Chemical Basis for Minimal Cognition

Presented in the Embryo Physics Course
http://www.embryophysics.org
November 24, 2010
By
Martin Hanczyc: martin@ifk.sdu.dk
University of Southern Denmark

Takashi Ikegami: ikeg@sacral.c.u-tokyo.ac.jp
University of Tokyo, Komaba

Chemical Basis for Minimal Cognition

Martin Hanczyc: martin@ifk.sdu.dk

Takashi Ikegami: ikeg@sacral.c.u-tokyo.ac.jp

Embryo Physics Course
Nov 24, 2010

UNIVERSITY OF SOUTHERN DENMARK

THE UNIVERSITY OF TOKYO

Perception, intelligence, and higher-order cognitive processes as currently understood are rooted in ***sensory-motor coupling*** in organisms

Environment

Agent

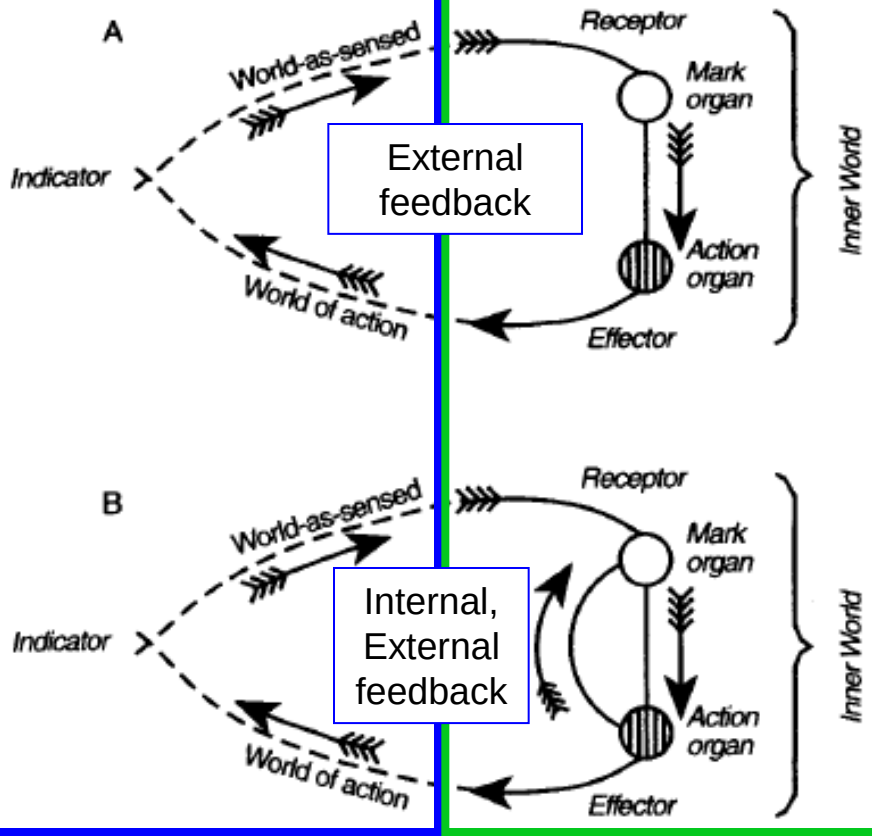


Figure 6.1. The flow of processing between the organism and its environment, according to Uexküll (1926). *A:* Primitive organism: reaction to external stimuli without internal feedback between the action organ and the receptor organ. *B:* Higher organism: the receptor organ is modulated by internal neural feedback from the action organ.

Concept of von Uexkull, 1926

Modified From Fuster, 2003

the protocell

simple artificial chemical model of a living cell

cell:	10^6 different types of molecules
protocell:	10 different types of molecules

