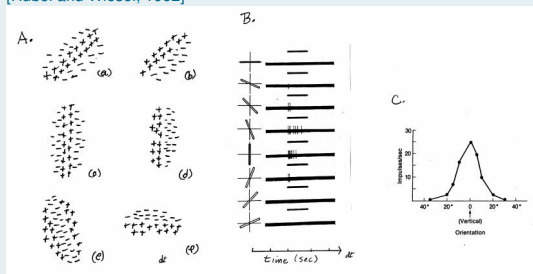


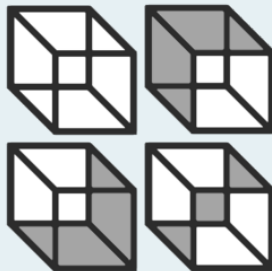
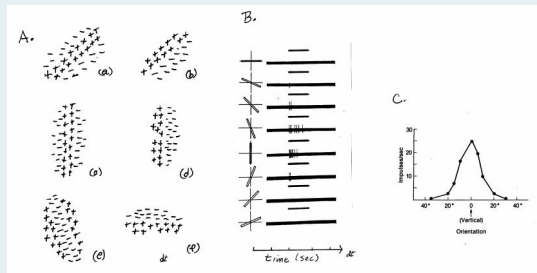
NEURONAL COMPUTATIONS

[Hubel and Wiesel, 1962]



NEURONAL COMPUTATIONS

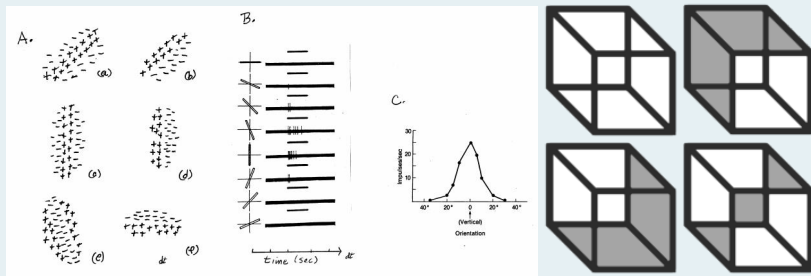
[Hubel and Wiesel, 1962]



The Bayesian brain hypothesis

NEURONAL COMPUTATIONS

[Hubel and Wiesel, 1962]

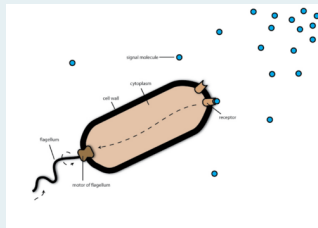
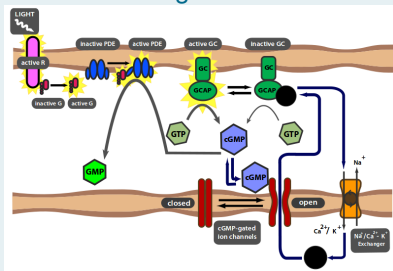


The Bayesian brain hypothesis

What about the phototransduction at the retina or modulation of neuronal activity by dopamine? What about unicellular organisms?

A CLOSER LOOK

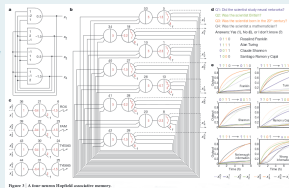
Transduction light/ionic currents in the retina [Houillon et al., 2010]



Chemotaxis of *E. coli*

Curiously, in one respect the mathematical formalism of artificial neural networks is a more accurate approximation for networks of proteins than for networks of real neurons.

