Design and Implementation of a Greener Lab Curriculum

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Evolution of a Green Chemistry Program

- Student empowerment
- Green lessons
- Other lessons …

… including the perils of a chronological presentation – “revisionist history” often leads to a better story.

But important lessons about academic chemistry and its practice, as well as about green chemistry, can arise from hearing the “real” story.

Evolution of Oregon's Green Laboratory Program

Pre 1992: capacity ~60

Evolution of Oregon's Green Laboratory Program

Smoke Clearance Test

A “Modern” Chemistry Lab

1992 - 2001: capacity 17

Some Simple Mathematics

$$\frac{\text{265 students/week}}{\text{17 students/lab section}} \longrightarrow \text{17 lab sections/week}$$

17 lab sections/week x 3 hours/lab section

\+ 2 x 1 hour/lecture/week = 53 contact hours/week

Some Simple Algebra

$$\frac{265 \text{ students/week}}{x \text{ students/lab section}} \longrightarrow y \text{ lab sections/week}$$

y lab sections/week x 3 hours/lab section

+ 2 x 1 hour/lecture/week = z contact hours/week

$$\boxed{\text{If } x > 17, \text{ then } z < 53}$$

An Inconvenient Truth

capacity >>17??

Green Chemistry Reduces Risk by Addressing Intrinsic Hazard

Risk = *f*(hazard, exposure)

Reducing risk through reduction of intrinsic hazard reduces or eliminates the risk even in the event of exposure.

Green Chemistry Reduces Facility Demands

capacity >>17

The First Offering of the Green Lab

15 students selected on the basis of interest, enthusiasm, and performance in previous classes.

Completely new experiments, sometimes designed only weeks before student exploration.

Recognition by students that …

things may not always work as planned;
this is how science works;
they were pioneers in developing a new approach.

Selecting and Adapting Labs That Teach Green Chemistry

Criteria for selecting experiments:

- Teach **modern reaction chemistry and techniques**
- Illustrate **green chemical concepts**
- **Complement the lecture course**
- Fit time and material **constraints**
- Use **greener solvents and reagents**
- **Reduce laboratory waste and hazards**
- Be adaptable to both **macroscale and microscale**
- Provides a platform for discussion of **environmental issues** in the classroom
- **Allow experimentation on the open bench**

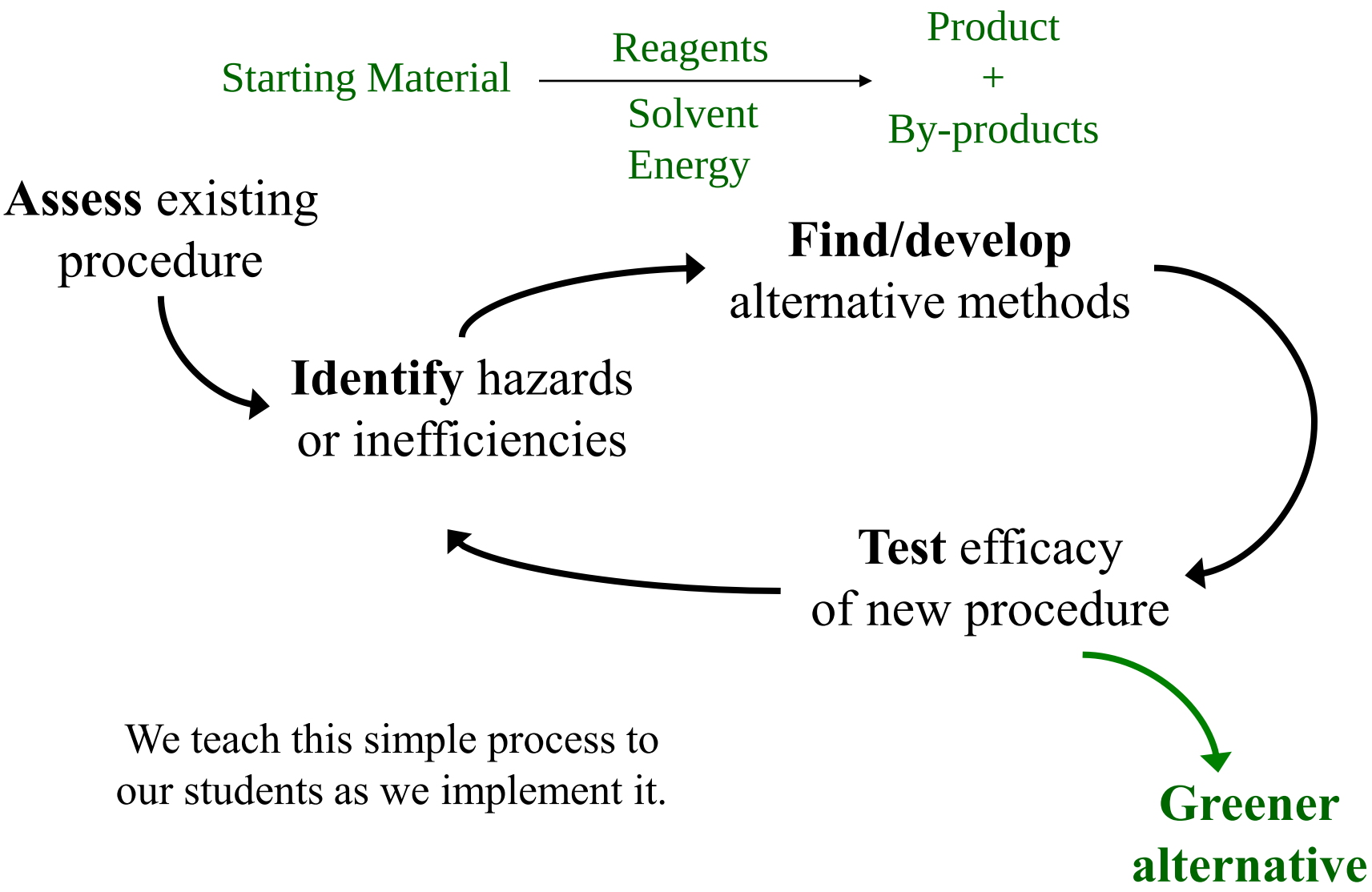
Need for Modernized Organic Laboratory Curriculum

Starting Material Employed in Classic Organic Laboratory Syntheses 1902-1980

Date	Author	Acetanilide	4-Bromoacetanilide	Benzoin
		Starting Materials Required (grams)		
		Aniline	**Acetanilide**	**Benzaldehyde**
1902	Levy, 4th ed.	46.2	-	50.0
1915	Cohen, 3rd ed.	25.0	5.0	25.0
1933	Adkins	25.0	13.5	10.0
1941	Fieser, 2nd ed.	18.2	13.5	25.0
1963	Adams	20.0	13.5	16.0
1980	Durst	10.0	5.2	10.0