the protocell

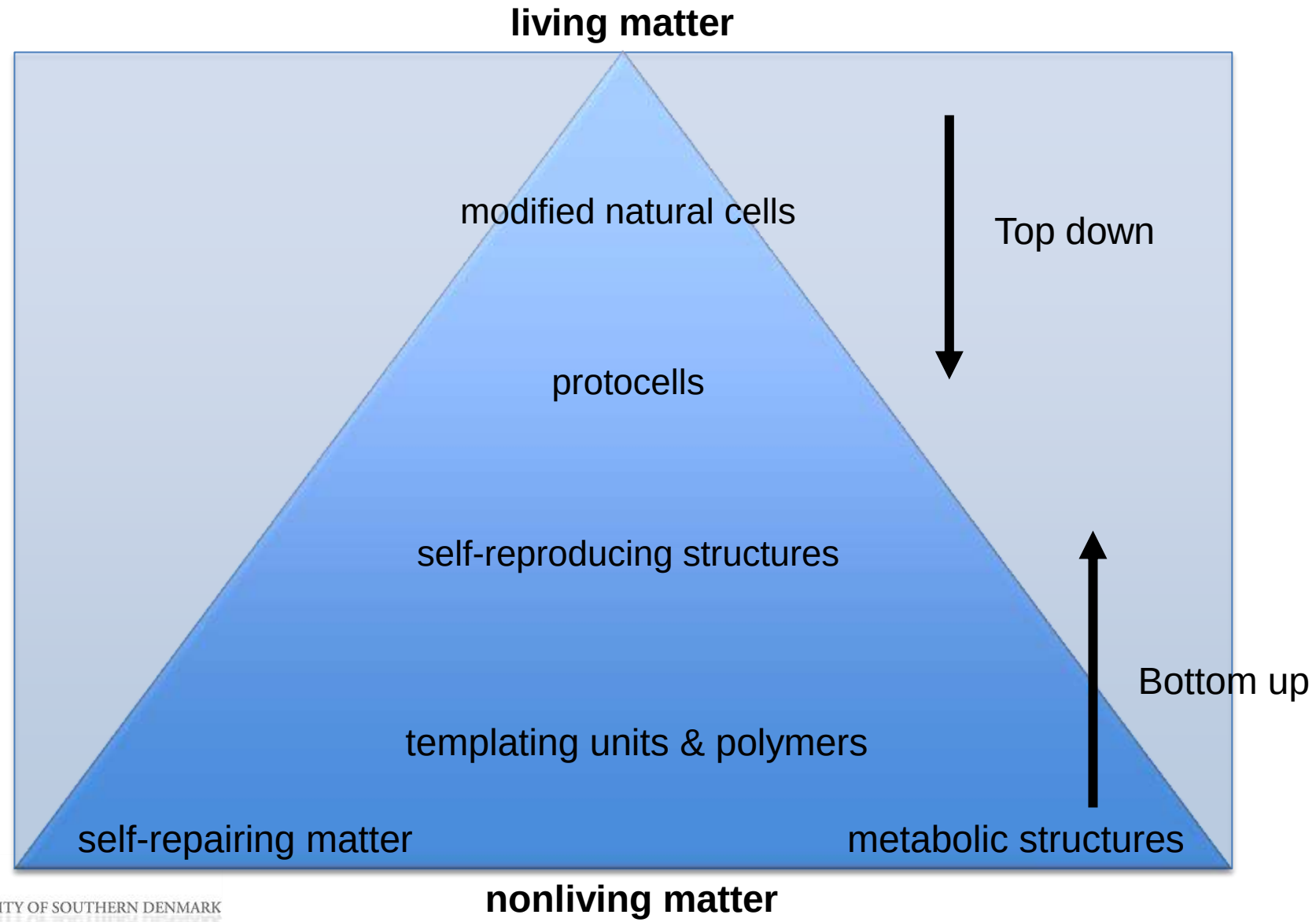
Characteristics

- Body
- Metabolism
- Inheritable information

→ Movement
Replication

→ Intelligence
Evolution

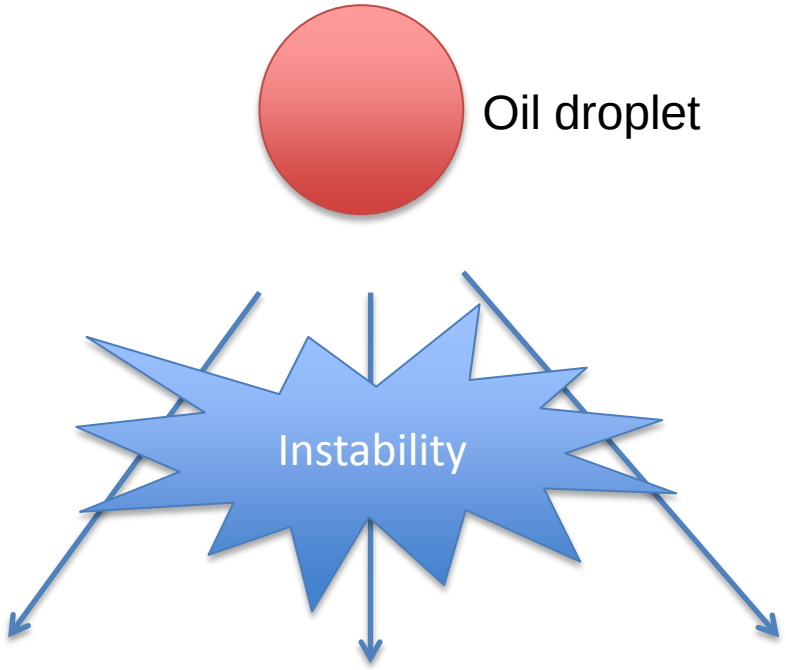
bottom up and top down, synthetic biology



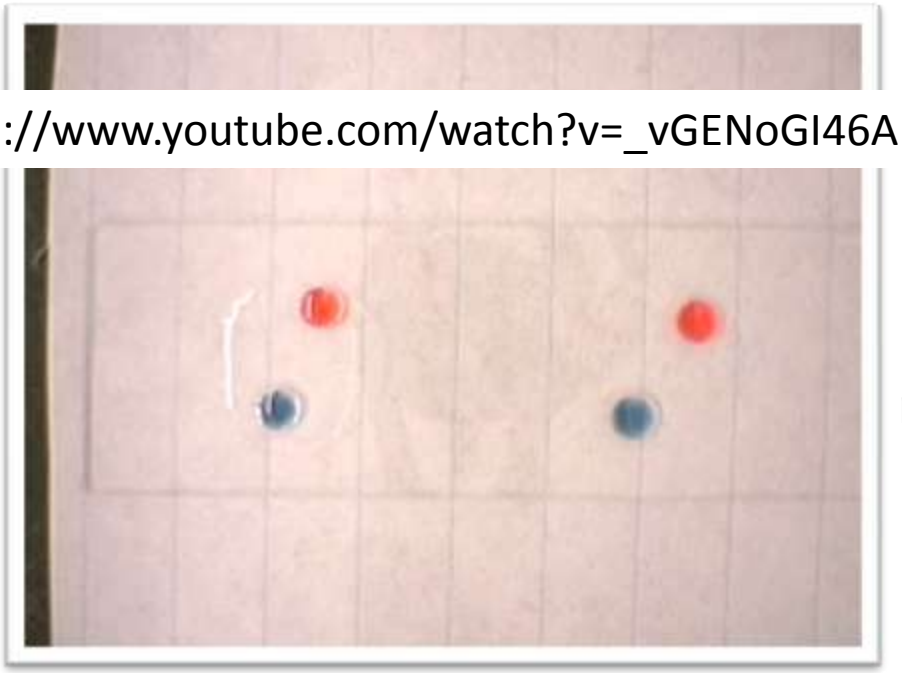
We want to understand…

- how the properties of life manifest in simple chemical/physical systems
- how simple systems, with all components specified, evolve
- the fundamental properties of matter in relation to intelligence and cognition
- the origin of life

