

Mathematical and Computational Approaches To Understanding Microbial Communities

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frontiers in
engineering biology



Outline

- The Power of the Microbial World
- The Need for Mathematics Tools
- The Kind of Tools We Need
- Maths Computation and the Rate of Innovation

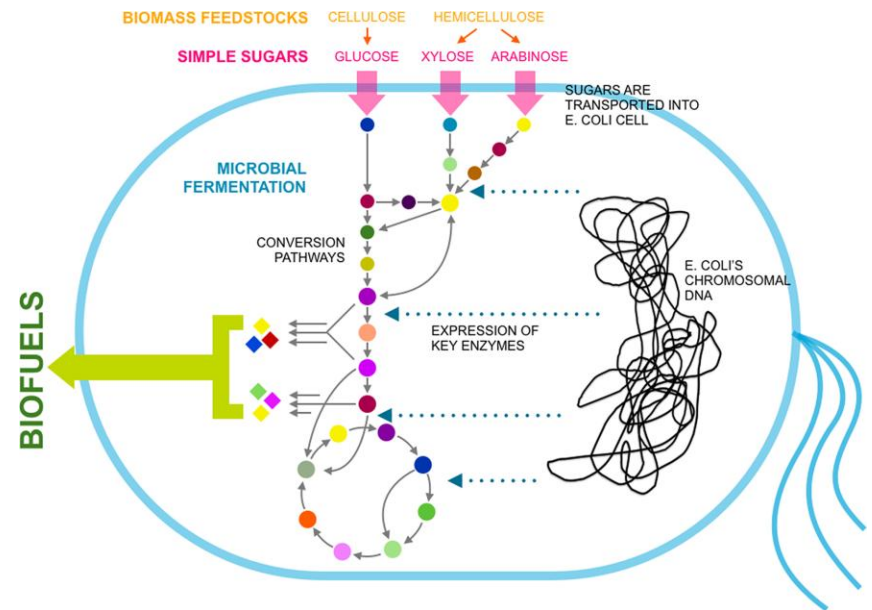
Microbial Communities

- 100s-1000s of species
- Most very poorly characterized
- Amazing things in hard to control environments



Microbial Cultures

- 1-3 “domesticated” species
- A small number of well characterized models
- Amazing things, in controlled environments



The Economy of Promises...

“The ability to routinely write the software of life will usher in a new era in science, and with it, new products and applications such as advanced biofuels, clean water technology, and new vaccines and medicines. “

<http://www.jcvi.org/cms/research/projects/first-self-replicating-synthetic-bacterial-cell/overview/>

Exxon & Synthetic Genomics

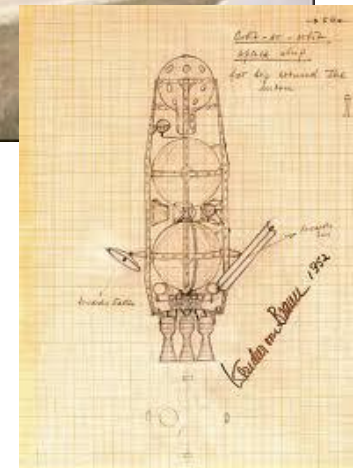
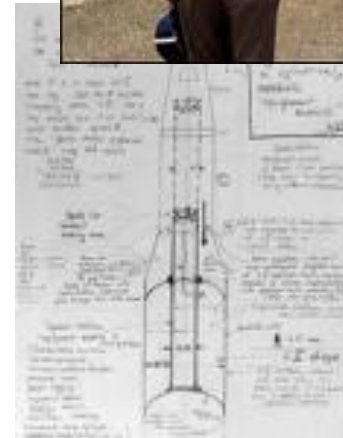
- 2009: 3-600 million USD committed to Synthetic Genomics
 - Fuels “in a decade”
- 2014 Program abandoned after 100 million Dollars expenditure
- Long term funding for Synthetic Genomics
 - 20 year time horizon

Engineering is not mere aspiration

Jules Verne

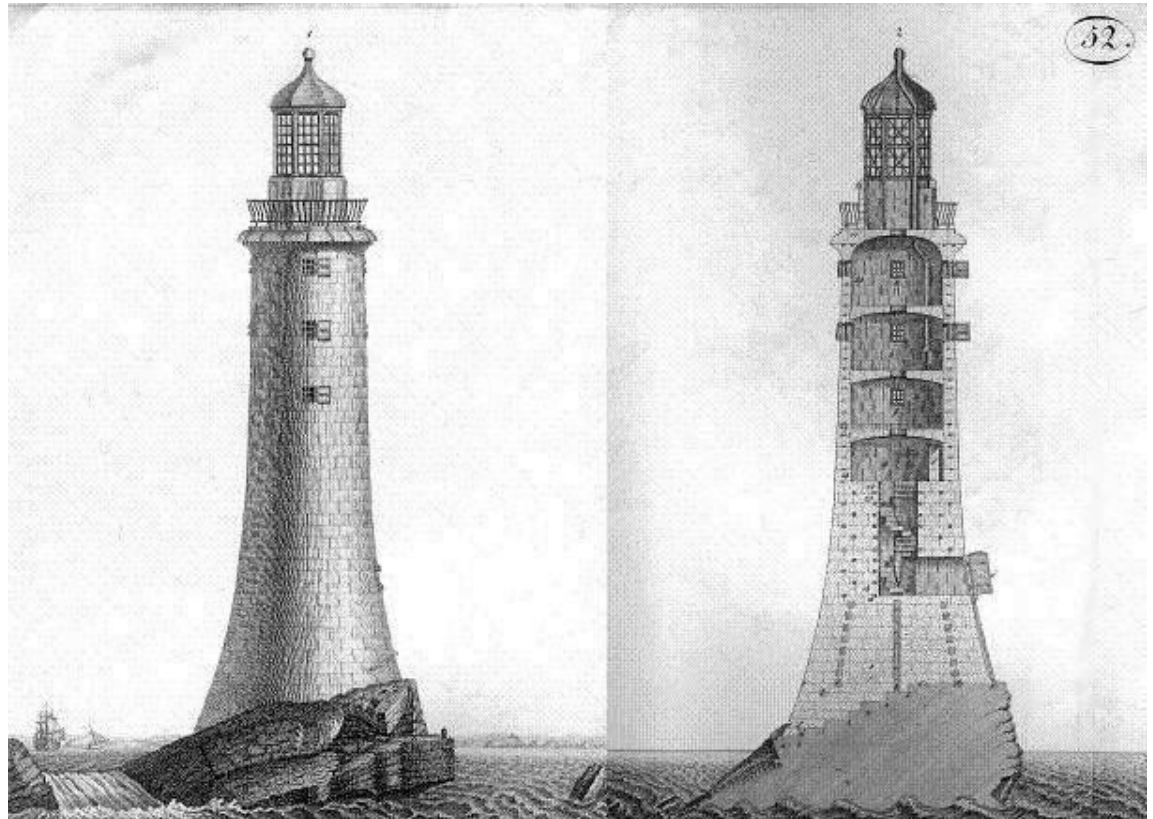


Werner von Braun



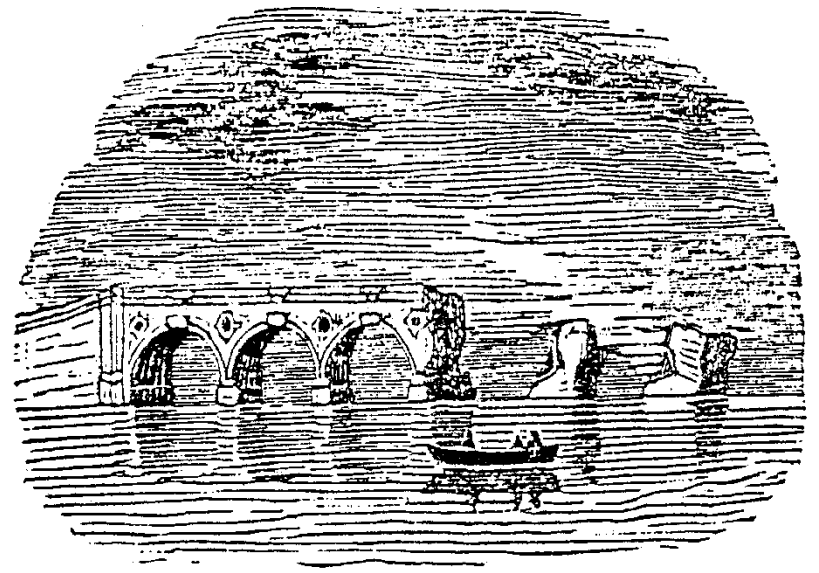
John Smeaton: 1724 - 1792

- Father of Civil Engineering
- Eddystone lighthouse



Smeaton + Hexham Bridge

- Old Bridge
 - Washed out in 1771
- Smeaton Builds New Bridge
 - Washed out in 1782
- Smeaton invited to build **THIRD** bridge
 - Declines to “chance my reputation”



