# Why Are Machines So Different From Organisms?

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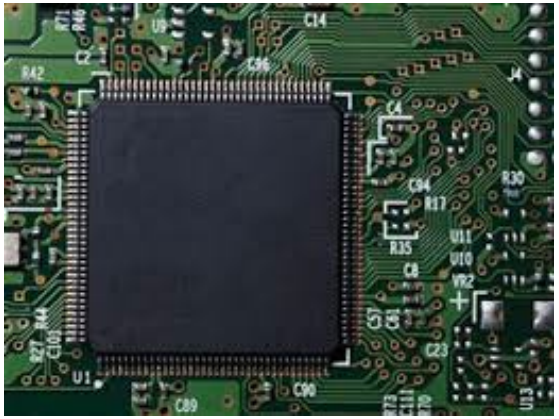
# Why are Machines so Different from Organisms ?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C23
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C89
U1
U3

Robert Rosen
(1934 - 1998)

Biophysics, Mathematical Biology

**Machines: Analysis = Synthesis**

**Organisms: Analysis ≠ Synthesis**

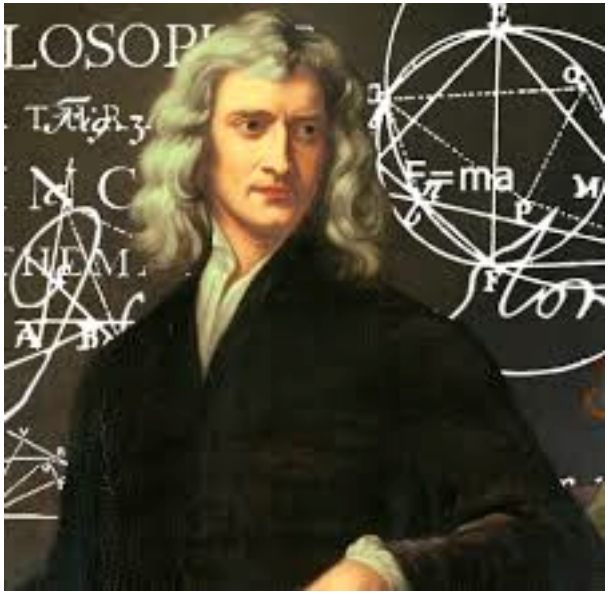
The processes that make machines are different from the processes that make organisms.

**"Technology" → Machines**

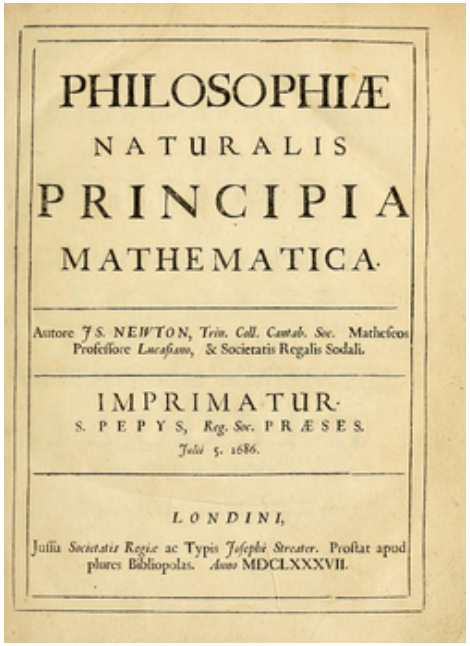
**"Self-replication!" → Organisms**

Self-Organization, no external design

# Newtonian Mechanical Universe




Isaac Newton (1642-1726)


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J. S. NEWTON, Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
*Julii* 5. 1686.

*LONDINI*,
Justu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Mass, Momentum, Force …. Context independent

*Time reversible laws*.

No laws of mechanics violated if time is reversed.

Future and past have no distinction

# The Success of Newtonian Mechanics (LaGrange, Laplace and Hamilton)

- If you consider an idealized system, in which the complexities of the real world have been removed or ignored, at the core, you find Nature is ruled my mathematical laws!!

- Law of gravity and an explanation of planetary motion was a great triumph of Mechanics.

- But mechanics was not able to deal with the complexities of the real world, especially those in living organisms. The usefulness of physics and engineering lies in their ability to construct machines that can be described by mechanics to a good approximation, not the path of a tornado or a butterfly!

# Physics/Mechanics Gave Us Machines

## "Mechanical" Universe Reversible Laws.

All change is fundamentally reversible.

Second Law of thermodynamics is a result of complexity

## World of Machines And Computers

"Irreversible processes" such a friction, heat generation are to be minimized. Lowering entropy production increases efficiency.

Context-independent parts

Context-independent machine

René Descartes (1596-1650)
Isaac Newton (1642-1726/1727)
Immanuel Kant (1724-1804)

**Descartes** famously thought that **animals** were merely 'mechanisms' or 'automata' – basically, complex physical machines without experiences – and that as a result, they were the same type of thing as less complex machines like cuckoo clocks or watches.

- Immanuel Kant noted "An organized being then, has the property that the parts exist for and by means of the whole"
- Kant thought physics can only describe inanimate nature.

# What Then Is The Science of Organisms?

## Thermodynamics Promises to be the Foundational Science of Organisms

- Science of the "Real World", friction and all such IRREVERSIBLE processes are essential part of Thermodynamics!

In contrast to mechanics:

- Its predictions are not of the details of the evolution of a system, but of the end state! EQUILIBRIUM STATE, or STATE OF HIGHER ENTROPY.

In this sense it predicts "End-directed" evolution.

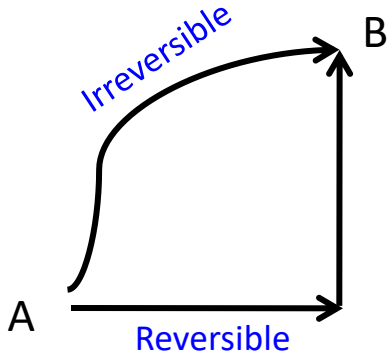
Extremum principles of thermodynamics are "end-directed"

## 19th Century Thermodynamics

$$dS = \frac{dQ}{T}$$ Reversible process (infinitely slow)

$$dS > \frac{dQ}{T}$$ Irreversible process (finite rate)

Incomplete theory




- Theory deals with only end-states, irreversible processes (heat conduction) that cause the system to evolve are not a part of the theory.