the protocell



Self-assembly and dynamics…



http://www.youtube.com/watch?v=_vGENoGI46A

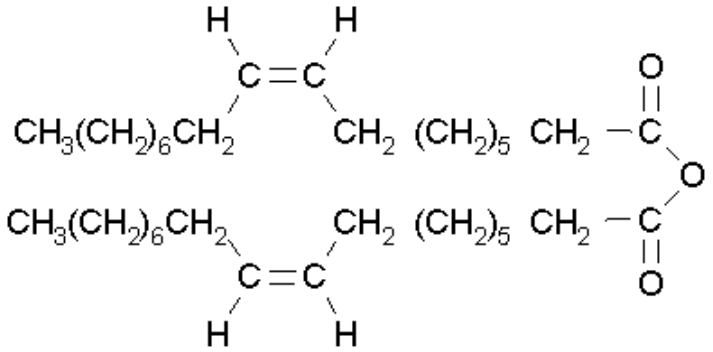
Real time movie
mineral oil in water

Additions: chemical activator (NaCl) control

1 cm

metabolism

Oleic anhydride

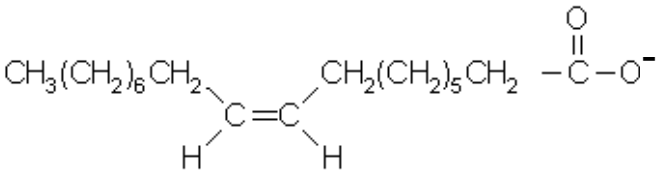


H_2O

pH 11

Oleate

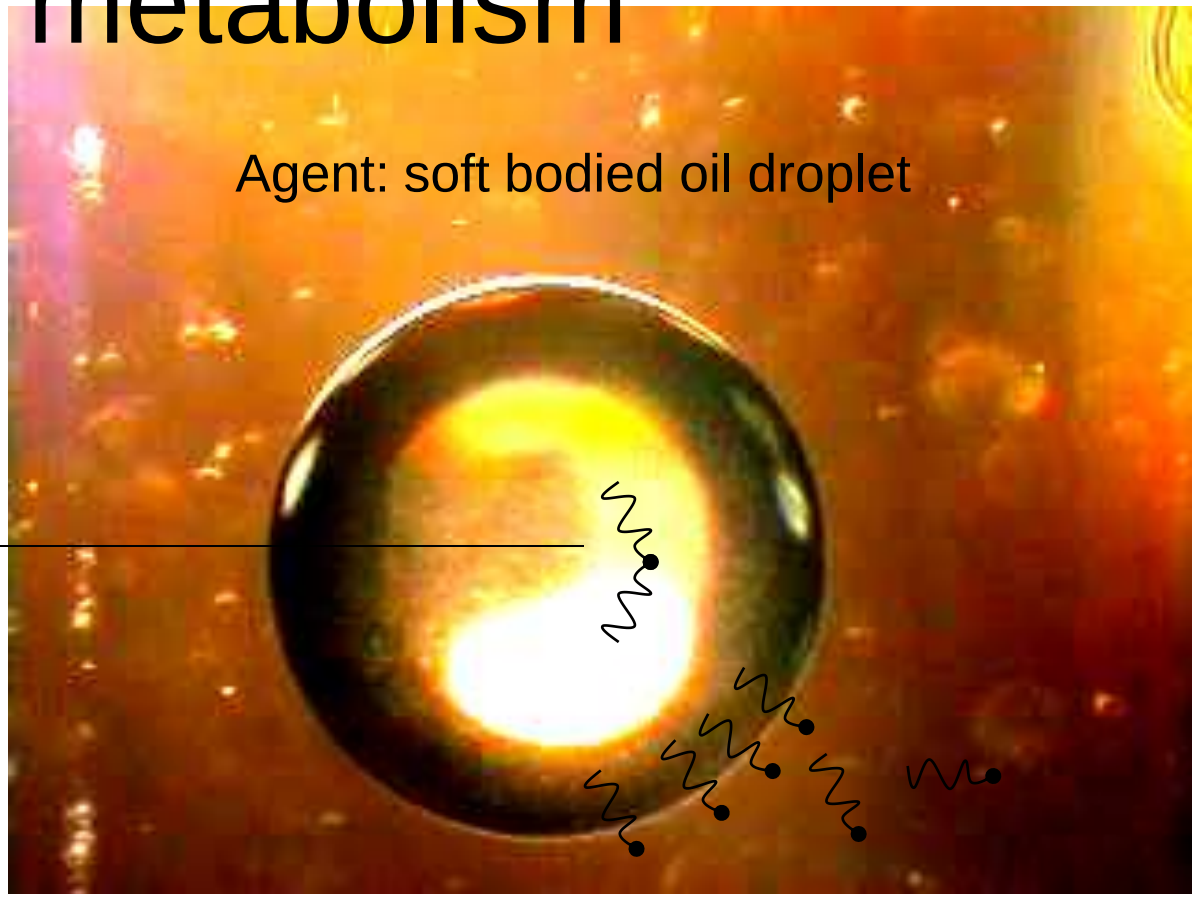
2



+ $2H^+$

Chemistry from: Autopoietic Self-Reproduction of Fatty Acid Vesicles. Walde, Wick, Fresta, Mangone, Luisi *J. Am. Chem. SOC. 1994,116,* 11649-11654

embedded metabolism



Chemistry:
Precursor

Environment:Surfactant, water

Movement….

http://www.youtube.com/watch?v=_ECkRZYMzaA

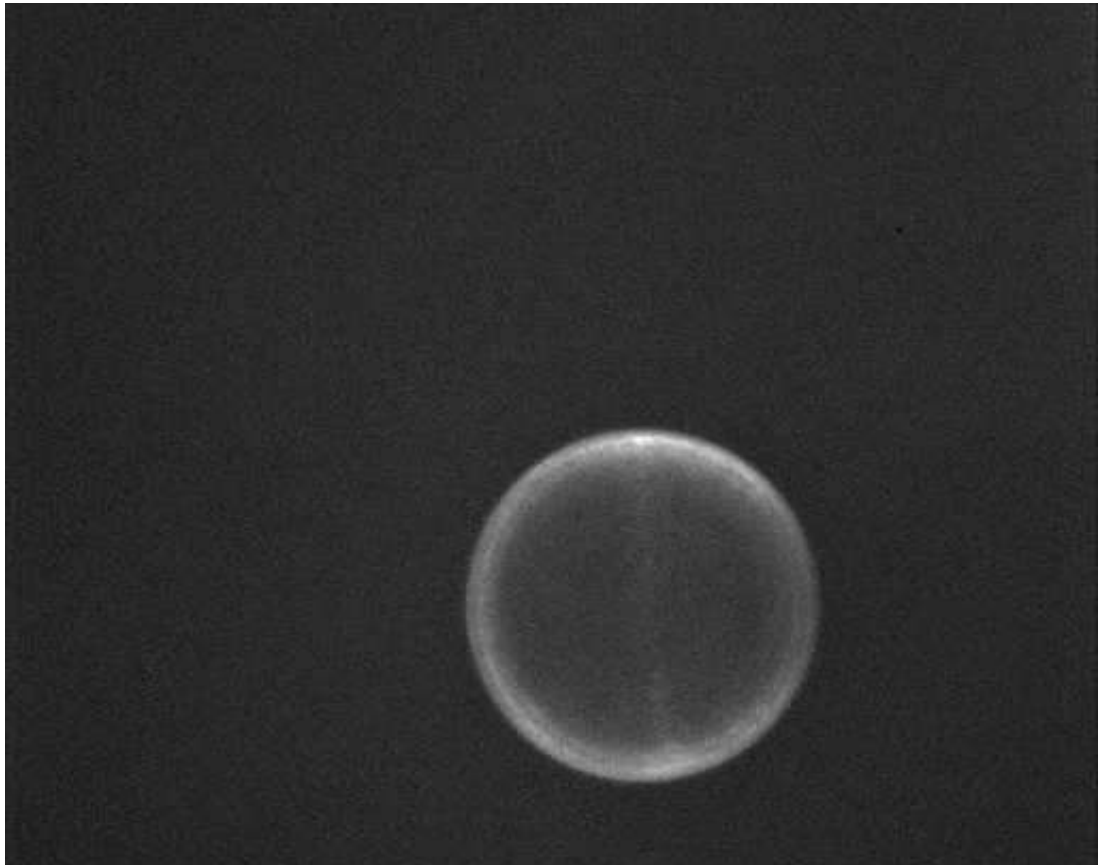
100 microns

2X real time

Internal movement

Internal flow structures

0.5M oleic anhydride in nitrobenzene in 10mM oleate micelles with 10uM calcein



http://www.youtube.com/watch?v=WlgOEZS_lWw

100 microns

Modification of environment

Self-movement

8X real time movie
5ul red active droplet
0.8mL water pH 12.0
0.1mg/ml pH indicator Thymolphthalein

