Greening the Lab (and Beyond!)

A Guide to Applying Green Chemistry to Practical Settings and Creating Displays to Spread the Word

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This guide is produced by the ACS Green Chemistry Institute®

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Not all chemistry laboratories are created equal. Broken fume hoods, confusing waste beakers, and distillations that have been running (as far as anyone can tell) since the lab bench was installed are common occurrences among universities. But labs shouldn't be so hazardous that they need to be navigated like minefields. This guide provides simple steps that your ACS student chapter can take to make safer, greener lab spaces while educating other students and faculty about green chemistry.

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Sustainable and green chemistry in simple terms is just a different way of thinking about how chemistry and chemical engineering can be done. Over the years different principles have been proposed that can be used when thinking about the design, development and implementation of chemical products and processes. These principles enable scientists and engineers to protect and benefit the economy, people, and the planet by finding creative and innovative ways to reduce waste, conserve energy, and discover replacements for hazardous substances.

It's important to note that the scope of these green chemistry and engineering principles go beyond concerns over hazards from chemical toxicity and include energy conservation and waste reduction, as well as life cycle considerations such as the use of more sustainable or renewable feedstocks and designing for end of life or the final disposition of the product.

By incorporating sustainable and green chemistry into your student chapter's activities you can:

- Become a spokesperson on your campus for sustainability and the solutions chemistry can bring through green chemistry
- Start a movement of sustainability across your campus and in the community
- Make a difference through chemistry
- Have a positive impact on human health, the environment & the future
- Improve the "image" of chemistry

Chapters who engage in at least three green chemistry outreach and educational activities during the school year are eligible to win a Green Chemistry Student Chapter Award.

Green Chemistry Themes to Consider[1]

It is better to:
Prevent waste than to treat or clean up waste after it is formed
Minimize the amount of materials used in the production of a product
Use and generate substances that are not toxic
Use less energy
Use renewable materials when it makes technical and economic sense
Design materials that degrade to innocuous products at the end of their usable life

[1] Middlecamp, Catherine, ed. *Chemistry in Context: Applying Chemistry to Society*. 8th ed. New York: McGraw Hill, 2014. Print

What's Wrong with this Picture?

You might not see anything immediately concerning when looking at a lab. But consider this: if it's the work area you've been taught to use and navigate since you first set foot in Gen. Chem. lab of course nothing will seem amiss. The first step in greening the lab is identifying what can be improved and then learning how the principles of green chemistry can be applied in a practical setting.

This document will focus on three "problem areas" that many colleges and universities contend with and which can be addressed by your ACS student chapter:

1. Experiments
2. Waste Management
3. Equipment or Facilities

But first things first. Most universities and colleges won't be comfortable with students going in on their own and changing their labs around – and with good reason. Lab equipment, chemicals, and maintenance are expensive and can be hazardous. It's important to work with chemistry department faculty when greening your lab. Plus, your professors might become interested in integrating more green chemistry into their curricula or research. The faculty will ultimately be the ones deciding what and how labs are conducted so approaching these changes gently – and smartly - is essential.

How to Bring it up with Your Professor[2]

If the faculty member you've chosen to speak with about making changes in the lab has never heard of green chemistry, you'll want to ease in to the conversation. Jumping right in to all the ways you want to change their space might seem intrusive, pushy, or overwhelming. Remember, they're busy, too! Schedule a time to meet with them so they're sure to be free and start first by defining green chemistry and why it's important, if they're unfamiliar with it. Note how easy it is to make changes that will benefit everyone including members of the faculty. Explain how any associated costs will be covered or, if you're requesting funds from the department, say how much and precisely what they will be used for. Start slow, start small.

