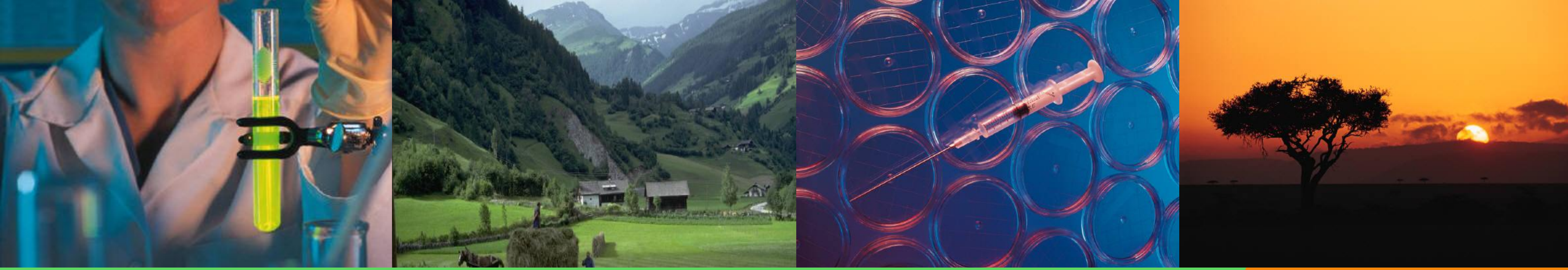
聲明

本檔案之內容僅供下載人自學或推廣化學教育之非營利目的使用。並請於使用時註明出處。[如本頁取材自○○○教授演講內容]。



Green Chemistry (I)

Ito Chao
Academia Sinica

Outline

- Definition and Spirit
- Principles
- Tools (metrics and solvent selection guides)
- Academic and Industrial Endeavors
- Successes and Benefits
- Examples of Exciting New Scientific Developments
- Challenges
- Resources

Benefits of the Chemical Industry













Green Chemistry at York

Waste Disposal

Disease

Pollution

Danger!

Depletion of natural resources

CHEMISTRY- A Dirty Word!

Toxic Emissions

Cancer

Land Fill

Accidents

Question 1

How many pounds of stuff does it take to make a 5 laptop computer? (Hint: think about mining, transport, manufacturing, packaging, etc.)

a) 50
b) 500
c) 20,000
d) 12,500

Ref: "Confessions of a Radical Industrialist," page 9 (adjusted for 5 lb)

Slide Courtesy Dr. Bob Peoples

ACS Chemistry for Life

ACS Green Chemistry Institute®

Question 2

What is the thermodynamic efficiency of the economy of the United States?

a) 10%

b) 5.5%

c) 2.5%

d) 22%

The National Academy of Engineering estimates the thermodynamic efficiency of the American economy is ~2.5%.

Ref: "Confessions of a Radical Industrialist," page 73

Slide Courtesy Dr. Bob Peoples

Question 3

How many trees does it take to produce the Sunday edition of the NY Times?

a) 10,000
b) 5,000
c) 45,000
d) 70,000 ←


The New York Times

Slide Courtesy Dr. Bob peoples

Question 6

For every kg of product produced, on average about how much waste is produced?

a) <1 kg
b) 5-10 kg
c) 25 kg
d) 25-100 kg
e) >100 kg

Waste and the Chemical Industry

- Where dose it come from?

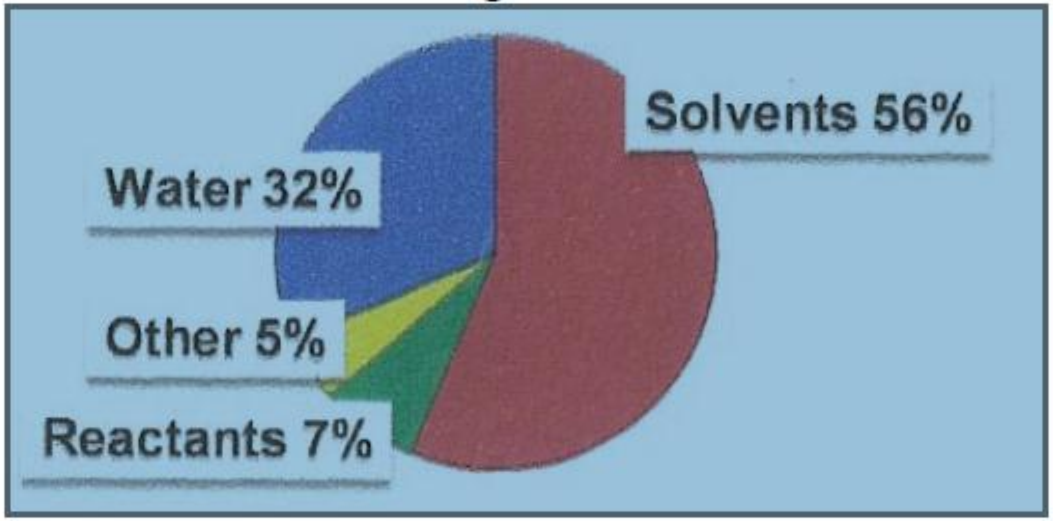
Industry Segment	TONNAGE	RATIO Kg Byproducts / Kg Product
Oil Refining	$10^6 - 10^8$	<0.1
Bulk Chemicals	$10^4 - 10^6$	1 - 5
Fine Chemicals	$10^2 - 10^4$	5 - 50
Pharmaceuticals	$10 - 10^3$	25 - 100+

- Areas traditionally thought of as being dirty (oil refining & bulk chemical production) are relatively clean - they need to be since margins per Kg are low.
- Newer industries with higher profit margins and employing more complex chemistry produce much more waste relatively.

Chem & Ind. ***1992**, Dec. 1*, 904.

Environmental impact of manufacturing processes of active pharmaceutical Ingredients

A 2007 study showed the median amount of **materials used to make 1 kg of API was 46 kg**, in which 56% of the mass used was solvent. That is, 22 kg of solvents are needed to make 1 kg of API. **E = 45**

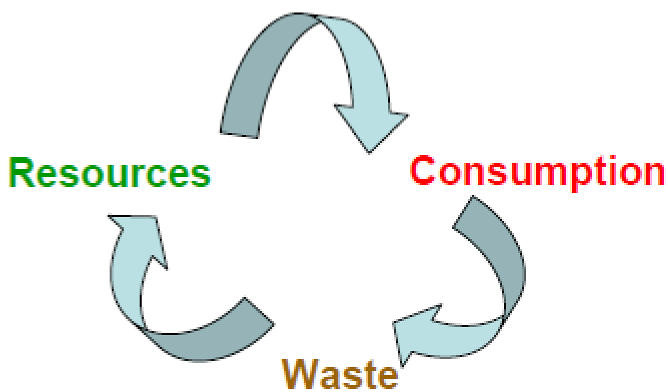


Org. Process Res. Dev. **2007**, *9*, 1173.

