Towards an enactive origin of life

Nathaniel Virgo

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The central point

- Enactivism - “**life is mind-like, mind is life-like**”

  or even “**life = mind**”

- If we take this seriously, we need an “**embodied, embedded, enactive, extended**” approach to life, not just mind

- And therefore also to the origin of life

- I believe this is possible, and indeed it gives us insights into both life and mind

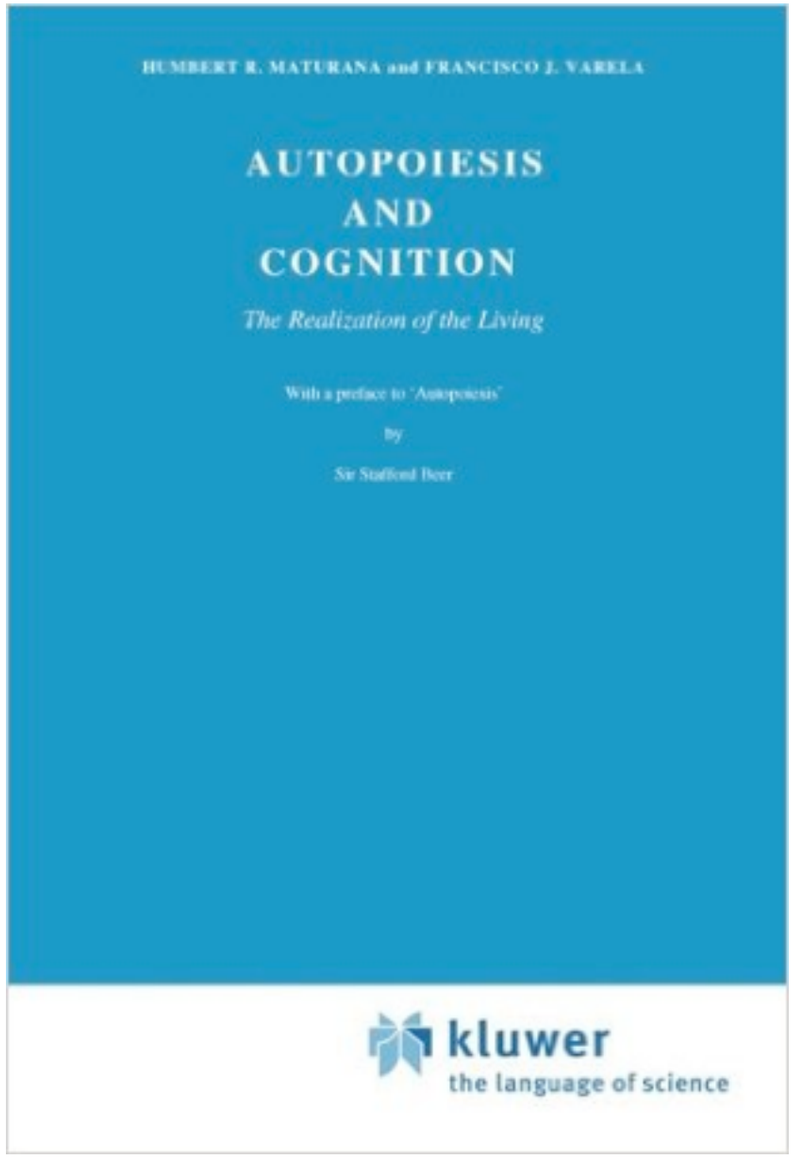
Overview [TENTATIVE]

- Background on autopoiesis (my own perspective)
- Extended autopoiesis
- Intro to dissipative structures
- The importance of death (“precariousness”)
- Dissipative structures as “model organisms”
- The origin of individuals

Part 1

Autopoiesis and extended autopoiesis

Autopoiesis



Humberto Maturana
Francisco Varela

Autopoiesis

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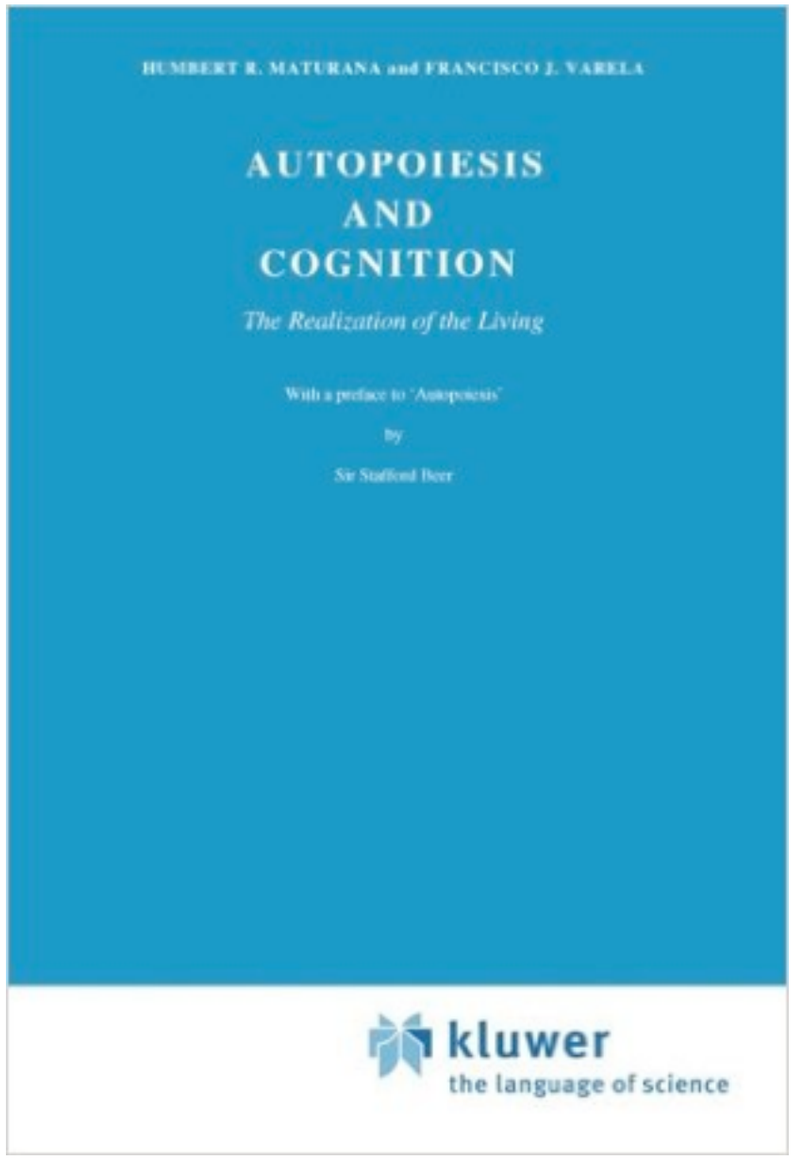
“autopoiesis”



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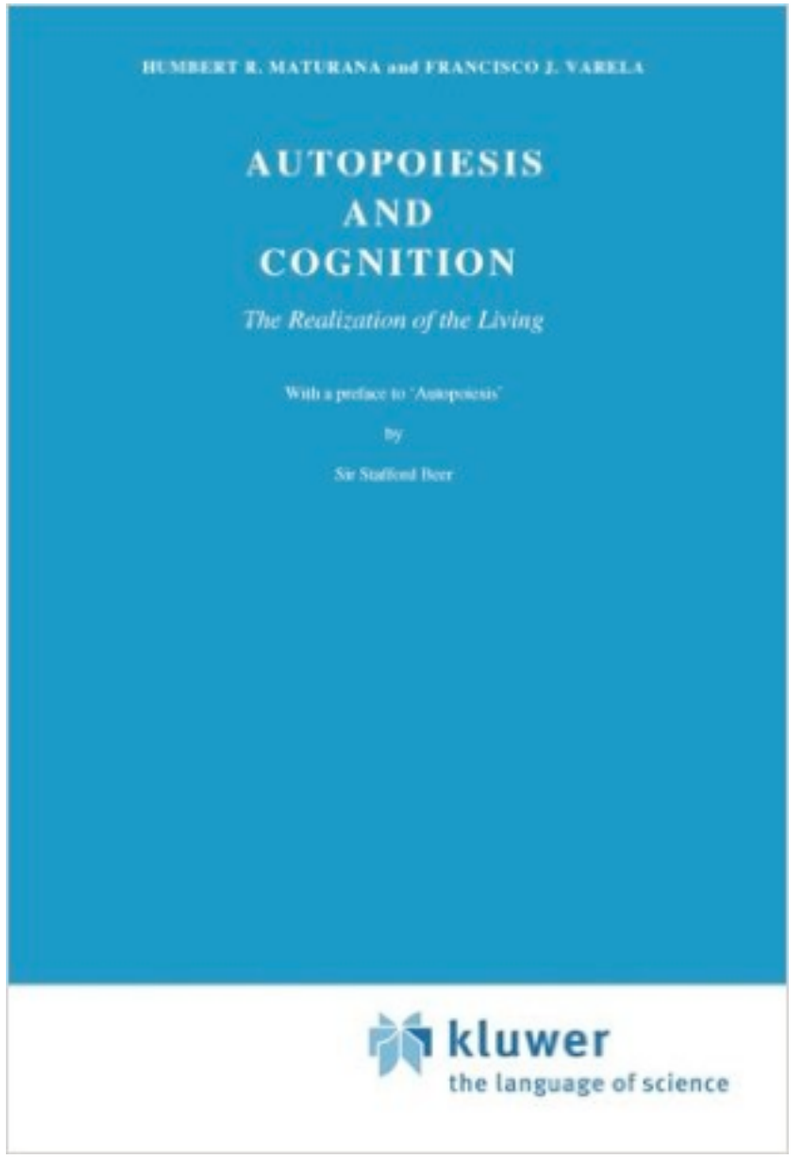
Autopoiesis

- First proposed in 1972 (1980 in English) as a tentative definition of life:



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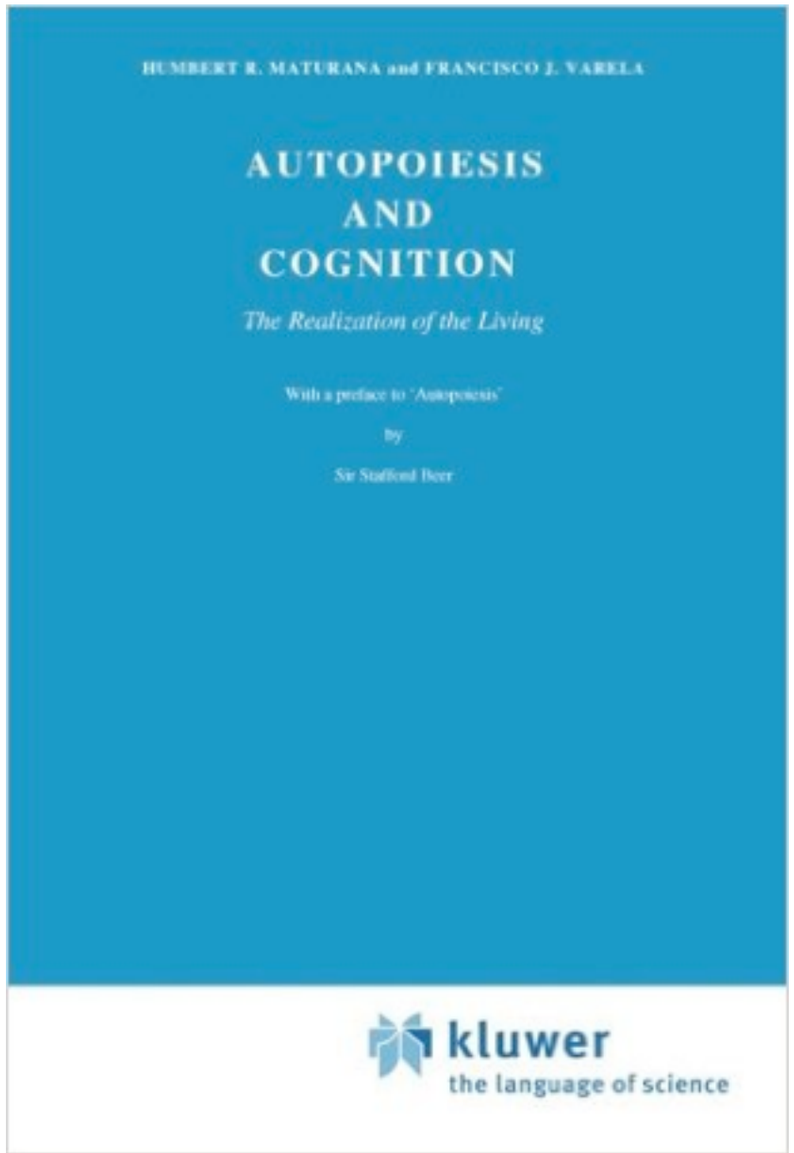
"An autopoietic machine is a machine organized (defined as a unity) as a network of processes of production (transformation and destruction) of components that produces the components which: (i) through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them; and (ii) constitute it (the machine) as a concrete unity in the space in which they (the components) exist by specifying the topological domain of its realization as such a network."



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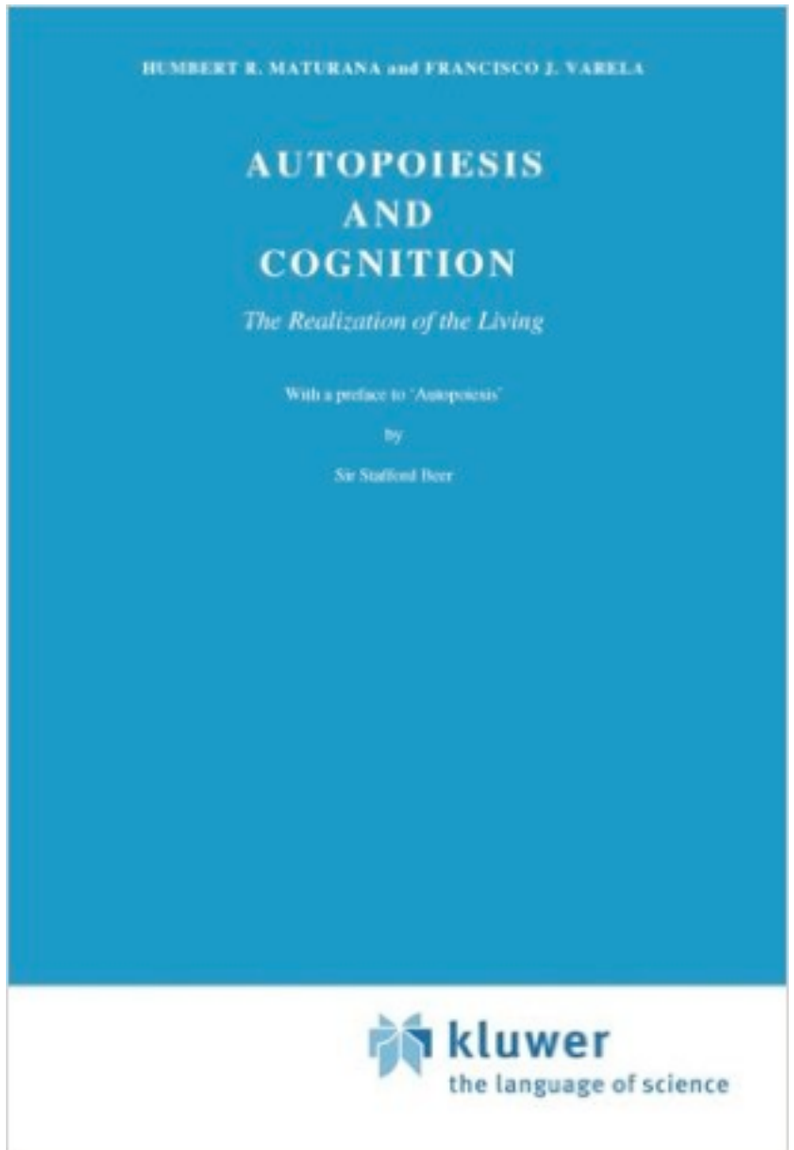
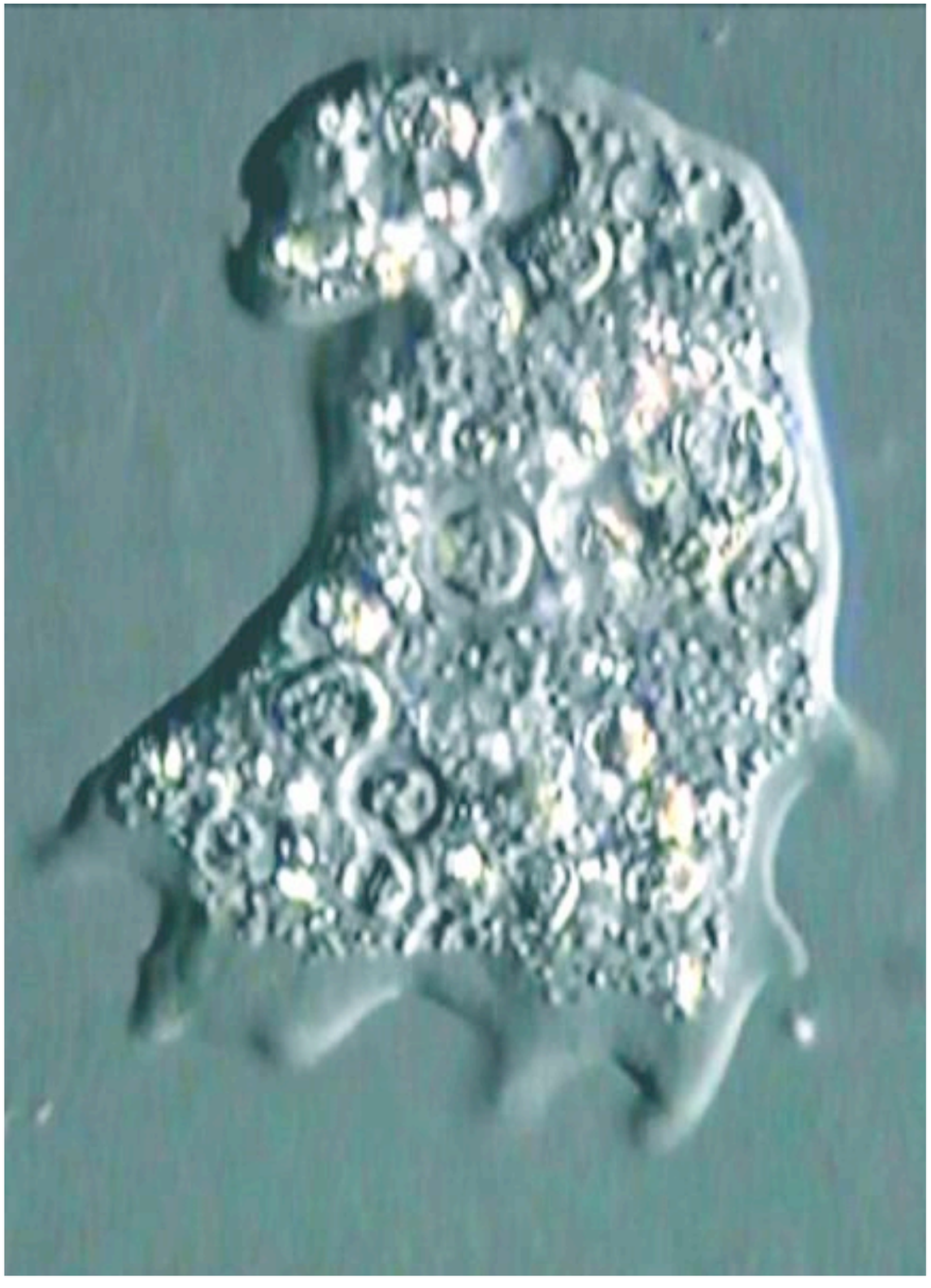
- Note: no reference to evolution - it's a reaction against that

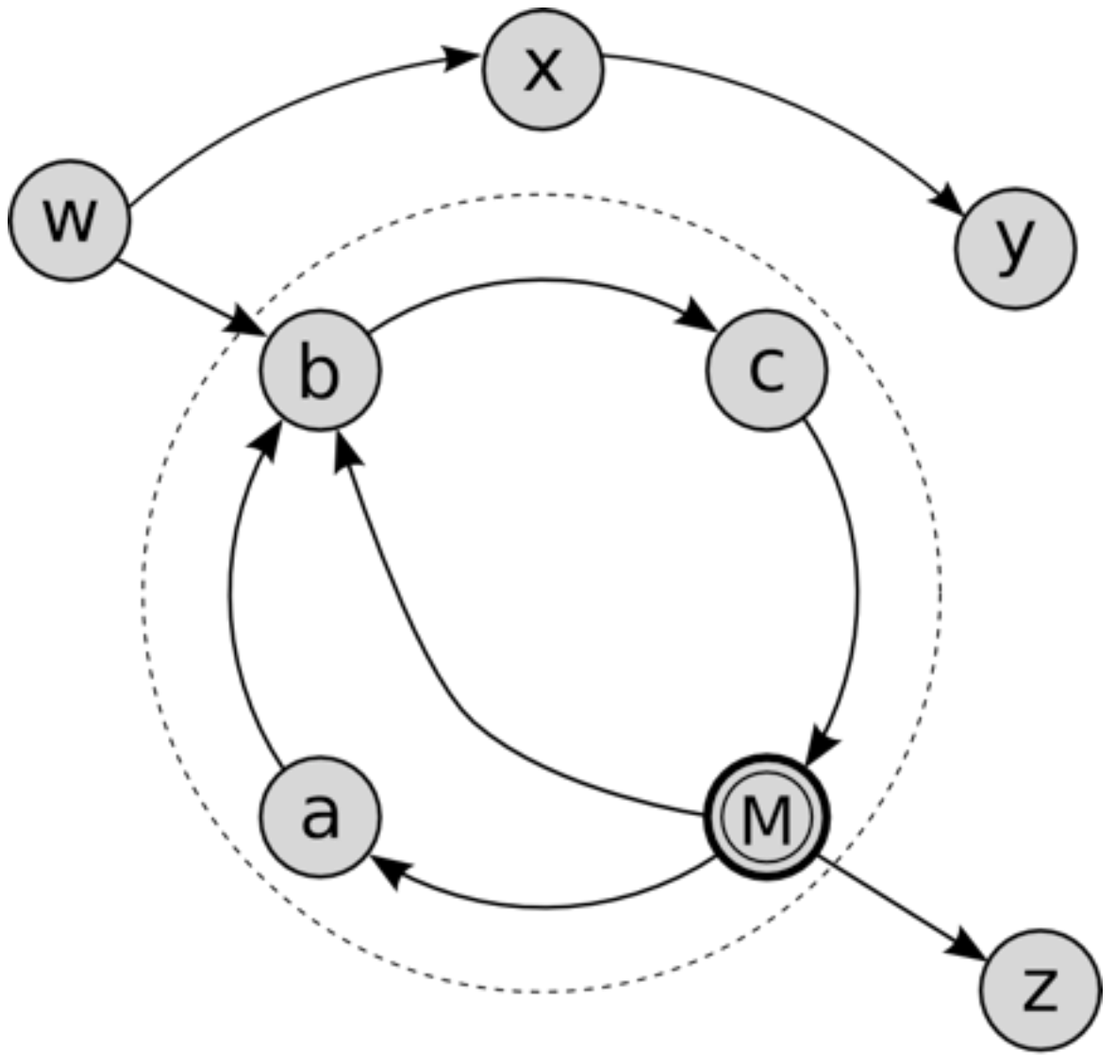


Humberto Maturana
Francisco Varela

What is a process?