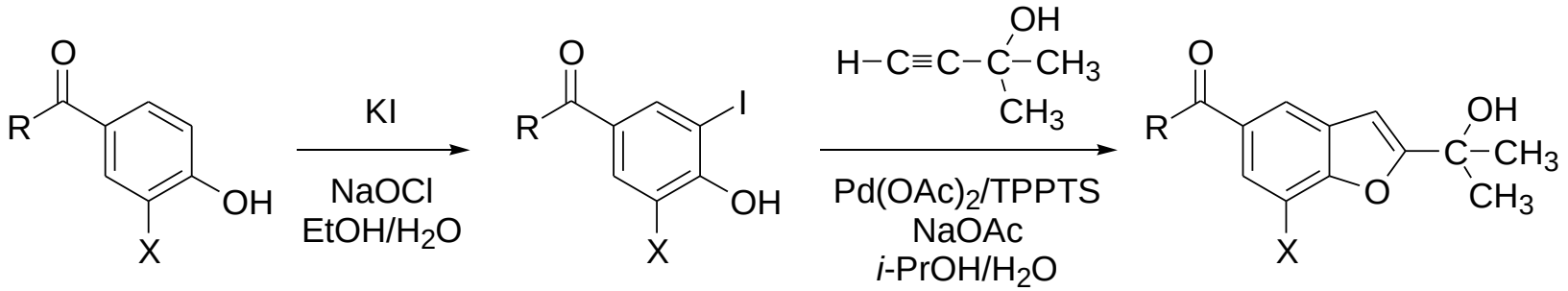
From *Microscale Organic Laboratory* by D.W. Mayo, R.M. Pike and S.S. Butcher, 1985

Green Experiment Development



We teach this simple process to our students as we implement it.

Aromatic Halogenation/Alkynes



R = X = H
R = H, X = OCH_3 (vanillin)
R = CH_3, X = H

R = X = H (spruce rot fungus)
R = H, X = OCH_3 (?)
R = CH_3, X = H (giant tree daisy)

<u>Lab Skills</u>

Electrophilic halogenation
Pd-catalyzed coupling
Alkyne chemistry
Natural product synthesis

<u>Green Lessons</u>

Safer reagents
Alternative solvents
Catalysis

An Exercise in Green Experiment Selection/Design

Consider the following experiment, from a recent lab manual:

"Consult a chemical catalog to … choose a halophenol and an alkyl tosylate to use for the experiment. Factors to consider are commercial availability of the compounds, costs, and relative reactivities.

Safety First!
Alkyl tosylates should be handled with care as they are cancer suspect agents and toxic irritants. Halogenated phenols are toxic and corrosive."

Discussion – Merits of this experiment

Possible Concerns

- Could/should one consider the health and environmental hazards of the starting materials being considered?

  Health and environmental impacts are as important as melting point, color, and other physical properties.

- Is it wise to have inexperienced students working with compounds known to present extreme health risks?

  Let's talk about this more in a few minutes. But, no.

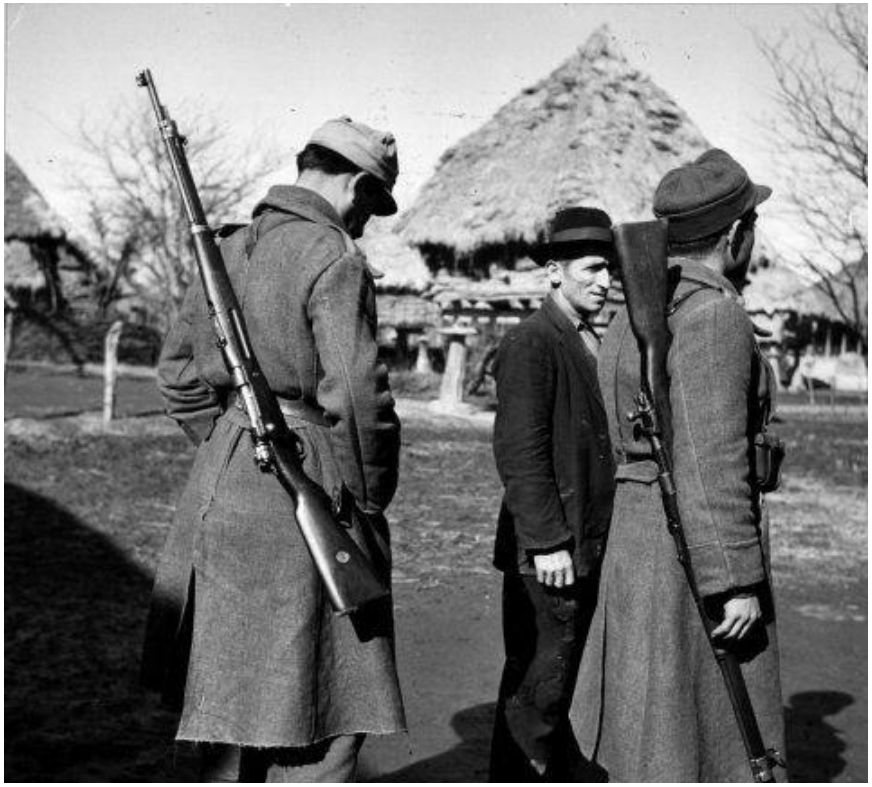
- Are all halophenols toxic and corrosive? Maybe some are safer? Maybe others are even worse?

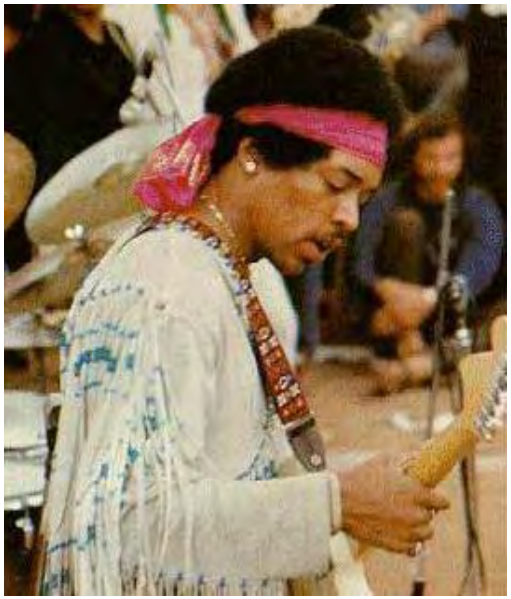
  Can we avoid teaching that all chemicals are harmful?