Nature vs Human

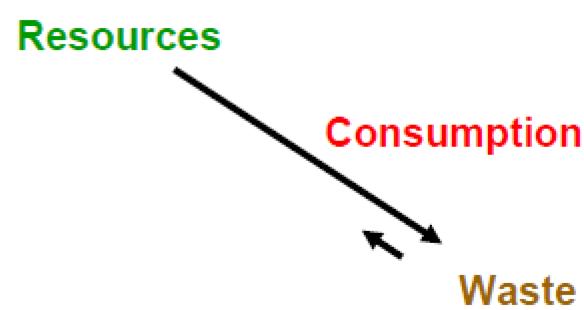
Nature

a cycle



Industrial Society

the natural cycle disrupted



Human are depleting resources and making wastes much faster than nature can take the wastes and convert them back into resources

Definition of Green Chemistry

*The **design** of products and processes that **reduce** or **eliminate** the use and generation of **hazardous** substances*

Fathers of Green Chemistry : Paul Anastas and John C. Warner

C&E News October 4, 2010

[Warner's talk at the Berkeley Green Chemistry Center](http://www.youtube.com/watch?NR=1&v=mrSy6RKOge8)
http://www.youtube.com/watch?NR=1&v=mrSy6RKOge8

Spirit of Green Chemistry

*The **design** of products and processes that **reduce** or **eliminate** the use and generation of **hazardous** substances*

- **Prevention!**
- **Reduction!**
- **Smart Chemistry!!**

- Not just looking for new energy materials
- Not equivalent to environmental chemistry

Reduction of What?

Spirit of Green Chemistry

Risk = f(hazard x exposure)

Before

Now

Minimize risk by minimizing hazard

2020 Sustianability Goals

Zero Waste: eliminate the concept of waste in product, process, materials and energy

Zero Toxic Substances: eliminate substances known or suspected to be harmful to human health or the health of biological systems

100% Closed Loop Processes: take 100% responsibility for our products at all stages of our product and process lifecycle

Sustainable Growth and Profitability: create an economy the planet is capable of sustaining indefinitely

(*Zero Waste Alliance*, 2001)

How to realize the goals?

12 Principles of Green Chemistry

1. Prevent waste
2. Maximize atom economy
3. Design less hazardous chemical syntheses
4. Design safer chemicals and products
5. Use safer solvents and reaction conditions
6. Increase energy efficiency
7. Use renewable feedstocks
8. Avoid chemical derivatives
9. Use catalysts, not stoichiometric reagents
10. Design chemicals and products that degrade after use
11. Analyze in real time to prevent pollution
12. Minimize the potential for accidents

Green Chemistry: Theory and Practice, Oxford University Press: New York, 1998.

12 Principles of Green Engineering

1. Inherent Rather Than Circumstantial
2. Prevention Instead of Treatment
3. Design for Separation
4. Maximize Efficiency
5. Output-Pulled Versus Input-Pushed
6. Conserve Complexity
7. Durability Rather Than Immortality
8. Meet Need, Minimize Excess
9. Minimize Material Diversity
10. Integrate Material and Energy Flows
11. Design for Commercial "Afterlife"
12. Renewable Rather Than Depleting

Env. Sci. and Tech. **2003**, *37(5)*, 94A.

Metrics

$$\text{Atom Economy} = \frac{\text{molecular weight of desired product}}{\text{molecular weight of all products}} \times 100\%$$

$$\text{E-factor} = \frac{\text{mass of waste}}{\text{mass of product}}$$

$$\text{Process Mass Intensity} = \frac{\text{mass of all materials in}}{\text{mass of products}}$$

$$\text{Solvent Intensity} = \frac{\text{mass of all solvent } (-\ H_2O)}{\text{mass of products}}$$

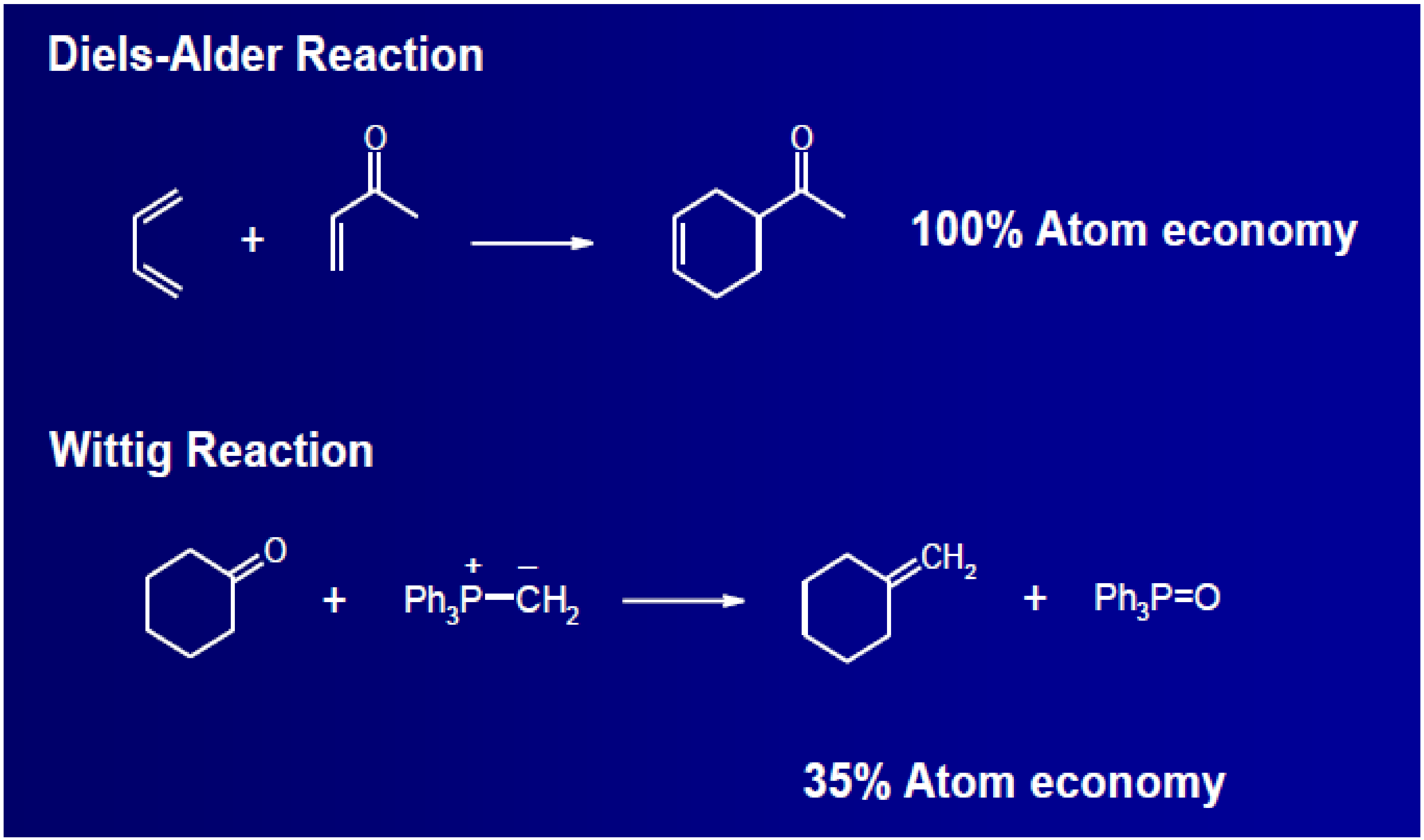
$$\text{Renewables Intensity} = \frac{\text{mass of all renewables used}}{\text{mass of products}}$$

c.f. **yield =** $\frac{\text{quantity of actual product}}{\text{quantity of predicted product}}$

and more…

Chem. Soc. Rev., 2012, **41**, 1485

$$\textbf{Atom Economy} = \frac{\text{molecular weight of desired product}}{\text{molecular weight of all products}} \times 100\%$$



