FH CAMPUS WIEN
UNIVERSITY OF APPLIED SCIENCES

DIE HOCHSCHULE, DIE MEHR KANN.

Robotic Lunch September 2024

DR.TECHN. DI MUGDIM BUBLIN

Brain-inspired Neuromorphic Computing

Digital computing technologies **challenges**:

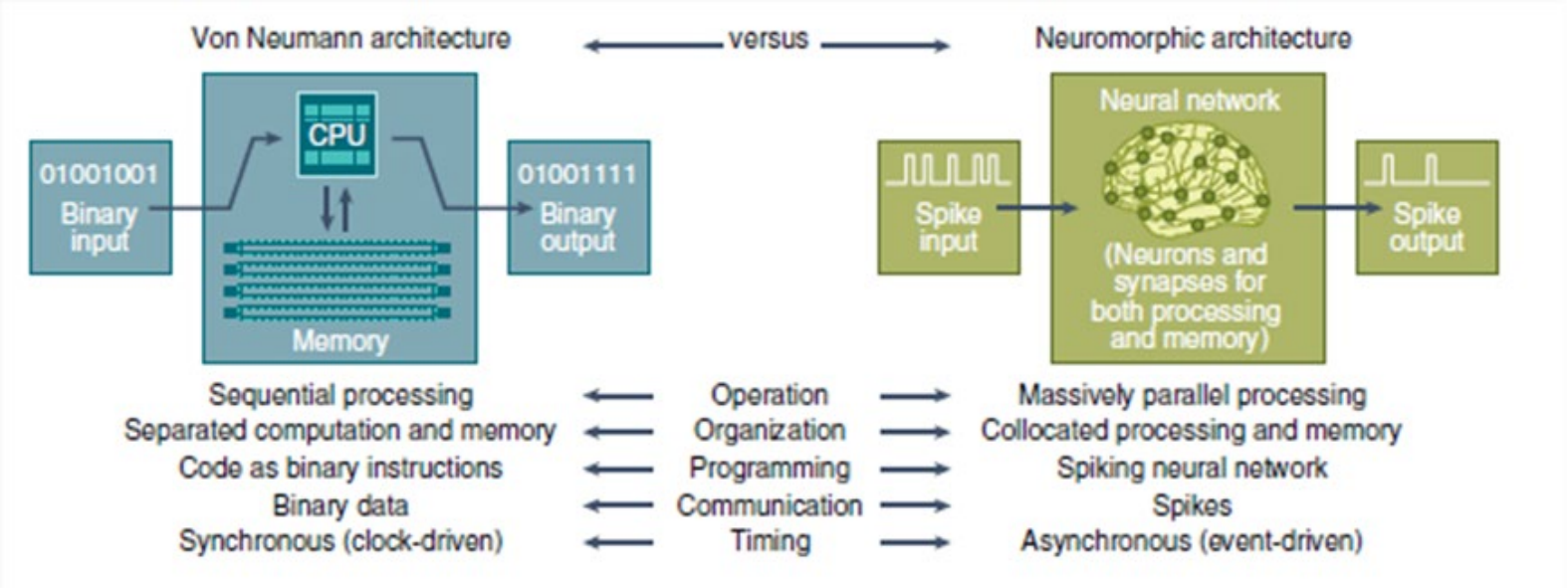
- **Energy** footprint: classical Deep Learning needs about 20 MW
- **Toxicwaste**
- Limits of **miniaturization**
- Vulnerabilities of ever-growing software **complexity**

Brain-inspired Neuromorphic Computing improves:

- **Energy efficiency,** our brain needs about 20 W
- **Noise robustness**
- **Adaptability**
- **Safety**
- **Costs**

=> **New Computing Paradigm**

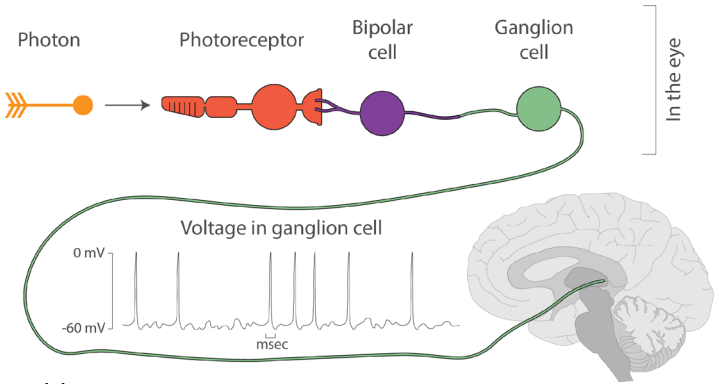
Traditional vs. Neuromorphic Architecture