The Second Offering of the Green Lab

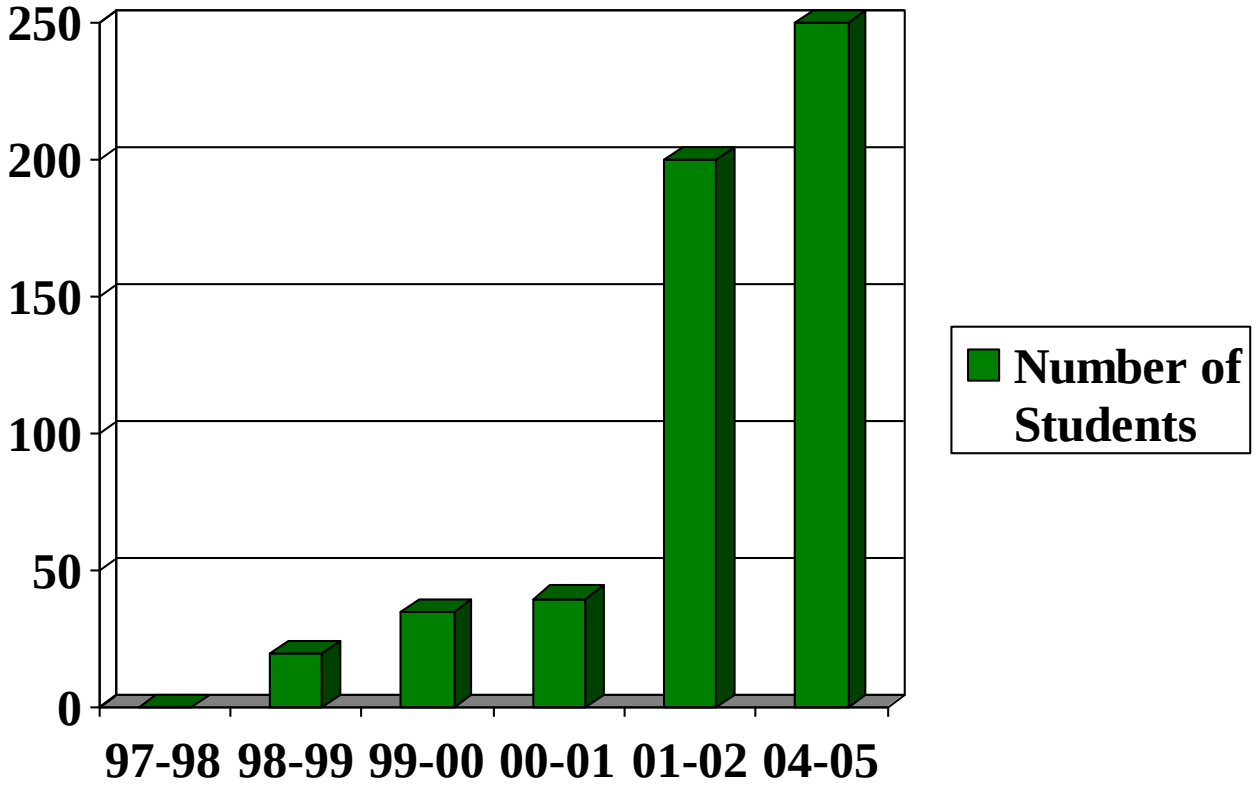
Conscription is a general term for involuntary labor demanded by some established authority.

From Wikipedia, the free encyclopedia





Laboratory curriculum project implementation



Laboratory curriculum project implementation

Fall term
Synthesis, separations, spectroscopy

1. Solventless Aldol condensation
2. Bromination of an alkene
3. Preparation/distillation of cyclohexene
4. Synthesis of adipic acid
5. Oxidative coupling of alkynes
6. Gas phase porphyrin synthesis
7. Solvent effects on kinetics
8. Molecular mechanics modeling

Winter term
Synthesis, spectroscopy, applications

1. Electrophilic iodination with KI/NaOCl
2. Palladium-catalyzed aryl halide/alkyne coupling
3. Polymer-supported oxidation chemistry
4. Friedel-Crafts acylation of ferrocene
5. Thiamine-mediated benzoin condensation
6. Self-assembled monolayers/patterning
7. Combinatorial synthesis of antibiotics

The Green Chemistry Lab

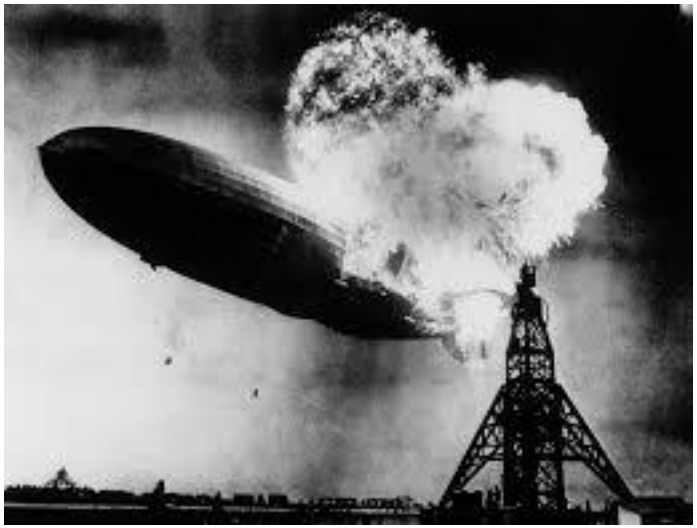
Green Chemistry in Education Workshop

Students Play a Key Role

- Experiment development
- Openness to new discoveries
- Recognition of the richness of green chemistry
- Participation in Green Workshops

Design Challenges

http://www.mcclatchy1958.com/images/edsel.jpg



http://www.historyinanhour.com/wp-content/uploads/2011/05/Hindenburg-disaster.jpg

http://media-2.web.britannica.com/eb-media/21/59921-004-9B396A7B.jpg

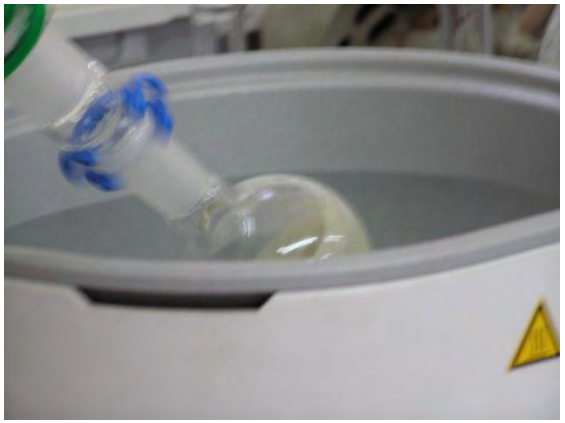
Reality in the Teaching Lab

Universidad Autónoma de Yucatán

Synthesis of 7-Hydroxy-4-Methylcoumarin by a Solid-Catalyzed Pechmann Reaction

Warner, John C.; in *Greener Approaches to Undergraduate Chemistry Experiments*, p. 25, Kirchhoff, Mary; Ryan, Mary Ann, Eds., American Chemical Society, **2002**.

