SECTION 1 : THE MOLECULES THAT GENERATE MOTION

LECTURE 2 : ROTARY MOTORS

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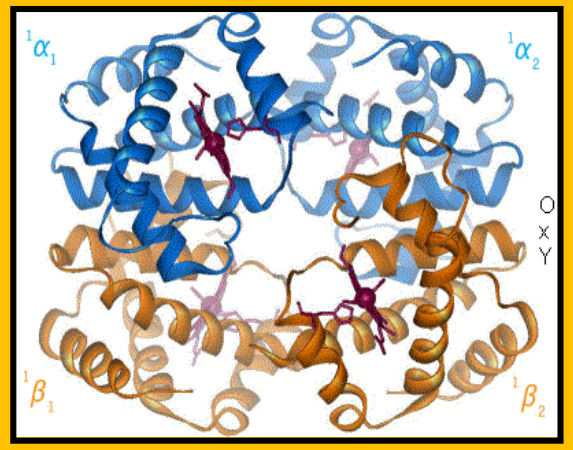
BB101 – Biology. Autumn Semester 2022-2023

Resources :-

Molecular Biology of the Cell: Alberts
Chapter 4, Single Molecule Biology : Alex Knight
Physical Biology of the Cell. Philips, Kondev, Theriot, Garcia
Article by R. Berry (Flagellar motor)

RECALL FROM LAST LECTURE



Molecular Motors – Special Protein Machines

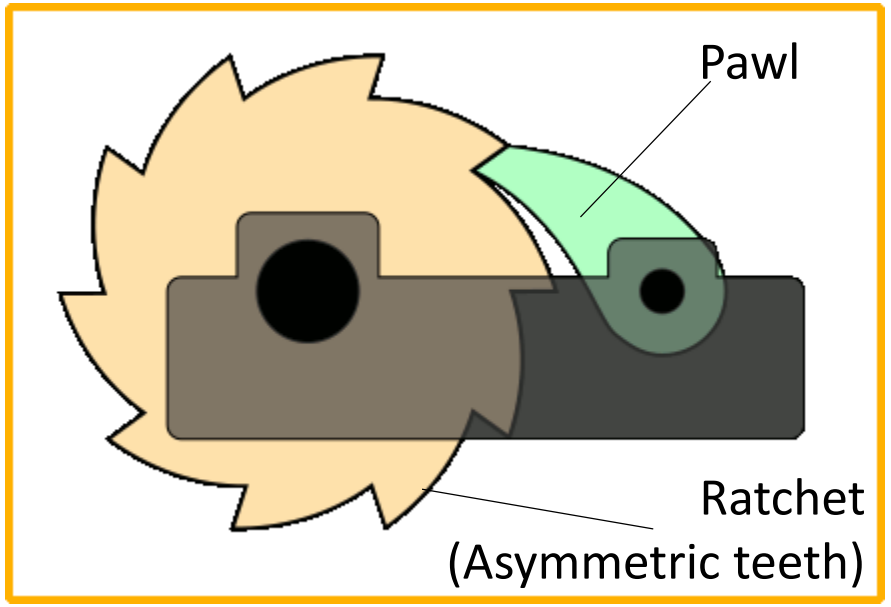
Generates Directed “Predictable” Motion using :-

- Electrical energy
- Chemical energy
- Light energy
- Other energy (?)

Motor

- “Mechano-chemical” Enzyme
- Motion drives metabolic functions
- Works at the Molecular Level … “Nano”

Theoretical Models
Ratchet and Pawl

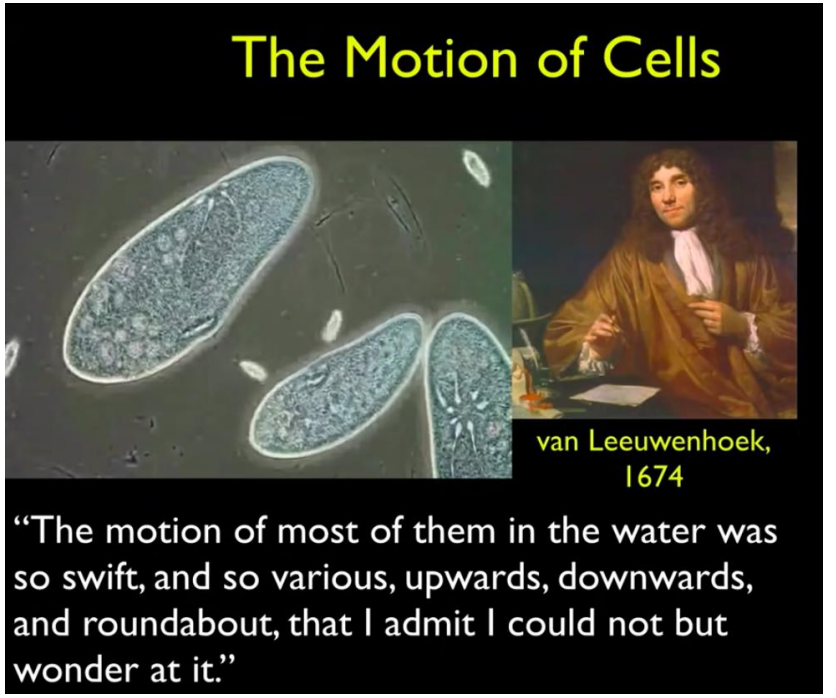


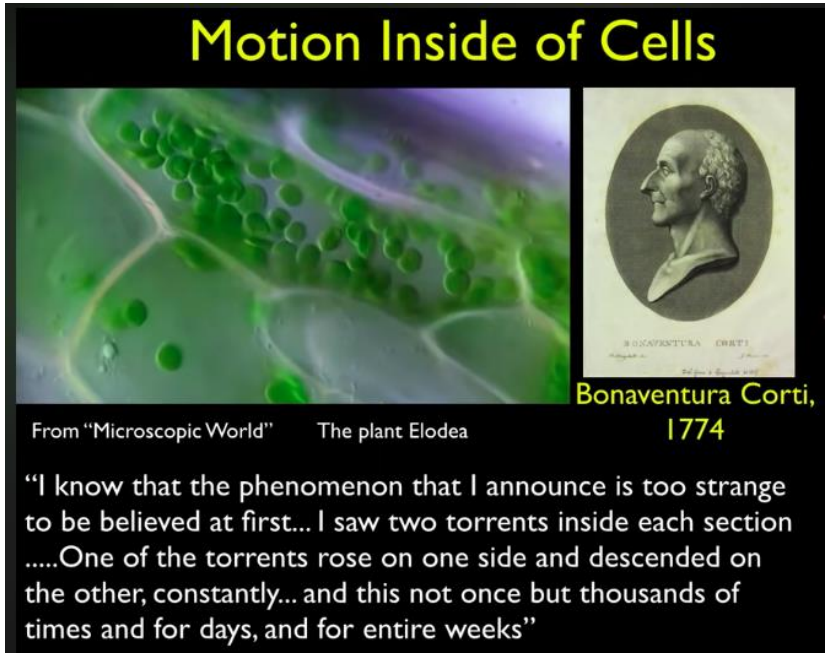
Rectify Thermal Motion to do Useful work

Why should you care ?

- Cannot imagine Life without Motion
- Essential – e.g. needed for cells to divide. Mutations lead to Neuronal degeneration, Developmental defects, Cancer
- Likely important to Evolve higher forms of Life.
- Efficient nanoscale machines - Can we make our own ?