- Maturana and Varela don’t give examples! But for me, these are some:
    - “metabolic” chemical reaction, e.g. a step in the Krebs cycle
    - transcription of RNA into a protein
    - transport of ions across a membrane
    - reacting to a stimulus
    - learning to walk
    - growing a liver

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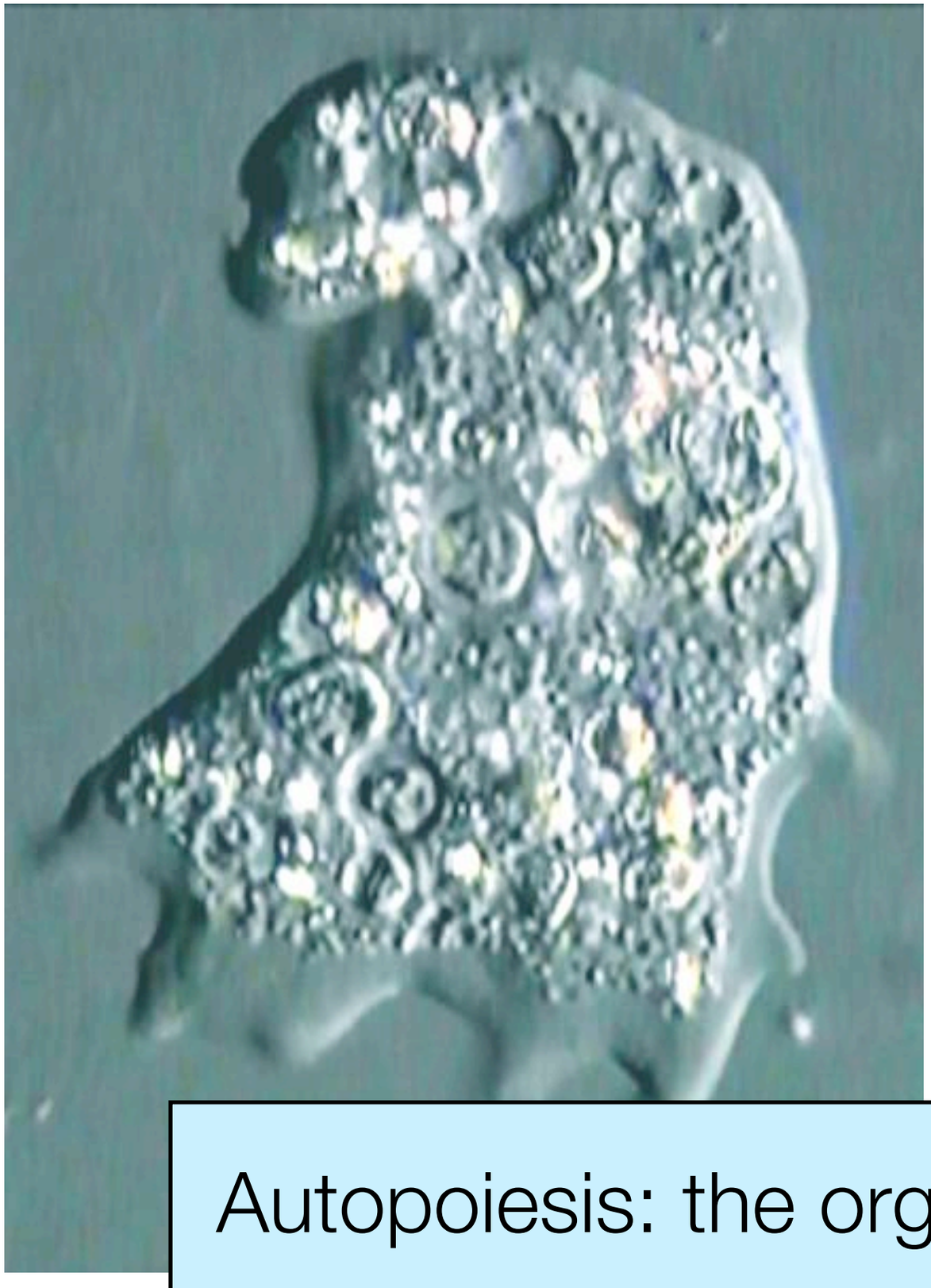

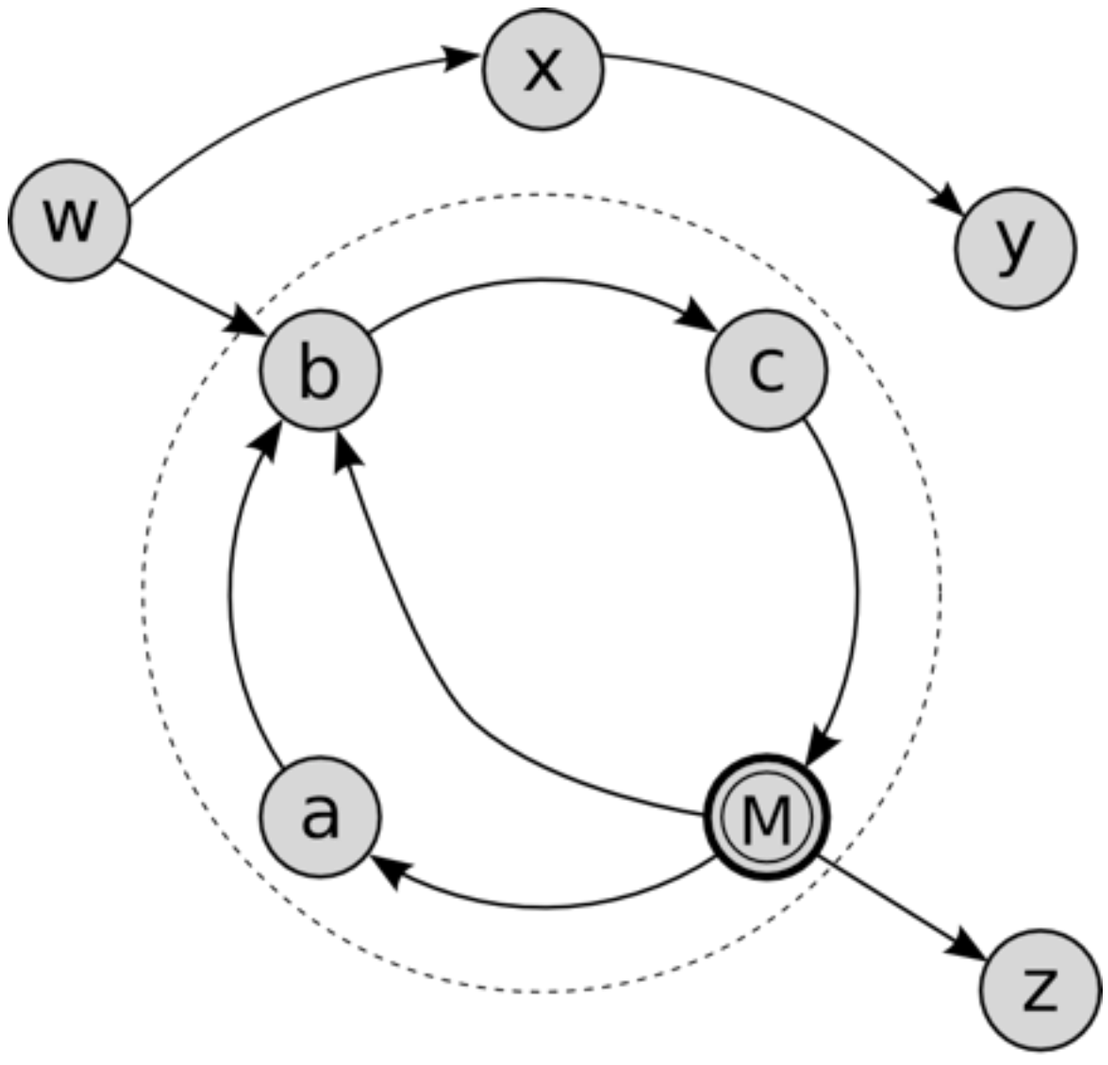

Autopoiesis: the organism *is* the network

What is a process?

- On my reading, at least:
    - Chemical reactions
    - Transport across membranes
        - But also: motion, reacting to stimulus, learning, ...
- These all form *one* network

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“metabolism”

What is a process?

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    - Transport across membranes
        - But also: motion, reacting to stimulus, learning, ...
- These all form *one* network
- So for Maturana and Varela, **life and cognition are deeply related**

What is a process?

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    - Chemical reactions
    - Transport across membranes
        - But also: m
- These all form

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“cognition”

- So for Maturana and Varela, **life and cognition are deeply related**

Autopoiesis and the Origins of Life

- There are a few groups and individuals working on models of autopoiesis in a pre-biological context

- Some examples follow...

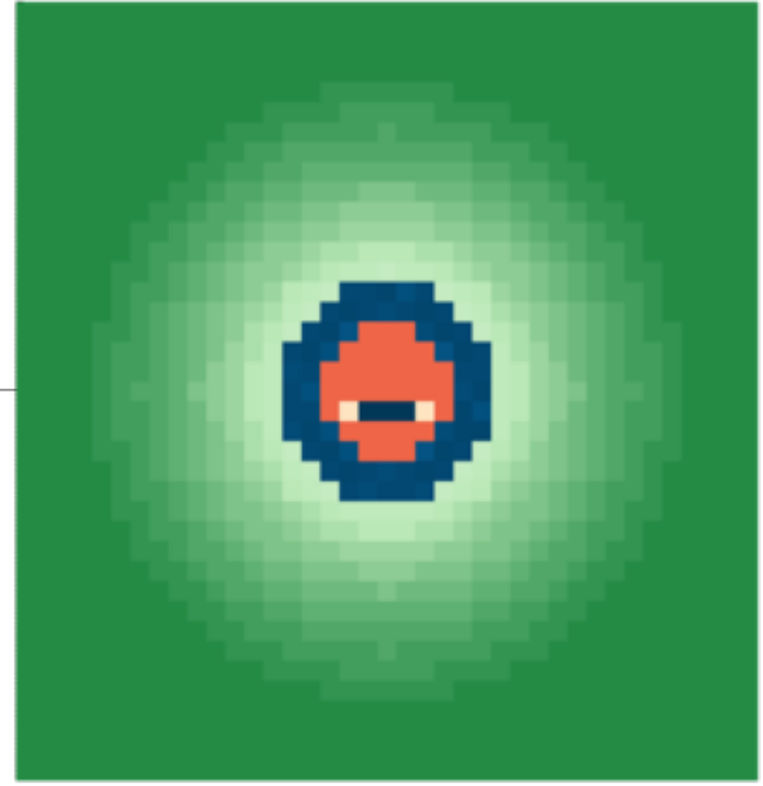
Modelling autopoiesis

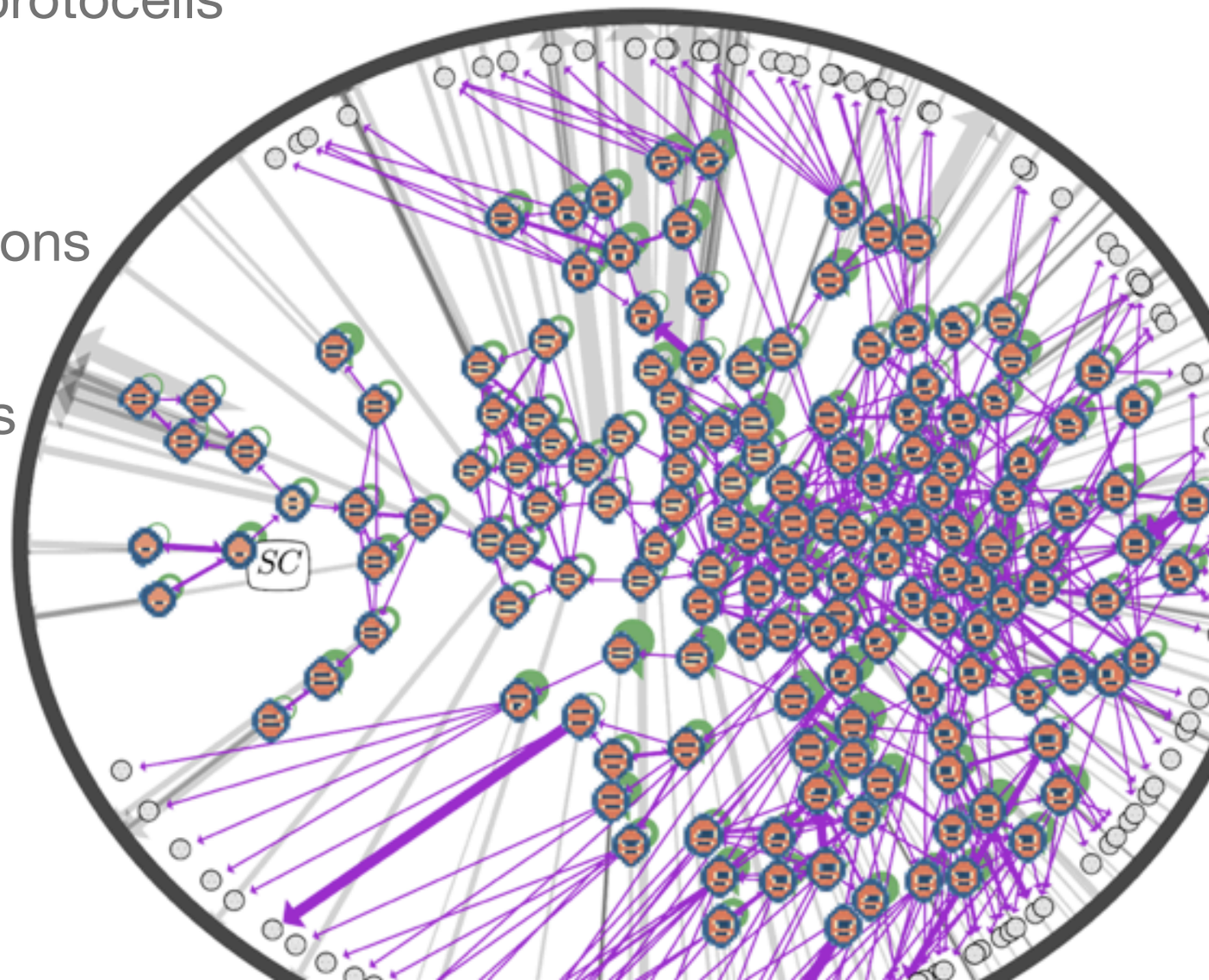
- Eran Agmon (with Gates, Beer)

- Spatial model of concentration dynamics supports emergence of “minimal protocells”

- “Network of possible ontogenies” mapped by exposing to perturbations

- Analysis reveals how perturbations change response to future perturbations





Example - self-propelled oil droplets

Fatty Acid Chemistry at the Oil−Water Interface: Self-Propelled Oil Droplets

Martin M. Hanczyc,[†] Taro Toyota,[‡] Takashi Ikegami,[‡] Norman Packard,[†] and Tadashi Sugawara*[,‡]

Contribution from ProtoLife Srl, Parco Vega, Via della Liberta 12, Marghera, Venice 30175, Italy, and Department of Basic Science, Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan

Received January 31, 2007; E-mail: suga@pentacle.c.u-tokyo.ac.jp

Abstract: Fatty acids have been investigated as boundary structures to construct artificial cells due to their dynamic properties and phase transitions. Here we have explored the possibility that fatty acid systems also demonstrate movement. An oil phase was loaded with a fatty acid anhydride precursor and introduced to an aqueous fatty acid micelle solution. The oil droplets showed autonomous, sustained movement through the aqueous media. Internal convection created a positive feedback loop, and the movement of the oil droplet was sustained as convection drove fresh precursor to the surface to become hydrolyzed. As the system progressed, more surfactant was produced and some of the oil droplets transformed into supramolecular aggregates resembling multilamellar vesicles. The oil droplets also moved directionally within chemical gradients and exhibited a type of chemotaxis.