- Time does not appear in the theory. No " dX/dt " (Thermostatics ? )

- Many texts have separate parts, Thermodynamics and Kinetics

# Modern Thermodynamics (20th Century)

Ilya Prigogine
(1917 – 2003)

Lars Onsager
(1903 – 1976)

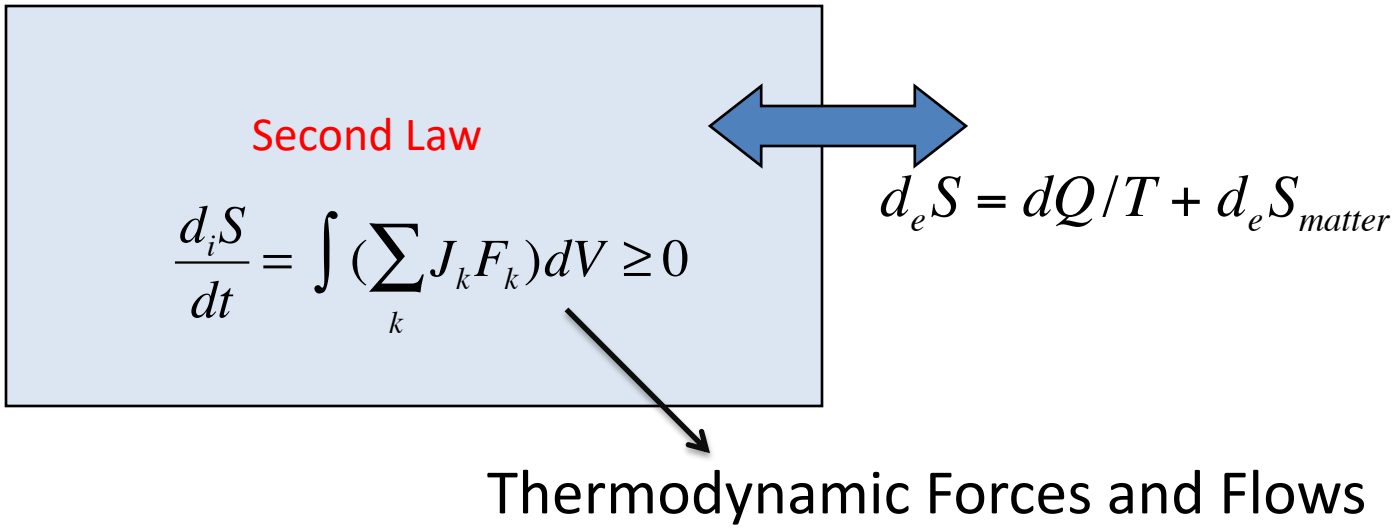
$$dS = d_e S + d_i S \qquad Second\ law : d_i S \geq 0$$

Can describe non-equilibrium open systems
Discovery of Self Organization

# "Modern" Thermodynamics

$$dS = d_e S + d_i S$$

*dS = change in time dt*




Can describe non-equilibrium open systems

**Self Organization**

# Consider Clocks
# Mechanical clock vs Biological Clocks

- Mechanical Clocks work best when irreversible processes such as friction are minimized

- Biological clocks (heart beat, chirping of crickets) are chemical clocks. Chemical reactions are inherently irreversible

Discovery of Self-Organization: Dissipative Structures (1950-1970). BZ reaction

Dissipative Structures: structure created and maintained by irreversible, entropy producing processes

# **Dissipative Structure (BZ Reaction.** Chemical Clock**)**

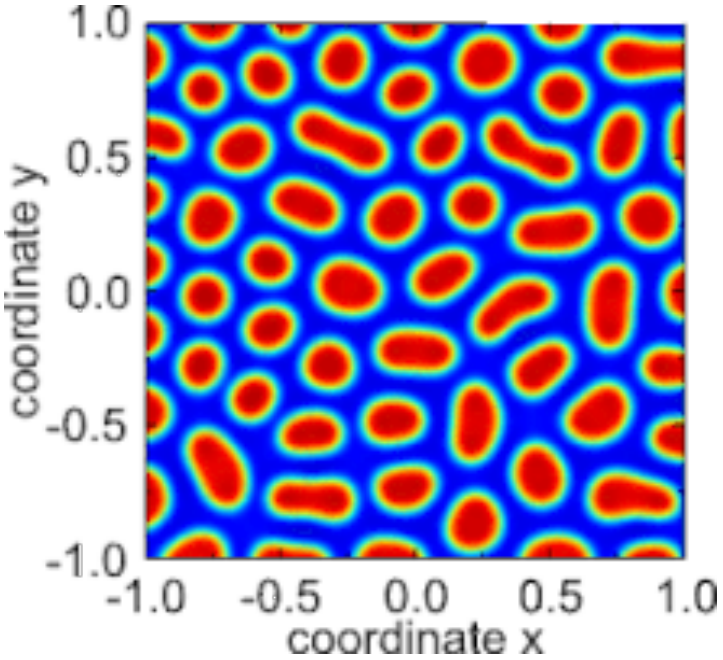
## Result of Entropy Producing Processes


- They arise spontaneously
- Maintenance requires $d_iS/dt>0$
- Generally involve one or more autocatalytic cycles

BZ and other reactions also show spatial patterns, propagating waves, similar to biological systems