Atom Economy

Atom economic reactions	Atom un-economic reactions
• Rearrangement	• Substitution
• Addition	• Elimination
• Diels-Alder	• Wittig
• Other concerted reactions	• Grignard

Green Chemistry: An Introductory Text, RSC, 2002.

Pfizer solvent selection guide

Preferred	Usable	Undesirable
Water	Cyclohexane	Pentane
Acetone	Heptane	Hexane(s)
Ethanol	Toluene	Di-isopropyl ether
2-Propanol	Methylcyclohexane	Diethyl ether
1-Propanol	Methyl *t*-butyl ether	Dichloromethane
Ethyl acetate	Isooctane	Dichloroethane
Isopropyl acetate	Acetonitrile	Chloroform
Methanol	2-MethylTHF	Dimethyl formamide
Methyl ethyl ketone	Tetrahydrofuran	*N*-Methylpyrrolidinone
1-Butanol	Xylenes	Pyridine
t-Butanol	Dimethyl sulfoxide	Dimethyl acetate
	Acetic acid	Dioxane
	Ethylene glycol	Dimethoxyethane
		Benzene
		Carbon tetrachloride

Green Chem. **2008**, *10*, 31.

Pfizer Solvent Replacement Table

Red Solvents	Alternative
Pentane	Heptane
Hexane(s)	Heptane
Di-isopropyl ether or ether	2-MeTHF or t-Butyl methyl ether
Dioxane or dimethoxyethane	2-MeTHF or t-Butyl methyl ether
Chloroform, dichloroethane or carbon tetrachloride	DCM
DMF NMP or DMAc	Acetonitrile
Pyridine	Et_3N (if pyridine used as base)
DCM (extractions)	EtOAc, MTBE, toluene, 2-MeTHF
DCM (chromatography)	EtOAc / Heptanes
Benzene	Toluene

Green Chem. **2008**, *10*, 31.

GSK solvent selection guide

	Few issues (bp°C)	Some issues (bp°C)	*Major* issues
Chlorinated	....before using chlorinated solvents, have you considered TBME, isopropyl acetate, ethyl acetate, 2-Methyl THF or Dimethyl Carbonate?		Dichloromethane ** Carbon tetrachloride ** Chloroform ** 1,2-Dichloroethane **
Greenest Option	Water (100°C)		
Alcohols	1-Butanol (118°C) 2-Butanol (100°C)	Ethanol/IMS (78°C) t-Butanol (82°C) 1-Propanol (97°C) 2-Propanol (82°C) Methanol (65°C)	2-Methoxyethanol **
Esters	t-Butyl acetate (95°C) Isopropyl acetate (89°C) Propyl acetate (102°C) Dimethyl Carbonate (91°C)	Ethyl acetate (77°C) Methyl acetate (57°C)	
Ketones		Methyl isobutyl ketone (117°C) Acetone (56°C)	Methyl ethyl ketone
Aromatics		p-Xylene (138°C) Toluene ** (111°C)	Benzene **
Hydrocarbons		Isooctane (99°C) Cyclohexane (81°C) Heptane (98°C)	Petroleum spirit ** 2-Methylpentane Hexane
Ethers		t-Butyl methyl ether (55°C) 2-Methyl THF (78°C) Cyclopentyl methyl ether (106°C)	1,4-Dioxane ** 1,2-Dimethoxyethane ** Tetrahydrofuran Diethyl ether Diisopropyl ether **
Dipolar aprotics		Dimethyl sulfoxide (189°C)	Dimethyl formamide ** N-Methyl pyrrolidone ** N-Methyl formamide ** Dimethyl acetamide ** Acetonitrile

Green Chem. **2011**, *13*, 854.

Table 1. Comparison of solvent use in GlaxoSmithKline Pharmaceuticals (GSK) prior to 2000 and in pilot plant processes carried out in 2005

	2005 rank	1990−2000 rank
2-propanol	1	5
ethyl acetate	2	4
methanol	3	6
denatured Ethanol	4	8
n-heptane	5	12
tetrahydrofuran	6	2
toluene	7	1
dichloromethane	8	3
acetic acid	9	11
acetonitrile	10	14
Average solvents used	**75 kg/kg API**	**94 kg/kg API**

