

# Biological Conversion of Cellulosic Biomass

Charles E. Wyman

Ford Motor Company Chair in Environmental Engineering  
Center for Environmental Research and Technology and  
Chemical and Environmental Engineering Department  
Bourns College of Engineering  
University of California  
Riverside, California 92507

Growing the Bioeconomy:  
From Foundational Science to Sustainable Practice  
Iowa State University  
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# Sustainable Technologies Must Be Commercialized

- Inexpensive energy is essential to our lifestyle but taken for granted
- Petroleum production is strained by increasing demand, declining access to reserves
- Greenhouse gas emissions increase while the ice caps melt
- There are limited large scale options to provide energy while reducing GHG emissions
- If we are waiting for a technical solution, we need to get far more serious in looking for it
- Also need to aggressively commercialize technology or saddle future generations with even larger populations, fewer energy choices, and environmental problems
  - It is unconscionable to declare the problem too hard to solve and push it off on the future

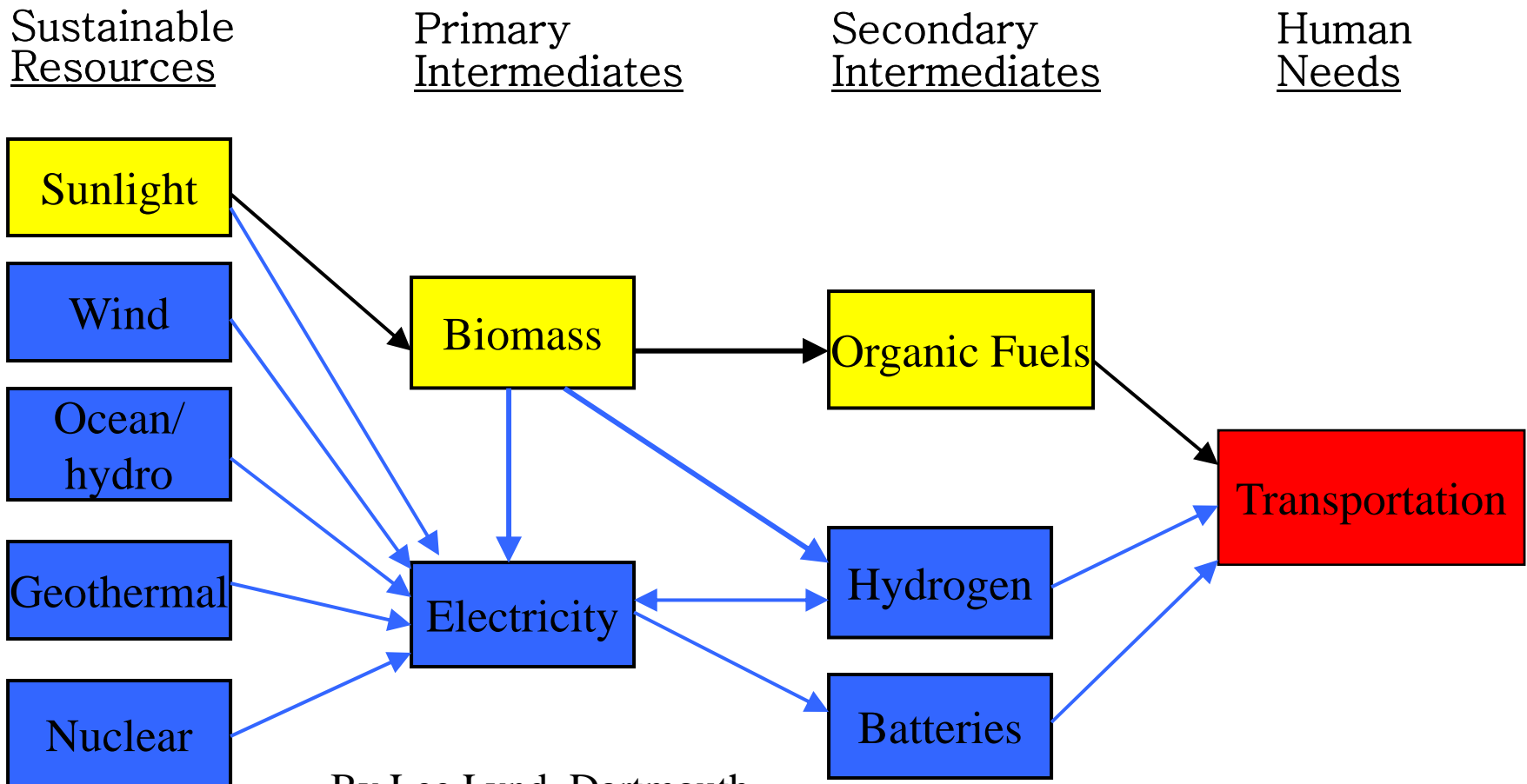
# Petroleum and Transportation

- U.S. domestic energy production and demand are nearly balanced for all but one petroleum: we import about 2/3
- Petroleum is single largest energy source in U.S. supplying ~38.5% of total energy
- About 2/3 of petroleum goes to transportation
- Transportation is almost totally dependent on petroleum (~96.4% in 2000)
- The largest source of greenhouse gases comes from transportation, ~32.8%
- Need to find sustainable alternatives to petroleum for transportation to avoid future transitions and reduce greenhouse gases

# Options to Reduce Petroleum Use

- More public transportation/Drive less miles
  - An important opportunity
  - Counter to historic trends
- Drive more efficient vehicles
  - Low hanging fruit not taken advantage of
  - Synergistic with new fuels
- Change the source of fuels
  - Must be sustainable to avoid GHG emissions
  - Sustainable fuels also avoid future transitions

# Sustainable Alternatives for Transportation



By Lee Lynd, Dartmouth

# Focus: Cellulosic Biomass - Abundant, Inexpensive

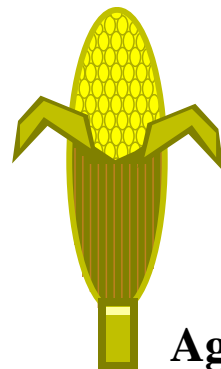
- Existing resources
  - Agricultural wastes
    - Sugar cane bagasse
    - Corn stover and fiber
  - Forestry wastes
    - Sawdust
  - Municipal wastes
    - Waste paper
    - Yard waste
  - Industrial waste
    - Pulp/paper sludge
- Future resources
  - Dedicated crops
    - Herbaceous
    - Woody
  - Not sugar or starch crops such as used for making ethanol in Brazil and the U.S. respectively