Cost is a Real Issue



Cost is a Real Issue

… and consideration of cost can lead to enhancement of the greenness of a procedure.

50 mL of toluene + 10 mL of methanol

vs.

10 mL of ethanol

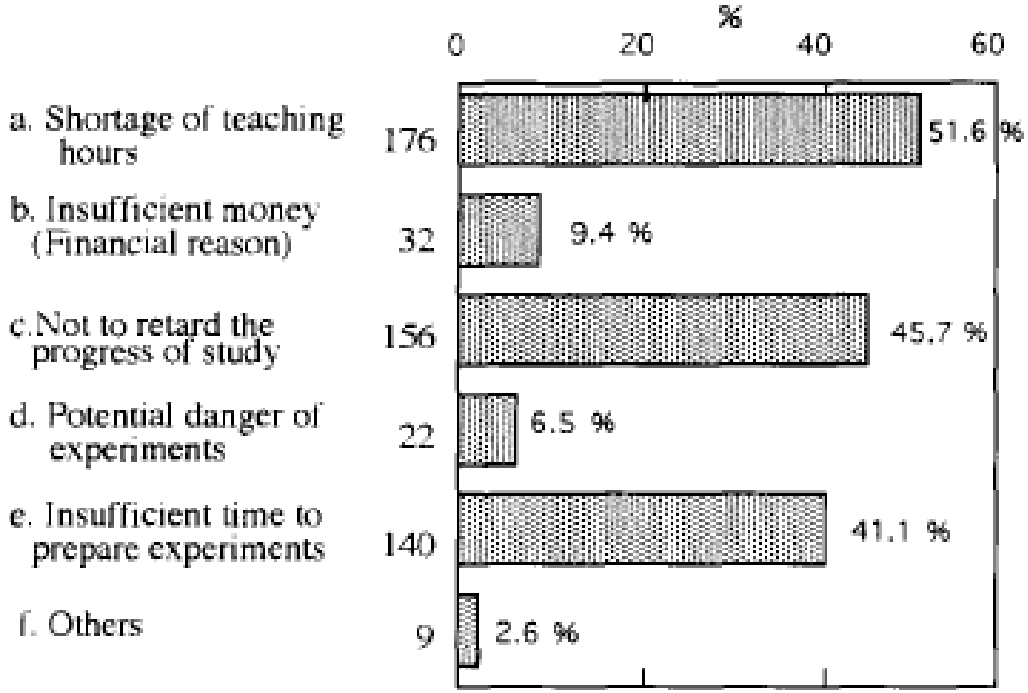
Green Synthesis of a Fluorescent Natural Product

Young, D. M.; Welker, J. J. C.; Doxsee, K. M., *J. Chem. Ed*. **2011**, *88(3)*, 319-321.

(*Is* Cost a Real Issue?)

The Situation of Senior-High School Chemistry Education in Tohoku District of Japan – From the Results of a Questionnaire to Chemistry Teachers in 1995

Kazuko Ogino, *et al*, *Bull. Coll. Med. Sci. Tohoku Univ*. **1997**, *6(1)*, 49-58.

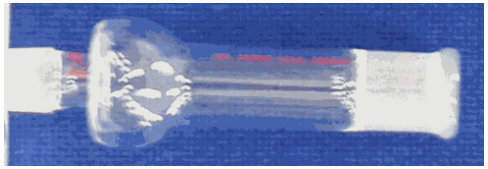


Reasons for the Scarcity of Experiments

“We” and “They”

- <u>We</u> discuss what type of equipment provides the best experience for our students.

Which of these …



… looks more like this?

“We” and “They”

- They wait two years to receive chemicals and supplies.

“We” and “They”

- And <u>they</u> have no electricity.

Cheap is Good

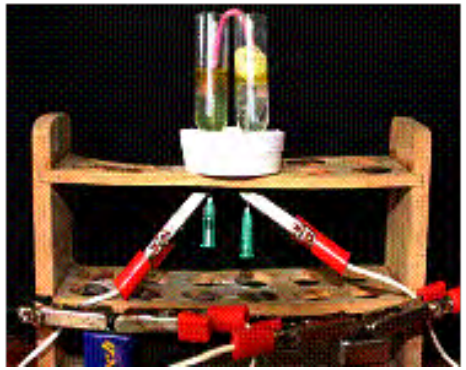
Marie du Toit (South Africa)
Peter Schwarz (Germany)

Free is Better

Chem. Educator **2006,** *11,* 181–183

Two Consecutive Reactions in Microscaled Electrolysis Cells

Sobhi Basheer[†] and Muhamad Hugerat[‡,*]



Experimental Science in Developing Countries

- Recognize and embrace local “limitations”
- Exploit locally available materials
- Develop locally relevant content
- Engage local teachers and students

Locally Relevant Content

Discussion – Possible topics for Middle-East labs

Locally Relevant Content

- Dead Sea – brine, high P_{atm}
- Olive oil
- Textiles and pigments (modern, ancient)
- Natural products (terrestrial, marine)
- Ceramics, glass
- Minerals, sand
- Myrtle wood
- Coins
- Fermentation

Perceptual Challenges

- Some of our tacit assumptions are easy to recognize and (relatively) easy to dismiss.
  - Chemistry is dangerous.
  - *Good* chemistry is dangerous.

Chemistry has to be Dangerous

The Skeptic Speaks

But [redacted], instructional lab supervisor in [redacted]'s chemistry department, said [redacted] is doing the opposite.

In addition to more fume hoods, [redacted] said, [redacted] hopes to also equip its organic labs with steel, glass and rubber "glove boxes." Stationed inside wider, deeper fume hoods, the glove boxes, up to $75,000 each, would let students handle chemicals so volatile they ignite upon touching air.

Only such experiments, he said, can prepare chemistry students for dangerous jobs in industry.

"We haven't even heard of (green chemistry) out this way. I don't think we'd even be interested in it. Yes, it may save money, but you're not doing any favors for students with it," [redacted] said. "We're trying to get students really interested in chemistry. This gives them a chance to perform processes that will really train them for when they go out into the world."

Discussion – What do YOU think?

Who are our Clientele?