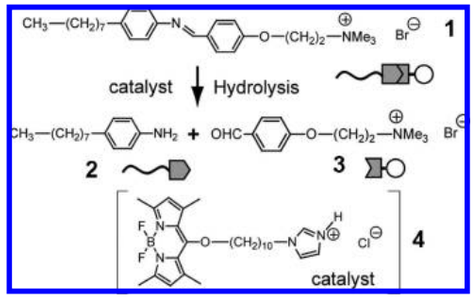
Self-Propelled Oil Droplets Consuming "Fuel" Surfactant

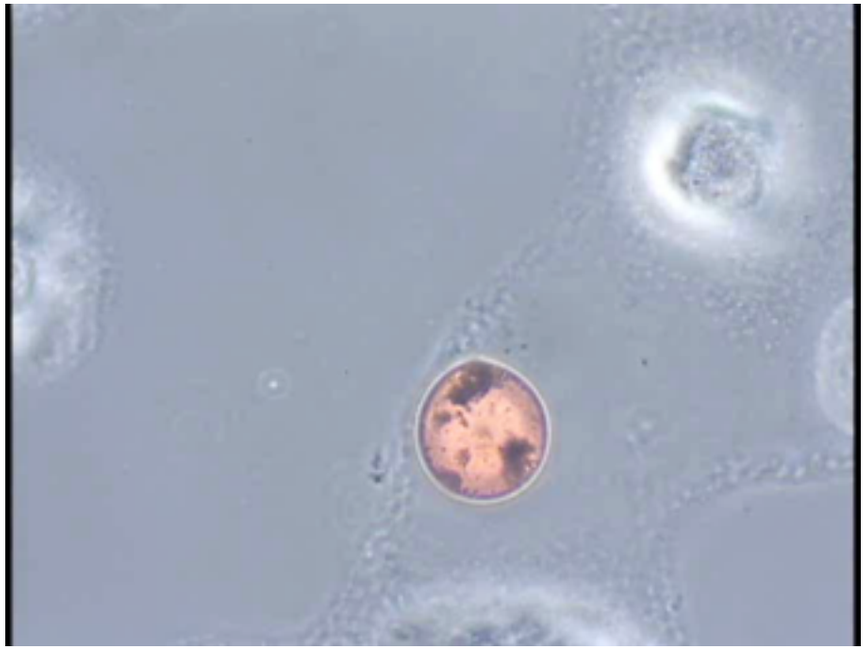
Taro Toyota,[†,‡] Naoto Maru,[†] Martin M. Hanczyc,[§] Takashi Ikegami,[||] and Tadashi Sugawara*[,†]

Department of Basic Science and Department of General Systems Sciences, Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan, Department of Applied Chemistry and Biotechnology, Graduate School of Engineering, Chiba University, 1-33 Yayoi-cho, Inage, Chiba 263-8522, Japan, and Department of Physics and Chemistry, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark

Received August 29, 2008; E-mail: suga@pentacle.c.u-tokyo.ac.jp

Self-propelled droplets have drawn much attention as a primitive type of inanimate chemical machinery, that is, the energy transduction from chemical energy to mechanical energy.[1,2] When the driving forces of these self-propelled droplets are examined, the droplets can be classified into one of three categories. First, a pentanol droplet[3] or a piece of camphor[4] on a water surface moves in the direction along which the surface tension around the self-propelled object decreases asymmetrically because of the gradual dissolution of the object itself. Second, an oil droplet on a surface of a substrate moves because the surface underneath the droplet is asymmetrically modified and causes the difference in the interfacial





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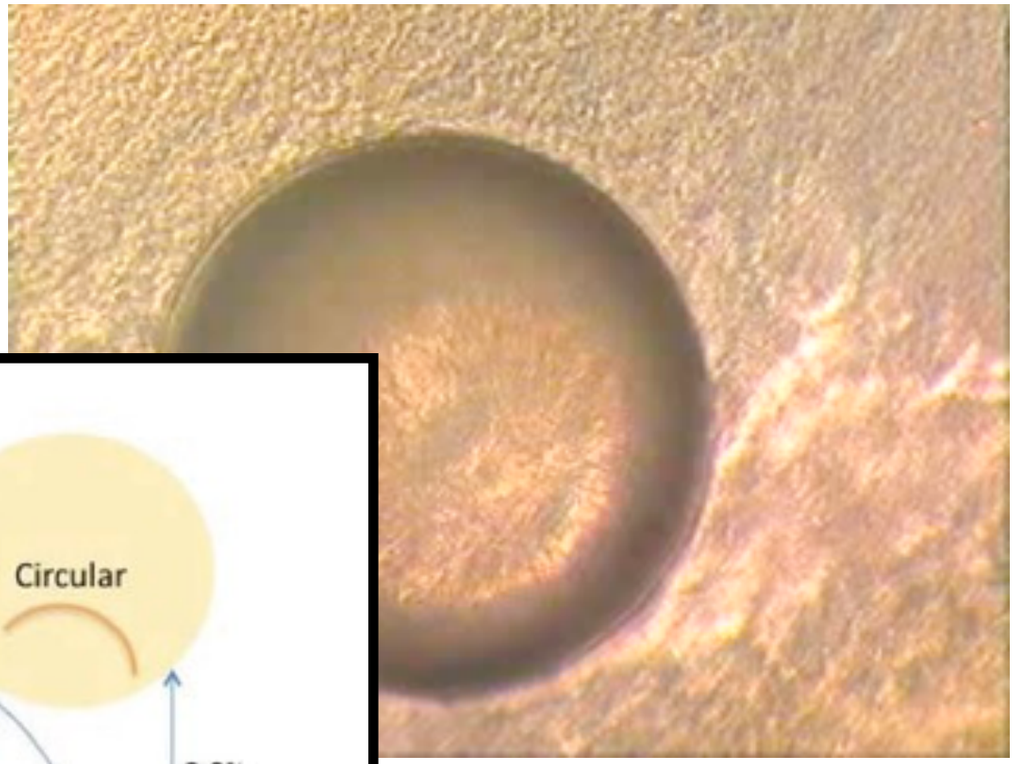

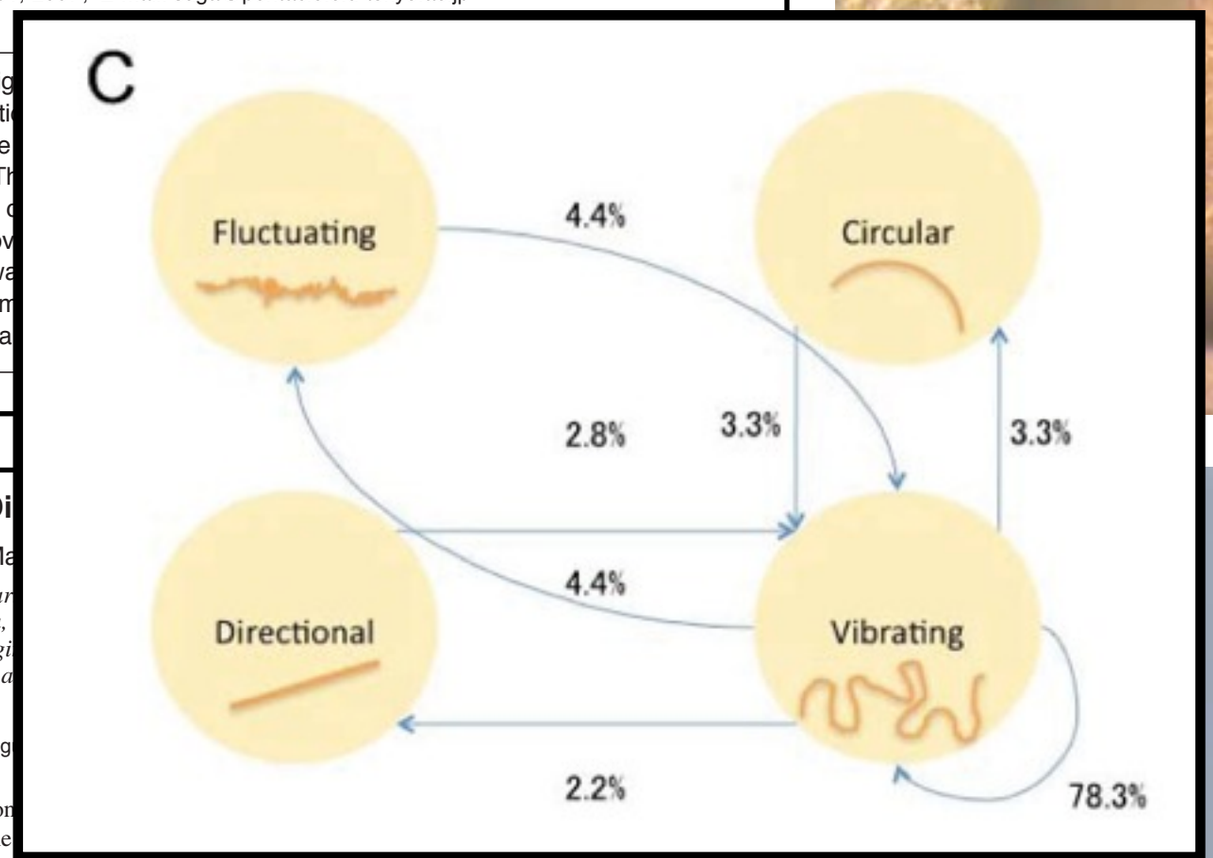

Self-Propelled Oi

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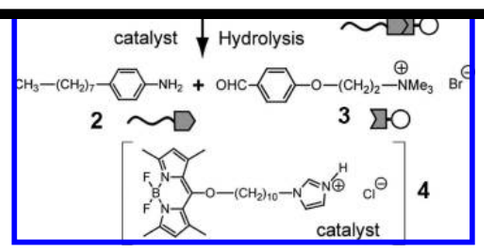
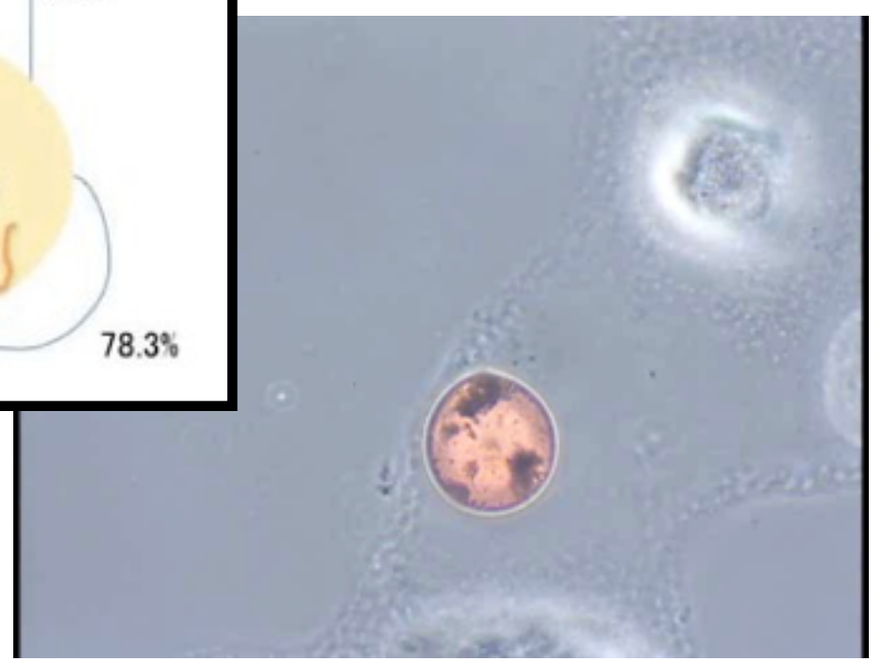
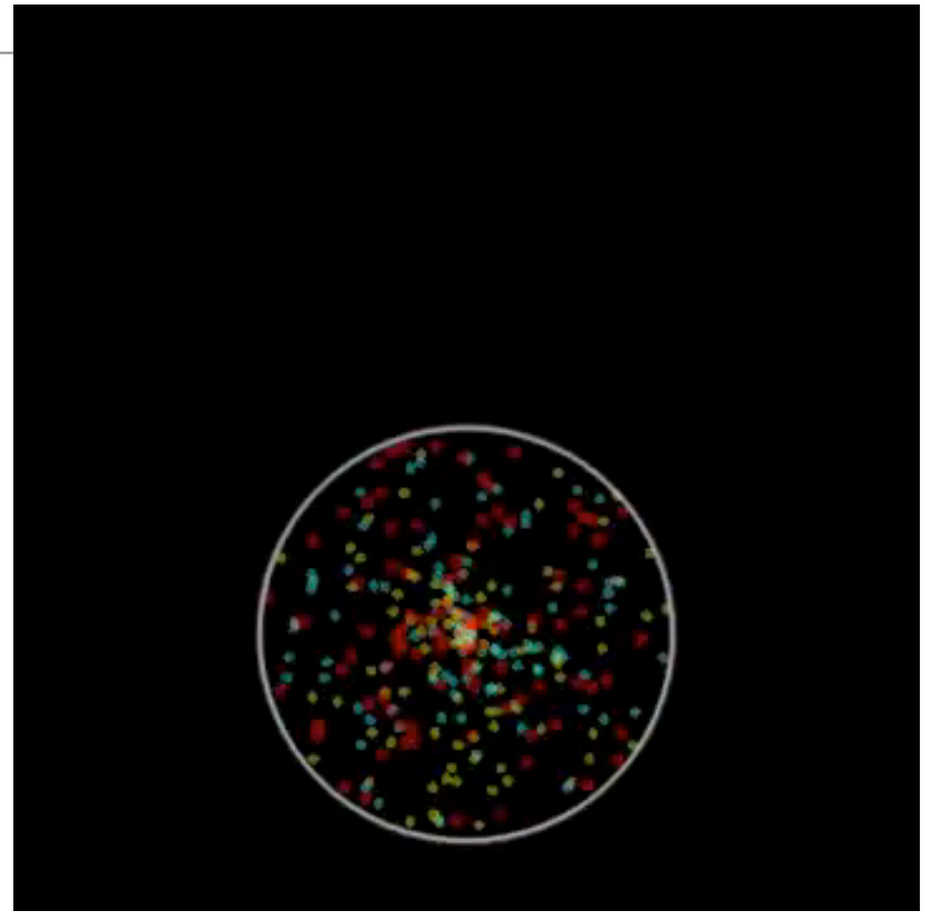




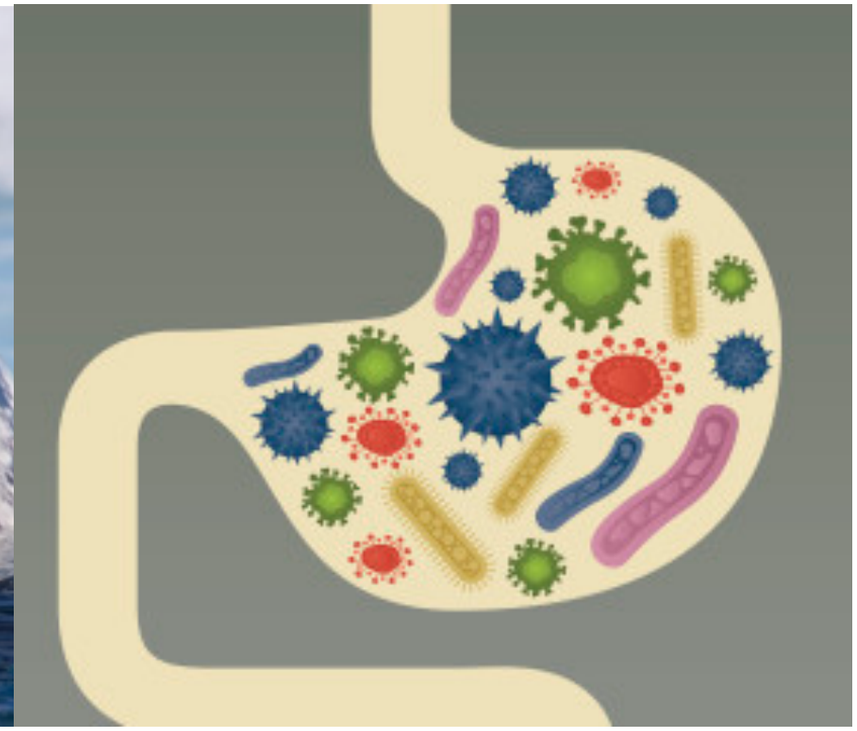
- Matthew Egebert - protocell with dynamical “metabolism-based behaviour”

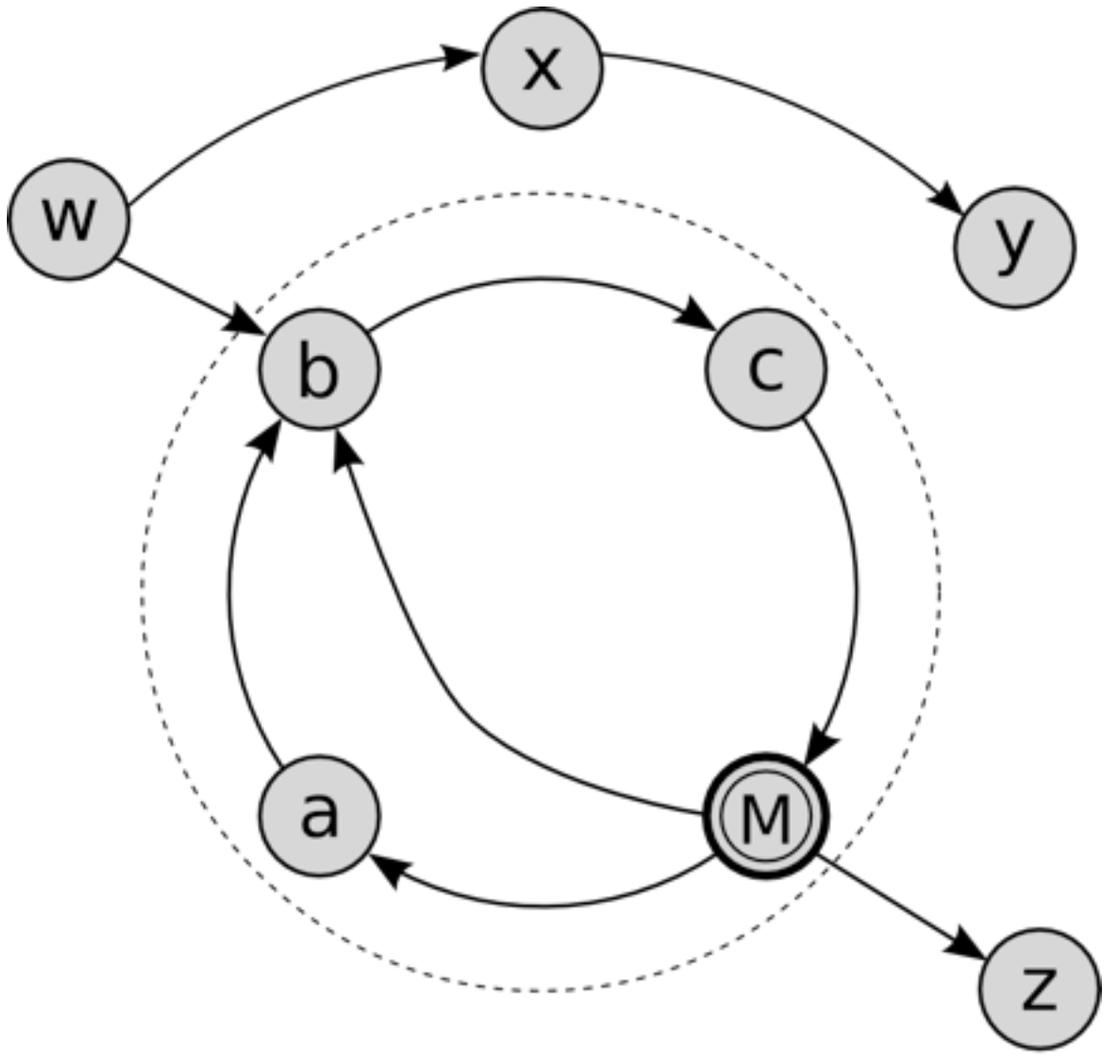


Also

- Kepa Ruiz-Mirazo (+ Ben Shirt-Ediss) at San Sebastian
    - philosophy and systems chemistry modelling
- Pierre Luigi Luisi
    - experimental work, but using a *very* different definition of autopoiesis
- Plus plenty of work on protocells

Extended life?

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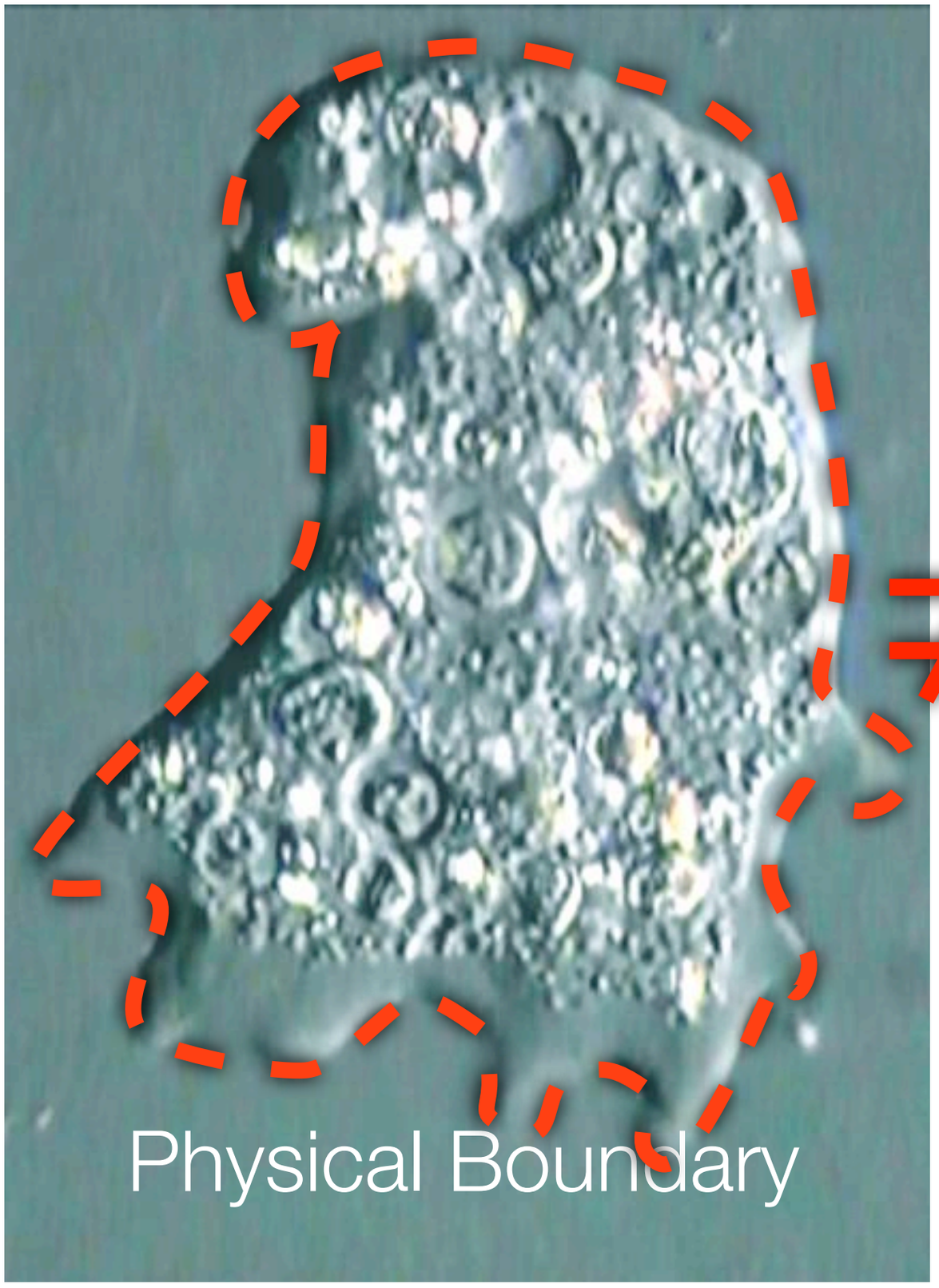

