Electroactive Microbes

ϵ-machines as environmental signal generators

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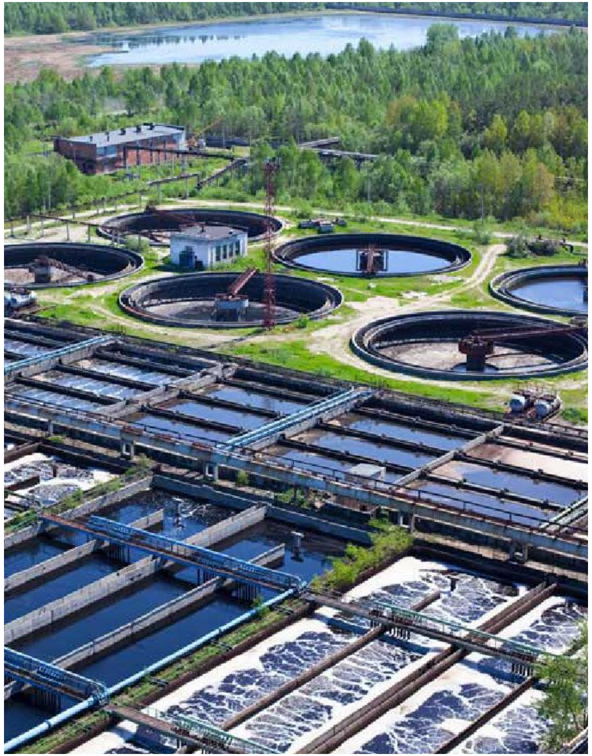
June 2, 2020

Presentation Outline

- **Motivation**
  - Wastewater treatment, climate change, resource recovery
- **Background Information**
  - Bacterial energetics
  - Electroactive bacteria & their uses
- **Project / Model**
  - Single cell-model + ϵ-machine
  - Incorporating memory into the model

Wastewater Treatment, Climate Change, Resource Recovery

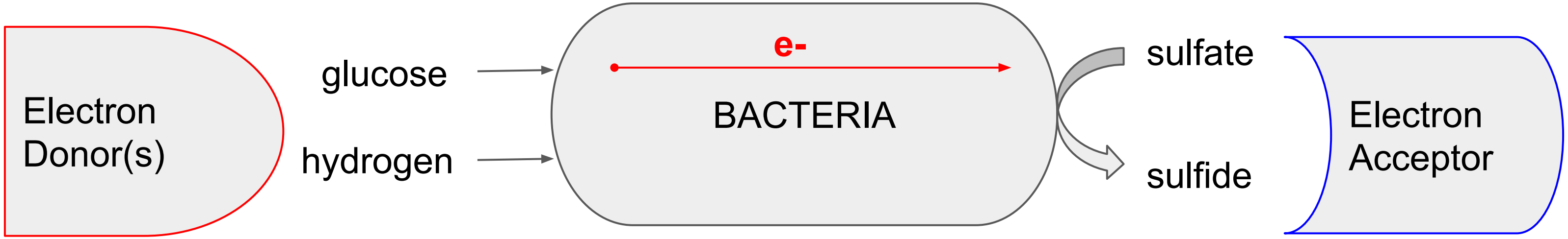
- Wastewater Treatment is an energy intensive process ~3% global energy consumption
- Wastewater treatment directly produces greenhouse gases (CO_2, CH_4, N_2O) ~1.8% global GHG emissions
- Opportunities to recovery a wide variety of materials and become carbon neutral or carbon sinks



https://www.calbrite.com/markets/water-wastewater/

Albert Szent-Györgyi: "Life is nothing but an electron looking for a place to rest"

