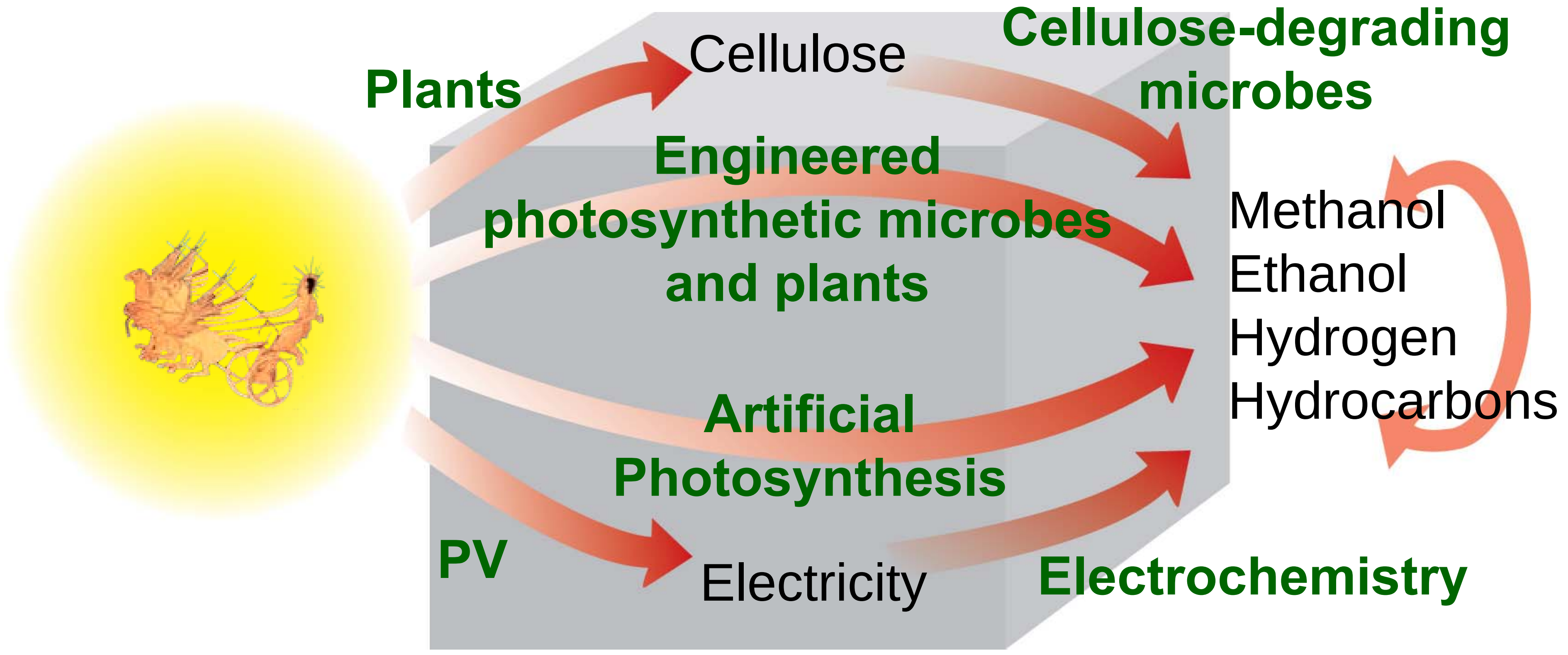
The Science of Photons to Fuels

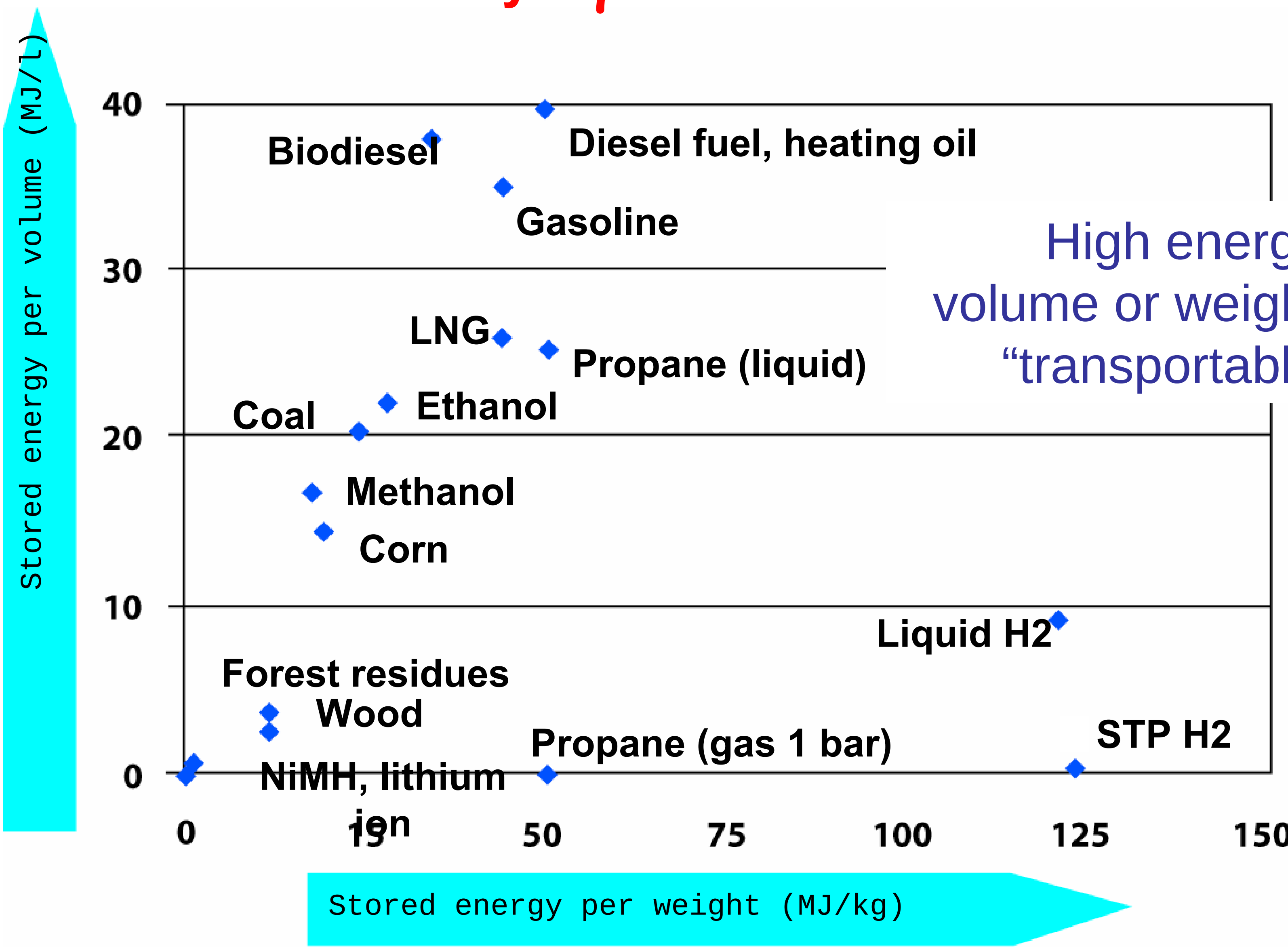
APS – Forum Physics and Society

1 March, 2008

Helios: Lawrence Berkeley Laboratory and UC Berkeley

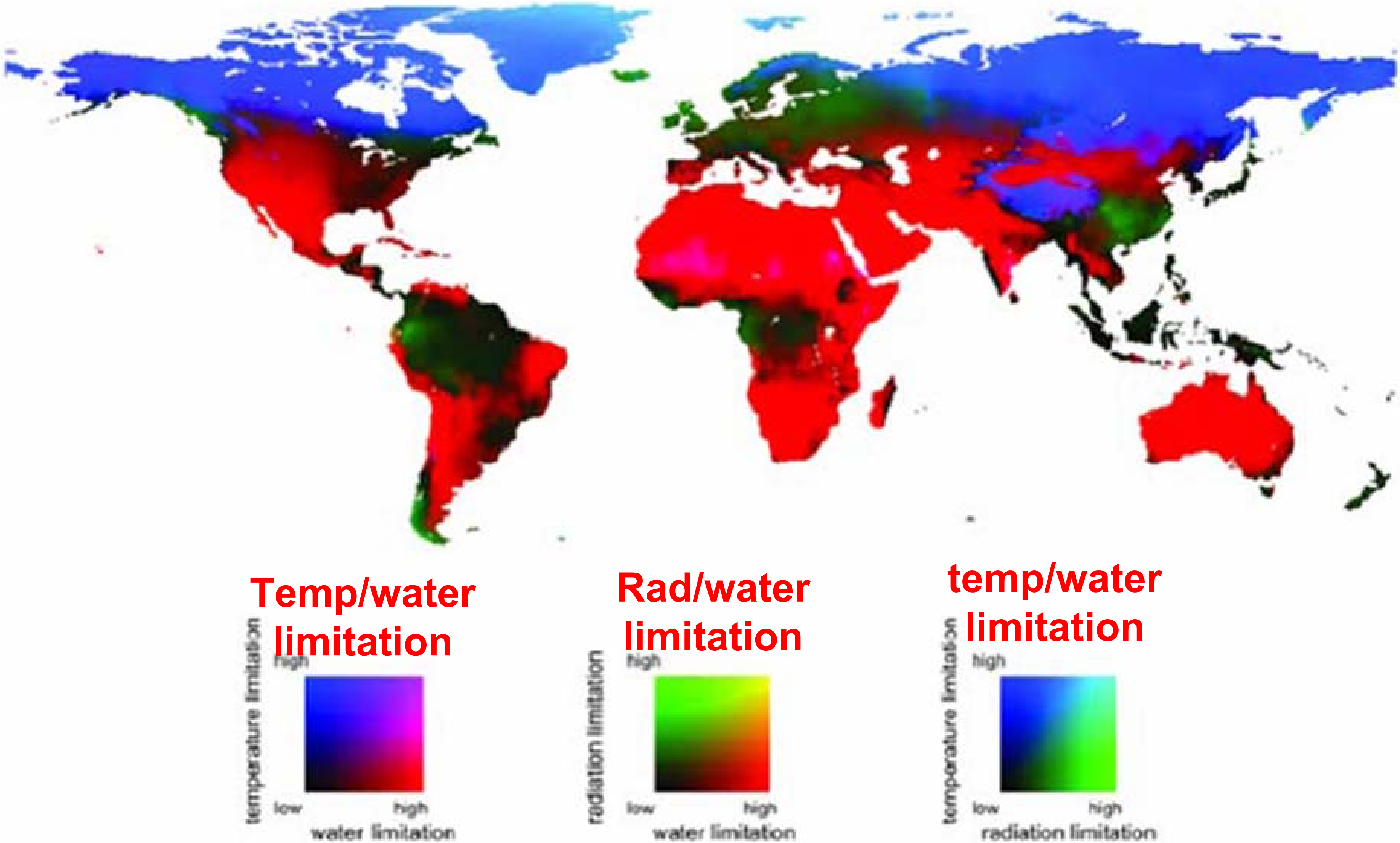


Why liquid fuels?