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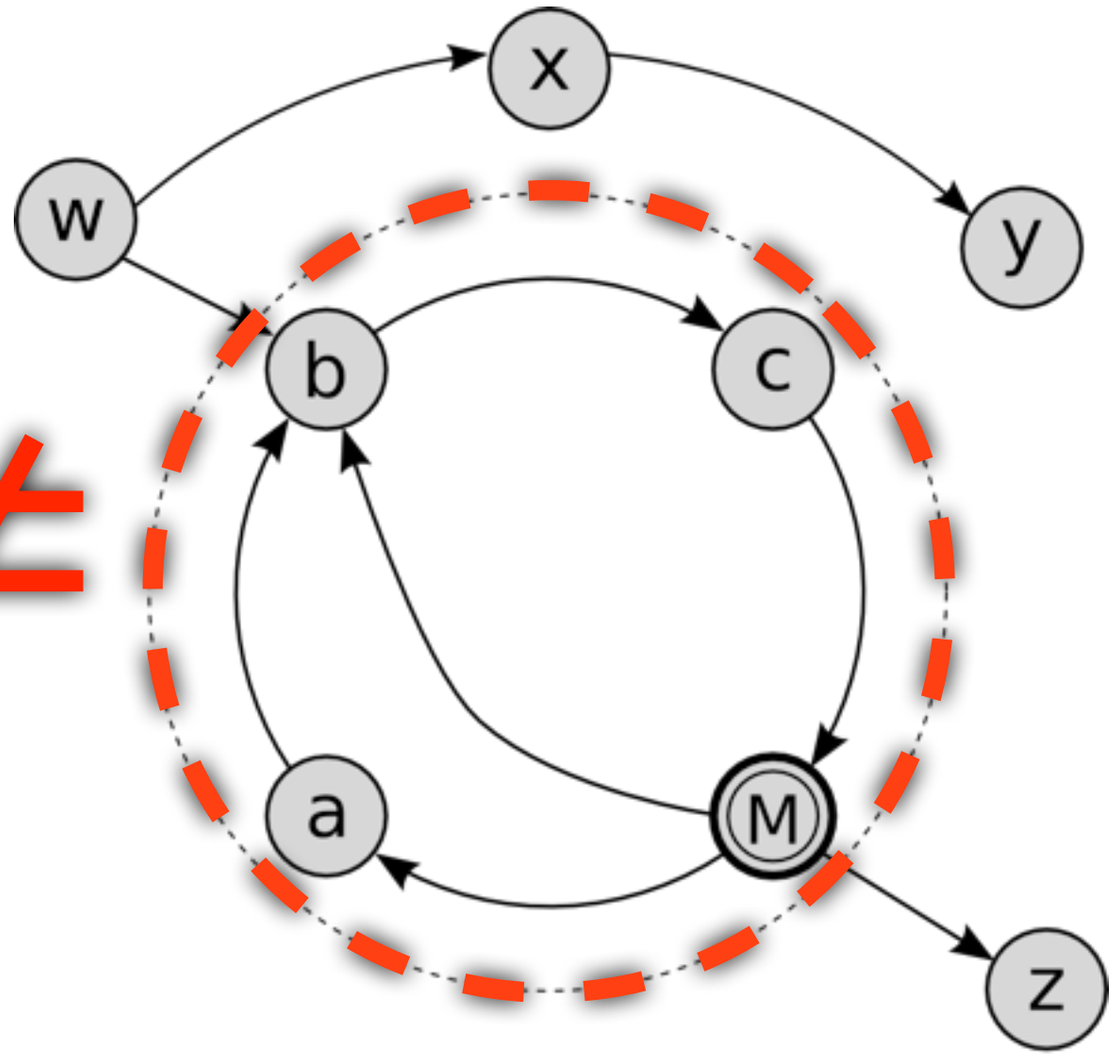
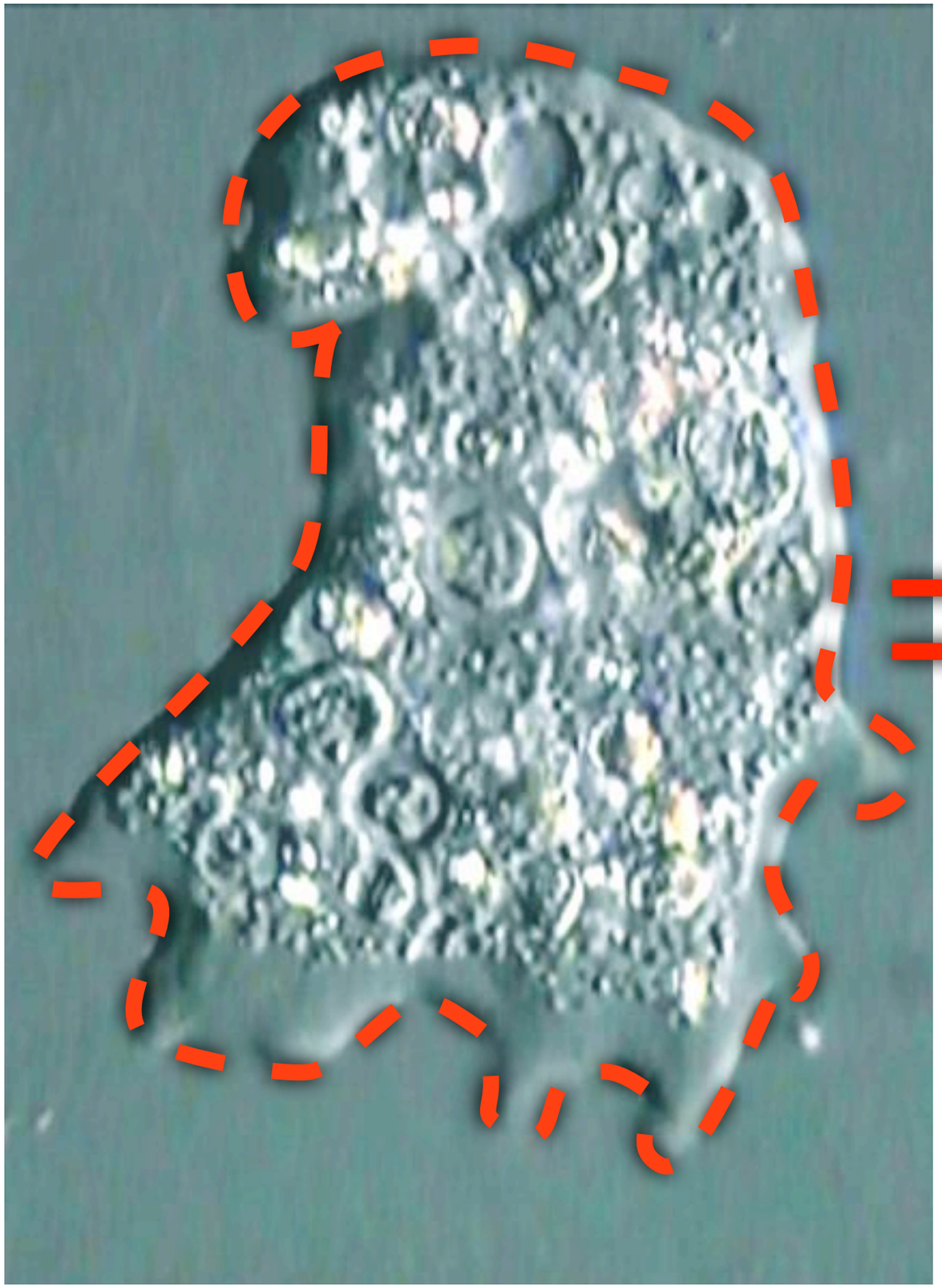
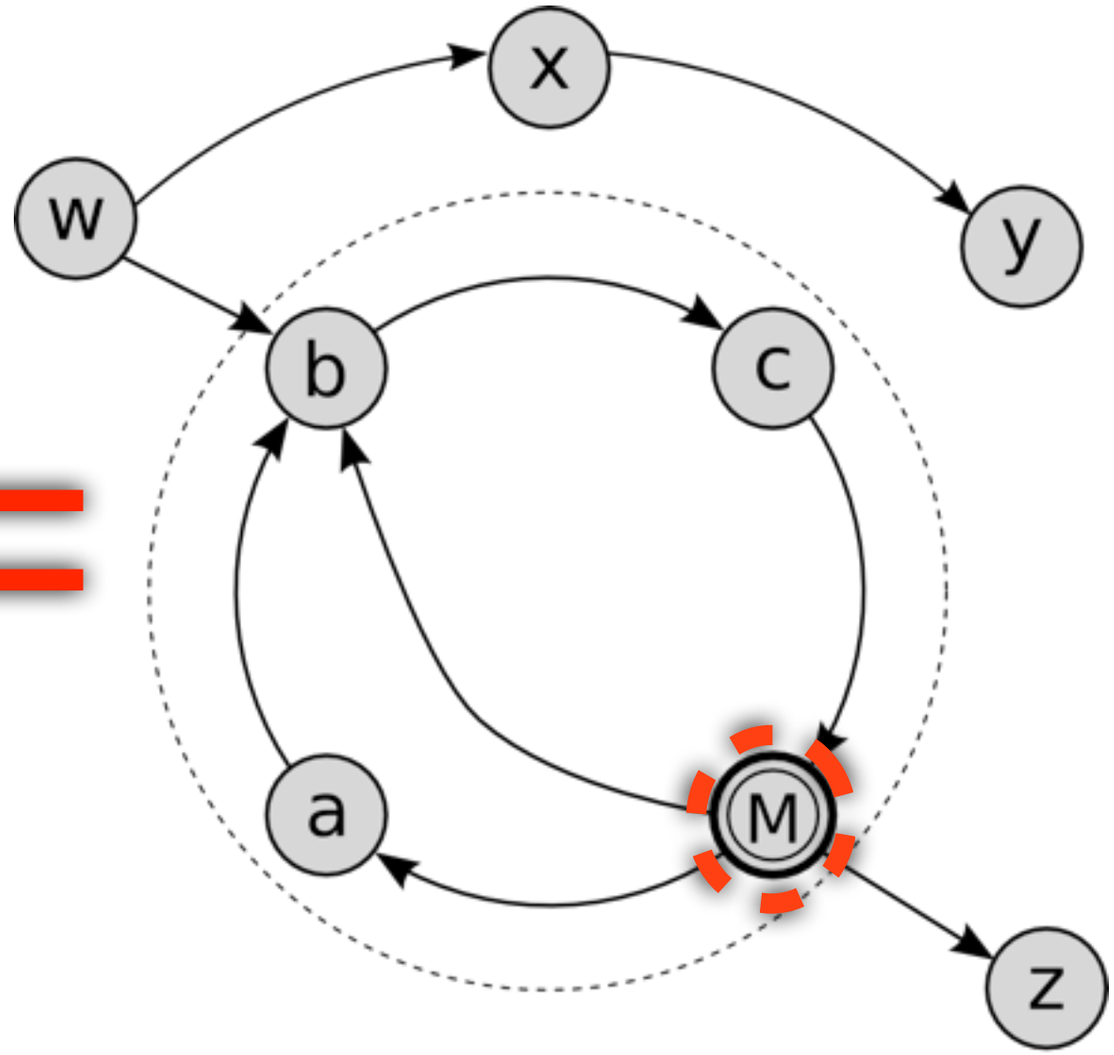


Operational Limits

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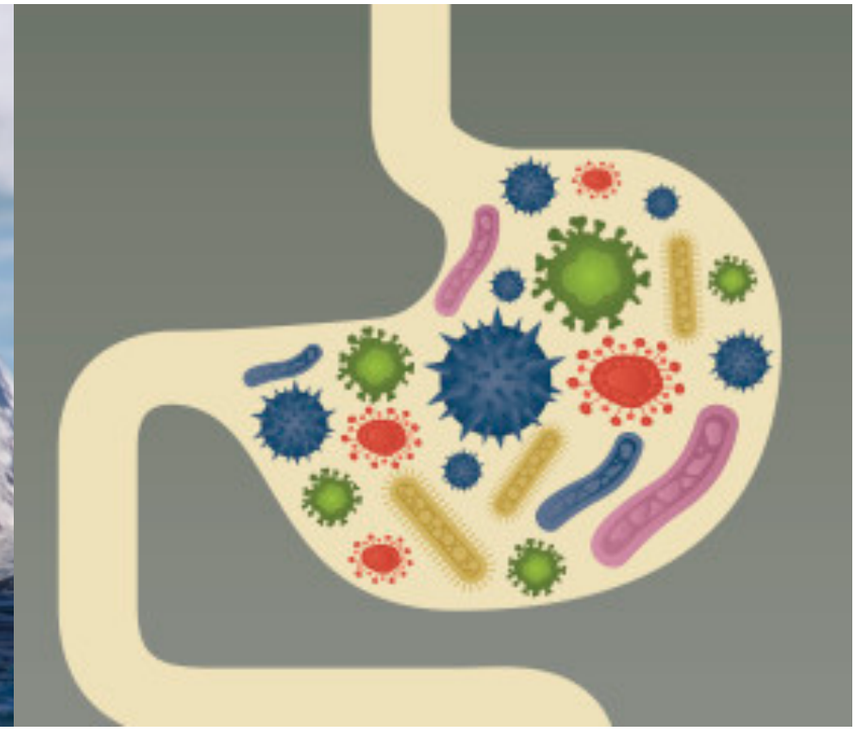
Another example (development)

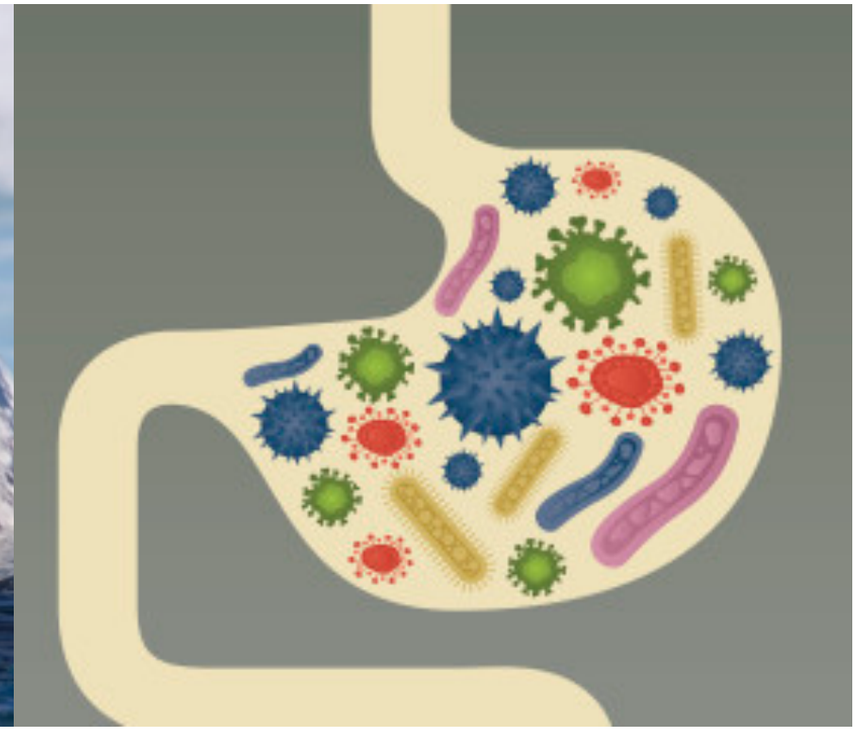
1917

Extended life?



Extended life?

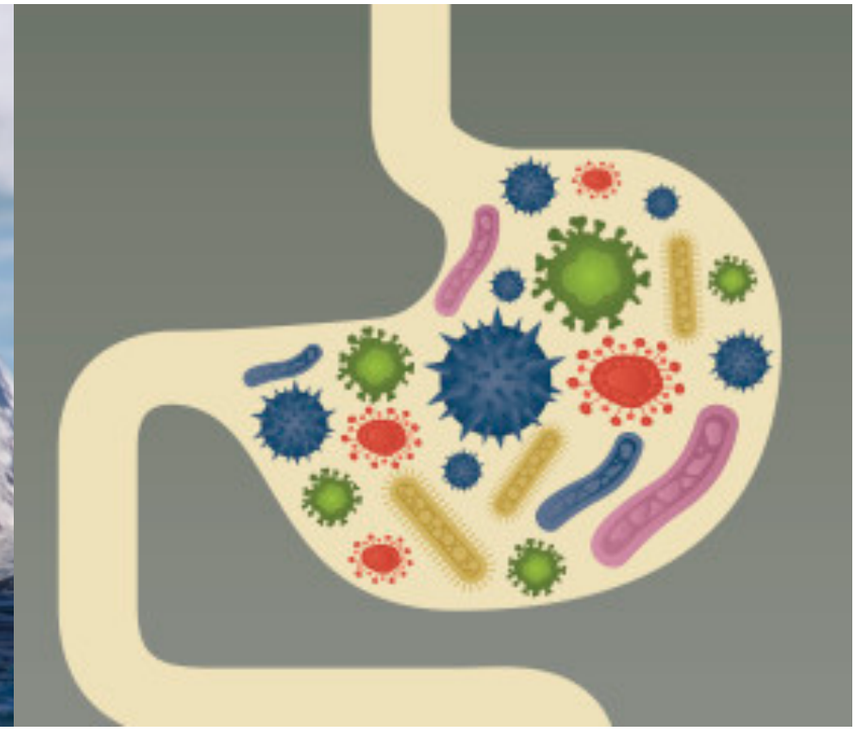




- “...an autopoietic machine is an homeostatic (or rather relationstatic) system which has its own organization (defining network of relations) as the fundamental variable which it maintains constant.” (Maturana and Varela, 1978)

Extended life?





- “If one says that there is a [homeostatic] machine M, in which there is a feedback loop through the environment so that the effects of its output affect its input, one is in fact talking about a larger machine M' which includes the environment and the feedback loop in its defining organization.” (Maturana and Varela, 1978)

A richer tapestry

- There are many processes (or sets of processes) that contribute in some way without being necessary (e.g. my hobbies)

- Others are detrimental (e.g. smoking)

- Barandiaran has written about *habits* as autonomous in their own right

- One may also consider viruses - not autopoietic but part of the tapestry of life

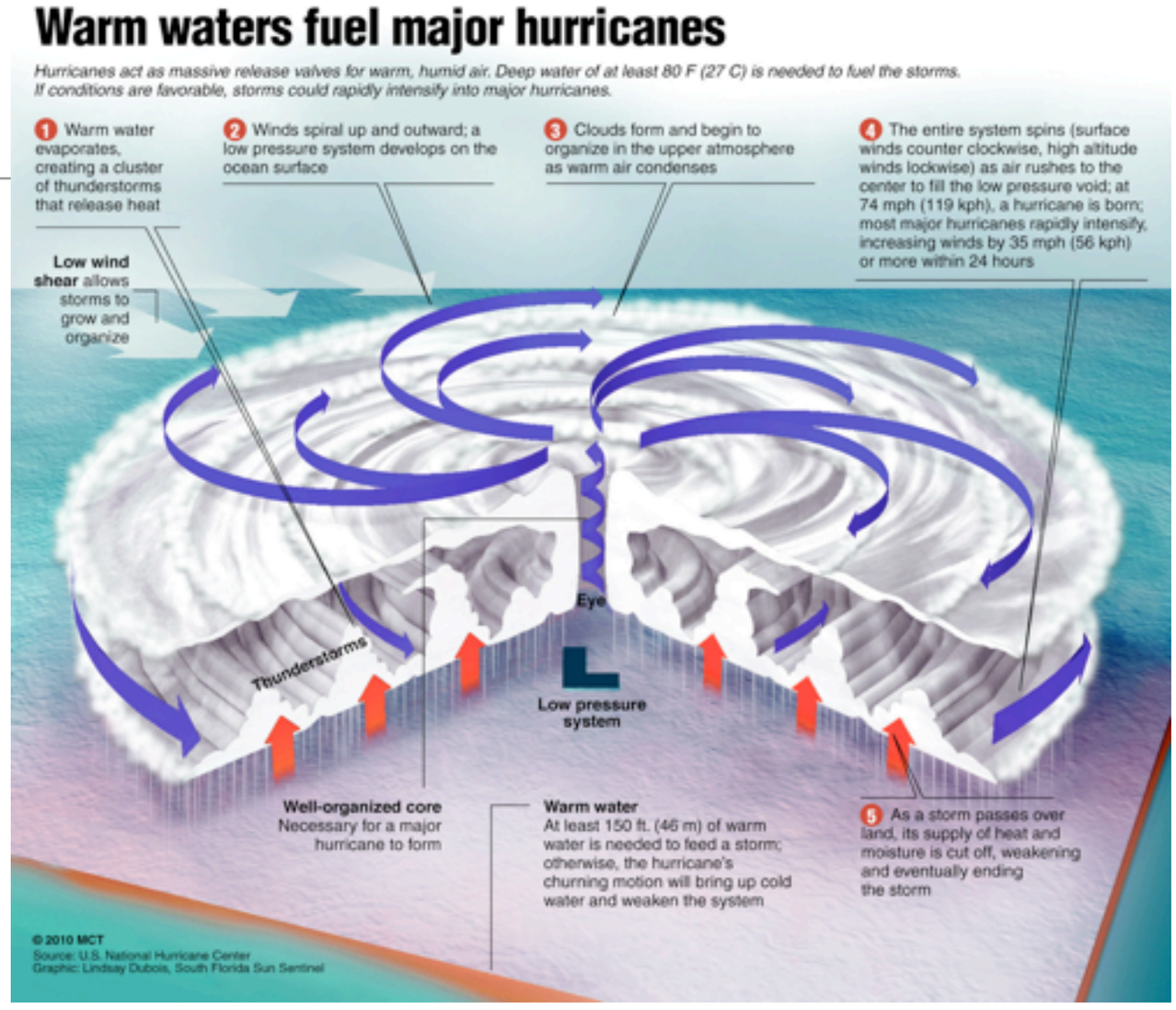
- Also society, man-made objects, etc.