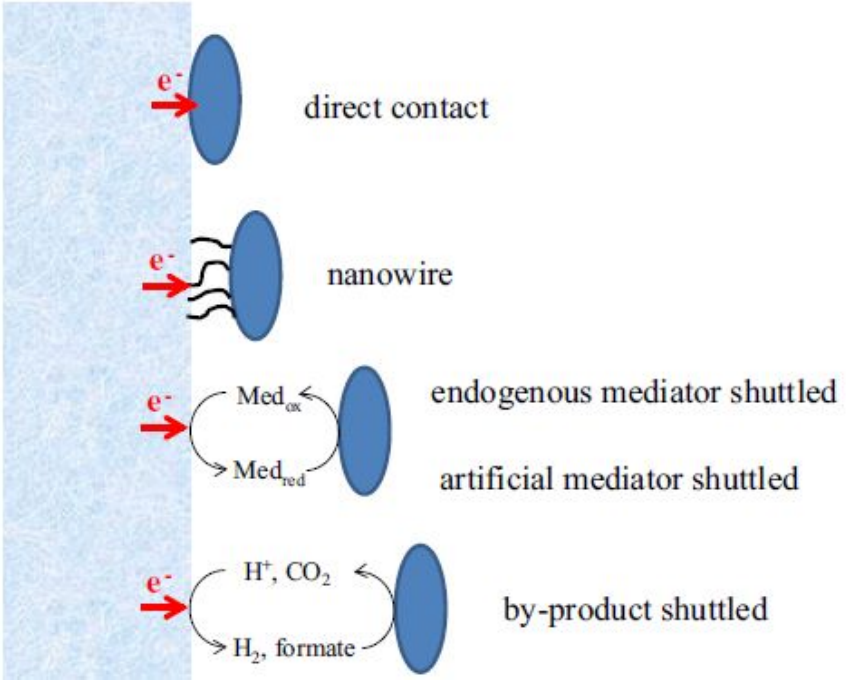
Life is driven by REDOX chemistry---chemical reactions involving electron transfer



Bacteria utilize different electron donors (EDs) and acceptors (EAs) for energy

The type and relative abundance of different EDs and EAs is referred to as the *redox environment*

Electroactive Microbes



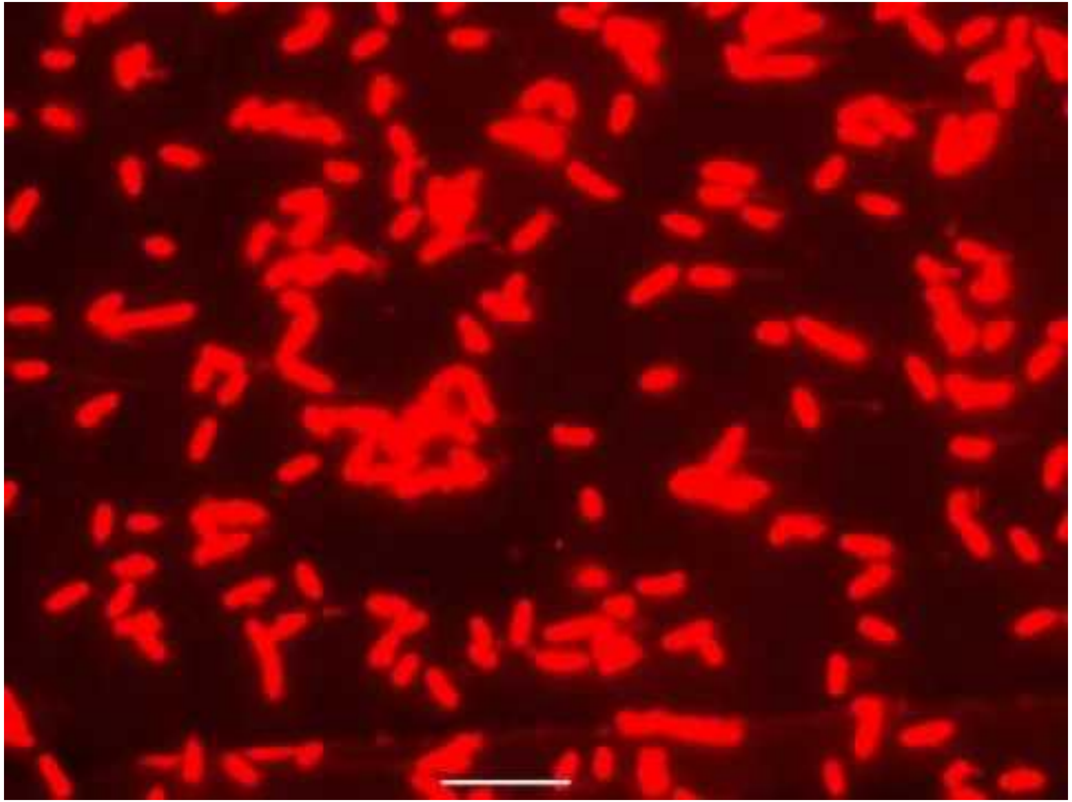
Choi, O., & Sang, B. I. (2016). Extracellular electron transfer from cathode to microbes: application for biofuel production. *Biotechnology for biofuels*, *9*(1), 11.

