Goals for this class:

- Become familiar with the 12 Principles
- Discuss specific examples of practical value
- See the principles from a chemist’s perspective
- Analyze the case of ibuprofen as an example of a green approach

Green Chemistry is a revolutionary approach to the way that products are made; it is a science that aims to reduce or eliminate the use and/or generation of hazardous substances in the design phase of materials development.

It requires an inventive and interdisciplinary view of material and product design. Green Chemistry follows the principle that it is better to consider waste prevention options during the design and development phase than to dispose or treat waste after a process or material has been developed.
Green Chemistry presents industries with an opportunity for growth and competitive advantage. This is because there is currently a significant shortage of green technologies; we estimate that only 10% of current technologies are environmentally benign; another 35% could be made benign relatively easily. The remaining 65% have yet to be invented!

Green Chemistry also creates cost savings: when hazardous materials are removed from materials and processes, all hazard-related costs are also removed, such as those associated with handling, transportation, disposal, and compliance.

For a technology to be considered Green Chemistry, it must accomplish three things:

- Through Green Chemistry, environmentally benign alternatives to current materials and technologies can be systematically introduced across all types of manufacturing to promote a more environmentally and economically sustainable future.
The big picture

**Strategic goal**: Sustainable development

- **Practical approaches**
  - Green chemistry
  - Green engineering
  - Industrial ecology
  - Renewable energy

- **Operational tools**
  - Catalysis
  - Waste management
  - Process intensification

- **Monitoring tools**
  - Life-cycle assessment
  - E-factor, atom economy

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The drivers of green chemistry

**Economic benefit**
- Lower capital investment
- Lower operating costs

**Societal pressure**
- Improved public image
- Safer and smaller plants
- Pollution control

**Government legislation**
- Less hazardous materials
- High fines for waste
- Producer responsibility

**Green chemistry**
12 Principles of Green Chemistry

1. Prevention. It is better to prevent waste than to treat or clean up waste after it is formed.
2. Atom Economy. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Less Harmful Chemical Synthesis. Whenever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Design for Energy Efficiency. Chemical products should be designed to preserve efficacy of the function while reducing toxicity.
5. Design for Energy Efficiency. The use of auxiliary substances (solvents, separation agents, etc.) should be made unnecessary whenever possible and, when used, innocuous.
6. Design for Energy Efficiency. Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.
7. Use of Renewable Feedstocks. A raw material or feedstock should be renewable rather than depleting whenever technically and economically practical.
8. Reduce Derivatization. Unnecessary derivationization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.
9. Catalysis. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Design for Degradation. Chemical products should be designed so that at the end of their function they do not persist in the environment and instead break down into innocuous degradation products.
11. Reduce Risk. Risk should be reduced whenever possible. Analytical methodologies need to be further developed to allow for real-time in-process monitoring and control prior to the formation of hazardous substances.
12. Inherently Safer Chemistry. Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires.


1. Prevention
Environmental Disasters

- Love Canal
  - in Niagara Falls, NY a chemical and plastics company had used an old canal bed as a chemical dump from 1930s to 1950s. The land was then used for a new school and housing track. The chemicals leaked through a clay cap that sealed the dump. It was contaminated with at least 82 chemicals (benzene, chlorinated hydrocarbons, dioxin). Health effects of the people living there included: high birth defect incidence and seizure-inducing nervous disease among the children.

2. Atom Economy
Definition of Sheldon environmental acceptability

Environmental acceptability (E)

\[ E = \frac{\text{Kg waste + unwanted byproducts}}{\text{Kg desired product(s)}} \]

<table>
<thead>
<tr>
<th>Volume of production in tons per Year</th>
<th>E value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^4 - 10^5)</td>
<td>0.1</td>
</tr>
<tr>
<td>(10^5 - 10^6)</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>(10^6 - 10^7)</td>
<td>5 - 50</td>
</tr>
<tr>
<td>(10^8 - 10^9)</td>
<td>25 - &gt;100</td>
</tr>
</tbody>
</table>

More optimized processes
Higher complexity of synthesis

General classification of atom economic reactions

ATOM ECONOMY

Rearrangements
Additions
Substitutions

ENVIRONMENTAL FRIENDLINESS
3. Less Hazardous Chemical Synthesis

Disadvantages
- phosgene is highly toxic, corrosive
- requires large amount of $\text{CH}_2\text{Cl}_2$
- polycarbonate contaminated with Cl impurities
Less Hazardous Chemical Synthesis

Polycarbonate Synthesis: Solid-State Process

- Advantages
  - Diphenylcarbonate synthesized without phosgene
  - Eliminates use of CH\(_2\)Cl\(_2\)
  - Higher-quality polycarbonates

Komiya et al., Asahi Chemical Industry Co.

4. Designing Safer Chemicals
Antifoulants are generally dispersed in the paint as it is applied to the hull. Organotin compounds have traditionally been used, particularly tributyltin oxide (TBTO). TBTO works by gradually leaching from the hull killing the fouling organisms in the surrounding area.

TBTO and other organotin antifoulants have long half-lives in the environment (half-life of TBTO in seawater is > 6 months). They also bioconcentrate in marine organisms (the concentration of TBTO in marine organisms to be 104 times greater than in the surrounding water).

