Unit 4 Life and Function

2. Life Far From Equilibrium: Autopoiesis and Autonomy

The Seeming Insufficiency of Negative Feedback

- Homeostasis and negative feedback seem to go a long way towards explaining the distinctive features of living organisms
  - How they are successful in maintaining themselves in the face of processes that might otherwise destroy them
- But alone they don't seem sufficient for characterizing life
  - Humanly designed negative feedback systems all involve a designer
    - Who so arranged the parts of the system so that it would reach the target
  - The designer imposed the goal/purpose on the system
    - But where is the designer of biological systems? How did the organism become so organized that it could compensate for deviations?
  - Natural Selection is a tempting answer
    - This, however, situates the source of goals far from the organisms that seem to have them

Characterizing the Organization of Living Organisms

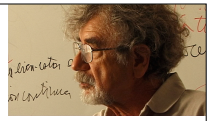
- Bernard, Cannon, and the Cyberneticists all, in some way, appealed to organization as what distinguishes living organisms
  - What is that organization? How do lots of cases of negative feedback result in an organized organism
- Varela: to understand life, focus on how living systems in general are organized to establish a *unity*
  - "the living organization can only be characterized unambiguously by specifying th**e network of interactions of components which constitute a living system as a whole, that is, as a 'unity'**. We also claim that all biological phenomenology, including reproduction and evolution, is secondary to the establishment of this **unitary organization**. Thus, **instead of asking 'What are the necessary properties of the components that make a living system possible?' we ask 'What is the necessary and sufficient organization for a given system to be a living unity?**'"
    - Varela, Maturana, and Uribe, 1974

Clicker Question

What do Varela and Maturana mean by calling living systems autopoetic?

A. Living systems generate their own poetry
B. Living systems are constructed from genes
C. Living systems make themselves
D. Living systems are complex molecular systems

Organization for What? Building the Organized System Itself



- What sort of organization defines a living system?
  - One that is capable of building itself: **Autopoiesis**
- "The autoipoietic organization is defined as a unity by a network of productions of components which (i) **participate recursively** in the same network of productions of components which produced these components, and (ii) **realize the network of productions as a unity** in the space in which the components exist."
- "Consider for example the case of a cell: it is a network of chemical reactions which produce molecules such that (i) through their interactions **generate and participate recursively in the same network of reactions which produced them**, and (ii) **realize the cell as a material unity**."

Multiple Material Realizations of the Same Organization

- For Varela, the material parts don't make an organism a living thing
  - It is the organization
- The material parts of organisms are constantly changing
  - what endures through time is not the matter but the organization
  - "the same organization may be realized in different systems with different kinds of components as long as these components have the properties which **realize the required relations**. It is obvious that with respect to their organization such systems are members of the same class, even though with respect to the nature of their components they may be distinct."
- Consequence: the material components are less important than how they fit together to form a larger whole

Mechanisms and Autopoietic Systems

- Mechanisms are organized systems
  - But they are not organized to generate themselves
  - Varela views most mechanisms as *allopoietic*
    - "mechanistic systems whose organization is such that they do not produce the components and processes which realize them as unities and, hence, mechanistic systems in which the product of their operation is different from themselves, we call allopoietic."
- Mechanism is not totally irrelevant: an autopoietic system is one kind of system of mechanisms
  - "These systems are different from any other mechanistic system in that the product of their operation as systems thus defined is necessarily always the system itself."

Autopoiesis and Autonomy

- Autonomy: the self provides its own governing law—it determines what it does
  - By virtue of making itself, an autopoietic system provides the law that governs itself
  - "in viewing self-production as the key to biological phenomena, the emphasis shifts, from a control viewpoint to an emphasis on the nature of autonomy. In fact, the notion of autopoiesis can be described as a characterization of the mechanisms which endow living systems with the property of being autonomous; autopoiesis is an explication of the autonomy of the living."
    - » Varela, 1981

Clicker Question

Varela and Maturana characterized living systems as closed. In what respect are they closed?