High energy/ volume or weight, “transportable”

Limiting factors for plant productivity



Baldocchi et al. 2004 *SCOPE 62*

Sunlight to energy via Bio-mass

Sunlight CO_2, H_2O, Nutrients → Biomass → Chemical energy

More efficient use of water, sunlight, nutrients.

Drought and pest resistant

Improved conversion of cellulose into fuel.

New organisms for biomass conversion.

Frequently asked questions:

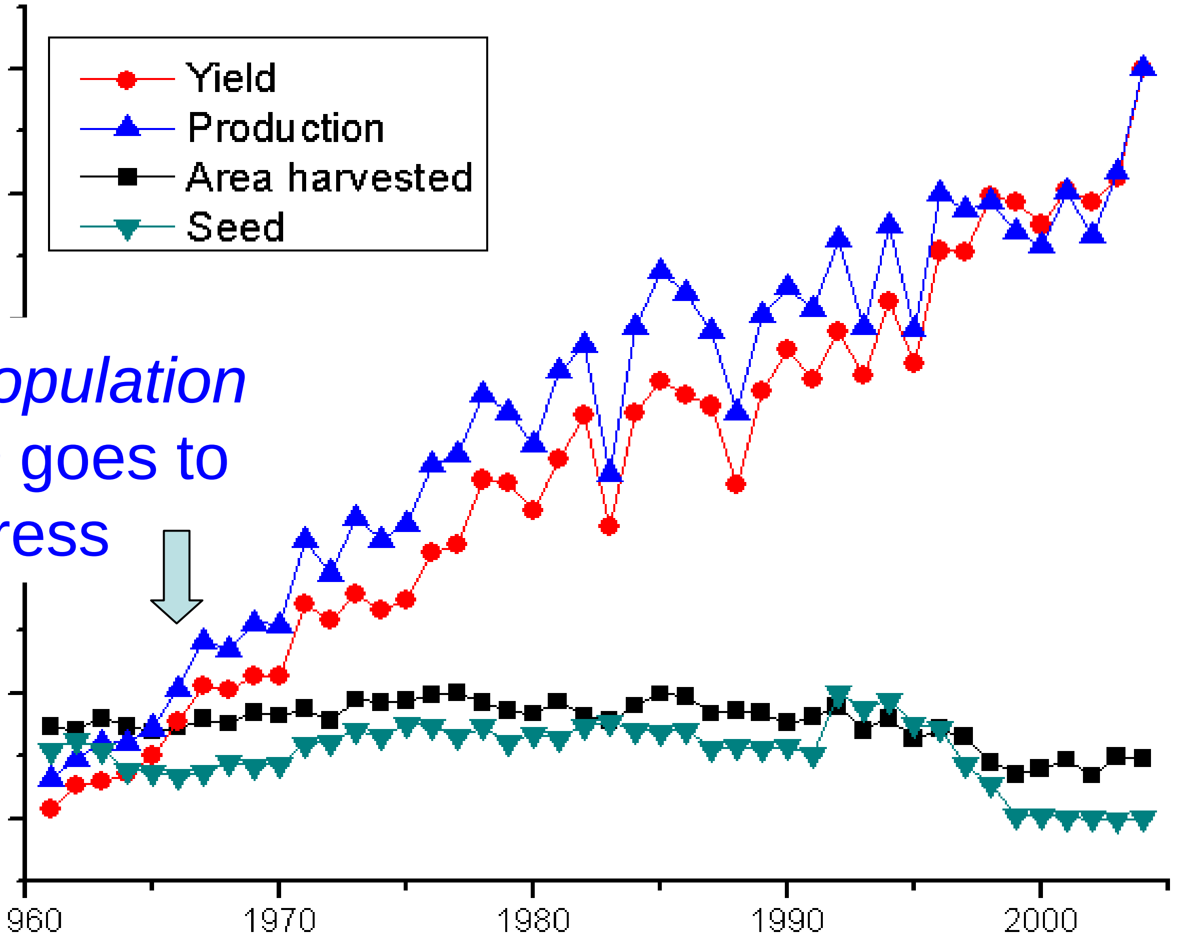
How can there be enough arable land to grow energy and food?

"The battle to feed all of humanity is over... In the 1970s and 1980s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now."

Prof. Paul Ehrlich, Stanford Biologist
The Population Bomb (1968)

World Production of Grain (1961 – 2004)

The Population Bomb goes to press



1960:
Population = 3 B

2005:
Population = 6.5 B

Source: Food and Agriculture Organization (FAO), United Nations

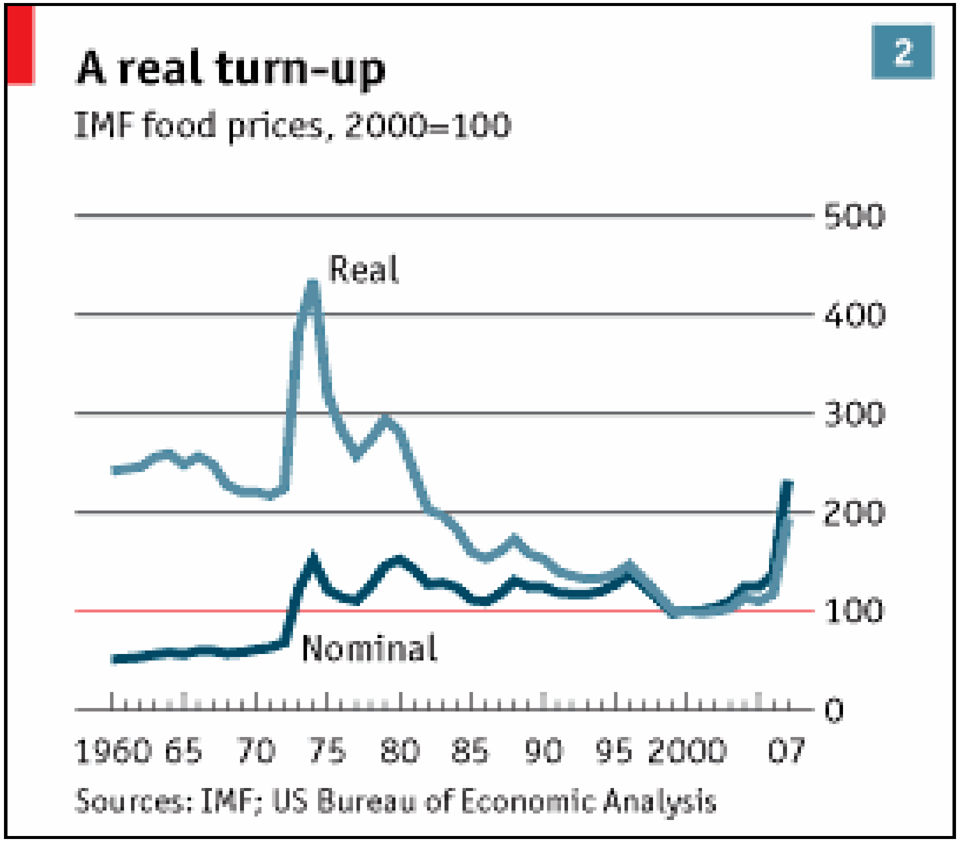
Frequently asked questions:

Current agriculture practice is not sustainable … the water tables are decreasing due to heavy irrigation and becoming polluted due to heavy fertilizer use. Also, the cost of food is rapidly increasing and causing hardship among poor people.

Won't growing crops for energy make this problem worse?

The rise in food prices is due to:

- The production to biofuels
- The cost of energy
- Rising wealth of developing countries and the increased consumption of meat.
- The impacts of climate change



Feedstock grasses (*Miscanthus)* is a largely unimproved crop.

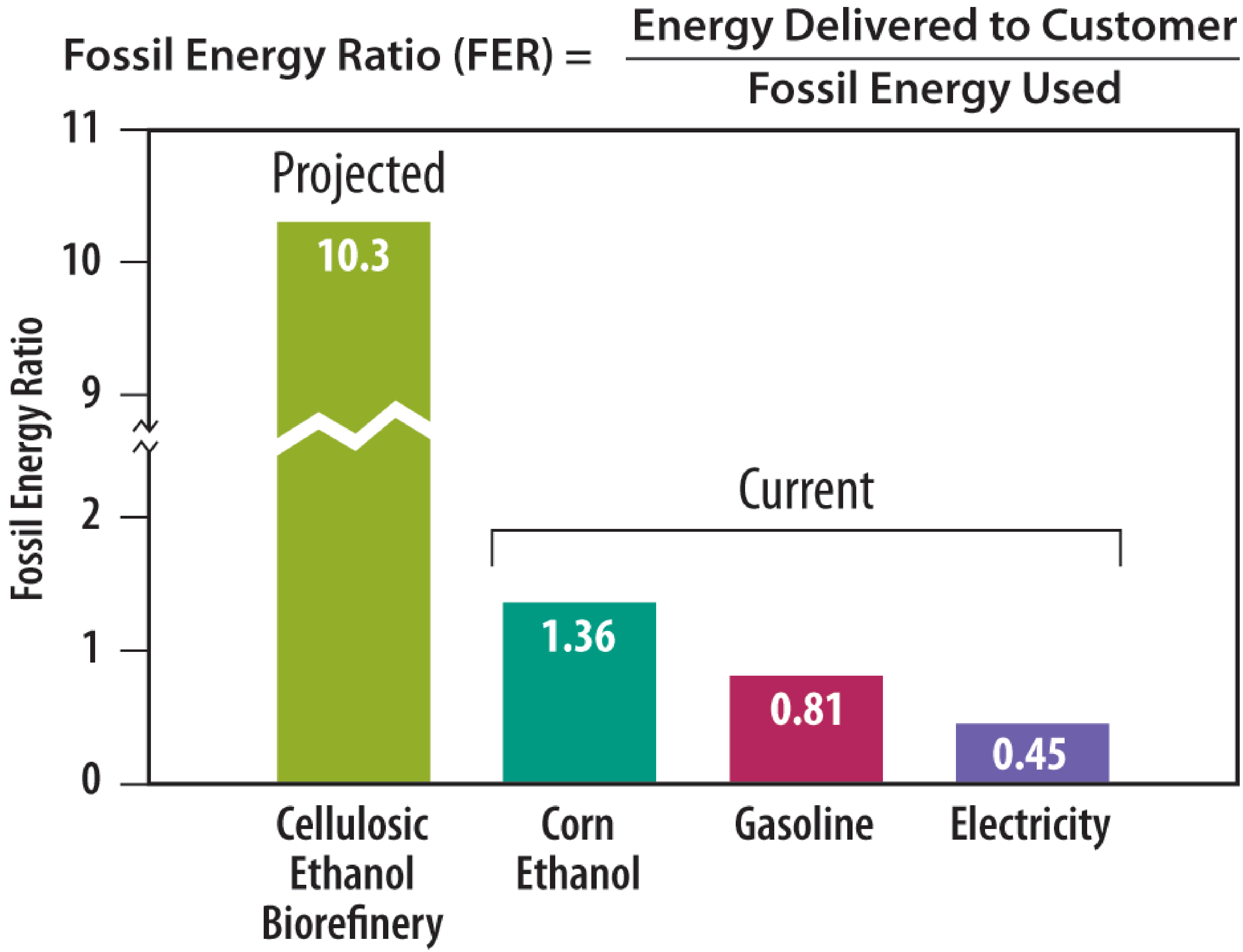
Non-fertilized, non-irrigated test field at U. Illinois yielded