https://www.youtube.com/watch?v=bH6bRt4XJcw

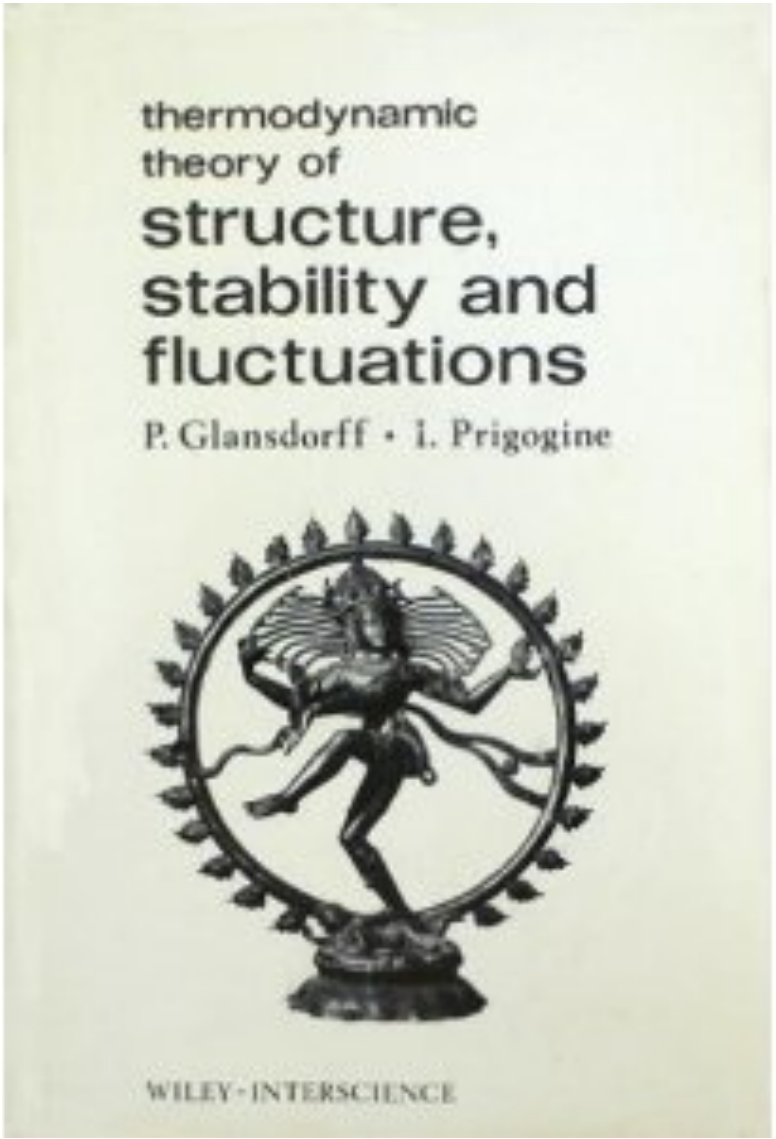
# Turing Patterns due to Chemical Reactions and Diffusion




These examples show how self-organization can produce bio-analogs of chemical clocks and morphological patterns.

No biological behavior

# The Dual Role of Irreversible Processes




Irreversible processes destroy order with one hand while creating it with the other, like Nataraja, Shiva in a cosmic dance of creation and destruction.

# The World of Thermodynamics

Thermodynamics based on Irreversible Laws.

Irreversibility and arrow of time are fundamental in nature.

Energy and Entropy

World of **Self-organization**, dissipative structures

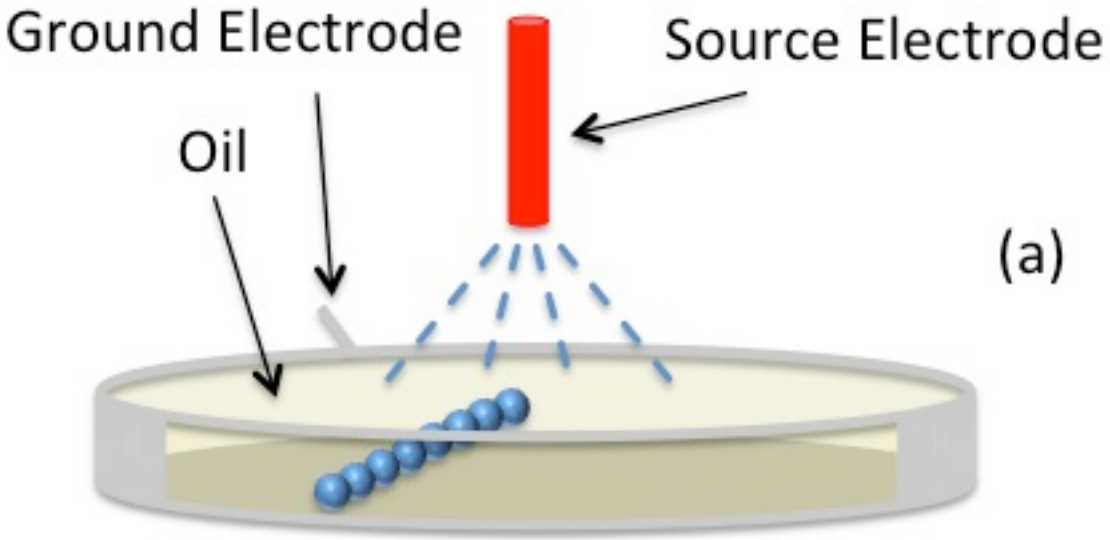
Irreversible processes essential to these systems. Without entropy production, there is no structure.

Open-systems interact with environment and hence are context-dependent

## What About **Behavior** We See in Organisms?

# A Dissipative Structure of Interest

(Voltage Driven. Organism Like)




Previous Studies: Static properties of networks

B. Merté et al., *Helv. Phys. Acta* **61***, 76* (1988).

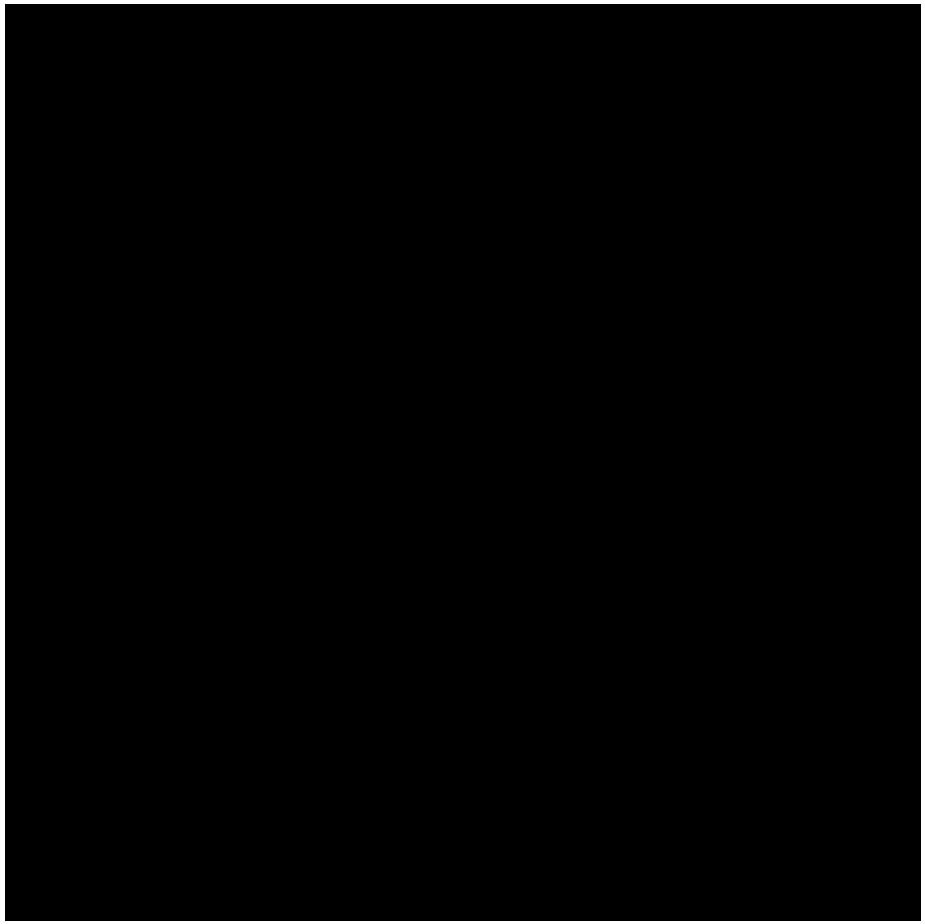
G. Hadwich, et al, *Helv. Phys. Acta* **63**, 487 (1990).