A. The components that carry out causal activities are themselves made by the organism
B. They have a boundary that doesn't let anything in or our
C. They are self-sufficient; they don't need anything from outside

Autonomy and Closure

- Autopoiesis is a process that loops back on itself
  - "Autonomous systems, then, are mechanistic (dynamic) systems defined by their organization. What is common to all autonomous systems is that they are **organizationally closed**."
- "An organizationally closed unity is defined as a composite unity by a network of interactions of components that (i) through their interactions **recursively regenerate the network of interactions that produced them**, and (ii) realize the network as a unity in the space in which the components exist by constituting and specifying the unity's **boundaries** as a cleavage from the background."
  - by virtue of its boundaries, the autopoietic/autonomous system is distinct from its environment

Closure Does Not Entail Closed Off

- By closure Varela does not mean that the living system is closed off from its environment
  - Quite the opposite: it must regularly draw resources from its environment
- What closure entails is that the causal processes that build the organism originate are themselves the product of its own activities—its activities are **recursive**
  - There is circularity in that the living system always refers back to itself: it generated its own boundaries
  - Cellular systems: build constituent molecules through reactions performed by its own constituents
  - Nervous system: neurons bring about activity in other neurons through their coupling

Autonomy: A Third Alternative to Vitalism and Mechanism

- Mechanists focus on explaining specific activities of living organisms, showing how a set of components could explain each activity
- Vitalists such as Bichat argued that living organisms exhibit properties that mechanist's could not explain
  - especially the apparent resistance to death: living organisms perform operations that counter the forces in the environment that would otherwise destroy them
- Bernard/Cannon/cyberneticists took a step towards addressing the vitalists concern by appealing to how organisms were organized to mobilize mechanisms to counter the affects of the environment on them
- Varela and Maturana go a step further
  - the organization arises recursively from the organism itself
  - by directing their own construction, organisms realize autonomy

A Missing Ingredient: Energy

- Varela and Maturana's "approach makes no consideration whatsoever of thermodynamic requirements or other energetic-material constraints, because . . . it does not affect the organization—the self-productive logic—of the system." (Ruiz-Mirazo & Moreno, 2004)
- But free energy is important—without it, nothing happens
  - It clearly takes free energy to move water uphill
    - But it seems to flow downhill on its own
      - Is there any energy involved?
        - » The potential energy stored in the water residing further from the center of the earth
  - How could you, using only the potential energy in some body of water, get other water to flow uphill?
    - An exergonic-endergonic coupling (one process gives up free energy, the other acquires it)

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Energy and Thermodynamics

- The development of classical and then statistical thermodynamics were crowning achievements of 19th century physics
  - The dynamics of the universe is understood in terms of free-energy—the unequal distribution of matter
  - The 2nd law of thermodynamics asserts that in a closed system entropy [a measure of how randomly matter is distributed] always increases
- Statistical thermodynamics: entropy increases on average
  - Allows for situations in which it decreases locally
- The puzzle of living organisms: they are far from equilibrium with their environment
  - Their continued existence requires maintaining themselves in a non-equilibrium relation to their environment
    - Approaching equilibrium would be to die

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Puzzle: How do living organisms resist the second law?

- The simple answer: they are not a closed system but open to a much larger system
  - Overall, that system exhibits increasing entropy
- That still leaves a puzzle: under what conditions can a local system produce reduced entropy
  - Examples of physical systems that exhibit complex patterns (non-equilibrium states): Bénard cells: sets of molecules that constrain each other and generate patterns when heat is applied
    - Heat is an external source of free energy
    - When it is taken away, cells disappear

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Procuring One's Own Energy

- Bénard cells are an example of what are termed "self-organizing systems"
  - The patterns that develop are not designed by the experimenter but emerge from the chemicals in the solution
  - But only so long as a source of free-energy is provided
- Some physical systems are able to acquire their own free-energy and maintain themselves far-from-equilibrium
  - For some time, storms and fires create their own organized system in which sources of free energy are drawn upon to maintain the system
- These systems tend to be short-lived as eventually they exhaust all the free energy, loose their ability to maintain themselves, and return to an equilibrium state with their environment
  - But living organisms are an exception
    - For almost 4 billion years a lineage of organisms has maintained itself, with each organism far-from-equilibrium with its environment

The Origins of Life

- Biological theories, including those of physiology, genetics, evolution, assume living organisms
- There was a period on earth before life.
  - Where did the first living organisms come from?
  - When did they first appear?
  - Where did they do so?
    - In what sort of environment?
  - How did this do so?
    - What were the first steps?
- Although there is great interest in these questions, they are extremely challenging
  - We don't know what materials were involved
  - We don't know the context in which they came together
  - We don't know what form early life took

Discussion Question

Living systems as we are familiar with them both perform metabolic activities (capture energy and materials from nutrients and put them to use) and reproduce themselves. Which came first?