HEXHAM BRIDGE, AFTER THE FLOOD.

The largest railway bridge: 1725
The second largest Roman bridge



Severan Bridge, Turkey ~200 AD

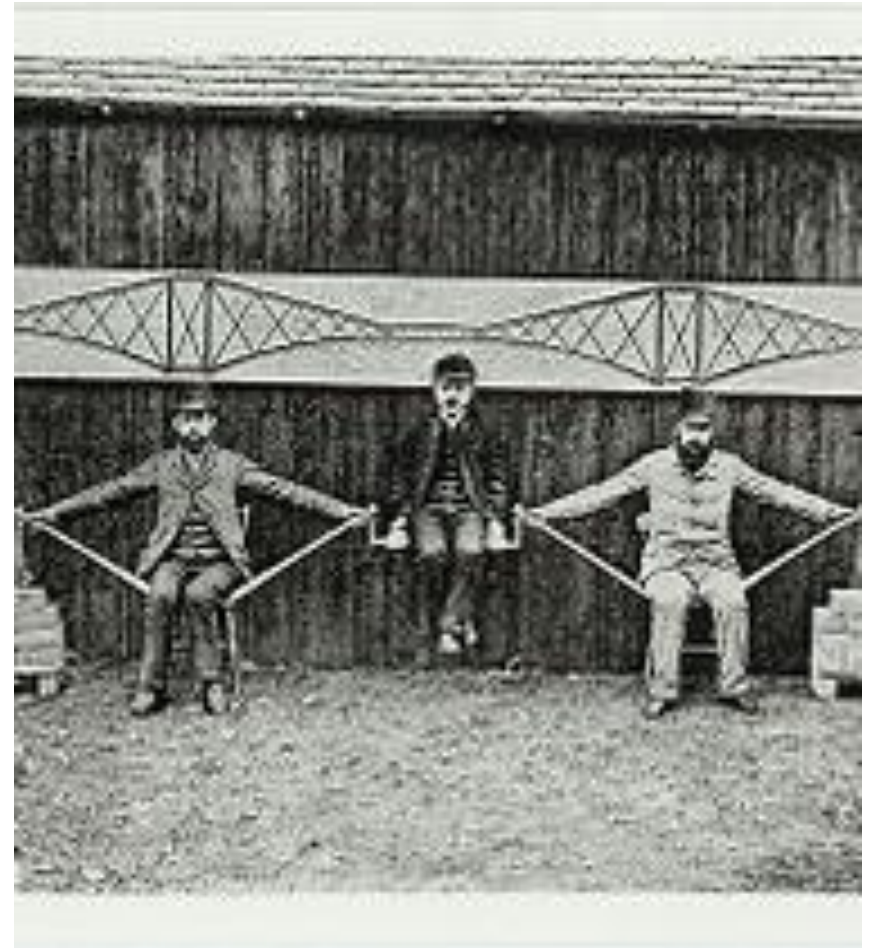
Causey Arch, Built 1725

Inspired by 19th Century Engineering



The Forth Rail Bridge

- Innovations
 - New materials
 - Standardization
 - Modularization
- Predictive Theoretical Description of Whole System



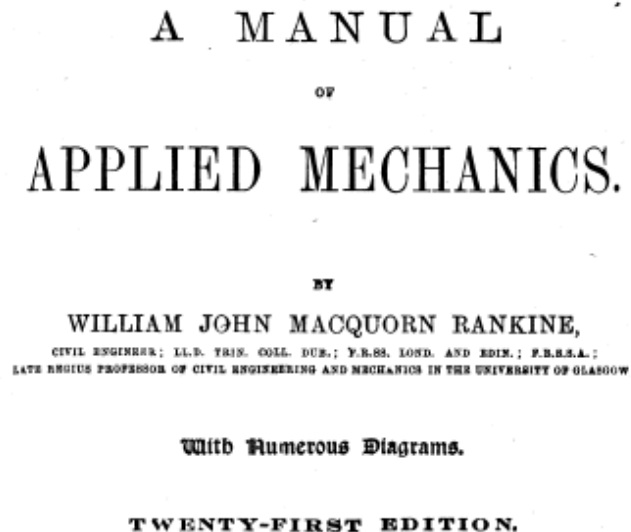
William John Macquorn Rankine

- Glasgow Regius Prof. of Civil Engineering 1853-82
- Rigidity of structure (with Maxwell)
- Thermodynamics of engines (Rankine) cycle
- Design of Dams
- Geotechnical engineering

