**UNIDO-Yale-Beyond Benign Curriculum**

**Green Chemistry Course**

**Note to Instructor: Update sections highlighted in red according to your own institution policies and information.**

**Spring/Fall 20XX**

**INTRUCTORS: List faculty/professor name**

**OFFICE HOURS: List office hours**

**COURSE WEBSITE: University portal/websites for supplemental course information**

**CLASS TIMES:** **Day and time for semester & room #**

**COURSE DESCRIPTION**

This course will explore the fundamentals of chemistry, how chemistry can help address global human health and environmental issues. It provides an introduction to the foundational principles of chemistry including atoms, molecules, chemical reactions, stoichiometry, chemical/physical properties, and periodic table trends. This knowledge is then related to various environmental and human health issues, and develop the appropriate solutions using green chemistry approaches covered in the course.

**COURSE OBJECTIVES**

1. Working knowledge of chemistry fundamentals including periodic table trends, electronegativity, stoichiometry, molecular structure, reactivity and nomenclature.
2. To appreciate the history of chemical accidents and how Green Chemistry can be used to design safer products and industrial systems without harming the environment and subsequent human health.
3. To understand the historical and current role of chemicals in our society and economy.
4. To qualitatively and quantitatively examine the impacts on human health and the environment of chemical products and processes.
5. To recognize the tools available to scientists and engineers in the design and synthesis of new chemical products and processes including energy efficiency.
6. To have a basic knowledge of toxicity and the molecular basis of hazard.
7. To analyze the efficiency of various approaches to chemical design.
8. To understand the transformational role of Green Chemistry in the global economy and the associated material and energy benefits.

**PREREQUISITES**

No prior undergraduate chemistry is required, however high school level chemistry is recommended.  
  
**GRADING (Variable to change depending on instructor preference)**  
Participation: 20% (Attendance and In-Class Participation: 15%, Peer Evaluation: 5%)

Exams: 30% (Exam 1: 15%, Exam 2: 15%)

Homework: 20% (6 Homework Assignments)

Final Exam: 30%

**HOMEWORK**

Students will be assigned homework which is due before the beginning of the class. And while students are encouraged to work together on the problem sets, everyone is required to turn in their individual work.

**PARTICIPATION**

Students are expected to watch assigned videos, read all assigned readings and participate in class discussions. Students should take an active role in the numerous in-class exercises during semester. Students’ in-class performances will be evaluated.

**COURSE MATERIALS**

**Required textbooks:**

“Green Chemistry: Theory and Practice”, Anastas and Warner, Oxford University Press, 1998. (Designated as T&P in the table below).

**Optional & Additional textbooks:**

1. “Chemistry in Context”, 8th Edition, McGraw Hill Education. Designated as CC in the table below.
2. “Chemistry for Changing Times”, John W. Hill; Terry W. McCreary, Pearson, 14th Edition, 2015
3. “Introduction to Green Chemistry”, Albert S. Matlack, CRC Press, 2nd Edition, 2010.
4. “Green Chemistry: An Introductory Text”, Mike Lancaster, Royal Society of Chemistry, 2002
5. “Green Techniques for Organic Synthesis and Medicinal Chemistry”, Wei Zhang; Berkeley W. Cue; Wiley Publishing, 2nd Edition, 2018

**VIDEOS:** Can be accessed through Yale Courses YouTube channel, and through NIH Toxicology Tutorials designated as **TT** in the table below.

**ACADEMIC INTEGRITY:** Students will be expected to adhere with standards of academic honesty in compliance with **your institution**. Academic dishonesty or cheating includes unacknowledged paraphrasing or quoting, use of another student's material, incomplete acknowledgement of sources including Internet sources, or submission of the same work to complete the requirements of more than one class. **Your institution may have resources available to assist you with questions about the proper referencing practices**.

**TEACHING ASSISTANTS**: **TBD** **OFFICE HOURS**: **TBD**

**EXAMS AND FINAL**

There will be **TWO** in-class exams during the semester. The exams will be closed-book and closed-note unless otherwise indicated. There will be a final exam at the end of the semester.