J. Jun, A. Hübler. *PNAS* **102**, 536-540 (2005).

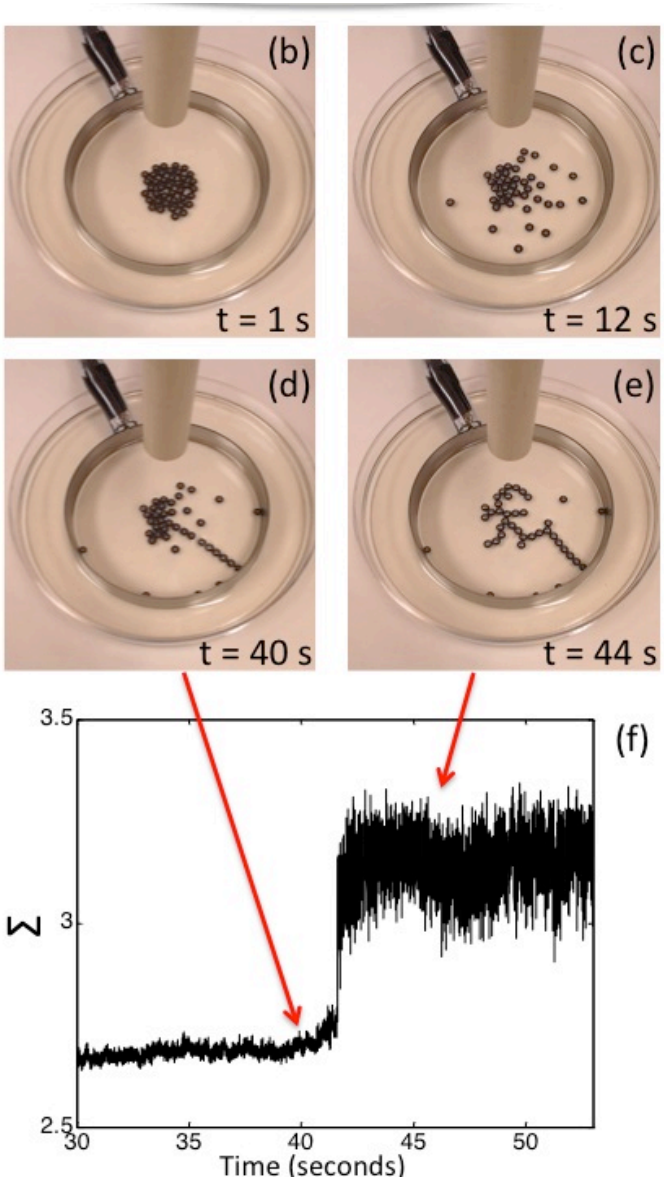
# A Dissipative Structure of Interest

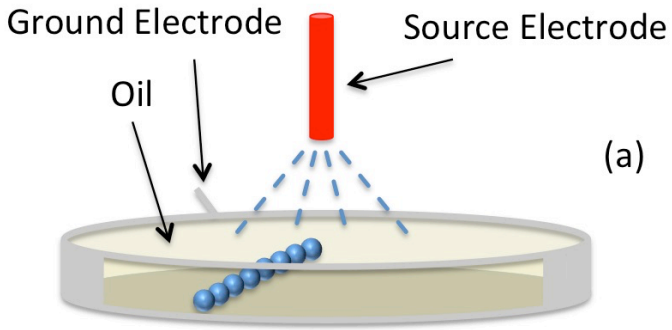
# End-Directed Evolution and Bio-Analog Behavior
## Study of  a Single Tree

Tree Formation Video



- Self organizing
- Self healing
- Forms trees that draw Higher current
- End-directed evolution Organism-like behavior