# Challenge: How Do You Put Low Cost Biomass in Your Car?



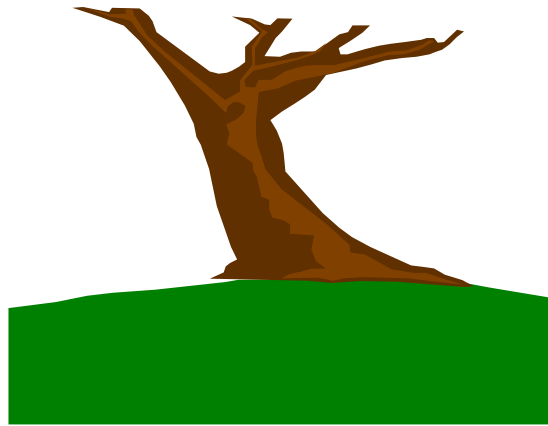
© Stoney Lonesome Photos

# Cellulosic Biomass Composition



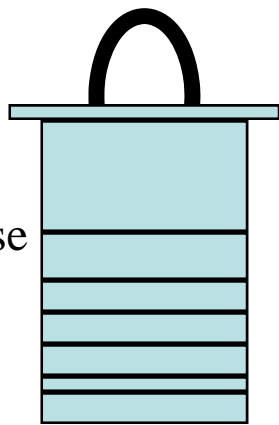
Cellulose 43%  
 Hemicellulose 27%  
 Lignin 17%  
 Other 13%

**Agricultural Residues**



Cellulose 45%  
 Hemicellulose 25%  
 Lignin 22%  
 Extractives 5%  
 Ash 3%

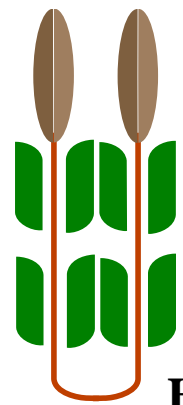
**Woody Crops**



Cellulose  
 45%

Ash 15%  
 Lignin 10%  
 Hemicellulose 9%  
 Other carbohydrates 9%  
 Protein 3%  
 Other 9%

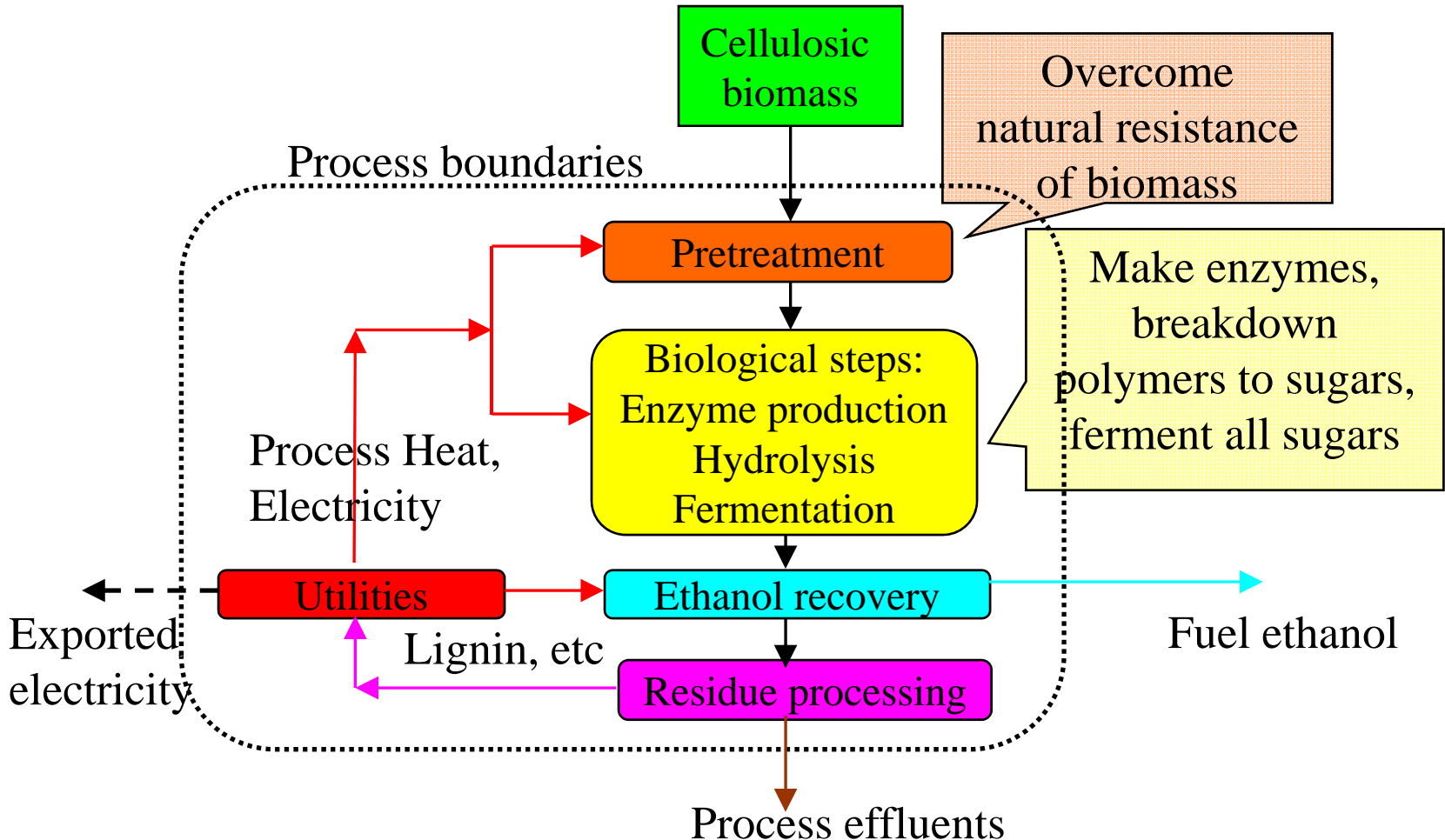
**Municipal Solid Waste**



Cellulose 45%  
 Hemicellulose 30%  
 Lignin 15%  
 Other 10%

**Herbaceous Energy Crops**

# Enzymatic Conversion of Cellulosic Biomass to Ethanol



# Biological Processing of Biomass

- Biological processing of cellulosic biomass offers the potential of high yields vital to economic success – stoichiometry and energetics
- High selectivity also reduces problematic byproducts
- Biological processing can take advantage of the power of biotechnology to dramatically reduce costs
- **Ethanol is a natural product for biological conversion processes**