**LECTURE SCHEDULE**

**Lecture 1:** Course Introduction and Accidents and Their Unintentional Consequences

**Required Readings:** none

**Optional/Supplemental Readings:**

* Bhopal Plant Disaster – Situation Summary

**Class Exercise:** This week’s exercise/ice breaker are incorporated into the beginning of the PowerPoint presentation.

**Videos:**  [Accidents](https://www.youtube.com/watch?v=wtg2NAyB6Aw&feature=youtu.be) [Modern Disasters](https://www.youtube.com/watch?v=wwBF1HNd-qU&feature=youtu.be)  [Accidents: Why we should care](https://www.youtube.com/watch?v=ZGhhFF47KVU&feature=youtu.be) [Green Chemistry Approach to Accidents](https://www.youtube.com/watch?v=8Uk4KWP3brk)

**Lecture 2:** Green Chemistry: Reimagining Chemistry

**Required Readings:** none

**Optional/Supplemental Readings:** see lesson plan for optional readings

* Anastas, Paul T.; “Meeting the Challenges to Sustainability through Green Chemistry”; *Green Chem.* 2003, *5*, G29-G34. <http://pubs.rsc.org/en/content/articlehtml/2003/GC/B211620K>
* Collins, T.; “The Importance of Sustainability Ethics, Toxicity and Ecotoxicity in Chemical Education and Research”; *Green Chem.*; 2003, *5*, G51-G52. <http://pubs.rsc.org/en/content/articlehtml/2003/gc/b307694f>
* Our Common Journey - Executive Summary. Board on Sustainable Development, National Research Council, 1-14. <http://www.nap.edu/catalog.php?record_id=9690>
* Beach et al; “Green Chemistry: A design framework for sustainability”; *Energy Environ. Sci.*; 2009, *2*, 1038–1049. http://pubs.rsc.org/en/Content/ArticleLanding/2009/EE/b904997p

**Class Exercise:** none

**Videos:** none

**Lecture 3:** 12 Principles of Green Chemistry

**Required Readings:**

* Anastas, P.T., Eghbali, N. “Green Chemistry Principles and Practice”; *Chem. Soc. Rev.*; 2010, 39, 301-312. <http://pubs.rsc.org/en/content/articlelanding/2010/cs/b918763b>
* Presidential Green Chemistry Awards: 1996 – 2016
* Anastas, Paul T.; Warner, John C.; “Green Chemistry: Theory and Practice”; Oxford University Press: Oxford, 1998, Chapter 4.

**Optional/Supplemental Readings:**

* Mulvihill et al, “Green Chemistry and Green Engineering: A Framework for Sustainable Technology Development”; *Annual Review of Environment and Resources*; 2011, 36, 271-293. (optional)

<https://www.annualreviews.org/doi/abs/10.1146/annurev-environ-032009-095500>

**Class Exercise:** E-factor (optional) and Writing the 12 Principles of Green Chemistry (optional)

**Videos:** [The 12 Principles of Green Chemistry](https://www.youtube.com/watch?v=NSozp4_QeLI&feature=youtu.be) [John Warner: Green Chemistry](https://www.youtube.com/watch?v=TL1zbAJIaDI) [Introduction: Definition of Green Chemistry](https://www.youtube.com/watch?v=rABpDIs3pBc&feature=youtu.be) [Introduction: Green Chemistry’s Role in Sustainability](https://www.youtube.com/watch?v=SumoaUDpe2I&feature=youtu.be) [Introduction: Life Cycle](https://www.youtube.com/watch?v=6s1b0Aok-HU&feature=youtu.be) [Historic and Ideal Community Relationships](https://www.youtube.com/watch?v=SSi9hribxrc&feature=youtu.be)

**Lecture 4:** Green Chemistry: It All Starts at the Beginning

**Required Readings:**

* Compound Interest: History of the Atom <http://www.compoundchem.com/2016/10/13/atomicmodels/>
* The Periodic Table’s Endangered Elements <http://www.compoundchem.com/2015/08/19/endangered-elements/>

**Optional/Supplemental Readings:** Additional readings from Instructors Chemistry textbook are encouraged.

**Class Exercise:** Periodic Table Battleship Game and Periodic Table “Guess Who” Game

**Videos:** [Introduction to Periodic Table](https://www.khanacademy.org/science/chemistry/periodic-table/copy-of-periodic-table-of-elements/v/periodic-table-introduction)  [Groups in the Periodic Table](https://www.khanacademy.org/science/chemistry/periodic-table/copy-of-periodic-table-of-elements/v/periodic-table-groups)  [Ionization Energy](https://www.khanacademy.org/science/chemistry/periodic-table/periodic-table-trends-bonding/v/ionization-energy-trends)  [Electronegativity](https://www.khanacademy.org/science/chemistry/periodic-table/periodic-table-trends-bonding/v/electronegativity-trends)

**Lecture 5:** The Molecule

**Required Readings:** none

**Optional/Supplemental Readings:** Readings from Instructors Chemistry textbook are encouraged.

**Class Exercise:** This week’s exercises are incorporated into the PowerPoint presentation. Animate slides according to your preference.

