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Transformational Energy Research on Plants

National Association of State Universities and Land-Grant Colleges

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Dr. Raymond L. Orbach
Under Secretary for Science
U.S. Department of Energy
www.science.doe.gov

Bioenergy: A Major New Role for Plants and U.S. Agriculture in the 21st Century

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- In the early 21st century, we are turning once again to the plant kingdom for a major source of our energy, but in an entirely new way
- For millennia humanity has burned biomass for fuel. Combustion of wood in early steam engines was used for transportation. Today we seek to derive from plants new forms of energy that are
  - Renewable
  - Carbon-neutral
  - Practical as alternatives to fossil fuels for transportation
- The effort to tap plants for renewable biofuels—particularly to unlock the energy bound up in plant fiber, or lignocellulose—has led us to the recognition that our fundamental knowledge of plants is barely adequate to this new challenge
- To realize the promise of biofuels and bioenergy, we will need a renaissance in basic plant science research.

A New Mission for State Universities and Land-Grant Institutions

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- Research on plants has been integral to the mission of the land-grant institutions since the 19th century.
- The development of biofuels—especially lignocellulosic biofuels—represents a major scientific opportunity that can strengthen U.S. energy security and protect the global environment.
- The U.S. is capable of producing 1 billion dry tons of biomass annually (agricultural and forestry wastes, grains, and 55 million acres of perennial bioenergy crops) – enough for 60 billion gallons of ethanol per year, or ~30% of today’s transportation fuel usage – and continue to meet food, feed, and export demands.
- To produce lignocellulosic biofuels, or biofuels from plant fiber, cost-effectively on a commercial scale will require transformational breakthroughs in basic science focused on both plants and processing methods.
- There are longer-term opportunities to mimic photosynthesis by producing fuels directly from sunlight.

Making Cellulosic Ethanol

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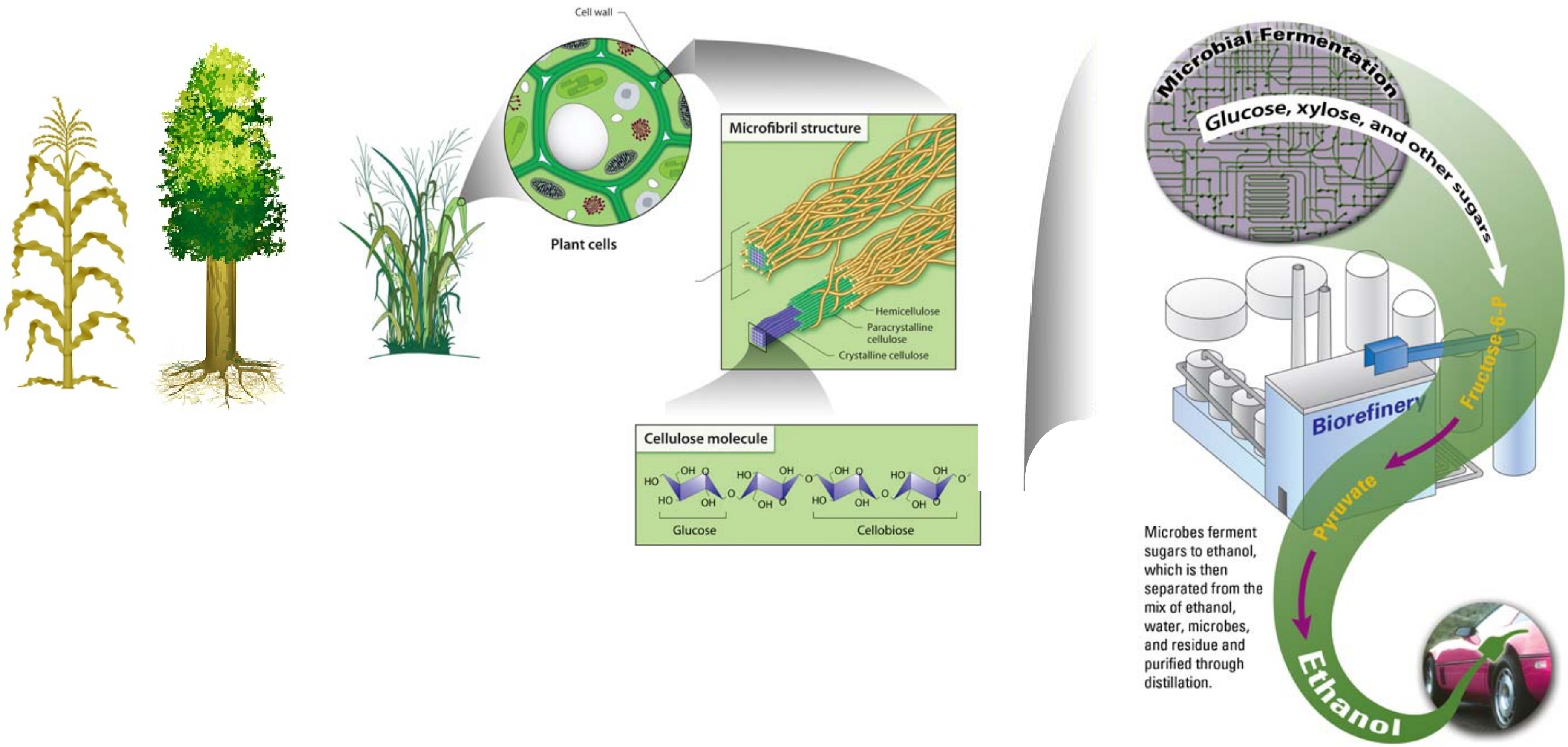
Basic Transformation

