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GTL: Transforming Our Energy Future Through Biology and Genomics

David Thomassen

Office of Biological and Environmental Research

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Microbes Provide Biotechnology Payoffs for the Nation

Within a Decade

Develop knowledge base for cost-effective cleanup strategies

Understand earth's natural carbon cycle and design strategies for enhanced carbon capture

Increase biological sources of fuels and electricity

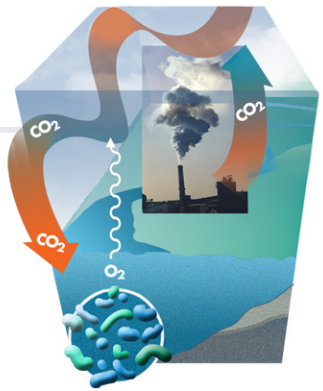
Longer Term

2020

Save billions of dollars in toxic waste cleanup and disposal

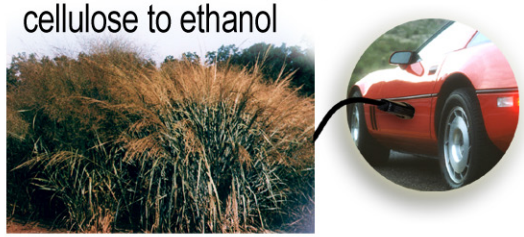
2040

Help stabilize atmospheric carbon dioxide to counter global warming

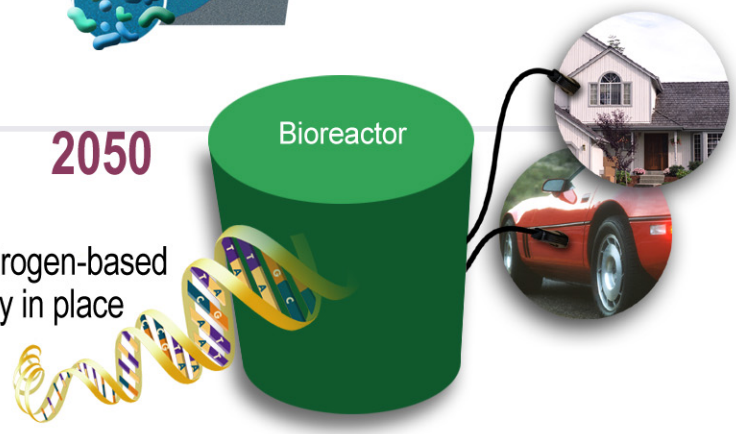


2025 Contribute to U.S. energy security **2050**

- Efficient conversion of plant cellulose to ethanol



- Biohydrogen-based industry in place



YGG-01-0521R8

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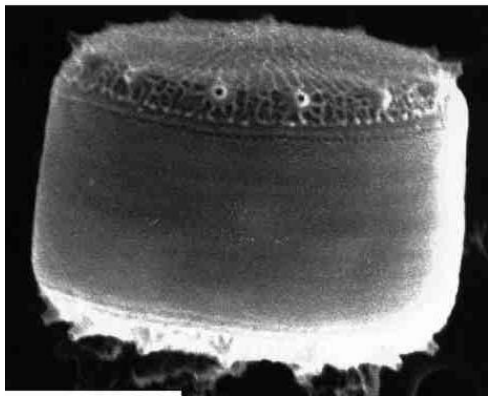
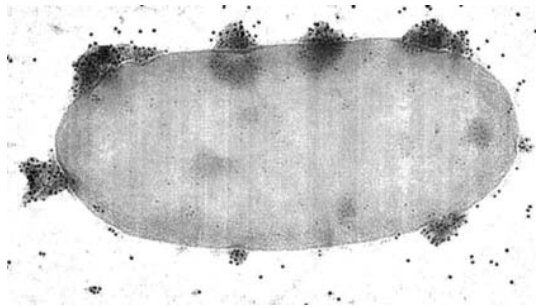
We can find biotechnology solutions using the natural diversity of microbes and microbial communities

Thalassiosira pseudonana



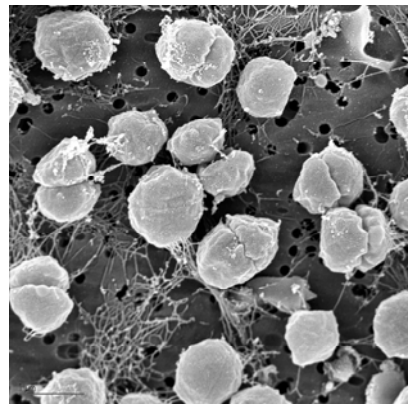
Ocean carbon pumping

Microbulbifer 2-40



Biomass conversion

Methanococcus jannaschii

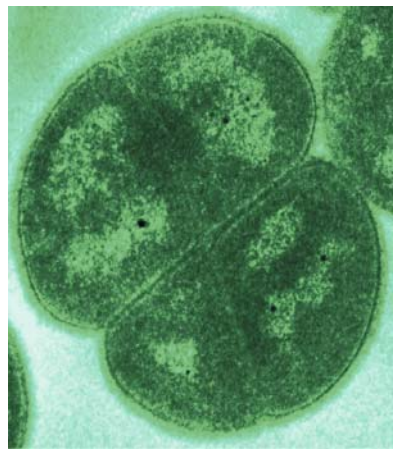


Methane production

Rhodopseudomonas palustris

Hydrogen production / Carbon sequestration

Deinococcus radiodurans



Radiation resistance - bioremediation

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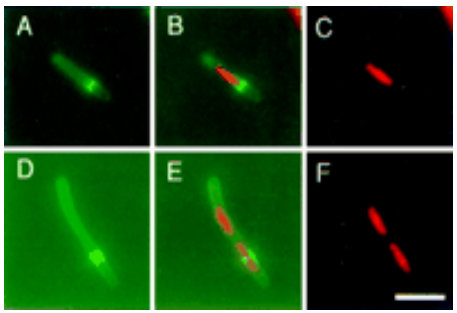
Genomics:GTL – A Systems Biology Research Program

