Driving microbial metabolism with electricity: challenges and opportunities in electrosynthesis

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ISF-2
DOE Listening Day
Outline

- Extracellular electron transfer and iron bacteria
- Reversing a dissimilatory metal reducing bacterium
- Domesticating new organisms for electrosynthesis
Electrodes

Anode

Cathode

e^-
e^-
Electrosynthesis

Cathode

Renewable Electricity

e^{-}
Outline

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Shewanella – the *E. coli* of the Environment

*S. oneidensis*

*Shewanella sp. ?*

*S. benthica*

*S. frigidimarina*

*Shewanella sp. ANA-3*

*S. amazonensis*
Respiratory Diversity

- Oxygen
- Nitrate
- Nitrite
- TMAO
- DMSO
- Sulfur
- Fumarate
- Urocanate
- Chromium
- Selenium
- Arsenic
- Technetium
- Uranium
- Tellurium
- Cobalt
- Vanadium
- Manganese
- Iron
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- Iron
Respiration of insoluble substrates

Iron Oxide

Manganese Oxide

“Extracellular Electron Transport”
Why is Extracellular Electron Transport Important?

- Respiration of *insoluble* substrates requires novel electron transfer pathways.

- EET allows the cell to respire electrodes to generate electricity, can also reverse flow *into* cells: *electrosynthesis*. 
Respiration of insoluble substrates
Core conduit for EET in *Shewanella*

MtrF – a paralog of MtrC in *S. oneidensis*

Clarke et al., 2011 PNAS Jun 7;108(23):9384-9
Respiration of carbon electrodes by *Shewanella*

Lactate $\rightarrow$ Acetate + ATP + $4e^- + 4H^+$
Electrode-dependent fumarate reduction

Outward Electron Flow

Reverse Electron Flow
Electrode-dependent fumarate reduction

![Graph showing current density against time with 50 mM fumarate addition.]

Ross et al., PLoS One, 2011
Electrode-dependent fumarate reduction requires FccA (the fumarate reductase)

Ross et al., PLoS One, 2011
The Mtr respiratory pathway catalyzes reversible electron transfer.
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The quinone oxidoreductase CymA is required for robust inward electron flow.
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Menaquinone is important for robust inward electron flow

Ross et al., PLoS One, 2011
*Shewanella* cannot fix CO$_2$

Robust ATP and NAD(P)H production would require O$_2$ as an electron acceptor.

Anaerobic metabolism and EET are HIGHLY repressed by O$_2$.

Iron respiration is thought to be one of the earliest forms of respiration on Earth – that’s a lot of selection for sending electrons OUT of the system rather than in.
Iron

Fe(II) → e⁻ → Fe(III) → e⁻ → Fe(II)
**Mariprofundus ferrooxydans PV-1**

Founding member: Zetaproteobacteria
Obligate Fe(II) oxidizer
Neutrophillic
Chemolithoautotroph
RuBisCo used to fix CO$_2$

\[
\text{Fe}^{2+} + 0.25 \text{O}_2 + 2.5\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 2\text{H}^+
\]
Mari profundus ferrooxydans PV-1
Mariprofundus ferrooxydans PV-1

$\text{Fe}^2+ + 0.25 \text{O}_2 + 2.5\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 2\text{H}^+$
If the mechanism of obtaining $e^-$ from Fe(II) is extracellular, we should be able to replace Fe(II) with a cathode.
Growth of *Mariprofundus* using a cathode

Summers et al., mBio, 2013
Growth of *Mariprofundus* using a cathode

Summers et al., *mBio*, 2013
Microbial Biocatalysis

• Self-sufficient
• Self-replicating
• Self-contained
• Self-optimizing
• Can be manipulated using synthetic biology and genetics

Bioelectrochemical Catalysis
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