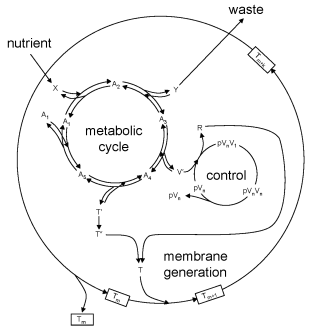
A. Metabolism
B. Reproduction
C. Both had to be present at once
D. Neither

Origins of Life and Exobiology

- Is there life anywhere else in the universe?
  - How would we know if we found it?
- Investigators into the origins of life often take their inquiry to be broader than figuring out what happened in the distant past on this planet
  - What are the general features of living organisms that would be manifest anywhere?

Gánti's Chemoton

- Working purely from theoretical considerations, Tibor Gánti advanced a proposal of a simple living chemical system consisting of
  - A metabolic cycle to extracted products from nutrients and expelled waste
  - A membrane generation system to create a barrier between the chemoton and its environment
  - A control mechanism, which largely determine division of the chemoton



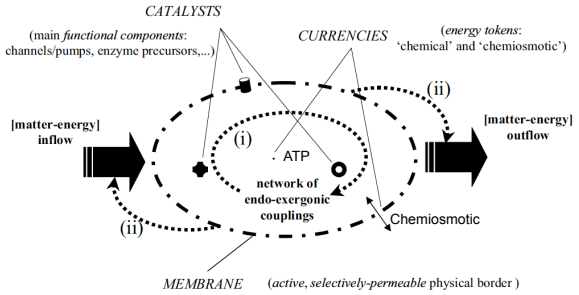
Basic Autonomy, Free Energy, and Constraints

- Ruiz-Mirazo and Moreno define "basic autonomy as the capacity of a system to **manage the flow of matter and energy** through it so that it can, at the same time, **regulate, modify, and control**: (i) internal **self-constructive processes** and (ii) **processes of exchange** with the environment. Thus, t**he system must be able to generate and regenerate all the constraints**—including part of its boundary conditions—that define it as such, together with its own particular way of interacting with the environment."
- A central feature of living systems is that they manage free-energy by coupling an energy source to energy consumption (endergonic-exergonic coupling)
  - For free-energy not to dissipate as heat, it must be constrained
  - Constraints must come from somewhere
    - It is the organism's body, which the organism builds by constraining the flow of energy, that provides the constraints

Cyclic organization of constraints: A key feature of life

- Living systems must maintain a recursive/cyclic process
- Constraints are needed so that the system can control its own operations—guide the flow of energy through the system so as to generate its own components as needed
  - Where do these constraints come from? From previous work
  - Kauffman: "Constraint begets work begets constraint"
- Specific components of the system dynamically constrain other components within the system
  - Tap specific exergonic reactions as needed to support other energy consuming activities
- Autonomy arises as a result of the network of constraints being closed over time—the constraints constituting an organism now are the result of its (or its parents) activities in the past

A Minimal Autonomous System



i. Network of energy coupling processes
ii. Control of boundaries

An Autonomy Theorist's Definition of Life

- An autonomous system is a "a far-from-equilibrium system that constitutes and maintains itself establishing an organizational identity of its own, a functionally integrated (homeostatic and active) unit based on a set of endergonic-exergonic couplings between internal self-constructing processes, as well as with other processes of interaction with its environment"
  - » Kepa Ruiz-Mirazo, Juli Peretó and Alvaro Moreno, A Universal Definition Of Life: Autonomy And Open-ended Evolution

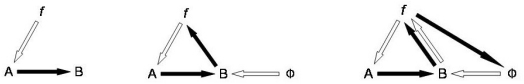
Discussion Question

Given Ruiz-Mirazo et al's definition, would you recognize an autonomous system if you ran into it?

A. Yes
B. Maybe if I could if ____
C. No

Robert Rosen and Repair

- All organized systems require repair
  - Why?
    - Don't forget the second law!
- Almost no human made artifacts can repair themselves
- Rosen's account of metabolism-repair or (M,R)-systems
  - Closed to efficient causation
    - black arrows—material causation—open
    - white arrows—efficient causation—closed



Assessing the Maintenance of the Organism Account

- Like the causal role account, it treats causal effects of operations within an organism as functions
  - But it supplies a normative perspective: when those effects serve to maintain the organism in a non-equilibrium relation to its environment
- Like the etiological account, it provide a normative perspective
  - But it does not require us to turn to history to identify functions
- But it may not provide a clear-cut account of function
  - Which is the organism?
    - the cancer cell or a person?
    - the bee or the bee colony?