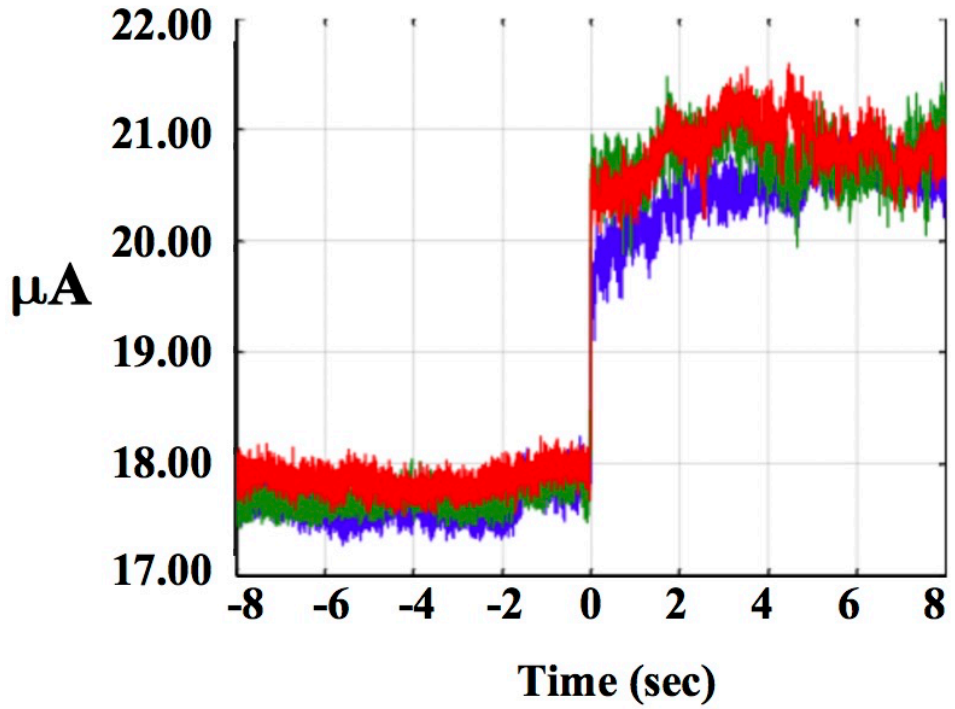




**"Tree" formation has a clear signature:**

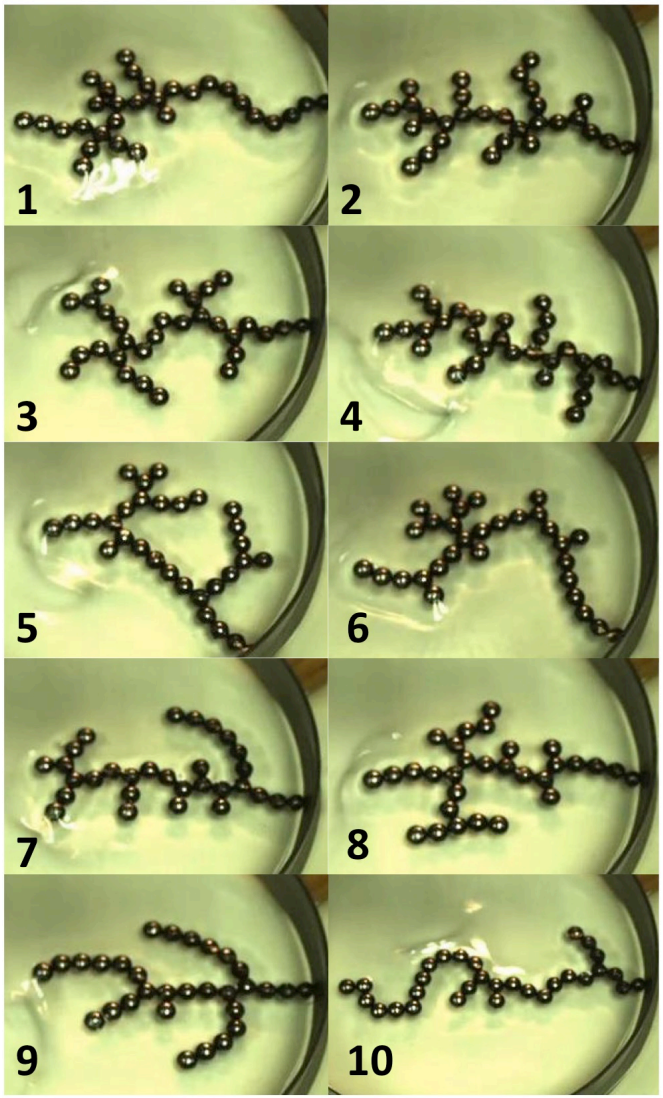
**Sharp increase in current thus the rate of entropy production**

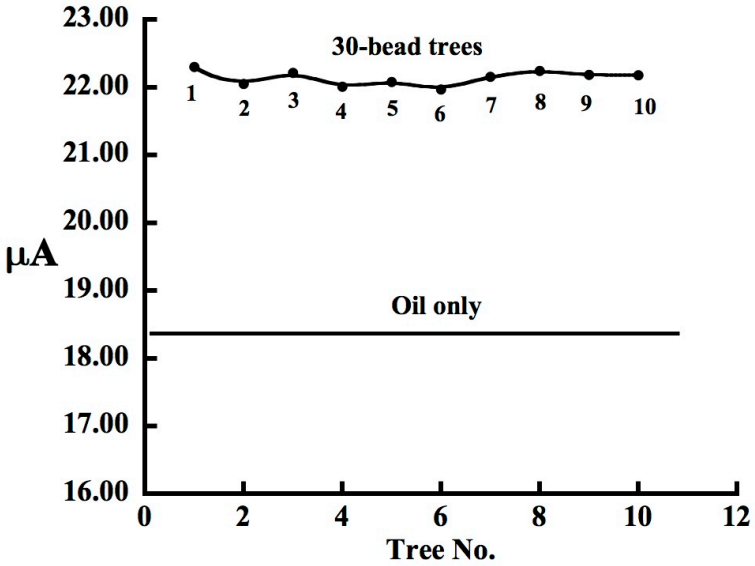
$$\frac{d_i S}{dt} = \frac{VI}{T}$$

# Invariance of the Rate of Entropy Production



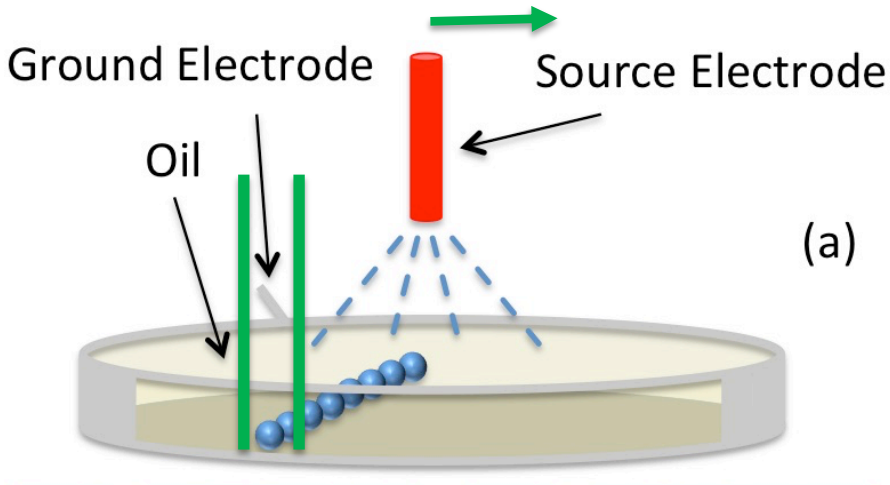
# Diversity of Structures in End-Directed Evolution




PHYSICAL REVIEW E **91**, 050902(R) (2015)

Chaos **27**, 104607 (2017)

