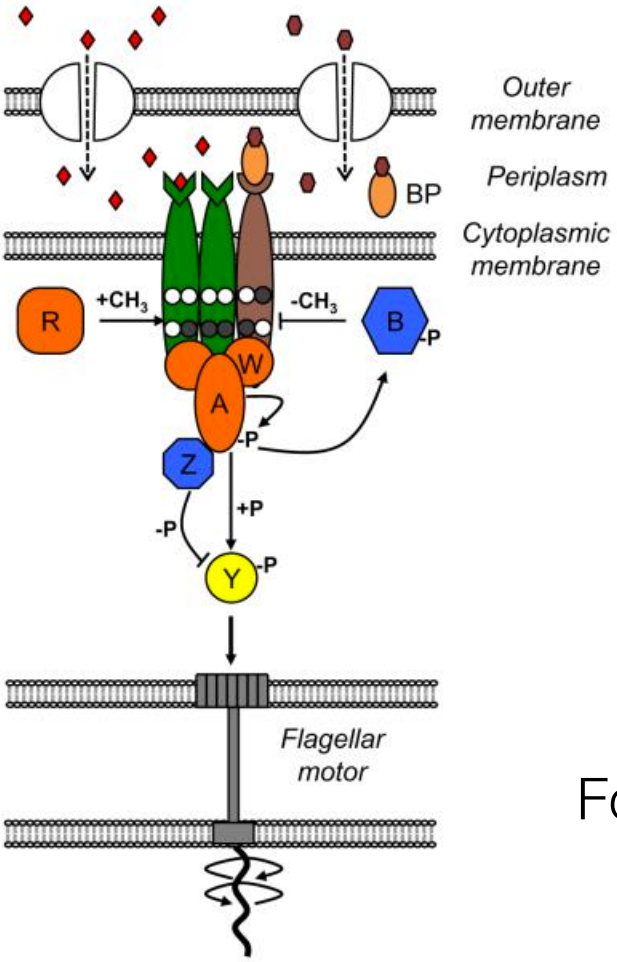
A most exquisite molecular machine

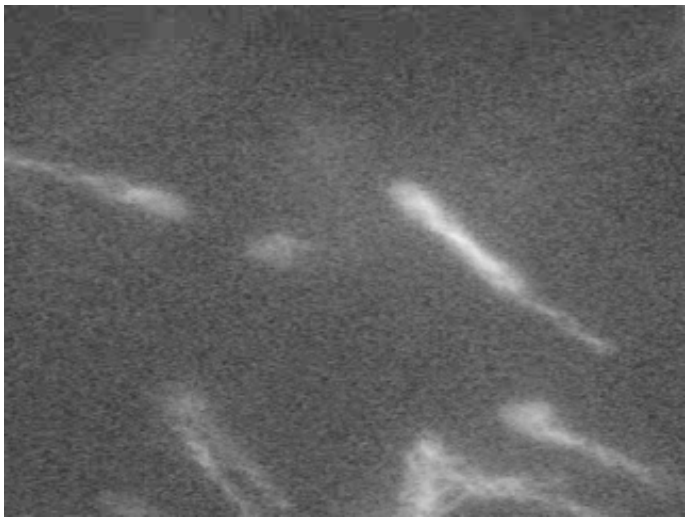
Berg Annual Review of Biophysics (2003)
Chevance and Hughes Nature Reviews Microbiology (2008)