There is an art to persuasion. Here are few tips for successful communication:

1. Be logistic specific. What changes would you like to be made and when, how much will they cost, and what help do you need from the faculty?
2. Stay focused. This is not about upcoming tests, how the cafeteria should recycle more, or polar bears in the arctic. It's about making changes to university labs so that they will be more efficient and safer for students, faculty, and the environment.
3. Go confidently with specific examples and details (provided in this document). Be able to explain why what you're doing is important without being vague or generalizing.
4. Explain how the changes will benefit whomever you're speaking with. A better image for the department? An opportunity to be a leader on campus? Grants? Remind him or her that it's not something else to squeeze into an already packed curriculum but painless substitutions that teach the same ideas and concepts with slightly altered methods.
5. Don't focus on what's bad about existing labs – this approach might come off as accusatory or insulting to their role and experience as a teacher. Focus on positive outcomes.
6. Get a commitment. Create a timeline for the proposed changes. Show your appreciation.
7. As with anything be determined but also considerate, respectful, and listen to what the person you're talking to has to say, as well.

[2] http://sustainability.berkeley.edu/sites/default/files/Promoting_Sustain_Behavior_Primer.pdf

Focus Areas

Some universities and colleges have programs in place to improve the safety and sustainability of their chemistry labs.

Universities with well-established green lab programs include:
Cornell University
University of Wisconsin Green Bay
University of British Columbia
University of California at Berkeley
Harvard University

Additionally, My Green Lab provides information on how to create sustainable labs.

If you've talked to your professor or student chapter advisor and found that your institution doesn't have such a program in place, don't fret! It's a big undertaking to green a lab, especially if the facility is somewhat outdated.

This document focuses on examples of potential improvements of the chemistry laboratory in three areas: experiments, efficiency, and waste.

Because greening a lab can be an extensive task just choose either one area (suggested below) or one activity in each area and report on three changes that are made. Pair the in-lab work with a display about green chemistry and what's been going on in the chemistry department to really round out this green chemistry activity.

Choose an area of focus:

- **A)** **Greener Experiments**
- **B)** **Making the Lab More Efficient**
- **C)** **Improving Chemical Waste Procedures**

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Undergraduate chemistry students have been doing **the same labs in the same ways for decades.** Updates to clock reactions, titrations, extractions, and other classic teaching experiments have not been widely implemented despite the use of hazardous solvents, overly reactive reagents, and unnecessary waste generation.

Greening a lab requires complex considerations. Even micro-scale techniques, which are intended to be more environmentally friendly by reducing the amounts of chemicals used, pose an inherent risk of exposure due to the nature of the chemicals used, even if only in small amounts.[3]

The examples of easy swaps in this section can be integrated on a wide scale into undergraduate course curricula. Of course this involves faculty time and serious commitment. Although you'll need faculty approval and support to make changes in the lab, it's up to you and your ACS chapter to communicate the importance of transitioning. Use the examples below to help support a case for greening the lab.

[3] Singh, M.M., Szafran, Z., Pike, R.M. Microscale Chemistry and Green Chemistry: Complementary Pedagogies *J. of Chem. Ed.,* 1999 **76** (12), 1684 http://pubs.acs.org/doi/pdf/10.1021/ed076p1684

Alternative Solvents

Even in undergraduate labs, hazardous solvent use is very common. A solvent must first of all function well, i.e. it needs to be an effective medium in which to carry out a reaction. However, there are safer solvents for human health and the environment that work as effectively as traditional solvents. It's simply a matter of making the switch.

Solvent	Alternative	Explanation
Dry ice/acetone	Dry ice/isopropanol	Isopropanol is the safer solvent to use in cooling baths as it works at about the same temperature while being less volatile, meaning a reduced risk of inhalation/exposure[4]
Hexane	Heptane, Pentane	Heptane is much less toxic than hexane (which is neurotoxic) while maintaining very similar chemical properties.[5]
THF	2-MeTHF	2-MeTHF is derived from renewable resources like sugarcane and corn, while THF is petroleum-based. In addition, 2-MeTHF is a cost-stable product that can also increase reaction yield while being easier to recycle[6]
	No Solvent (solid state or reagents as solvents (i.e. melted reagents))	Solvent-less reactions can be used in a variety of applications. Specifically in the organic chemistry lab, this is effective for aldol condensations (forming carbon-carbon bonds)[7]

[4] http://www.chem.utoronto.ca/green/_shared/pdfs/Simple%20Techniques%20to%20Make%20Everyday%20Lab%20Work%20Greener.pdf