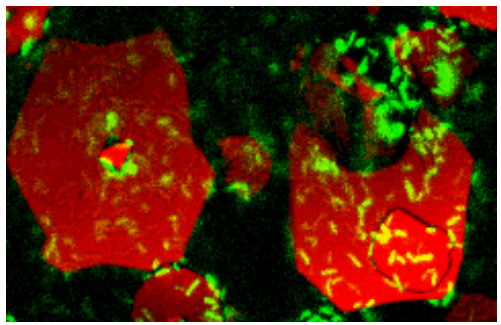
From Molecules to Cells to Ecosystems

Subcellular



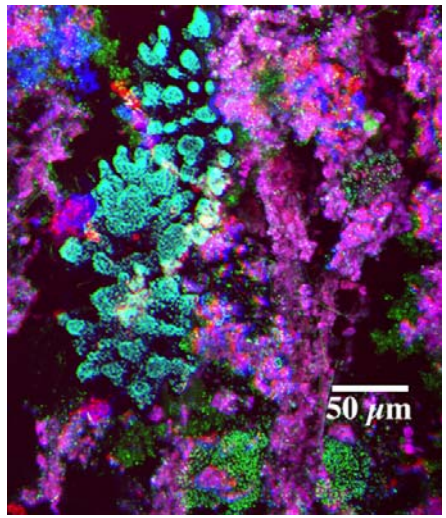
Identification, subcellular location, and dynamics of molecular machines

Cellular



Regulation of gene expression in individual cells

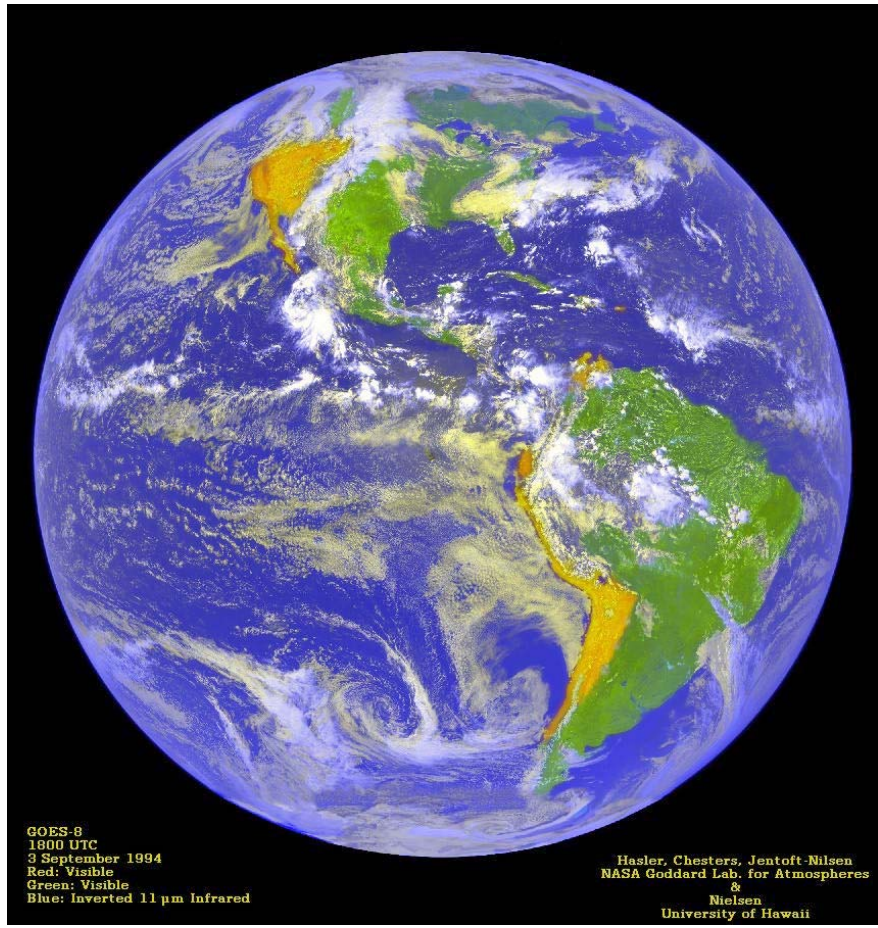
Ecosystems



Who is expressing what, when, where, and under what conditions? How do they work together?

Ecogenomics – A New Frontier

- < 1% of microbes are culturable
- Many unculturables live in interdependent consortia of considerable diversity
- Ecogenomics – applying the tools of genomics, proteomics, etc to ecology
- Can we recover genome-scale sequences and reveal metabolic capabilities?
- What is the structure of natural microbial populations? How do they interact? Are they interdependent?
- Can we harness their metabolic capabilities?