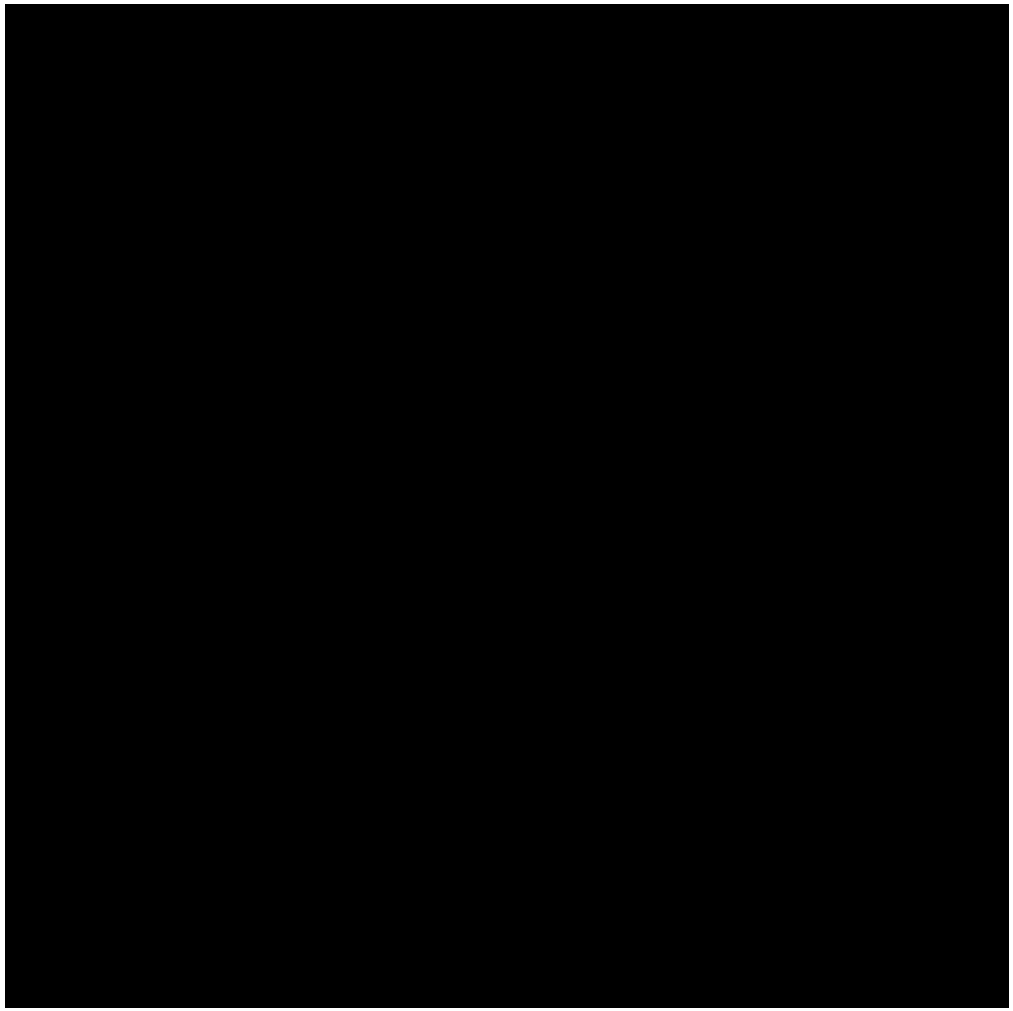



After the tree has formed:

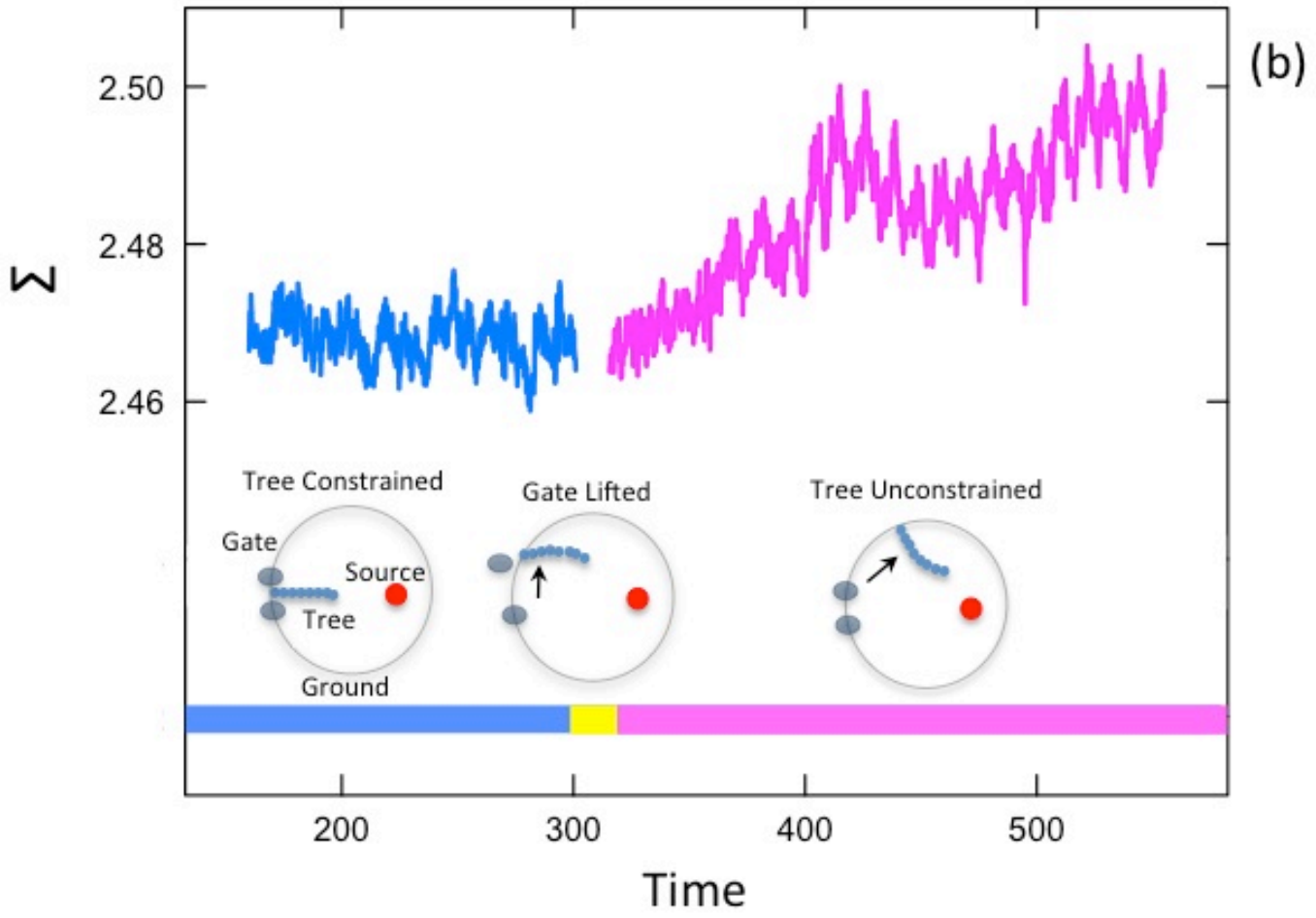
- The base of the tree is held in place
- The source electrode is moved to a place that decreases the current

What does the tree do now?