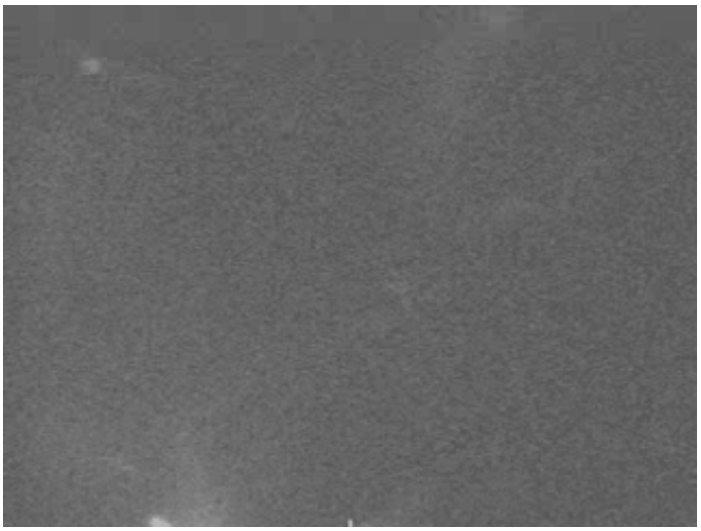
Chemotaxis network

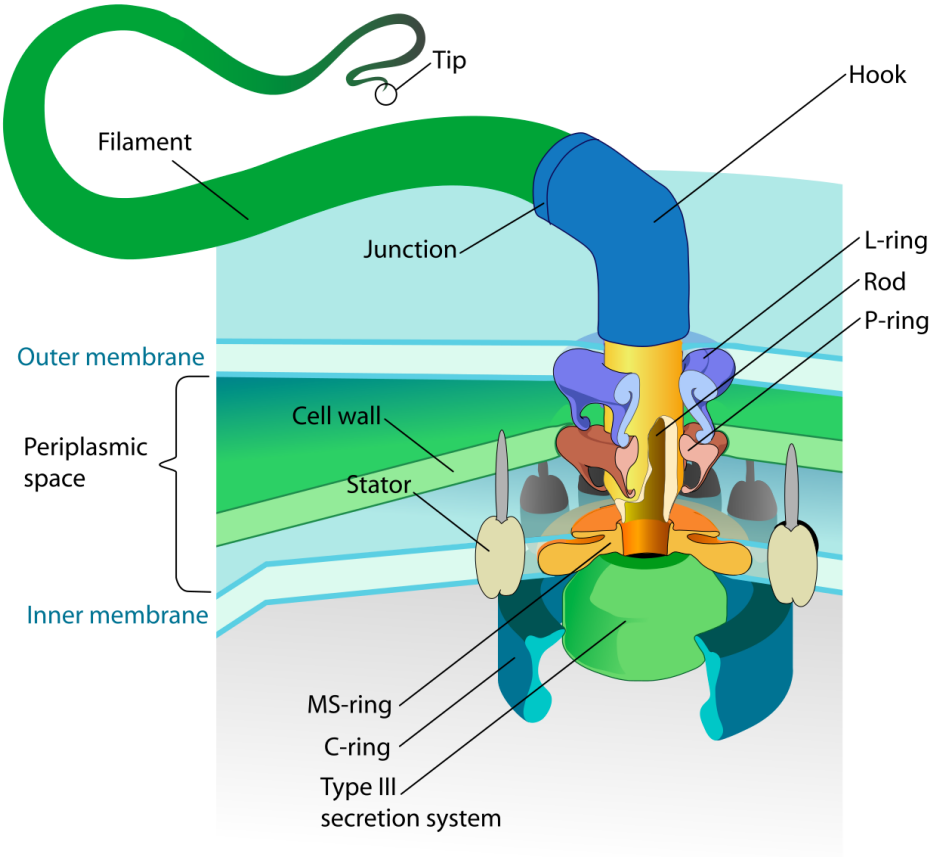


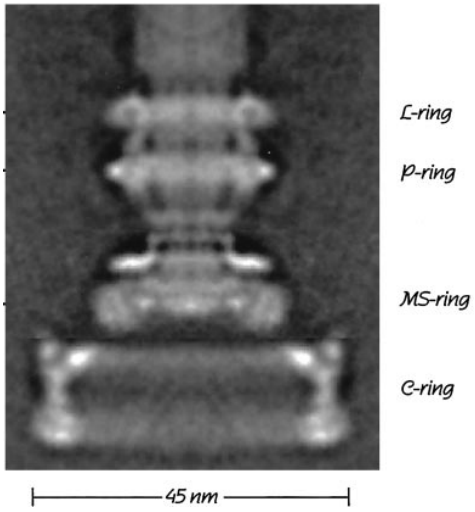
Focus today

Swimming

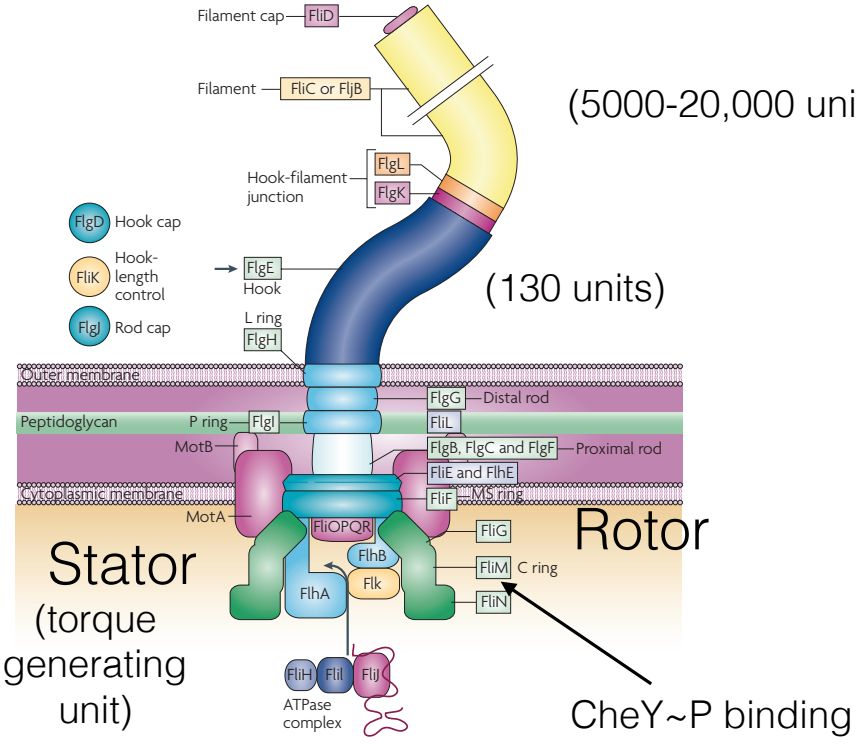


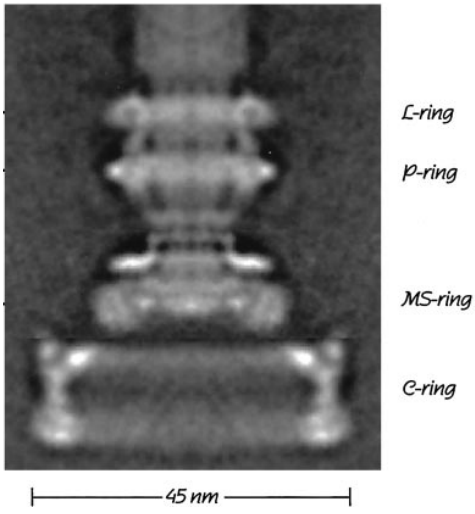



Tip
Hook
Filament
Junction
L-ring
Rod
P-ring
Outer membrane
Cell wall
Periplasmic space
Stator
Inner membrane
MS-ring
C-ring
Type III secretion system


L-ring
P-ring
MS-ring
C-ring
45 nm

Made of 20 parts! (more for assembly)
~50 nm in width
~length 5,000-10,000 nM





Questions

1. What is the structure of the motor?
2. How is the motor assembled?
3. What is power source?
4. How does it generate torque?
5. How do we think about torque-speed curves and “duty ratios”?

What is the structure of the motor?

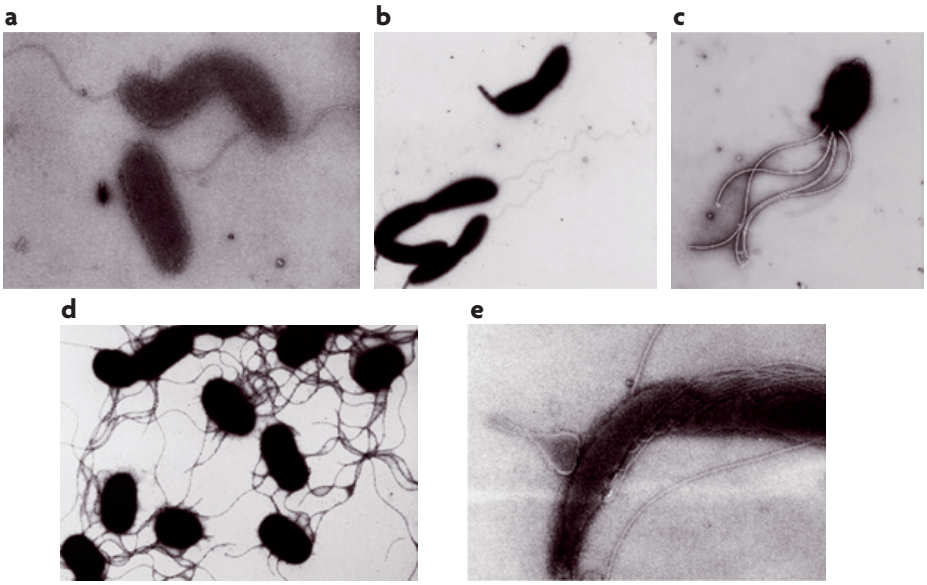
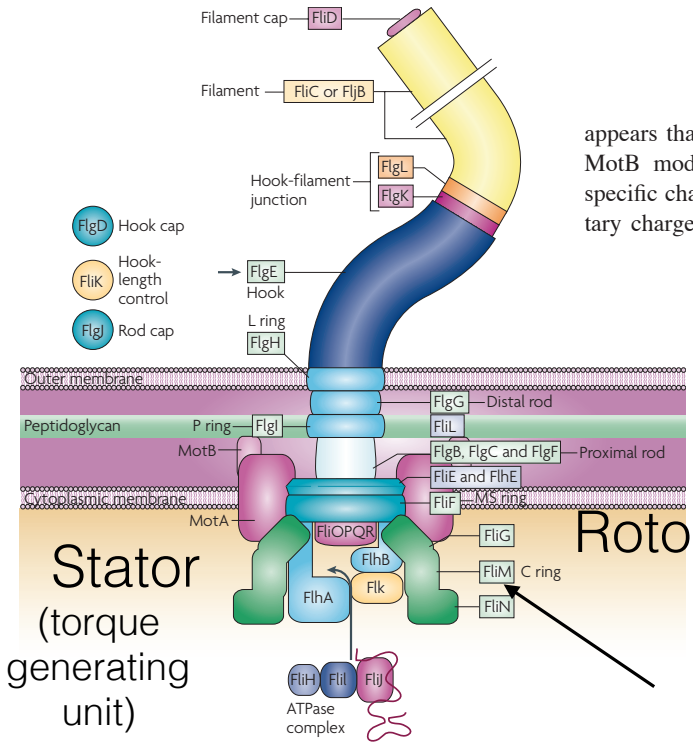
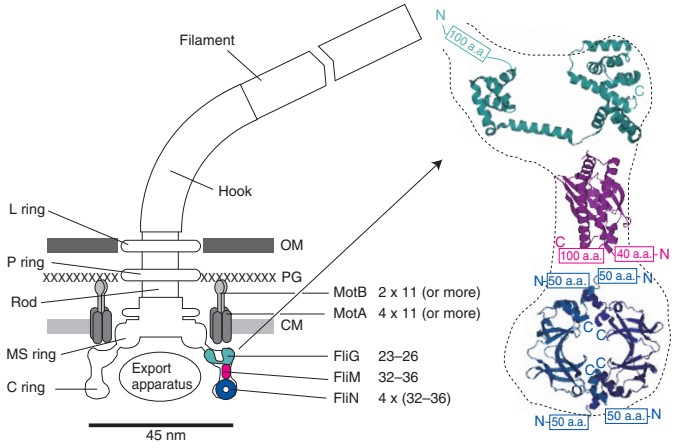