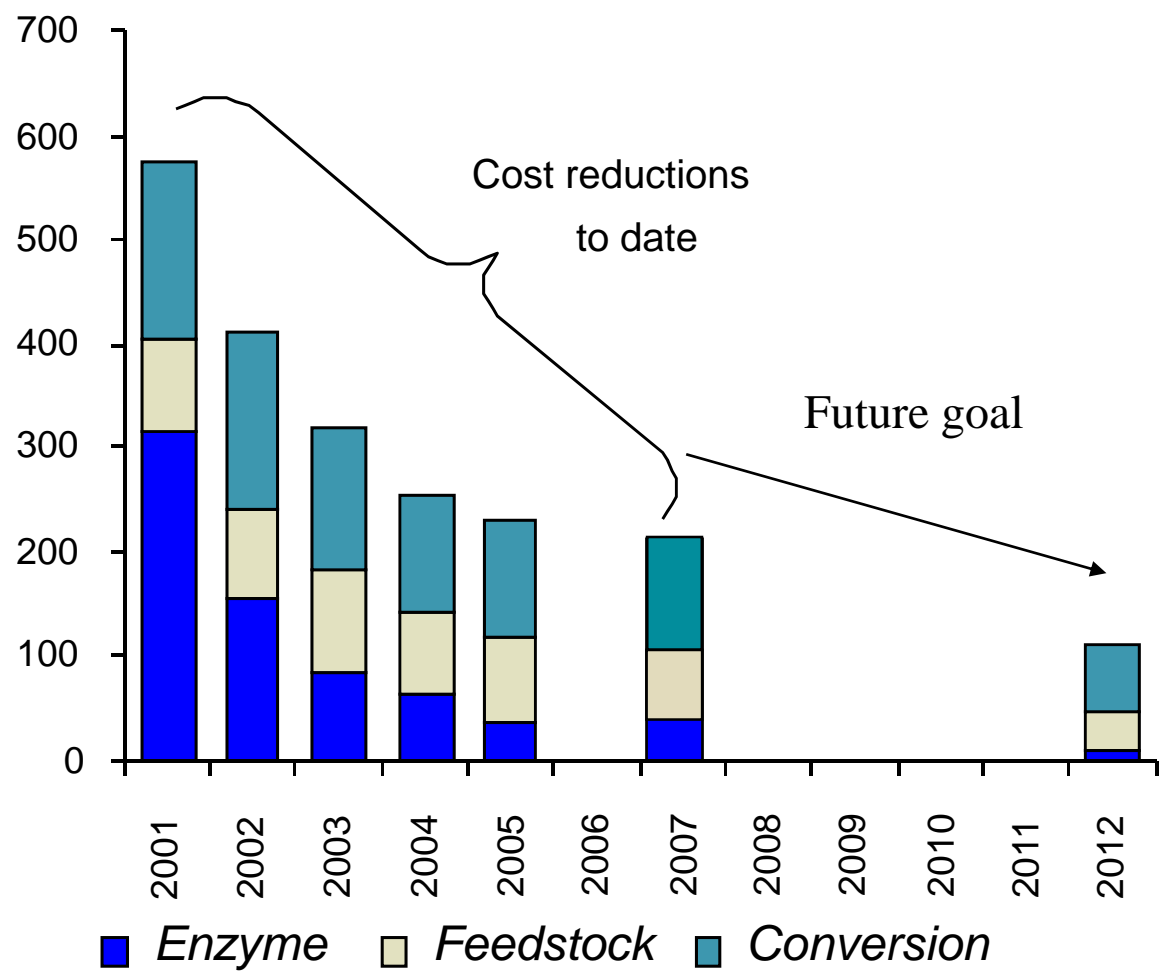
# Ethanol

- Ethanol, ethyl alcohol, fermentation ethanol, or just “alcohol”
- Ethanol is one of the broader alcohol family of chemical form ROH in with R for ethanol has two carbon atoms:



- Beverage alcohol (mixed ethanol/water) referred to in Sumerian language in Mesopotamia in about 2500BC
- Used in beverages, solvents, medicines, lotions, tonics, cologne, rubbing compounds, organic synthesis
- Clear, colorless, volatile, flammable liquid that is completely miscible with water
- **Excellent fuel properties for SI engines**
  - **High octane – 98 (RON + MON)/2**
  - **High heat of vaporization**

# Historical and Projected Cellulosic Ethanol Costs



NREL Modeled Cost

# Key to Advances To Date in Cellulosic Ethanol Technology

- Overcoming the recalcitrance of cellulose
  - Improved pretreatment to increase yields from hemicellulose and cellulose
  - Improved cellulase enzymes to increase rates from cellulose, reduce enzyme use
  - Integrated systems to improve rates, yields, concentrations of ethanol (SSF)
- Overcoming the diversity of sugars
  - Recombinant organisms ferment all five sugars to ethanol at high yields

# CAFI Feedstock: Poplar

Feedstock: USDA-supplied hybrid poplar (Alexandria, MN)

- Debarked, chipped, and milled to 1/4 inch round screen



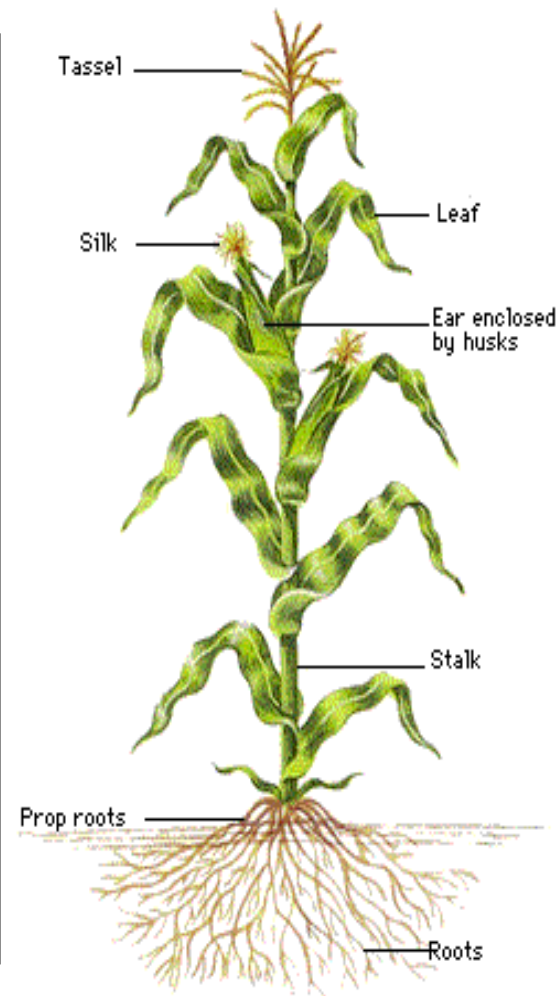
1/4 inch Milled Poplar

Component	Composition	Ethanol yield
	wt %	gal/ton
Glucan	43.8	75.4
Xylan	14.9	26.1
Arabinan	0.6	1.1
Mannan	3.9	6.8
Galactan	1.0	1.8
Lignin	29.1	
Protein	nd	
Acetyl	3.6	
Ash	1.1	
Uronic Acids	nd	
Extractives	3.6	
<b>Total maximum ethanol potential</b>		<b>111.1</b>