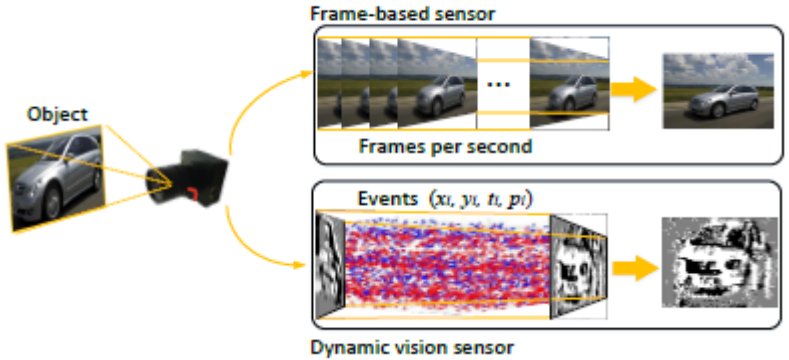
Schuman, Catherine D., et al. "Opportunities for neuromorphic computing algorithms and applications." Nature Computational Science 2.1 (2022): 10-19.

Event Based Processing

- The standard camera outputs frames at a **fixed rate**, thus sending **redundant information when there is no motion** in the scene
- Event cameras respond to pixel-level **brightness changes** with microsecond latency



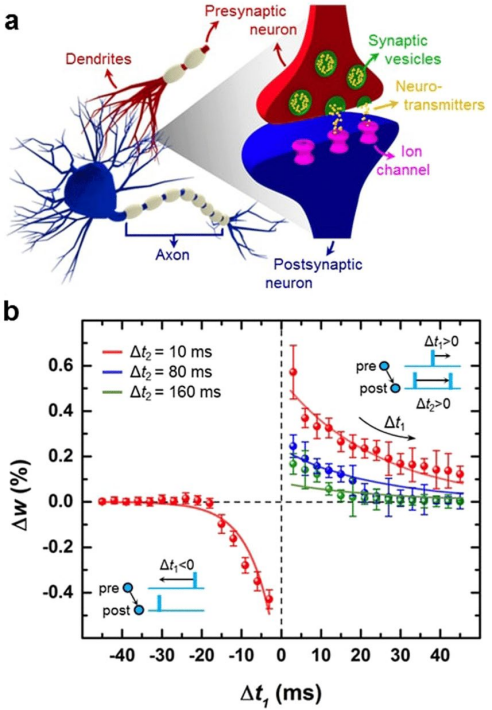
Human vision:
https://i-kh.net/2021/03/01/human-vision-system-an-overview/



Gao, Shan, et al. "An end-to-end broad learning system for event-based object classification." IEEE Access 8 (2020): 45974-45984.

Collocated Processing and Memory

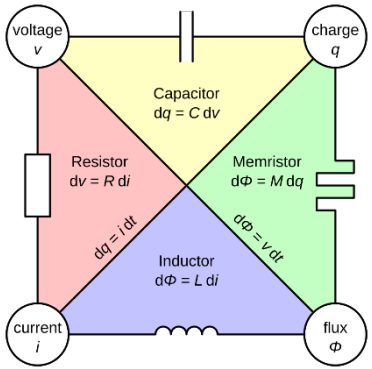
- Connections between nerve cells (**Synapses**) serve as **both processing and memory elements**
- **Spike-timing-dependent plasticity (STDP)** is a biological inspired learning that adjusts the strength of connections between neurons in the brain
- Only **local information** (pre – and post-times) are used
- **Backpropagation** requires **global information** (cost-function gradients)

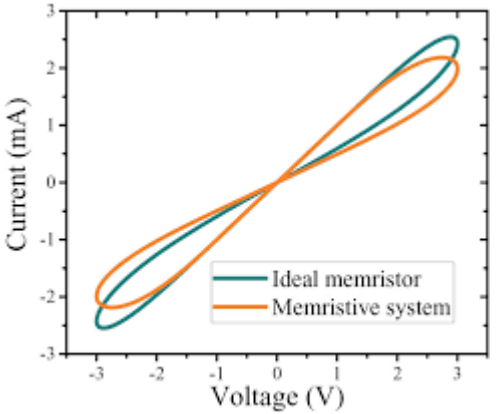


Ahmed, Taimur, et al. "Time and rate dependent synaptic learning in neuro-mimicking resistive memories." Scientific Reports 9.1 (2019): 15404.