Figure 1 | Electron micrograph images illustrating the different types of flagellar arrangement in bacteria. A single flagellum can be present at one end of the cell (monotrichous); for example, in *Vibrio cholerae*, *Pseudomonas aeruginosa*, *Idiomarina loihiensis* (**a**) and *Caulobacter crescentus* (**b**). Many bacteria have numerous flagella and, if these are co-located on the surface of the cell to form a tuft, the bacterium is lophotrichous; for example, *Vibrio fischeri* (**c**) and *Spirillum* spp. Peritrichous flagella are distributed all over the cell; for example *Escherichia coli* and *Salmonella enterica* serovar Typhimurium (**d**)**.** For spirochaetes, such as species of *Borrelia* (**e**), *Treponema* and *Leptospira*, a specialized set of flagella are located in the periplasmic space, the rotation of which causes the entire bacterium to move forward in a corkscrew-like motion. Images kindly provided by S.-I. Aizawa, Prefectural University of Hiroshima, Japan.

How is torque transmitted from stator to rotor?



appears that torque is generated as protonation and deprotonation of Asp32 of MotB modulates the conformation of MotA, changing the interaction of a specific charged region in the cytoplasmic domain of MotA with a complementary charged region in the C-terminal domain of FliG. To see how this might



Hook filaments are flexible

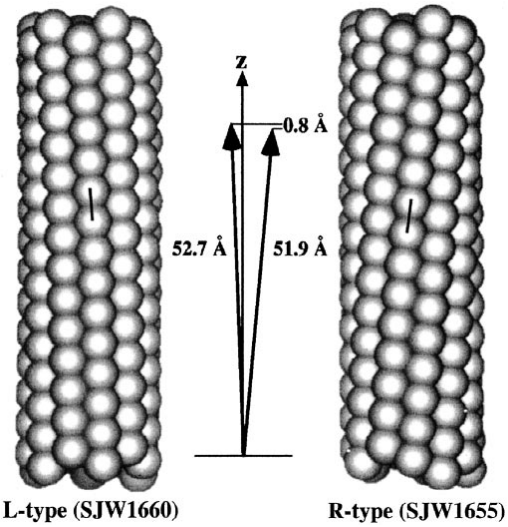
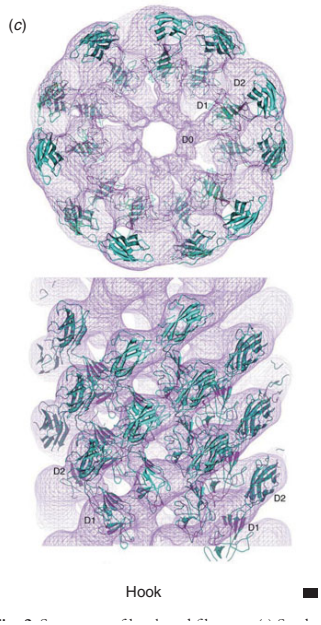


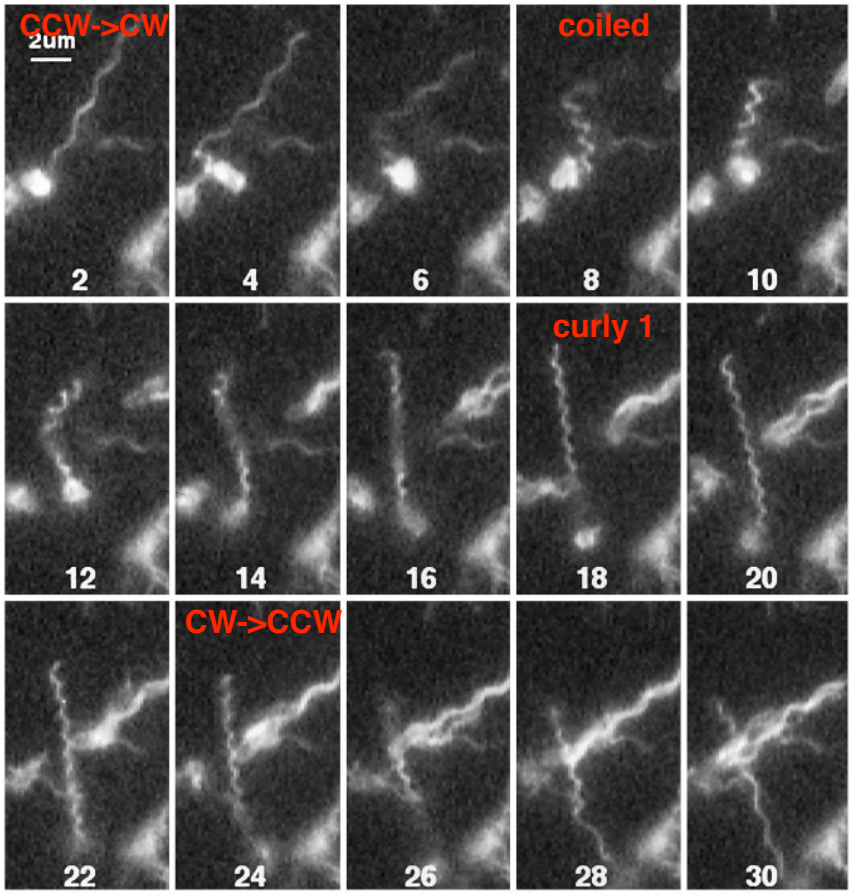
Figure 2 The surface lattice of L- and R-type straight flagellar filaments. The spacing between flagellin subunits along an 11-start helix (a protofilament) of the R-type is 0.07 nm less than between corresponding subunits of the L-type. L and R refer to the handedness of the filament twist. The SJW numbers designate particular bacterial strains. The distances are measured at a radius of 4.5 nm and are shown magnified in the middle of the drawing. (From Reference 19, Figure 19.)