# CAFI Feedstock: Corn Stover

From BioMass AgriProducts, Harlan IA and Kramer Farm, Wray, CO

Component	Composition wt %	Ethanol yield gal/ton
Glucan	36.1	62.1
Xylan	21.4	37.7
Arabinan	3.5	6.2
Mannan	1.8	3.1
Galactan	2.5	4.3
Lignin	29.1	
Protein	nd	
Acetyl	3.6	
Ash	1.1	
Uronic Acids	nd	
Extractives	3.6	
<b>Total maximum ethanol potential</b>		<b>113.3</b>



# Experimental Performance for Corn Stover\*

- Stage 1 – Dilute acid pretreatment
  - Acid concentration – 0.5%
  - Temperature – 160°C
  - Reaction time – 20 minutes
  - Hemicellulose sugar yield – 85.1%
  - Glucose yield – 6.3%
  
- Stage 2 – Enzymatic hydrolysis
  - Enzyme loading – 15 FPU/g cellulose
  - Reaction time – 6 days
  - Hemicellulose sugar yield – 8.5%
  - Glucose yield – 85.4%

\*Lloyd TA, Wyman CE. 2005. “Total Sugar Yields for Pretreatment by Hemicellulose Hydrolysis Coupled with Enzymatic Hydrolysis of the Remaining Solids,” *Bioresource Technology* 96(18): 1967-1977, invited.

# Cash Cost for Corn Stover Ethanol

Feed rate = 2,000 tons/day  
 Ethanol production = 62.7 million gals/yr  
 Ethanol yield = 89.6gals/ton

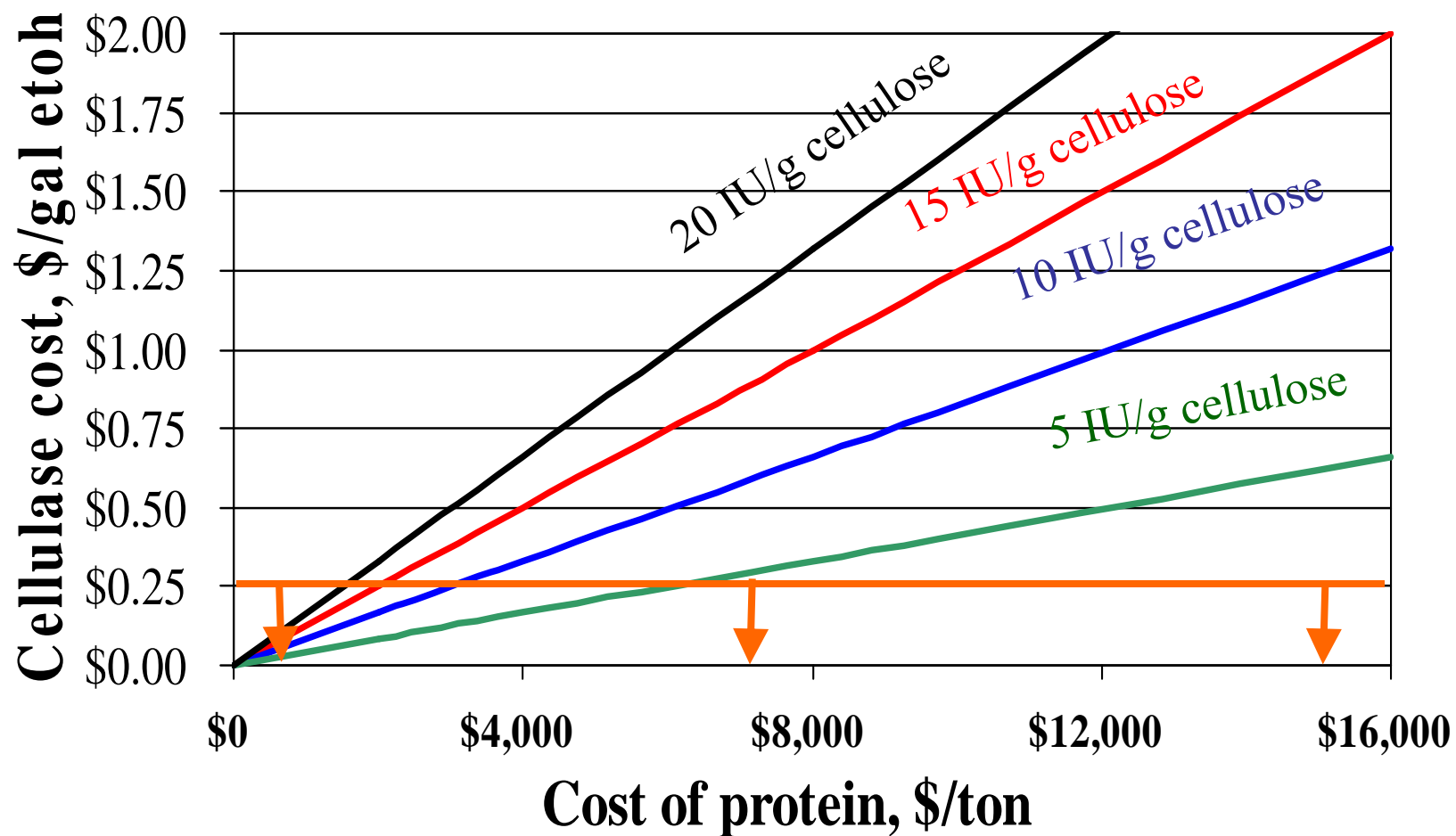
Item	Cost, \$/gallon ethanol
Feedstock (\$50/ton)	0.558
Sulfuric acid (\$200/ton)	0.017
Lime (\$70/ton)	0.009
Nutrients (\$70/ton)	0.071
Labor	0.019
<b>Total without enzymes</b>	<b>\$0.674</b>
Sale of excess power	Not included
Amortization of capital (>\$4/annual gallon)	>0.800

## Key Question: How Much Does Cellulase Cost?

- Typically require about 15 IU/g cellulose to hydrolyze
- At a specific activity of 0.5 IU/mg protein, this translates into about 0.25 lbs of protein or more per gallon of ethanol
  - Includes ethanol produced from hemicellulose fraction, most of which can actually be released during many pretreatments
- What does a pound of protein cost?