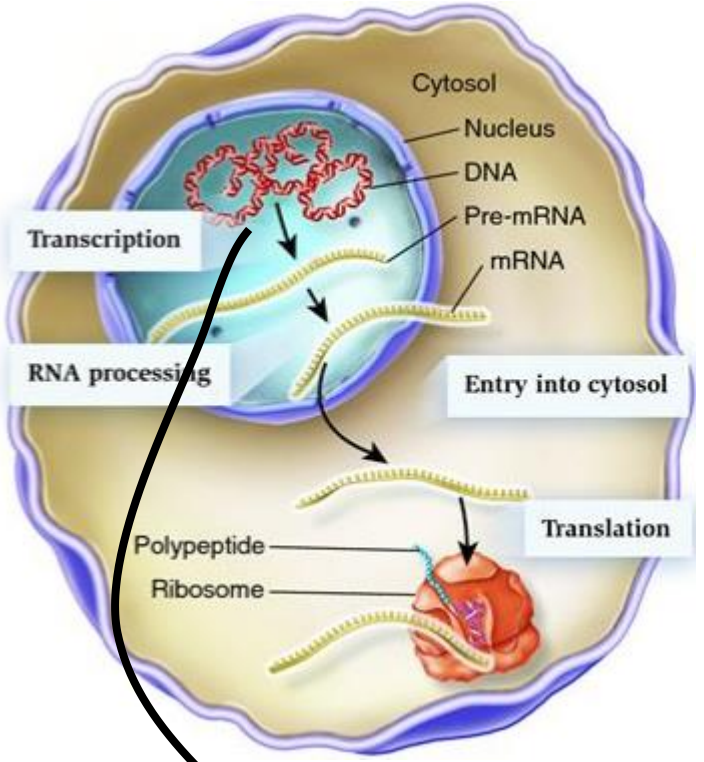
More Info :- [iBiology Talk Ronald Vale Motor Proteins in Disease]





What kind of motion do Motor Proteins generate ?

1) Linear Motors

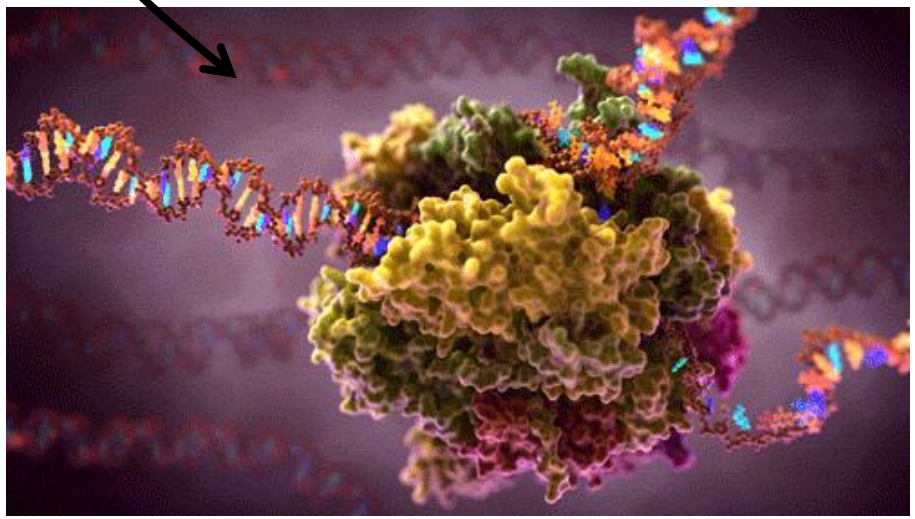


We'll return to Linear Motors in next class

DNA based	Use of Genetic Information (RNA Polymerase) Making Proteins (Ribosome)
Protein based	Moving muscles (Myosin) Moving things in the cell (Myosin, Kinesin, Dynein)

DNA Out

DNA In



RNA Out

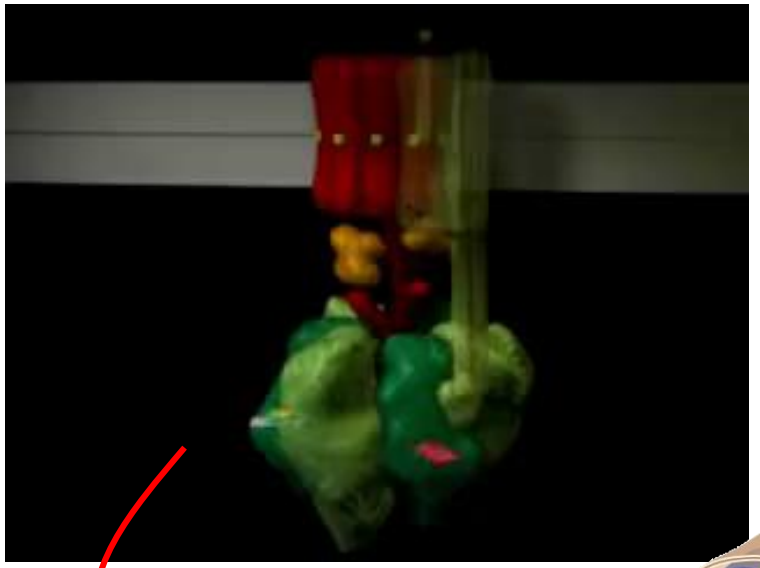
RNA Polymerase

Artofthecell

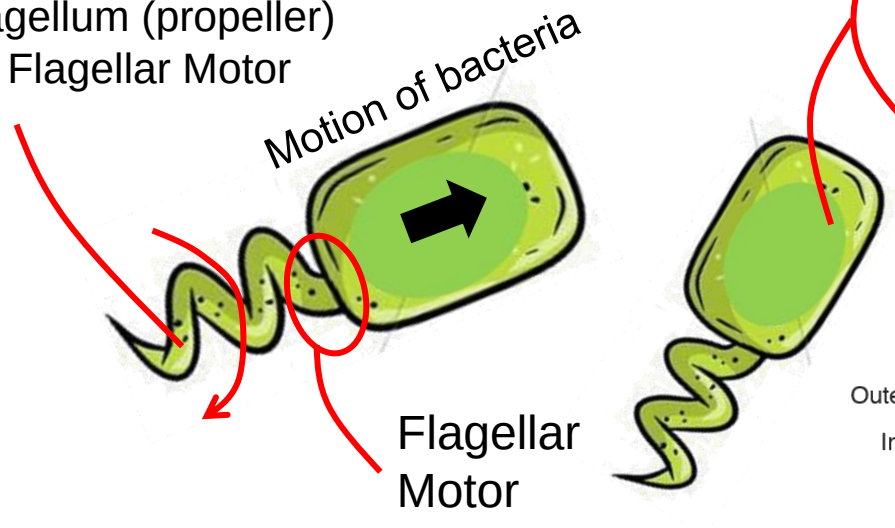
2) Rotary Molecular Motors

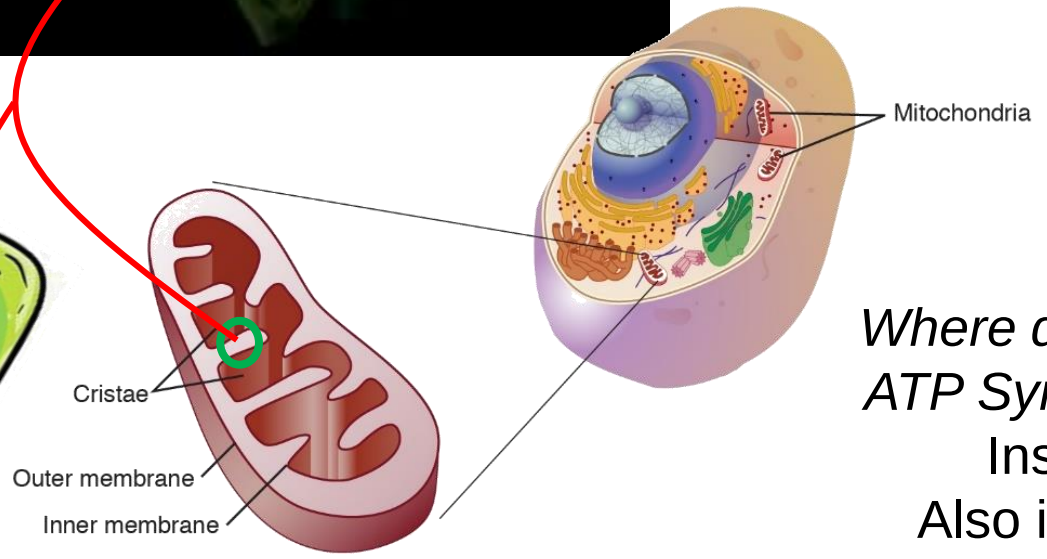
Example 1
Bacterial Flagellar Motor

Example 2
ATP Synthase



Helical Flagellum (propeller)
rotated by Flagellar Motor





Where do you find the ATP Synthase Motor?
Inside your Cells
Also inside bacteria

Rotary Motors play a critical role in your body …

- Allow bacteria to hunt for food (by burning ATP)
- Make ATP to store Chemical energy → Use inside Cells