X-ray/EM

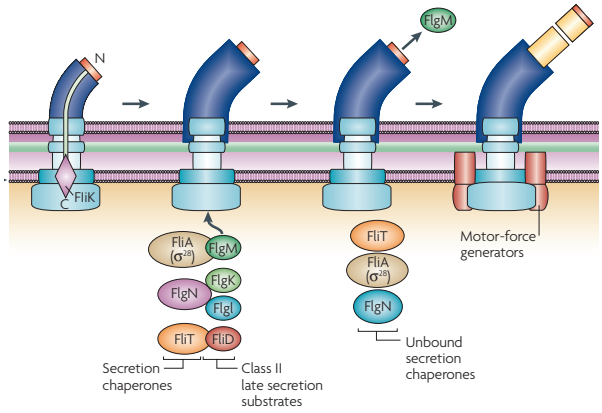
- Two different global packings
- Energy minimization: short w short/ and long with long
- Hook flexibility comes from switching between these configurations

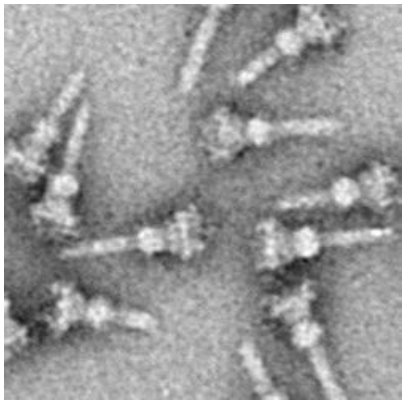
Filaments switch configurations

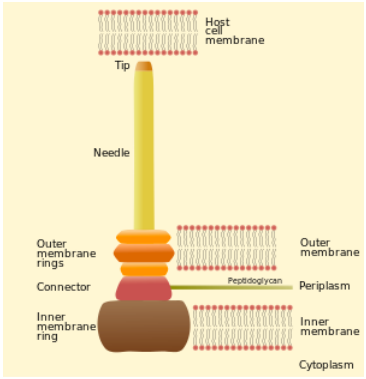


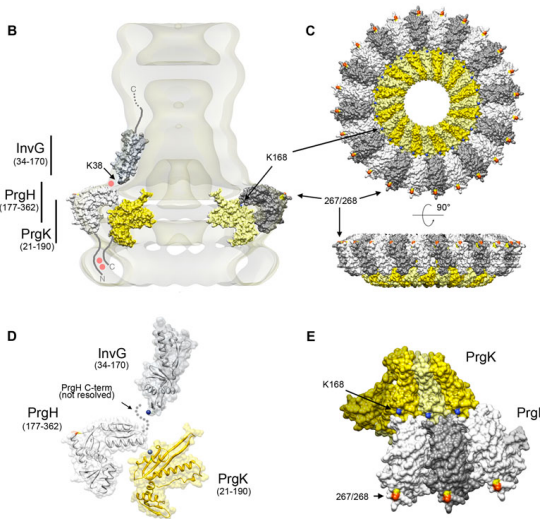
How is motor and flagella assembled?

Type III Secretion System

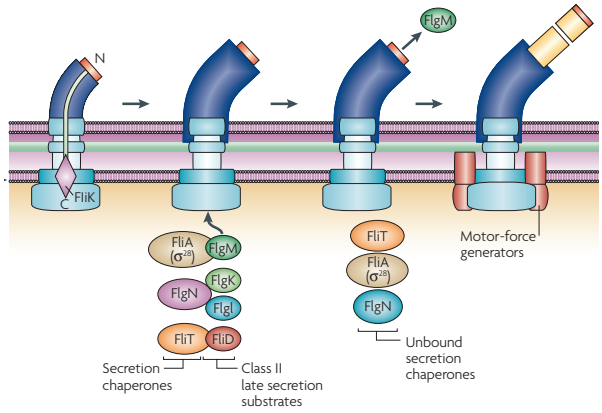


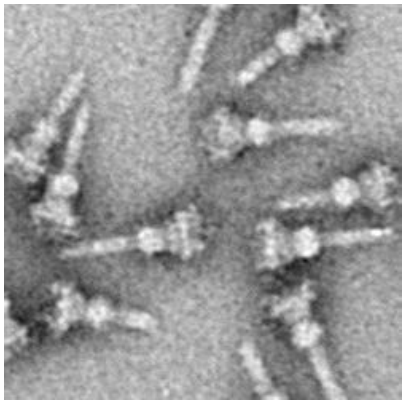


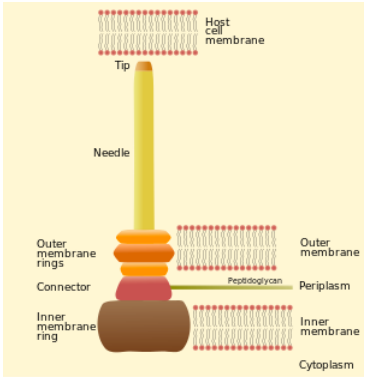


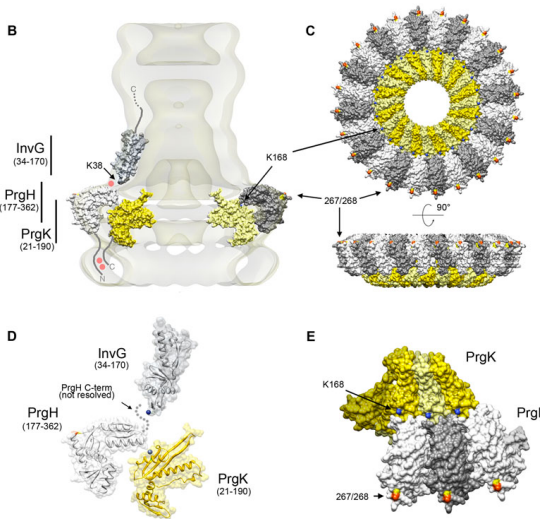


Type III Secretion System









Some mysteries

1. How does cell know to transition from hook to flagella?

2. How does it control/measure length?

What powers the motor?