15x more ethanol / acre than corn.

50 M acres of energy crops plus agricultural wastes (wheat straw, corn stover, wood residues, urban waste, animal manure, etc.) can produce ***half*** to ***all*** of current US consumption of gasoline.

Advantages of perennial plants such as grasses:

- No tillage for ~ 10 years after first planting
- Long-lived roots establish symbiotic interactions with bacteria to acquire nitrogen and mineral nutrients.
- Some perennials withdraw a substantial fraction of mineral nutrients from above-ground portions of the plant before harvest.
- Perennials have lower fertilizer runoff than annuals. (Switchgrass has ~ 1/8 nitrogen runoff and 1/100 the soil erosion of corn.)



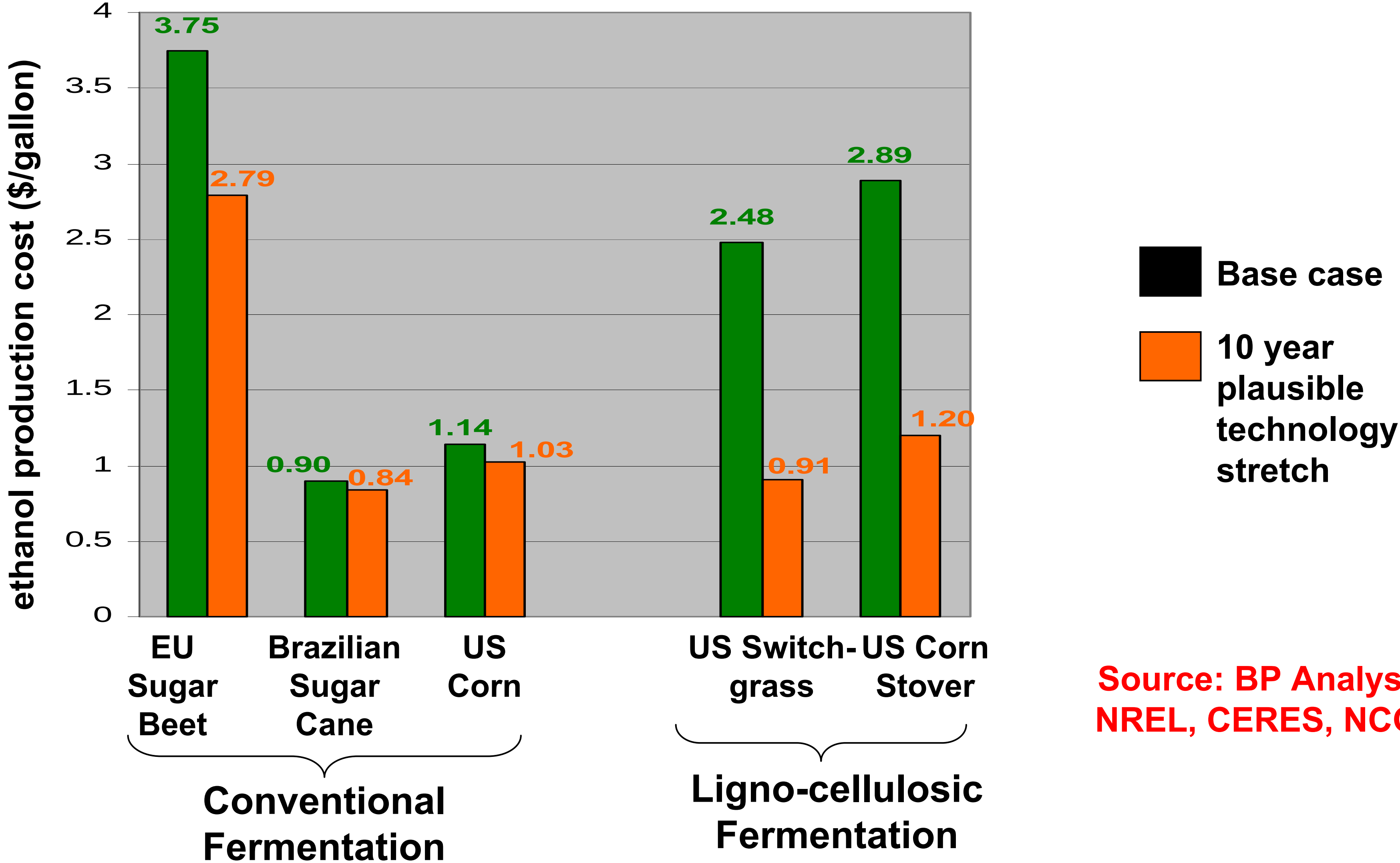
Source: DOE Report
"Breaking the Biological Barriers to Cellulosic Ethanol" June, 2006

Frequently asked questions:

If these grasses are so much better than corn or even sugar cane, why aren't they being grown today?

Current and projected production costs of ethanol

Courtesy Steve Koonin, BP Chief Scientist



Source: BP Analysis, NREL, CERES, NCGA

Energy Biosciences Institute

$50M/ year for 10 years

Joint Bio-Energy Institute (JBEI)