Glucose —Respiration→ ATP

(ATP) (ADP)

A-p-p-p + H_2O → A-p-p + P_i + H^+

ENERGY FROM 1 ATP

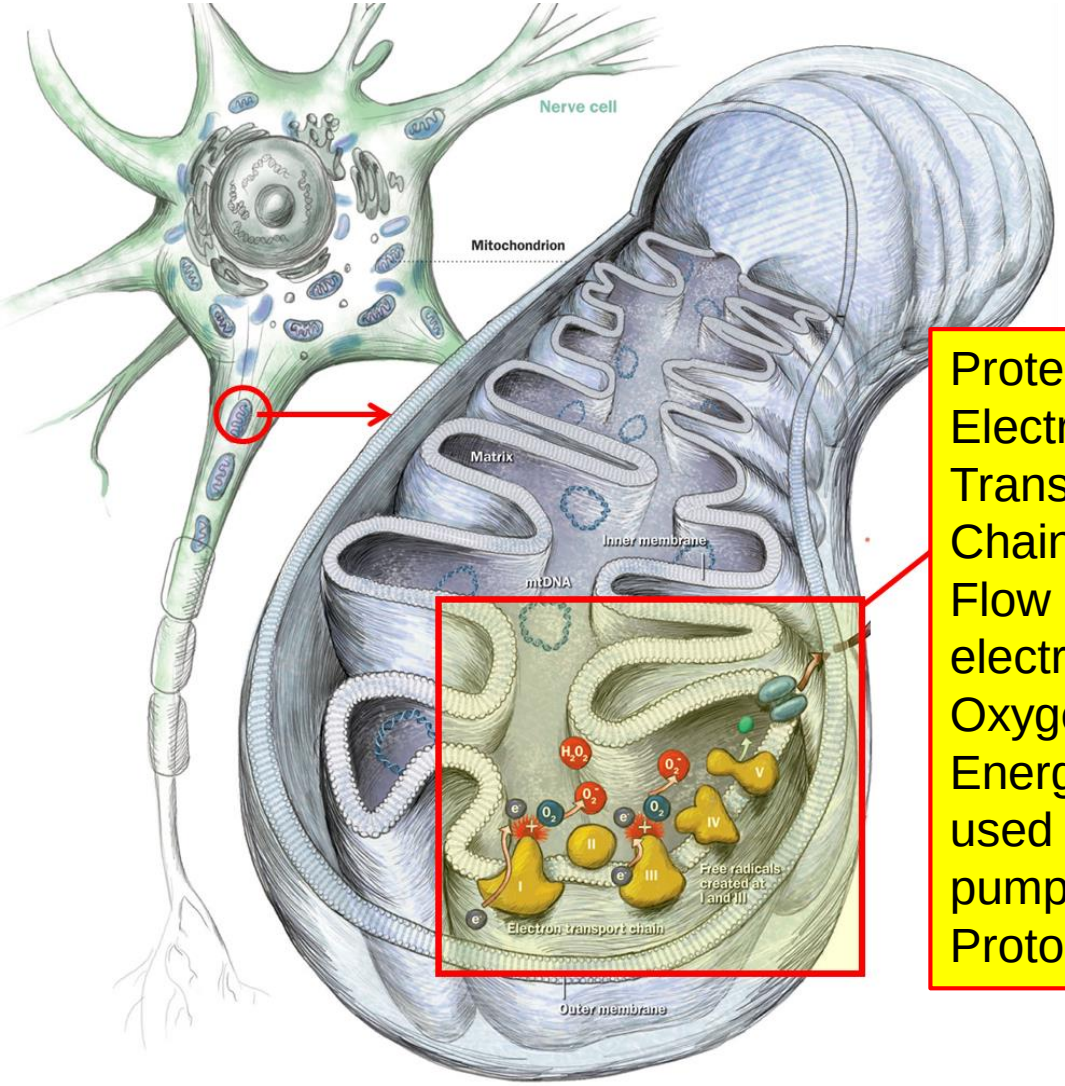
10^{-19} Joules = 25 kT = 100 pN-nm

Nanoscale Protein Machines burn ATP to generate Force

Assume one ATP burnt per Cycle.

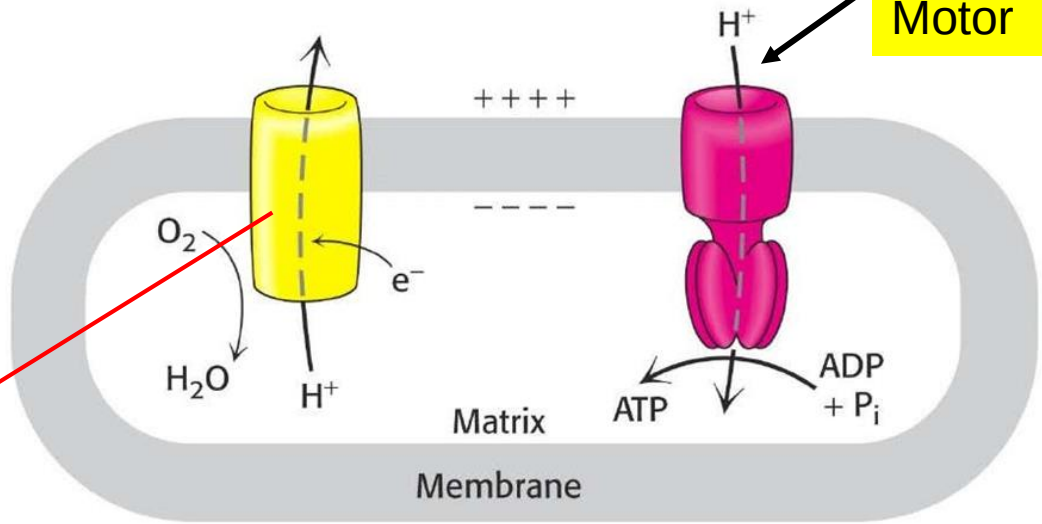
What does this number tell you ?

Making ATP in your Body
The ATP synthase Motor in Mitochondria



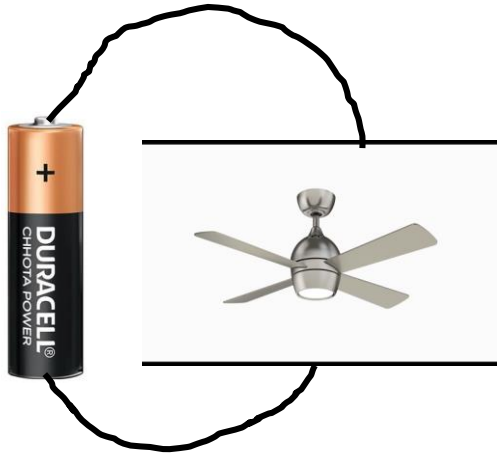
Proteins in Electron Transport Chain → Flow of electrons to Oxygen → Energy is used to pump out Protons

ATP Synthase Motor



Simplified Cartoon view Biochemistry by Lehninger

Proton gradient across mitochondria membrane acts like a battery



Turns the fan (ATP synthase).