Memory Implementation - Memristors

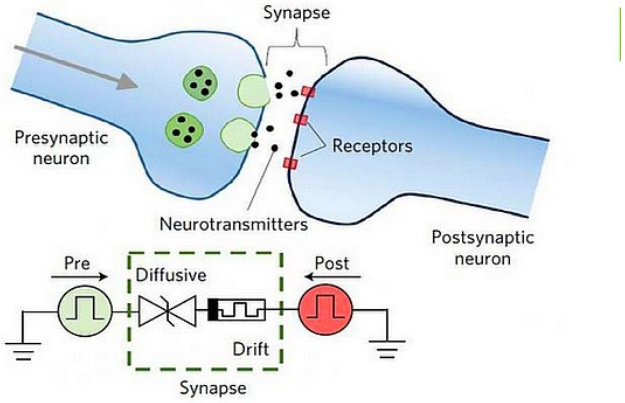
- A **memristor** (/ˈmɛmrɪstər/; a portmanteau of memory resistor) is a non-linear two-terminal electrical component ***whose resistance depends on the magnitude, direction, and duration of the applied voltage*.**





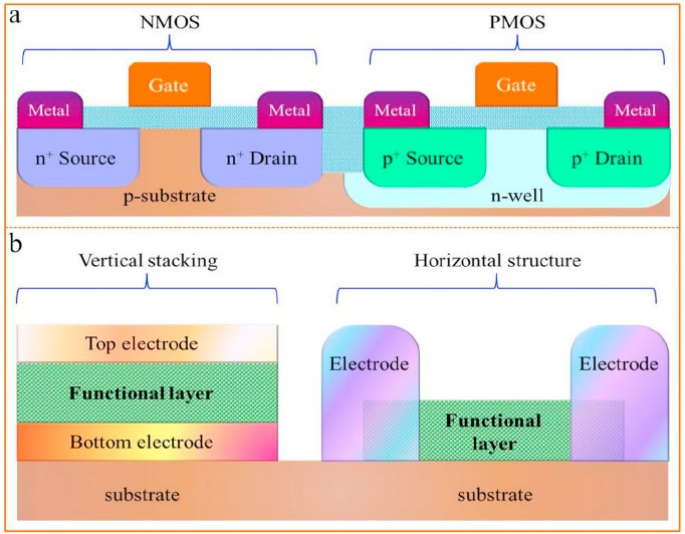
Chua, Leon. "Memristor-the missing circuit element." IEEE Transactions on circuit theory 18.5 (1971): 507-519.

- Memristor can actually express **both long-term and short-term plasticities in synapses.**