CH_3CH_2Br

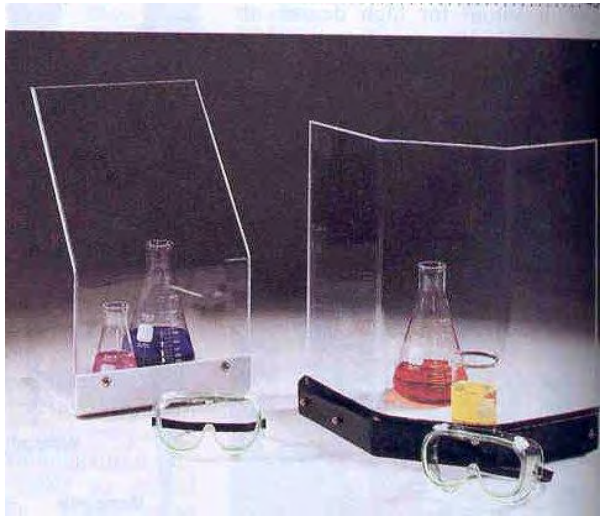
Benzene
vs.
$AgNO_3$

Most students will not work with hazardous substances.

Proper technique can be learned with safe substances.

Good Chemistry has to be Dangerous

"Dr. _____ has 44 years of experience in the synthesis of novel high energy oxidizers and rocket propellants. He has achieved the first syntheses of many spectacular compounds, such as ClF_3O, ClF_3O_2, halogen perchlorates, OIF_4OF, OsF_4O_2, ..."



Chemistry has to be Dangerous?

- Safer reagents
- Cheaper reagents
- Better product
- Less hazardous waste
- Higher profits

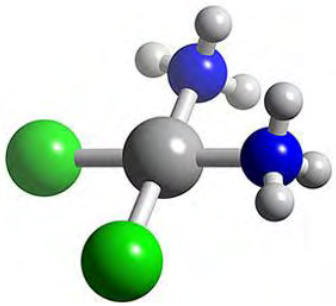
Challenging Assumptions

- Other assumptions are so deeply ingrained in the chemist's psyche as to be not just hard to change, but unrecognized.
  - Percent yield is a good measure of reaction efficiency.
  - Fume hoods, gloves, and other "environmental controls" protect us.
  - Chemical reactions require solvents.
  - Intrinsic chemical hazards are unavoidable.

Deeply Ingrained Assumptions

- Percent yield is a good measure of reaction efficiency.

Reaction Efficiency



Cisplatin

Experimental Procedure

Prepare a solution of 63 mg (0.202 mmol) of silver sulfate in 10 mL of water in a 25-mL beaker containing a magnetic stirring bar. Add 100 mg (0.207 mmol) of the *cis*-diiodo derivative prepared in Part 48.A, in small portions, to this Ag^+ solution.

Heat the suspension, with stirring, on a sand bath (70-80 ºC) for 10-12 min. Filter the mixture to separate the precipitate of AgI.

Isolation of Product

Concentrate the filtrate to a volume of about 2.0 mL. Treat this solution with 330 mg (4.43 mmol, a large excess) of KCl. Heat the mixture on a sand bath at 70-80 ºC for 2-3 min. Bright yellow crystals of *cis*-diammine dichloroplatinum(II) should precipitate out. The heating is continued for an additional 5-8 min. Cool the mixture to 0 ºC in an ice-water bath. Filter the product using a Hirsch funnel. Wash the crystals with 500 μL of ethanol followed by 1 mL of ether and dry them under suction in air. Determine the percentage yield.

Is This a Good Experiment?

<u>Yes</u>

- Balancing Equations
- Mole Ratios
- Stoichiometry
- Coordination Chemistry
- Chemotherapy
- Laboratory Techniques
  - Filtration, Elevated Temperatures

Measures of Reaction Efficiency

- Chemical yield (82%)
- Atom economy (32%)
- Experimental atom economy (12%) (theoretical yield vs. mass of reactants)
- Actual atom economy (10%)
- Waste generation (8.9 g / 1.0 g product)
- Solvent usage (11.1 g)
- Yield based on all inputs (0.4%)

(No chromatography or recrystallization)

Cisplatin in Action

Dosage: 2-3 mg/kg every 3-4 weeks

- May cause severe allergic reaction …
  … which may get worse with continuing exposure.

- Very toxic if inhaled, swallowed, or absorbed through the skin.

- Experimental carcinogen, teratogen; IARC probable human carcinogen.

- May cause reproductive damage.

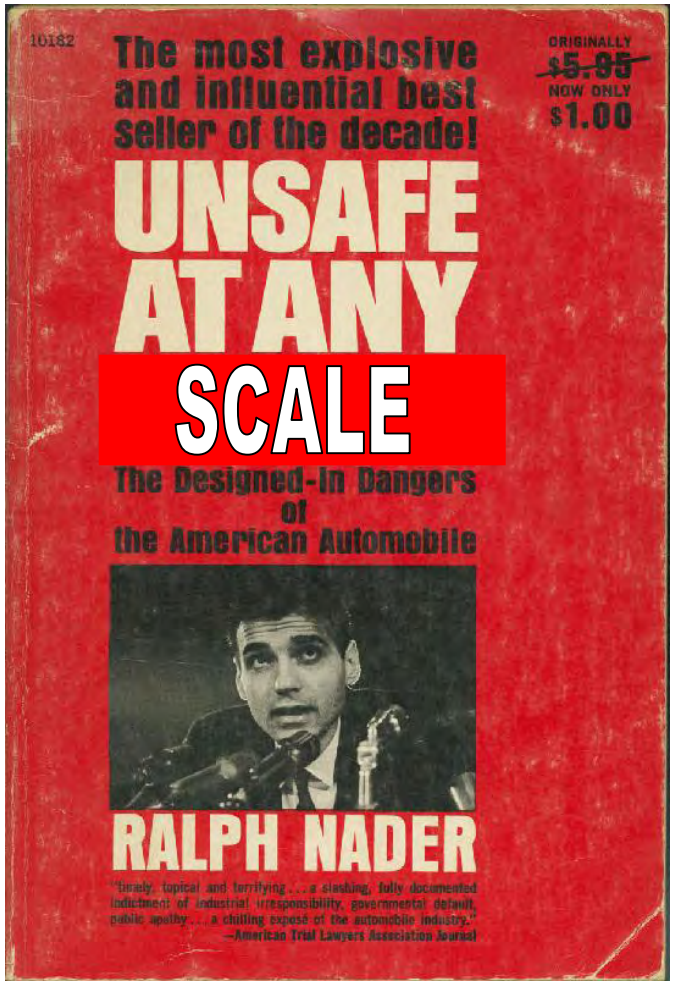
- Most effects of overdosage are not usually seen immediately, but occur several days to months after the event.

Is This a Good Experiment?

No

- Physiologically active product!!

- 232 g waste per 1 g product
- Requires heating (energy usage)



Always Ask Questions

- Why are we making this compound?
- What are its properties – particularly in terms of health and environmental impact?
- Can we accomplish the same goals by making a different and safer compound?
- Can we make the compound from safer starting materials, or using safer solvents, or using less energy input (either heating or cooling)?
- Can we reduce the amount of waste that is generated, or eliminate it entirely?