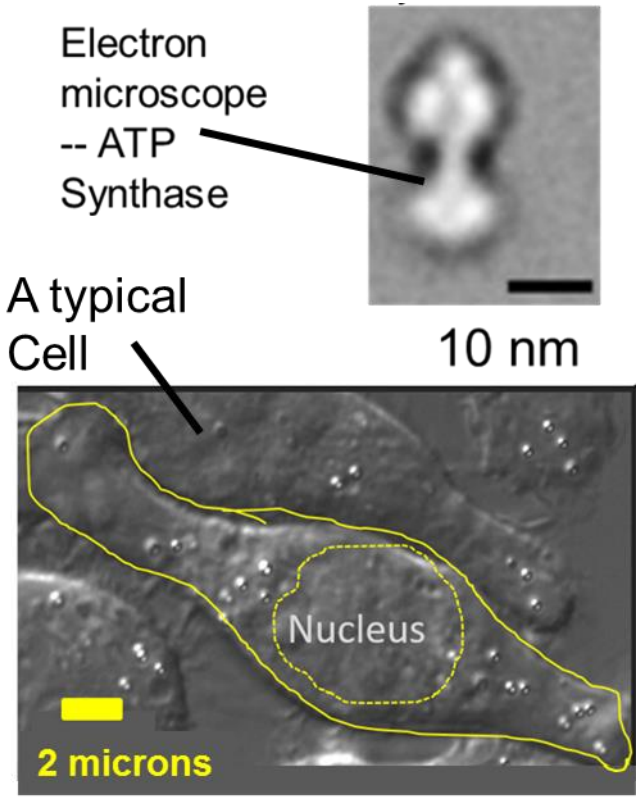
Rotary motion compresses ADP and Pi together to make ATP

Some numbers …

Will not discuss ATP Synthase.
You can read more :-
(1) Molecular Biology of the Cell by Alberts
(2) Biochemistry by Lehninger

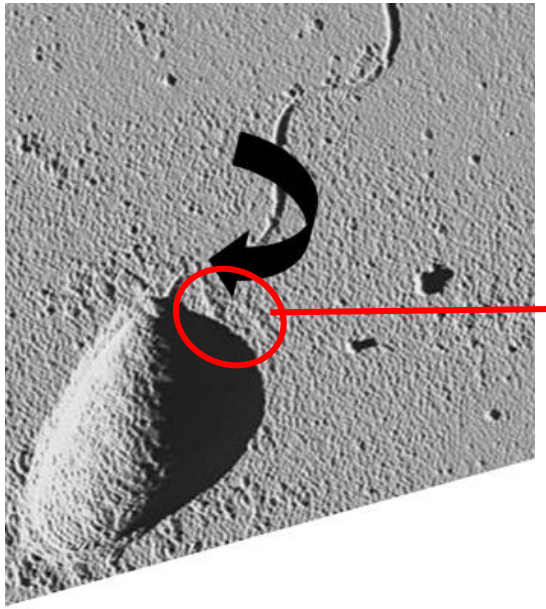
Daily energy intake for an adult = approx. 2400 Kilo calories
= 2400 x 1000 x 4.2 = 10^7 Joules
Energy in 1 ATP molecule = 10^{-19} Joules
If all food is converted into ATP, then you make
$10^7/10^{-19} = 10^{26}$ molecules of ATP/day

How much does this ATP weigh? ATP Molecular weight = 507
So, 6 x 10^{23} ATP molecules weigh 507 grams
10^{26} molecules of ATP would weigh ~85 Kilograms
(More than my body weight !)
Thus, most ATP is continuously converted into *Energy*.

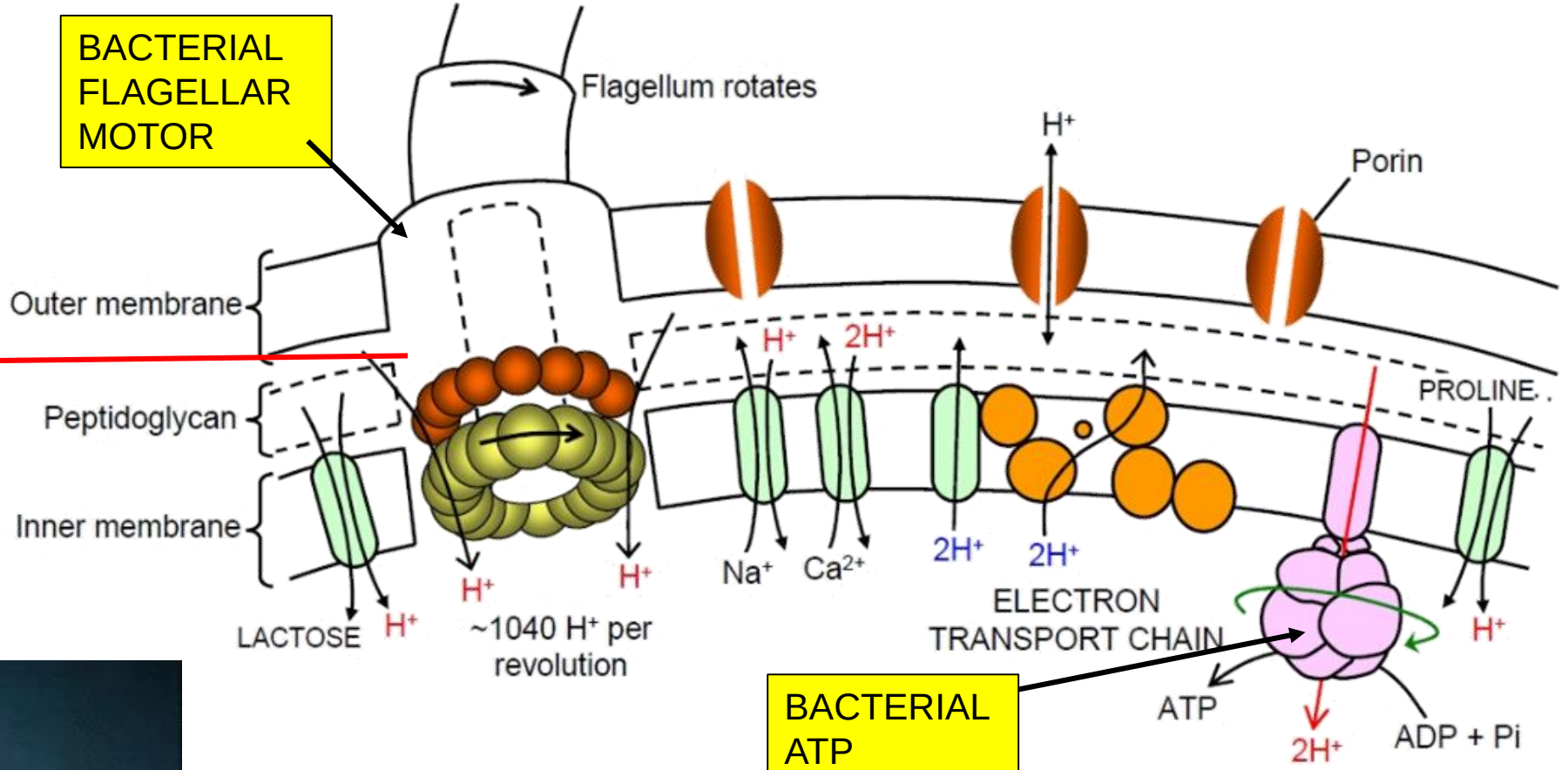


1 ATP synthase can make 300 molecules of ATP per second
In 24 hours, it makes 25 x 10^6 ATP molecules
You need 10^{26} / (25 x 10^6) = 4 x 10^{18} ATP synthases
to convert your daily food intake into ATP

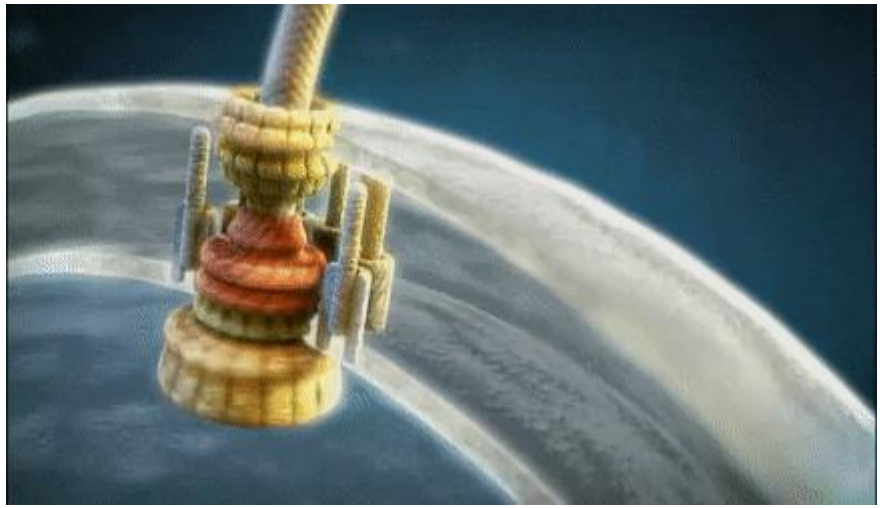
Human body has ~10^{12} Cells, So an average cell should have ~4 million ATP synthases.
Homework :- *Would so many ATP synthases fit inside a Cell?*