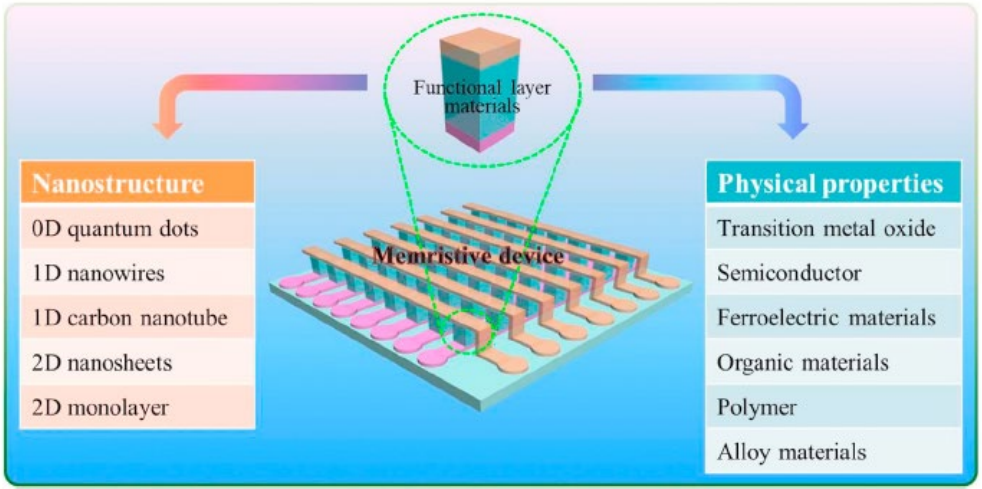


Cai, Weiran, and Ronald Tetzlaff. "Synapse as a Memristor." Handbook of Memristor Networks (2019): 351-367.

Memristor Implementations



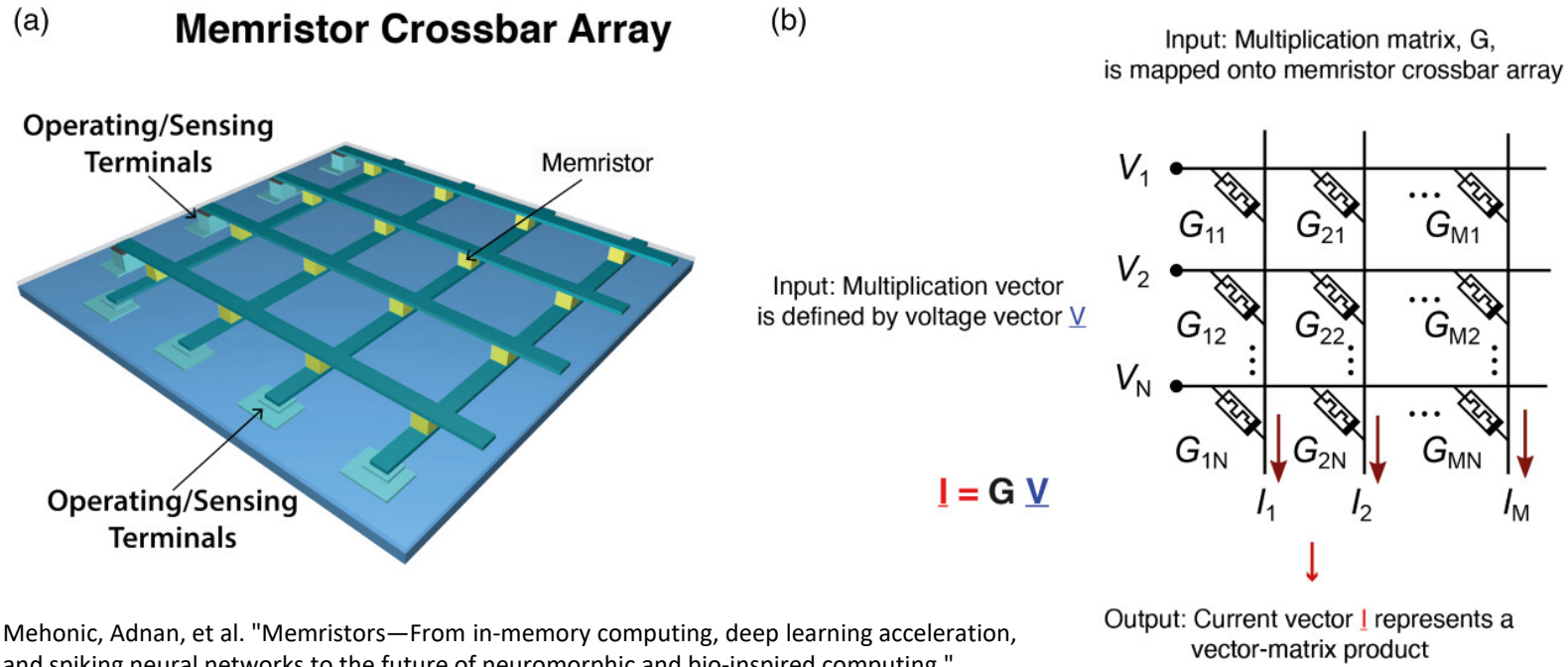
(a) Structures of CMOS devices
(b) Structures of memristive devices



Sun, Bai, et al. "Synaptic devices based neuromorphic computing applications in artificial intelligence." Materials Today Physics 18 (2021): 100393.