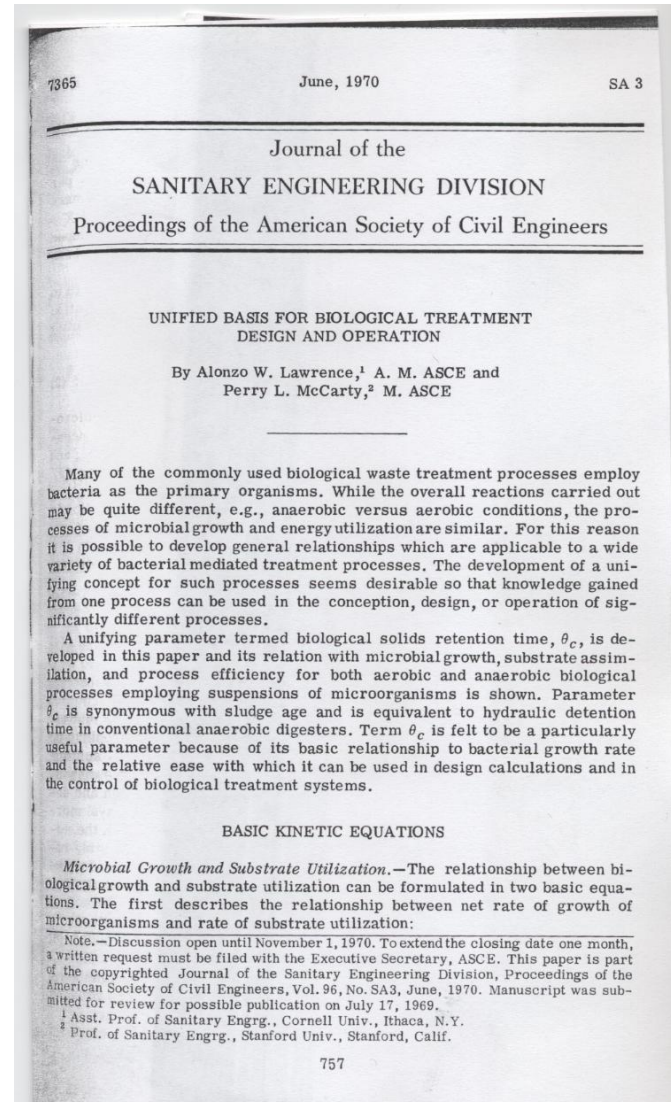
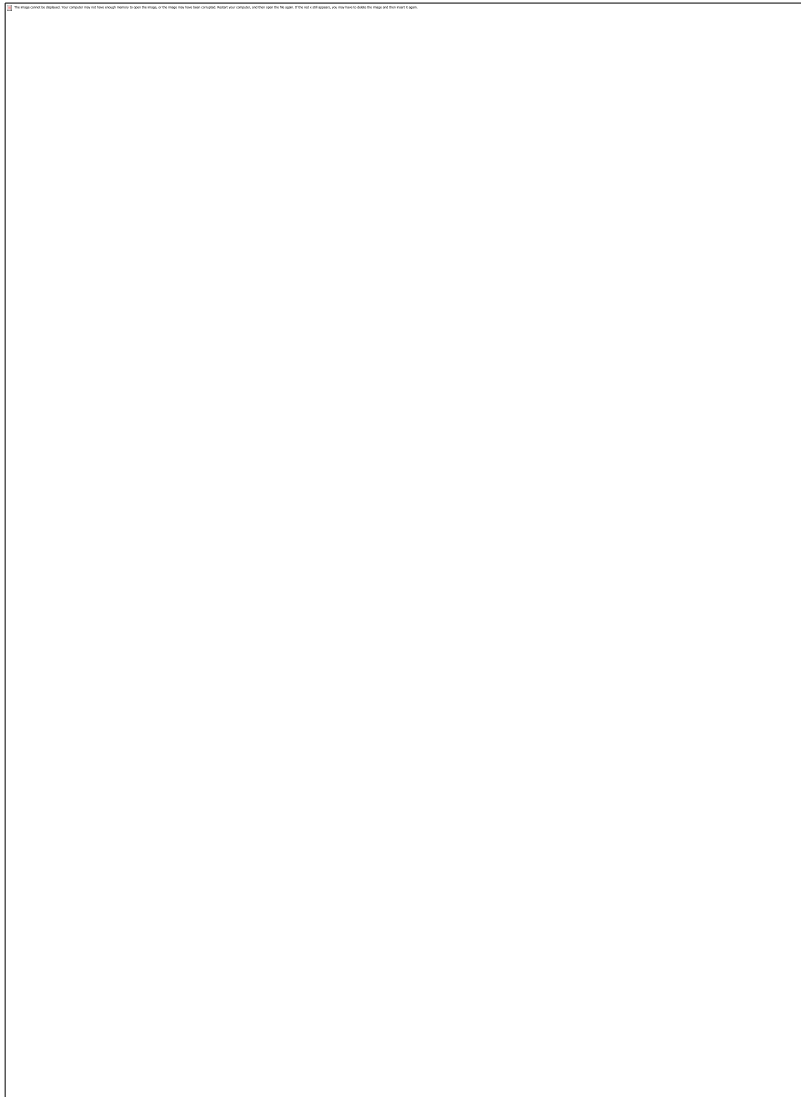


The Harmony of Theory and Practice in Mechanics (1853)

- “avoids risks, but stops the progress of all improvement”
 - “Lavish expenditure of material and labour”
 - “Failure within a limited number of years”
- “Misdirected ingenuity...vain pursuit of unworkable innovations



We do have theory..