BACTERIAL FLAGELLAR MOTOR



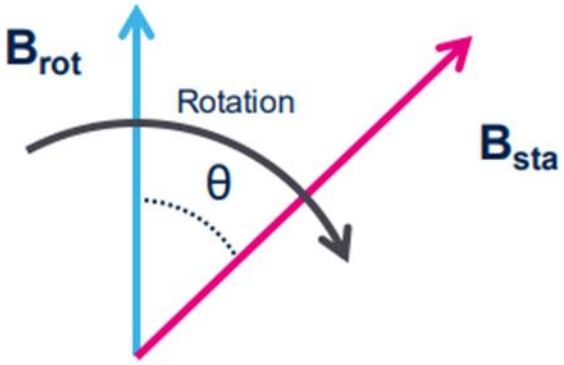
BACTERIAL ATP SYNTHASE

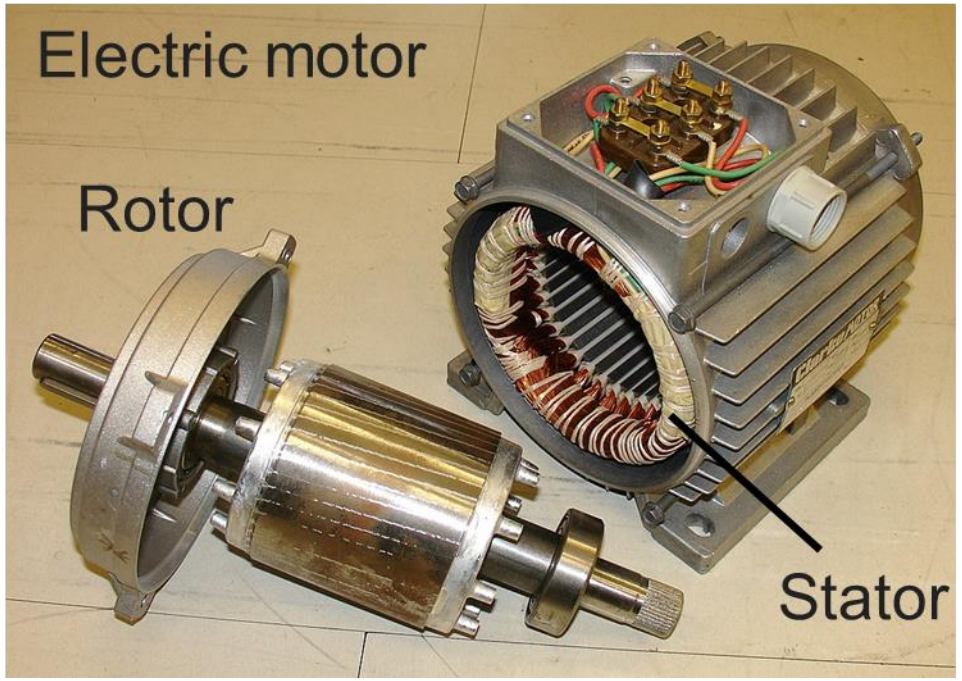


Proton gradient used to:-

- ❑ Run the Flagellar Motor to Swim around (find food)
- ❑ Run ATP synthase (Make ATP for other enzymes)