Reference:

pH 12

< pH 11

http://www.youtube.com/watch?v=DIAQMe2wKZE

1cm

pH 9.3-11.5 transition from blue to colorless solution

Chemotaxis

10X real time movie
5ul red active droplet
0.8mL 10mM oleate pH 11.0
0.1mg/ml pH indicator
0.1ul 3M NaOH gradient

http://www.youtube.com/watch?v=bikzGbcYj10

Reference:

> pH 12

pH 11

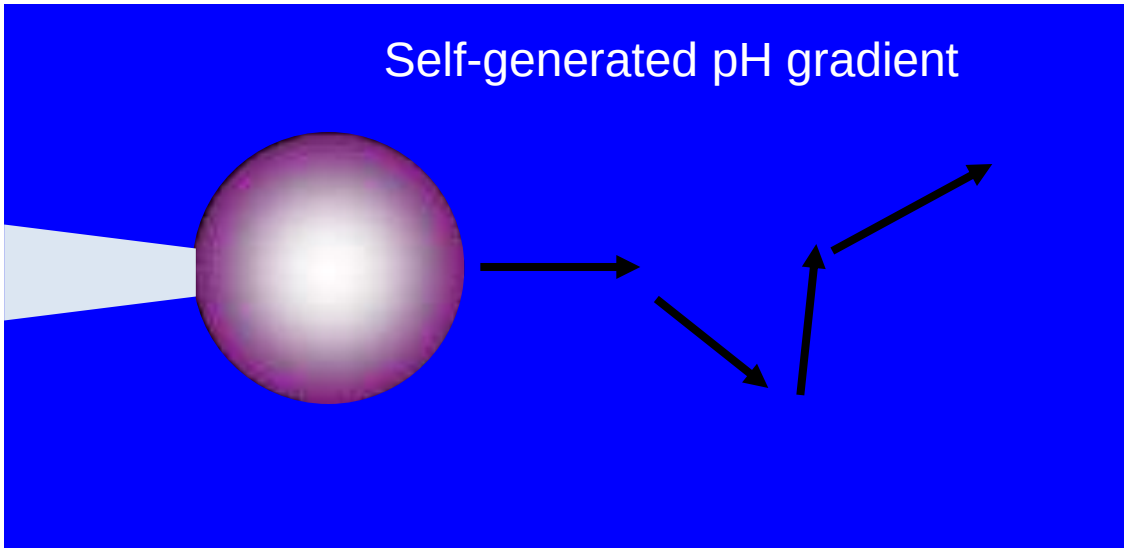
1cm

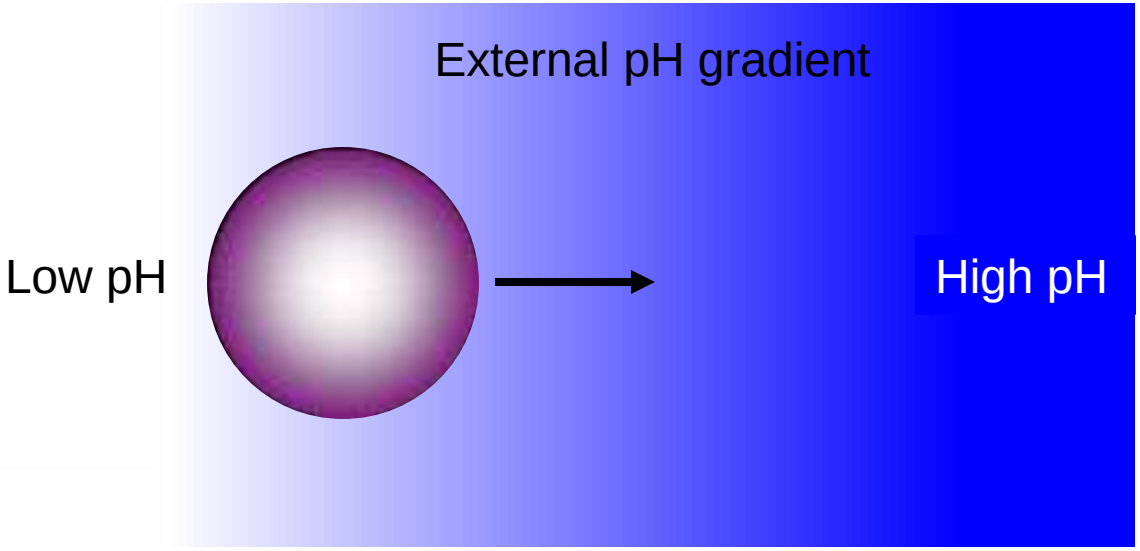
pH 9.3-11.5 transition from clear to blue solution