Electroactive microbes are capable of donating or receiving electrons to or from external sources

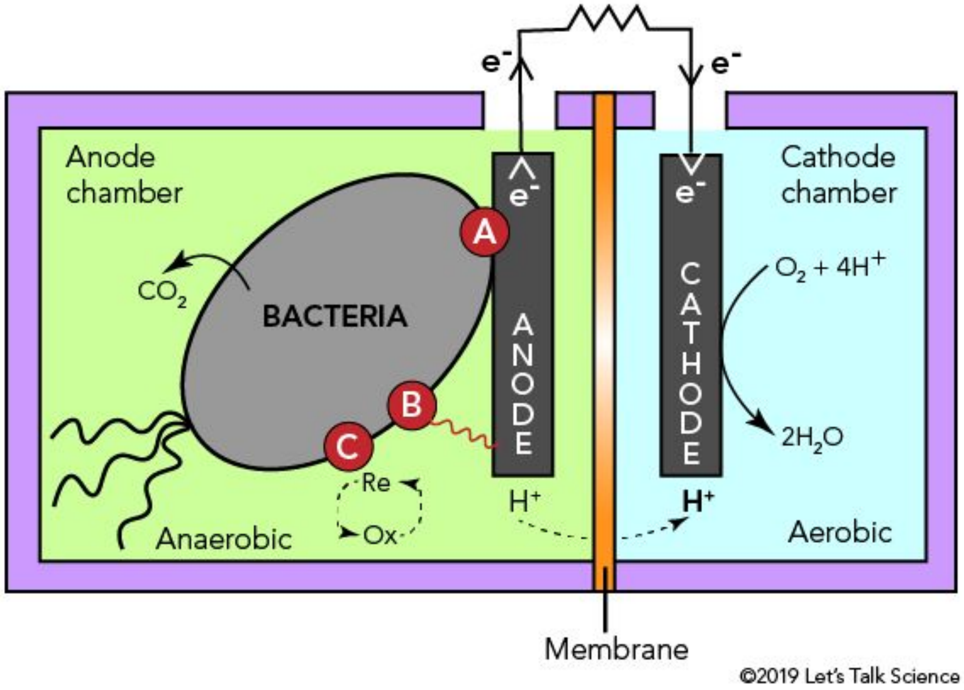
Exoelectrogens - donate e^-s

Electroautotrophs - accept e^-s

Behold! Bacterial nanowire growth in real-time

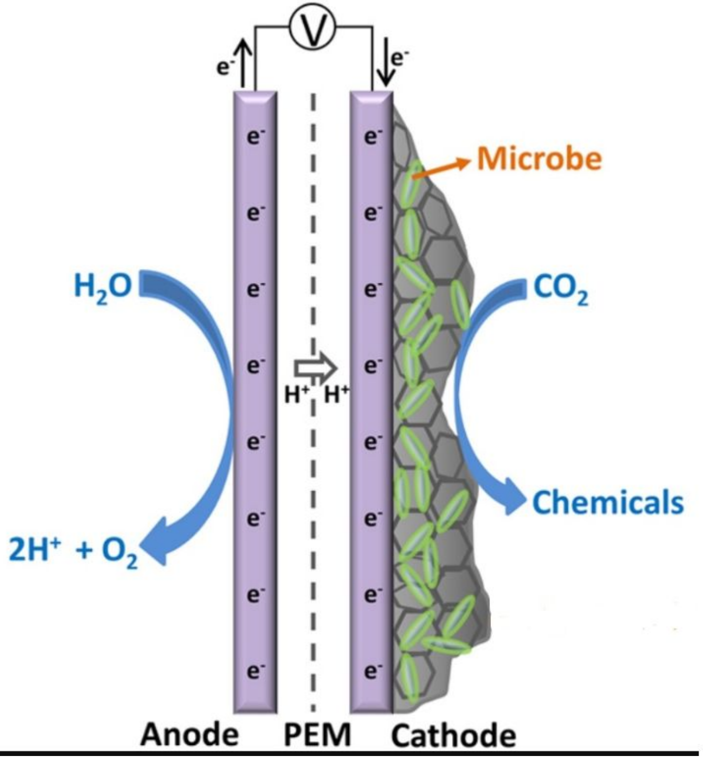


Microbial Fuel Cell



https://letstalkscience.ca/educational-resources/stem-in-context/microbial-fuel-cells

Microbial Electrosynthesis



Aryal, N., et al (2016). Enhanced microbial electrosynthesis with three-dimensional graphene functionalized cathodes fabricated via solvothermal synthesis. *Electrochimica Acta*, *217*, 117-122.