Downing et al.,1964

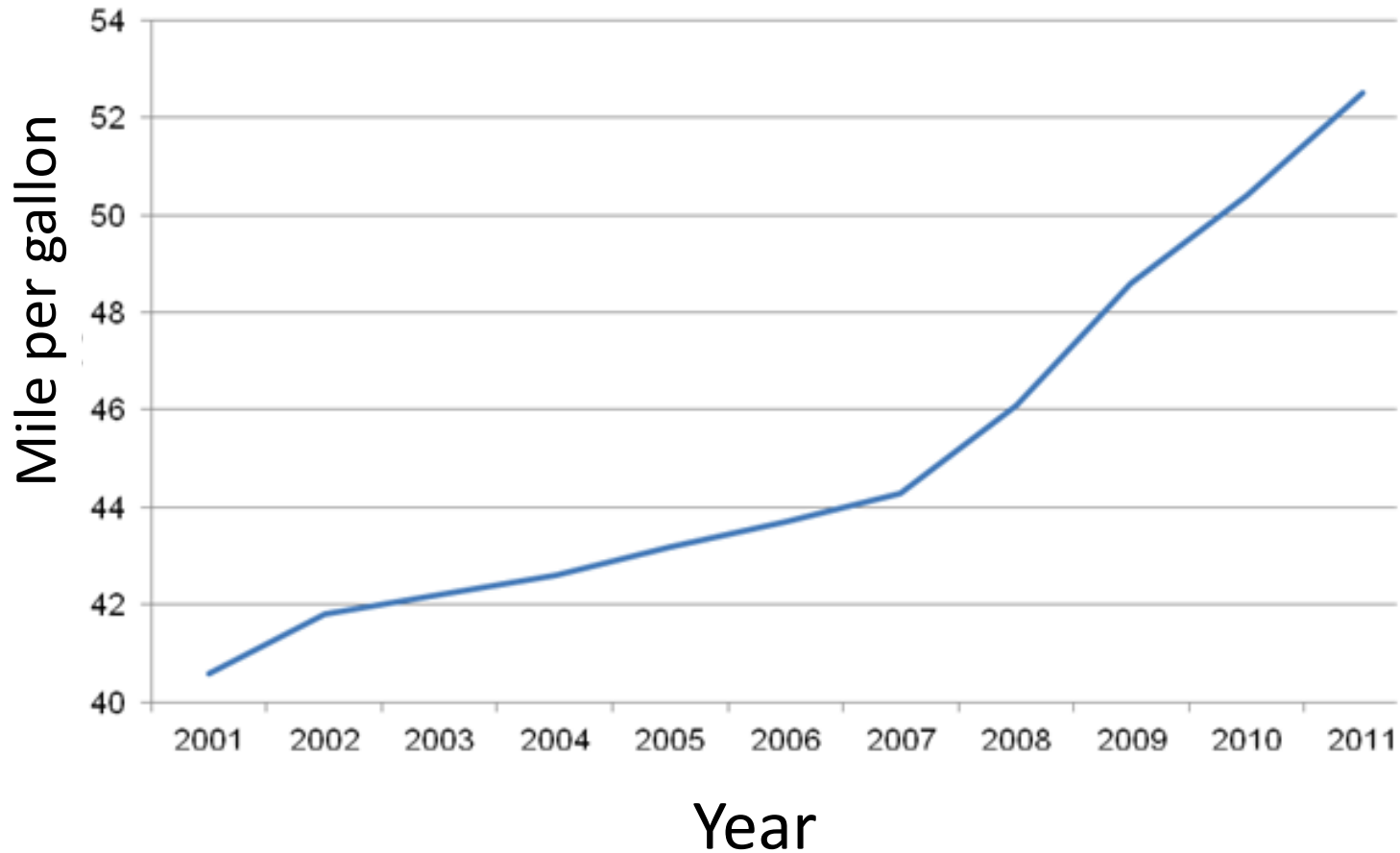
Lawrence and McCarty 1970

We don't have much theory

We don't have much time

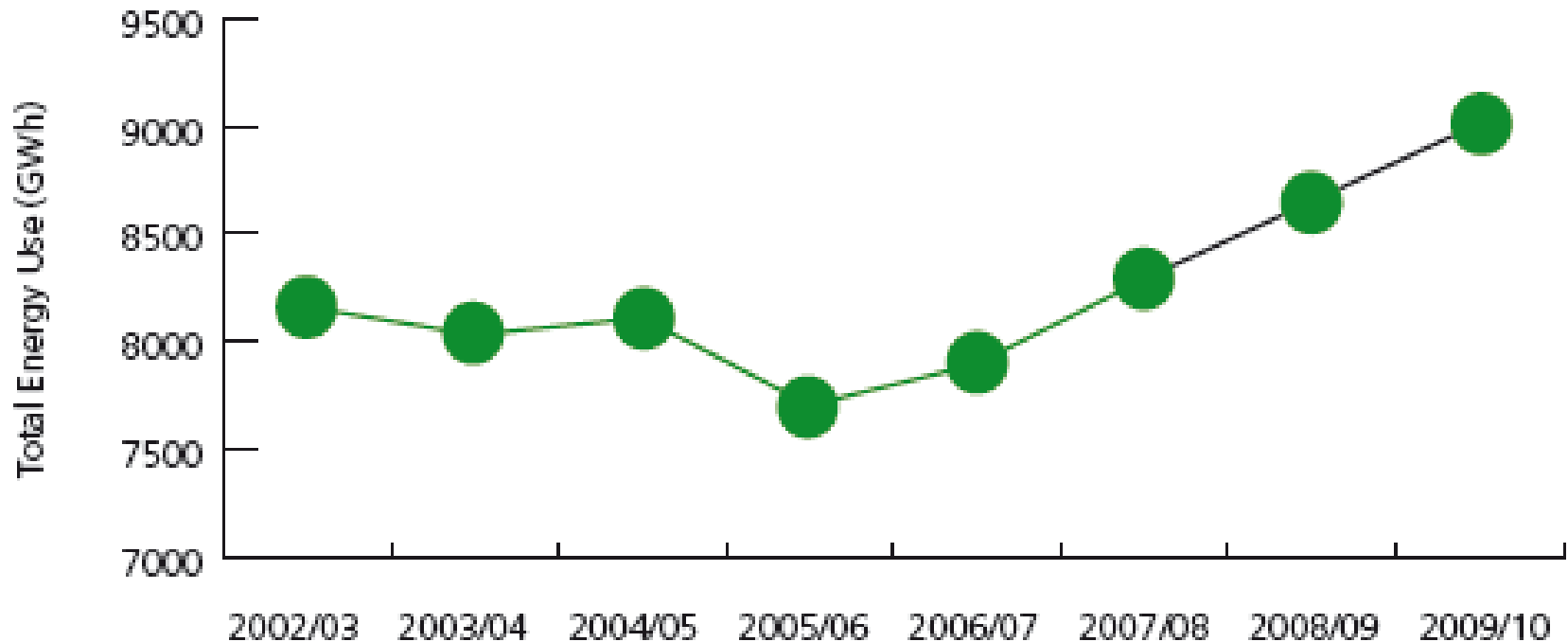
- Urbanization to hit 4 billion
- Energy prices to double
- CO₂ to rise with unknown consequences

Fuel Efficiency of New UK Registrations



Latest figures for energy use in the UK Water Industry

Figure 3 – Energy used for operational purposes and administrative functions
(2002/03 – 2008/09)



Source UK Water

Anaerobic Treatment of Domestic Wastewater: in Brazil

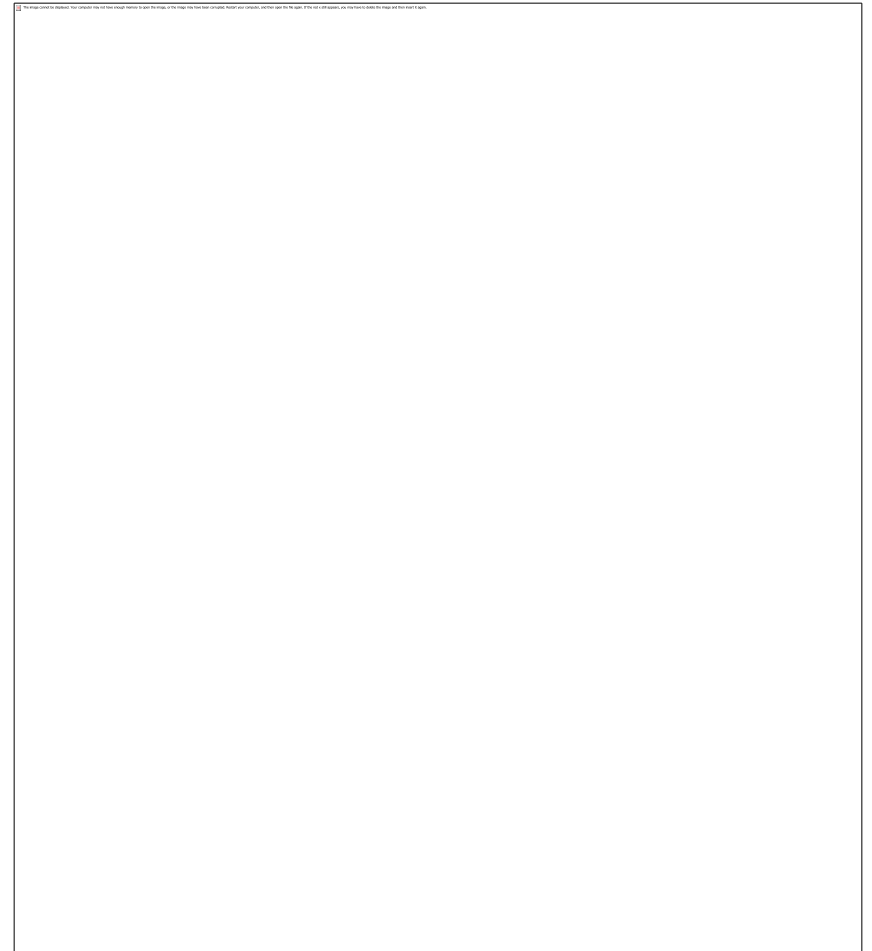
- Eg Belo Horizonte
Minas Gerais
- Large Scale Technology
- PE 1,000,000
 - 1800 litres /second