**Videos:** [Introduction to Molecules](https://www.youtube.com/watch?v=hj9RTDiZBrA&feature=youtu.be)  [Drawing and Naming Molecules](https://www.youtube.com/watch?v=Fzm_desW2Ag&feature=youtu.be)  [Naming Simple Alkanes](https://www.khanacademy.org/science/organic-chemistry/bond-line-structures-alkanes-cycloalkanes/naming-alkanes/v/naming-simple-alkanes)  [Functional Groups](https://www.khanacademy.org/science/organic-chemistry/bond-line-structures-alkanes-cycloalkanes/functional-groups/v/functional-groups-first)

**Homework #1:** Molecules and Nomenclature

**Lecture 6:** Stoichiometry and Reactions

**Required Readings:**

* Anastas, Paul T.; Warner, John C.; “Green Chemistry: Theory and Practice”; Oxford University Press: Oxford, 1998, Chapter 7.
* Readings from Instructors Chemistry textbook are encouraged.

**Optional/Supplemental Readings:** Readings from Instructors Chemistry textbook are encouraged.

**Class Exercise:** Beyond Benign Reactions Lab, Biomimicry Matching Game, Stoichiometry Challenge

**Videos:** [Balancing Equations Part 1](https://www.khanacademy.org/science/chemistry/chemical-reactions-stoichiome/balancing-chemical-equations/v/balancing-chemical-equations-introduction)  [Balancing Equations Part 2](https://www.khanacademy.org/science/chemistry/chemical-reactions-stoichiome/balancing-chemical-equations/v/balancing-chemical-equation-with-substitution) [Balancing Equations Part 3](https://www.khanacademy.org/science/chemistry/chemical-reactions-stoichiome/balancing-chemical-equations/v/visually-understanding-balancing-chemical-equations) [Stoichiometry Example](https://www.youtube.com/watch?v=UL5k7_G0l_A&feature=youtu.be)  [Types of Reactions](https://www.youtube.com/watch?v=eWQO3aTgFDg&feature=youtu.be)

**Lecture 7:** Limiting Reagent, Yield, and the Atom Economy

**Required Readings:** Readings from Instructors Chemistry textbook are encouraged.

**Optional/Supplemental Readings:**

* Giraud, R., Williams, P., Sehgal, A., Ponnusamy, E., Phillips, A., Manley, J. “Implementing Green Chemistry in Chemical Manufacturing: A Survey Report”; *ACS Sustainable Chemistry & Engineering;* 2014, *2* (10), 2237-2242. <https://pubs.acs.org/doi/abs/10.1021/sc500427d>
* Mastronardi, M., Reyes, L. “Green Chemistry Principle #2: Atom Economy”; 2014, at GreenChemofT.wordpress.com. <https://greenchemuoft.wordpress.com/2014/04/04/greenchemprinciple2/>

**Class Exercise:** Greener Synthesis of Ibuprofen

**Videos:** [Yield and Limiting Reagent](https://www.youtube.com/watch?v=U5UTb9c78vE)  [Theoretical Yield](https://www.youtube.com/watch?v=3QNKmMNO5wA) [Percent Yield](https://www.youtube.com/watch?v=pFmCn-cwOW8) [Quick Snapshot of Atom Economy](https://www.youtube.com/watch?v=Zuyk4hfbjSA) [Atom Economy](https://www.youtube.com/watch?v=Y9NVz7_9zw4)

**Homework #2:** Stoichiometry and Reactions

**Lecture 8:** Exam #1

**Lecture 9:** Sustainability

**Required Readings:** none

**Optional/Supplemental Readings:**

* “Our common vision”, *Nature Sustainability,* Volume 1, Page 1 (2018), <https://www.nature.com/articles/s41893-017-0020-x>
* U.N. Sustainable Development Goals, United Nations, <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>
* Report of the World Commission on Environment and Development: Our Common Future (Brundtland Report), World Commission on Environment and Development, 1987, <http://www.un-documents.net/our-common-future.pdf>