Deeply Ingrained Assumptions

- Fume hoods, gloves, and other “environmental controls” protect us.

Environmental Controls

Does avoidance of exposure make us safe?

"working in a fume hood."

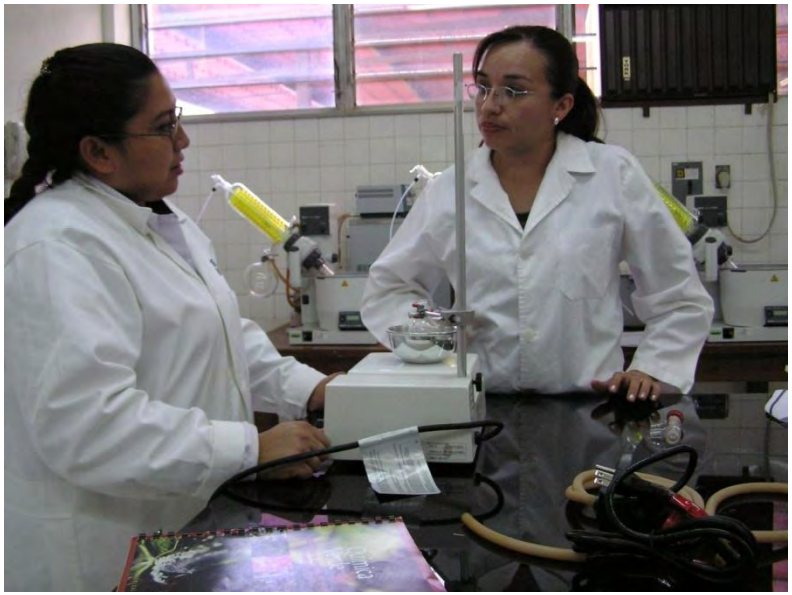
Karen Wetterhahn
Dartmouth College,
1996

Deeply Ingrained Assumptions

- Chemical reactions require solvents.

Solvent is a Given

Synthesis of 7-Hydroxy-4-Methylcoumarin by a Solid-Catalyzed Pechmann Reaction
Warner, John C.; in *Greener Approaches to Undergraduate Chemistry Experiments*, p. 25, Kirchhoff, Mary; Ryan, Mary Ann, Eds., American Chemical Society, **2002**.



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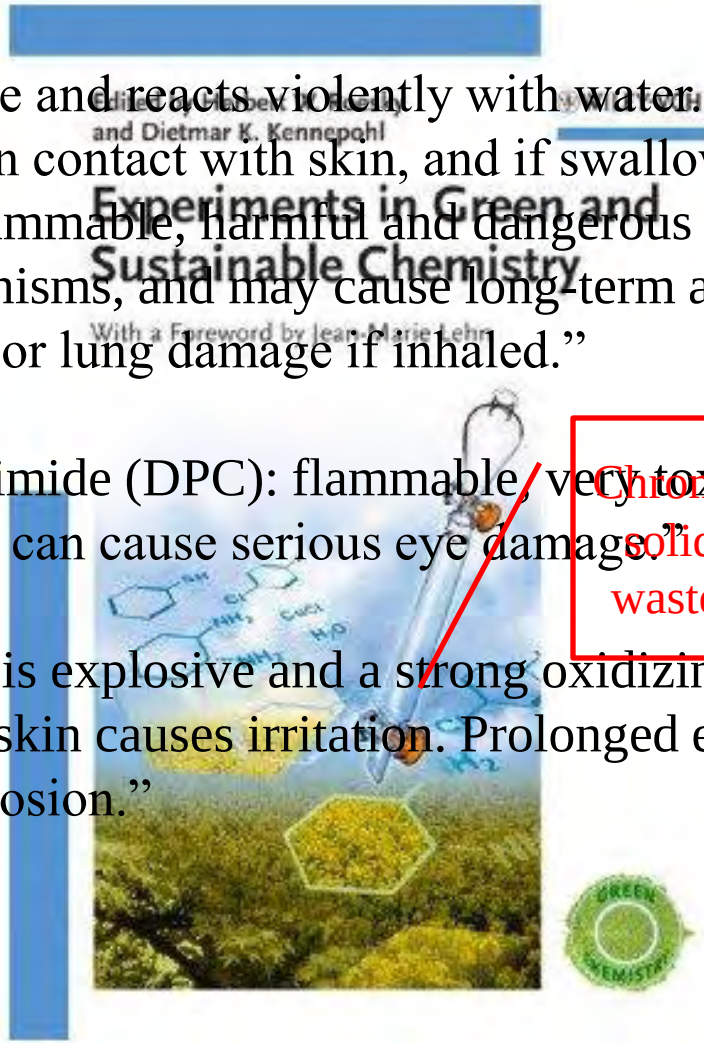
Deeply Ingrained Assumptions

- Intrinsic chemical hazards are unavoidable.

Intrinsic Chemical Hazards



"$LiAlH_4$ is flammable and reacts violently with water. … $(CF_3)_3COH$ is toxic by inhalation, in contact with skin, and if swallowed. … Petroleum ether is extremely flammable, harmful and dangerous for the environment, toxic to aquatic organisms, and may cause long-term adverse effects in the aquatic environment or lung damage if inhaled."

"Diisopropylcarbodiimide (DPC): flammable, very toxic by inhalation, irritating to skin, and can cause serious eye damage."

Chromatography—solid and liquid waste generation

"Barium perchlorate is explosive and a strong oxidizing agent. Inhalation or contact with eyes or skin causes irritation. Prolonged exposure to fire or heat may result in an explosion."

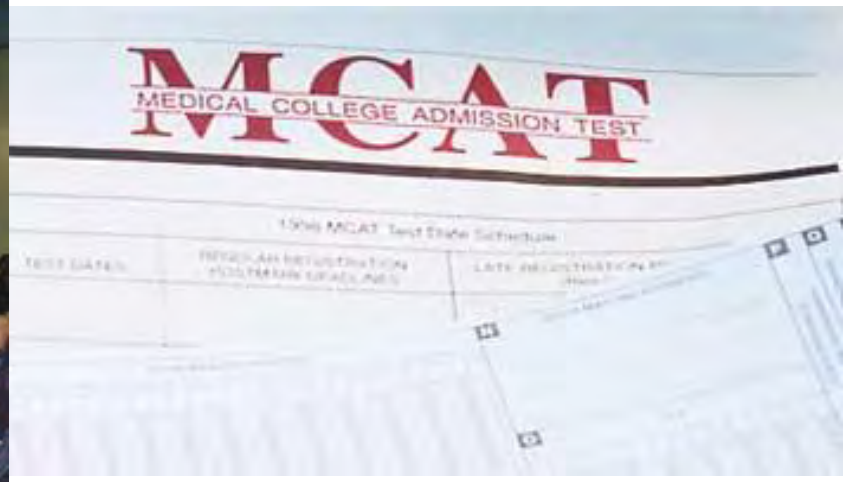
Academic Barriers to a Green Curriculum

Exercise

What (else) might a skeptical person say about a Green Chemistry curriculum?