# Cost of Cellulase vs Cost of Protein

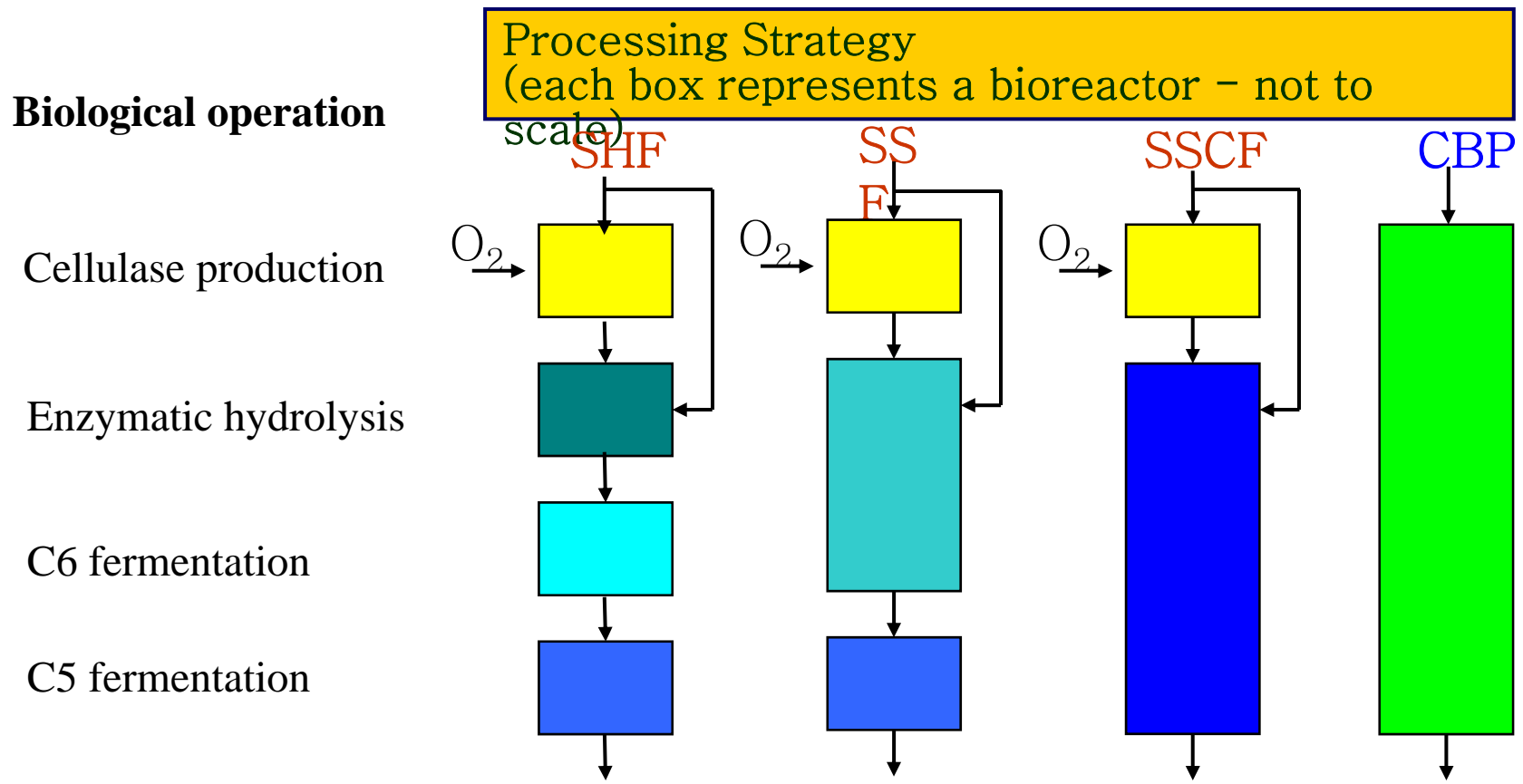
Specific Activity = 0.5 IU/mg protein



# Opportunities for Low Cost Enzymatic Hydrolysis

- High specific activity enzymes
  - Thermotolerant or other more active enzymes
  - Better enzyme synergy
- Improved utilization of enzymes
  - Reduced non productive binding to lignin and others
  - Lower enzyme deactivation
  - Less end product inhibition
- Low cost enzyme production
  - Higher yields
  - Faster production
  - Low cost substrates
  - Much lower power inputs - anaerobic production?
- Easier to hydrolyze substrate
  - Better pretreatment
  - More digestible plants – transgenic crops?

# Evolution of Biomass Processing Based on Enzymatic Hydrolysis



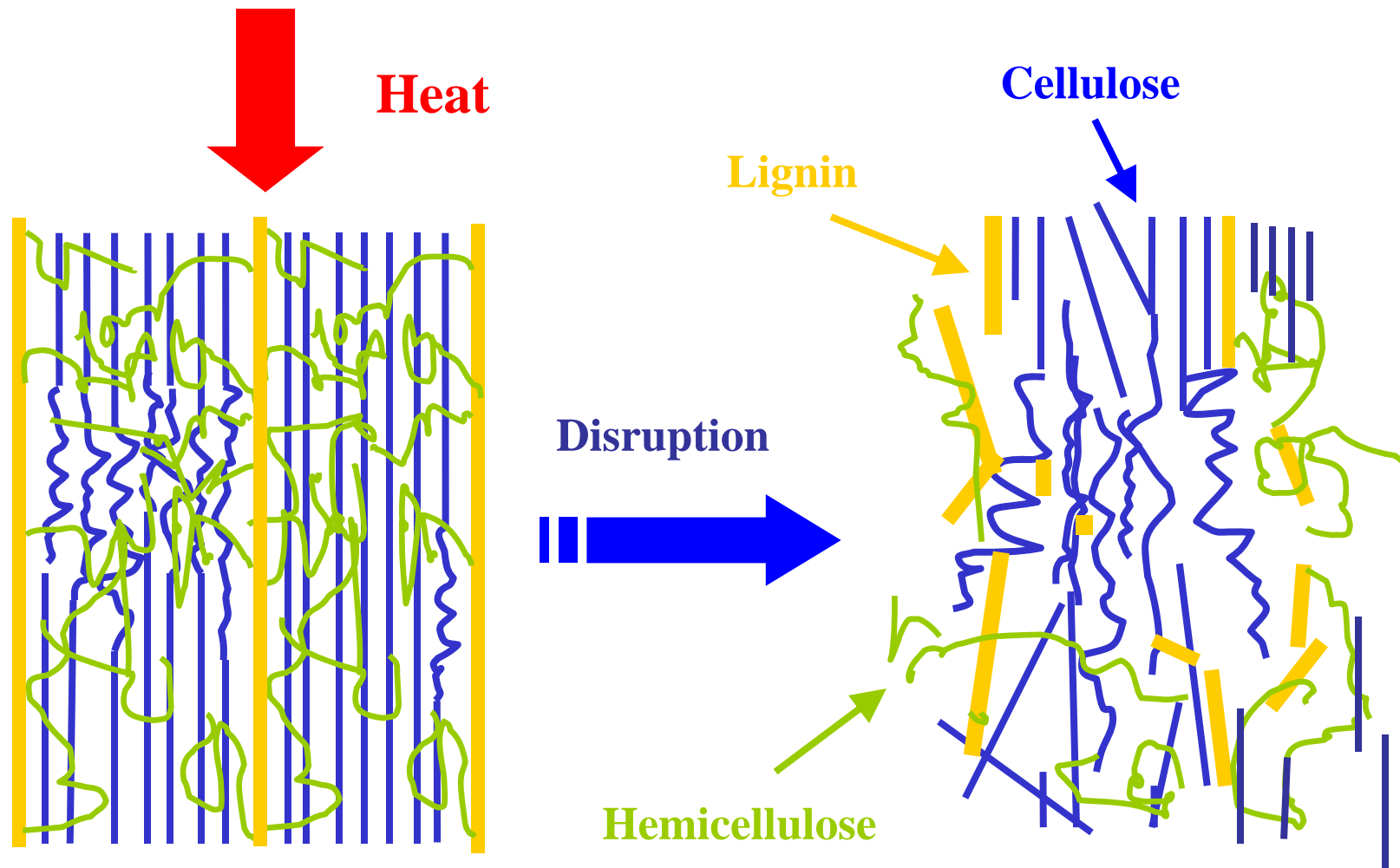
SHF: Separate hydrolysis & fermentation      SSCF: Simultaneous saccharification & co-fermentation