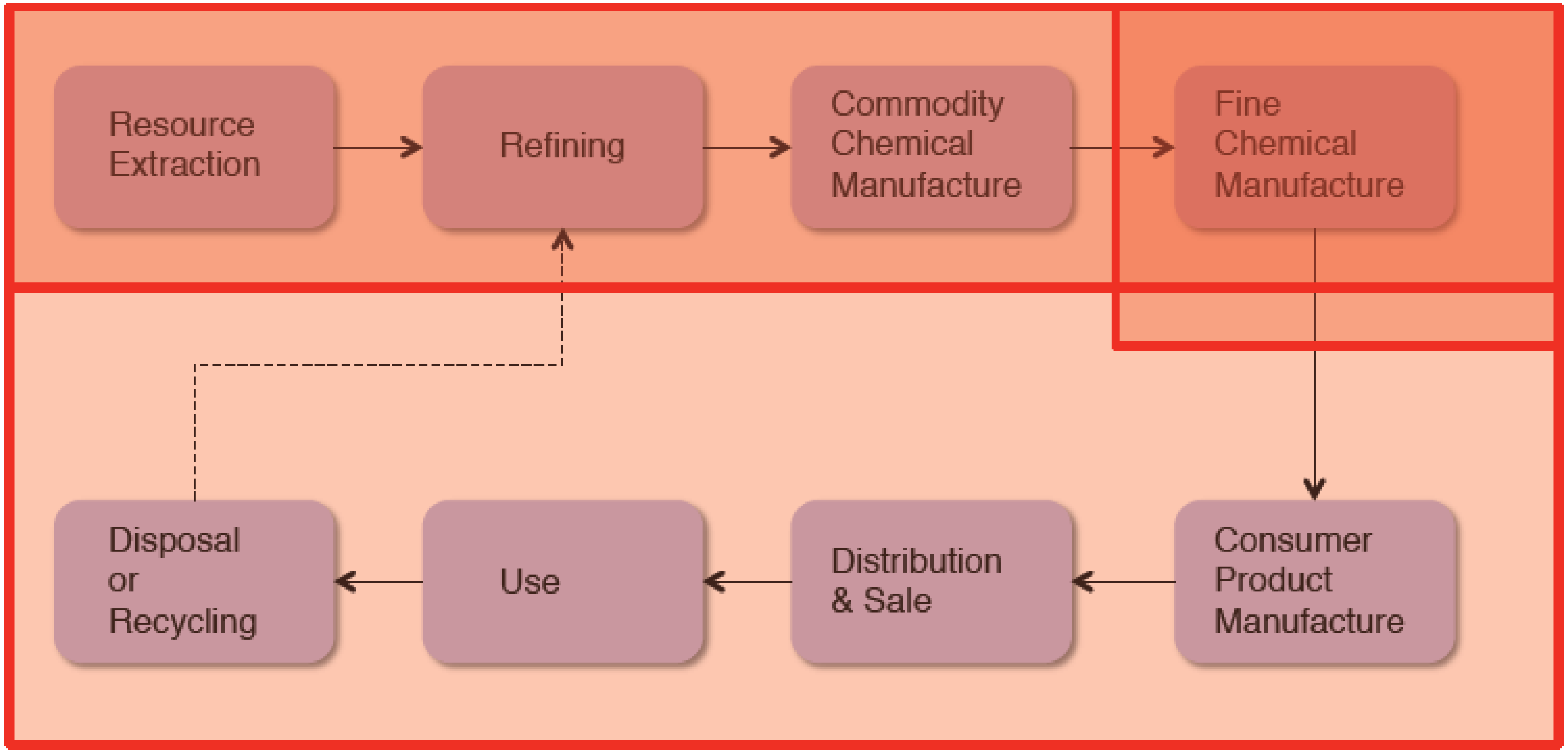
Green Chem. **2011**, *13*, 854.

Rowan Solvent Greenness Index

- Inhalation Toxicity – Threshold Limit Value (TLV)
- Ingestion Toxicity
- Biodegradation
- Aquatic Toxicity
- Carcinogenicity
- Half-Life
- Ozone Depletion
- Global Warming Potential
- Smog Formation
- Acidification
- Soil Adsorption Coefficient
- Bioconcentration Factor

Chem. Soc. Rev. **2012**, *41*, 1452

Life Cycle Assessment



Slide courtesy Dr. Philip Jessop

Academic and
Industrial Endeavors

Green Chemistry at the University of Oregon

Welcome to the University of Oregon's Green Chemistry website. In the links that follow there is information about our green chemistry curriculum, research programs, database of educational materials, workshop on incorporating green chemistry into the undergraduate curriculum and our textbook on Greener Organic Chemistry.

Curricular Innovations in Green Chemistry *Organic and Beyond (March 2006)*

Going Green *Lecture Assignments and Lab Experiences for the College Curriculum*, Presentations from the National ACS Meeting (March 2005)

Greener Education Materials (GEMs) for Chemists An interactive database of education materials focused on green chemistry. Available in June 2005, a comprehensive resource of education materials including laboratory exercises, lecture materials, course syllabi and multimedia content that illustrate chemical concepts important for green chemistry. Each entry includes a description of the item and is searchable by a variety of parameters, including chemistry concepts, laboratory techniques, green chemistry principles, and target audience. Database entries incorporate both published and unpublished materials.

Green Organic Chemistry: Curriculum Development and Dissemination provides a brief description of our work in this area and the history of the program.

Green Chemistry Education Network (GCEdNet) serves as a catalyst for integrating green chemistry in chemical education at all levels. As a network of educators we support opportunities to research, develop, implement and disseminate green educational materials. The GCEdNet reaches out to all chemistry educators through collaboration and mentoring, facilitating professional growth, and fostering the synergistic integration of green chemistry in education.

Map of the Green Chemistry Community Looking for a green chemistry contact in your area? Consult the recently updated Green Chemistry Google map, listing over 500 individuals and organizations worldwide. The map project was initiated at the University of Oregon and its growth and success is the result of an amazing three-year partnership with the green chemistry community. We invite you to add yourself to the map.

Green Organic Chemistry: Tools, Strategies and Laboratory Experiments A textbook/laboratory manual for undergraduate organic chemistry laboratory. Includes ten comprehensive introductory chapters describing the strategies and tools used in practicing greener chemistry and nineteen extensively student-tested laboratory experiments that teach fundamental organic chemistry concepts and lab skills in a more environmentally-friendly (greener) fashion.

Green Chemistry in Education Workshop A week-long, hands-on workshop for university educators that wish to adopt a greener organic laboratory curriculum. Please visit the Center for Workshops in the Chemical Sciences (CWCS) for application information.

Green Product Design Network this virtual center brings together talent from around the UO and the world to catalyze implementation of greener products by addressing each stage of innovation – from chemical content to product design to supply chains to consumer awareness.

http://greenchem.uoregon.ed

http://bcgc.berkeley.edu/

Pfizer Green Chemistry Initiative

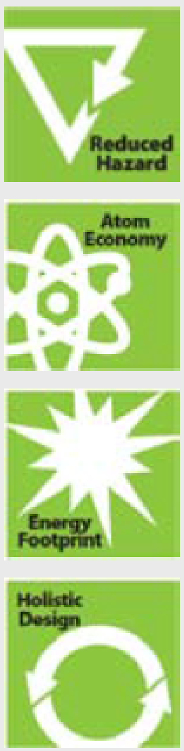
- Site-based green chemistry teams, first in Groton, CT: 2001
  - ✓ Members: Across disciplines & divisions
  - ✓ Results-oriented, senior management support

Importance of Culture!

- Activities:
  - ✓ Annual Green Chemistry Award - establish recognition of principles of green chemistry, prominently acknowledge performance
  - ✓ Brought leading green chemists for seminars
  - ✓ Sponsored onsite workshops
  - ✓ Prepared award nomination packages – won US PGCC Award
  - ✓ Created a solvent selection guide
  - ✓ Published scientific papers highlighting benefits and achievements
  - ✓ Reduced or eliminated the use of some hazardous solvents
  - ✓ Contributed to lab and manufacturing process improvements
  - ✓ Community outreach

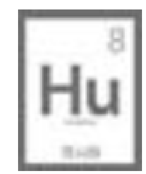
Slide Courtesy Dr. Rich Williams

The Principles Workshop – Key Learning Objectives



Day one

- Sustainability matters to the Chemical Industry
- Introduction to the Principles of Sustainable Chemistry and Engineering
- Introduction to “Tox 101 for R&D”
- Overview of Life Cycle Thinking (“Holistic Design”)
- Industrial case study: Glycerin to Epichlorohydrin, is it more sustainable?
- Overnight – homework!