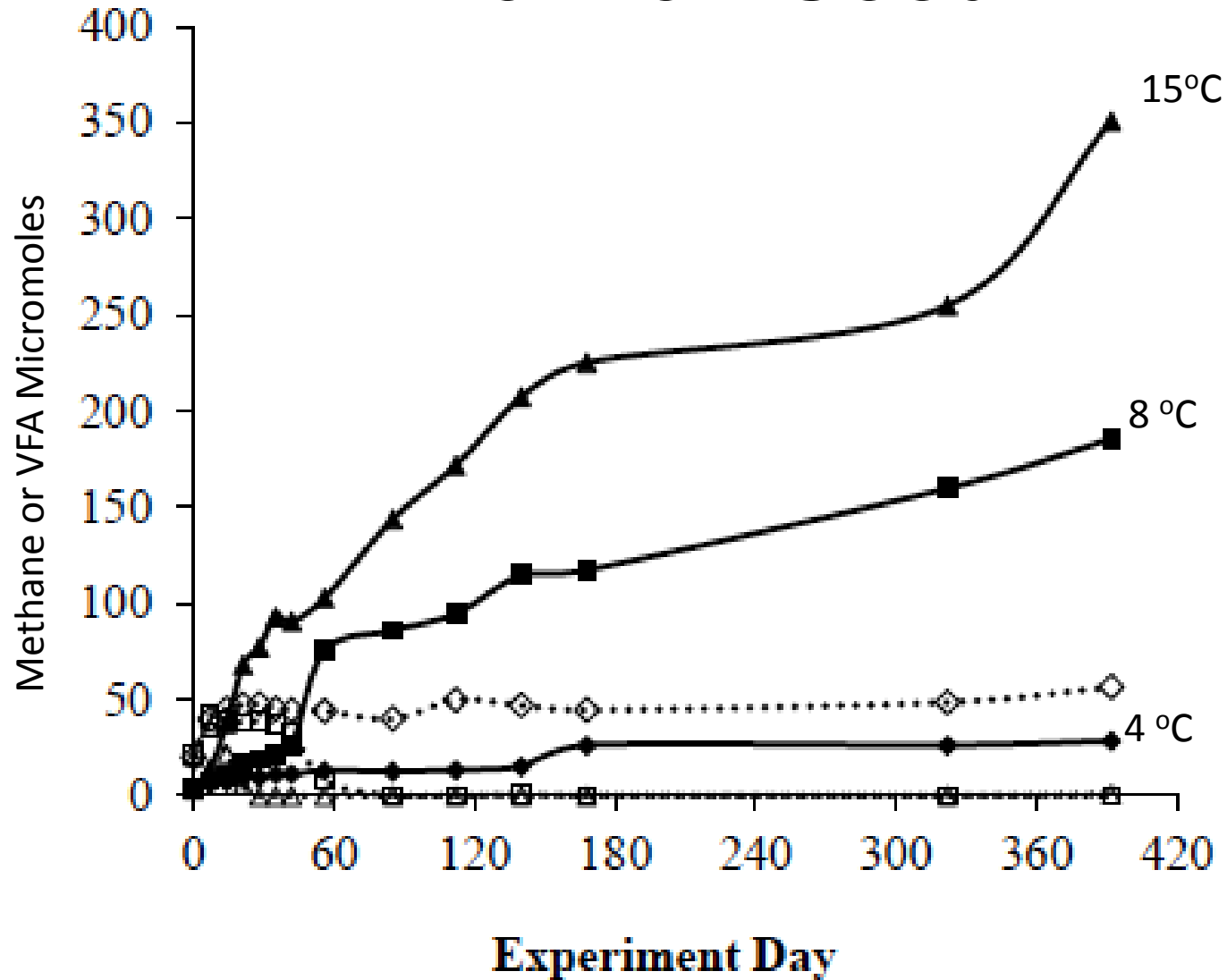
www.copasa.com.br

Anaerobic Treatment of Domestic Wastewater in the UK

- Cranfield University
 - ST and Yorkshire Water
- Best Performance of such a reactors
- Temperature sensitive
>10 °C



How Low Can You Go With “normal” Seed?



Methanogenesis in the High Arctic



Neutral Theory:

- Random sampling from a reservoir

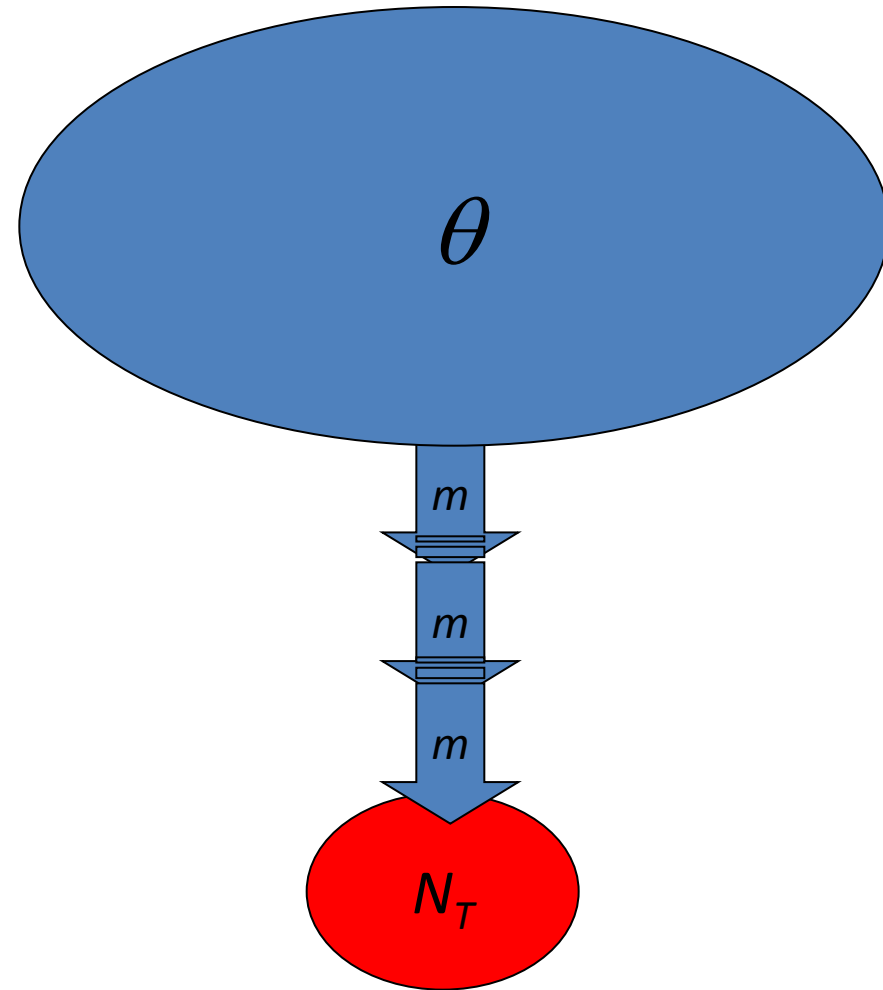
θ

- At a rate (per death)

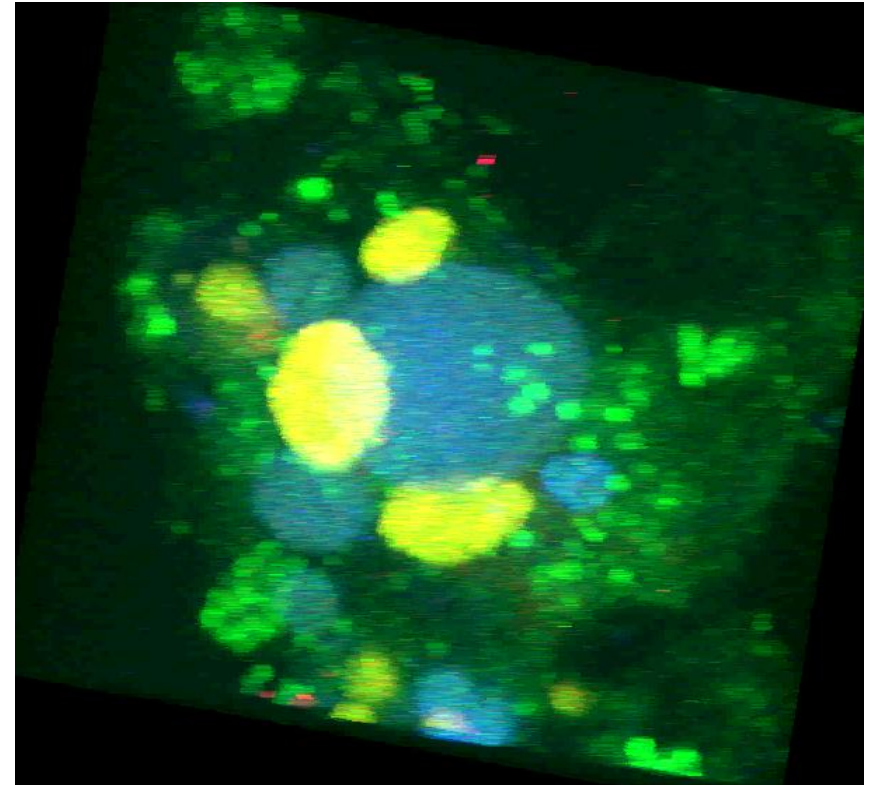
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- Into a community of size