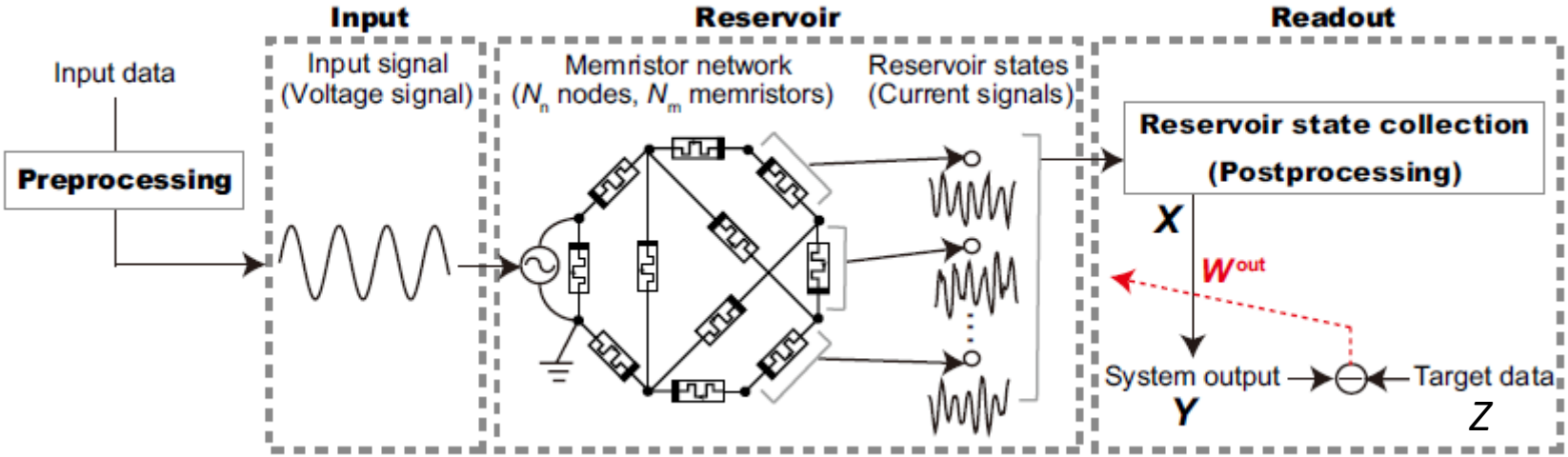
In-Memory Computing with Memristors

Simple implementation of Matrix – Vector Product:



Mehonic, Adnan, et al. "Memristors—From in-memory computing, deep learning acceleration, and spiking neural networks to the future of neuromorphic and bio-inspired computing." Advanced Intelligent Systems 2.11 (2020): 2000085.

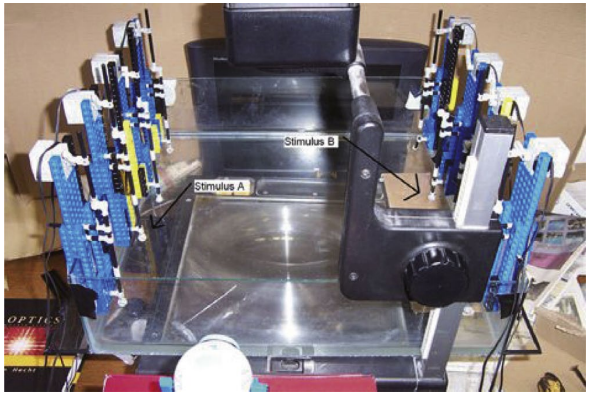
Random Memristor Network as a Reservoir

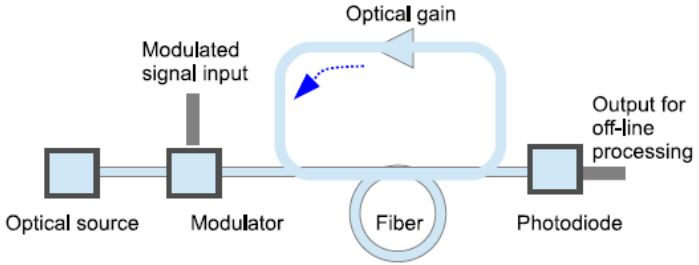


Tanaka, Gouhei, and Ryosho Nakane. "Simulation platform for pattern recognition based on reservoir computing with memristor networks." Scientific Reports 12.1 (2022): 9868