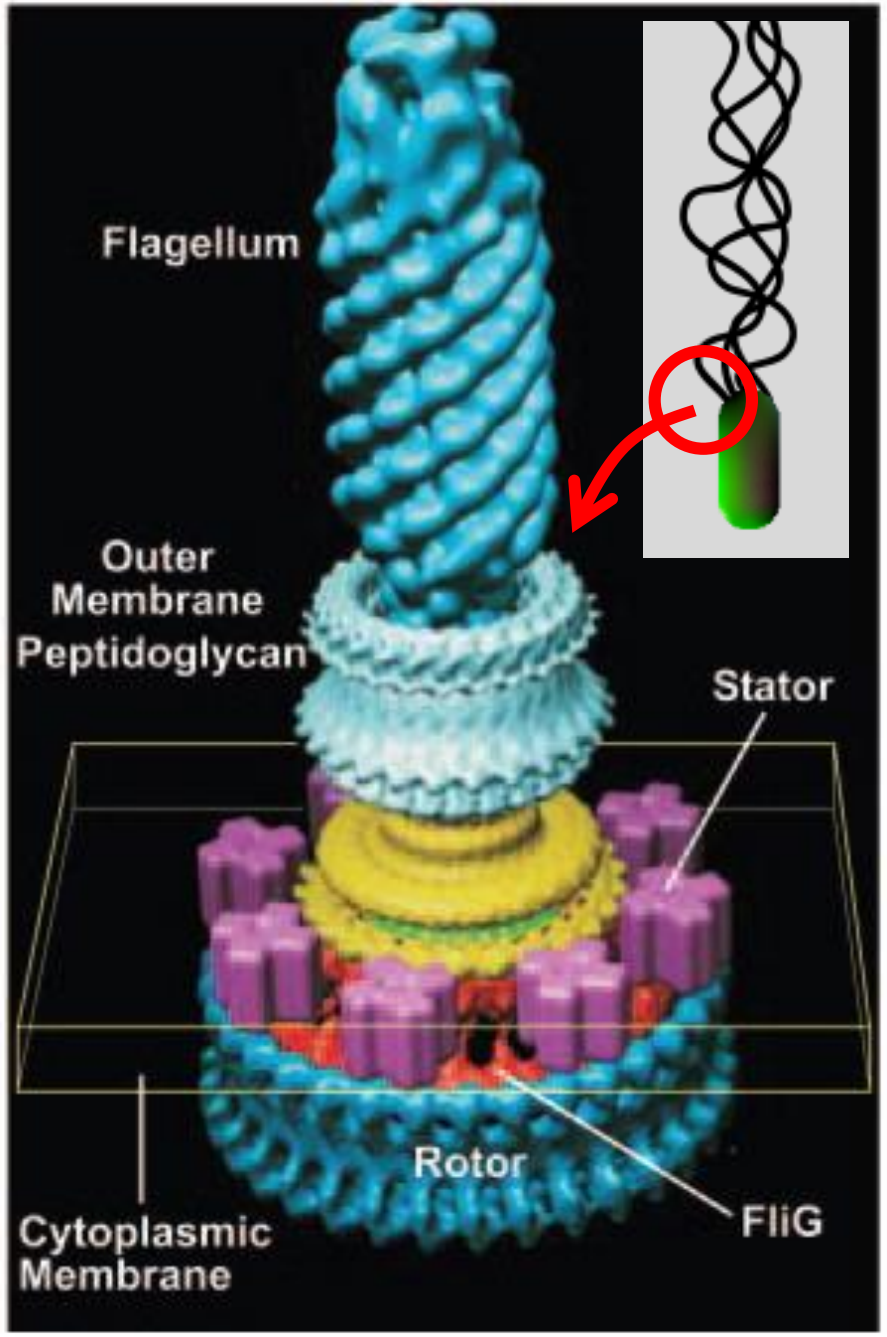
MORE INFO : CRONODON



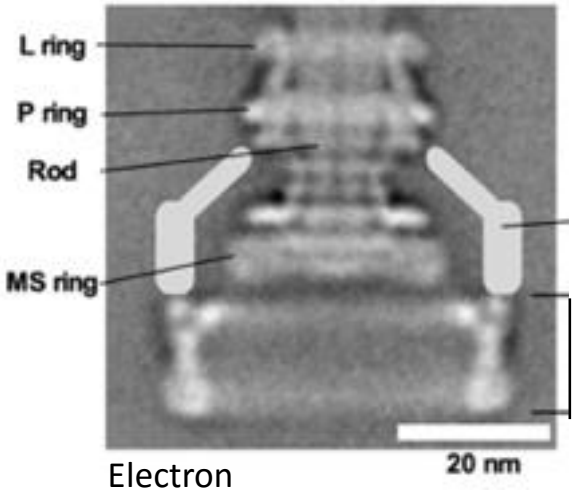


Flagellar Motor

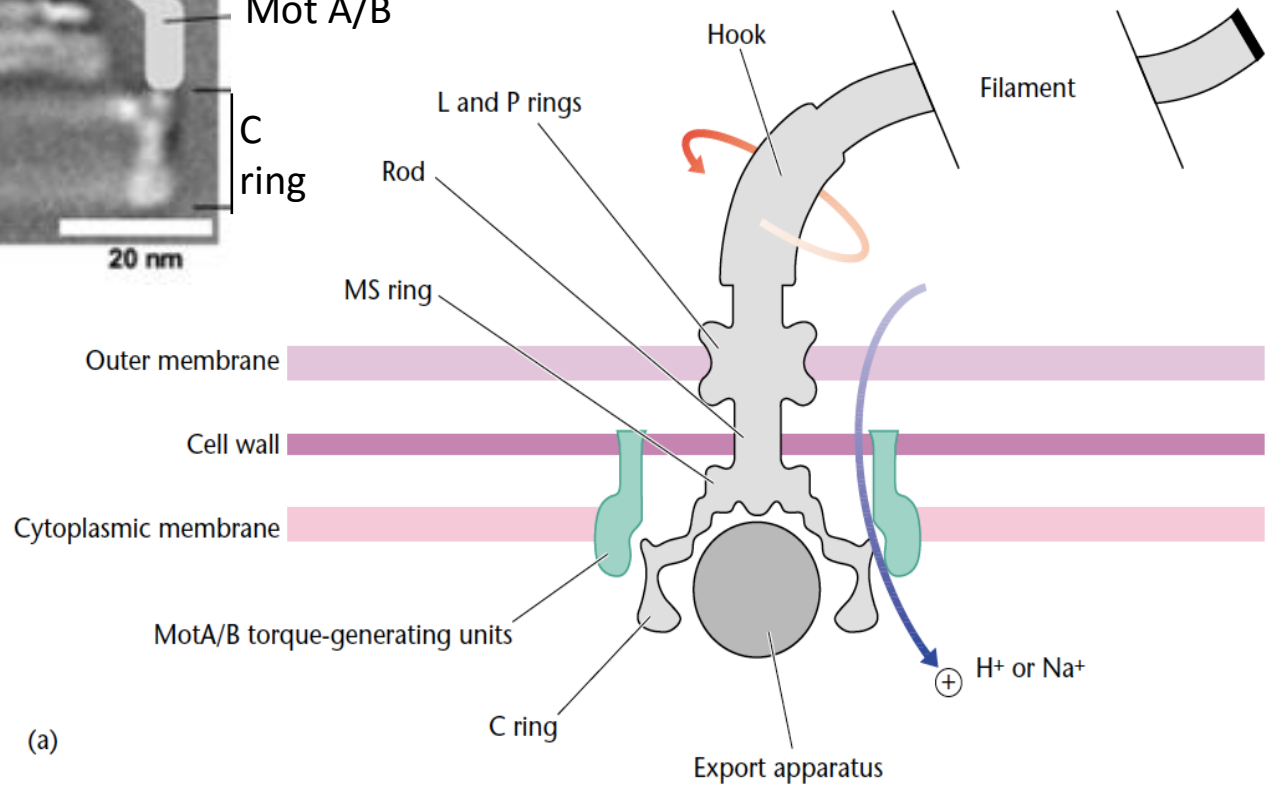
- No Magnetic field
- Reversible rotary machine, 45 nm dia, hundreds of RPM
- Rotating flagella (~10 mic long, 20nm thick) helical filament
- Maximum power ~10^{-15} W
- Propels bacteria at speeds upto 100 μm/s

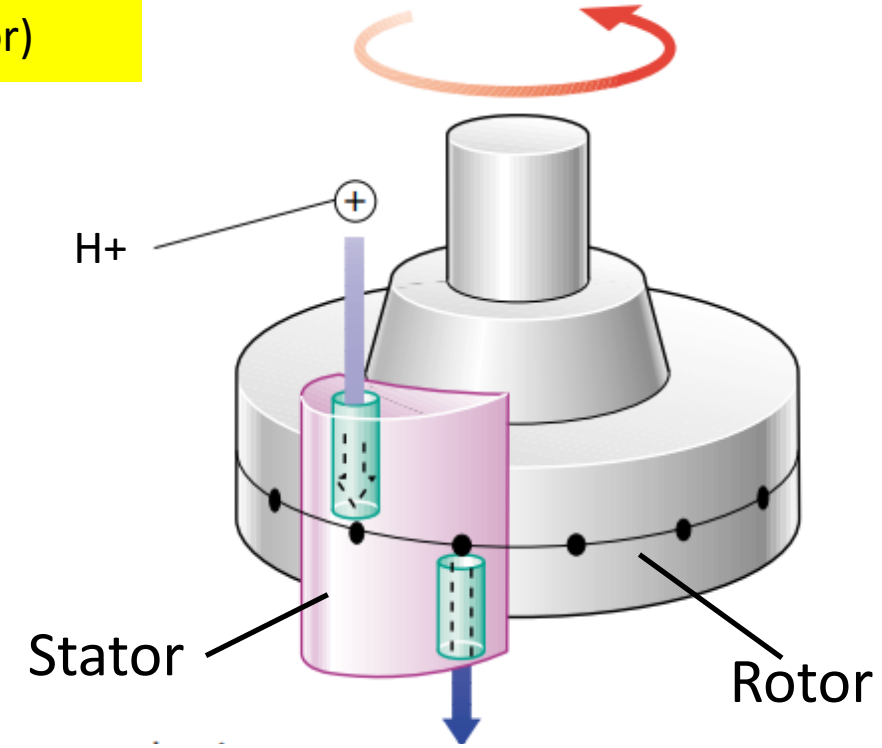


Article by R. Berry (Bacterial Flagellar motor)