SSF: Simultaneous saccharification & fermentation      CBP: Consolidated

# Cellulosics Pretreatment

- Need to open up structure to make cellulose accessible to enzymes - high digestibility
- High sugar yields from hemicellulose are also vital
- Low capital cost – pressure, materials of construction
- Low energy cost
- Low degradation
- Low cost and/or recoverable chemicals
- A large number of pretreatment technologies have been studied to improve cellulose digestion

# Disruption of Cellulosic Biomass by Pretreatment



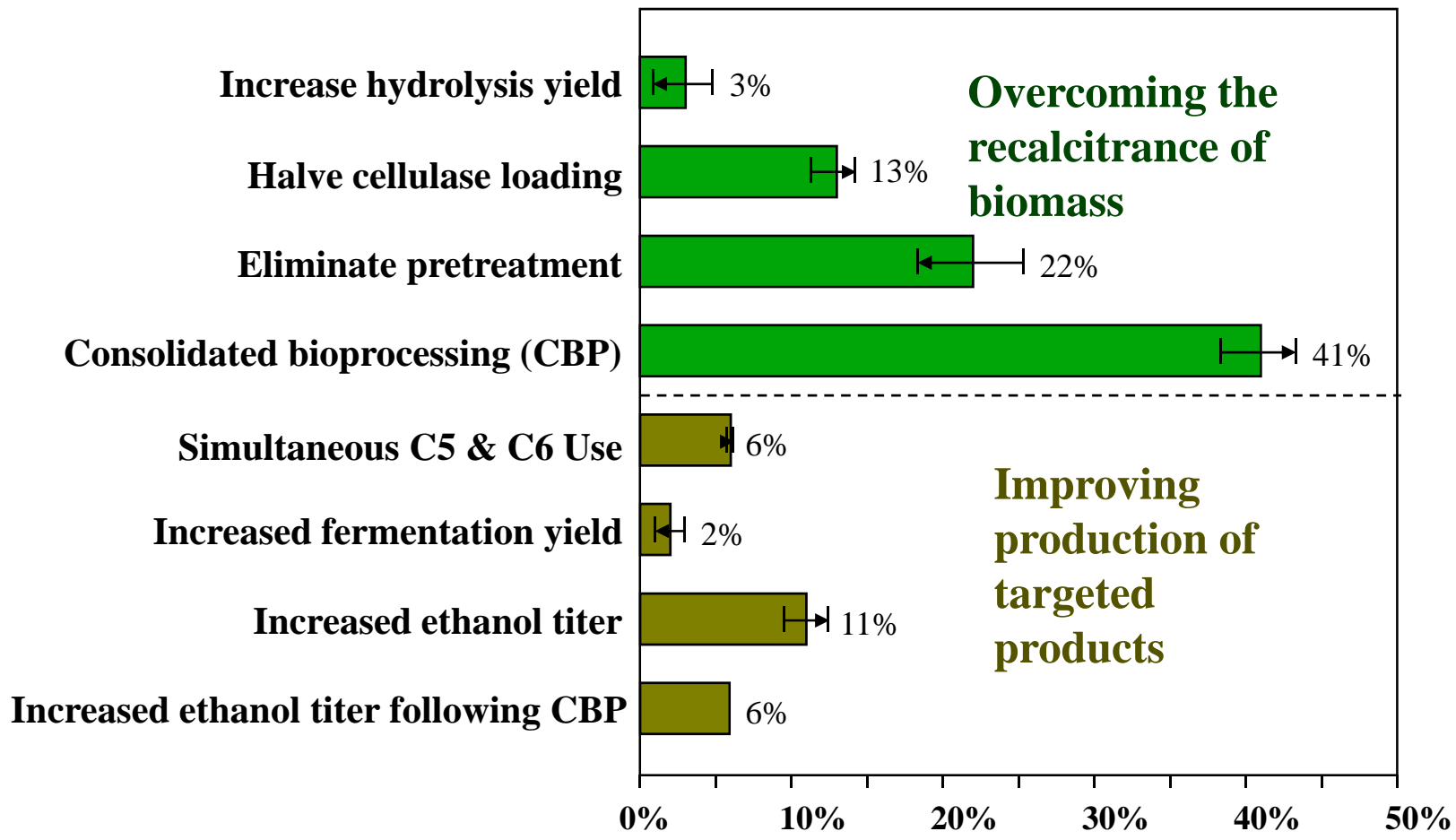
# Importance of Pretreatment

- Although significant, feedstock costs are low relative to petroleum
- In addition, feedstock costs are a very low fraction of final costs compared to other commodity products
- Pretreatment is the most costly process step: **the only process step more expensive than pretreatment is no pretreatment**
  - Low yields without pretreatment drive up all other costs more than amount saved
  - Conversely enhancing yields via improved pretreatment would reduce all other unit costs
- Need to reduce pretreatment costs to be competitive

# Leading Pretreatment Options

- Ammonia Fiber Expansion - AFEX
- Dilute sulfuric acid
- Lime
- Neutral pH
- Sulfur dioxide steam explosion
- Uncatalyzed steam explosion

# Economic Impact of R&D-Driven Improvements



*Error bars denote two different base cases*

**Processing Cost Reduction**

**From Nature Biotech. 2008**

# Commercial Status of Cellulosic Ethanol

- Operating costs are low
- Technology is ready to be commercialized
- Lower costs are foreseeable
- The economic, environmental, and strategic benefits of cellulosic ethanol could be huge
- The vital goal: Commercialize cellulosic ethanol to realize its benefits
- **HOWEVER, NO biological processes for cellulosic biomass conversion are commercial**