[5] Takeuchi Y., Ono Y., Hisanaga N., Kitoh J., Suguira, Y. A comparative study on the neurotoxicity of n-pentane, n-hexane, and n-heptane in the rat. *Brit. J. Ind. Med.* 1980 (37), 241-247. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1008702/pdf/brjindmed00067-0029.pdf

[6] D. F. Aycock , Solvent Applications of 2-Methytetrahydrofuran in Organometallic and Biphasic Reactions. *Org. Process Res. Dev*. 2007, 11, 156–159 http://pubs.acs.org/doi/abs/10.1021/op060155c

[7] Doxsee, K.M., Hutchinson, J.E. (2004*) Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments,* Brooks/Cole Cengage Learning: University of Oregon

Alternative Reagents

Although the conventional reagents for many organic syntheses are highly effective, they also pose unnecessary health and/or environmental risks. Often, less reactive, less toxic chemicals work as well as their hazardous counterparts.[8] Consider where alternatives might be of use in your university or college labs.

Reagent	Alternative	Explanation
m-chlorobenzoic acid, tin hydride	Electrochemistry	Redox reactions are often initiated with hazardous or precious chemicals. In this example, non-toxic, environmentally friendly electrochemistry allows for "oxidation of olefins to epoxides and reduction of vinyl halides to olefins"[9]
Metal catalysts	Light	Metal catalysts are often used to produce radical reactions. However, some of these metals are scarce or toxic elements. Light is essentially the perfect green reagent: completely renewable, pollution-free, and effective. Solid supports in photochemistry can often be recycled resulting in a high atom economy.[10]

Alternative Feedstocks

Many chemical feedstocks are derived from non-renewable fossil fuels. Biomass-derived products are not only renewable but also provide a great variety of selective compounds. Additionally, unlike the waste products of fossil fuel extraction and production, biomass wastes can be utilized such as in pharmaceuticals and generally have low-toxicity. Of course, it's important to remember that even promising bio-based feedstocks fall into gray areas, including the environmental effects of growing the plants necessary for the supply (water use, fertilizer, pesticides, etc.)[11]
Talk to a faculty member at your college or university about ordering chemicals from a company that uses bio-based feedstocks instead of fossil fuel derivatives.

Feedstock	Bio-based Alternative	Explanation
Crude Oil-derived succinic acid	Corn-derived succinic acid	A bacteria ferments glucose from corn to create succinic acid, a chemical used in the manufacture of 1,4-butanediol, THF, N-methyl pyrrolidinone and more[12]

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[8] Doxsee, K.M., Hutchinson, J.E. (2004*) Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments,* Brooks/Cole Cengage Learning: University of Oregon pp.79-95
[9] http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/951/report/F
[10] Jack, Lorna. 2005. "Green Chemistry's Shining Light," *Royal Society of Chemistry; Chemistry World.* http://www.rsc.org/chemistryworld/Issues/2005/January/shininglight.asp
[11] Doxsee, K.M., Hutchinson, J.E. (2004*) Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments,* Brooks/Cole Cengage Learning: University of Oregon pp.97-99
[12] Doxsee, K.M., Hutchinson, J.E. (2004*) Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments,* Brooks/Cole Cengage Learning: University of Oregon p.98

Additional Resources for Greener Experiments

Two ACS publications, *Introduction to Green Chemistry* and *Greener Approaches to Undergraduate Chemistry Experiments,* provide green chemistry activities and labs and can be ordered online here and here.

The Green Chemistry Initiative based at the University of Toronto provides a wealth of information on alternative solvents, reagents, and more. Check it out here for more examples on easy lab swaps.

In addition, a database called Greener Education Materials for Chemists (GEMs) and an initiative called Beyond Benign also provide labs, some of which can be downloaded for free while others include an overview and the source where they can be found (such as a textbook).

For more chemical and process alternatives, also check out MIT's green chemistry wizard.