- So I think the “enactive world” is best thought of not as a collection of individuals but as a rich tapestry in which individuals sometimes emerge

Part 2

Precarious, individuated dissipative structures

Is this a problem?



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Is this a problem?

- Confronted with such examples, Maturana and Varela changed their definition to try and exclude them

- They focused on the cell's membrane as a dividing line between "inside" and "outside"

- But I think this was a mistake!

- It's far more interesting to think about what typhoons *share* with cells than how they differ

The view from physics

- Things like typhoons are called “dissipative structures” (Prigogine)

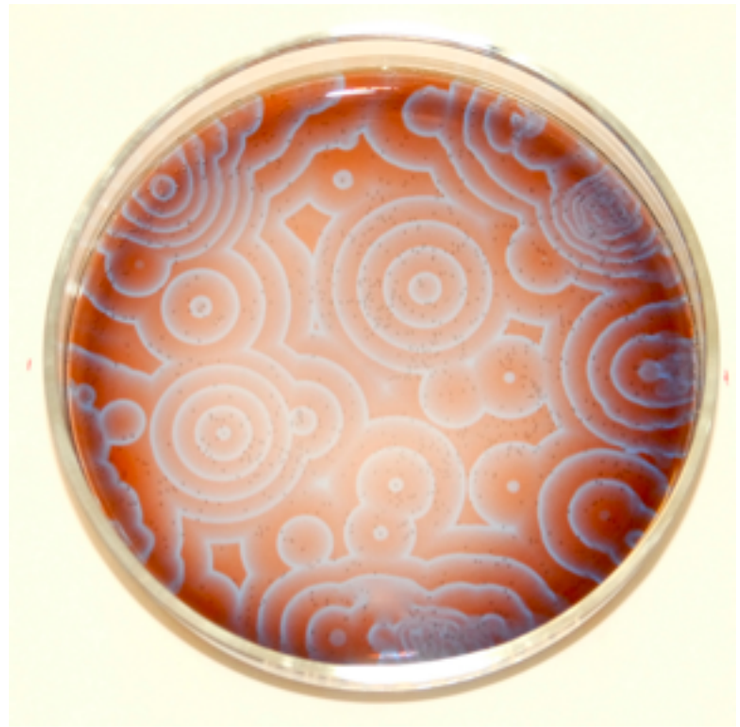
- They all have the property of
  being maintained by a dynamical balance of processes
  rather than just being solid

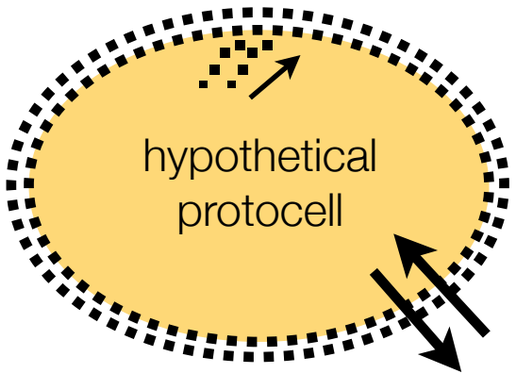
- They persist by consuming free energy from their environment
  (“producing entropy”)

- And they have the “ship of Theseus” property - persists despite every atom being replaced

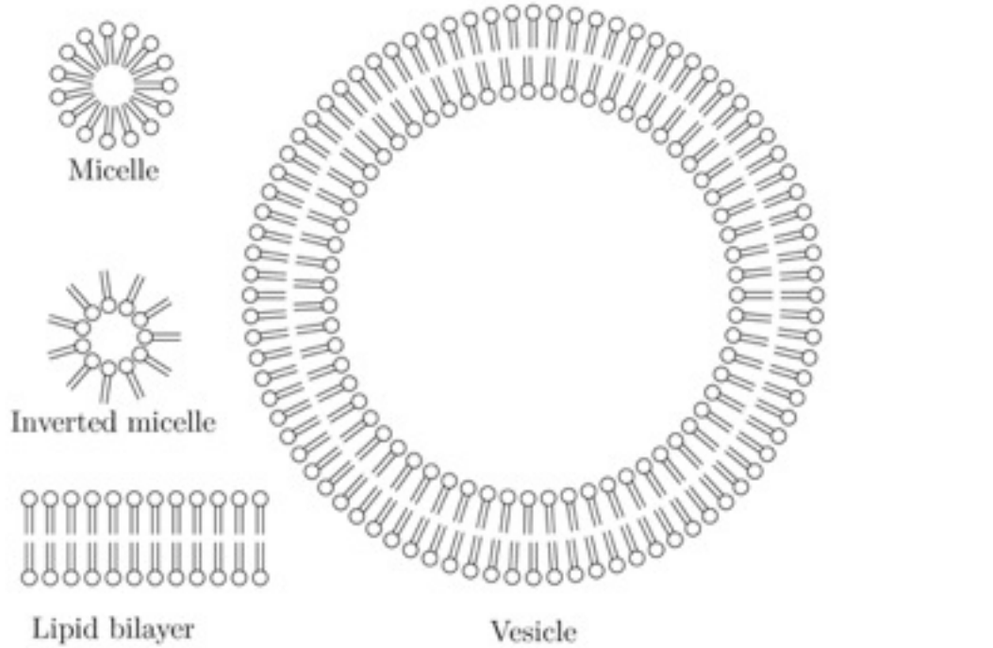
- Let’s look at some other examples

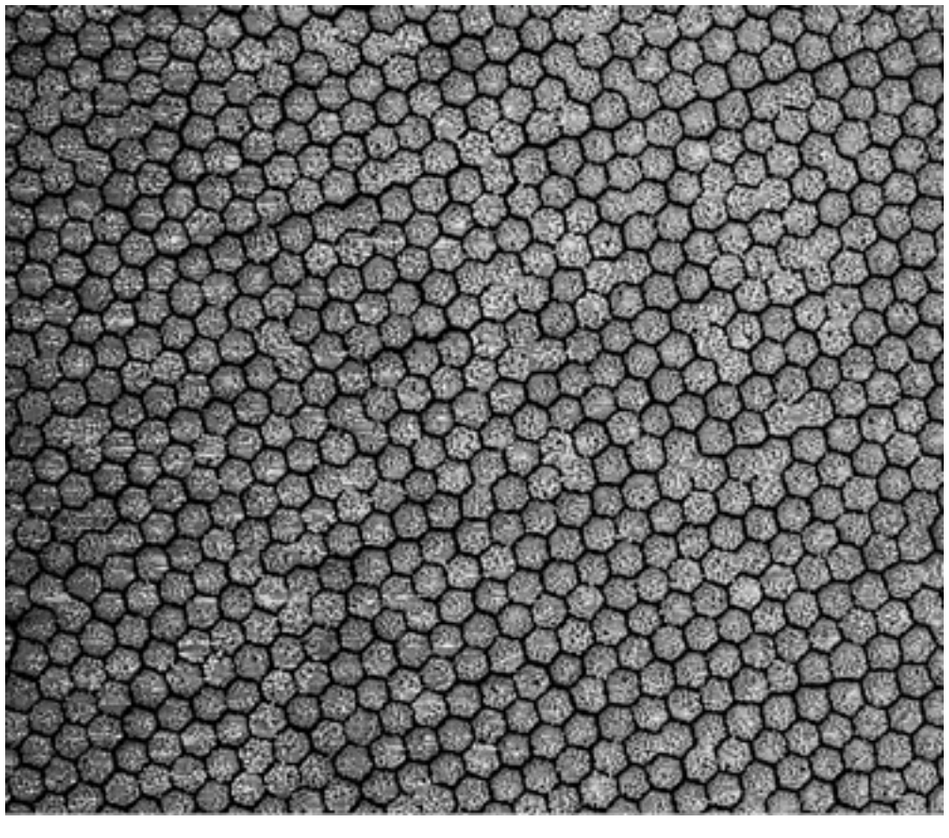
Dissipative structures - examples





Some non-dissipative structures





Dissipative structures

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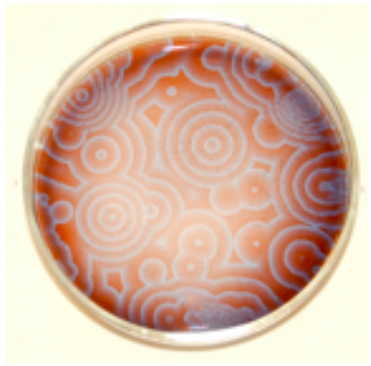
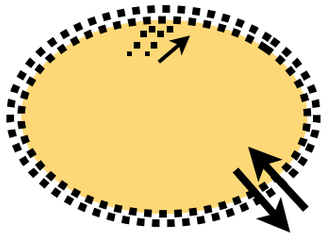
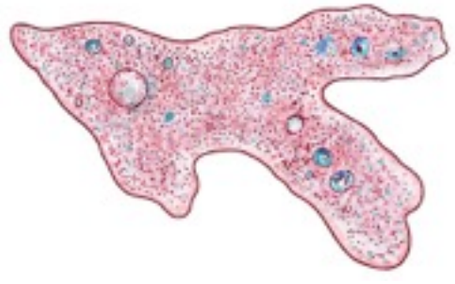
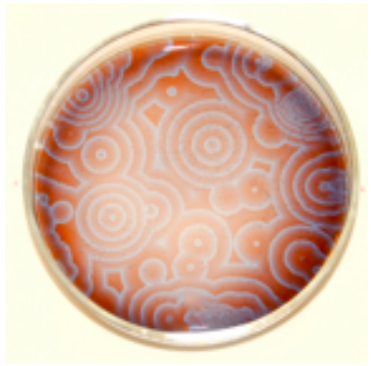
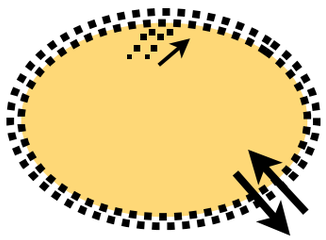


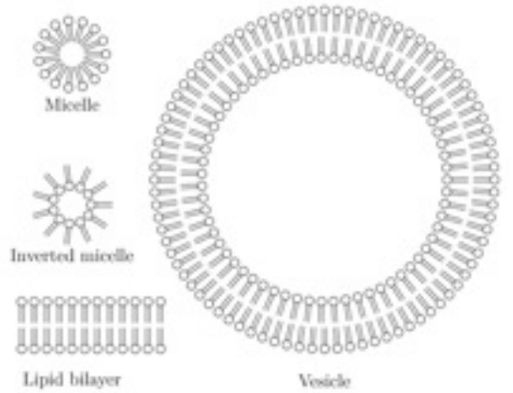




Dissipative structures







Precariousness

- Important idea in enactive literature

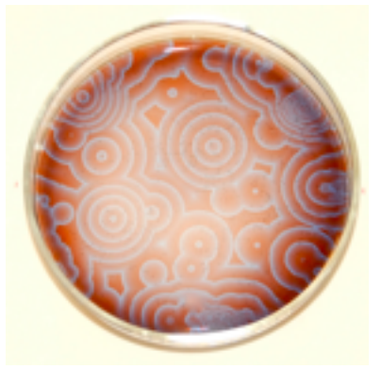
- Implies the possibility of death - some things can be bad for the organism
  - My definition: *conditions for formation ≠ conditions for maintenance*

- Not “all or nothing” property, but a variable one

- Very common in dissipative structures

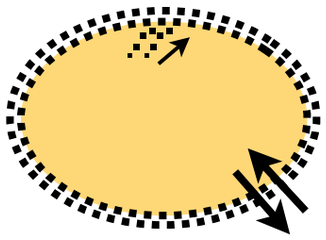
Dissipative structures

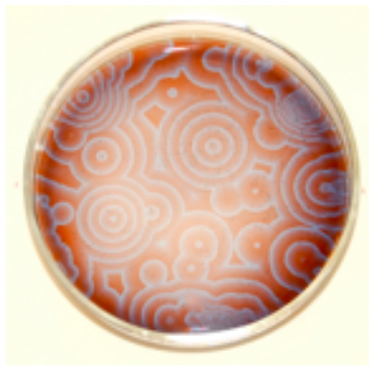
Precarious

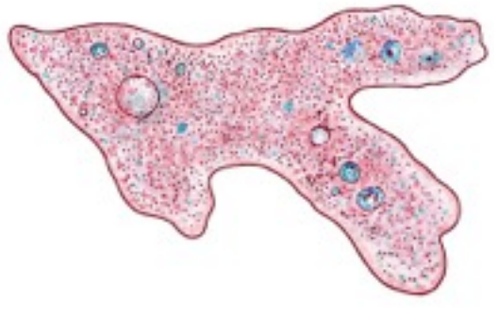


Dissipative structures

Precarious

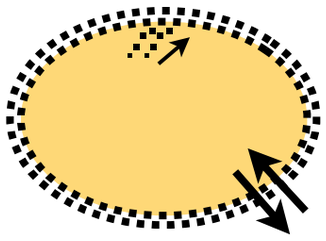


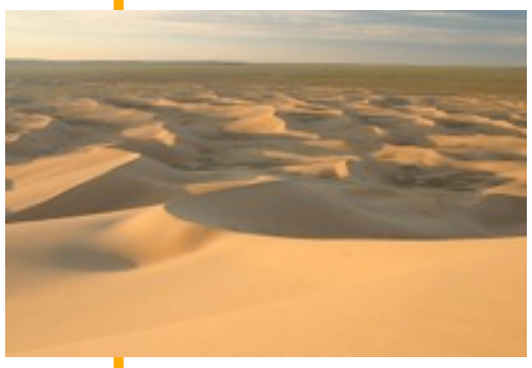


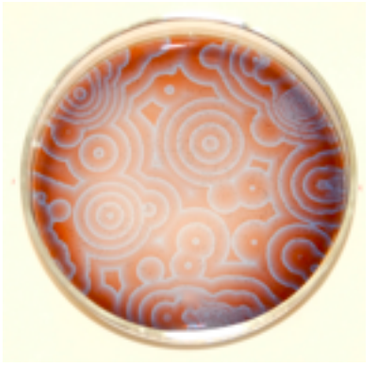


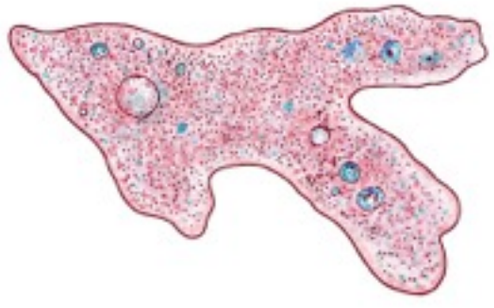
Dissipative structures

Precarious









Precariousness

- Precariousness: *conditions for formation ≠ conditions for maintenance*

- conditions for formation can be a lot more specific than conditions for maintenance (e.g. human), or just a little.

Individuation

- Another common life-like property:
  the formation of *distinct, similar, spatially separated* ‘individuals’

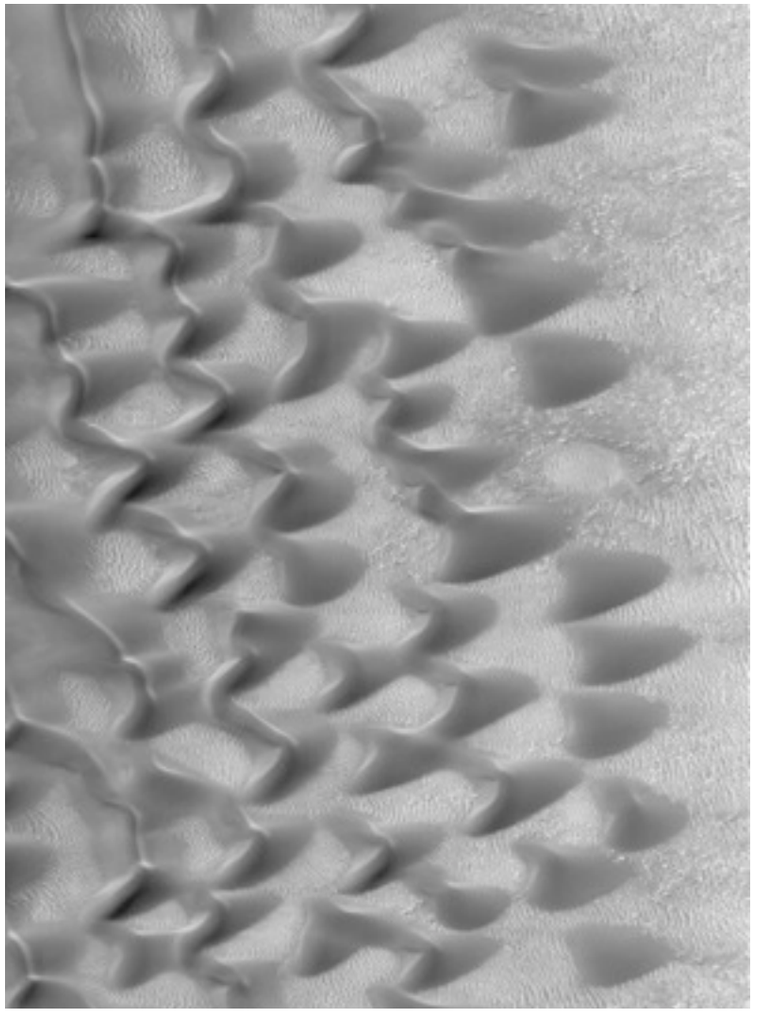
- distinct individuals have distinct life-histories

- almost ubiquitous in living systems (counterexamples)

- can occur on multiple levels (cells, organisms, colonies)

- not about genetics (clones, chimeras)

- not all-or-nothing...



unindividuated, individuated and ambiguous dunes on Earth and Mars

Individuation

- This version of individuation does not imply a “hard” separation between an individual and its environment

- This is really important! Even in the case of a living cell, molecules continually move across the membrane, and the membrane can break and re-form

- Thus the question of whether something is “inside” or “outside” the cell is ill-defined on the molecular level.