# Several Companies Seek to Commercialize Cellulosic Ethanol Technologies

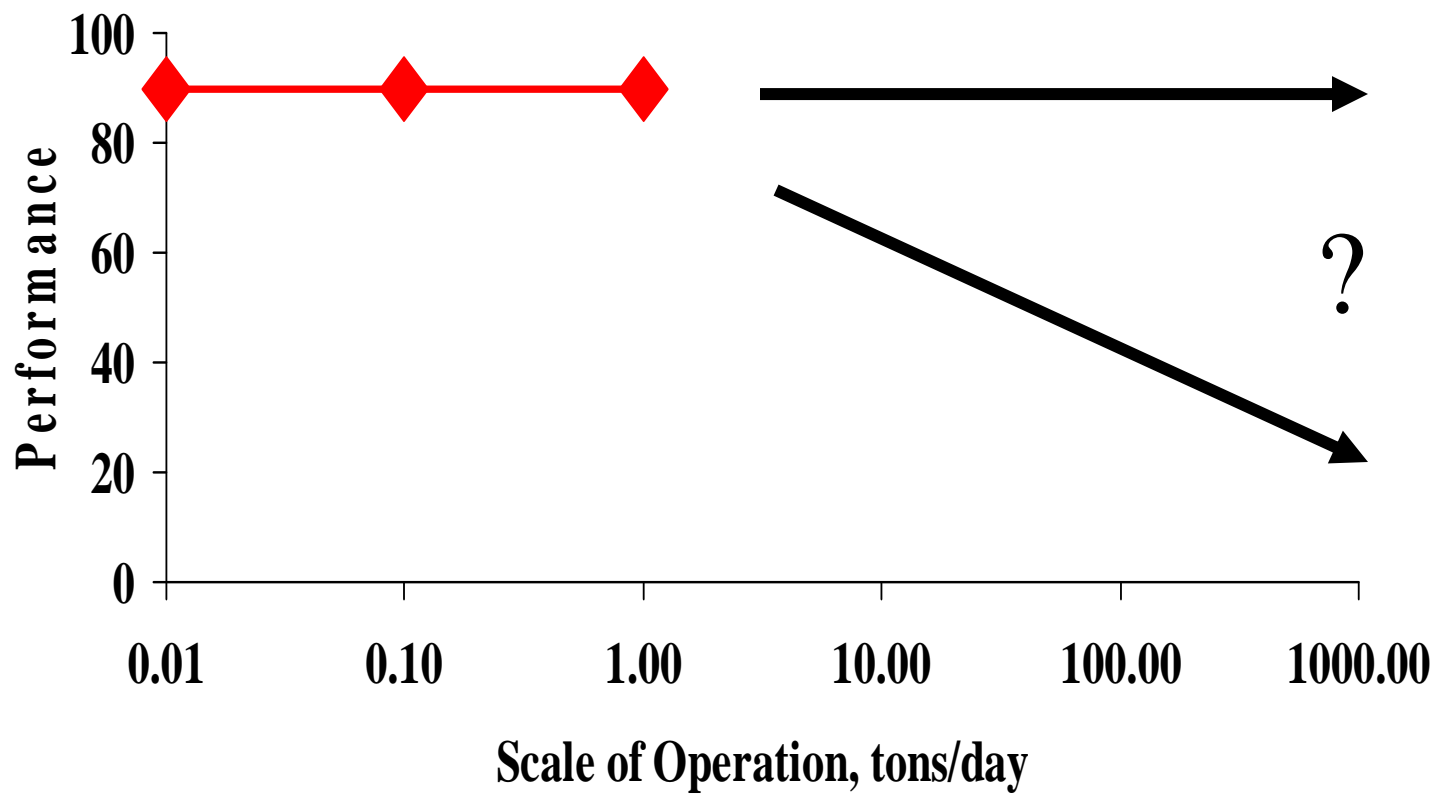
- BlueFire - concentrated acid
- Broin/Poet – enzymes
- Dupont Danesco - enzymes
- Iogen - enzymes
- Mascoma – advanced enzymes and CBP
- Verenium – enzymes

# What is Slowing Us Down?

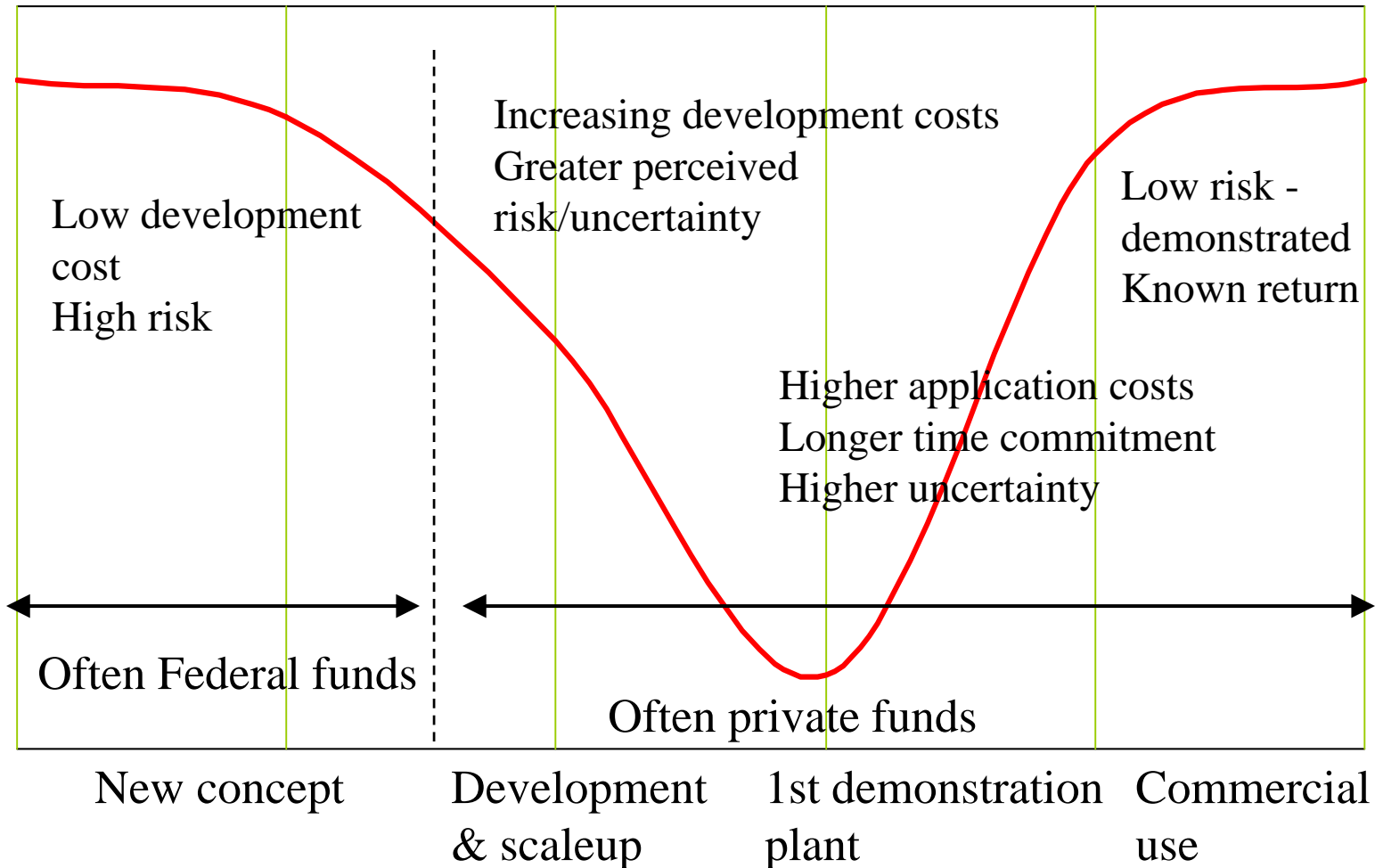
- Capital costs are high
- The technology is not proven at large scale
- Ethanol is a commodity product with low returns
- The cost of capital is high – particularly for new technologies
- The challenge: CAPITAL RISK vs REWARDS