A few more alternative chemistry labs can be found in these locations:

Title	Description	Organization	Contact	Relevant Link(s)	Notes
Does Makes the Poison: Estimating the Relative Ecotoxicity of Various Biofuels	A 3-part lab that includes synthesizing biofuel, assessing potential hazards, and writing a short paper on alternative fuels	BCGC, University of California	marty_m@berkeley.edu	http://bcgc.berkeley.edu/sites/default/files/GreenChemistry_Biofuels_Unit.pdf	undergraduate lab topics: heat transfer, toxicology intro, dilutions, stoichiometry, limiting reagents, reaction yield & efficiency
Candy Chromatography	candy chromatography experiment teaching basic lab techniques: solutions and chromatography	Scifun.org, University of Wisconsin-Madison		http://www.scifun.org/HomeExpts/candy.htm	middle/high school; other "home experiments" that introduce basic topics here: http://www.scifun.org/HomeExpts/HOMEEXPTS.HTML
Super Gelatin: Teacher Lesson Plan	"students investigate the refraction properties of gelatin to calculate its index of refraction…"	University of Texas at Austin		http://stardate.org/sites/default/files/SuperGelatin.pdf	primarily a physics experiment
Green Chemistry: Three Step Synthesis of Acetaminophen	downloadable lab procedure with a few "green" changes	St. Catherine University		http://sophia.stkate.edu/undergraduate_research_symposium/2013/Sciences/26/	uses hexane…may be a good example of how implementing one or two green principles may not make the overall process greener
Solventless Syntheses of Mesotetraphenylporphyrin: new experiments for a greener organic chemistry laboratory curriculum	two solvent-free syntheses that are intended for teaching undergraduate green chemistry labs	RSC, University of Oregon	hutch@uoregon.edu	http://pubs.rsc.org/en/content/articlehtml/2001/gc/b107999a	

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What actually happens to the guck in those waste beakers? You know the ones – shoved into the corners of fume hoods until one day they mysteriously disappear, hauled away in a truck with biohazard bumper stickers. Have you ever had a beaker full of solution at the end of a lab period and - a lab aid nowhere in sight - decided "this can probably just go down the sink"? Most students don't question the disposal of chemicals used in lab. Even if safer alternatives are employed, as mentioned in the above section, measures should still be taken to ensure that materials are disposed of responsibly. Many labs have too few disposal beakers, place the ones they have in sinks, give them improper labels, or provide students with minimal instruction on waste disposal practices.[13] Remember, nothing is ever just thrown away – all chemicals end up somewhere after they leave the lab bench.

Talk to a faculty member at your college or university about programs that can be put in place to ensure that when waste must be produced it is safely and effectively managed.

Waste Management

a. *Establish a green lab certification program*.
   i. What you need:
      i. Guidelines – how will the "greenness" of the lab be measured?
      ii. Checklist – a tool for participants to assess their lab
      iii. Review Panel – an objective assessment team to observe lab practices
      iv. The University of British Columbia is a great example of such a program.

b. *Recycling Solvents* (adapted from the Green Chemistry Initiative at the University of Toronto)
   i. Solvents used to wash glassware is easily recyclable through distillation.
   ii. Solvents that are removed during rotovap/distillation can often be recycled if pure or they can be re-used as wash solvents.

c. *Chemical Disposal*
   i. Even if your lab uses some greener alternatives there will still be risks involved in the disposal and treatment of waste. Most colleges and universities have detailed guidelines about waste disposal but students may forget or be unaware of them. Putting signs over sinks, ensuring waste beakers are properly labeled, and having a lecture on why waste disposal and prevention are important are all ways to decrease the hazards associated with chemical wastes generated by a lab.

d. Chemical Exchange Program
   i. A number of universities have established programs through which unused/unwanted chemicals can be obtained by other members of the university rather than purchasing new chemicals. This not only saves the university money but also reduces chemical waste.
   ii. This proposal from the University of California at Berkeley is great place to start for detailed information on how to set up a chemical exchange program.

e. Education
   i. If you or other chemistry students have noticed a lack of instruction on chemical disposal procedures, talk to your professor or another faculty member about why your student chapter feels it's an important topic to emphasize.

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[13] http://environment.uwaterloo.ca/research/watgreen/projects/library/820/final.html#formal

In those beginning-of-term safety videos, **carelessness in the lab** usually refers to things like pointing pipettes at your classmates, running between tables, or accidentally lighting something on fire. But carelessness can also refer to how energy is being used. Are fume hoods left running for weeks on end? Are faucets leaky? What kinds of light bulbs have been installed and do they ever turn off? In addition to energy consumption, are the facilities where students spend hours every week actually safe?