- This is why “extended autopoiesis” is the appropriate notion here

Dissipative structures

Precarious

Dissipative structures

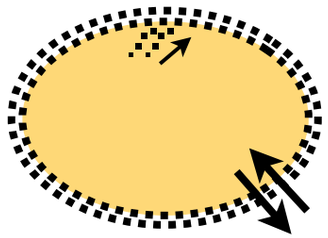
Precarious

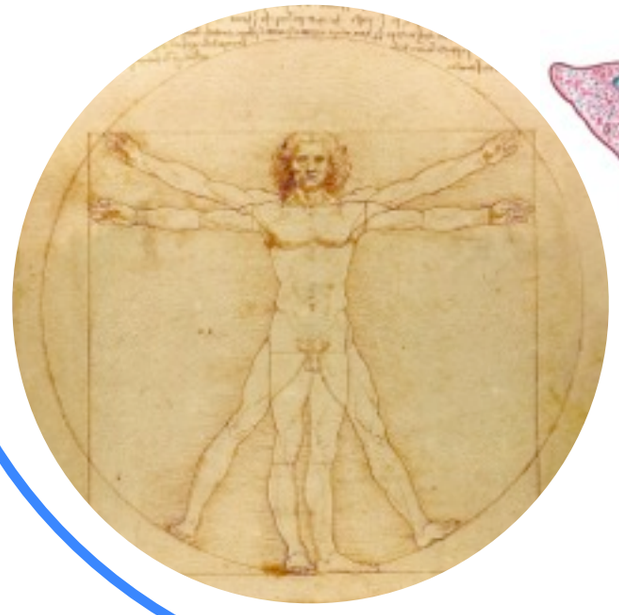
Individuated

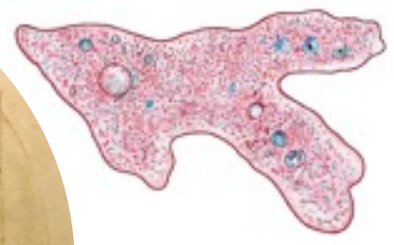
Dissipative structures

Precarious

Individuated



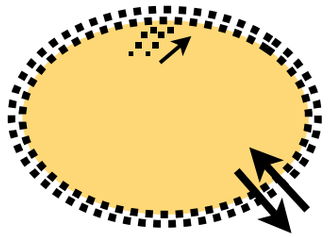


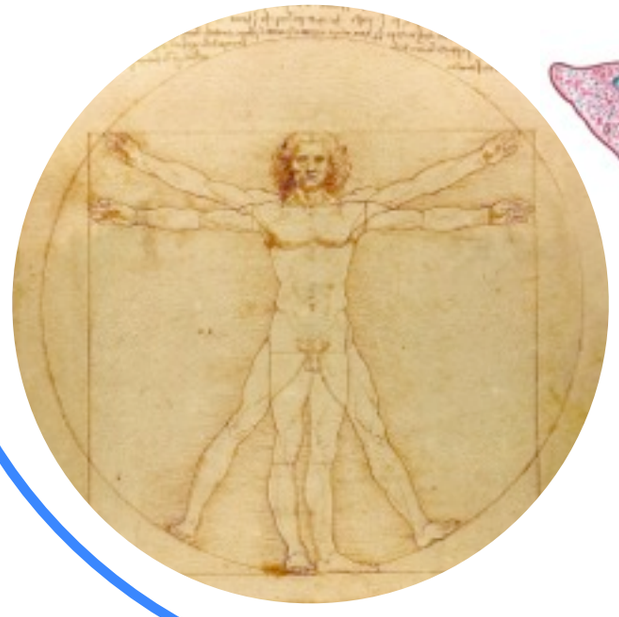


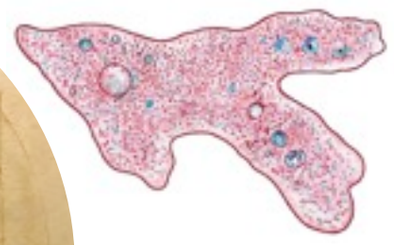
Dissipative structures

Precarious

Individuated



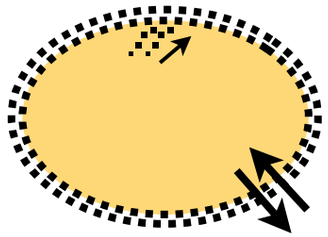


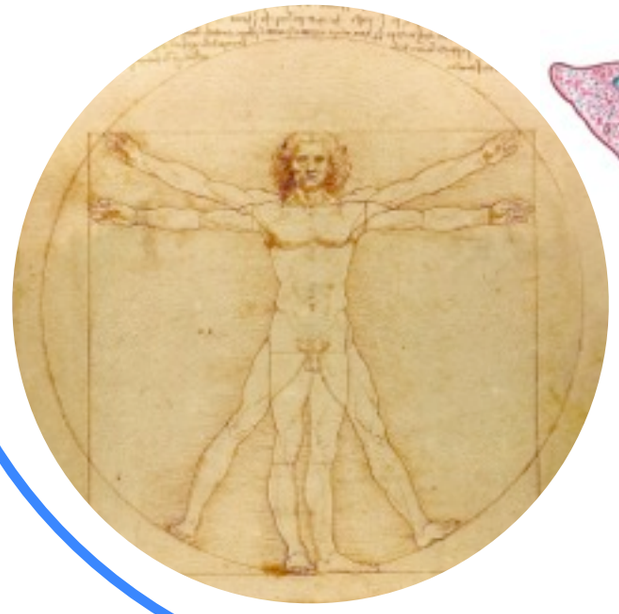


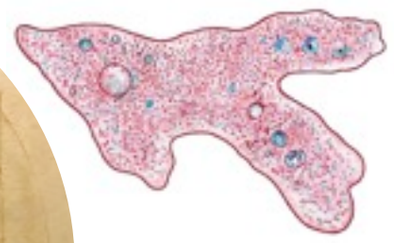
Dissipative structures

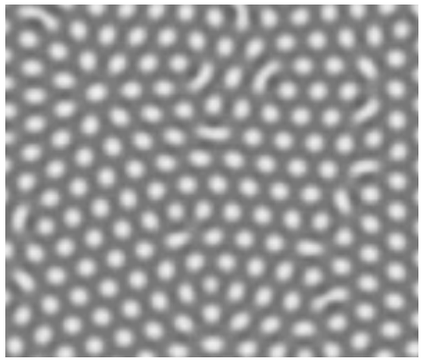
Precarious

Individuated





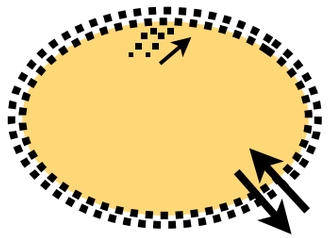


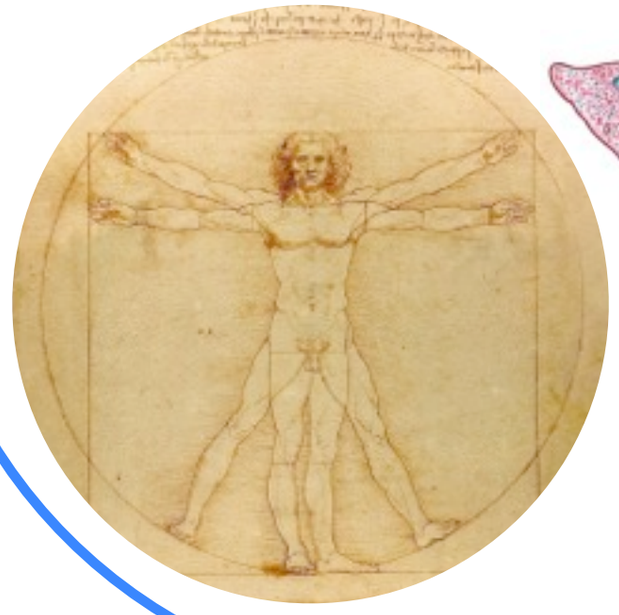


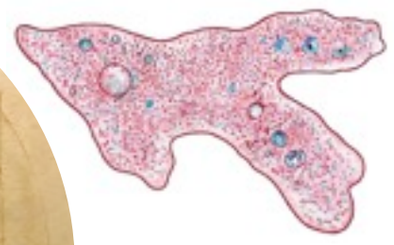
Dissipative structures

Precarious

Individuated







Dissipative structures

Precarious

Individuated

Precarious, individuated dissipative structures

Dissipative structures

Precarious

Individuated

Precarious, individuated dissipative structures

These all have analogues of

Dissipative structures

Precarious

Individuated

Precarious, individuated dissipative structures

These all have analogues of

Metabolism

Dissipative structures

Precarious

Individuated

Precarious, individuated dissipative structures

These all have analogues of

Metabolism

Anatomy

Dissipative structures

Precarious

Individuated

Precarious, individuated dissipative structures

These all have analogues of

Metabolism

Anatomy

Behaviour

Dissipative structures

Precarious

Individuated

Precarious, individuated dissipative structures

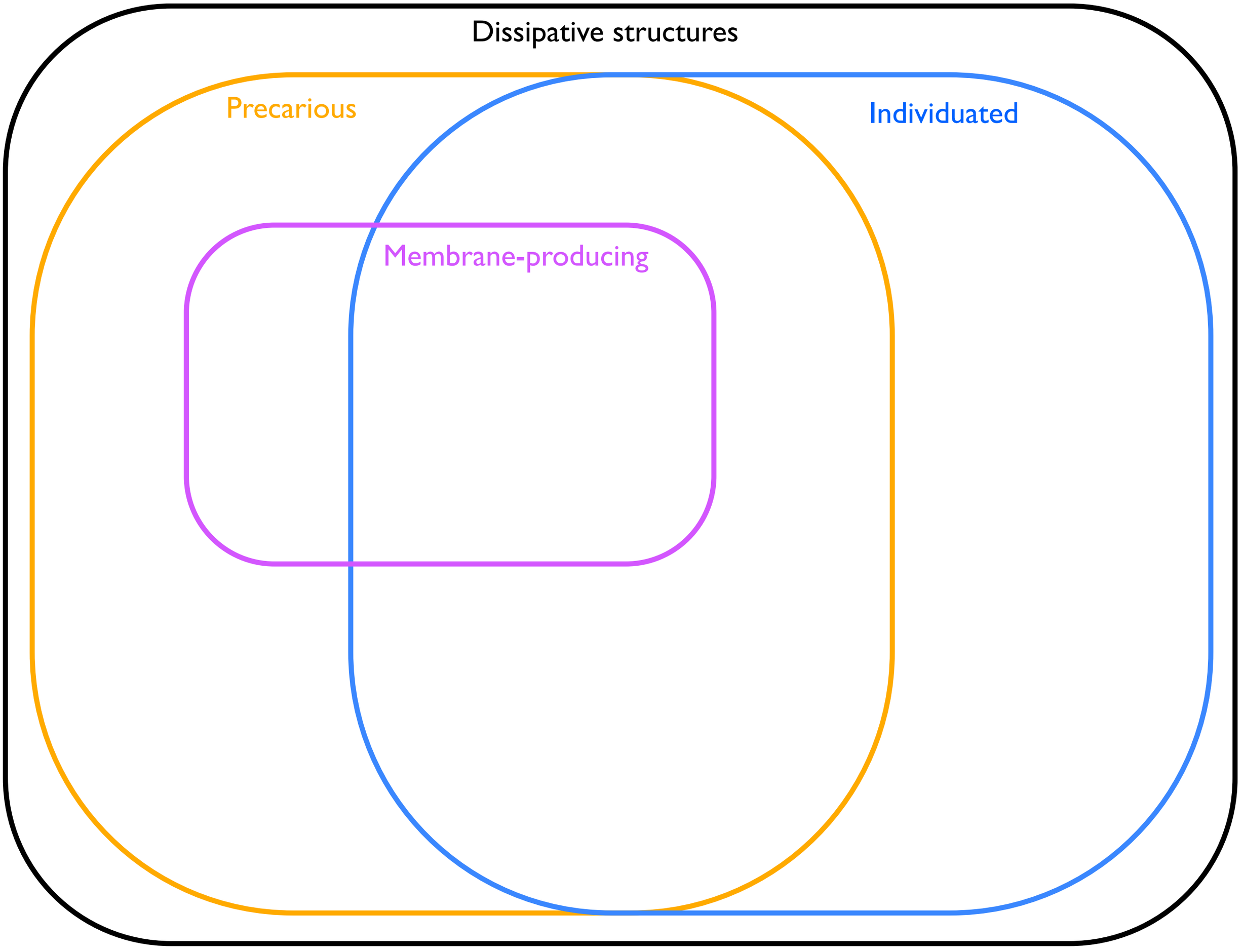
These all have analogues of

Metabolism

Anatomy

Behaviour

Similar to early version of autopoiesis
(constitution of a unity)


Dissipative structures
Precarious
Individuated
Membrane-producing

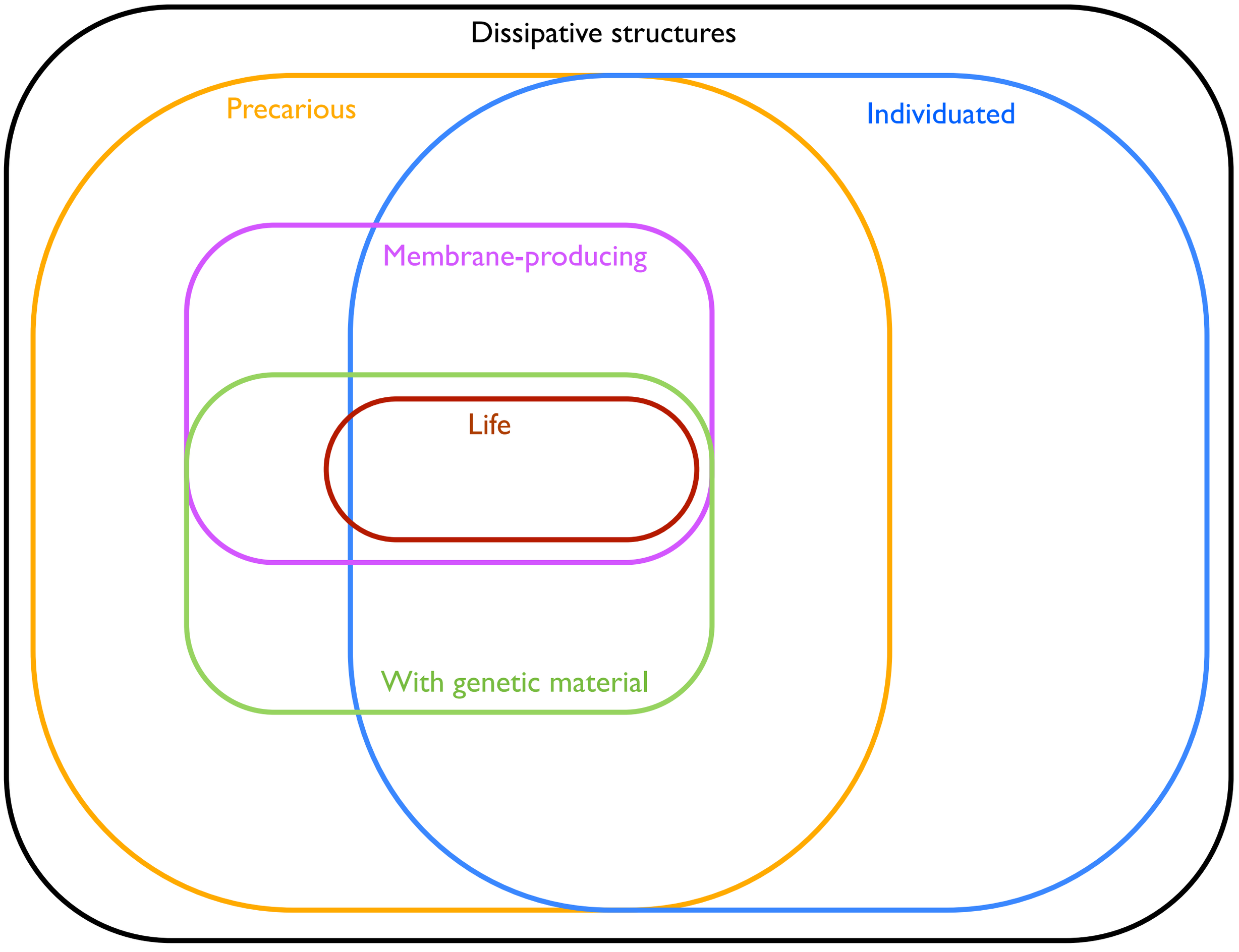
Dissipative structures

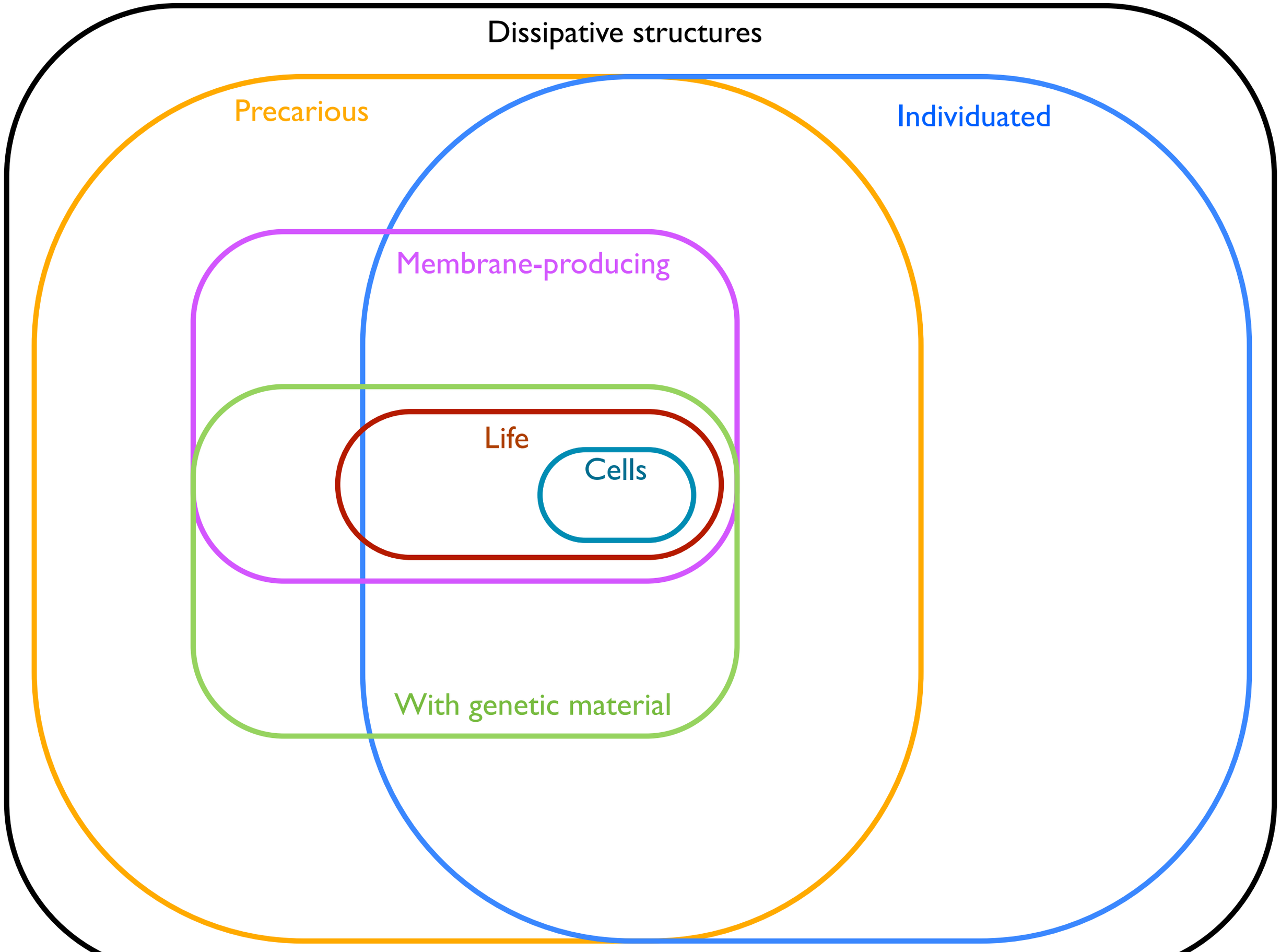
Precarious

Individuated

Membrane-producing

With genetic material


Dissipative structures
Precarious
Individuated
Membrane-producing
Life
With genetic material


Dissipative structures
Precarious
Individuated
Membrane-producing
Life
Cells
With genetic material

Life, mind and dissipative structures

- The point is that we can *readily observe and create* systems that
    - are constituted as individuals by self-producing networks of processes (you can decide if this is autopoiesis)
    - homeostatically maintain their organisation
    - can “die”
    - can respond to their environment (see next)
    - can accumulate adaptations (see later)

Reaction-Diffusion Systems

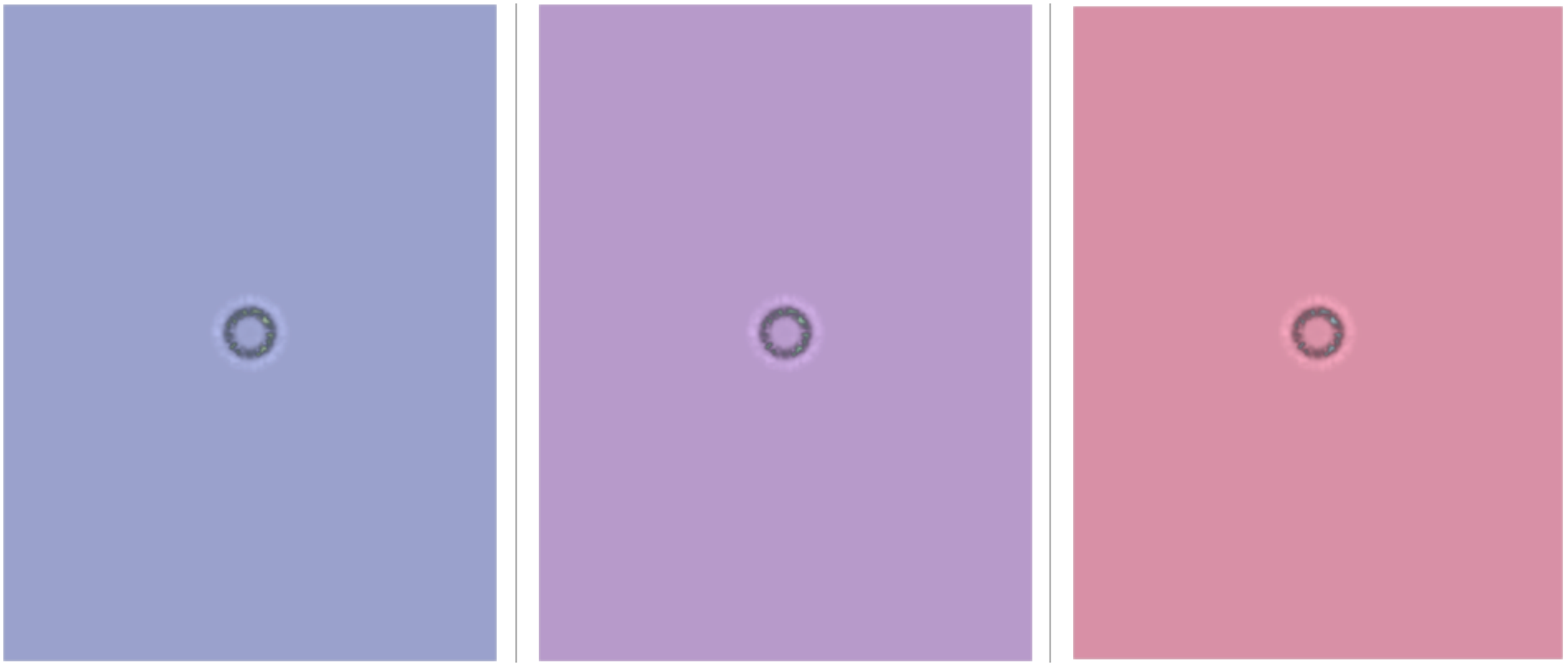
- Implemented like a cellular automaton, except that each “cell” contains a continuously variable amount of several chemicals