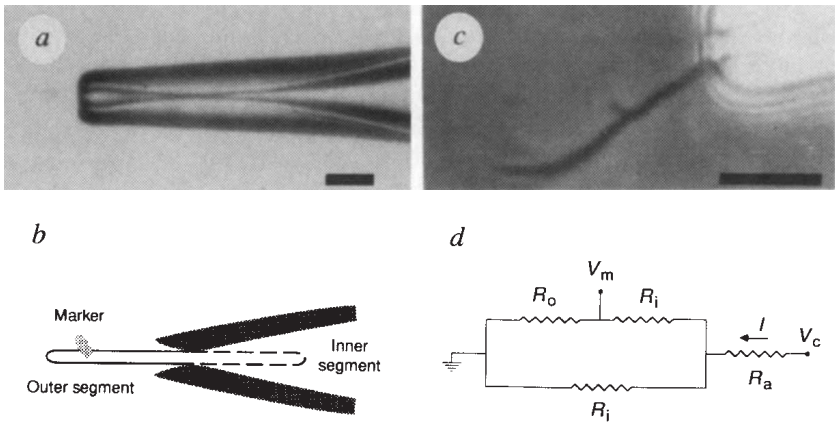
Introduction to Nerst equation,

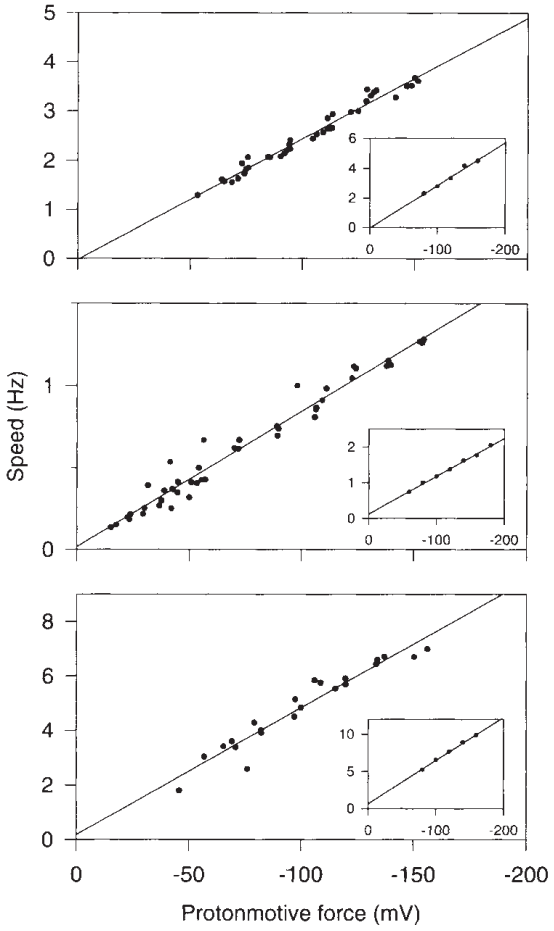
electroosmotic effects, ion pumping

Powering the flagellar motor of *Escherichia coli* with an external voltage source

David C. Fung* & Howard C. Berg

NATURE · VOL 375 · 29 JUNE 1995



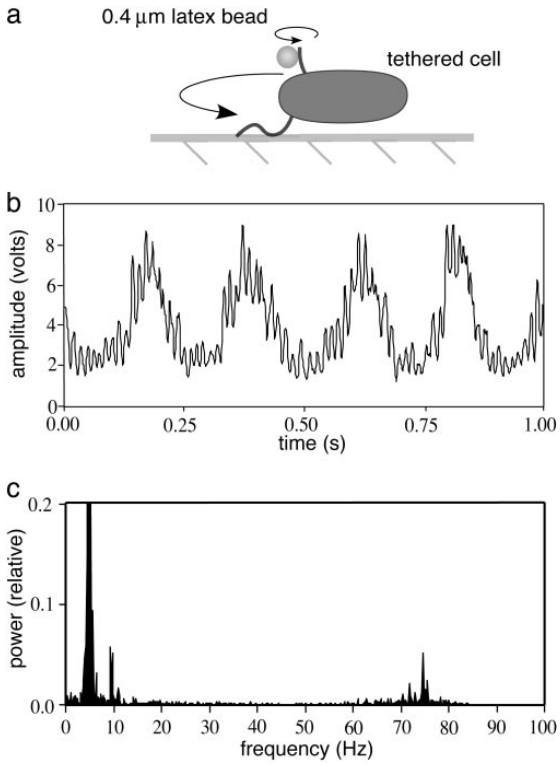


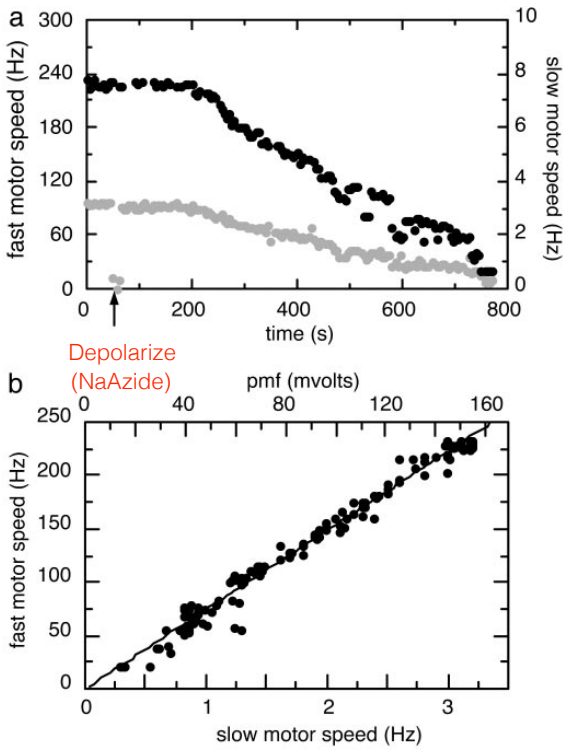
The speed of the flagellar rotary motor of *Escherichia coli* varies linearly with protonmotive force

Christopher V. Gabel and Howard C. Berg*

Departments of Molecular and Cellular Biology and of Physics, Harvard University, Cambridge, MA 02138; and Rowland Institute at Harvard, Cambridge, MA 02142