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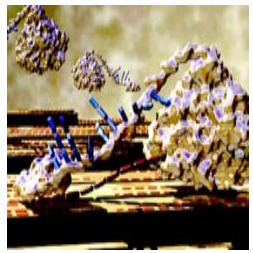
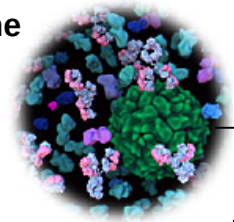
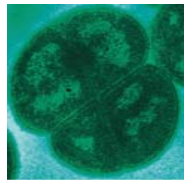
High-Performance Computing is a Major GTL Partner



Protein machine Interactions

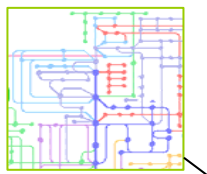




Molecule-based cell simulation

Molecular machine classical simulation

Cell, pathway, and network simulation



Community metabolic regulatory, signaling simulations

1000 TF

100 TF

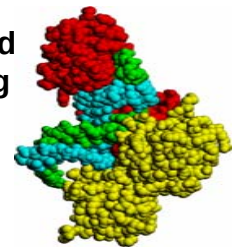
Current U.S. Computing for Open Science

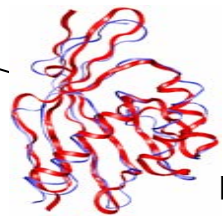
10 TF

1 TF*

Constrained rigid docking

Constraint-Based Flexible Docking





Genome-scale protein threading

Comparative Genomics

*Teraflops

Biological Complexity

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Genomics: GTL – A Vision of Systems Biology Research

In 10-15 years we would like to be able to start with a microbe or microbial community of interest and in a matter of days or weeks:

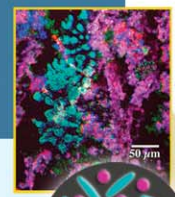
- **Generate an annotated DNA sequence**
- **Produce proteins and molecular tags for most/all proteins**
- **Identify the majority of multi protein complexes**
- **Generate a working regulatory network model**
- **Identify the biochemical capabilities**
- **Design reengineering or control strategies in silico**

DOE Genomics:GTL

High-Throughput User Facilities

Understanding Biological Capabilities at all Scales

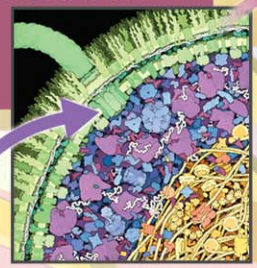
Cellular Systems Facility
Develops predictive understanding of cell and community function



Ecosystem

Community

Proteomics Facility
Explores how living cells respond to environmental cues



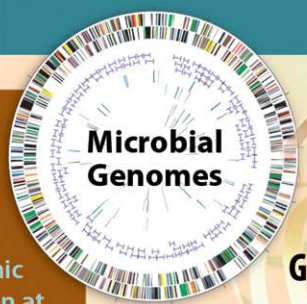
Cell

Molecular Machines Facility
Determines how molecular machines are formed and how they function

Machine

Protein Production Facility
Produces and characterizes cellular components encoded in genomes

Proteins



Genes

DOE Joint Genome Institute
Sequences the genomes of microbes with capabilities important to DOE missions.
The genome determines dynamic biological structure and function at all scales, from genes to ecosystems.

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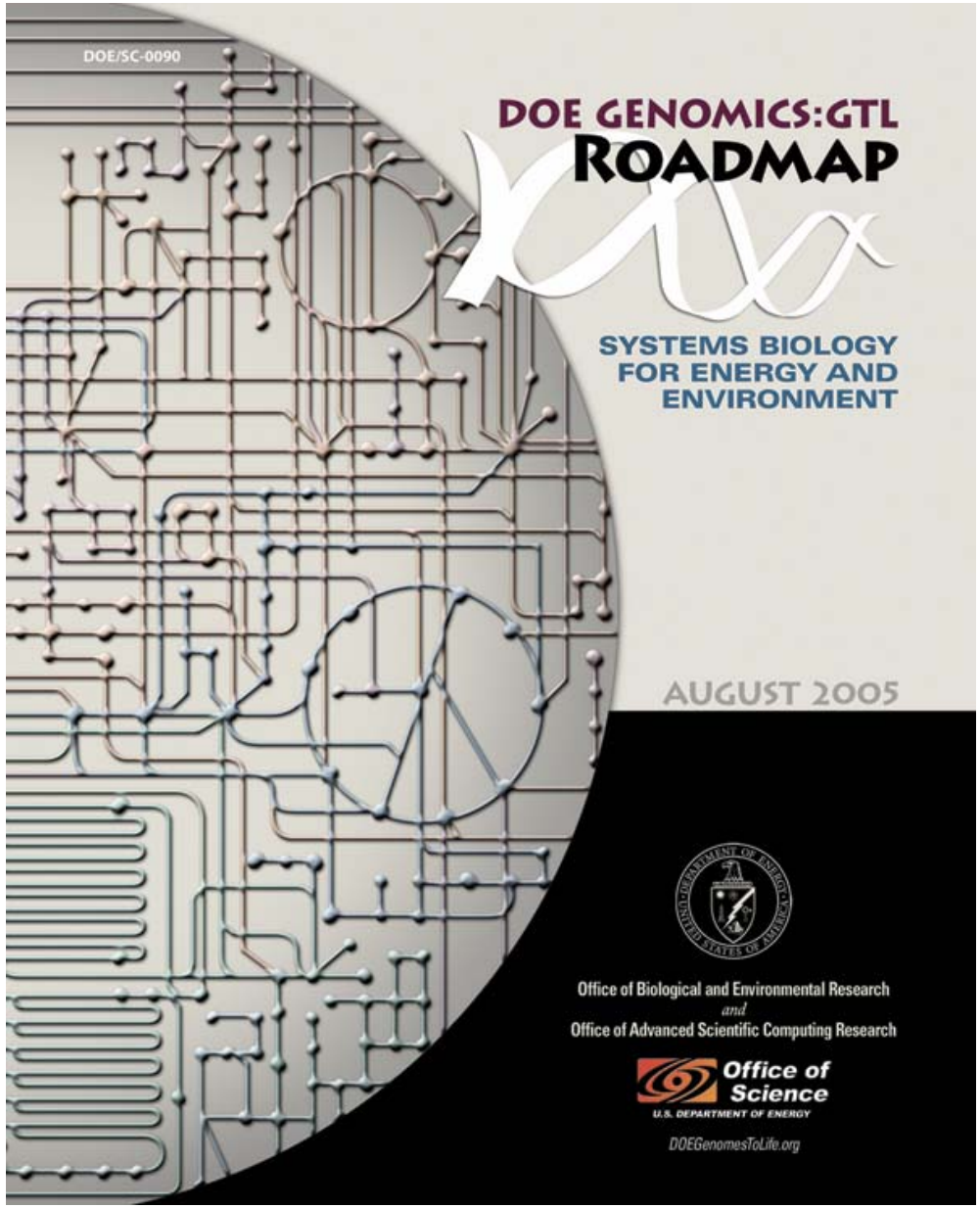
GTL roadmap now available at program web site.