Pedagogical Concerns

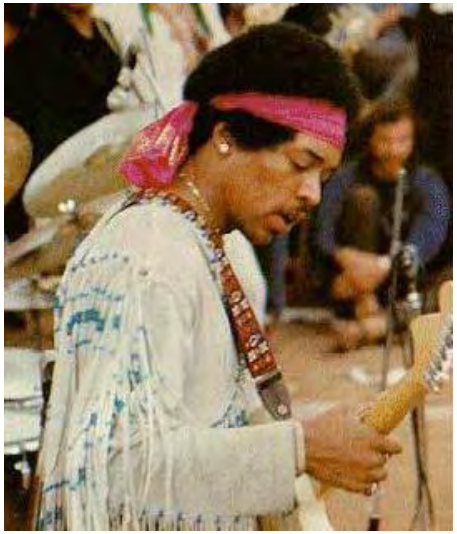
"The curriculum will not teach students what they need to know for admission to graduate school or for standardized examinations."



Academic Preparation

	Traditional	Green ¶
Fundamentals of chemistry	+	+
Practical lab procedures	+	+
Green chemical concepts	-	+
Process chemical concepts	-	+
Waste generation/disposal	-	+
Safety	+	+
Realistic scale and apparatus	+/-	+
State-of-the-art curriculum	-	+

Skepticism



"Green is political, not scientific."

"Green is a passing fad. It is hippie chemistry."

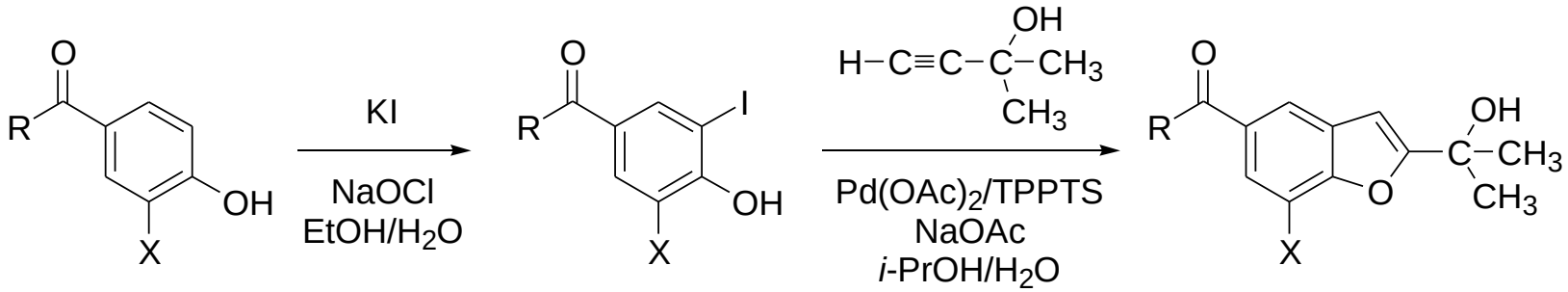
"Green chemistry is not rigorous."

Process Research

Designing better products and better processes is what synthetic chemists do. Green chemistry is intrinsically more rigorous than traditional chemistry due to the imposition of significant “boundary conditions.”

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r},t)\right]\Psi(\vec{r},t) = i\hbar\frac{\partial\Psi(\vec{r},t)}{\partial t}$$

State-of-the-Art Experimentation



R = X = H
R = H, X = OCH_3 (vanillin)
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R = X = H (spruce rot fungus)
R = H, X = OCH_3 (?)
R = CH_3, X = H (giant tree daisy)

Electrophilic halogenation
Pd-catalyzed coupling
Alkyne chemistry
Natural product synthesis