According to Harvard University's Green Labs Program, labs make up 50% of their university energy consumption but only take up 23% of the space[14]. Here are a few common examples of sub-par lab practices and how universities have made improvements in safety and environmental impact.

Efficiency of Equipment and/or Facilities

a. Fume Hoods
    a. Fume hoods require a huge amount of energy. The University of British Columbia approximates that 10% of the entire university's energy consumption is from fume hoods alone[15]. One study estimated that a building with fume hoods requires four to five times as much energy as a building without them (University of South Florida).
    b. Shut the Sash! Campaigns and competitions are popular ways to save energy simply by closing fume hoods. As an added bonus, keeping the hood open to a minimum decreases the risk of exposure to chemicals. Students at the University of British Columbia put stickers up near the fume hoods reminding others that a fume hood uses as much energy as three homes.
b. Faucets
    a. As if water waste during experiments isn't enough, many lab facilities have inefficient faucets, such ones that leak. Turning off faucets when not in use and using closed-loop cooling systems are easy ways to save water.
    b. Consider applying for a grant for the installation of motion-operated/automatic faucets.
    c. Using less distilled water, such as when washing glassware, can save energy – regular tap water must be heated to boiling for purification.[16]
c. Electronic efficiency
    a. Saving energy from lights and electronics is just about the easiest thing ever: simply turn off the lights when not in use and shut down/sleep-mode computers rather than leaving them on for long periods of time. Your student chapter can put signs up near computers and light switches to encourage these behaviors.
d. Freezers
    a. Laboratory freezers, like fume hoods, are energy-intensive pieces of equipment. Harvard University suggests scheduling an annual "de-frosting" day.
    b. Leaving a one-foot space all the way around refrigerators/freezers allows the cooling mechanisms to work more efficiently.[17]

[14] http://green.harvard.edu/programs/green-labs
[15] http://sustain.ubc.ca/campus-initiatives/green-research/shut-the-sash
[16] Buie, J. (2011). MindMap: Reduce My Lab's Environmental Impact. *Lab Manager Magazine*, 6(3), 70-71. Retrieved from: http://www.labmanager.com/lab-product/2011/04/mindmap-reduce-my-lab-s-environmental-impact#.U-t_KfldVyw
[17] Borchardt, J. K. (2009). Achieving Laboratory Energy Efficiency. *Lab Manager Magazine*, 4(3), 16-19. Retrieved from: http://www.labmanager.com/business-management/2009/04/achieving-laboratory-energy-efficiency#.U-t-fPldVyw

e. Applying for a grant to improve labs
    a. The EPA has awarded grant money for the improvement of educational facilities. [18]
    b. DOW Chemical company provided a $3.5 million grant to the University of California at Berkeley which was to be used in part to create greener lab spaces – other chemical companies may offer similar opportunities[19]
    c. State governments and individual universities may also offer grants for greening labs, such as the state of Michigan's Department of Environmental Quality.

See the University of British Columbia's virtual lab to view energy-saving changes in action.

If you're thinking, **"But wait, this lab-efficiency stuff sounds like sustainability, not green chemistry"** you're not wrong. Remember that green chemistry is a tool, along with many others, used to build a sustainable society. From a chemical perspective, energy consumption is often a concern because of the material used to generate it. Fossil fuels have long been the standard for meeting energy demands due to their relatively high energy output and low cost. However, these materials are non-renewable, the energy cost to extract them from the earth is high, and they release greenhouse gases when burned that would otherwise remain stored in the earth. According to the U.S. EPA, "Fossil fuel-fired power plants are responsible for 70 percent of the nation's sulfur dioxide emissions, 13 percent of nitrogen oxide emissions, and 40 percent of carbon dioxide emissions from the combustion of fossil fuels. These emissions can lead to smog, acid rain, and haze." Such processes as mining, drilling, and hydraulic fracturing for extraction of non-renewable resources do not return safe substances to the environment as would be preferred for a green chemistry process, but rather they input materials known to be hazardous to ecosystems and which might pollute ground water. This kind of "upstream thinking" is essential for green chemistry. All stages of a process – even if that process is as simple as flipping a light switch – should be considered. How can it be made better (a lab's set-up, a chemical synthesis, a solvent choice, etc.): i.e. less costly, less hazardous, and less wasteful?