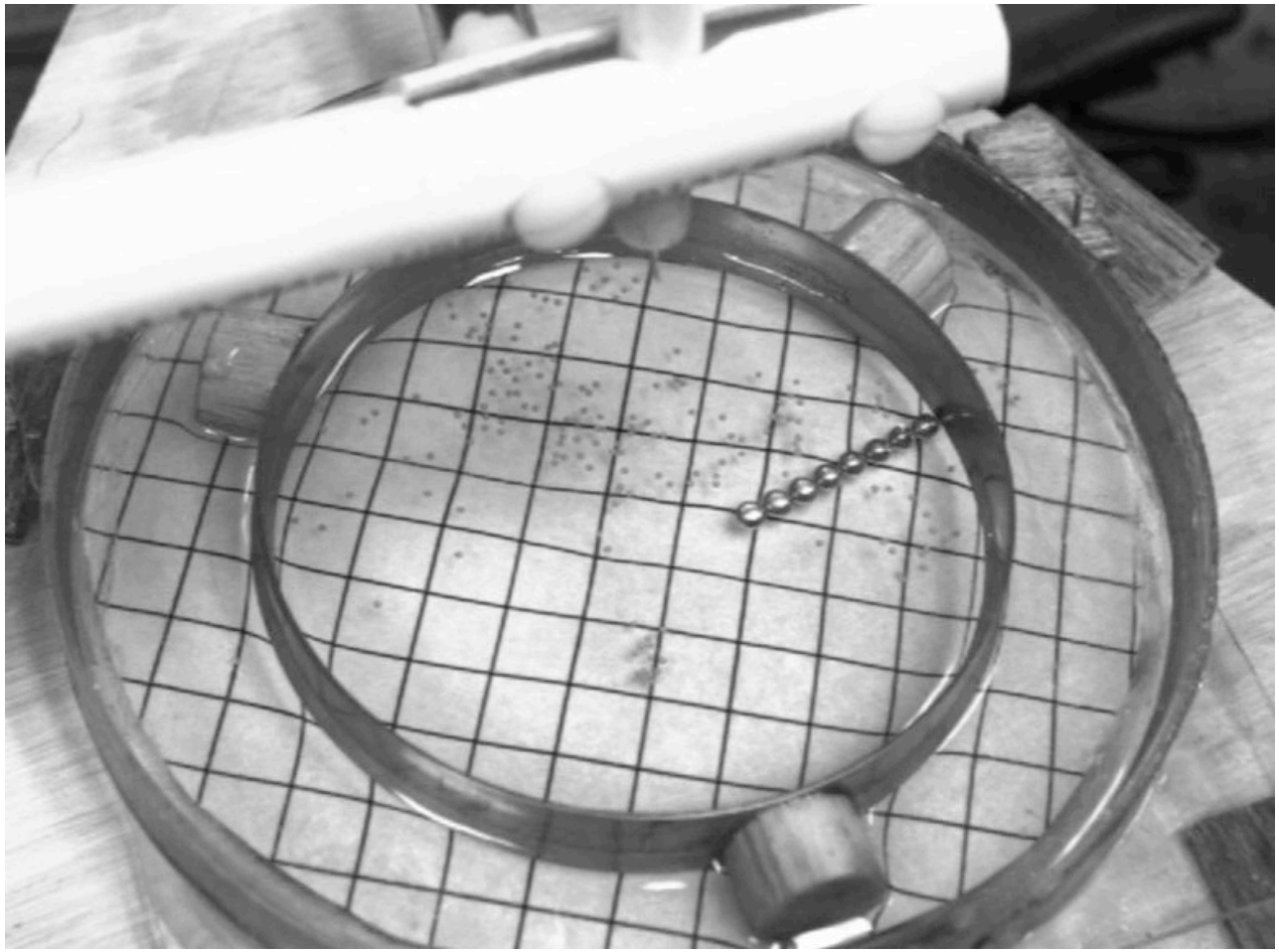
# End-Directed Behavior (Bio-Analog Behavior)
# State of Higher Current (diS/dT)