http://DOEGenomesToLife.org

Currently under review by the National Academies



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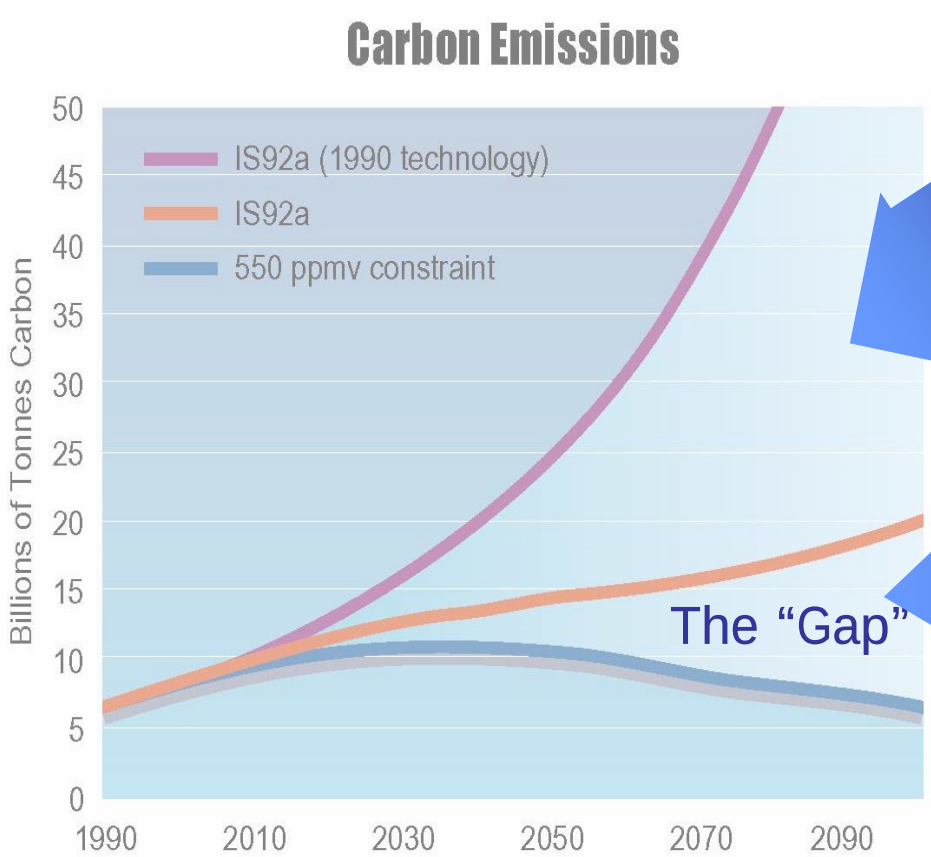
The Challenge of Reducing Carbon Emissions



Assumed Advances In

- Fossil Fuels
- Energy intensity
- Nuclear
- Renewables

Gap Technologies

- Carbon capture & disposal
  - Adv. fossil
- H2 and Adv. Transportation
- Biotechnologies
  - Soils, Bioenergy, adv. Biological energy

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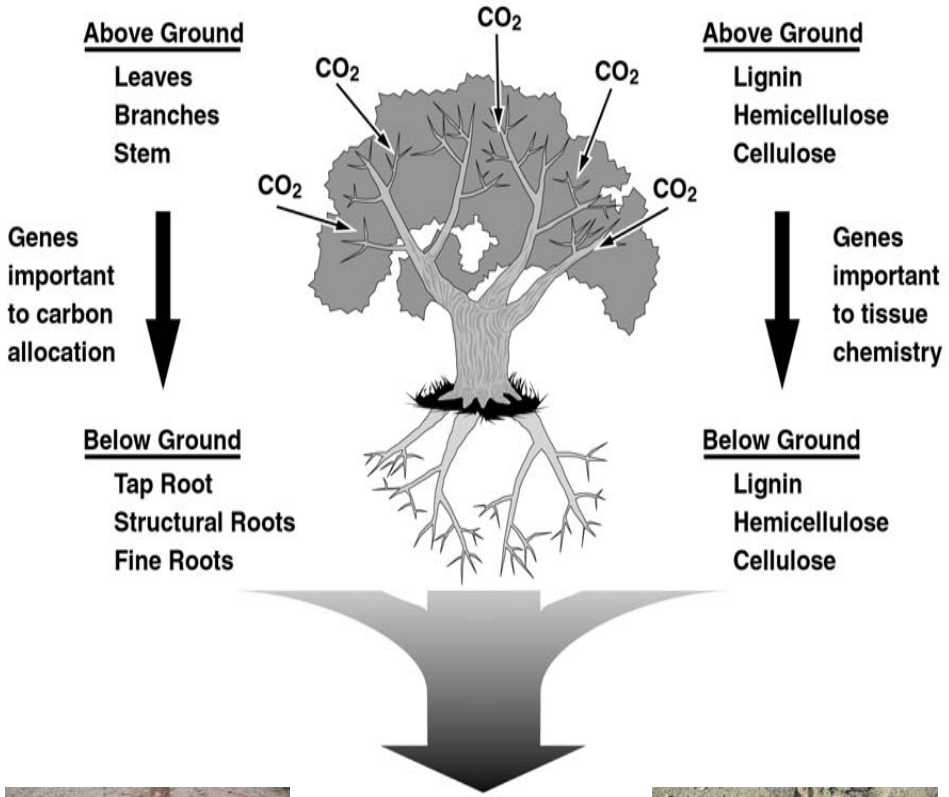
Carbon Sequestration and the Populus Tree