Electron Microscope Image



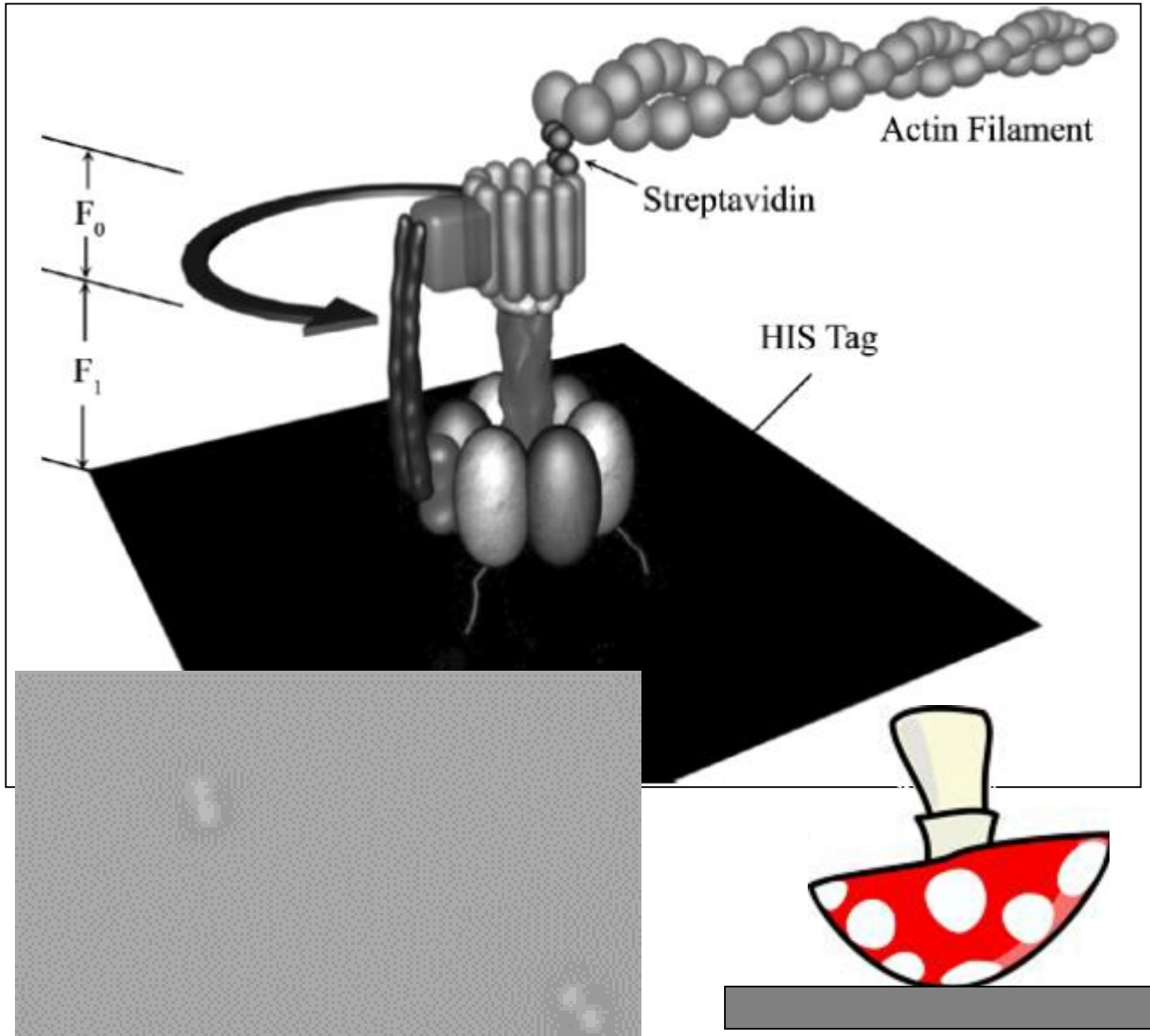


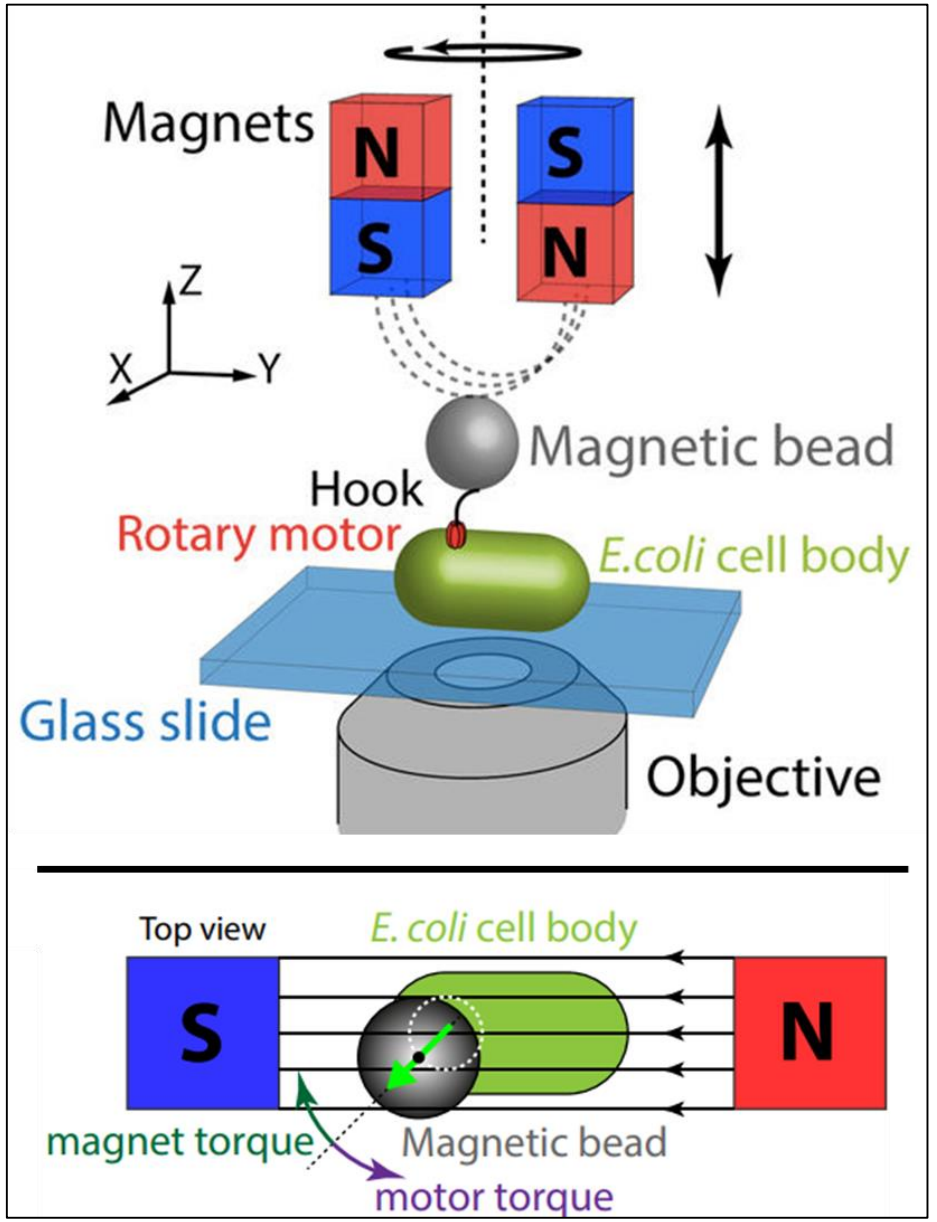
Think of it like a Windmill …

Bacterial Flagellar Motor

Protons bind the rotor, introduced from outside the cell by channels in the stator. In order to pass into the cell they must be transferred to a second set of channels by rotation of the rotor, so that rotation and proton flow are coupled.

You can see Motors rotate on a Coverslip





Maarten M. van Oene, SciRep 2017

How Good is the Bacterial Flagellar Motor?

Rotates upto 18,000 rpm
(Car engine ??)

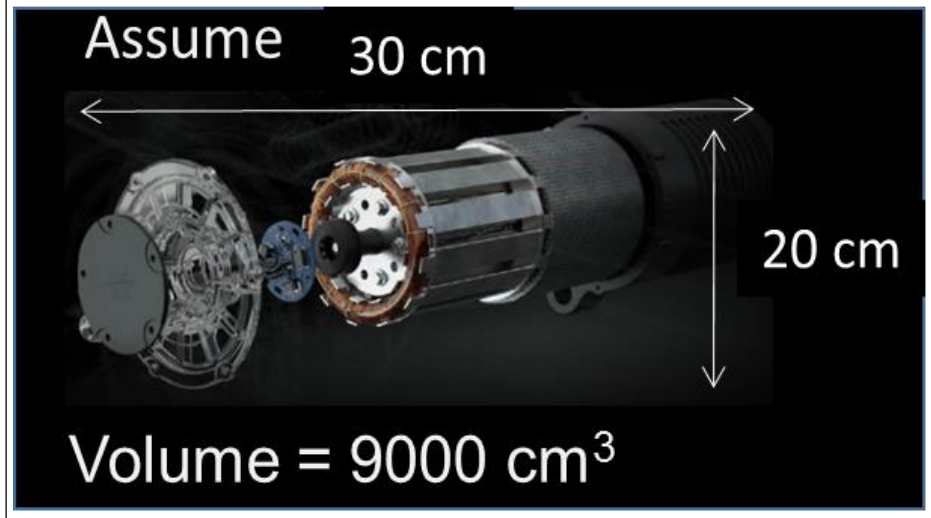
Torque ≈ 2000 pN-nm = 2×10^{-18} N-m
Power ≈ 10^{-15} Watts