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[18] http://www2.epa.gov/home/grants-and-other-funding-opportunities
[19] http://chemistry.berkeley.edu/publications/news/2012/dow-grant-sustainable-chemistry.php

Making a Display – Getting Green Beyond the Lab

As much of an accomplishment it may be to implement greener lab practices, very few students or faculty will be aware of any change if they are not involved with the chemistry department. Take your activity one step further and create a display or visual that tells everyone on campus about what's been done and why it's important.

The student chapters at the University of Texas at Tyler, the University of St. Francis, Augustana College, Alvernia University, and the South Texas College all created unique educational displays about green chemistry. Several listed the 12 Principles of Green Chemistry along with their explanations and some information on the importance and role of each principle. Some displays included information on ways green chemistry is relevant both in research and to everyday life, including examples such as the ones in Appendix A of this document. Of course, displays relating to changes made in the lab should have information about what has been done and why it's important to all of the non-chemistry students.

Making an Attention-Grabbing Display

Displays can be more than just posters. The student chapter at Augustana College made a giant crossword puzzle about the 12 principles of green chemistry as described by the ACS. Visual representations of environmental and health impacts can be more powerful than posters. This E-factor visualization from Gordon College and this hands-on biomagnification activity are great examples of out-of-the box displays. Be creative!

For posters, bulletin boards, and other flat displays there a few things to keep in mind.

- Create an outline first. Don't just start gluing things on.
- Start the "story" in the upper left hand corner: put information here on what green chemistry is, followed by examples of why it's important in everyday life, and only then continue across the board to details about what changes are being made in your college or university labs
- Make sure the fonts are large enough (16+) for both the title and the text
- Keep it neat: use rulers, a consistent coloration, printed rather than hand-written information, glue sticks, etc. for a professional appearance. There may be a printing facility on campus that prints large posters.
- Set up in a high traffic area. Since the display is for a general audience consider somewhere like a dining hall where people will have time to read.
- Include visuals but make sure they're not too small. Use the tools that are available to make your poster really stand out – do you have access to Photoshop, InDesign, Adobe Illustrator, etc.? Creating unique images and designs is fun and more likely to engage passers-by.
- Keep it simple – i.e. putting everything on a poster will crowd it. Students at the University of Texas at Tyler highlighted two green chemistry principles a week instead of trying to cover them all at once.
- As with anything, don't wait until the last minute to put it together
- Are you able to set up a table with your display? Members of your student chapter could take turns talking to students about the display. Put out a bowl of free candy. Seriously. Never underestimate the power of free food.
- Reference any information you use, including images if they're taken from the internet

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Submitting Your Green Student Chapter Activity

Once your ACS student chapter has completed a green activity it's time to fill out the student report with details about what's been done. Feel free to send along photographs or a mention of your work in the university or college news.

See this webpage for information on deadlines, submission requirements, and the report form.

In addition**, find ways to quantify the changes your student chapter has made**. If a chemical exchange program is set up, how many grams of chemicals have been saved? If repairs are done on fume hoods, how many have been fixed? What are the energy savings? Please report as much quantified data as possible to increase the likelihood of receiving an ACS Green Student Chapter Award.

Appendix A: Everyday Examples of Green Chemistry [20]

Below are some interesting examples of how green chemistry affects everyone.