LBNL, Sandia, LLNL, UC Berkeley, Stanford, UC Davis

$25M / year for 5 years

Univ. California, Berkeley

Lawrence Berkeley National Lab

Univ. Illinois, Urbana-Champaign

bp

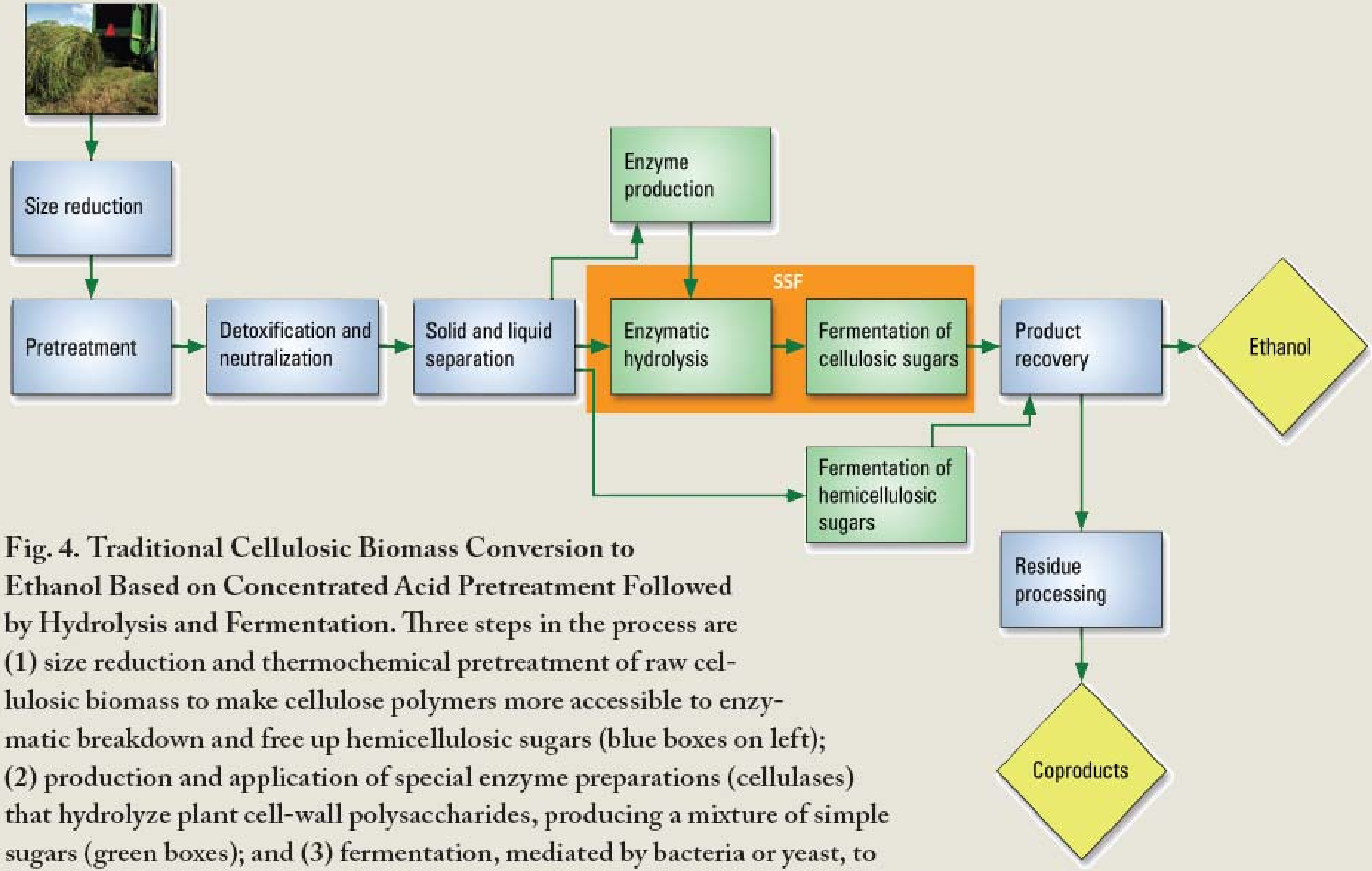
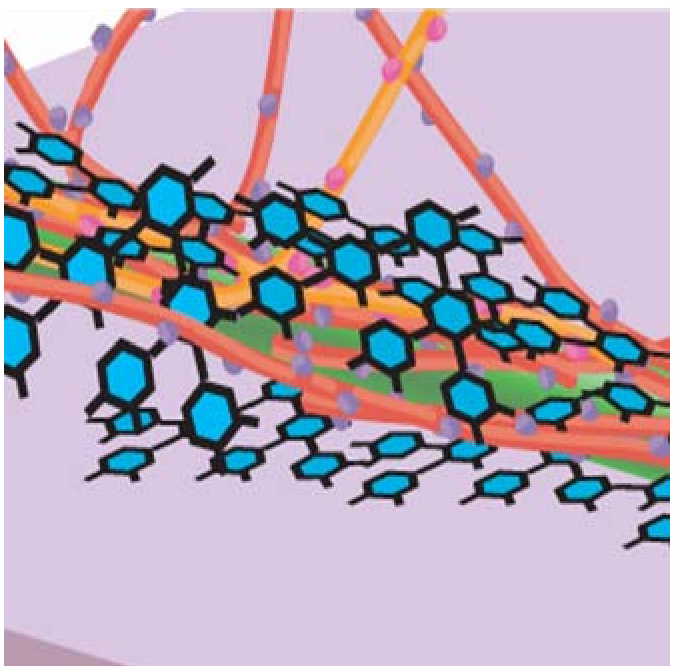
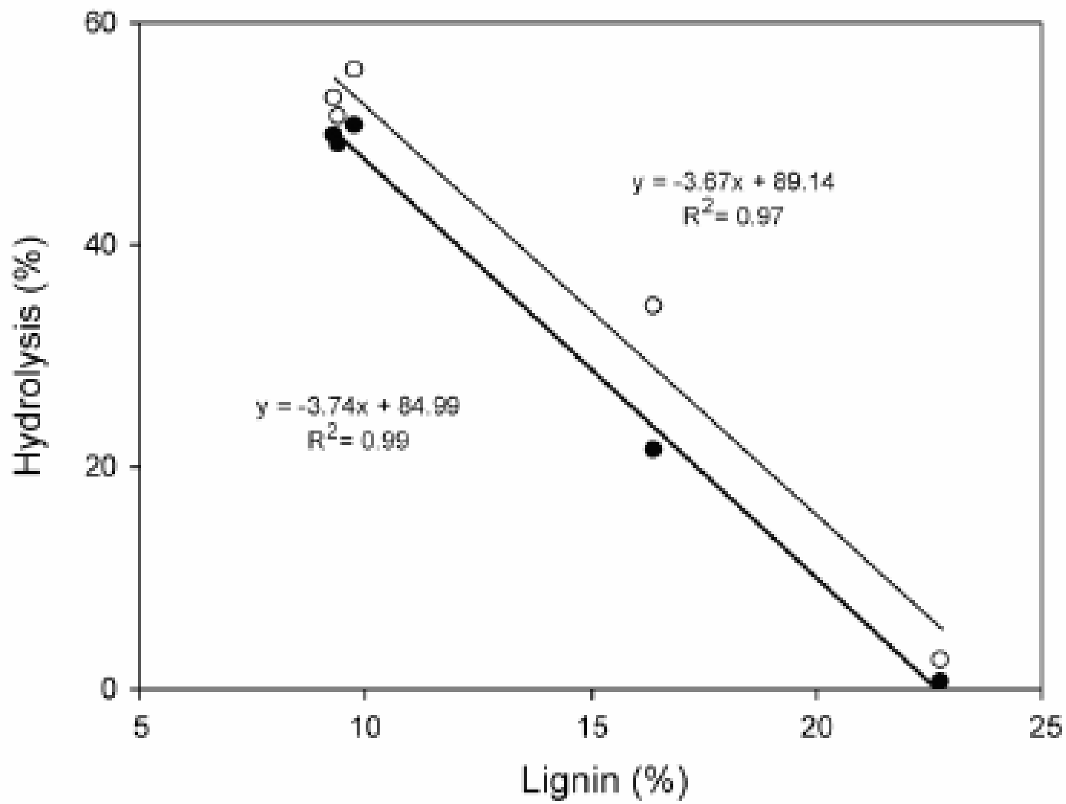


Fig. 4. Traditional Cellulosic Biomass Conversion to Ethanol Based on Concentrated Acid Pretreatment Followed by Hydrolysis and Fermentation. Three steps in the process are (1) size reduction and thermochemical pretreatment of raw cellulosic biomass to make cellulose polymers more accessible to enzymatic breakdown and free up hemicellulosic sugars (blue boxes on left); (2) production and application of special enzyme preparations (cellulases) that hydrolyze plant cell-wall polysaccharides, producing a mixture of simple sugars (green boxes); and (3) fermentation, mediated by bacteria or yeast, to convert these sugars to ethanol and other coproducts (yellow diamonds). Recent

The effect of lignin on enzyme recovery of sugars in miscanthus

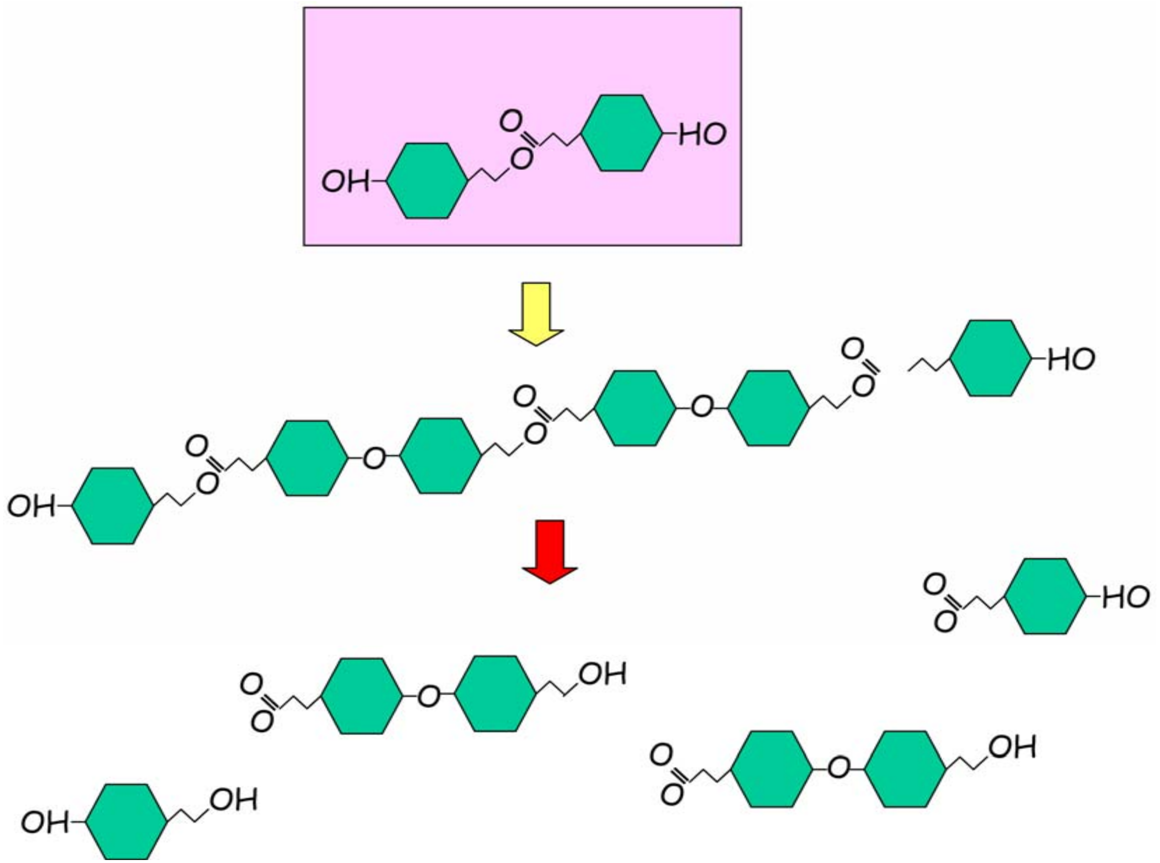
Cellulose	40-60% Percent Dry Weight
Hemicellulose	20-40%
Lignin	10-25%