N_T



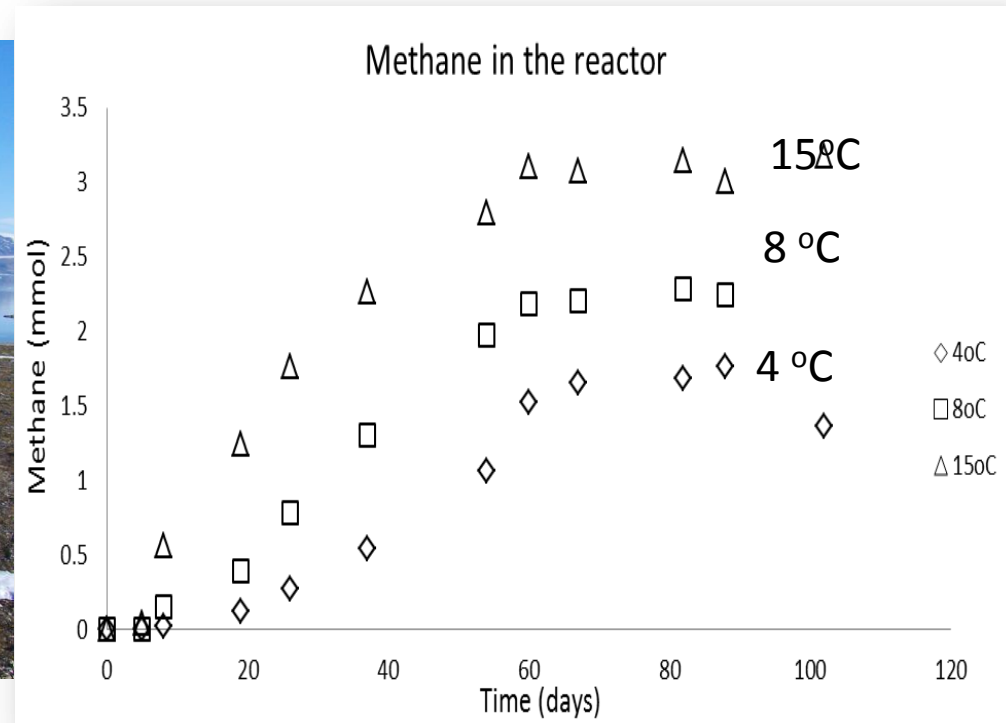
Mathematics and Molecular Ecology



Probability of new bacteria
invading

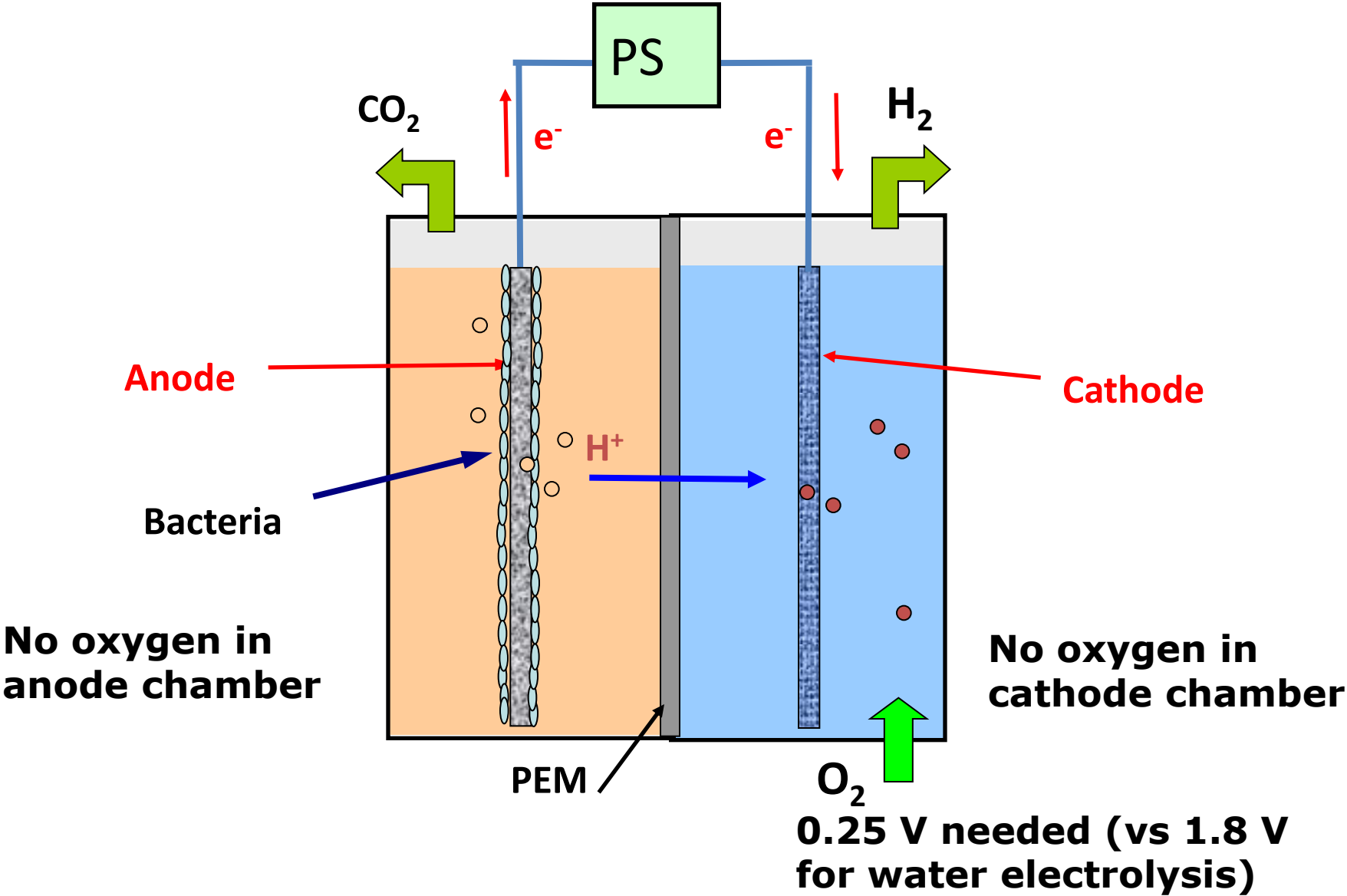
Nitrifying bacteria labelled with
fluorescent gene probes