Day two

- Group breakout and debrief: Glycerin to Epichlorohydrin
- Wrap-Up: End of Life Considerations, The Future

Slide Courtesy Dr. Dawn Shiang

ACS GCI Pharmaceutical Roundtable

Slide Courtesy Dr. Rich Williams

Developing Tools

- Process Mass Intensity (PMI) - done

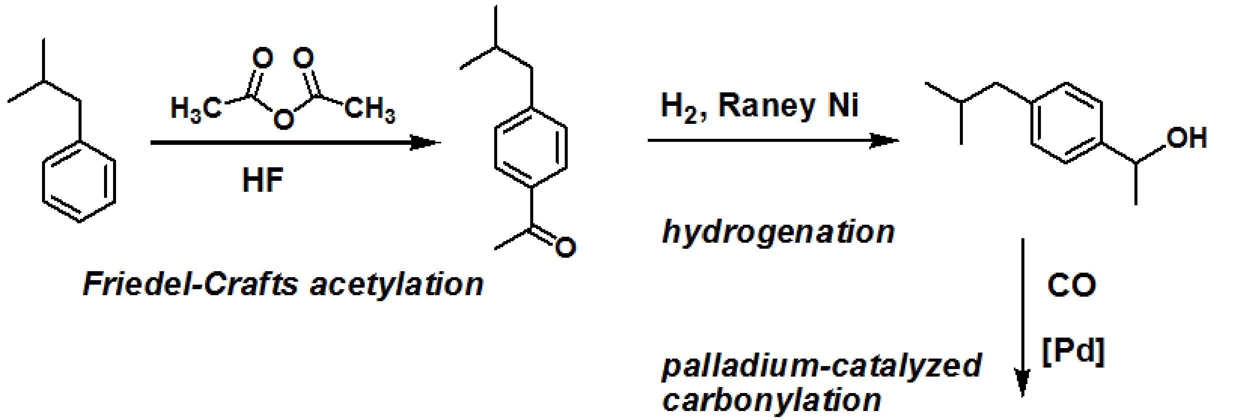
$$\text{Process mass intensity} = \frac{\text{quantity of raw materials input (kg)}}{\text{quantity of bulk API out (kg)}}$$

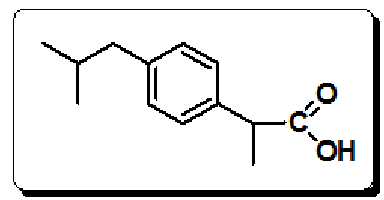
- Solvent Selection Guide - done
- Reagent Selection Guide - ongoing
- Greener Reaction Mechanisms - ongoing

Slide Courtesy Dr. Rich Williams

Success

Green synthesis of ibuprofen





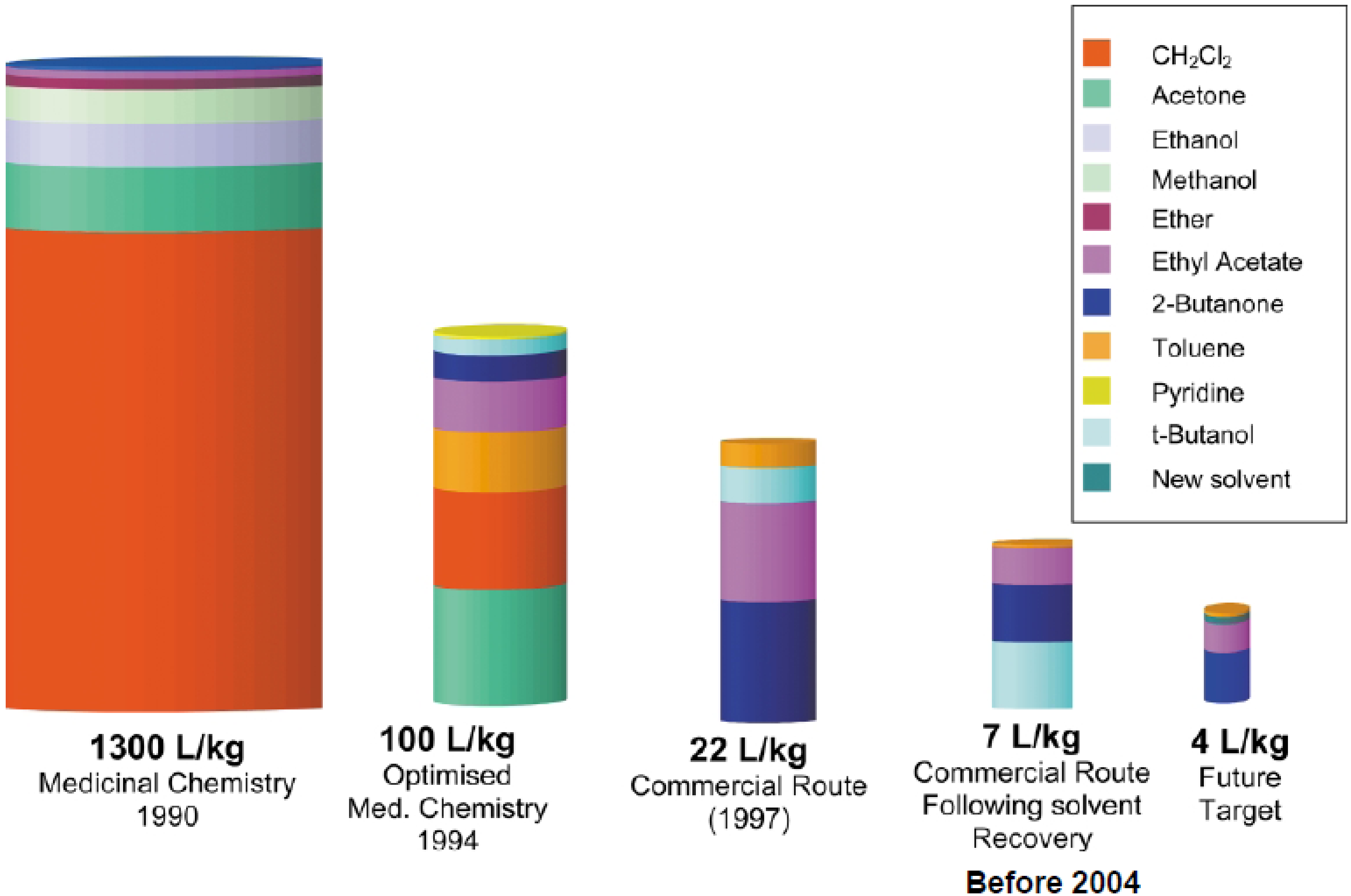
UK market for ibuprofen is about 3,000,000 kg per year!

- Greater overall yield (**3** steps vs. **6** steps)
- Greater atom economy (**80%** atom economy vs. < **40%** atom utilization)
- Fewer auxiliary substances (products and solvents separation agents)
- **Less waste:** greater atom economy, catalytic vs. stoichiometric reagents, recovery of byproducts and reagents, recycling, and reuse, lower disposal costs.