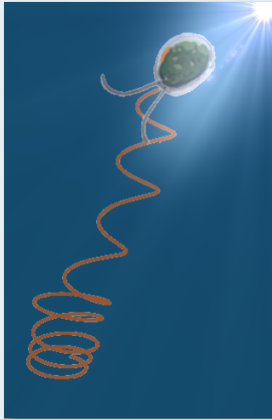
Dennis Bray (1995) in [Bray et al., 1995]



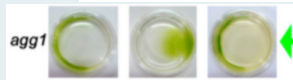
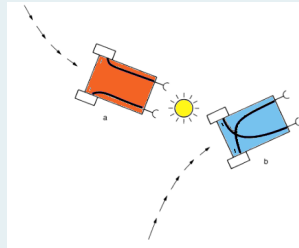
Example in DNA computing: Hopfield network [Qian et al., 2011]

PHOTOTAXIS IS A WAY TO REGULATE INPUT LIGHT FOR MICROALGAE

IT IS ALSO A COMMON MODEL FOR ROBOTICS.



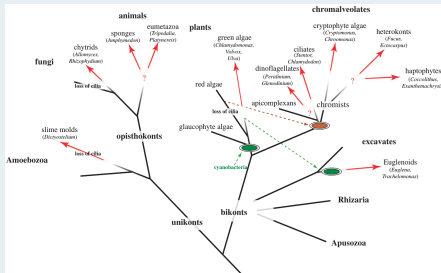
[Braitenberg, 1986]



[Wakabayashi et al., 2011]

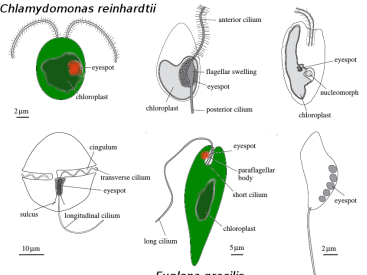
- ▶ Models and experiments towards an integrated model of phototaxis and photosynthesis.
- ▶ Minimal computational architecture achieving energy regulation and information processing.

Evolution of phototaxis [Jékely, 2009]

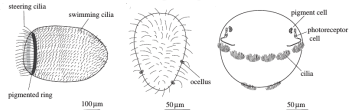


Many evolutionary paths to phototaxis

Chlamydomonas reinhardtii



Euglena gracilis



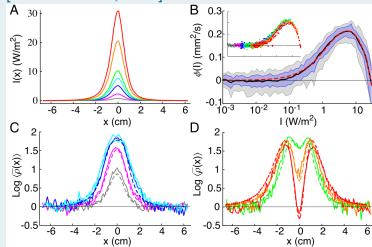
...diverse morphologies.

EXAMPLE WITH EUGLENA

Generalized receptor law governs phototaxis in the phytoplankton *Euglena gracilis*

Andrea Giometto^{Ab,1}, Florian Altermatt^{b,c}, Amos Maritan^a, Roman Stocker^a, and Andrea Rinaldo^{Ab,1}

[Giometto et al., 2015]



Micro

Ornstein-Uhlenbeck process:

$$\frac{dx}{dt} = \mathbf{v}$$

$$m \frac{d\mathbf{v}}{dt} = -\gamma \mathbf{v} + \sigma \xi + \gamma \frac{d\phi(\mathbf{I})}{dx}$$

σ	stoc. in \mathbf{v}	$0.032 \text{ mms}^{-3/2}$
γ	autocor. of \mathbf{v}	0.077 s^{-1}
D_{micro}	$\frac{\sigma^2}{2\gamma^2}$	$0.09 \text{ mm}^2 \text{ s}^{-1}$
$\phi(I)$	potential	$aI \frac{I_c - I}{I_r + I}$
v_p	photactic vel.	0.007 mms^{-1}

Macro Keller-Segel model (1D)

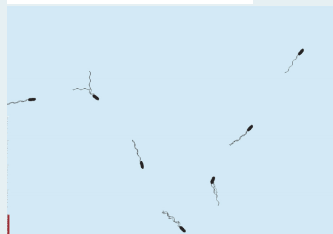
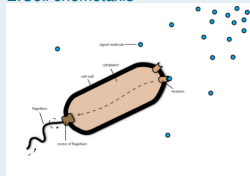
$$\frac{\partial \rho(x, t)}{\partial t} = - \frac{\partial (\nabla \phi(I(x)) \rho(x, t))}{\partial x} + D \frac{\partial^2 \rho(x, t)}{\partial x^2}$$