A *Populus* tree

Greenhouse testing

Genome-Enabled Discovery of Carbon Sequestration Genes in *Populus*



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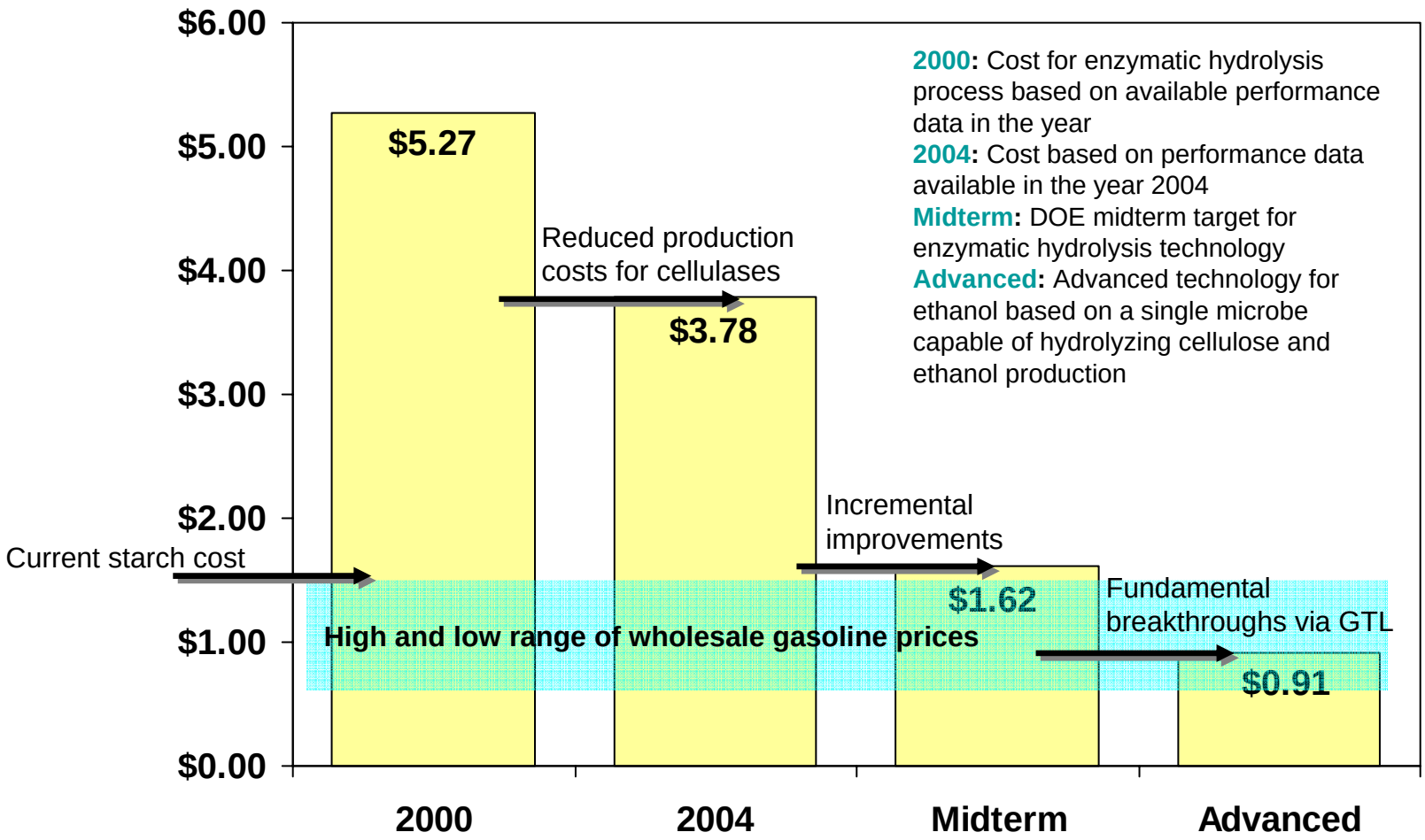
Projected Wholesale Ethanol Costs Making Ethanol Cost Competitive

($/gal gasoline equivalent)