UNIVERSITY OF SOUTHERN DENMARK

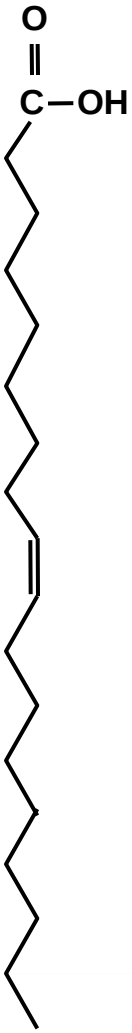
090407

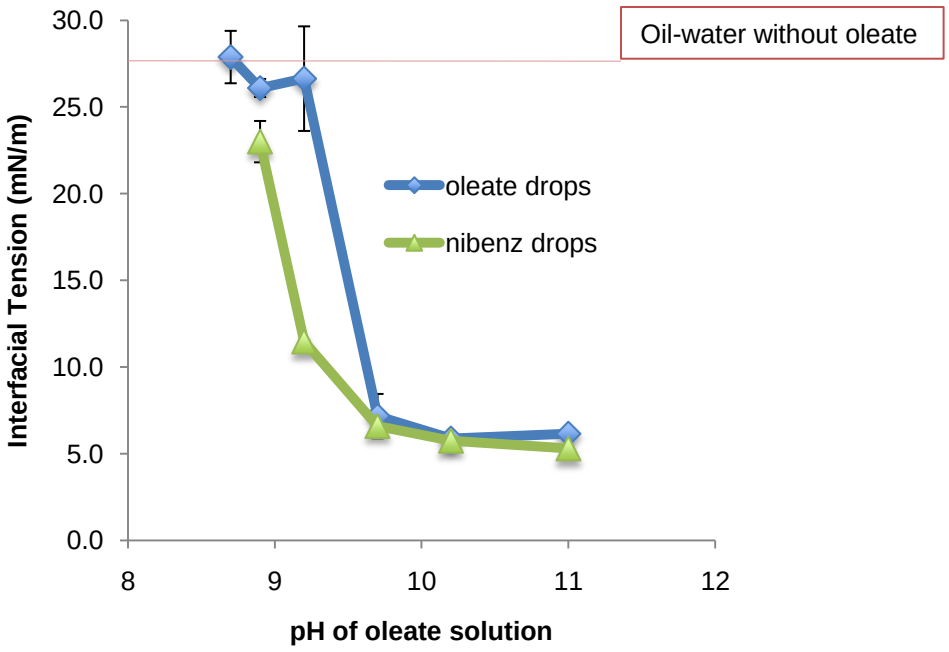
Droplet movement responds to local pH

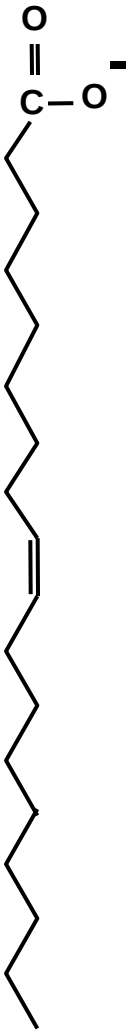




There is a difference in interfacial tension around the droplet which leads to flow and affects motion of droplet







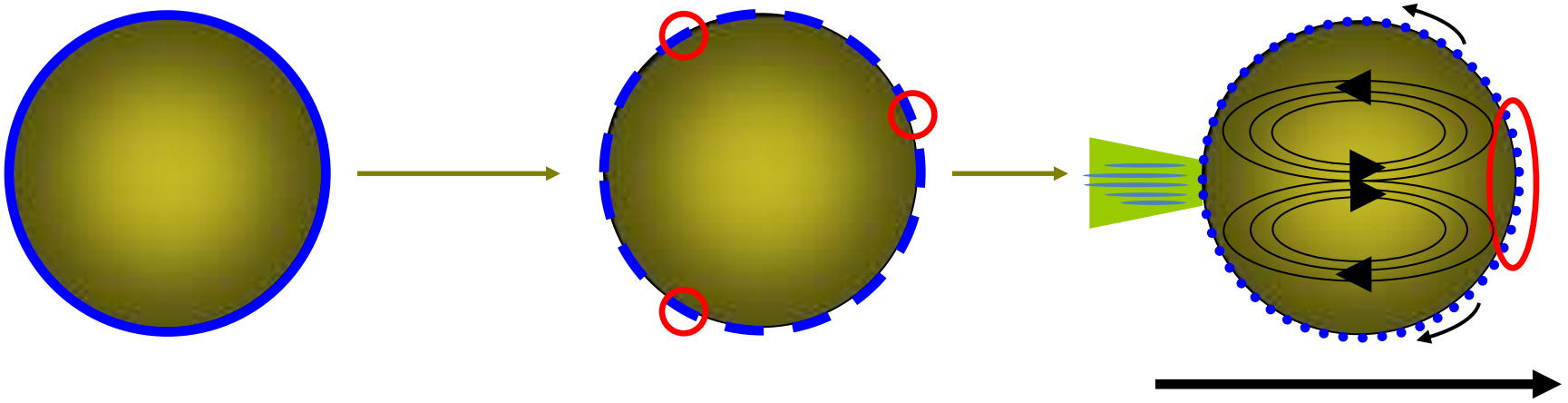
The liquid-liquid interface acts as a dynamic boundary that *senses* and responds to the local environment.

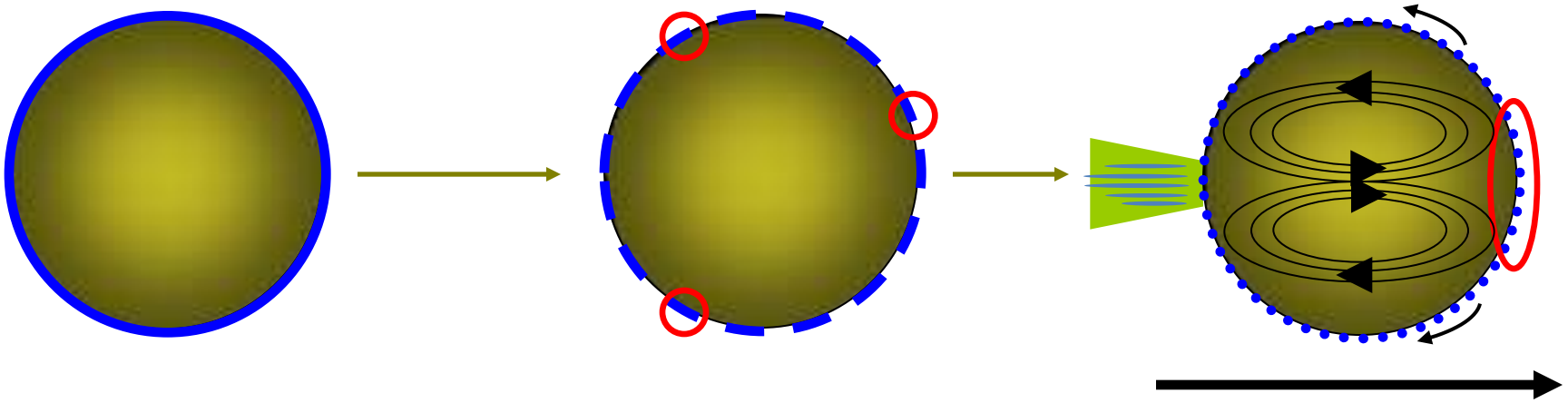
pH gradient (externally imposed or self-generated) changes the interfacial tension around the droplet.

This is enough to initiate a Marangoni instability and convective flow.

The droplet can now *move* from point A to B.

This is a simple instance of *sensory-motor coupling*.