Lignocellulose → Sugars → Ethanol



Key Challenges in Converting Plant Fiber to Liquid Fuels

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- Biggest cost barrier lies in breaking down lignocellulose, or plant fiber, into sugars – process is difficult and creates byproducts that impede fermentation.
- Problem is known as "recalcitrance" – plant fiber has evolved over the millennia to be extremely resistant to breakdown by biological or natural forces.
- Cell walls (where plant fiber resides) are extremely resilient, complex structures (likened to "flexible concrete") little understood in detail; very little understood about how cell walls are synthesized in cell.
- Little is understood about how enzymes, either alone or as part of microbial processes, act on cell walls to break them down or act on cellulose to degrade it.
- Further challenges must be overcome to get efficient fuel synthesis.

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A New Generation of Technologies to Accelerate Discovery

- **Genomic Sequencing** (DOE Joint Genome Institute: 3 billion base pairs per month)
  - Provides unprecedented capabilities for understanding and modifying organisms (both plants and microbes) – JGI recently sequenced poplar, working on switchgrass, multiple microbes
  - **Foundational** for field of systems biology
- **High-Throughput Screening/Assays**
  - Key to accelerating pace of discovery – using current technologies and developing new ones
- **Bioprospecting/Metagenomics**
  - Scouring Nature for new, more effective cellulases
- **Directed Evolution (utilizing a new generation of sequencing technologies)**
  - Letting Nature to do our work for us—controlled natural selection to accelerate development of optimized microbes
  - Aimed at developing microbes more effective at degrading lignocellulose as well as fuel-synthesis microbes that resist pretreatment toxins and produce more fuel
- **Synthetic Biology**
  - Redesigning microbes to produce molecules more like petroleum-based fuels
  - Redesigning microbes for Consolidated Bioprocessing (CBP)—one-microbe or microbe commmunity approach to deconstruction and fuel synthesis
- **Advanced Imaging (NMR, High-Intensity Light Sources)**
  - Taking advantage of new capabilities of observing at nanoscale in ultrafast time intervals
- **High-End Computational Modeling**

Seeking Greater Efficiencies by Moving "Upstream" to Photosynthesis

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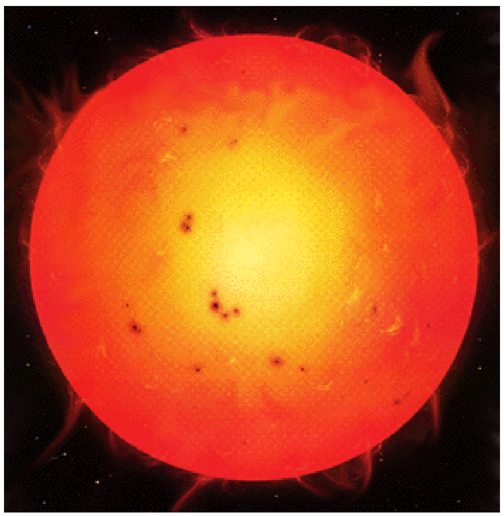