Adapted from a diagram by Mike Himmel and John Sheehan, NREL

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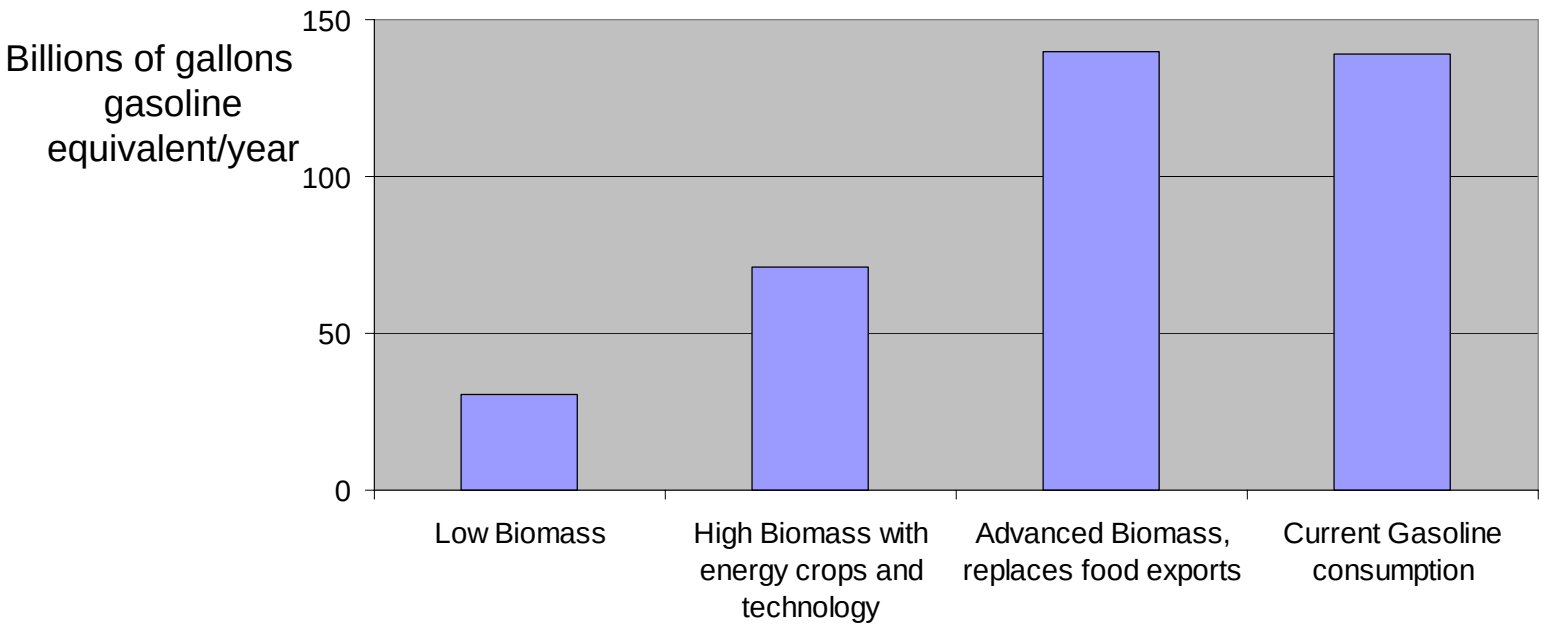
Cellulosic Ethanol Can Replace a Substantial Amount of Liquid Fuels



***Low Biomass: uses byproducts from food crops and forest, near-term scenario, no dedicated energy crops**

***High Biomass with energy crops: higher agricultural and ethanol yields, meets predicted food-agriculture demands including exports**

Advanced Biomass: ethanol substitutes for exported food crops, higher biomass and conversion yields

Analysis by ORNL

*from "Billion-ton study"

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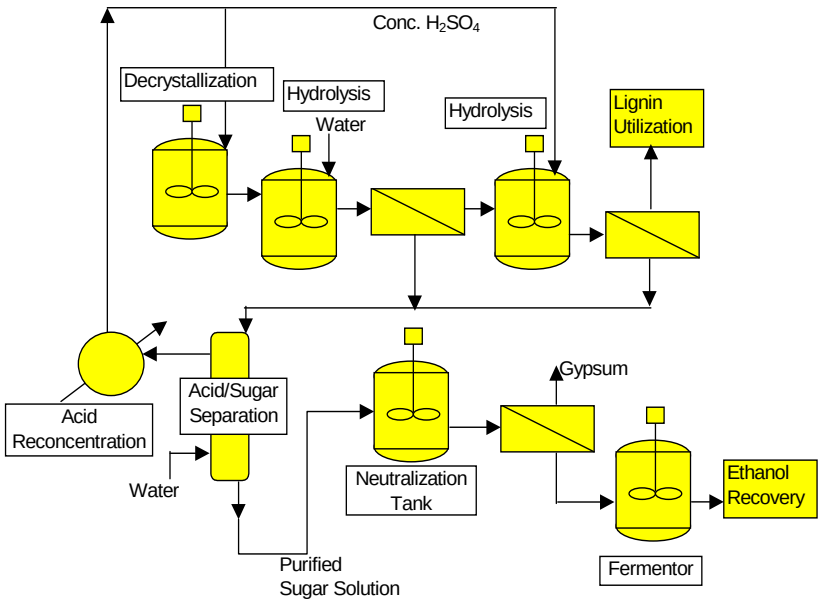
Cellulosic Ethanol: Microbes as Processing Plants

Today we utilize food starch to make alcohol and complex and costly processing of cellulose

Tomorrow we want to utlitize high yield cellulose crops with integrated processes in microbes to convert to alcohols and other fuels