- *Have you ever had you clothes dry-cleaned?* [21]
  - Dry Cleaning: dry-cleaning processes have conventionally used the chemical perchloroethylene (perc). Several organizations have stated that perc is a hazardous substance to human health. The International Agency for Research on Cancer (IARC) concluded that perc is a "probable human carcinogen" meaning it is likely to cause cancer in addition to its short term effects like dermatitis. Workers in a dry-cleaning facility can be exposed to perc in a number of ways from cleaning the machine to simply loading clothing.[22] In addition, perc is categorized as a hazardous air pollutant by the U.S. EPA's Clean Air Act and it may contaminate groundwater when it is disposed.[23]
  - *Applying green chemistry to this situation has resulted in a markedly improved process using liquid carbon dioxide – a substance that is essentially non-toxic and is equally effective at removing grease and dirt from fabric. This simple innovation of replacing a hazardous chemical for a benign one is a perfect example of green chemistry at work in everyday life.*
- *Do you own something involving a computer chip?*
  - Have you ever considered what goes into making a smartphone, computer, or television work? As technology progresses so does our consumption of endangered elements: the 44 critical materials which will soon face supply limitations. These limitations can stem from factors such as geographic concentration, political motivations, regulatory laws, or consumer demand. Some green chemists are researching more abundant alternatives, more efficient syntheses where alternatives are not found, diversifying the supply and better recycling and recovery programs for these scarce materials. A smartphone, for example, usually contains over 80 elements, many of which are considered "endangered," for everything from the touch screen (dysprosium, europium, etc.) to the color display (yttrium, terbium, and more). To manufacture computer chips, many chemicals, large amounts of water, and energy are required. In a study conducted in 2003, the industrial estimate of chemicals and fossil fuels required to make a computer chip was a 630:1 ratio! That means it takes 630 times the weight of the chip in source materials just to make one chip! Compare that to the 2:1 ratio for the manufacture of an automobile. This is an example of very poor atom economy. Scientists at the Los Alamos National Laboratory have developed a process that uses supercritical carbon dioxide in one of the steps of chip preparation, and it significantly reduces the quantities of chemicals, energy, and water needed to produce chips. Richard Wool, director of the Affordable Composites from Renewable Sources (ACRES) program at the University of

[20] http://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/examples.html
[21] Ryan, M. (ed.), Tinnesand, M. (ed.) (2002*) Introduction to Green Chemistry*, American Chemical Society: U.S.A. pp.23-29
[22] https://www.osha.gov/dsg/guidance/perc.html
[23] http://yosemite.epa.gov/opa/admpress.nsf/0/e99fd55271ce029f852579a000624956

Delaware, found a way to use chicken feathers to make computer chips! The protein, keratin, in the feathers was used to make a fiber form that is both light and tough enough to withstand mechanical and thermal stresses. The result is feather-based printed circuit board that actually works at twice the speed of traditional circuit boards. Although this technology is still in the works for commercial purposes, the research has led to other uses of feathers as source material, including for biofuel.

- *Who owns clothes? By the looks of it, all of you!*
    - Micro-organisms are everywhere, even in our clothes. They cause odors, wearing, and color changes to fabrics in textiles. To reduce the number and effects of micro-organisms on our clothes, antimicrobial textiles have been developed. Unfortunately, some of these synthetic agents have toxic effects on humans. For example, silver antimicrobial agents have caused dermatitis, some synthetic dyes have been found to cause cancer, and still others like zinc pyrithione are mildly neurotoxic. Not only are these compounds harmful to humans, they are often not biodegradable and the waste created by their manufacture is difficult to treat and sometimes become ineffective over time. *Green chemistry approaches have created benign antimicrobial textile solutions. These include materials called biopolymers that are made from a huge variety of renewable materials found in nature such as chitosan from crustaceans and fungi, cyclodextrin from starch, and alginate from brown sea weeds. Antimicrobial agents made from these ingredients are less harmful to the environment, have lower toxicity, are renewable, and still highly functional.* [24]
- *Have you ever eaten food?*
    - Many people are surprised to learn that even what they eat is a product of chemical design. Decaffeination and the production of flavors are just two examples of food-industry processes that green chemistry principles have been applied to with success. Decaffeination of coffee beans using dichloromethane, a suspected carcinogen, was the accepted process for about 70 years. However, greener methods have been developed and applied on an industrial scale. The Swiss water process and the use of supercritical CO_2 are both the result of green chemical innovation. The Swiss water process uses water, green bean extract and a difference of caffeine concentrations. No harmful solvents are used and very little waste is produced as the water is easily recycled. Decaffeination by supercritical CO_2 is also a safer and more environmentally friendly method because it is a very low-waste process using a relatively non-toxic substance; the carbon dioxide is recycled throughout the process and the caffeine solution produced is sold to other manufacturers.[25]
    - Consider everything vanilla-flavored you've ever eaten or vanilla-scented candles, soaps, and more that you've used. The production of synthetic vanillin, the main flavor component of natural vanilla extract, has undergone several changes through industry