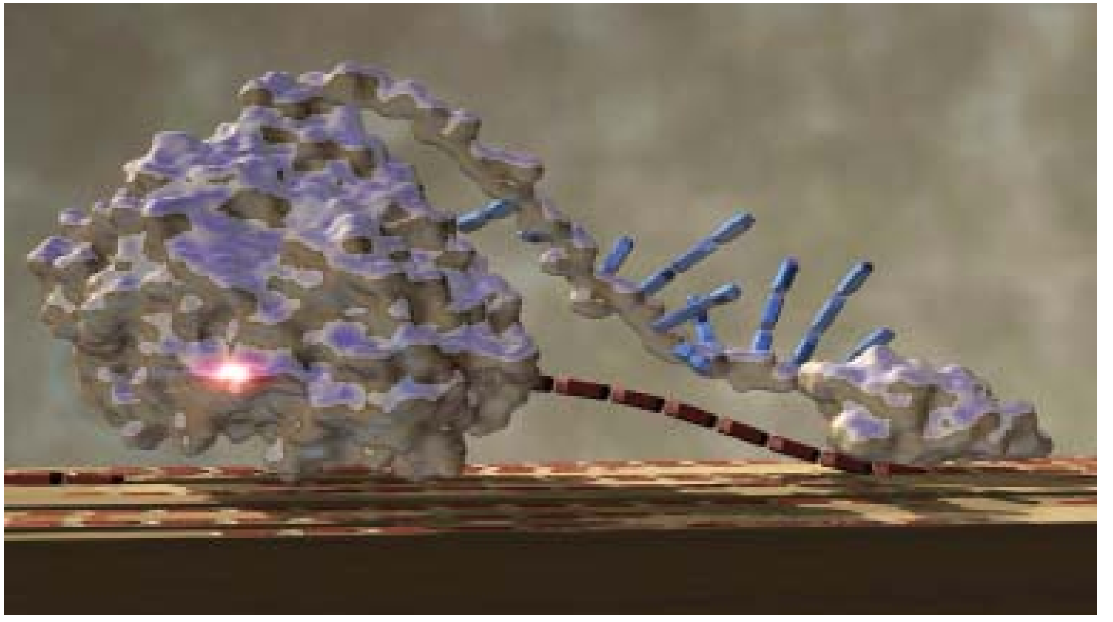




Feedstock Development

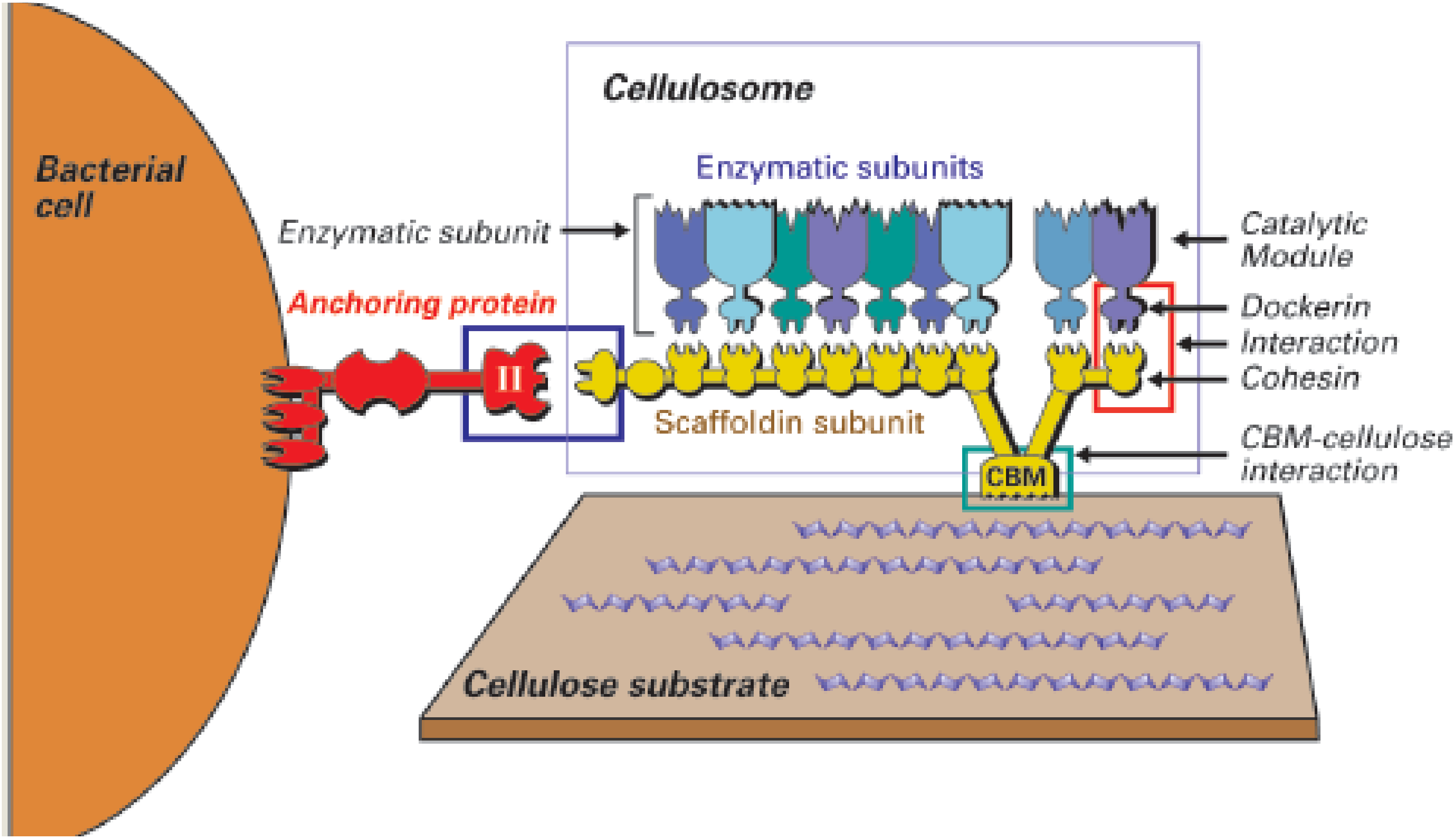
Introduce easily hydrolyzed bonds into lignin
→ easily unzippable lignin





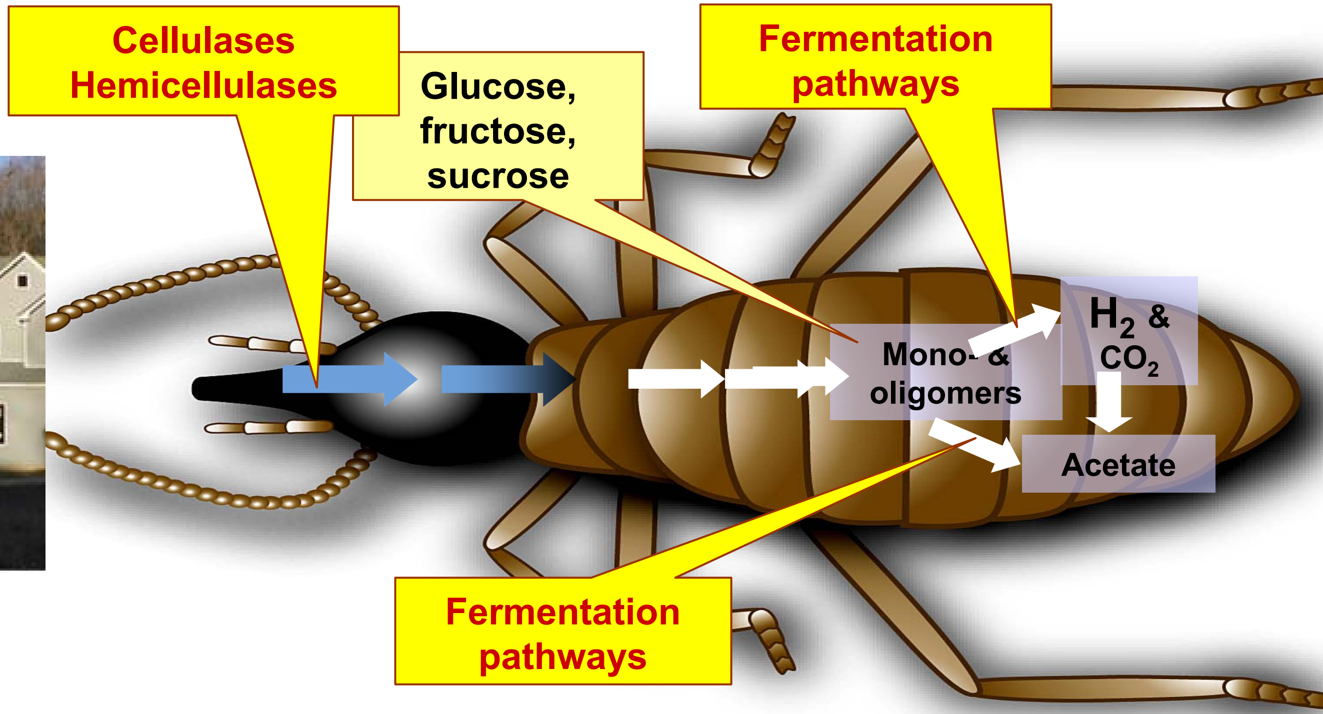
Departmant of Energy, working with Genencor and Novozymes, achieved a 20 -30 fold reduction in enzyme costs. A cocktail of three different enzymes were found to work more efficiently in converting cellulose into simple sugars.

Further cost reductions are required: Current costs are over 20¢ /gal.



Cellulosomes can be designed with complementary enzymes to form a single multi-enzyme complex. Cellulose hydrolysis rates were shown to be 2.7- to 4.7-fold higher compared with purified enzyme preparations.

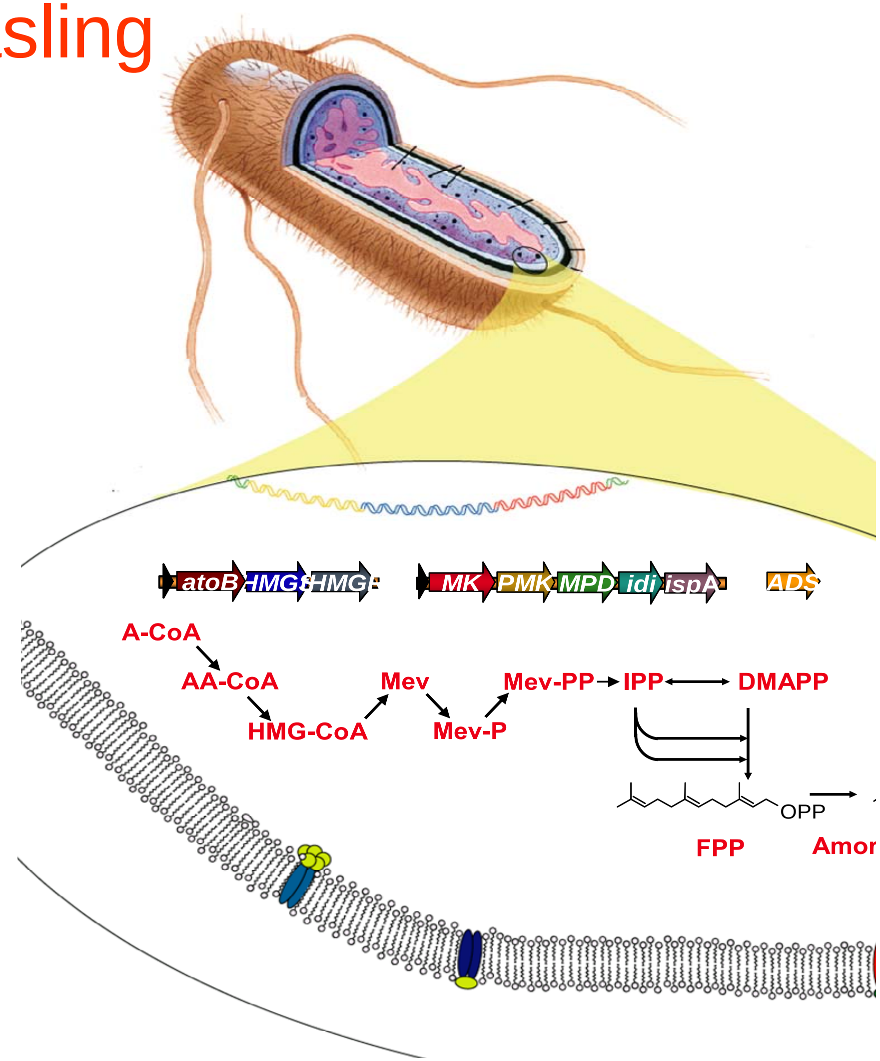
Termites have many specialized microbes that efficiently digest lignocellulosic material



