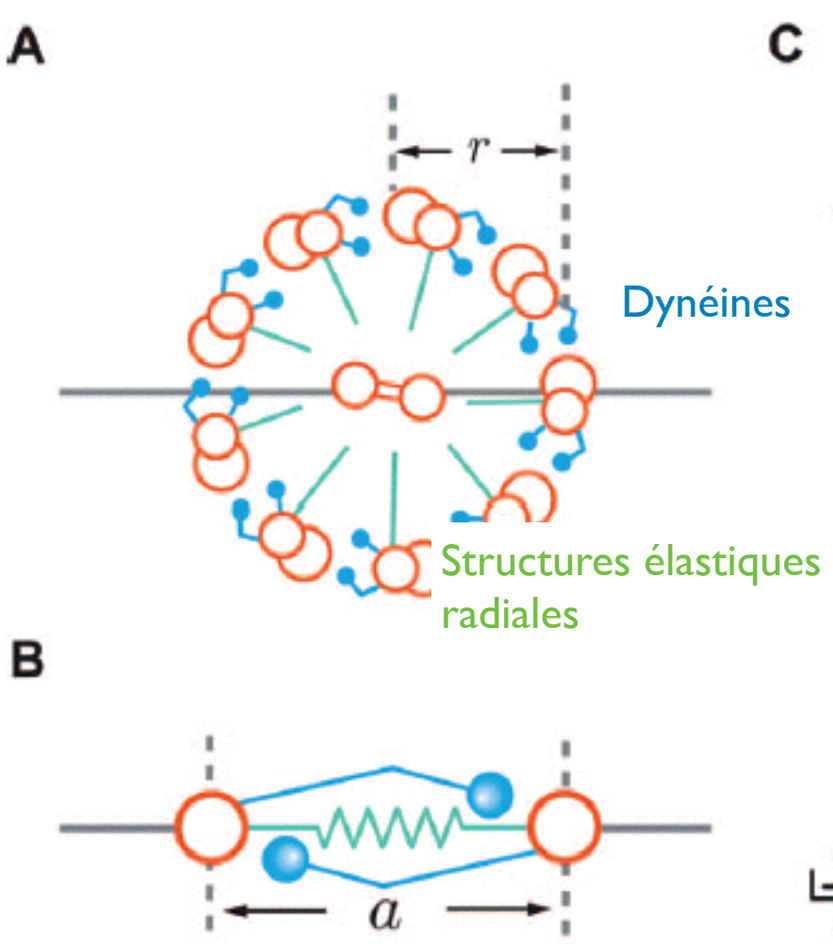
Structure des cils

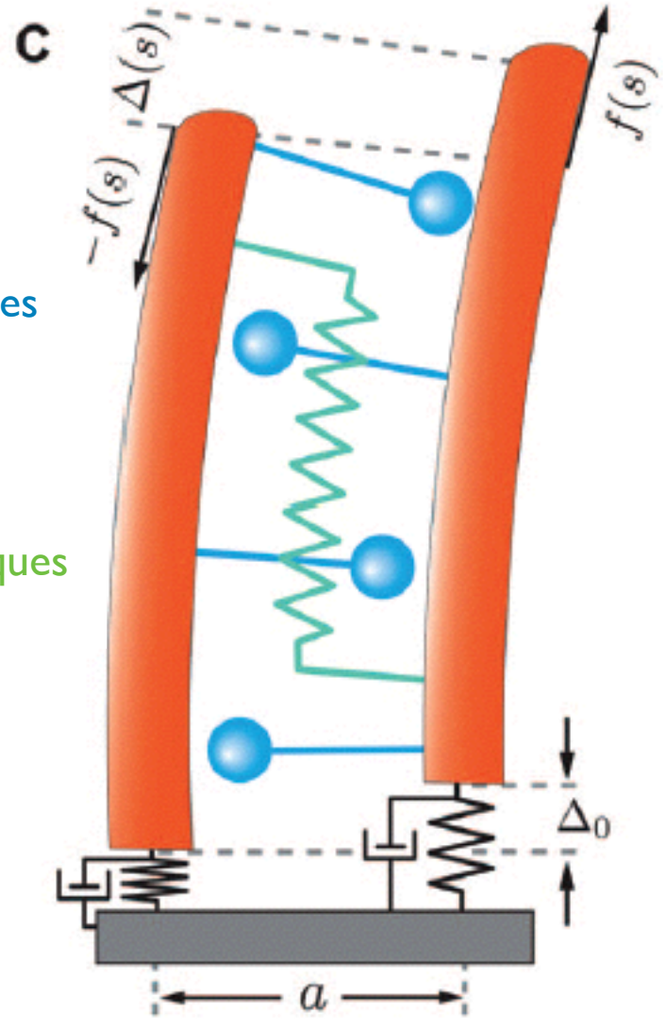


axoneme 9+2



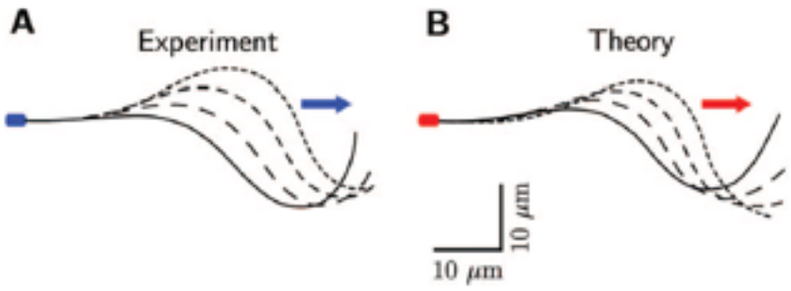
Motorisation des cils





Taux de détachement des dynéines dépendant de la force appliquée

Mode d'oscillation collective des moteur (Julicher & Prost 1997)



Reproduction du mouvement d'un flagelle de spermatozoïde

I. Riedel-Kruse et al., HFSP J. 1 192 (2008)