Dimension of Bacterial Motor ~ 45nm
Volume ≈ 45 x 45 x 45 ≈ 90000 nm^3
= 9000×10^{-20} cm^3

Ola Motor ~ 10^{20} times larger than Bacterial Motor
Scale up the Flagellar Motor by 10^{20} to Ola Size …

Flagellar Motor could now be 10^5 Watts = 100 kW
(Compare to Ola 8.5kW)

It's Torque could now be 200 N-m
(Compare to Ola 58 N-m)



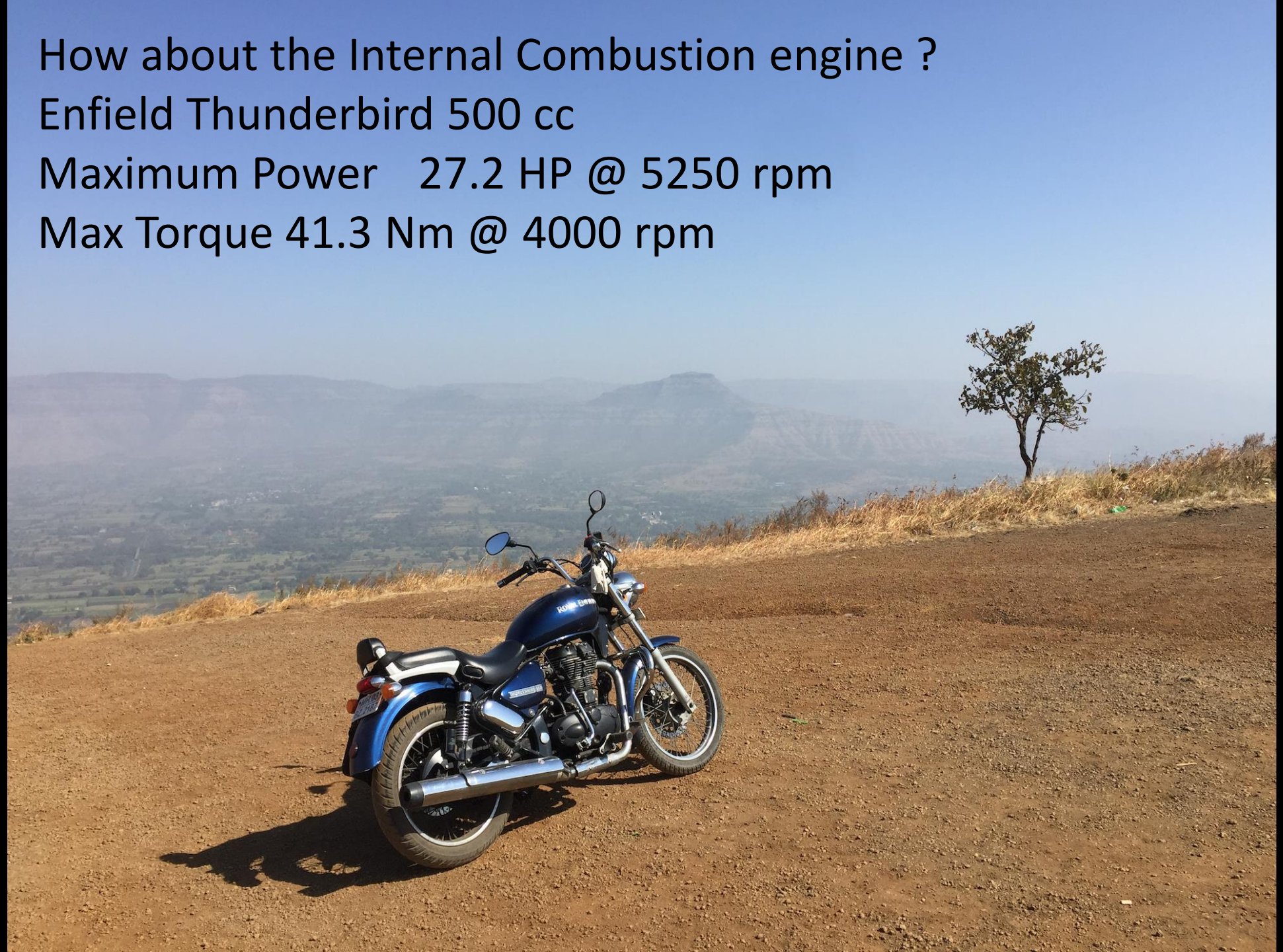
More Information :
The biophysicist's guide to the bacterial flagellar motor

How about the Internal Combustion engine ?

Enfield Thunderbird 500 cc

Maximum Power 27.2 HP @ 5250 rpm

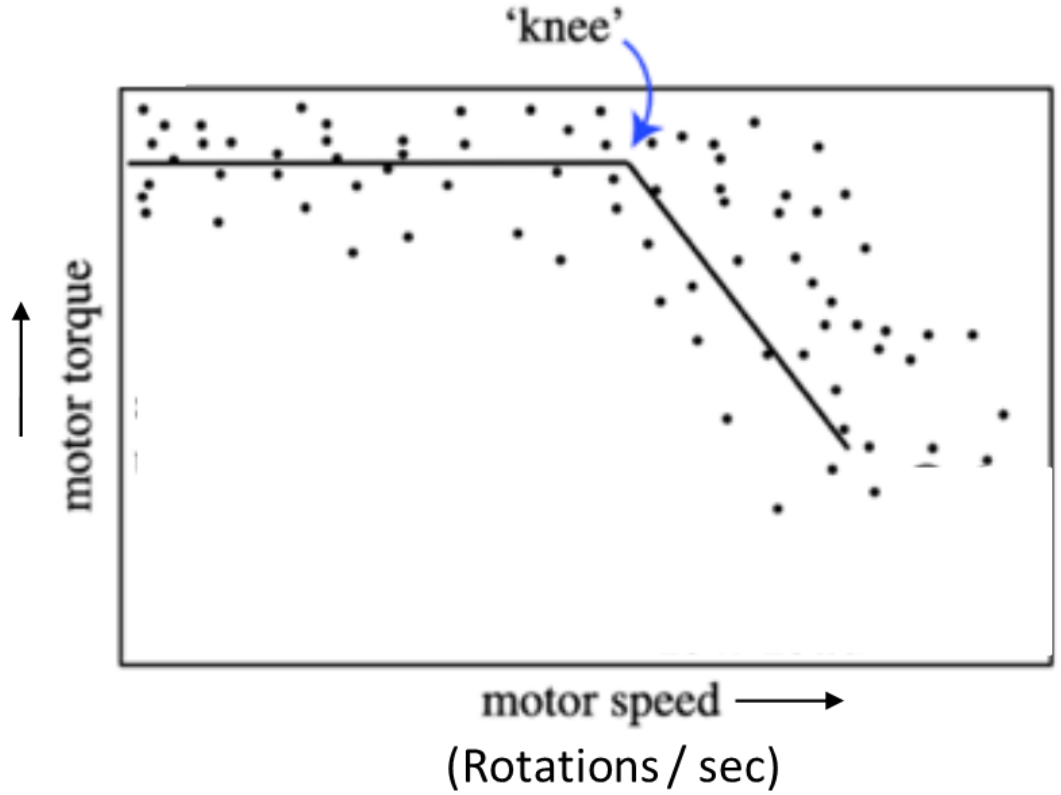
Max Torque 41.3 Nm @ 4000 rpm



FOR YOU TO THINK ABOUT/READ …

- Energy from 1 ATP = 10^{-19} Joules. If a Nanomotor uses 1ATP/Cycle, what does this tell you about the working of the Nanomotor?
- What would happen if a flagella of the bacteria gets stuck to a rigid surface as the bacteria is swimming along ?
- How is the Torque and Power of Bacterial Flagellar Motor measured?

The torque versus speed response of bacterial flagellar motor is shown in a diagram taken from this PAPER



- How can the motor speed be varied in such experiments?
- What are the approximate values of Torque at low motor speed?
- Why is there a "knee" in this response?