Fluctuating Redox Environments

In both natural and engineered environments bacteria are subjected to stochastic fluctuations in their local redox environments.

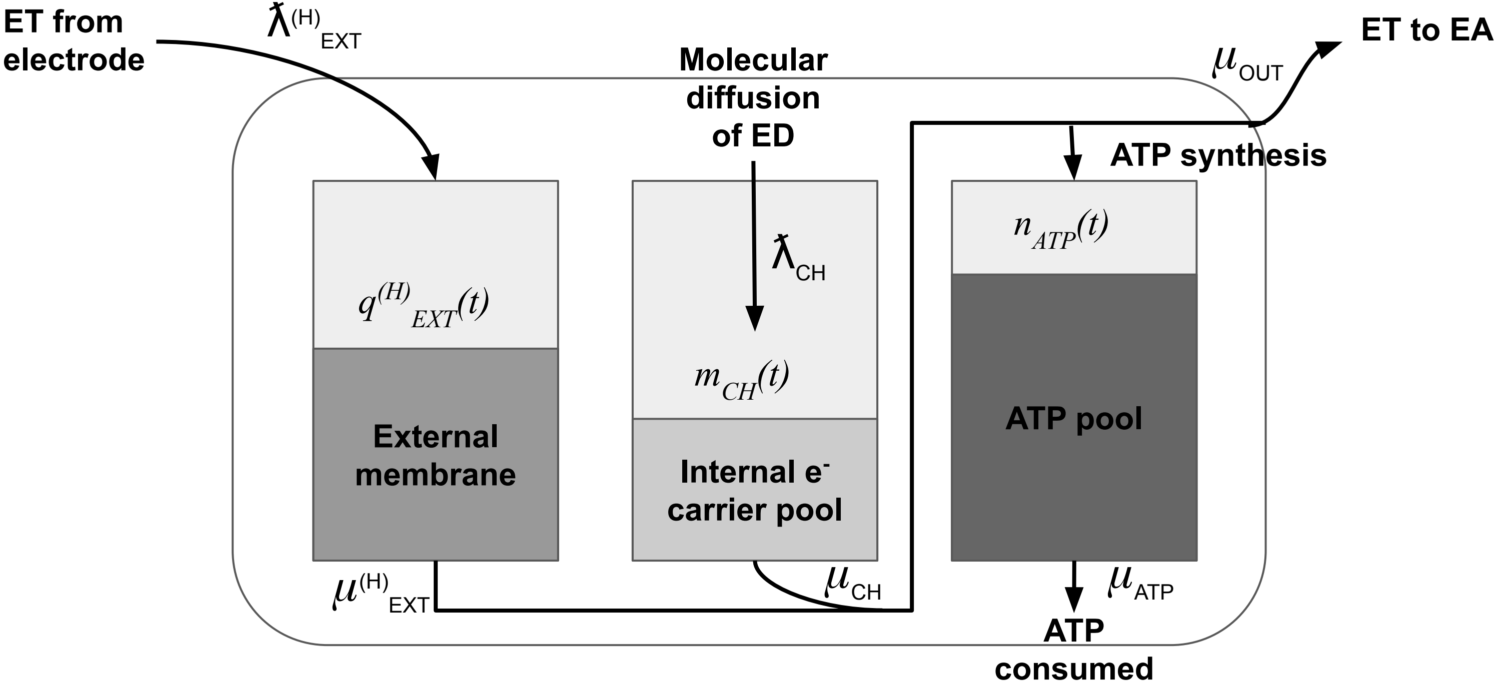
A series of questions follow:

- How does degree of randomness in redox environment impact intracellular redox state?
- What are the consequences of the different intracellular redox states?
- Can my model predict average cell life time?
- Are memories of past environmental redox fluctuations stored by bacteria? If so, how? How do these memories influence behavior?
- How does one quantify the predictability of the redox environment?