$$D_{\text{macro}} = 0.13 \text{ mm}^2 \text{ s}^{-1}$$

MECHANISM FOR ORIENTED BEHAVIOR

Local intensity

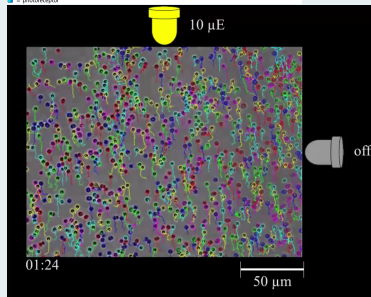
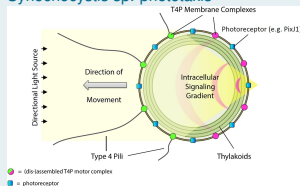
E.Coli chemotaxis



[Bray et al., 2007]

Direction to light source

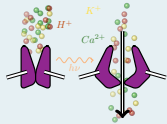
Synechocystis sp. phototaxis



[Schuergers et al., 2016]

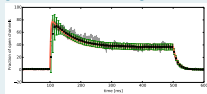
Chlamydomonas reinhardtii

Sensor

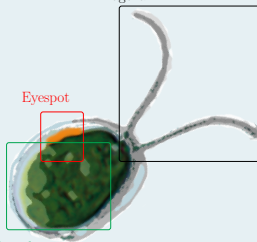


10^4 to 10^5 rhodopsins
by eyespot, and 10 to
100 charges by channel

[Schneider and Hegemann, 2015]. Chloroplast



Flagella

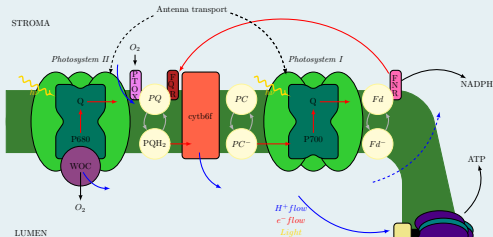


Motor

flagellar beating (50Hz):

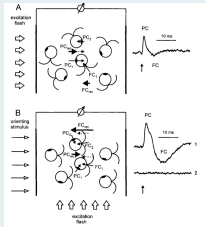
- ▶ from molecular motors activity.
- ▶ modulated by calcium signals (among others).
- ▶ generates 2Hz helical trajectory.

Energy Conversion
Photosynthetic electron transport chain.

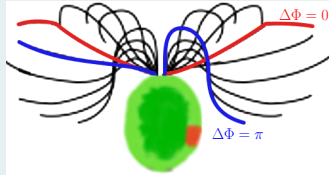


Chlamydomonas reinhardtii

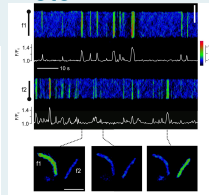
Sensor



Population voltage
[Sineschekov and Govorunova, 2001]



Motor

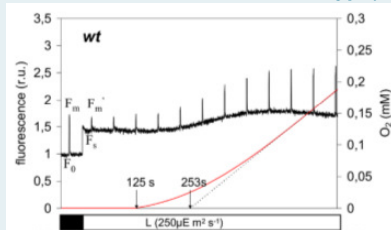


Calcium imaging

[Collingridge et al., 2013]

Energy Conversion
Photosynthetic electron transport chain.

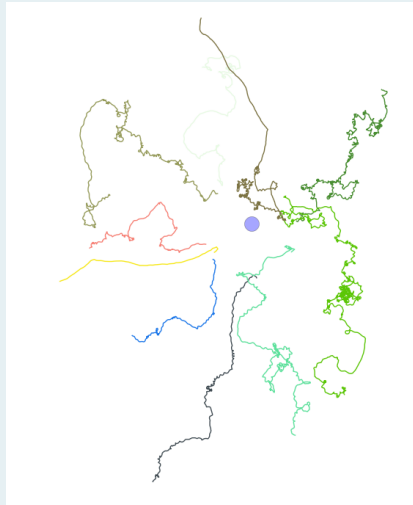
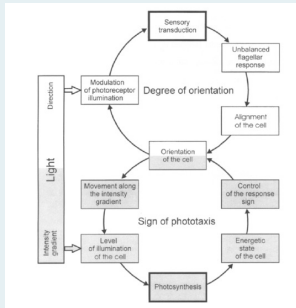
Fluorescence recording [Ghysels et al., 2013]



COUPLING WITH SLOWER PHOTOSYNTHETIC PROCESSES

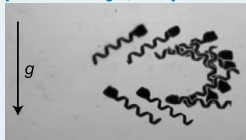
Candidate signals to play the role of internal state?