(USA) Presidential Green Chemistry Challenge Awards

Greener Synthetic Pathways Award in 1997

Solvents used in the sildenafil citrate process



2003 CRTSTAL Faraday Award

Green Chem. **2004**, *6*, 43; *Org. Proc. Res. Dev*. **2005**, *9*, 88.

Green Chemistry at Nike

Stricter rules
Consumer
Cost down

- Developed technology to grate waste from outsole molds into REGRIND for premium performance outsoles
- Substitution of water-based solvents in adhesives, primers, degreasers, and mold release agents for petroleum-based solvents. Millions of dollars saved.
- Substituting for Nike 'AIR', which is really sulfur hexafluoride. One gram of SF_6 has the global warming potential of 23,900 g of CO_2 (~24,000 times)

Courtesy Slide Prof. K.-T. Liu

The Magnitude of What Can be Accomplished

Presidential Green Chemistry Challenge Award Winners (all sectors). Results through 2011 (16 years of results)*:

- 199 million pounds of hazardous chemicals and solvents eliminated each year
  - ✓ Enough to fill almost 900 railroad tank cars - - a train nearly 11 miles long
- 21 billion gallons of water saved each year
  - ✓ Amount used by 820,000 people annually
- 57 million pounds of carbon dioxide releases to air eliminated each year
  - ✓ Equal to taking 6,000 automobiles off the road

* Source: US EPA, Green Chemistry Program, Fact Sheet EPA744F11001, June 2011.

Slide Courtesy Dr. Rich Williams

Examples of Exciting New Scientific Developments

Alternative solvents

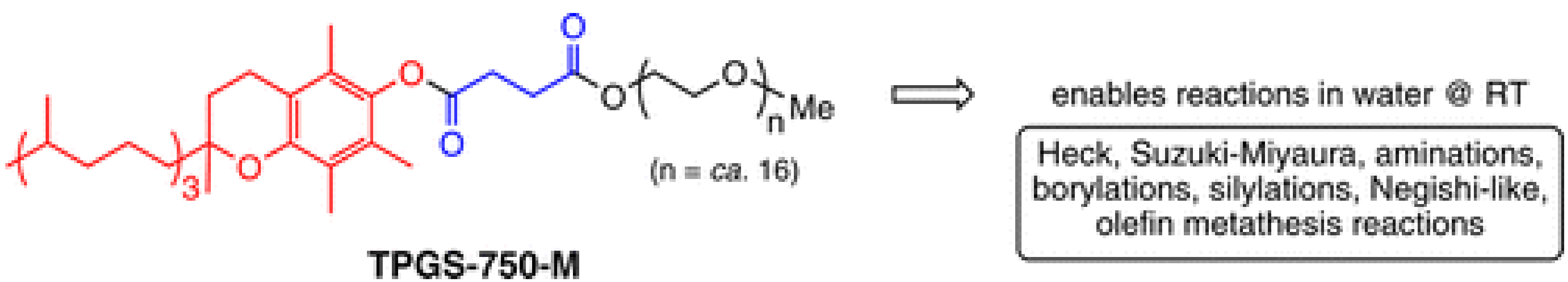
- Water
- Supercritical and near-(or sub-)critical fluid systems
- Other benign solvents (ionic liquids, gas-expansion liquids, etc.)
- Polymeric solvents and less-volatile solvents
- Renewables(organic carbonates, glycerol derivatives, etc.)
- Switchable systems

Alternative Solvents for Green Chemistry, RSC, 2009

Surfactant for aqueous-organic reactions

Innovation and Benefits

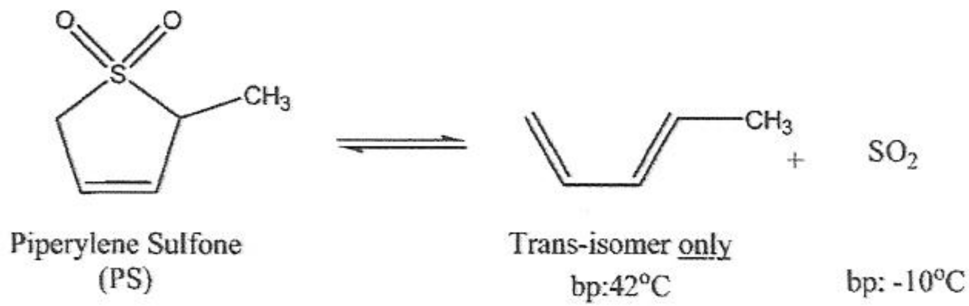
Most chemical manufacturing processes rely on organic solvents, which tend to be volatile, toxic, and flammable. Chemical manufacturers use billions of pounds of organic solvents each year, much of which becomes waste. Water itself cannot replace organic solvents as the medium for chemical reactions because many chemicals do not dissolve and do not react in water. Professor Lipshutz has designed a safe surfactant, **TPGS-750-M,** that forms tiny droplets in water. Organic chemicals dissolve in these droplets and react efficiently, allowing water to replace organic solvents.