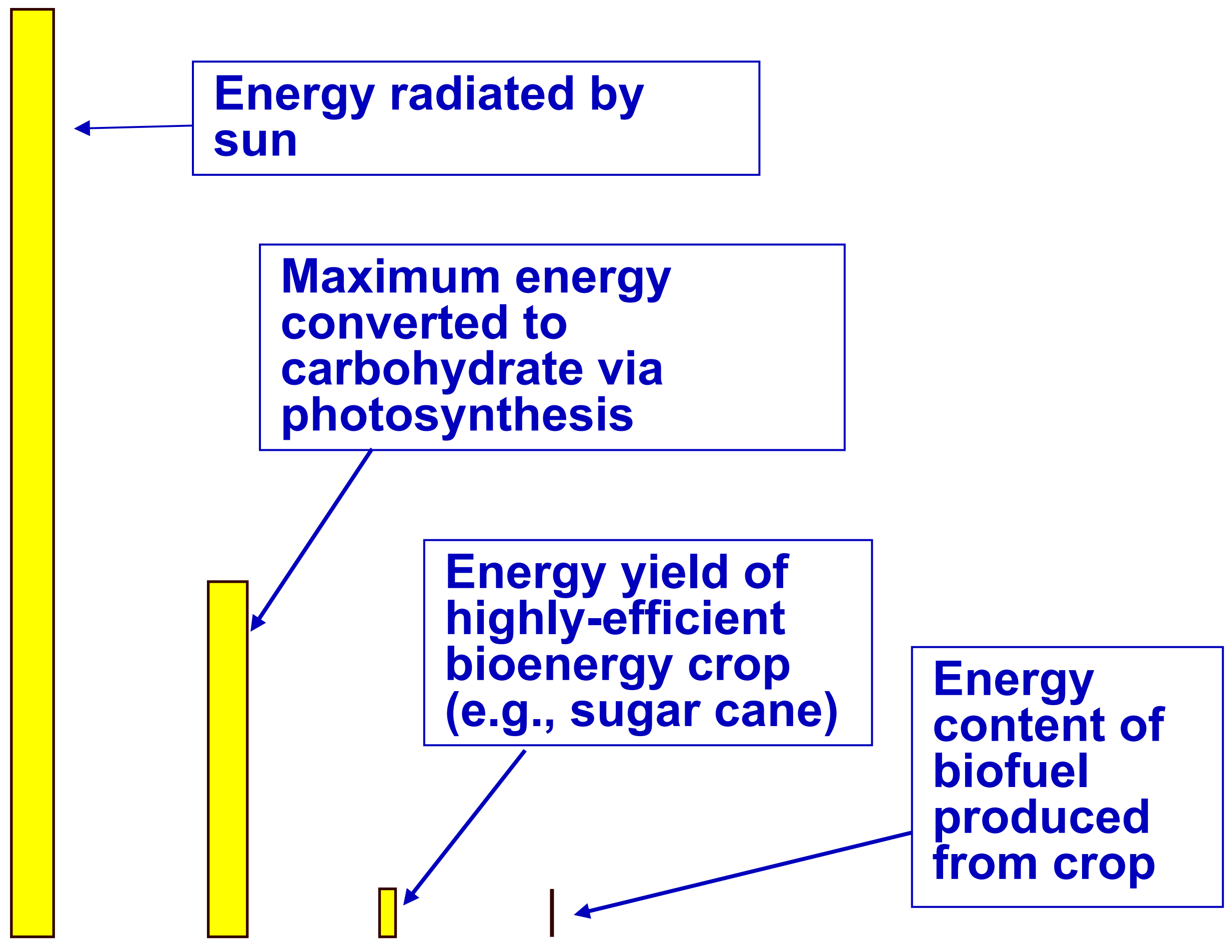

Unlocking Nature's Secret to the Production of Fuels from Sunlight

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- Elucidation of the molecular basis for photosynthesis is essential for construction of artificial and bio-hybrid devices that could eventually produce solar fuels with higher efficiency and more convenience than is offered by the biomass to biofuels pathway.
- The structure, biochemical composition, and physical principles of natural photosynthetic energy conversion remain a grand scientific challenge.
- In photosynthetic organisms, light is harvested by antenna consisting of pigment-protein complexes that are tuned to the optimize light absorption.
- The captured light energy is transferred to reaction center proteins, where it is converted by electron transfer into electrochemical energy.
- The resulting oxidizing and reducing equivalents are transported to catalytic sites, where they oxidize water and produce reduced fuels.
- The photosynthetic machinery, developed over 3 billion years of evolution, drives one of the most energetically demanding reactions in biology, the oxidation of water.

A New Generation of Imaging Technologies is Transforming the Field

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- At the heart of the photosynthetic complex in natural systems lies an active site with a cluster of four Manganese and one Calcium atom.
- The exact structure of this site had remained a mystery until recently elucidated from analysis of advanced x-ray absorption spectra taken at the Stanford Synchrotron Radiation Laboratory.
- Armed with the active site structure, synthetic chemists have now created an artificial version of it that captures three key features:
  - I. Appropriate assembly of neighboring oxygen atoms to promote coupling between them.
  - II. Activation of a water molecule via proton coupled electron transfer.
  - III. Appropriate positioning of a hydroxide to the activated water to promote formation of the oxygen molecular bond.

Plants as an Energy Resource

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- In recent years, our vision of plants as a potential energy source has undergone a major transformation
- Multiple scientific opportunities remain for discoveries that can transform our energy economy
  - Nearer-term: conversion of lignocellulose to liquid fuels
  - Longer-term: unlocking the secrets of producing fuels directly from sunlight
- State universities and land-grant institutions have a major role to play in this new quest for greater energy security and a more environmentally sound energy economy

Opportunities from the DOE Office of Science

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- New $100 million DOE Office of Science initiative to establish multiple **Energy Frontier Research Centers** (EFRCs) around the nation in FY 2009
- Centers to be funded at $2-5 million each per year for 5 years
- Mission: multidisciplinary, fundamental research toward transforming the U.S. energy economy for the 21st century
- Open competition: Universities, National Laboratories, nonprofit organizations, and private firms invited to apply, singly or in partnerships
- Awards to be selected by scientific peer review
- Funding Opportunity Announcement to be issued this year

Possible EFRC Research Areas

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- Conversion of Plants to Biofuels
- Solar Energy Utilization
- Solid State Lighting
- Electrical Energy Storage
- Superconductivity
- Advanced Nuclear Energy Systems
- Combustion of 21st Century Transportation Fuels
- Hydrogen Production, Storage, and Use
- Catalysis for Energy
- Materials Under Extreme Environments
- Geosciences for Nuclear Waste and CO2 Storage