Reservoir Examples

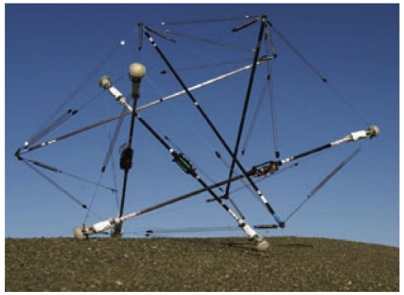
Fluidic RC where the reservoir is the water in a bucket



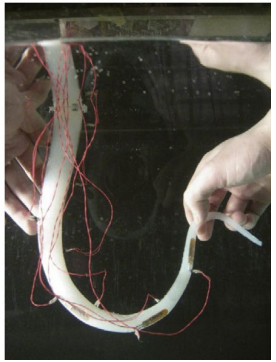


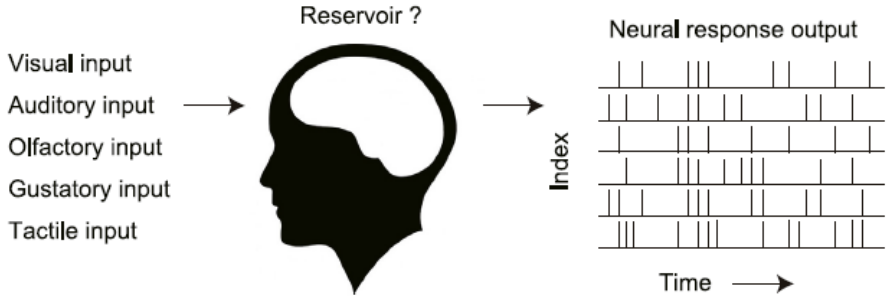
(a) A tensegrity structure-based reservoir (b) A reservoir based on a soft octopus robot

(a)



(b)





Tanaka, Gouhei, et al. "Recent advances in physical reservoir computing: A review." *Neural Networks* 115 (2019): 100-123.

Safety & Security Considerations

- **Security**

  More difficult to access and change analog hardware like Memristors or Reservoir over internet

- **Safety**

  For analog systems it is possible to use continuity properties when pondering system behavior in different points of their state space. If a system exhibits intended behavior in a situation A and in a related situation B, it can be argued that it will show intended behavior also when $C=\alpha A+(1-\alpha)B$, where $0<\alpha<1$[1]

[1]Wahlström, Björn. "Differences between analog and digital I&C." Proceedings of the 9th International Conference on Nuclear Plant Instrumentation, Control & Human–Machine Interface Technologies (NPIC & HMIT 2015). 2015.

Total Turing Test

- Some modern AI systems like ChatGPT can already pass classical Turing Test?
- Turing viewed the physical simulation of a person as unnecessary to demonstrate intelligence.
- Modern robots are much further away from human physical capabilities than ChatGPT from human cognitive capabilities.
- Other researchers have proposed a **total Turing test**, which requires **interaction with objects and people** in the real world:
  - **Robotics** to manipulate objects and move about

Physical Embedding

Studying brain not enough, we need:

- **Embedding** of brain into organism
- **Interaction** with environment
- Exploit the “intelligence” of underlaying **physics and materials**

Bio-Inspired Robotics

Same Fundamental Principles valid in Design of Biological and Technical Systems:

- Distributed
- Hierarchical
- Adaptive
- Feedback
- Simple rules leads to complex behaviour
- Learning
- Self-organized
- Emergent
- Stygmergy
- Redundancy
- ...

Principles of Neuromorphic Robotics

- Communicate only if something changes => Spiking neurons
- Use local information for local learning => STDP learning rule
- Use available physics as much as possible => Reservoir
- Exploit “physical body intelligence” => Embodiment
- Distributed control => Self Organization
- Complex behavior from simple rules => Emergence

Highly interdisciplinary endeavor!

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Thank You For Your Attention