- Within each cell, chemicals react and can enter or leave system from outside (**reaction**)

- Chemicals slowly leak between cells (**diffusion**)

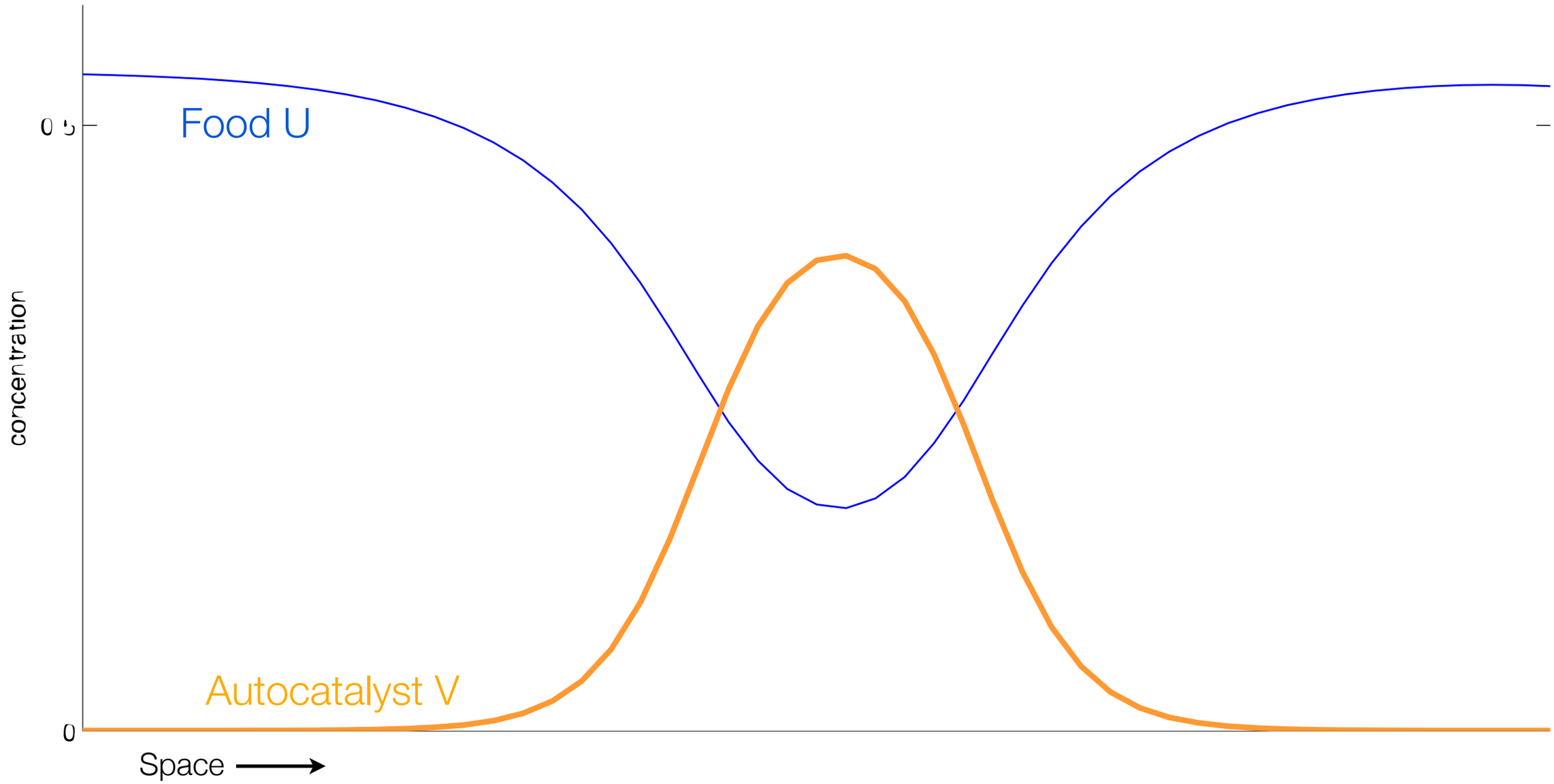
Reaction-Diffusion Systems

- Gray-Scott system based on autocatalysis: **U** + **2V** → **3V**
- In addition, **U** fed into each cell, and **V** decays, leaving system
- Can form spots, lines, chaotic patterns, depending on parameters

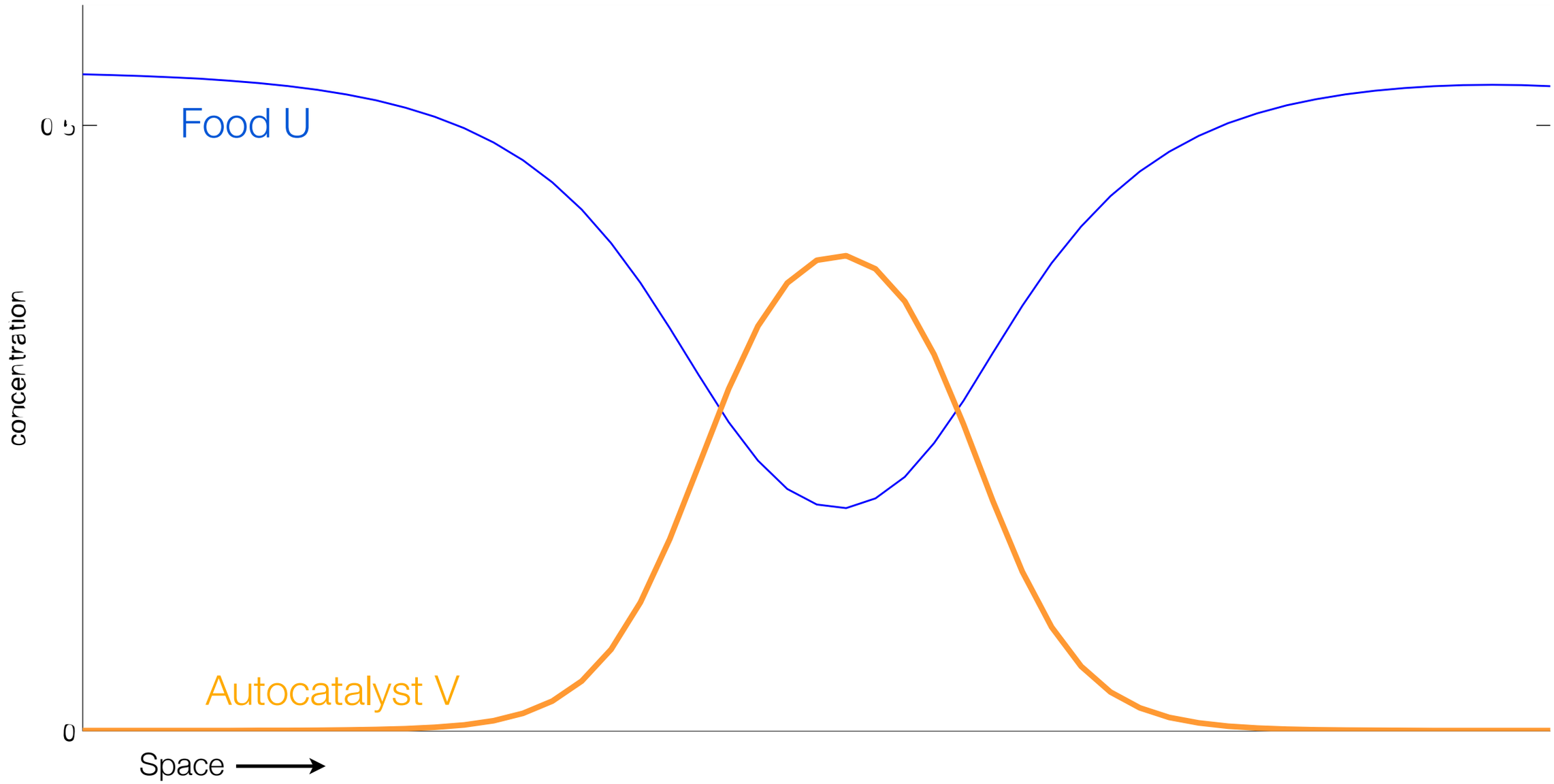


Three patterns formed by different parameter ranges in the Gray-Scott system (colours are arbitrary)

Anatomy of a Spot



Anatomy of a Spot



U + 2V → 3V

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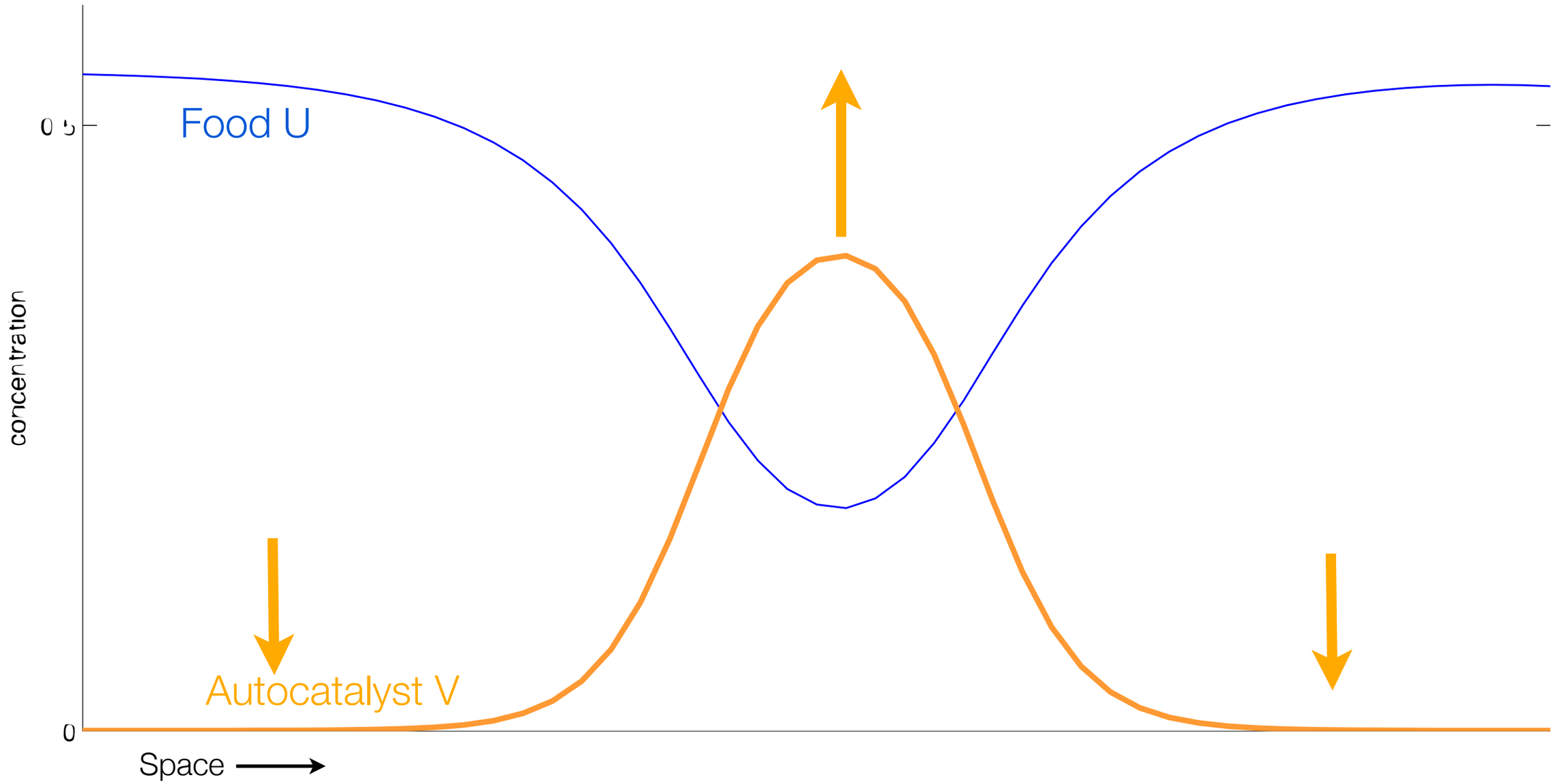

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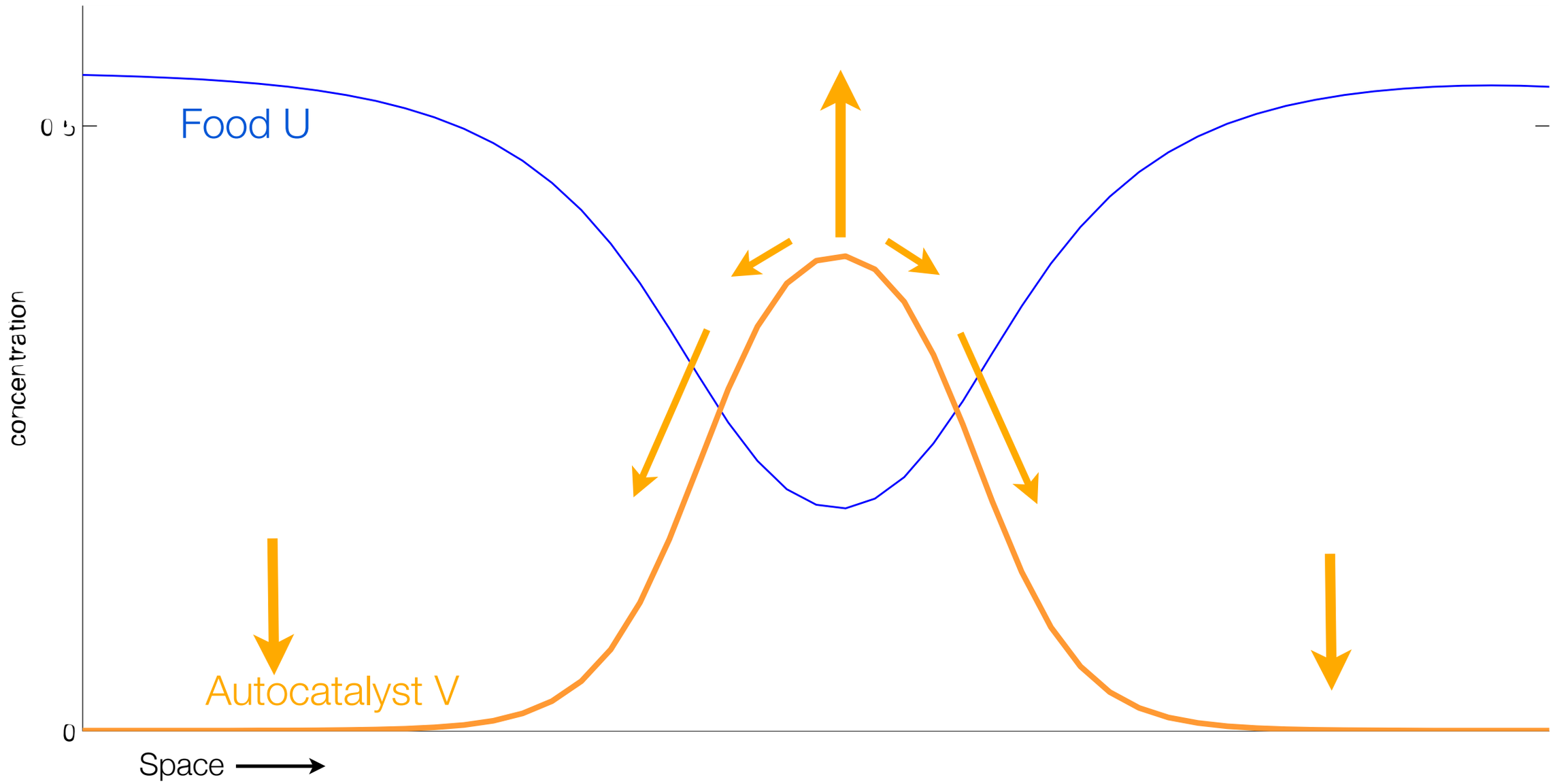
Anatomy of a Spot



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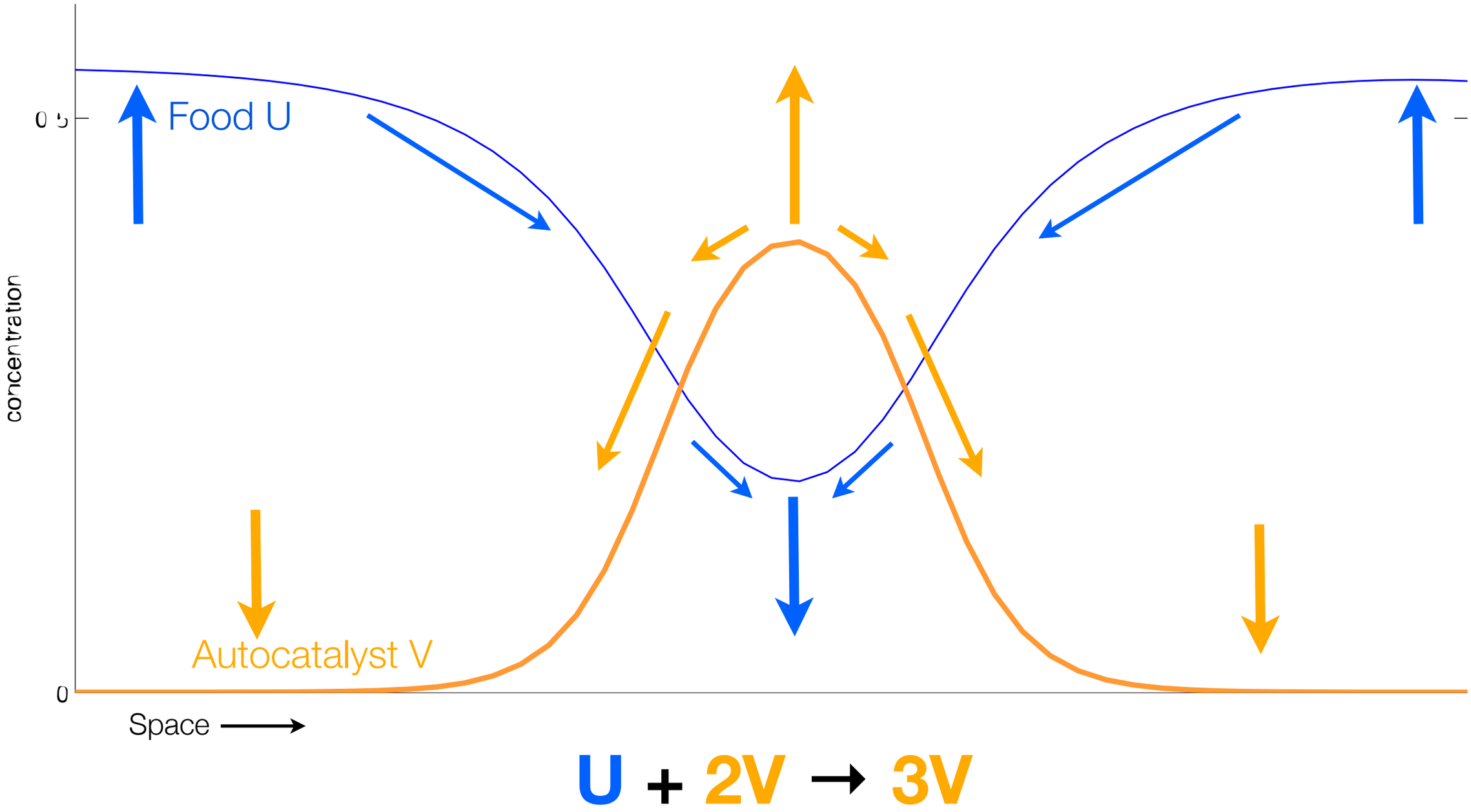
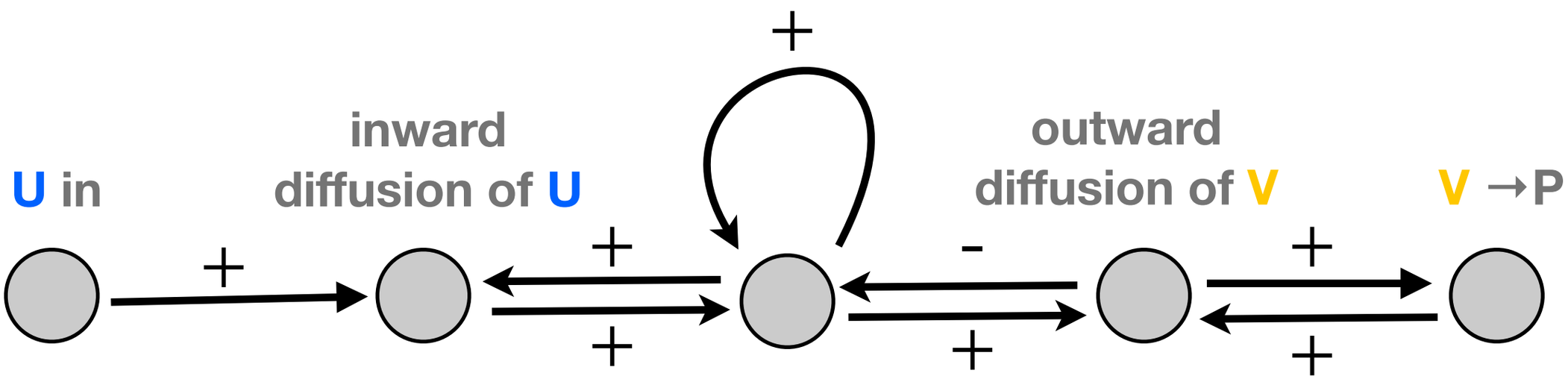
Anatomy of a Spot