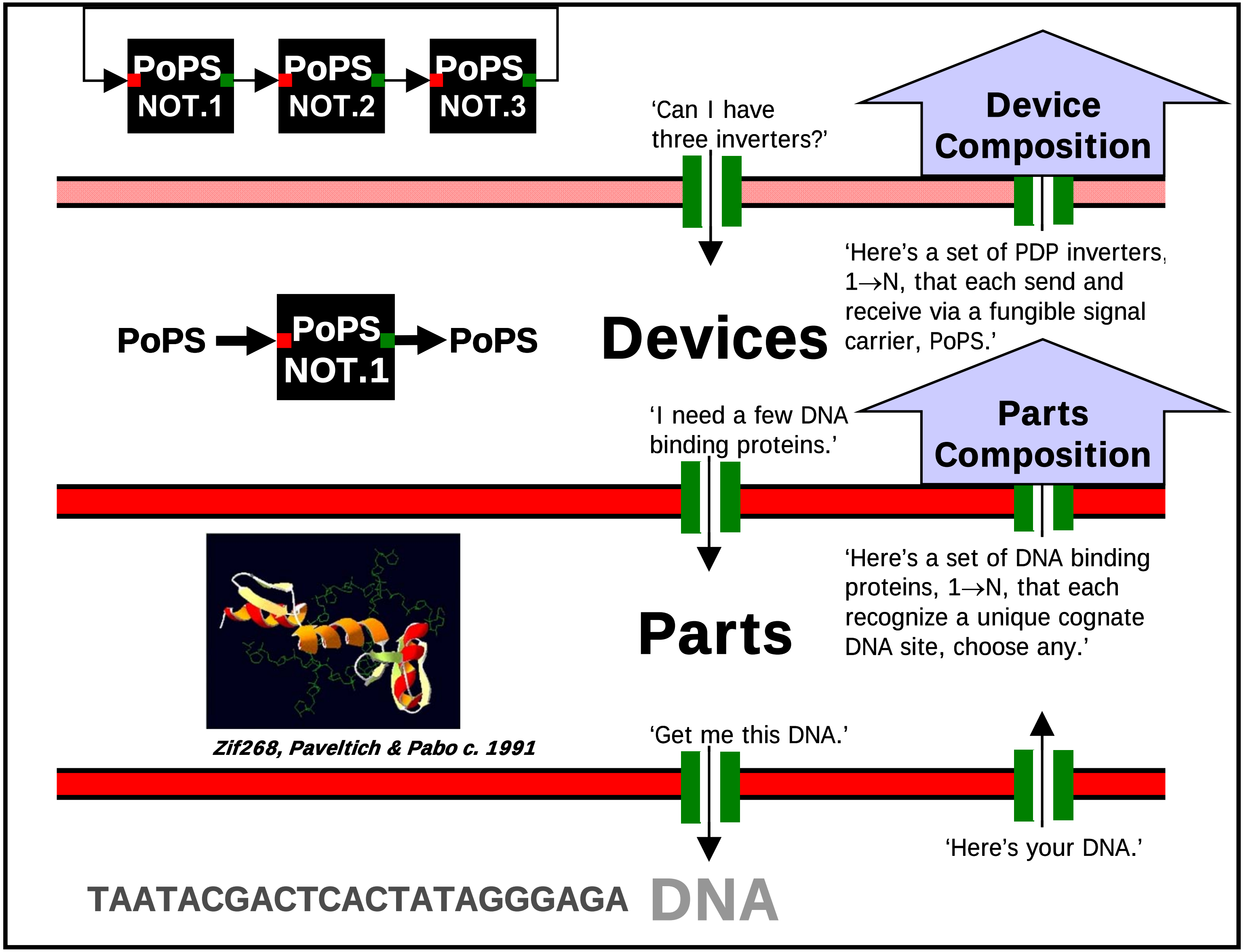
Production of artemisinin in bacteria

Jay Keasling

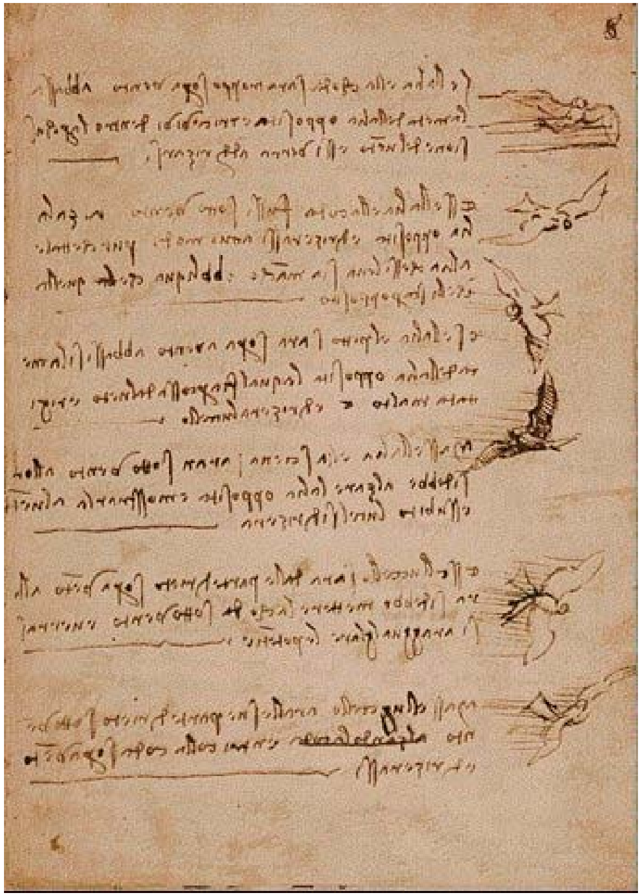
Identify the biosynthesis pathways in *A. annua*

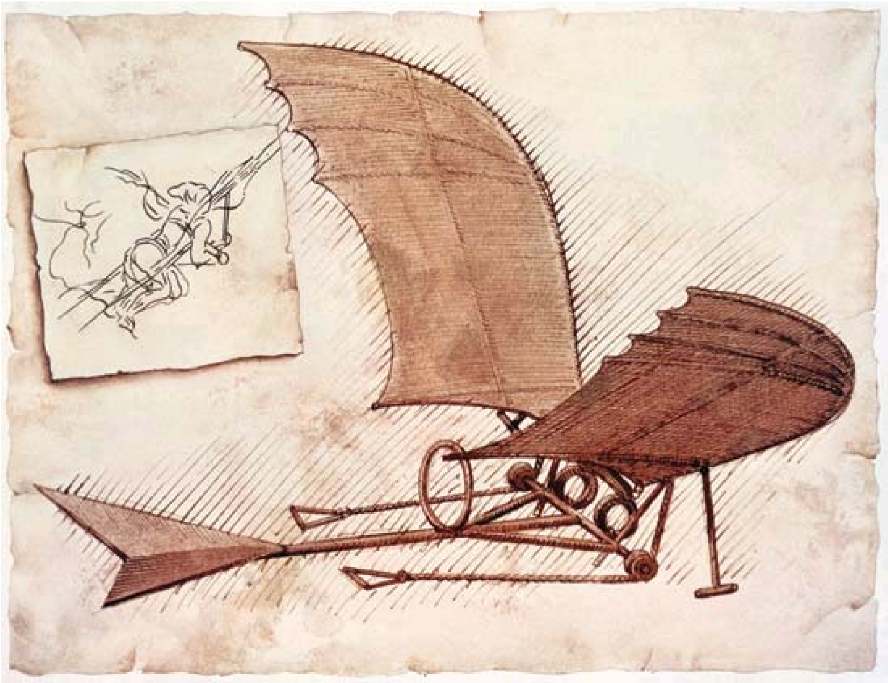


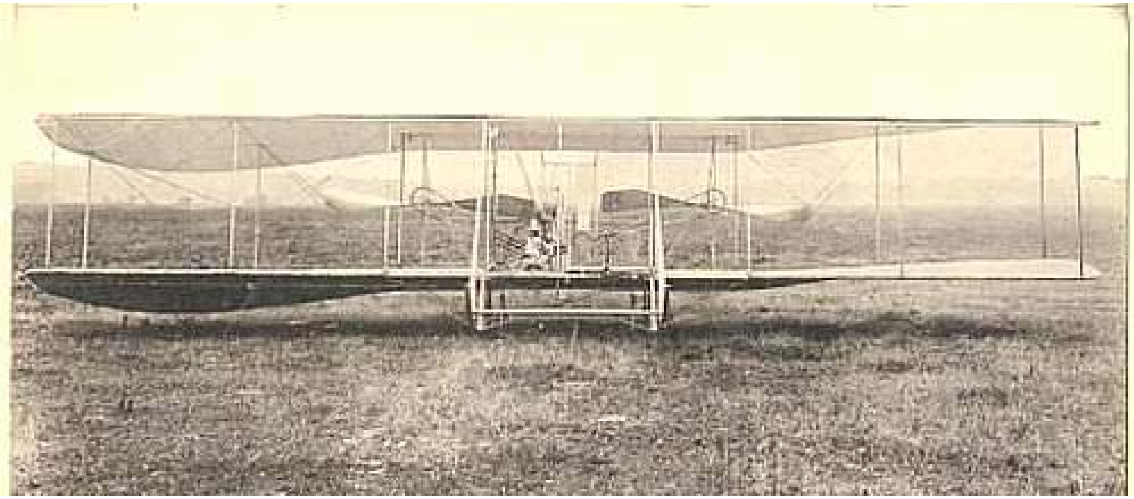
Construction of platform hosts and genetic tools