8748–8751 | PNAS | **July 22, 2003** | vol. 100 | no. 15





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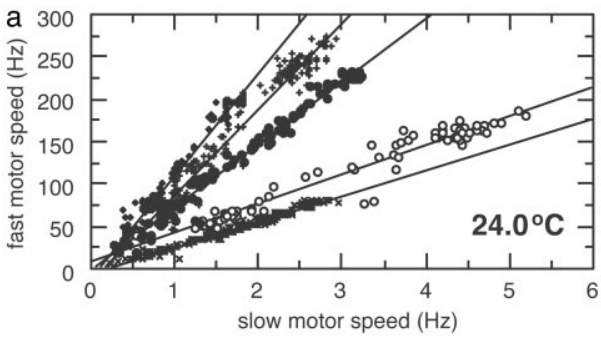

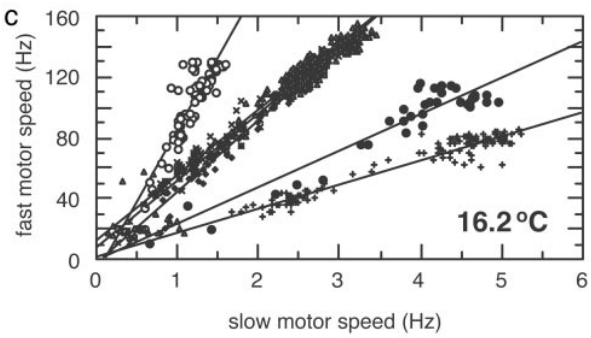

Why are slopes different for different cells?

The speed of the flagellar rotary motor of *Escherichia coli* varies linearly with protonmotive force

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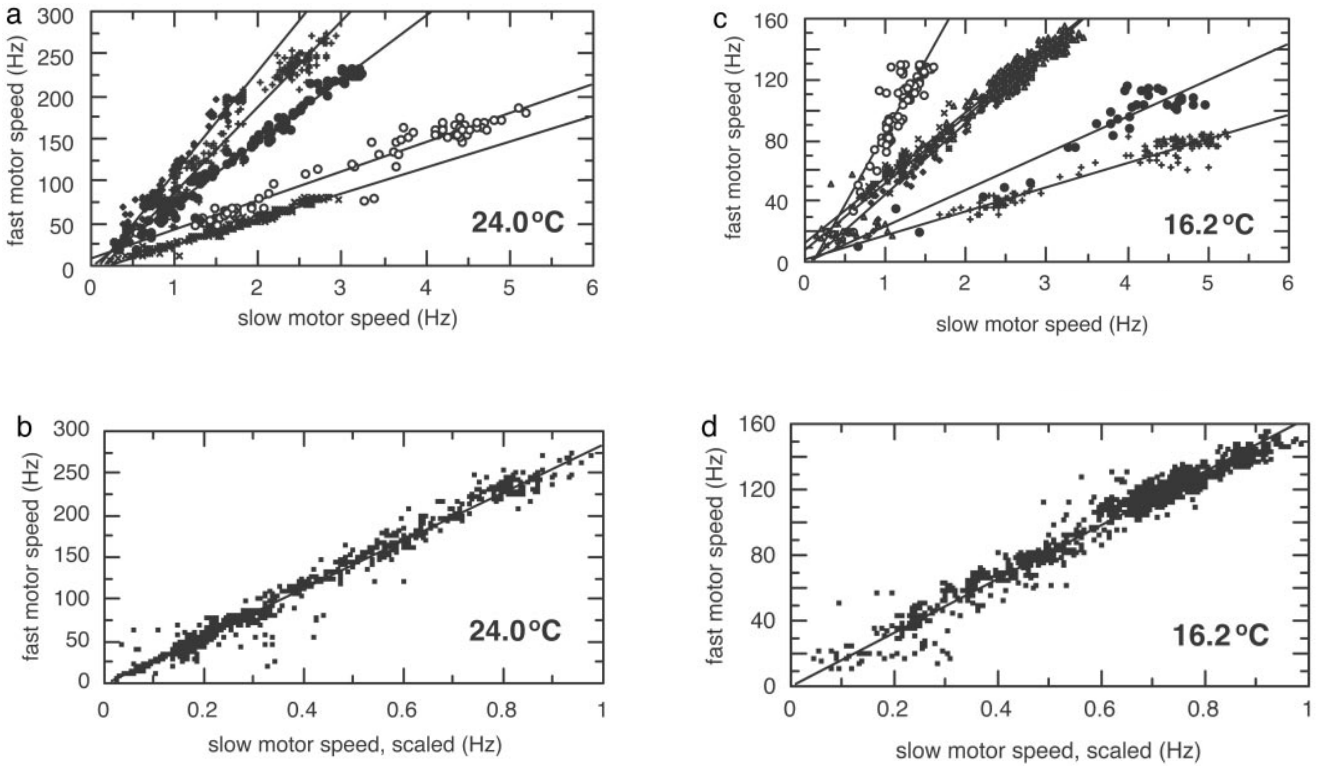
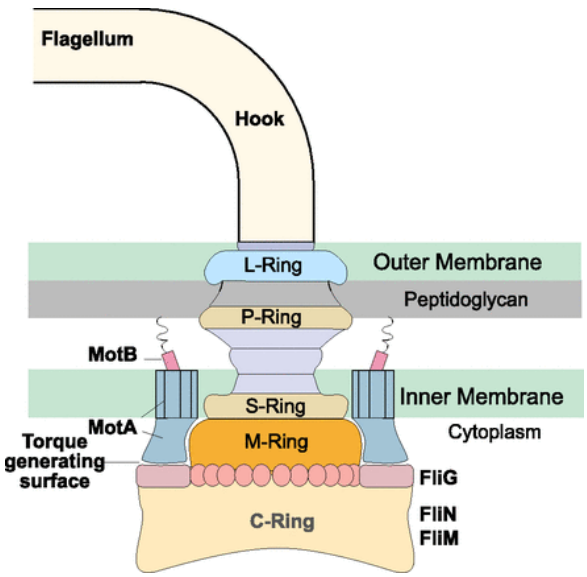
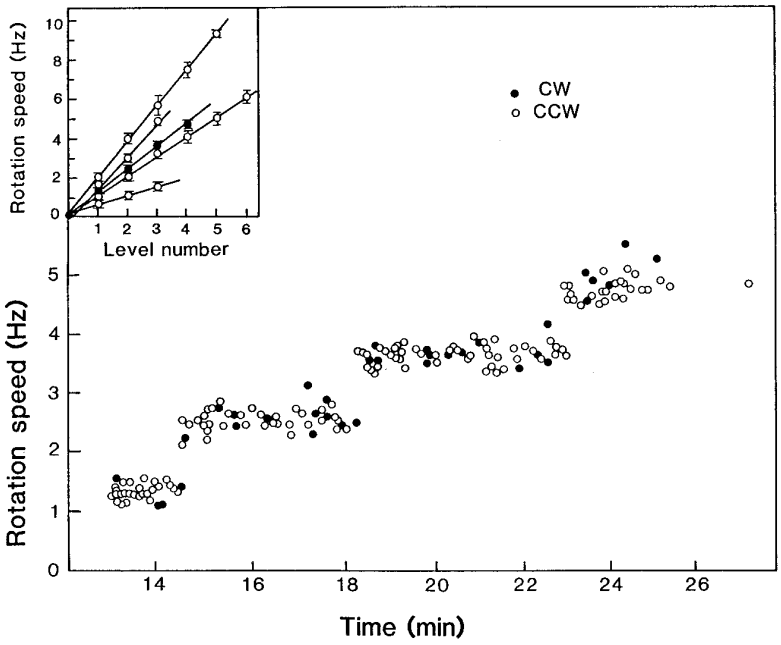