# First-of-a-Kind Technology Scale-Up/Extrapolation

## Performance vs Scale of Operation



# The Valley of Death for New Technology



# What Can Be Done?

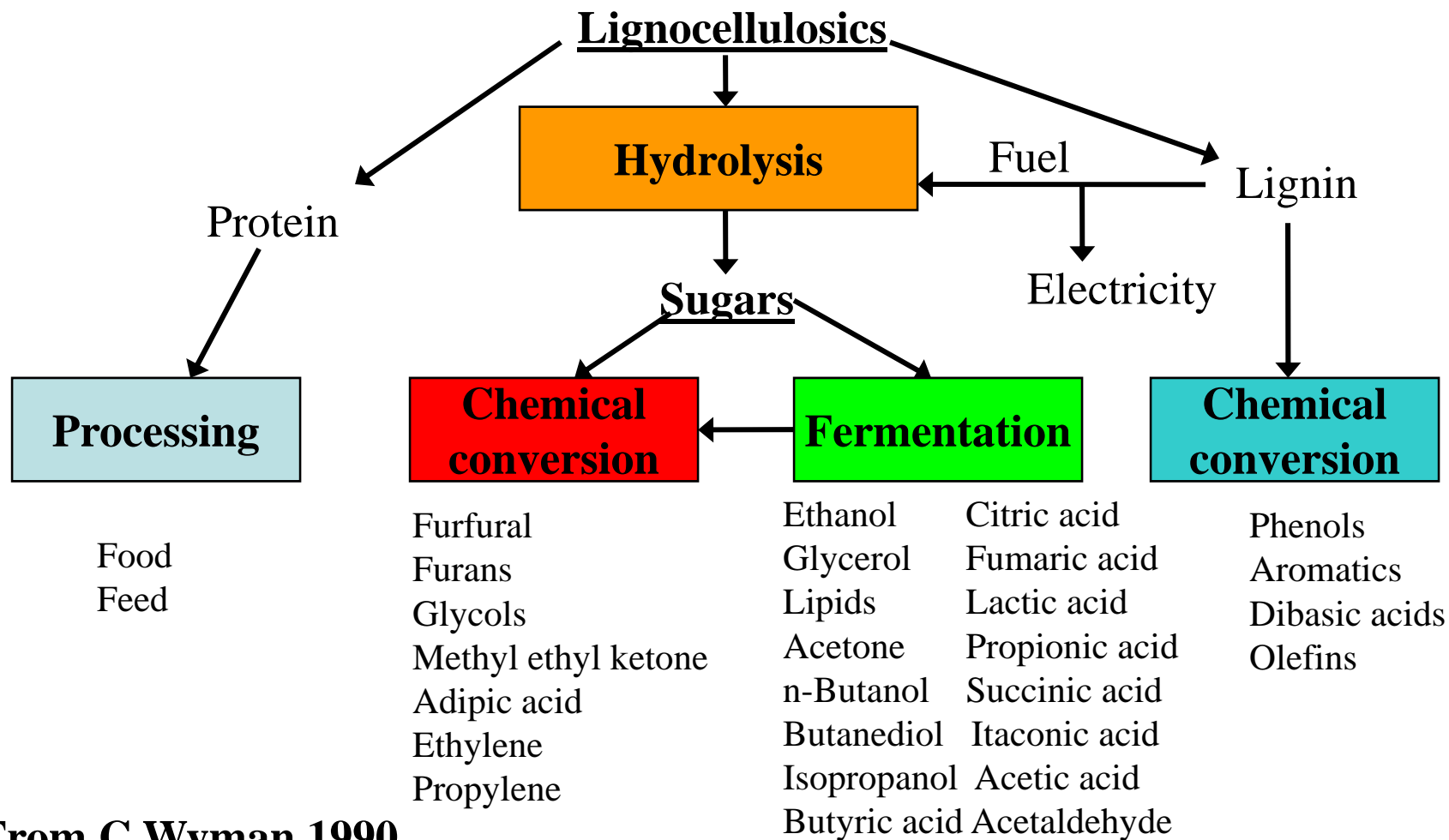
- Provide incentives
  - Investors tend not to trust government subsidies
  - Afraid that they will be withdrawn
  - Don't want to have large capital investments that are vulnerable to changes in policy
- Government investment in sound – not political - projects
  - Need societal benefits
  - Must protect taxpayer
  - Should not interfere with due diligence
  - Provide a portion to compensate for first-of-a-kind risk
- Aggressively fund research to lower costs to be more economically attractive for risk involved
- Wait for a crisis and then try to respond

# Biological and Thermochemical Conversion

- Biological routes
  - High selectivity
  - High yields possible
  - Opportunities for advanced technologies
  - Substantial experience with starch and sugar
  - Low temperatures, pressures
  - Ethanol can replace gasoline
- But
  - Slow
  - Specific to certain substrates
  - Not commercial for cellulose
- Thermochemical routes
  - Rapid
  - Broad range of substrates
  - Robust
  - Substantial related commercial experience
  - Can make “diesel fuel”
- But
  - Generally large scale
  - High temperatures, pressures
  - Product clean up can be costly
  - Less control of by products

Keys: cost, efficiency, environmental benefits, markets

# Refinery for Cellulosic Biomass to Fuels, Chemicals, Power, Food, and Feed



From C Wyman 1990

# Closing Thoughts

- Cellulosic fuels offers significant environmental, economic, and strategic benefits
- Tremendous progress has been made in improving the biological processing of cellulose so it is ready to be commercialized
- Challenge is to overcome perceived risk of initial commercial applications to realize benefits and capitalize on learning curve to reduce costs
- Also need to focus on developing leap forward advances to lower cost biological processing
- Thermochemical and biological routes are complementary and synergistic
- Must fund research and applications much more aggressively to make it happen

# Acknowledgments

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- The University of California at Riverside
- Numerous past and present students, coworkers, and partners who make our research possible

We do not inherit the  
Earth from our Ancestors.  
We borrow it from our  
children!

Native American Proverb