[24] Shahid-ul-Islam, Shahid, M., Mohammad, F. Green chemistry approaches to develop antimicrobial textiles based on sustainable biopolymers – a review. *Ind. Eng. Chem. Res.* 2013, 52, 5245-5260.
[25] Jimenez-Gonzalez, C., Constable, D. J. C. (2011) *Green Chemistry and Engineering: A Practical Design Approach.* Hoboken, New Jersey: John Wiley & Sons, Inc.

attempts to improve efficiency, reduce waste, and increase the quality as demand grows at a faster rate than vanilla bean production. In the 1930's, use ligninsulfonates (organic material from wood pulp production) became the conventional starting material for vanillin production but were eventually replaced by a petrochemical starting material due to the large amounts of waste created through the wood-production by-product process[26]. New research has found that vanillin molecules can be collected and purified using ionic solvents which are often greener than the solvents they replace (less volatile) and can be derived from renewable resources unlike petrochemicals[27]. Although this synthesis is still in development the pathway towards greener production is being paved.

- *Have you ever used plastic?*
    - Several companies have been working to develop plastics that are made from renewable, biodegradable sources.
    - NatureWorks of Minnetonka, Minnesota, makes food containers from a polymer called polylactic acid branded as Ingeo. The scientists at NatureWorks discovered a method where microorganisms convert cornstarch into a resin that is just as strong as the rigid petroleum-based plastic currently used for containers such as water bottles and yogurt pots. The company is working toward sourcing the raw material from agricultural waste.
    - BASF developed a compostable polyester film that called "Ecoflex®." They are making and marketing fully biodegradable bags, "Ecovio®,"made of this film along with cassava starch and calcium carbonate. Certified by the Biodegradable Products Institute, the bags completely disintegrate into water, CO_2, and biomass in industrial composting systems. The bags are tear-resistant, puncture-resistant, waterproof, printable and elastic. Using these bags in the place of conventional plastic bags, kitchen and yard waste will quickly degrade in municipal composting systems.
- *Have you ever taken a medication?*
    - Merck and Codexis developed a second-generation green synthesis of sitagliptin, the active ingredient in Januvia™, a treatment for type 2 diabetes. This collaboration lead to an enzymatic process that reduces waste, improves yield and safety, and eliminates the need for a metal catalyst. Early research suggests that the new biocatalysts will be useful in manufacturing other drugs as well.
    - Originally sold under the brand name Zocor®, the drug, Simvastatin, is a leading prescription for treating high cholesterol. The traditional multistep method to make this medication used large amounts of hazardous reagents and produced a large amount of toxic waste in the process. Professor Yi Tang, of the University of California, created a synthesis using an engineered enzyme and a low-cost feedstock. Codexis, a biocatalysis company, optimized both the enzyme and the

[26] Calvo-Flores, F.G., Dobado, J.A. Lignin as a renewable raw material, *Chem Sus Chem.,* 2010, 3, 1227-1235. http://onlinelibrary.wiley.com/enhanced/doi/10.1002/cssc.201000157/
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chemical process. The result greatly reduces hazard and waste, is cost-effective, and meets the needs of customers.

- *Have you ever painted something?*
    - Oil-based "alkyd" paints give off large amounts of volatile organic compounds (VOCs). These volatile compounds evaporate from the paint as it dries and cures and many have one or more environmental impacts.
    - Procter & Gamble and Cook Composites and Polymers created a mixture of soya oil and sugar that replaces fossil-fuel-derived paint resins and solvents, cutting hazardous volatiles by 50 percent. Chempol® MPS paint formulations use these biobased Sefose® oils to replace petroleum-based solvents and create paint that is safer to use and produces less toxic waste.
    - Sherwin-Williams developed water-based acrylic alkyd paints with low VOCs that can be made from recycled soda bottle plastic (PET), acrylics, and soybean oil. These paints combine the performance benefits of alkyds and low VOC content of acrylics. In 2010, Sherwin-Williams manufactured enough of these new paints to eliminate over 800,000 pounds, or 362,874 kilograms of VOCs.

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