Cellulose Today

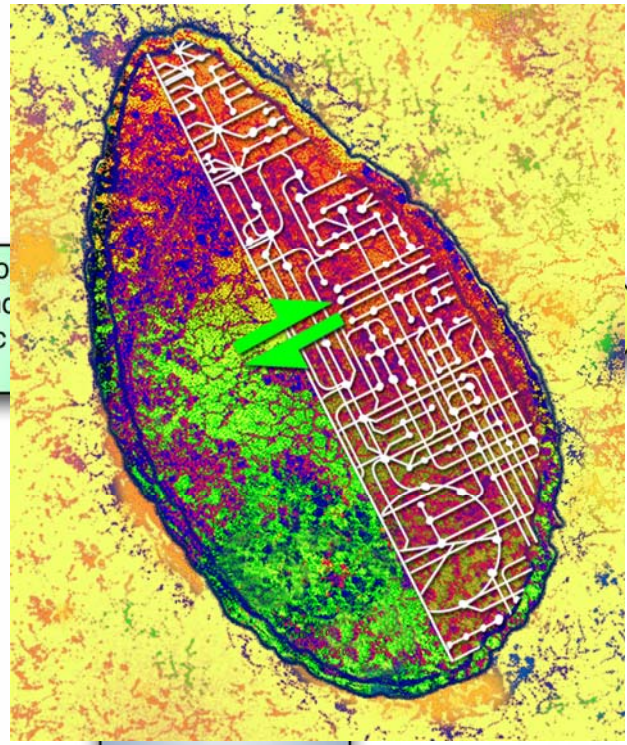
Decrystallization
Hydrolysis of Cellulose, Hemicellulose, and Lignin
Multiple Sugar Metabolism
Alcohol Synthesis

Tomorrow?

Next Generation Biology will Reduce Costs of Cellulosic Ethanol Production: Combine Hydrolysis with Fermentation in One Reactor

Pretreatment

Direct conversio
of Cellulose and
Hemicellulosic
Sugars



Needs: Full Consolidation

- Engineer new microbes (not known in nature)*
- Produce enzymes, sugars, and ethanol*
- Process tolerant*
- Stable integrated traits*
- Outstanding demonstration of “systems biology”*

*Needs addressable by GTL

2010 2020 2030

Coproducts

Diagram provided by: Mike Himmel and John Sheehan, NREL

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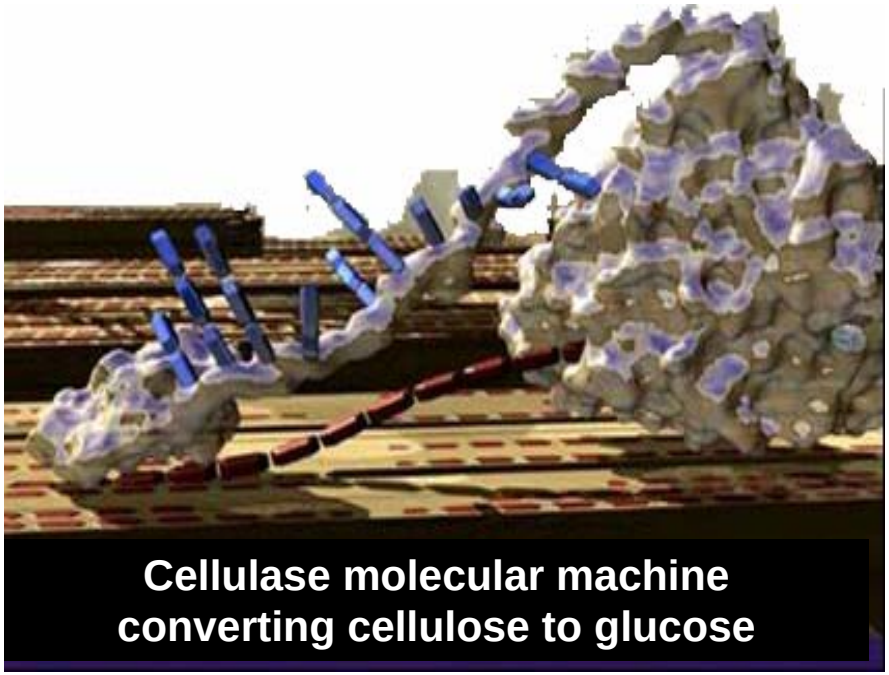
Understanding Molecular Machines & Putting Them to Work