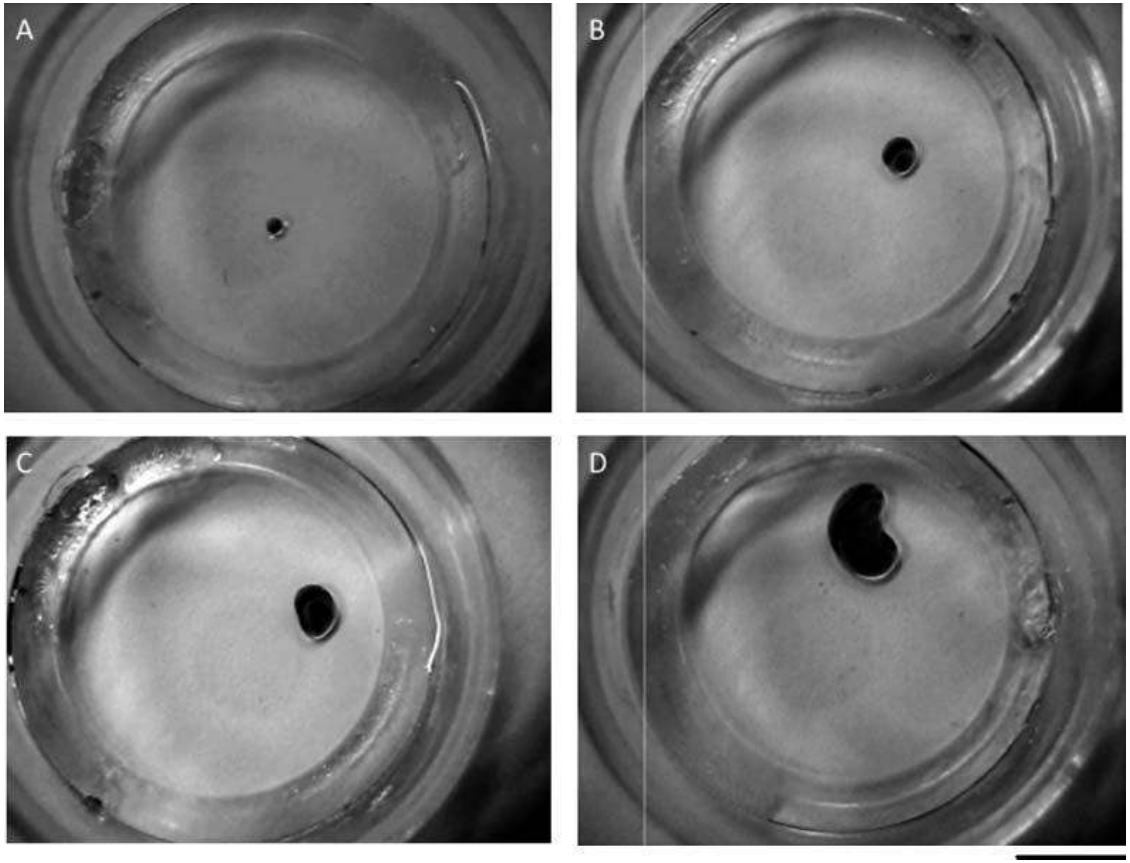


The droplet continues to move (more than 2 hours) because the initial convection brings fresh precursor to the interface to be hydrolyzed which then adds to the pH gradient.

This provides a positive *feedback loop* and the movement of the oil droplet is sustained due to a link between physical fluid dynamics and the embedded chemistry.

Convection provides a physical feedback loop for sustained motion as it supports Newton's third law and hydrodynamic pressure.

Shape matters



Study of motion

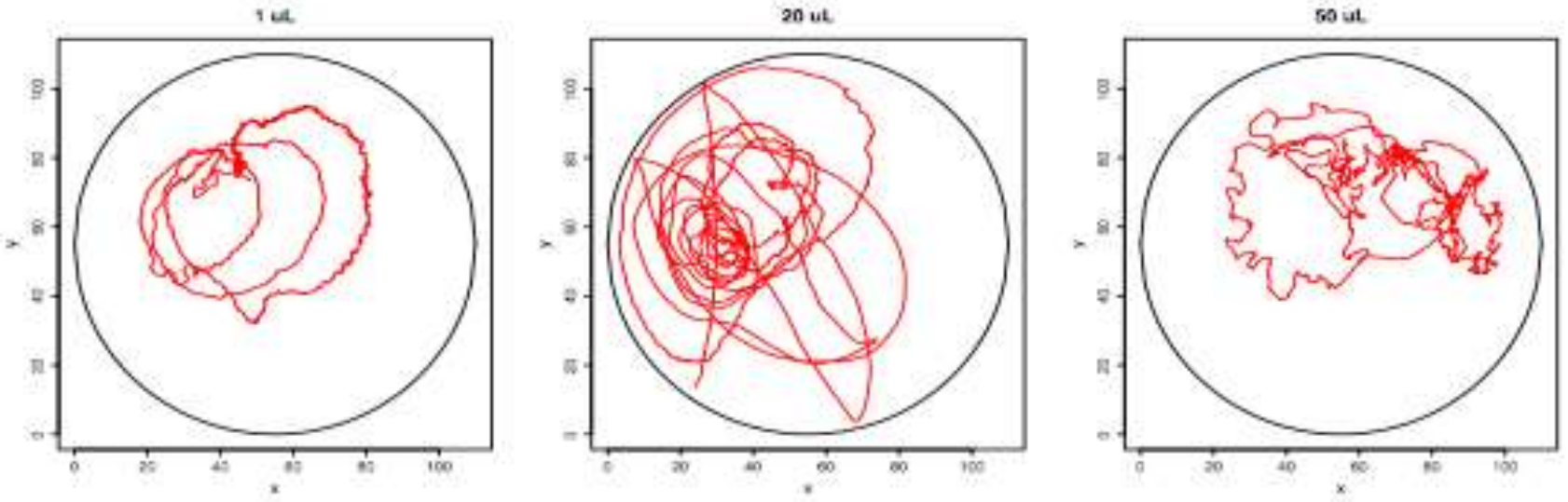


Figure 4: Trajectory of a droplet in a glass plate (110mm in diameter).