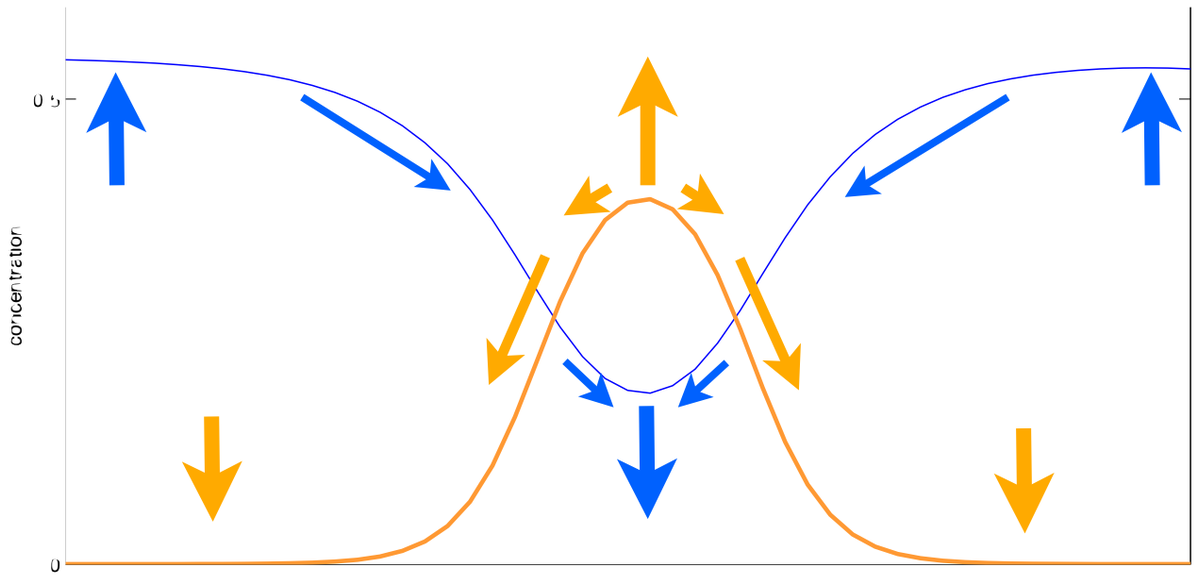


U + 2V → 3V

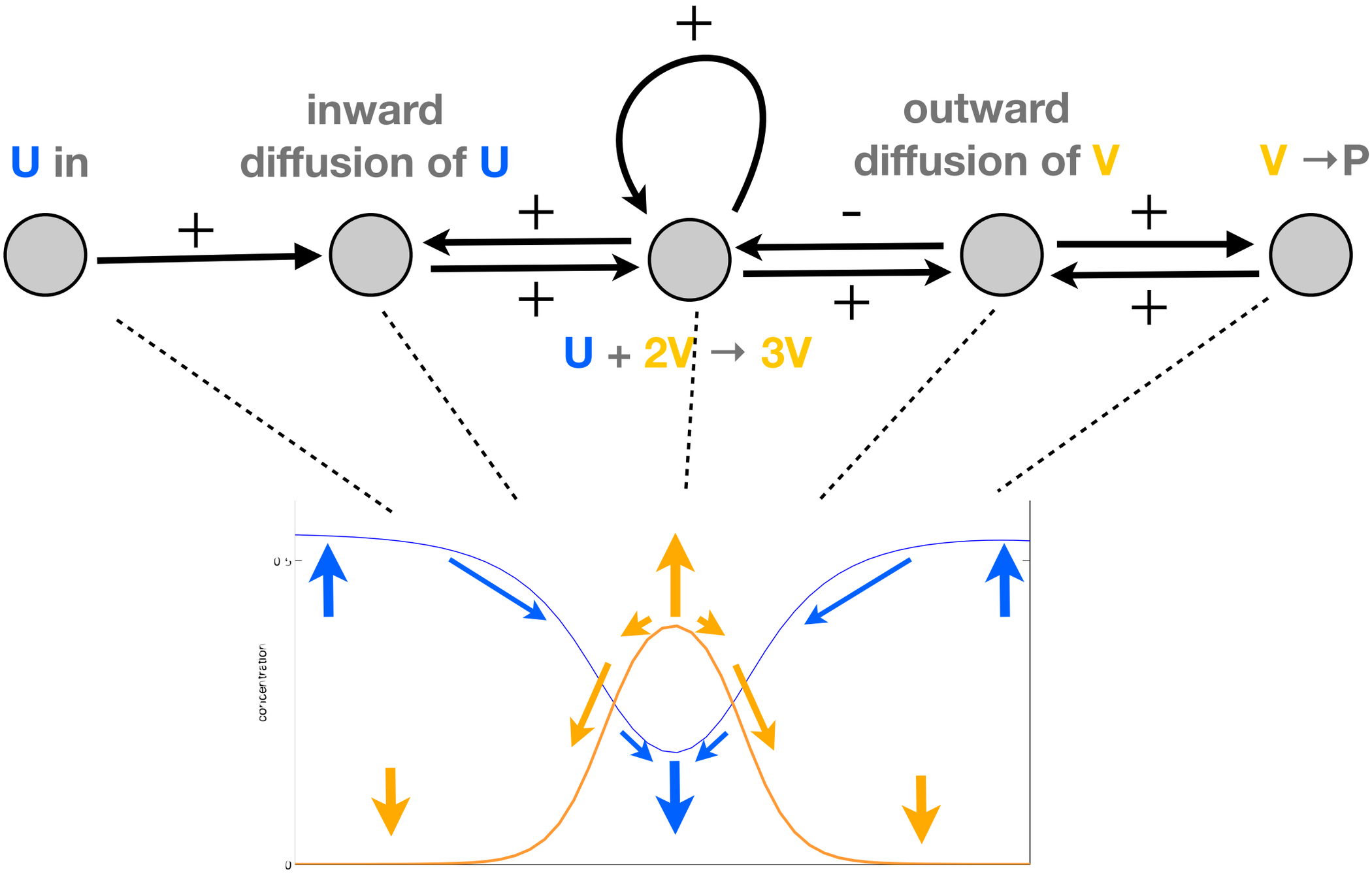
“Metabolism” of a spot



U + 2V → 3V



“Metabolism” of a spot



Cognition?

- Reaction-diffusion spots are maintained by a balance in the rates of several processes

- A perturbation will cause an imbalance

- Large perturbations will destroy the spot (boundary of viability)

- But we would never observe spots if they weren't stable to small perturbations

- Crucially, a small perturbation may return the spot to a *different* stable configuration (e.g. moving it to a different place) - "cognitive domain"

- See demo

Adding a permanent perturbation

- What if there was another autocatalyst that could “feed on” the first?

- **U** + **2V** → **3V** ***and***
  V + **2W** → **3W**

- With the right parameter settings, a stable spot of **V** continuously moves away from a “tail” of **W**

- The direct effect of the tail is purely negative, but it can enable survival in new environments...

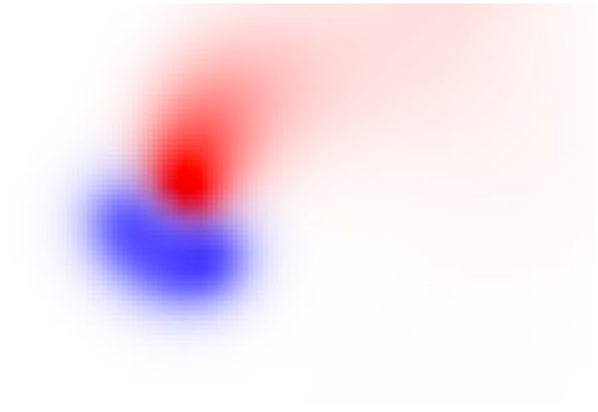
Adaptations and precariousness

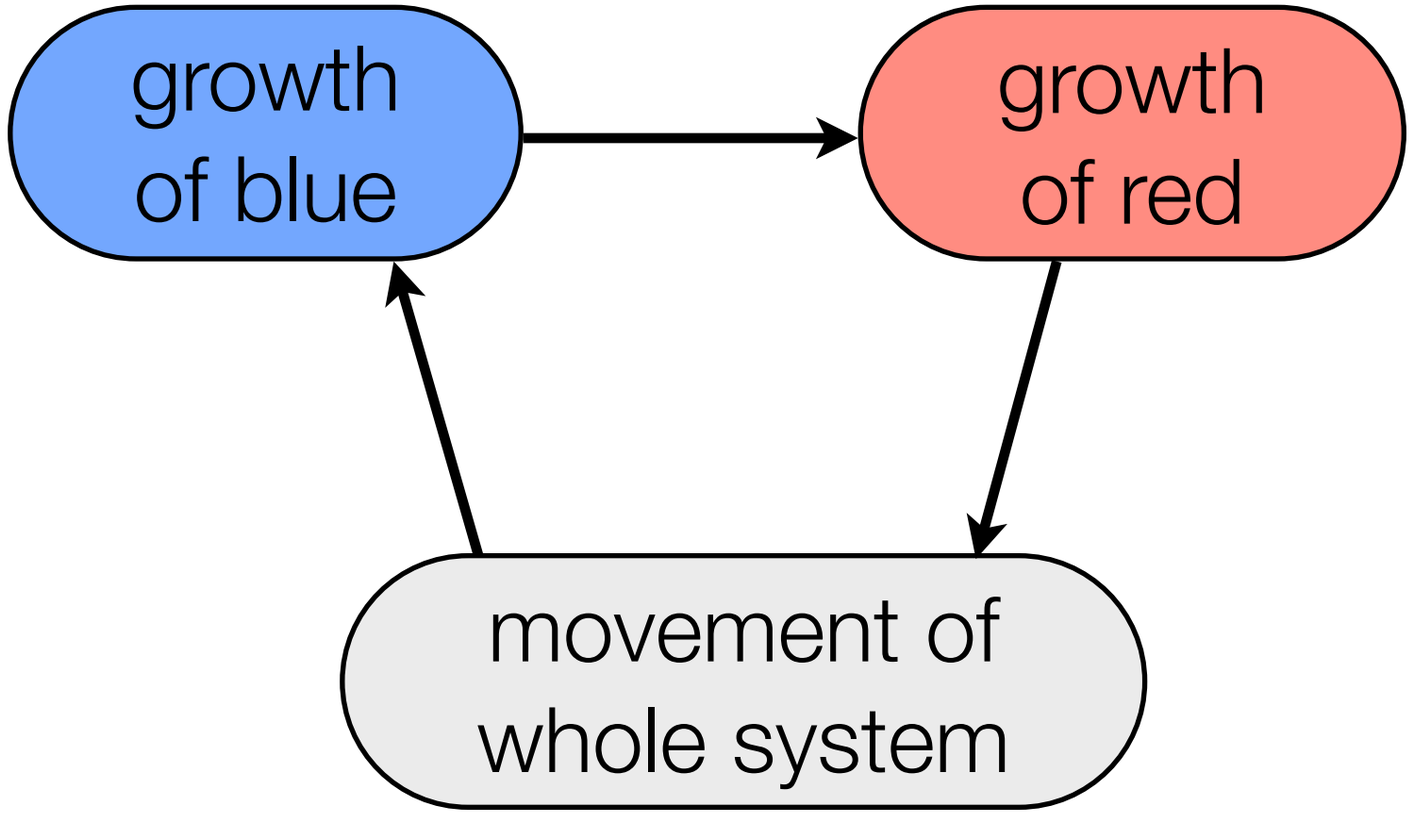
- The tail is “metabolically costly”, but can provide greater “fitness” through modulation of behaviour
    - (compare with brain)
- The environment changes to one where only “spot-with-tail” can survive
- These structures have a more non-trivial precariousness - now you need quite specific conditions to create them (both red *and* blue)

Processes across levels

- Earlier I said that chemical-level and behaviour-level processes form a single operationally closed network

- Here we have a nice example:



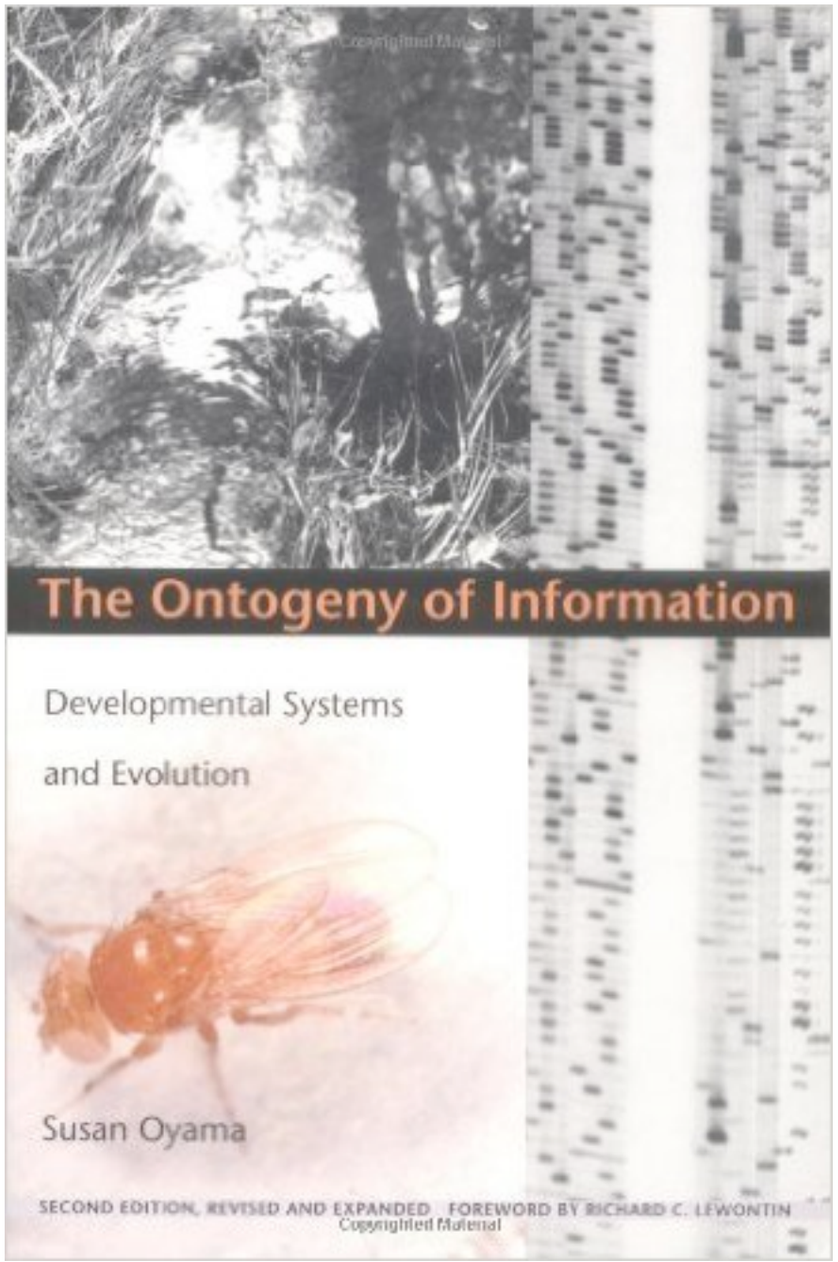


Part 3

Wrapping up

The role of information

- I didn't really mention the debates about mental representations
- Or about the role of genetic information in biology
- But I think these are deeply related, and a rich seam of possible future ideas



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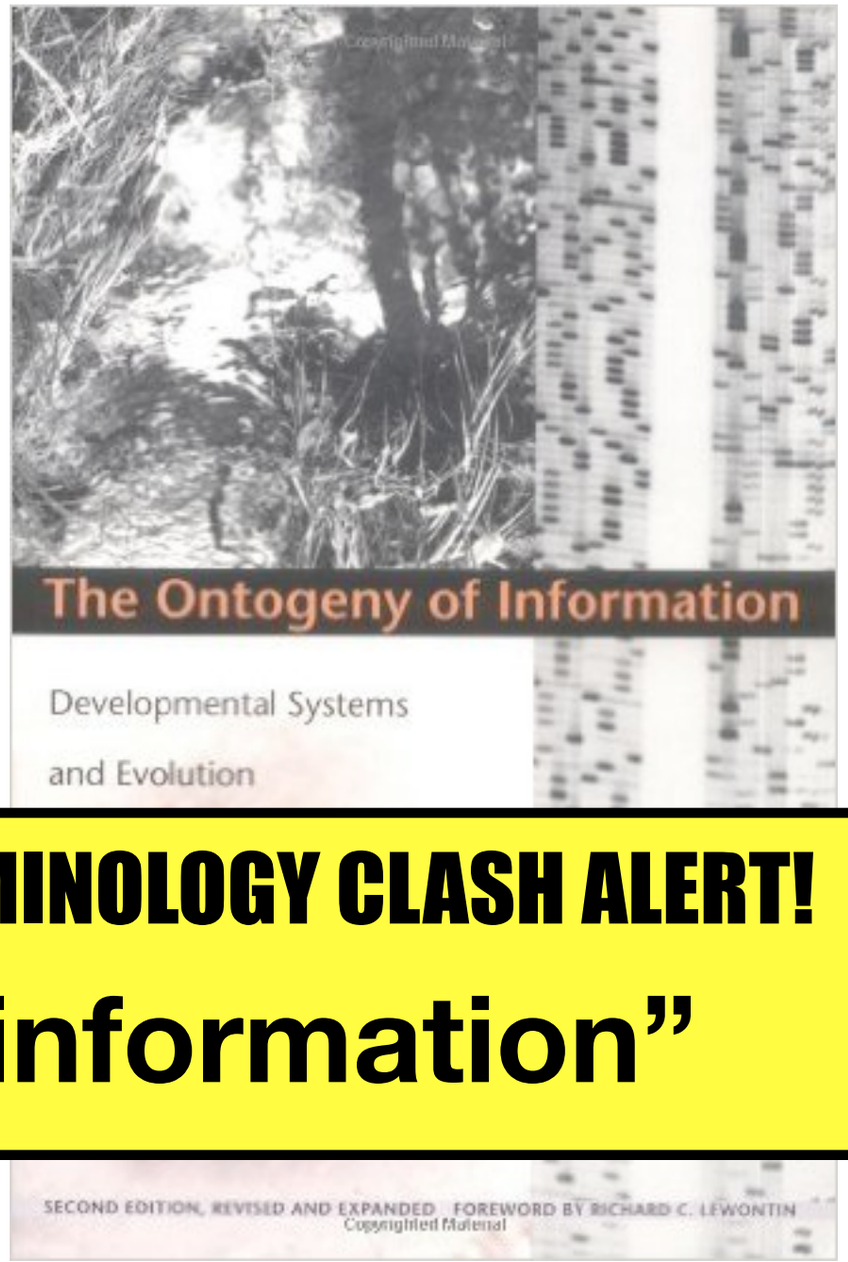

TERMINOLOGY CLASH ALERT!

"representation"

TERMINOLOGY CLASH ALERT!

"information"

Origins of life

- Many approaches to origins of life (even some of the autopoiesis based ones) strike me as not very “lively”

- People imagine that the environment must do a lot of work to produce the first organism
    - e.g. just exactly the right chemistry to produce RNA, or catalyse the citric acid cycle, or produce a protocell

- But we’ve seen that there is plenty of liveliness in physics already!

- Can this lead to a research programme that helps us understand life’s origins?

Origins of life

- I think “yes”, but there are many questions to be answered:
- The simulations I showed are quite limited - only a few processes can occur
- Biology is more “open-ended” - huge range of things proteins can catalyse
- How to really capture this in theory / simulation?
- ...and how to observe it in the lab?

Questions for discussion

- What is the relationship between life and mind?
    - Are they similar to each other? Do they overlap? Are they the same?
    - Did life come first and then mind, or the other way around?
- What about other complex, self-perpetuating systems?
    - e.g. economic systems, smoking...?
- What is the role of information in all this?

Thank you