Project Description

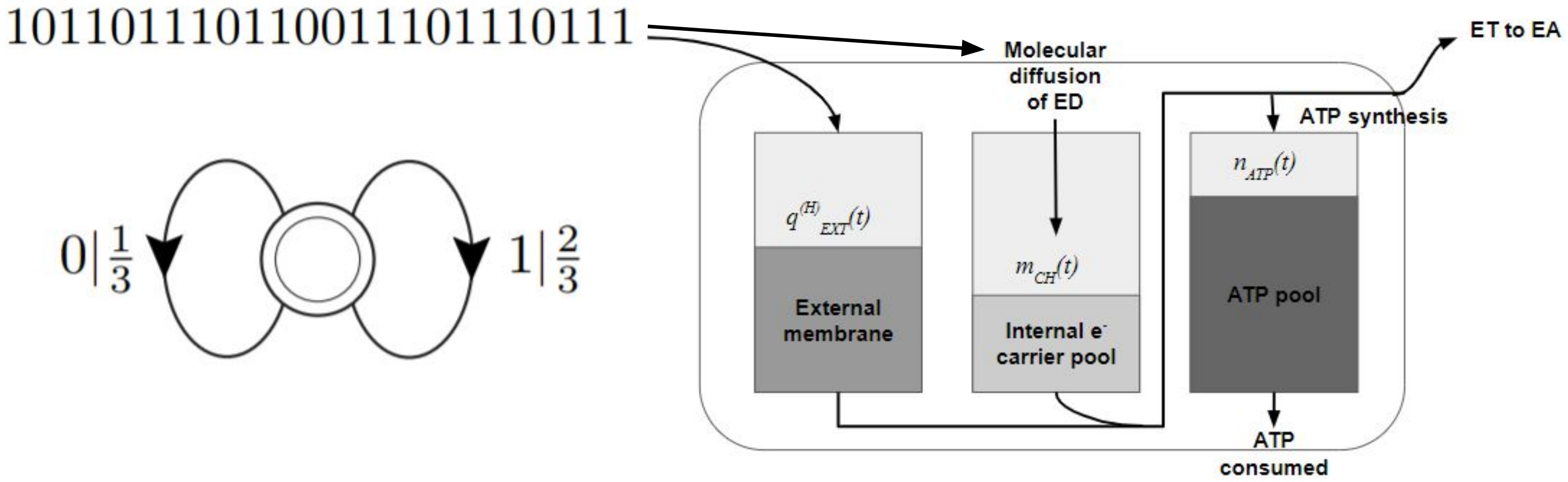
1) Redox environment can be controlled experimentally
   a) Use ϵ-machines w/ $A = \{0,1\}$ to generate time series of redox states, defined below. These bit strings then serve as actual experimental protocol to be carried out in lab.
2) ED is the cathode
   a) 0 = no electron available
   b) 1 = electron available
3) ED is hydrogen gas (H_2)
   a) 0 = no H_2 available
   b) 1 = H_2 available
4) EA is constant
5) Generated bit strings are input into single cell model

Single cell model



Michelusi, N., Pirbadian, S., El-Naggar, M. Y., & Mitra, U. (2014). A stochastic model for electron transfer in bacterial cables. *IEEE Journal on Selected Areas in Communications*, *32*(12), 2402-2416.

Environmental Redox Signal + Cell Model



Intracellular redox state & epigenetic memory

“Numerous characterized epigenetic marks, including......DNA methylation, have direct linkages to central metabolism through critical redox intermediates such as NAD+....Fluctuations in these intermediates.....may thus have direct effects on epigenetic signaling that lead to measurable changes in gene expression.”

Cyr, A. R., & Domann, F. E. (2011). The redox basis of epigenetic modifications: from mechanisms to functional consequences. *Antioxidants & redox signaling*, *15*(2), 551-589.

Environmental predictability & epigenetic memory

Marzen and Crutchfield** (2018) derived expressions relating the statistics of a fluctuating environment to epigenetic memory in bacteria:

"Value of information" is $\Delta r^* = I[Y_{t-1}; X_t]$ = increase in max expected log-growth rate

From data processing inequality: $I[Y_{t-1}; X_t] \leq I[X_{-\infty:t};X_t]$

Where $I[X_{-\infty:t};X_t] = H[X_t] - h_\mu$ is the "predicted information rate....largely controlled by environment's intrinsic randomness", i.e. h_μ

Goal: Use ϵ-machines with range of h_μ values as environmental signal generators in experiments and measure cell growth rates and/or DNA methylation levels (epigenetic memory)

**Marzen, S. E., & Crutchfield, J. P. (2018). Optimized bacteria are environmental prediction engines. *Physical Review E*, *98*(1), 012408.

Questions?

Thanks for your attention!