Methane Production on domestic wastewater with an Arctic Seed

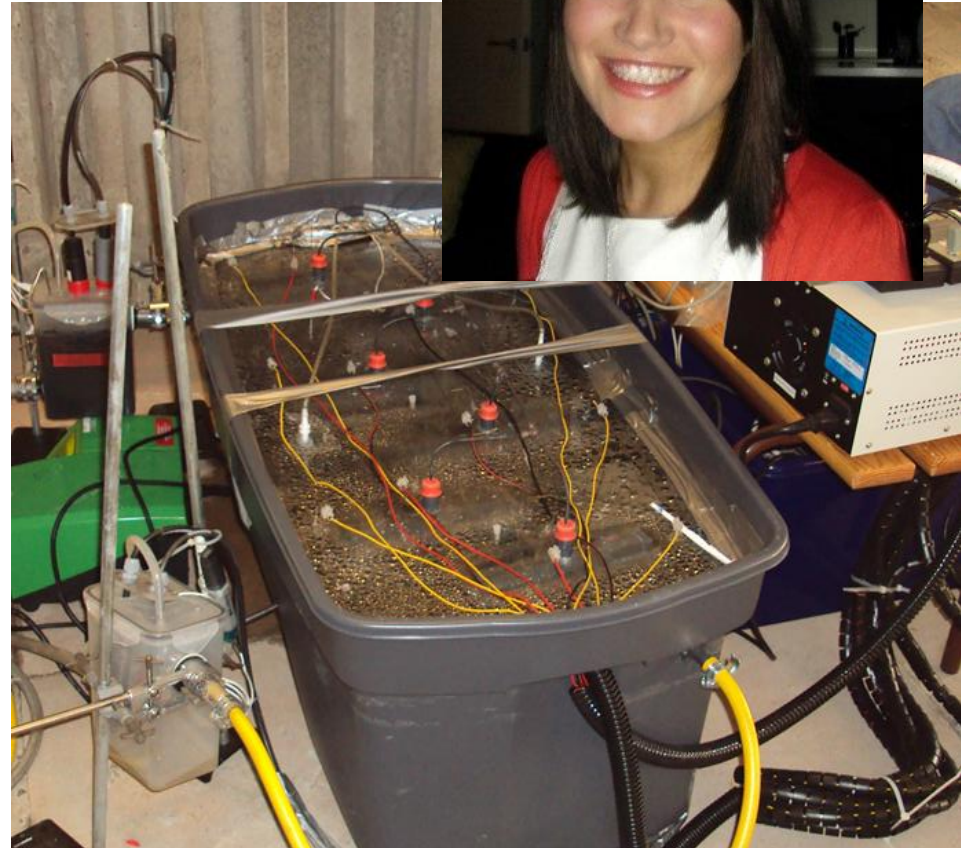
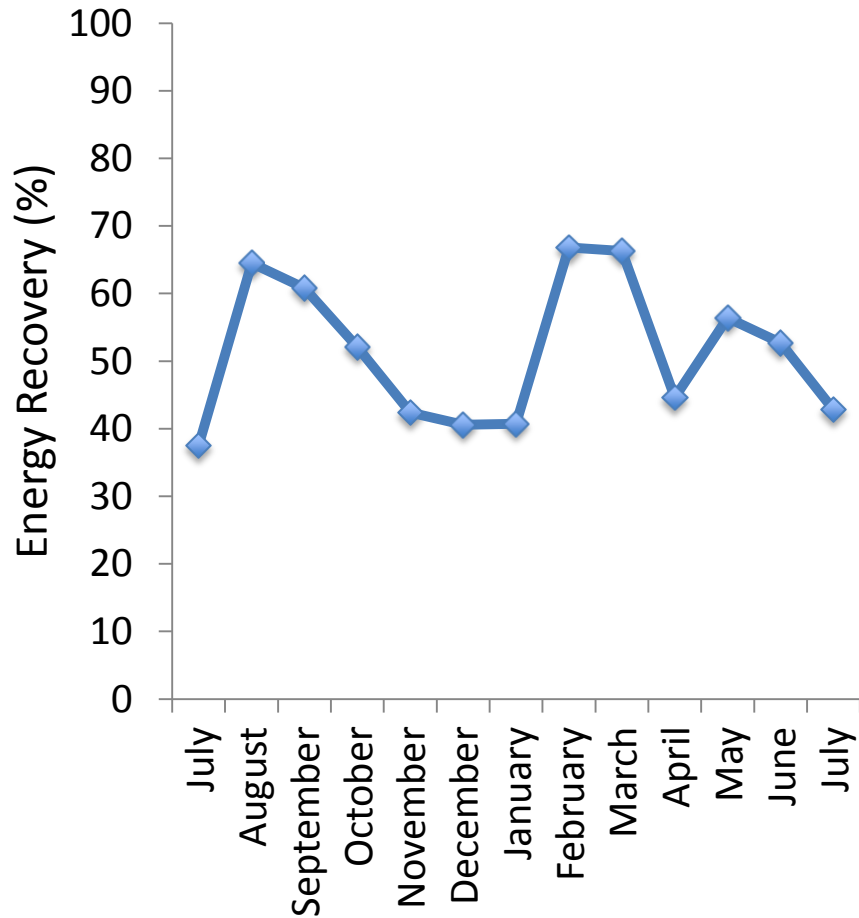


Petropolous et al in prep

Microbial Electrolysis Cell: Make Hydrogen from Sewage



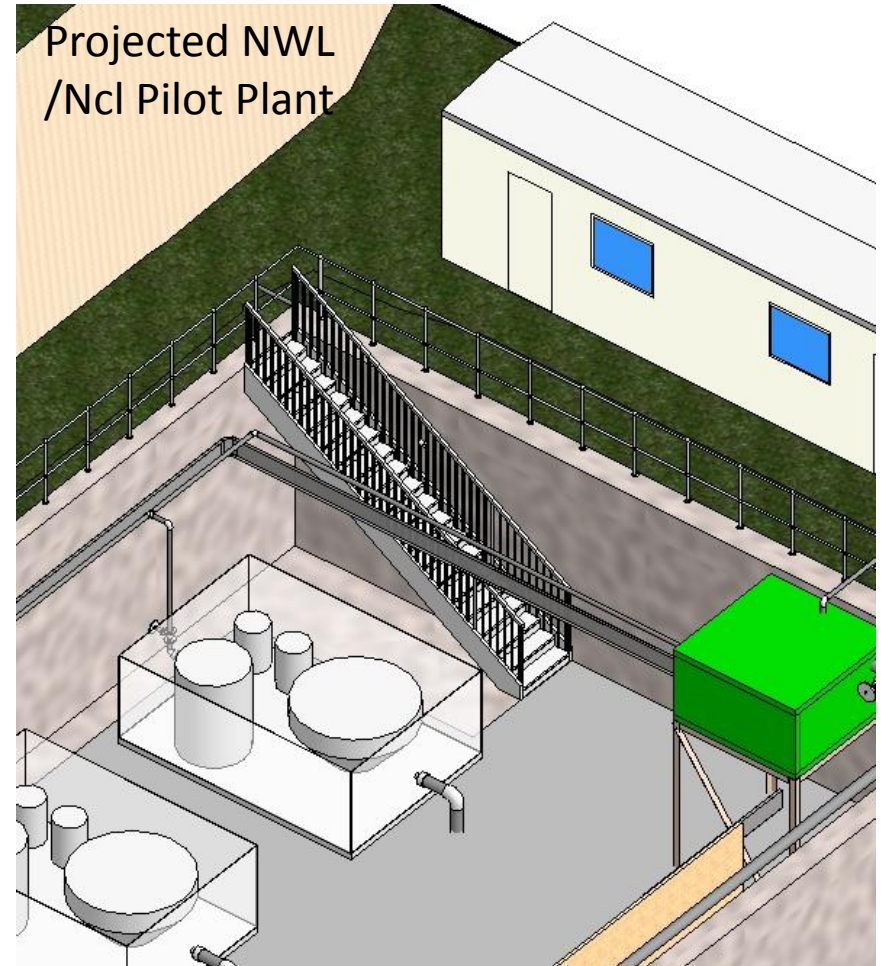
First Pilot Test on Domestic Wastewater



Heidrich et al in 2014

Fail Early, Fail Often

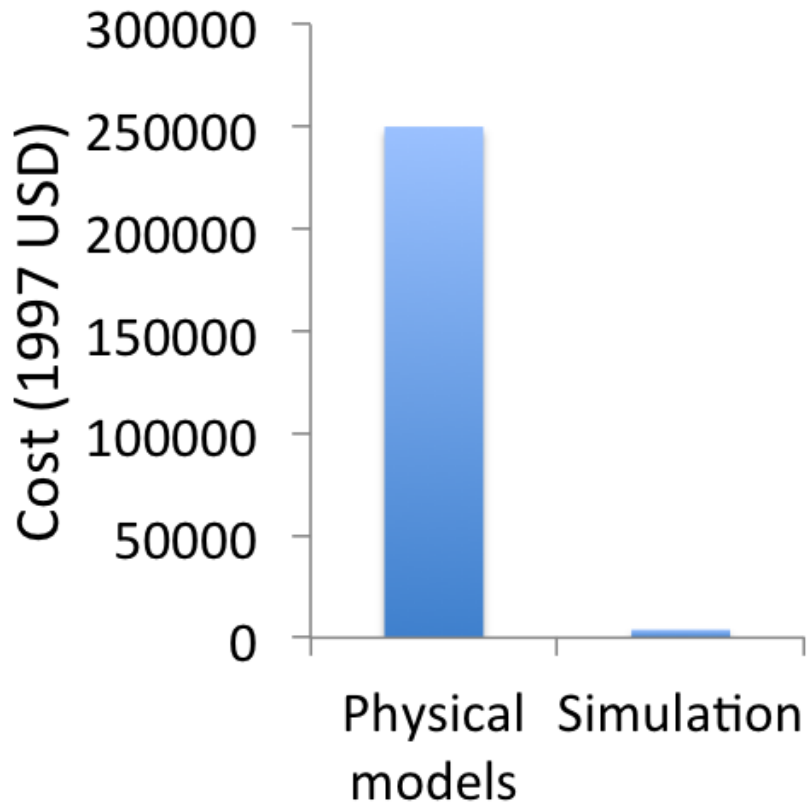
- Our first pilot “failed”
 - All success begins as failure
- Cycles of prototypes lead to success
- Credible pilot plants are
 - expensive and
 - Slow
 - A nuisance
- But do it anyway