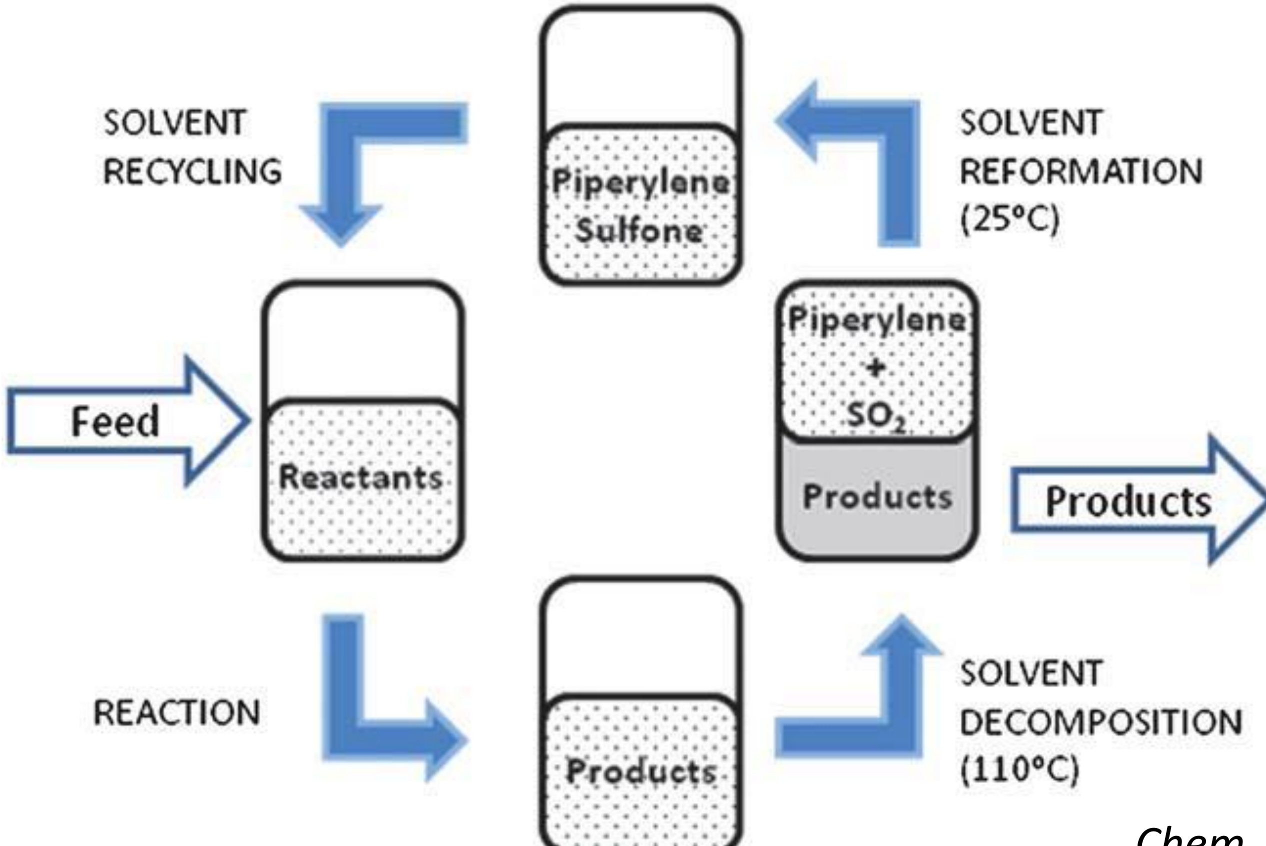


PGCC Academic Award 2011

J. Org. Chem. **2011**, *76*, 4379.

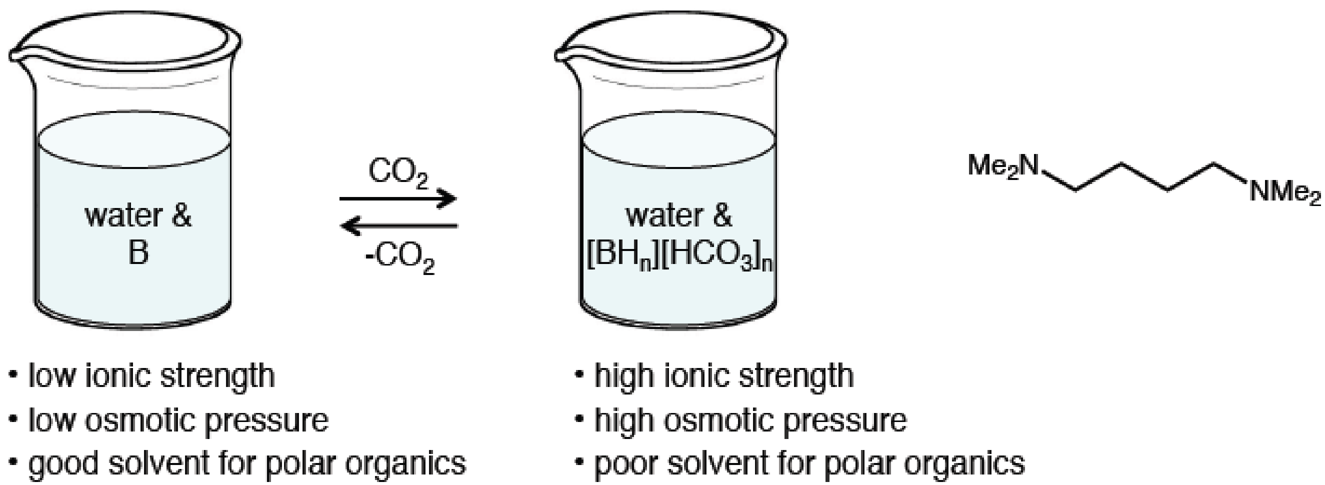
Switchable solvent and recycling

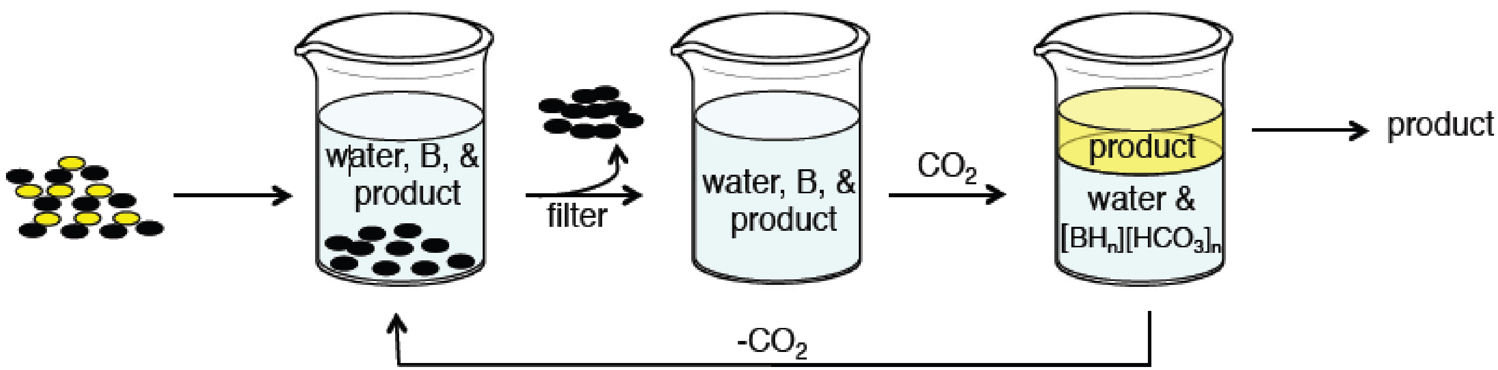




Chem. Sci. **2011**, *2*, 609

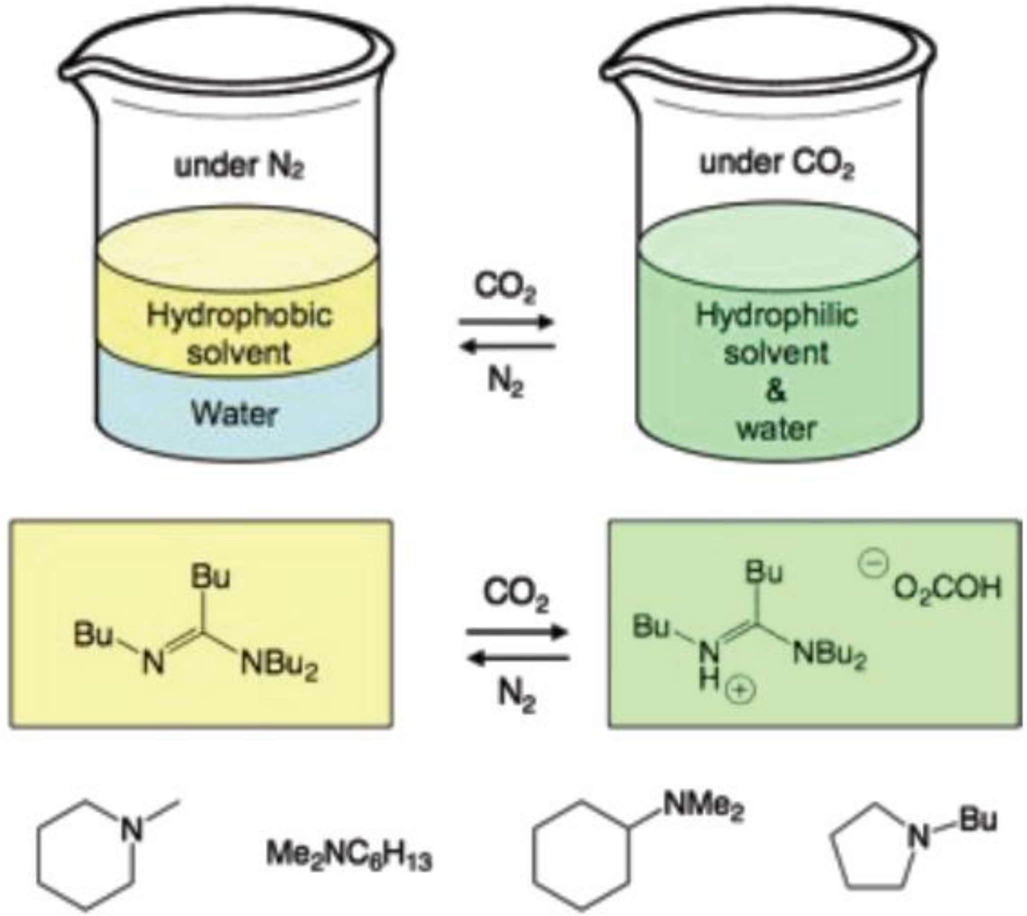
Switchable Water: Aqueous Solutions of Switchable Ionic Strength





ChemSusChem **2010**, *3*, 467.
Green Chem. **2012**, *14*, 832.

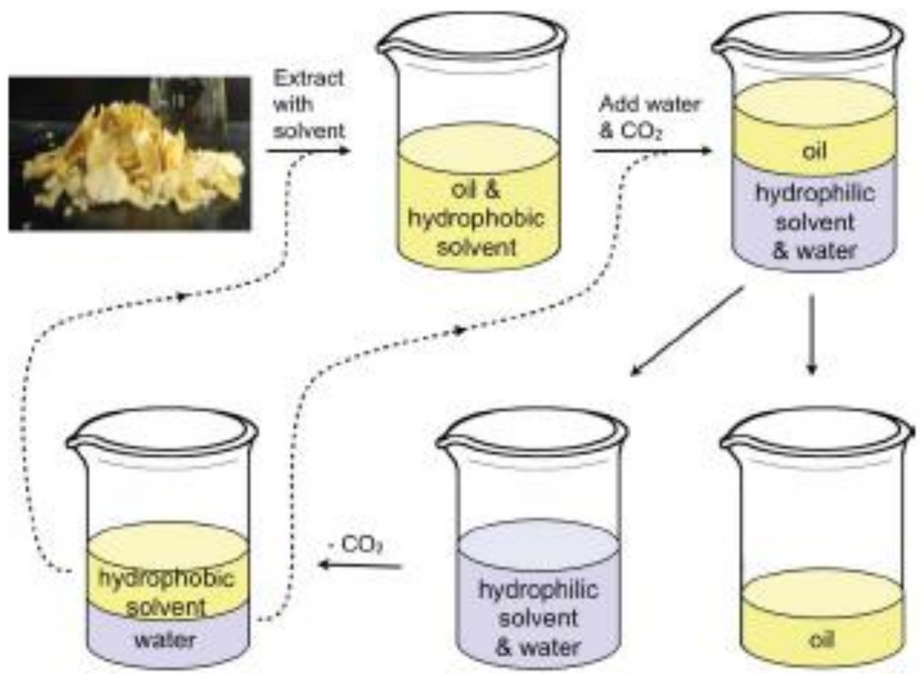
SWITCHABLE-HYDROPHILICITY SOLVENTS



Green Chem. **2010**, *12*, 809
Green Chem. **2011**, *13*, 619

A real world case

Conventional distillation Method for obtaining Soybean oil



The use of SHS method avoids distillation

Green Chem. **2010**, *12*, 809.

Resources

Presidential Green Chemistry Challenge Awards (USA EPA 1996)

- Greener **Synthetic Pathways** Award
- Greener **Reaction Conditions** Award
- Designing **Greener Chemicals** Award
- **Small Business** Award
- **Academic** Award

The European Sustainable Chemistry Award (EuCheMS 2010)

- Alternative **Synthetic Pathways**
- Alternative **Feedstocks**
- Alternative **Reactor Design and Reaction Condition**
- Design and Use of **Less Hazardous Chemicals** and Chemical Products

Website

- GreenChemWeb (http://www.greenchem.org)

On-Line Learning

- ACS course: **Toxicology for Chemists**
- Free ACS webinar: **Green Chemistry Series**
- ACS Summer School on Green Chemistry and Sustainable Energy (Lecture files available)
- Free video course: Carnegie Mellon Univ. The Institute for Green Science
  - **Introduction to Green Chemistry** (http://igs.chem.cmu.edu/)

Free App