Safer reagents
Alternative solvents
Catalysis

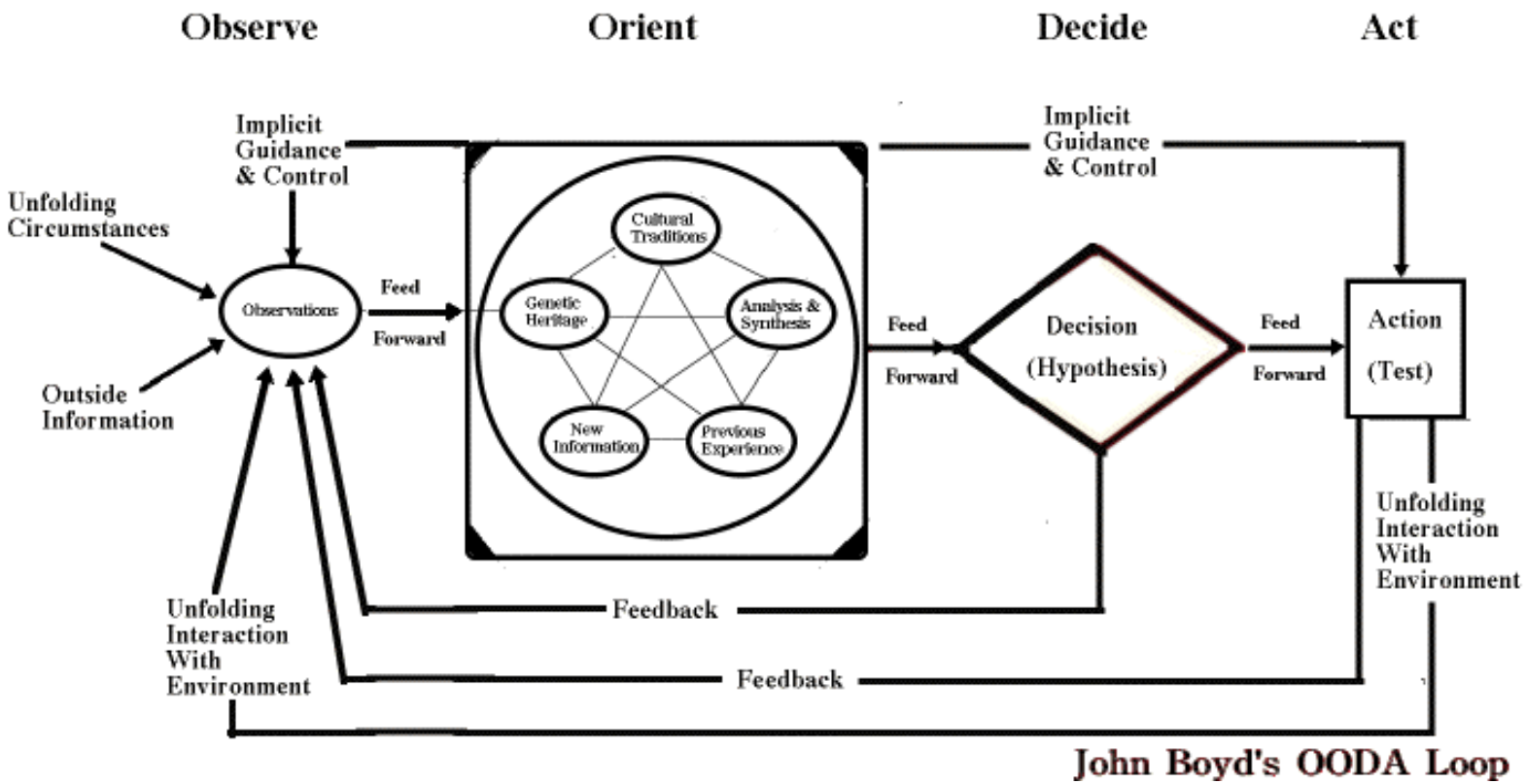
Inertia

“We’ve always done it this way.”

“We just revised our curriculum when we converted to microscale.”

Sustainability is Complicated

… and requires complicated choices and decisions



Complex Problems

"… complexity should not be equated with intractability …"

John S. Dryzek, 2002

"The extent and complexity of the problem does not matter as much as does the willingness to solve it."

Ralph Marston, 1998

"The difficult I'll do right now; the impossible will take a little while."

Linda Ronstadt

Toma de Decisiones Estrategica

How do we make personal choices?

A. Personal impact

Benefit: Increased athletic performance

Risk: Disqualification, heart disease

Toma de Decisiones Estrategica

How do we make personal choices?

B. Impact on others ("inflicted choice")

Benefit: Enjoyment of enhanced athletic exhibitions (observers)

Risk: Decreased chances of winning (competitors)

None? (observers)

"*Quantification of Steroid Hormones ... in Municipal Wastewater Effluent*"

Androgens (testosterone and androstenedione) were detected at concentrations as high as 6.1 and 4.5 ng/L, respectively ..."

E. P. Kolodziej, J. L. Gray, and D. L. Sedlak
Environ. Toxicology and Chem. **2003**, *22*, 2622-9

Decisiones Personales Que Pueden Afectar a Otros

Choice: Exceeding the speed limit

Personal Impact

Benefit: Arrive faster

Risk: Accident

Citation

Impact on Others

Benefit: ?

Risk: (health care costs)

Decisiones Personales Que Pueden Afectar a Otros

Choice: Thalidomide

Personal Impact
Benefit: Treat multiple myeloma (plasma cell cancer)
Risk: ?

Treat erythema nodosum leprosum (leprosy-related)

Impact on Others
Benefit: ?
Risk: Birth defects (health care costs)

Decisiones Grupales Que Pueden Afectar a Otros

Choice: Bioethanol from corn

Benefit: Renewable fuel source

Risk: Loss of food source
Environmental impacts

MEXICAN FARMERS REPLACE TEQUILA PLANT WITH CORN
Ethanol demand has doubled corn prices, making it more profitable than agave.

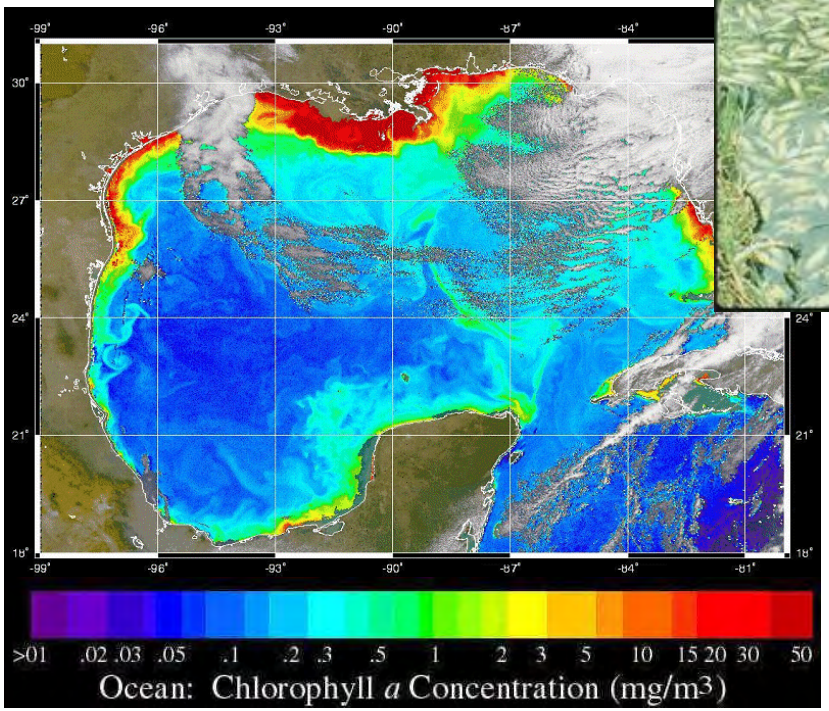
Christian Science Monitor, June 21, 2007

Hipoxia – “La Zona Muerta”

US corn biofuels will expand Gulf of Mexico 'dead zone'

Mar 10, 2008

http://www.smm.org/deadzone/



http://cas.bellarmine.edu/tietjen/Ec&Ev_Distance_learning/EcologyIntro/gulf_of_mexico_dead_zone.htm

Decisiones en la Industria Quimica

Choice: Environmental controls for hazardous chemicals

Benefit: Make desired product
Protect workers

Risk: Failure of controls
Release of hazardous materials
Security

Choice: Intrinsically safer chemicals and products (Sustainable Chemistry)

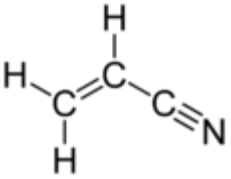
Benefit: Make desired product
Protect workers
Increase profits
Improve public relations
Comply with regulations
Save the planet

Risk: ?

Decisiones en el Curriculo de Quimica

- Students select their major field of study.
- Students select courses, but must meet faculty-defined requirements.
- Faculty choose what materials to present to students.
  - Lecture – “fair and balanced” coverage.
  - Laboratory – exposure to chemicals.

A Qualitative Organic Analysis That Exploits the Senses of Smell, Touch, and Sound



Agents for Change

An **agent of change**, is someone who intentionally or indirectly causes or accelerates social, cultural, or behavioral change.

From Wikipedia, the free encyclopedia

An **agent of change** is **YOU**.