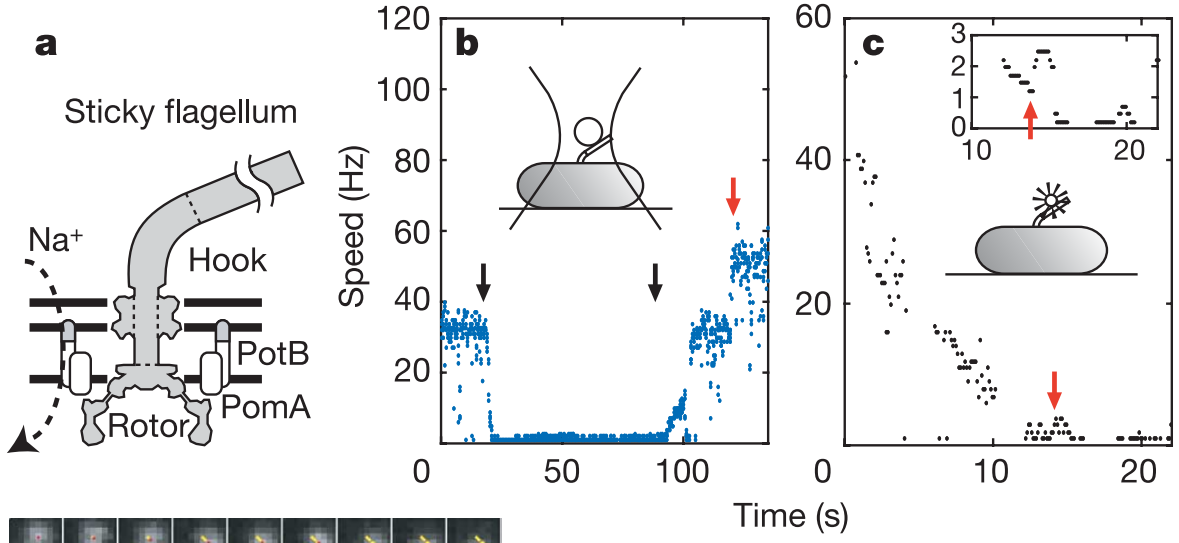
How does the motor generate torque?

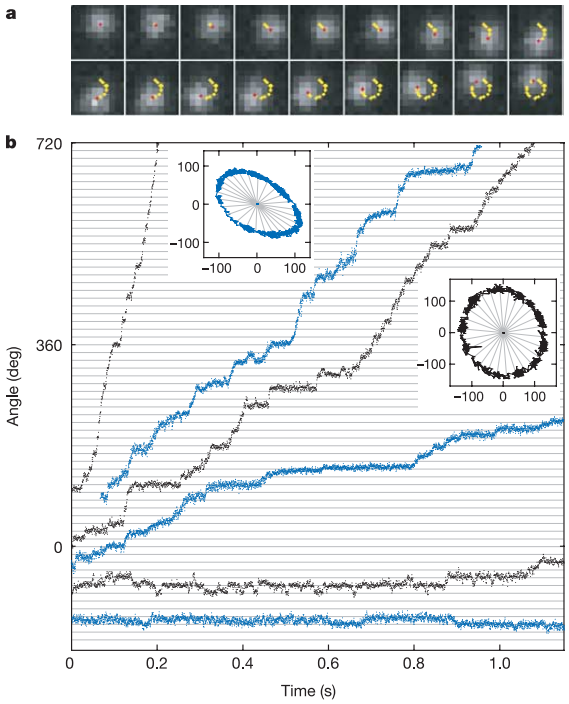
How much torque are we talking about?

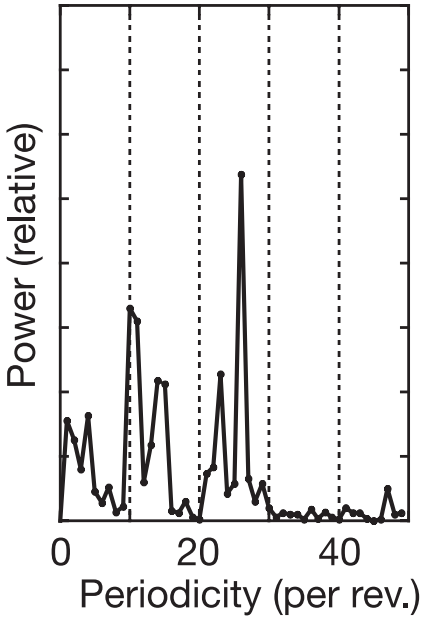
2500-4500 pN-nM


Flagellum
Hook
L-Ring
Outer Membrane
Peptidoglycan
P-Ring
MotB
S-Ring
Inner Membrane
MotA
Torque generating surface
M-Ring
Cytoplasm
FliG
FliN
FliM
C-Ring


Rotation speed (Hz)
Level number
CW
CCW
Rotation speed (Hz)
Time (min)







26 steps/rev

FliG subunits

11 steps/rev

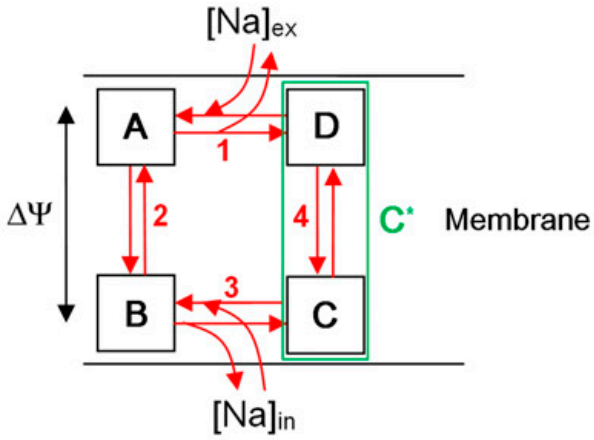
Hook

$$\frac{dP_A}{dt} = k_{BA}\cdot P_B + k_{DA}\cdot P_D - \left(k_{AD} + k_{AB}\right)\cdot P_A = 0$$

$$\frac{dP_B}{dt} = k_{AB}\cdot P_A + k_{CB}\cdot P_C - \left(k_{BA} + k_{BC}\right)\cdot P_B = 0$$

$$\frac{dP_C}{dt} = k_{BC}\cdot P_B + k_{DC}\cdot P_D - \left(k_{CB} + k_{CD}\right)\cdot P_C = 0$$

$$\frac{dP_D}{dt} = k_{AD}\cdot P_A + k_{CD}\cdot P_C - \left(k_{DA} + k_{DC}\right)\cdot P_D = 0.$$



$$k_{DA} = k_1 c_{out}\exp\left(\frac{\lambda_1\alpha_1 U - \mu_1\beta_1 W + \nu_1\Delta G_1^0}{k_B T}\right),$$

$$k_{AD} = k_1\exp\left(\frac{(\lambda_1-1)\alpha_1 U - (\mu_1-1)\beta_1 W + (\nu_1-1)\Delta G_1^0}{k_B T}\right)$$

$$k_{AB} = k_2\exp\left(\frac{\lambda_2\alpha_2 U - \mu_2\beta_2 W + \nu_2\Delta G_2^0}{k_B T}\right),$$