Organotin compounds are chronically toxic to marine life and can enter food chain. They are bioaccumulative.
The active ingredient in Sea-Nine® 211, 4,5-dichloro-2-n-octyl-4-isothiazolin-3-one (DCOI), is a member of the isothiazolone family of antifoulants.

Sea-Nine® 211 works by maintaining a hostile growing environment for marine organisms. When organisms attach to the hull (treated with DCOI), proteins at the point of attachment with the hull react with the DCOI. This reaction with the DCOI prevents the use of these proteins for other metabolic processes. The organism thus detaches itself and searches for a more hospitable surface on which to grow.

Only organisms attached to hull of ship are exposed to toxic levels of DCOI.

Readily biodegrades once leached from ship (half-life is less than one hour in sea water).

http://academic.scranton.edu/faculty/CANNM1/environmentalmodule.html
5. Safer Solvents and Auxiliaries

- Solvent Substitution
- Water as a solvent (?)
- New solvents
  - Ionic liquids
  - Supercritical fluids
### Solvent Selection

<table>
<thead>
<tr>
<th>Preferred</th>
<th>Useable</th>
<th>Undesirable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Cyclohexane</td>
<td>Pentane</td>
</tr>
<tr>
<td>Acetone</td>
<td>Heptane</td>
<td>Hexane(s)</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Toluen</td>
<td>Di-isopropyl ether</td>
</tr>
<tr>
<td>2-Propanol</td>
<td>Methylcyclohexane</td>
<td>Diethyl ether</td>
</tr>
<tr>
<td>1-Propanol</td>
<td>Methyl t-butyl ether</td>
<td>Dichloromethane</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>Isooctane</td>
<td>Dichloroethane</td>
</tr>
<tr>
<td>Isopropyl acetate</td>
<td>Acetonitrile</td>
<td>Chloroform</td>
</tr>
<tr>
<td>Methanol</td>
<td>2-MethylTHF</td>
<td>Dimethyl formamide</td>
</tr>
<tr>
<td>Methyl ethyl ketone</td>
<td>Tetrahydrofuran</td>
<td>N-Methylpyrrolidinone</td>
</tr>
<tr>
<td>1-Butanol</td>
<td>Xylenes</td>
<td>Pyridine</td>
</tr>
<tr>
<td>t-Butanol</td>
<td>Dimethyl sulf oxide</td>
<td>Dimethyl acetate</td>
</tr>
<tr>
<td></td>
<td>Acetic acid</td>
<td>Dioxane</td>
</tr>
<tr>
<td></td>
<td>Ethylene glycol</td>
<td>Dimethoxyethane</td>
</tr>
<tr>
<td></td>
<td>Benzene</td>
<td>Carbon tetrachloride</td>
</tr>
</tbody>
</table>

*Green chemistry tools to influence a medicinal chemistry and research chemistry based organization*

Dunn and Perry, et. al., Green Chem., 2008, 10, 31-36

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### Solvent replacement table

<table>
<thead>
<tr>
<th>Undesirable Solvent</th>
<th>Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentane</td>
<td>Heptane</td>
</tr>
<tr>
<td>Hexane(s)</td>
<td>Heptane</td>
</tr>
<tr>
<td>Di-isopropyl ether</td>
<td>2-MethylTHF or tert-butyl methyl ether</td>
</tr>
<tr>
<td>Dioxane or dimethoxyethane</td>
<td>2-MethylTHF or tert-butyl methyl ether</td>
</tr>
<tr>
<td>Chloroform, dichloromethane or carbon tetrachloride</td>
<td>Dichloromethane</td>
</tr>
<tr>
<td>Dimethyl formamide, dimethyl acetamide or N-methylpyrrolidinone</td>
<td>Acetonitrile</td>
</tr>
<tr>
<td>Pyridine</td>
<td>Et_N (if pyridine is used as a base)</td>
</tr>
<tr>
<td>Dichloromethane (extraction)</td>
<td>EtOAc, MTBE, toluene, 2-Methylthef</td>
</tr>
<tr>
<td>Dichloromethane (chromatography)</td>
<td>EtOAc/tetrahydrofuran</td>
</tr>
<tr>
<td>Benzene</td>
<td>Toluene</td>
</tr>
</tbody>
</table>

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Use of Solvent Replacement Guide resulted in:
- 50% reduction in chlorinated solvent use across the whole of their research division (more than 1600 lab based synthetic organic chemists, and four scale-up facilities) during 2004-2006.
- Reduction in the use of an undesirable ether by 97% over the same two year period
- Heptane used over hexane (more toxic) and pentane (much more flammable)

"Green chemistry tools to influence a medicinal chemistry and research chemistry based organization"
Dunn and Perry, et. al., Green Chem., 2008, 10, 31-36

6. Design for Energy Efficiency
Energy in a chemical process

- Thermal (electric)
- Cooling (water condensers, water circulators)
- Distillation
- Equipment (lab hood)
- Photo
- Microwave

Source of energy:
- Power plant – coal, oil, natural gas

Laboratory scale energy use