A droplet often changes its speed and direction

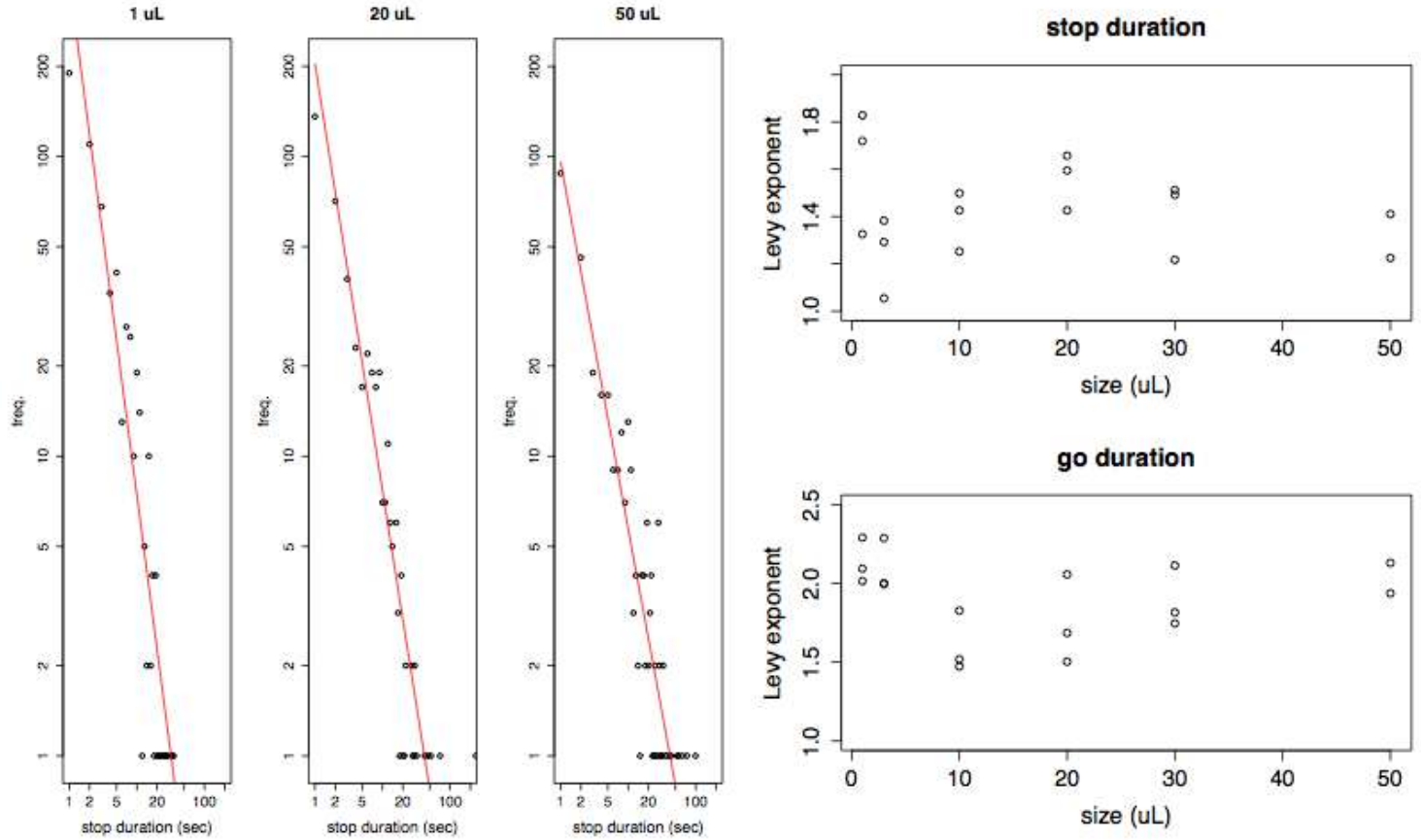


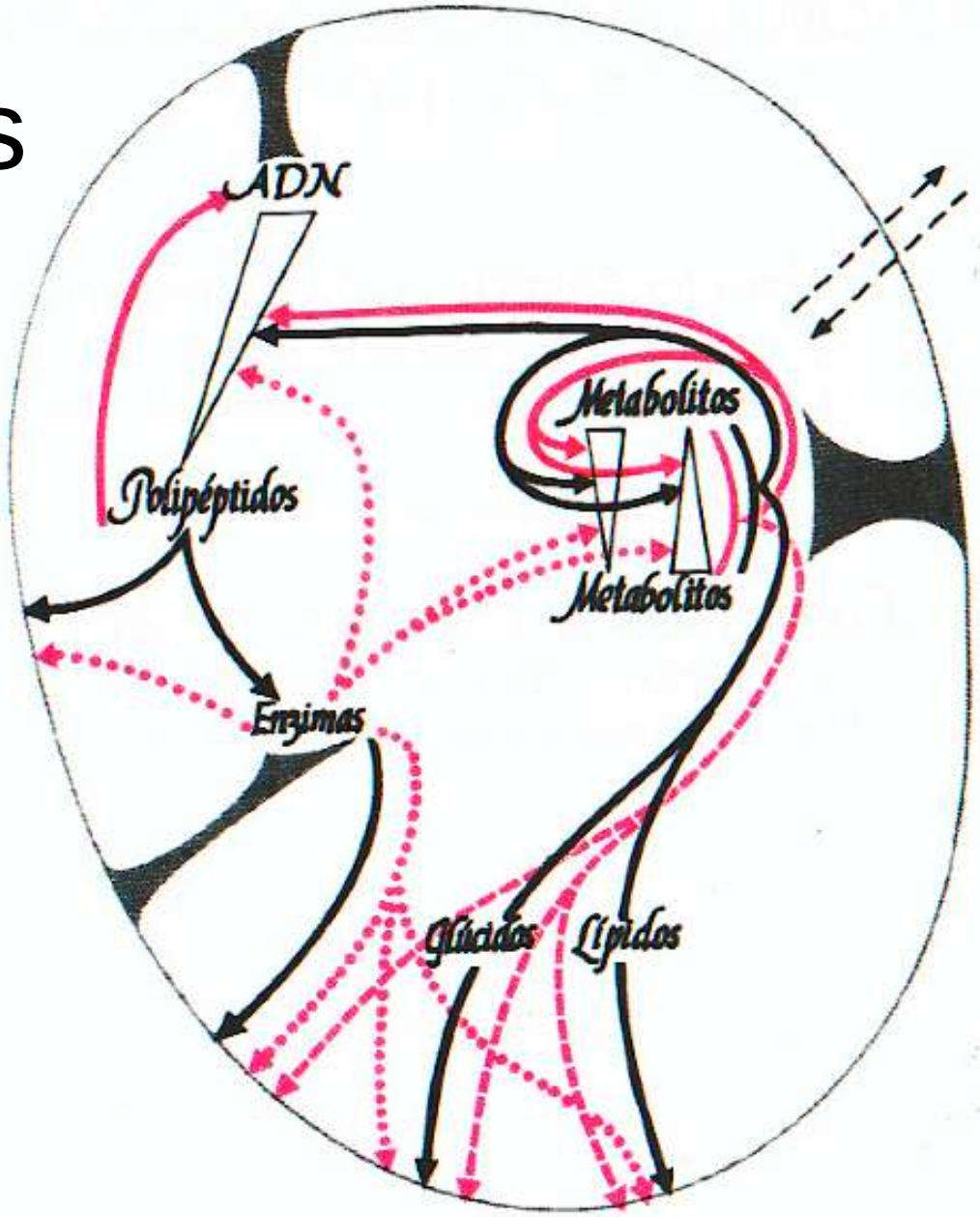
Figure 8: The distribution of the stop-go interval. The distribution obeys power-law (left) and the exponent calculated from the stop-go interval distribution is depicted as a function of a droplet size (right).

