Metabolism-based Bioelectronic Networks

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Motivation

The **transition from unliving to living matter** requires a constant exchange of energy, matter and information between a system and its environment and forms the basis of life. The system properties of living systems can be traced back to the following basic principles: growth, functional spatial organization, development, movement, communication (irritability and regulation), reproduction, mutability and metabolism. Metabolism and energy metabolism are the indispensable prerequisites for all other principles of life. Motivated by this fact, this project aims to explore how to **integrate metabolism into micro-electronic networks**. Our goal is to provide neuromorphic systems with a novel degree of freedom, enabling the realization of artificial neuronal networks with both high conductivity and energy efficiency, as well as high adaptivity and thus adaptability to their environment.

Objectives

Our goal is to realize **active bioelectronic networks based on electroactive microorganisms.** The prokaryotic cells (bacteria) supply the network with their chemical-biological entropy export (metabolic activity) for the **development of emergent complex dynamics**.

Why using prokaryotic electroactive microorganisms?

Electroactive microorganisms (EAMs) like *Geobacter, Shewanella oneidensi, Desulfovibrio spp.* have the ability to utilize insoluble minerals both as electron sinks for respiration and as energy sources for growth via extracellular electron transfer. This process facilitates bidirectional electron flow across insulating bacterial membranes (fig. 1).

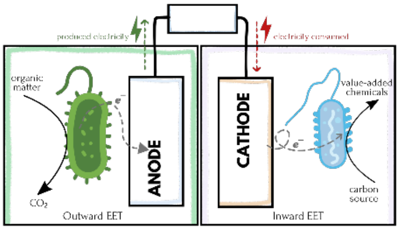


Fig. 1 Direct electron transfer with EAMs can involve electrons transferred extracellularly to an anode (outwardly) and/or accepted from a cathode (inwardly)

Why using thin-film technology?

We will employ thin-film technology for the development of a micro-electronic substrate which allows to integrate metabolism into a neuromorphic architecture.

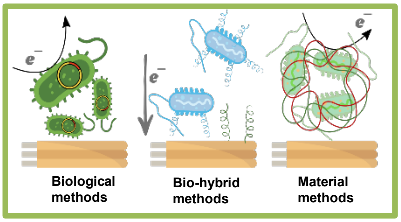


Fig. 2 Methods for enhancing the interaction between cells and electrodes range from strictly biological to bio-hybrid and materials

How can electron transfer at biotic-abiotic interface be optimized?

To enhancing direct electron transfer to improve microbial fuel cells and microbial synthesis system performance is the effective coupling of cellular metabolism to electrodes. The most direct approach is to promote EAM growth on electrodes by improving their adhesion and biofilm formation. Some methods are show in fig.2.

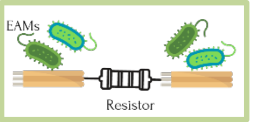


Fig. 3 Individual bioelectronic cells

What does the electrical and bioelectronic characterization involve?

The bioelectronic network should also have an external electrical control for a target learning of complex tasks. Therefore, we will study the dynamics of bioelectronic single cells (fig. 3) and networks (fig. 4) and their sensitivity and tunability to external stimuli to realizing local learning for complex emergent dynamics.

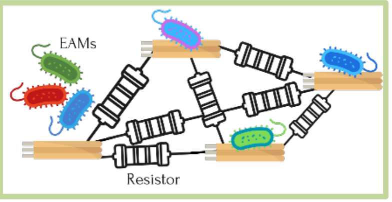
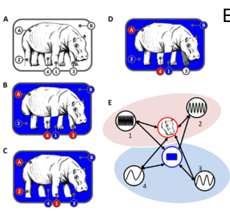


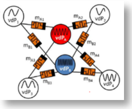
Fig. 4 Network bioelectronic cells

Preliminary Work

Neuromorphic Systems

Emergent dynamics in memristive coupled oscillator networks[1,2]

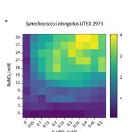


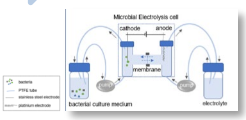


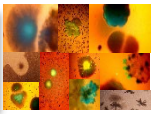
MNES ⟷ PC/MRT

EAMs isolation and culturing optimization

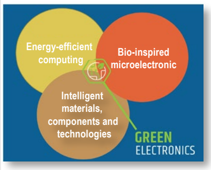
converting excess energy into biomass[3,4]







Contribution to ISGE



- Dynamical (oscillator) computing
- Bioelectronic networks based on electroactive bacterial cells
- Micro-Nano-Biotechnology

Work Program

WP1: Development of the experimental substrate platform

(T1.1) Fabrication and Development of a Thin Film System on a Dielectric Substrate with the Layer Structure: Adhesive Layer - Resistance Layer - Electrode Layer - Dielectric Covering Layer .
(T1.2) Cultivation-compatible assembly and connection techniques are developed for electrical connections to facilitate the electrical stimulation of bacteria and the measurement of the response behavior of bioelectronic microsystems.
(T1.3) Cultivation of electrode-active bacteria, which grow adherently on platinum microelectrodes is conducted.

WP2: Electrical and bioelectronic characterization of individual cells

(T2.1) Identification of suitable equivalent circuit models for individual bioelectronic cells and measurement of the corresponding electrical parameters depending on the culture condition and electrolyte conditions (static behavior).
(T2.2) Determination of the representation of electrical stimulation on the growth and metabolic activity of bacteria in the characteristics and determination of the time-dependent response behavior or the associated time constants (dynamics over time).

WP3: Electrical and bioelectronic characterization of network structures

(T3.1) Connecting multiple bioelectronic elementary cells through coupling resistors to form elementary networks and determining their characteristics and response behavior.
(T3.2) Developing a suitable stimulation, readout, and evaluation strategy for larger networks of coupled micro-bioelectronic elements with multi-electrode control.
(T3.3) Construction, electrical stimulation, and empirical characterization of the signal response behavior of higher-integrated networks; identification of emergent structures and dynamics.
(T3.4) Analysis and evaluation of measurement results regarding their potential application in future bioelectronic signal processing and communication systems. Compilation of the dissertation.

Work Packages		Year 1				Year 2				Year 3			
		I	II	III	IV	I	II	III	IV	I	II	III	IV
WP1	T1.1	■											
	T1.2	■	■										
	T1.3	■	■										
WP2	T2.1			■	■	■							
	T2.2				■	■	■						
WP3	T3.1							■	■				
	T3.2							■	■				
	T3.3									■	■	■	
	T3.4											■	■

References

1. Ignatov, M., **Ziegler, M.** et al. (2017) Memristive stochastic plasticity enables mimicking of neural synchrony: Memristive circuit emulates an optical illusion. *Sci. Adv. 3,* e1700849.
2. Zahari, F., **Ziegler, M.** et al· (2024) Neuromorphic Circuits with Redox-based Memristive Devices. pp 43–85, Springer International Publishing, Cham.
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Some illustration using canva program