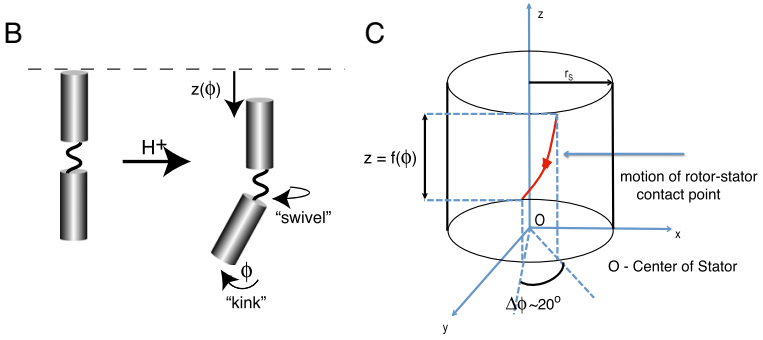
$$k_{BA} = k_2\exp\left(\frac{(\lambda_2-1)\alpha_2 U - (\mu_2-1)\beta_2 W + (\nu_2-1)\Delta G_2^0}{k_B T}\right)$$

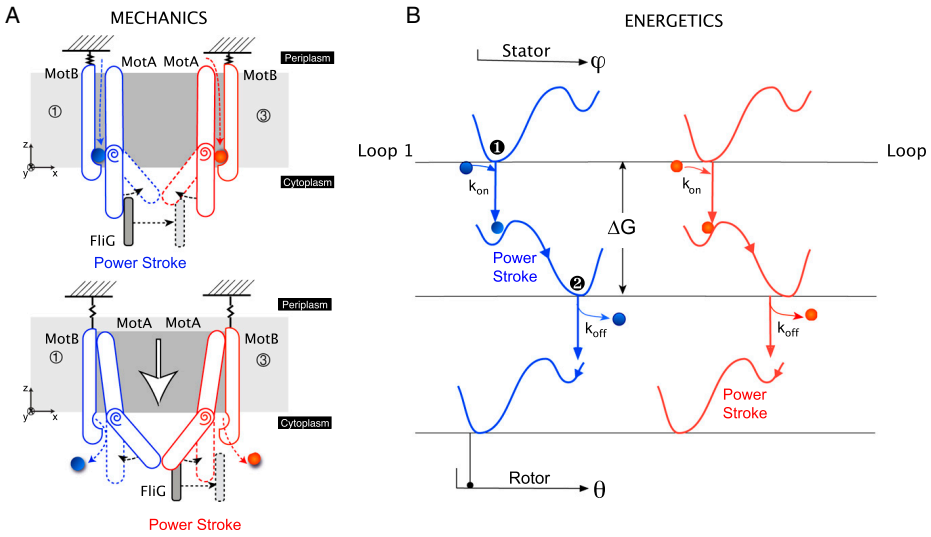
$$k_{BC} = k_3\exp\left(\frac{\lambda_3\alpha_3 U - \mu_3\beta_3 W + \nu_3\Delta G_3^0}{k_B T}\right),$$

$$k_{CB} = k_3 c_{in}\exp\left(\frac{(\lambda_3-1)\alpha_3 U - (\mu_3-1)\beta_3 W + (\nu_3-1)\Delta G_3^0}{k_B T}\right)$$

$$k_{CD} = k_4\exp\left(\frac{\lambda_4\alpha_4 U - \mu_4\beta_4 W + \nu_4\Delta G_4^0}{k_B T}\right),$$

$$k_{DC} = k_4\exp\left(\frac{(\lambda_4-1)\alpha_4 U - (\mu_4-1)\beta_4 W + (\nu_4-1)\Delta G_4^0}{k_B T}\right).$$


B
z(ϕ)
H+
"swivel"
ϕ
"kink"
C
z
r_S
z = f(ϕ)
motion of rotor-stator
contact point
O
x
O - Center of Stator
Δϕ~20°
y


A
MECHANICS
MotB
MotA MotA
MotB
Periplasm
①
③
Cytoplasm
FliG
Power Stroke
MotB
MotA MotA
MotB
Periplasm
①
③
Cytoplasm
FliG
Power Stroke
B
ENERGETICS
Stator
φ
Loop 1
Loop
❶
k_{on}
k_{on}
ΔG
Power
Stroke
❷
k_{off}
k_{off}
Power
Stroke
Rotor
θ

$$\textbf{Stator}: \zeta_S \frac{d\phi_S}{dt} = \underbrace{-\frac{\partial G(\phi_S, j)}{\partial \phi_S}\ell_p}_{\substack{\text{Torque from} \\ \text{Proline hinge}}} \underbrace{-\frac{\partial V_{RS}}{\partial \phi_S}}_{\substack{\text{Reaction} \\ \text{from rotor}}} \underbrace{-\frac{\partial \psi}{\partial \phi_S}\ell_p}_{\substack{\text{Electrostatic} \\ \text{attraction}}} + \underbrace{\sqrt{2\mathrm{k_B T}\zeta_S} f_n(t)}_{\text{Thermal fluctuations}}$$

$$\textbf{Rotor}: \zeta_R \frac{d\theta_R}{dt} = \underbrace{-\frac{\partial V_{RS}}{\partial \theta_R}}_{\substack{\text{Torque} \\ \text{from stator}}} \underbrace{-\frac{\partial \psi}{\partial \theta_R}R}_{\substack{\text{Electrostatic} \\ \text{attraction}}} \underbrace{-\kappa(\theta_R - \theta_L)}_{\substack{\text{Spring connection} \\ \text{to load}}} + \underbrace{\sqrt{2\mathrm{k_B T}\zeta_R} f_n(t)}_{\text{Thermal fluctuations}}$$

$$\textbf{Load}: \zeta_L \frac{d\theta_L}{dt} = \underbrace{\kappa(\theta_R - \theta_L)}_{\substack{\text{Spring connection} \\ \text{to rotor}}} + \underbrace{\sqrt{2\mathrm{k_B T}\zeta_L} f_n(t).}_{\text{Thermal fluctuations}}$$

How does the motor switch directions?