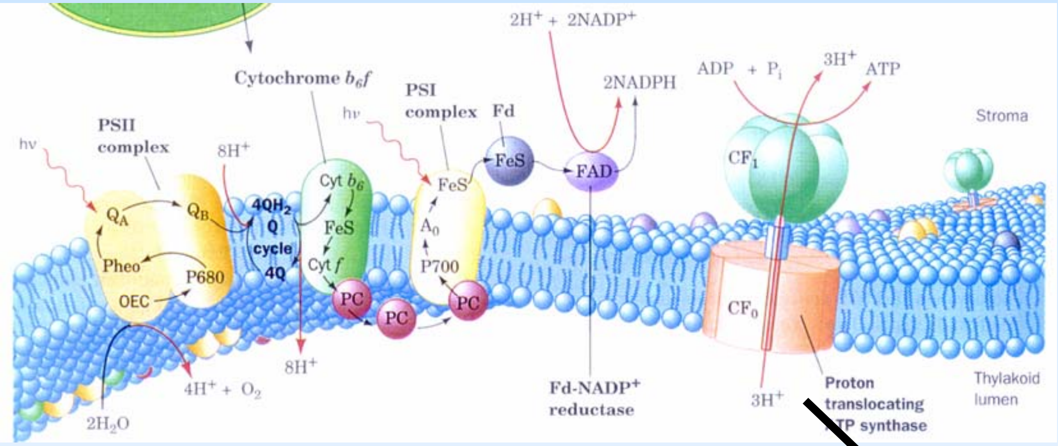
Man first learned to fly by imitating nature

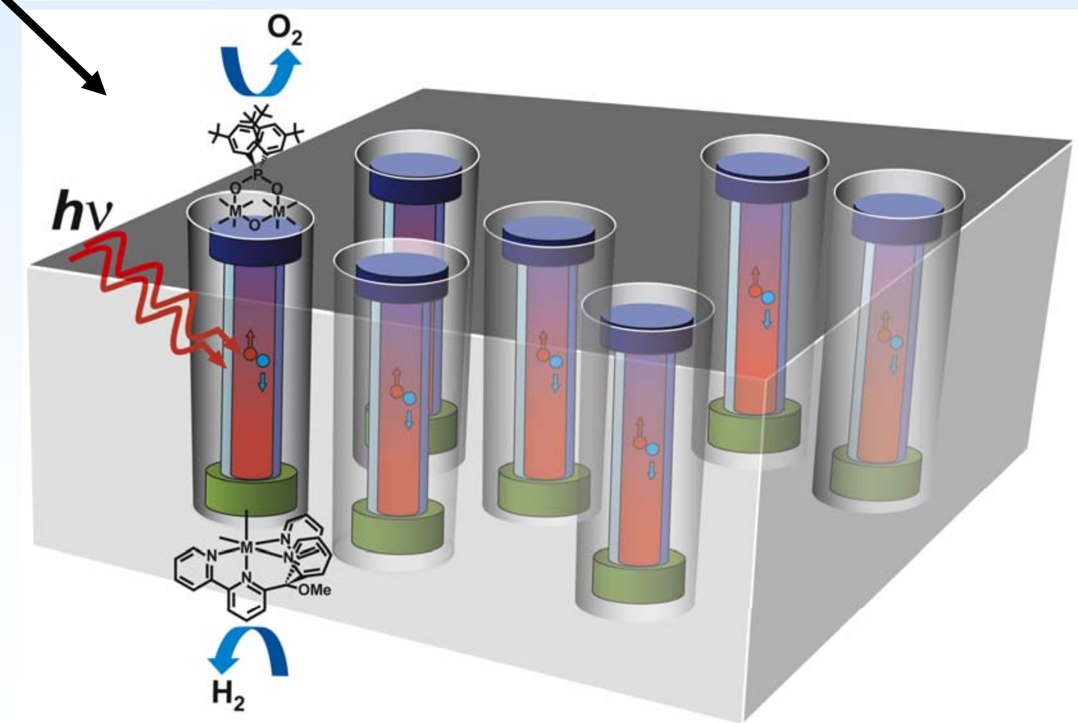






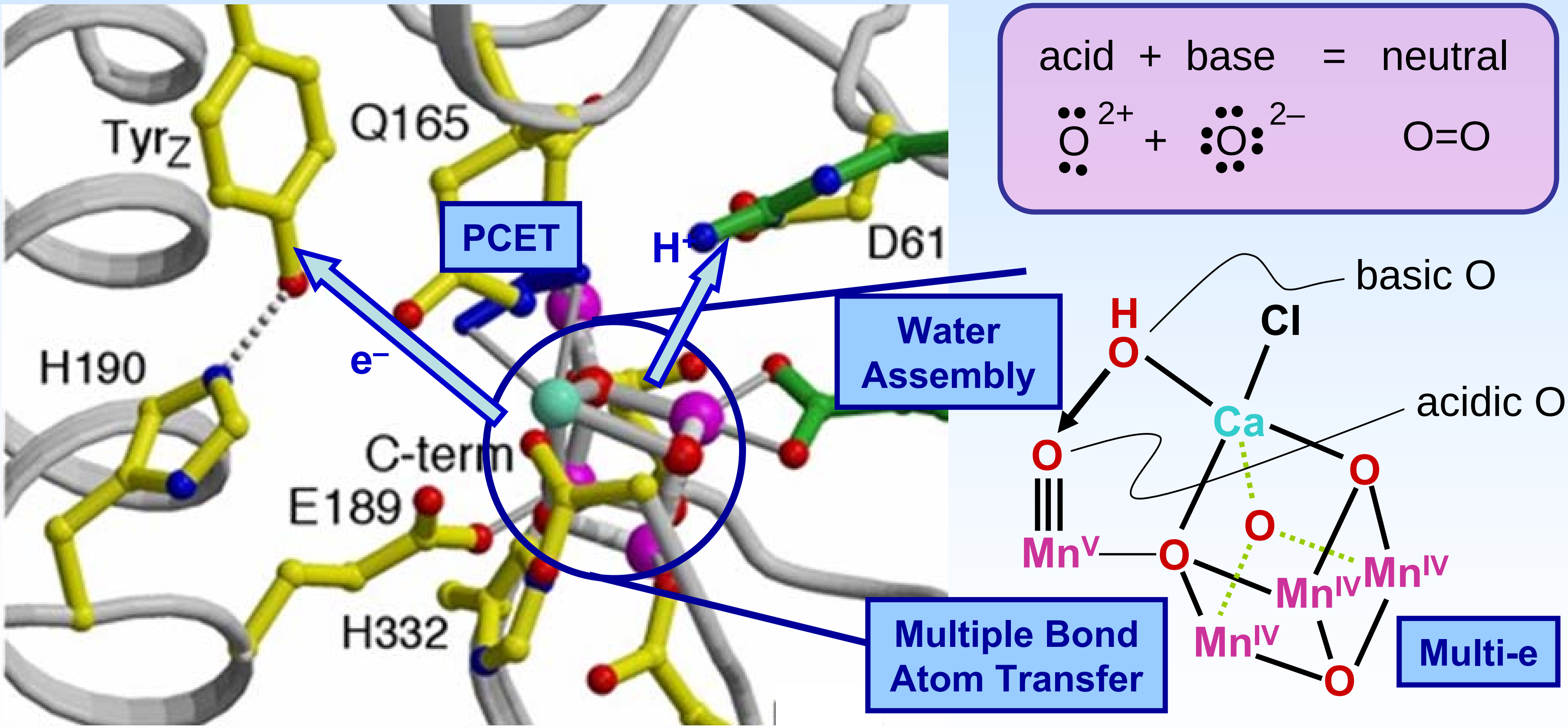
Helios Artificial Photosynthesis Project





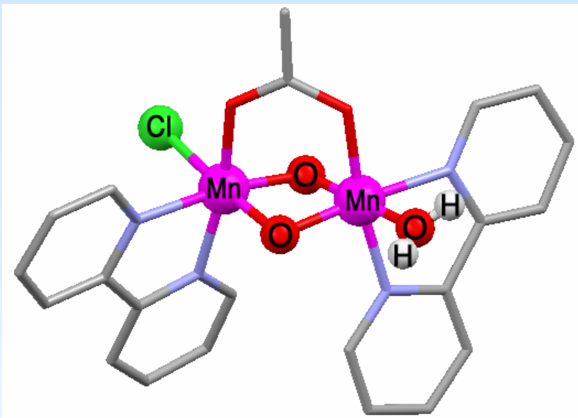
A Clue from Nature

The OEC Active Site of PSII (Imperial College structure)