Conclusions so far…

- An oil droplet can act as an agent with sensory motor coupling and act in response to and act on its environment
- The droplet can move independently or chemotactically
- The movement style is similar to movement in living organisms, with some evidence of memory effects
- Simple sensory motor coupling in these systems may be used to understand the basis of intelligence.
- The oil droplet system, because of its simplicity in composition, dynamic behavior in multidimensional spaces, and possible emergent behaviors, could be used as an artificial life model system in a chemistry [illegible] game of Life is used in the virtual

Autopoiesis

Autopoiesis is a self-regulating mechanism of an internal metabolic network that maintains the boundary of the cell. The basic notion of autopoiesis is self-organization of a *circular link* between a metabolic network and a membrane.



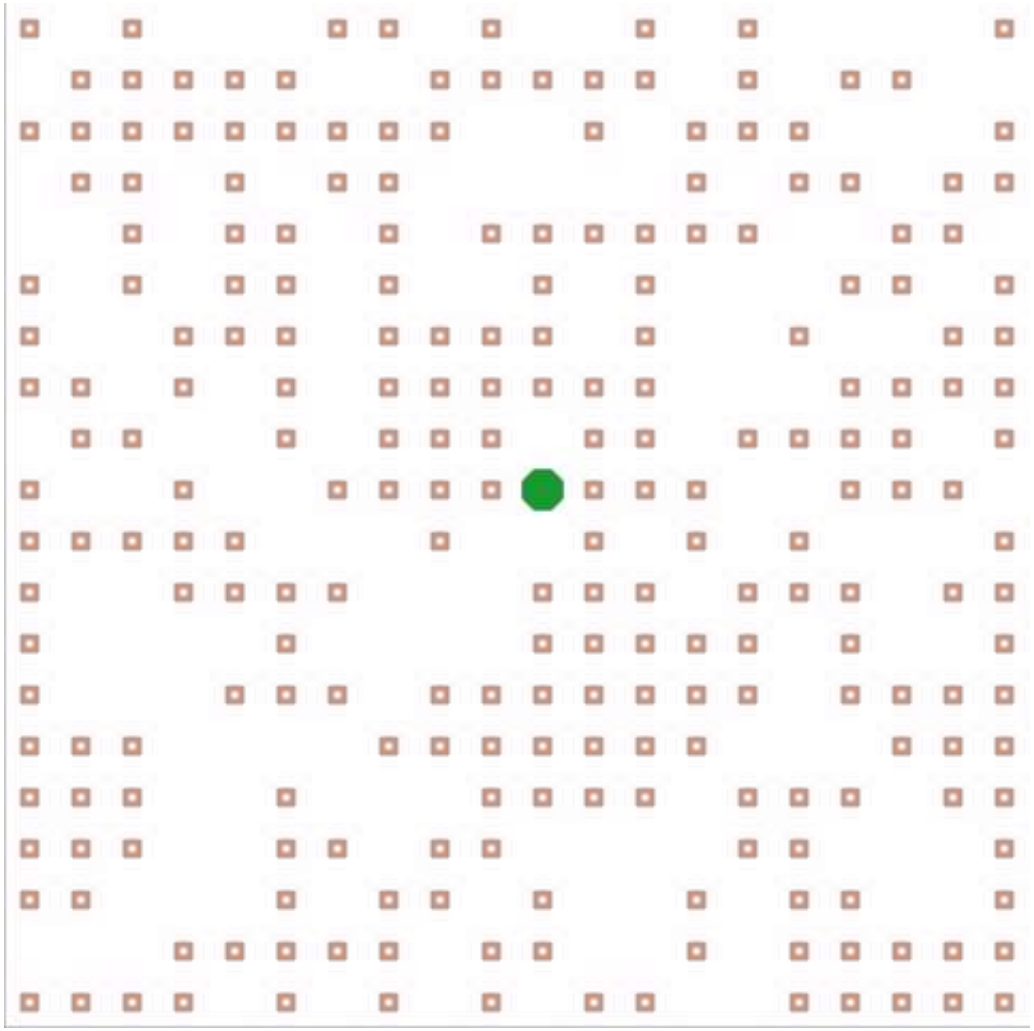
From De Maquinas y seres vivos (“on machines and living beings”) by Maturana and Varela

Autopoietic Cell

- The autopoietic cell having the autopoietic property can be explicitly modeled by a simple stochastic automaton on a two –dimensional grid space.

S=substrate C=catalyst L=Membrane particles

Production: 2S+C→L
Bonding: L+L →L=L
Disintegration: L→ S+S



surfactant structures → membrane system → selecting chemical system

This circular relationship is called AUTOPOIESIS

Varela, F. J., Maturana, H. R. & Uribe, R. (1974), `Autopoiesis: The Organization of Living Systems, its Characterization and a Model', BioSystems 5, 187-196. This simulation program is by Keisuke Suzuki.

Dynamic Autopoiesis

What is missing in the original picture of autopoiesis is temporal organization. Dynamic component extends the notion of autopoiesis in that we can interpret the droplet's self-movement as action selection. As we have seen in the previous slides, droplets *spontaneously* starts to move and stops abruptly but re-starts again by changing its speed and direction.

What is homeodynamics?

Homeostasis is described as a property of a self-regulating dynamics. Homeodynamics is defined as a *meta-dynamics*. A system changes the dynamics itself (i.e. changes parameters or boundary condition) to adapt to the environment. We say *self-movement is a meta-dynamics* to the internal chemical reaction and hydro-dynamics.

In the other words, we say that, contrary to homeostasis, homeodynamics is to not sustain states but to sustain fluctuation of states and parameters.

Conclusions

- A missing notion in the robotics field and autopoiesis is the self-organization of self-movement and homeodynamics. The transition from homeostatic self (self-maintained statically) to homeodynamic self (self-sustained dynamically) emphasizes the potential for homeostasis as a source for purposeful behavior even in simple systems.
- Once self-motility becomes inevitable, we begin to see an extended view of the self; autopoiesis is no longer just a stationary state that maintains itself. By realizing the homeodynamic dimension of autopoiesis, we speculate that there would be no life without self-movement.

Thank you!

International Embryo Physics Course

- Evgenii Rudnyi
- Dick Gordon

For more information, contact:

- Martin Hanczyc: martin@ifk.sdu.dk
- Takashi Ikegami: ikeg@sacral.c.u-tokyo.ac.jp

Collaborators:

Takashi Ikegami	University of Tokyo
Tadashi Sugawara	University of Tokyo
Taro Toyota	University of Tokyo
Naoto Horibe	University of Tokyo

UNIVERSITY OF SOUTHERN DENMARK

THE UNIVERSITY OF TOKYO