- Green Solvent

Organizations

- ACS Green Chemistry Institute
  - The Nexus Newsletter
  - ACS GCI Industrial Roundtables
    - ACS GCI Pharmaceutical Roundtable
    - ACS GCI Formulator's Roundtable
    - ACS GCI Chemical Manufacturer's Roundtable
- Warner-Babcock Institute for Green Chemistry
- SusChem
  - Strategic Research Agenda /Implementation Action Plan

Journals

- Green Chemistry (RSC)
- Green Chemistry Letters and Reviews (Taylor & Francis)
- ChemSusChem (Wiley)
- ACS Sustainable Chemistry and Engineering (ACS)

Challenges

Alternative feedstocks

- Move from petroleum to renewable or biologically derived sources
  - Petroleum chemistry => need oxidation chemistry
  - Sugar => need reduction chemistry
- CO_2 => need new catalysts

Alternative solvents

- No solvent (neat solution; grinding)
- Supercritical CO_2, ionic liquid…

Alternative synthetic pathways

- New catalysts
- Move to biocatalysts (no toxic metals; intrinsically safer)
- Research into reuse and recycling catalysts still in infancy

http://www.sciencemag.org/cgi/content/full/297/5582/807

Challenges

Education

When to use what metrics

Lack of toxicology training

Address the problems of waste, toxicity, energy consumption altogether, rather than individually.

Green Chemistry and Sustainability

Green chemistry: a tool in achieving sustainability

- –Fundamental approach to pollution prevention
- –Not a solution to all environmental problems
- –Chemistry's unique contribution to sustainability

Conclusion

"It's more **effective**,
it's more **efficient**,
it's more **elegant**,
it's simply **better chemistry**,"

says Anastas.