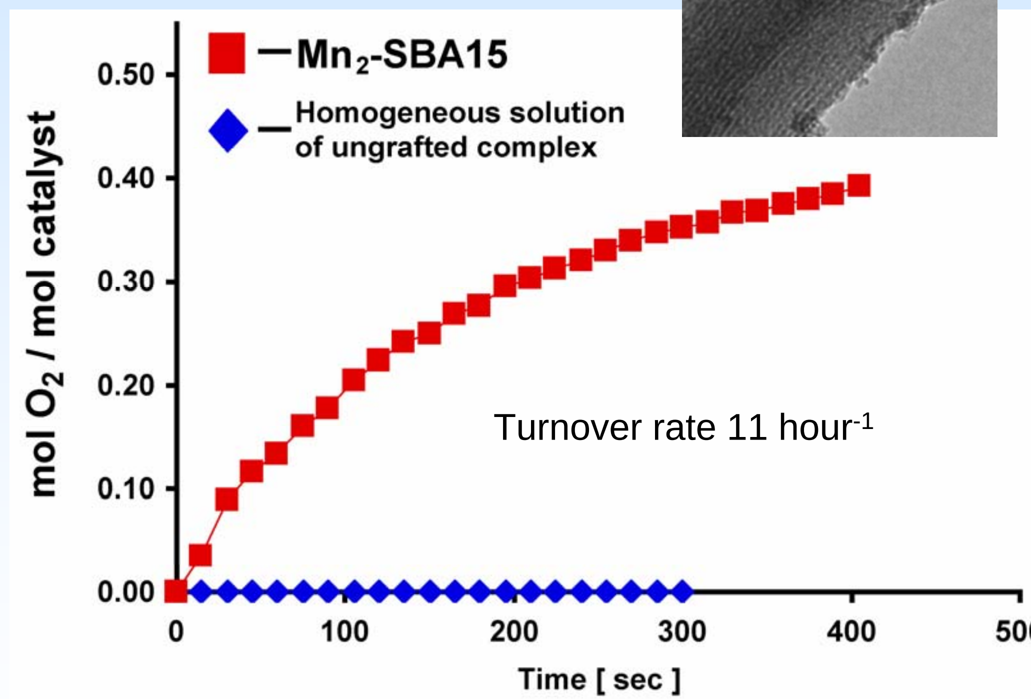


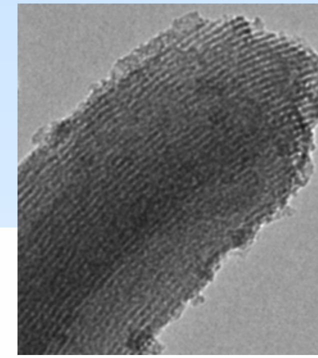
Turnover rate 300 s^{-1}

Synthetic Water Oxidation Catalyst on Nanoporous Silica Support

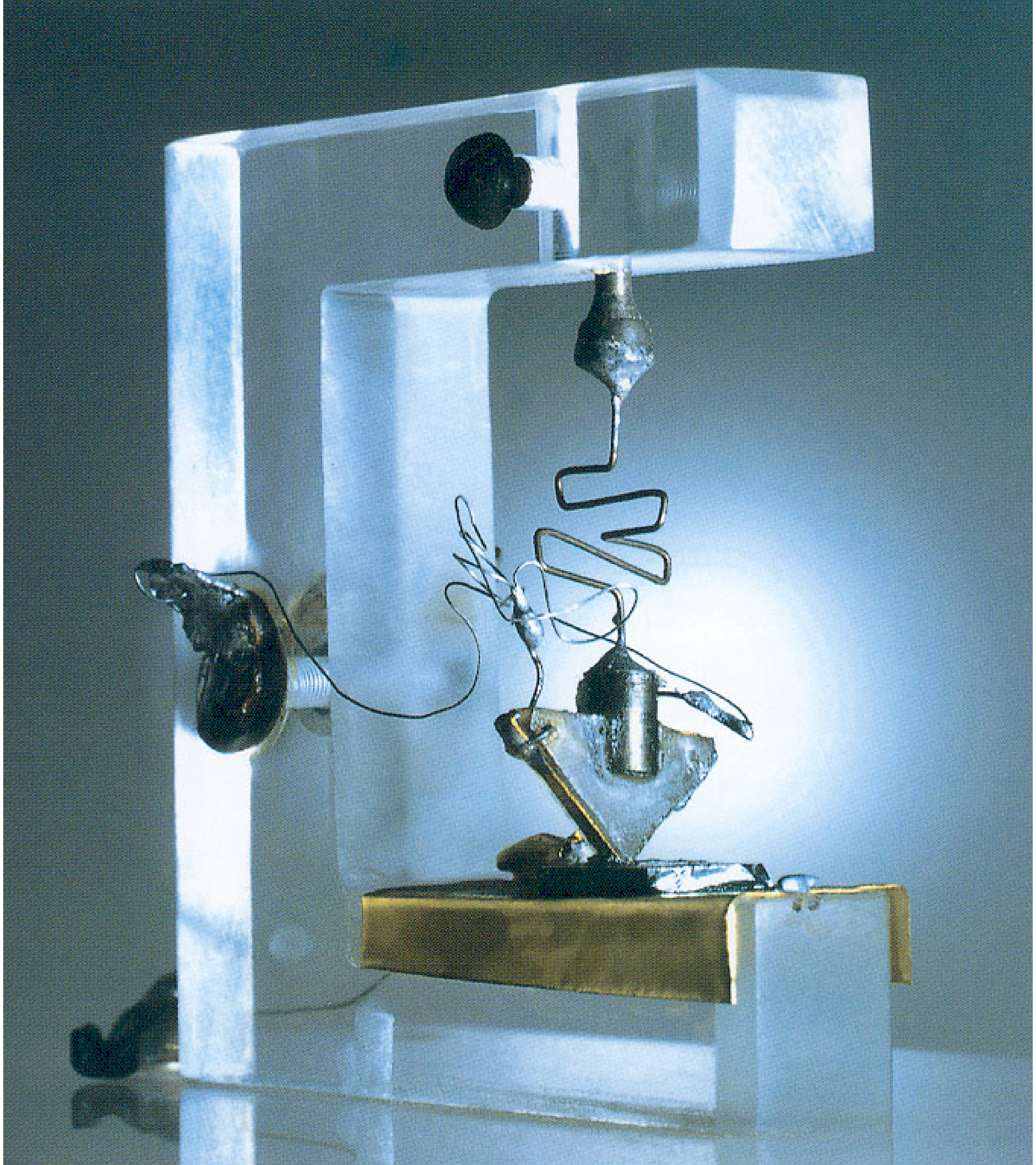


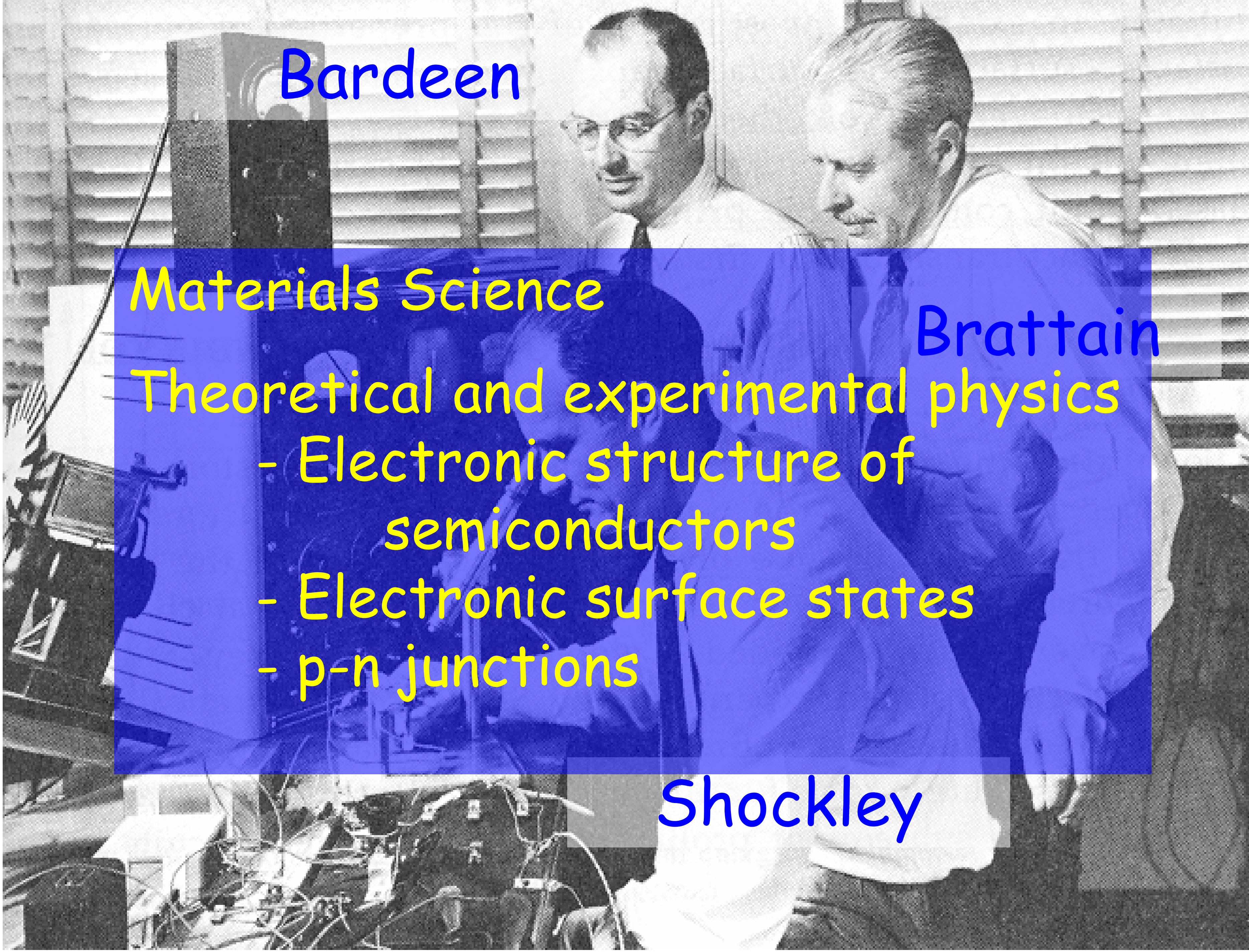
[$Mn_2(\mu\text{-}O)_2(O_2CCH_3)Cl(H_2O)(bpy)_2](NO_3)_2$





- O_2 evolution is only observed for Mn dimer complex in silica nanopores
- Turnover rate among the highest observed for synthetic Mn dimer catalyst




Bardeen
Materials Science
Brattain
Theoretical and experimental physics
- Electronic structure of semiconductors
- Electronic surface states
- p-n junctions
Shockley

Armstrong, et al. *Dalton Trans.*, 4152 (2003) showed that the [NiFe] hydrogenase enzyme from *Allochromatium vinosum*, when absorbed onto a graphite electrode, functions as well as platinum for catalytic H_2 oxidation.

These hydrogenase enzyme-modified electrodes lose catalytic activity when exposed to CO, but quickly recover once the CO gas is removed. Hydrogenase enzymes are derived primarily from strictly ***anaerobic*** organisms and are extremely sensitive to O_2.

More recently, (*Proc. Natl. Acad. Sci. USA* 102, 16951 (2005) a [NiFe] hydrogenase derived from the ***aerobic*** bacterium *Ralstonia eutropha* functions as an H_2 oxidation catalyst in the presence of high concentrations of CO, and immediately recovers catalytic activity after exposure to high concentrations of O_2.

Structure and the mechanism of this enzyme is not known.

Improve Nature's Design or Rational Design?

Chlamydomonas reinhardtii

Can the efficiency and/or rate of energy conversion be increased in algae or other micro-organisms?

Can we make algae that thrive at

- **High density,**
- **Continuous process for hydrogen or lipid production,**
- **Very high CO_2 concentrations?**

What if we built light-concentrating, algae systems that operate at 0.5 % CO_2 concentration?