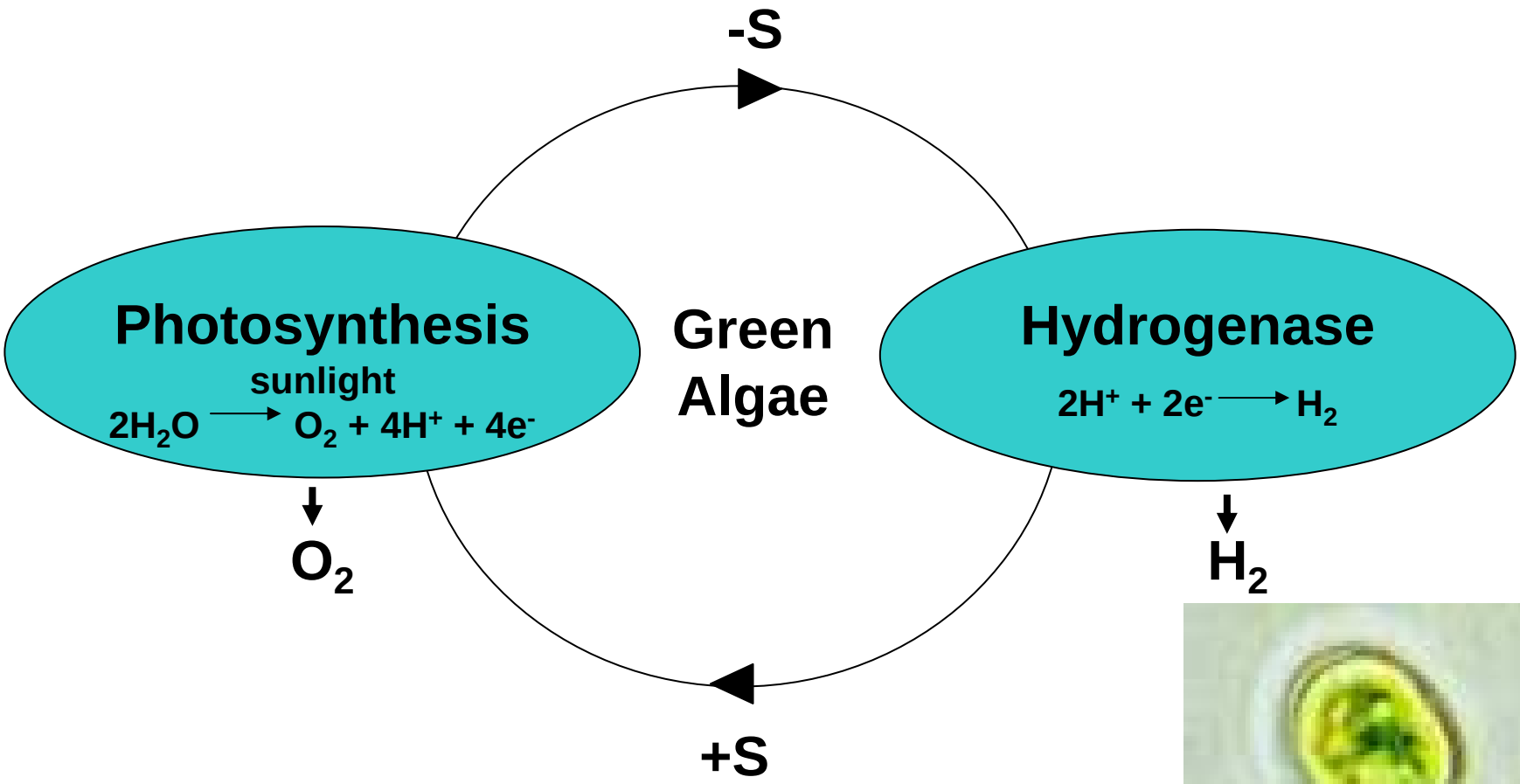


Cellulase molecular machine converting cellulose to glucose

- **Natural forms of cellulase machines are too inefficient for commercial ethanol production.**
- **Fundamental knowledge of plant and microbial processes gained in GTL can be applied to develop more efficient methods.**

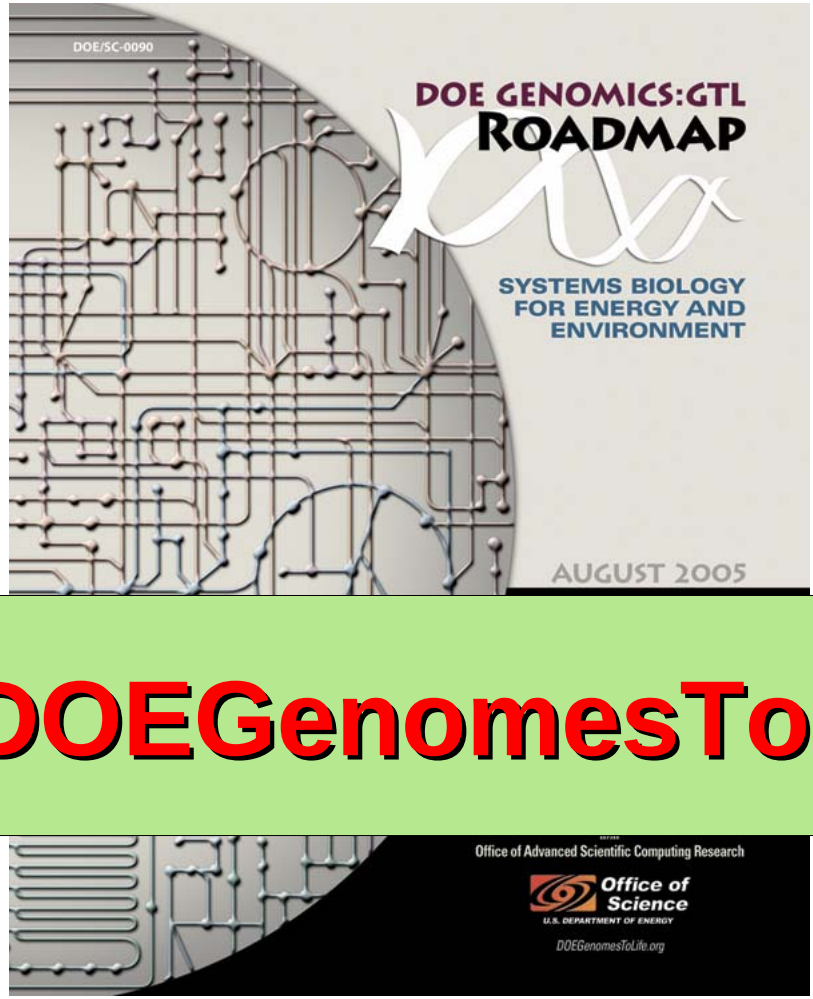
Potential to make cellulose a viable energy feedstock and to create a new energy industry that improves energy security and helps displace greenhouse gases created by fossil fuel combustion.

Improving Nature's Design



Chlamydomonas reinhardtii

- Can the efficiency of energy capture from sunlight be increased?
- Can a continuous process for hydrogen production be developed?
- Can a hydrogenase with lower sensitivity to oxygen be engineered?



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