# Seeking Higher Current

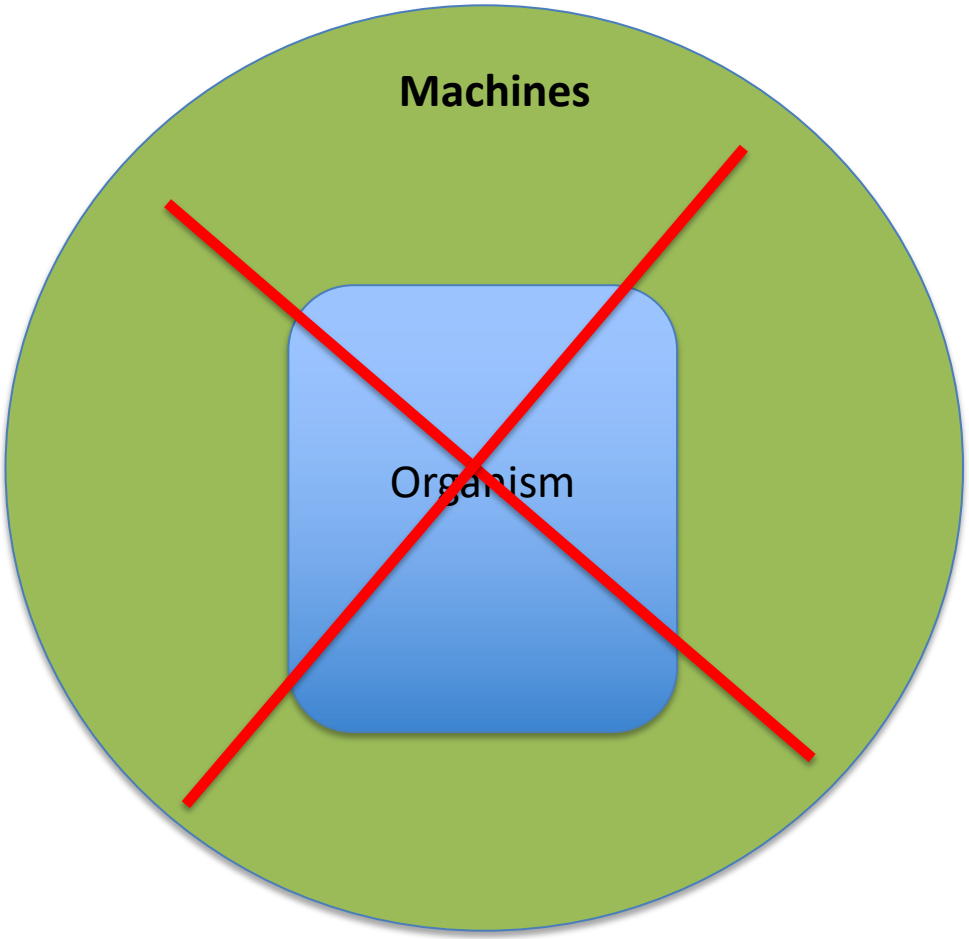


# Complexity of the System

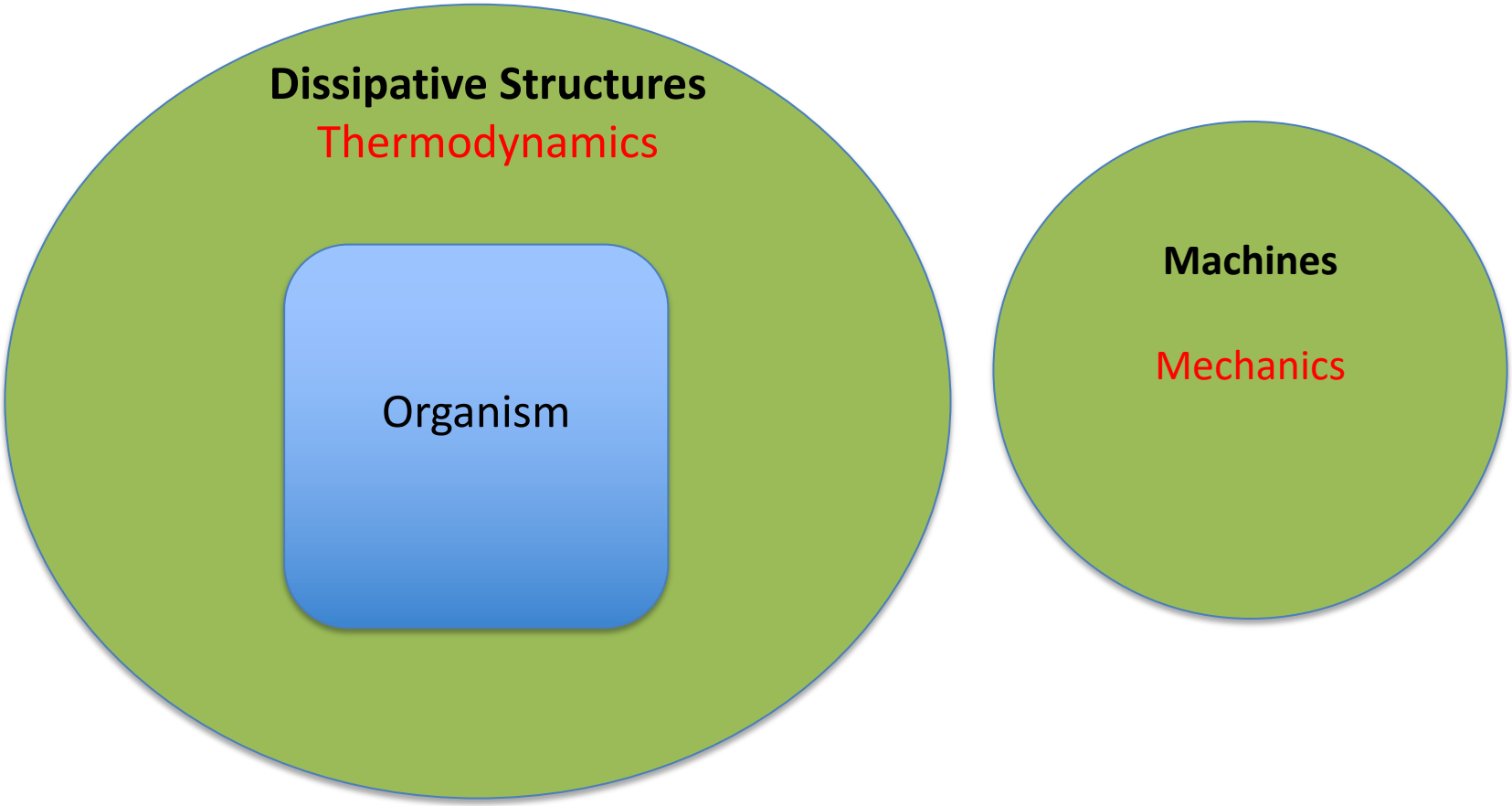


| Designed structures Machines | Dissipative Structures Organisms |
| --- | --- |
| • Generally based on laws of mechanics and computer logic. | • Based on irreversible, entropy producing processes |
| • The structure is designed by an external process. | • Structure through self-organization arising from dissipative processes that are within the system. |
| • Entropy generation and dissipation limits the efficiency of its function. | • Entropy generating processes are essential; without them, the structure ceases to exist. |
| • Not Self-Healing | • Self Healing (functional stability) |
| • The structure is designed to perform targeted functions. No functional stability, or Function Specific Variability. | • Context-dependent ”function“ arises because of structure. Functional Stability. Exhibits Function Specific Variability |

# Organism Are Not A Subset of Machines



# Organism-Like Dissipative Structures



# End-Directed Evolution in Thermodynamics

Evolution to the equilibrium state

Minimization of Helmholtz and Gibbs energy

The Second Law $\frac{d_i S}{dt} \geq 0$

Constant V and T : F = U – ST → Minimum

Constant p and T : G = U – ST + pV → Minimum

**Non-Equilibrium Time-evolution**

$\frac{d_i S}{dt} \rightarrow Maxinum?$

*Other End-Directed Laws*

# Thermodynamics

**19th Century: Dawn of Thermodynamics (**Equilibrium**)**

Heat Engines and Industrial Revolution

**20th Century: Thermodynamics** (Non-equilibrium)

Self-organization, dissipative structures

**21st Century: Thermodynamic (**Structure, Function, End-Directed Behavior)

Understanding of Organisms

Thank you

Questions?