- ▶ Membrane potential.
- ▶ Calcium (recent review on the role of calcium).
- ▶ pH (Lumen pH is good indicator of the PETC activity).
- ▶ ATP (needed to swim, produced by PETC).



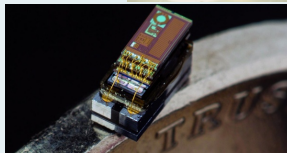
WHAT ARE THE LESSONS FOR MICROROBOTICS?

[Kim and Steager, 2012]



Artificial microsystems:

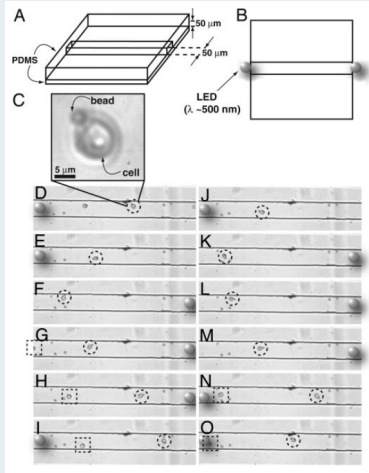
- ▶ face similar constraints as microorganisms
- ▶ take inspiration from their living counterparts



[M³-Michigan Micro Mote]

DIFFICULT TO BEAT BIOLOGY

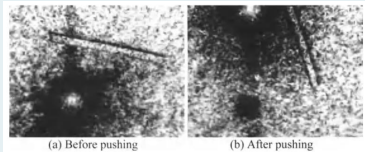
Microoxen



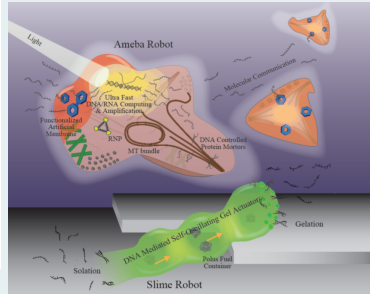
[Weibel et al., 2005]

Light control of Euglena

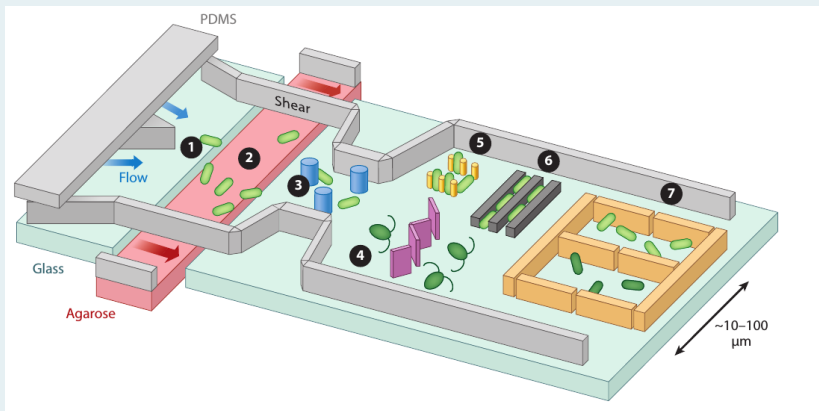
[A. Itoh, W. Tamura 2008]



Molecular robotics? molbot.org



MICROFLUIDIC PLAYGROUNDS





MERCI


Pierre Bessière (ISIR-CNRS)

Jacques Droulez (ISIR-CNRS)




Claude Yeprémian (MNHN)

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William Andrew.

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