Thanks to Motts Newcastle

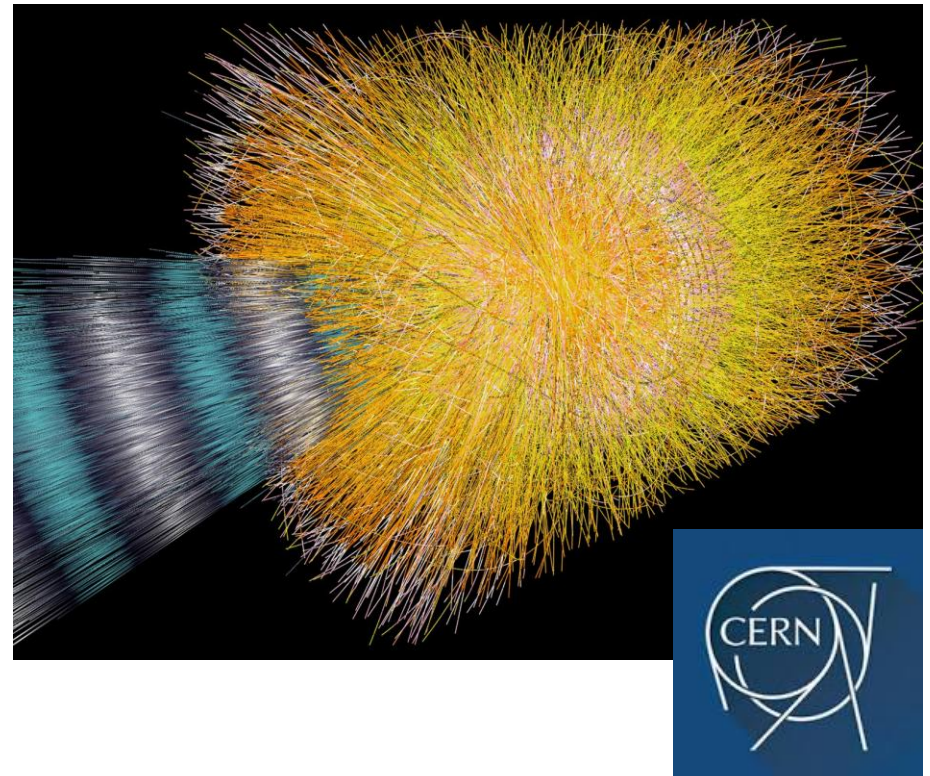
BMW use testing

and simulation to fail fast and cheap



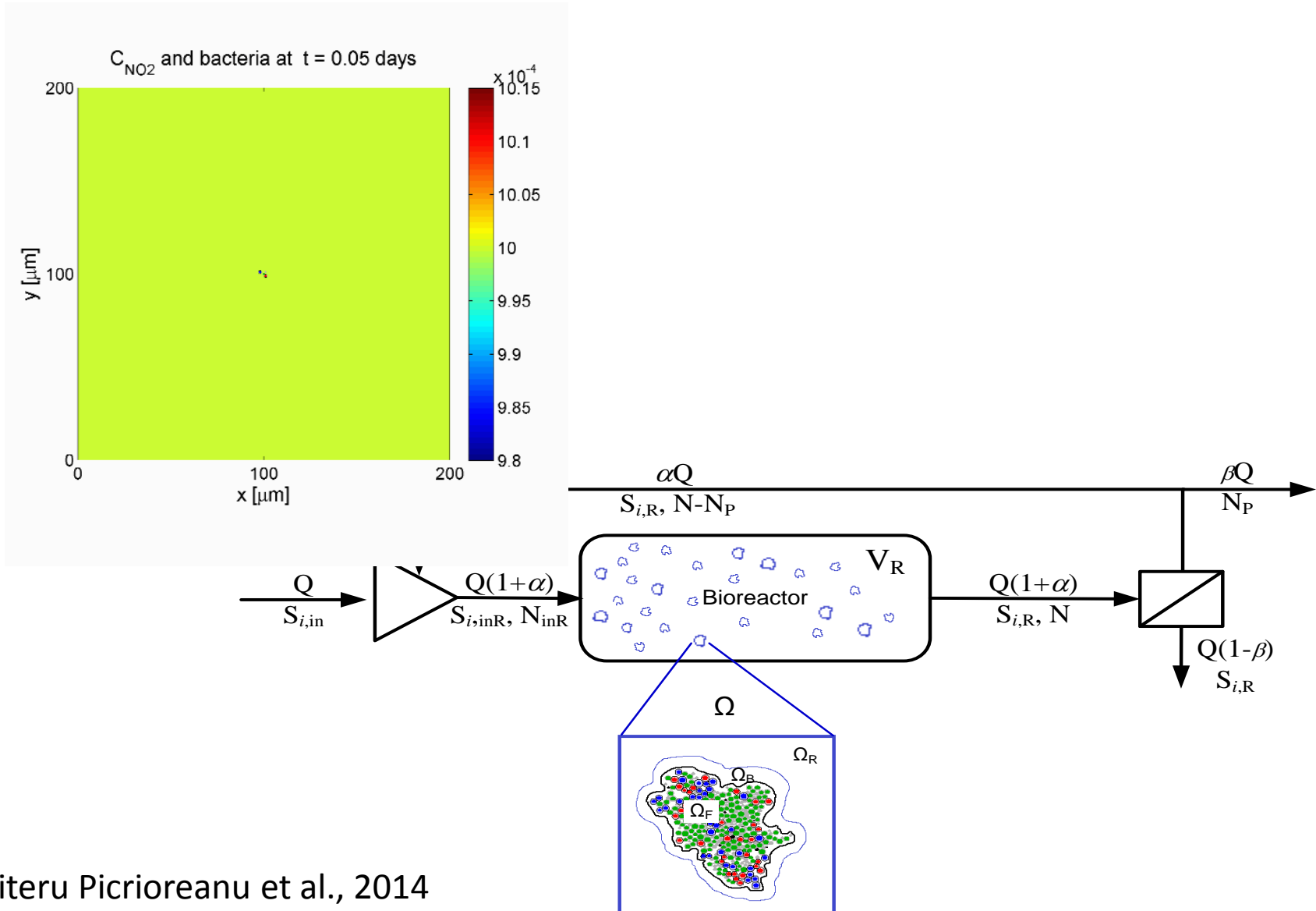
The simulation of large systems is possible

- One Activated plant
 - 10^{18} individuals in a treatment plant
 - 3000 species
 - More genes than the human genome
- Big systems can be modeled



Simulation of lead ion collision in the ALICE detector

In Silico Simulation of Wastewater Treatment



Mathematics and Computation

- Essential to fully exploit the power of the microbial world
- Tools we have are not yet good enough
 - But we are working on it
- Mathematics and computation is “cheap”
 - But “leverages” microbial science base
 - But need more engagement/cultural change