**Class Exercise:** none

**Videos:** none

**Lecture 10:** Life Cycle Assessment

**Required Readings:** none

**Optional/Supplemental Readings:**

* Guidance on Life-Cycle Thinking and Its Role in Environmental Decision Making, Sustainable Materials Management Coalition, March 2014, <https://www.michaeldbaker.com/wp-content/uploads/2014/03/Guidance-on-Life-Cycle-Thinking-031014.pdf>

**Class Exercise:** Explore the materials flow of petrochemicals. See lesson plan for more details

**Videos:** [Life Cycle Assessment Video](https://youtu.be/KrJUpSiCOoU)

**Lecture 11:** Renewable Feedstocks

**Required Readings:**

* “Green Chemistry: Theory and Practice”, Anastas and Warner, Oxford University Press, 1998. Ch. 4 Section 7
* “Green Chemistry: Theory and Practice”, Anastas and Warner, Oxford University Press, 1998. Ch. 6

**Optional/Supplemental Readings:**

* “Chemistry in Context”, 8th Edition, McGraw Hill Education. Ch. 9.1-9.10, 12.6

**Class Exercise:** none

**Videos:** [Feedstocks](https://www.youtube.com/watch?v=088WCtNjYIE&feature=youtu.be) [Feedstocks: Renewable Feedstocks](https://www.youtube.com/watch?v=5-TtEE5C2_E&feature=youtu.be)  Feedstocks (in PowerPoint)

**Lecture 12:** Renewable Feedstocks for Energy

**Required Readings:** none

**Optional/Supplemental Readings:**

* Clark, J.H., Luque, R., Matharu, A.S., Annu. Rev. Chem. Biomol. Eng., 2012, 3: 183-207, <https://www.ncbi.nlm.nih.gov/pubmed/22468603>
* “Agriculture: Beyond food versus fuel”, Graham-Rowe, D., Nature, 474, S6-S8, 2011, <https://www.nature.com/articles/474S06a>
* “Introduction: Next generation biofuels”, Fairley, P., Nature, 474, S2-S5, 2011, <https://www.nature.com/articles/474S02a>
* “Ethics of Biofuels”, by Sharon Astyk, Resilience, originally published by Energy Bulletin, December 28, 2006, <https://www.resilience.org/stories/2006-12-28/ethics-biofuels/>
* “Grass Makes Better Ethanol than Corn Does”, Scientific American, Biello, D., January 8, 2008, <https://www.scientificamerican.com/article/grass-makes-better-ethanol-than-corn/>
* “Switchgrass may unlock the future of biofuel”, March 3, 2017, Silke Schmidt, University of Wisconsin – Milwaukee, <https://phys.org/news/2017-03-switchgrass-future-biofuel.html>

**Class Exercise**: none

**Videos:** none

**Lecture 13:** Real-World Cases in Green Chemistry

**Required Readings:** none

**Optional/Supplemental Readings:**

* “Presidential Green Chemistry Challenge: Award Recipients 1996-2016”, US EPA. <https://www.epa.gov/sites/production/files/2016-10/documents/award_recipients_1996_2016.pdf>
* Newlight Technologies:
  + Popular Science, 2014: <http://bestofwhatsnew.popsci.com/newlight-technologies-aircarbon>
  + Plastics Today, 2016: <https://www.plasticstoday.com/materials/newlight-licenses-aircarbon-ikea/57710583724253>
  + Making Plastic from Pollution, January 11, 2017: <https://powerpalletinc.com/making-plastic-from-pollution/>
  + BCA Chemistry, 2013: <https://bcachemistry.wordpress.com/tag/aircarbon/> (includes a good overview of the chemistry, including Thermodynamics and polymer chemistry)
* Buckman:
  + A 2012 article is included with some further information (Pulp & Paper International (PPI)) <https://www.buckman.com/wp-content/uploads/2018/04/PPI-2012-Greener-Pckg.pdf>
  + 2017 Paper Fact Sheet from Green America’s Paper Project
  + 2018 Environmental Paper Network report titled “State of the Global Paper Industry”, <http://environmentalpaper.org/wp-content/uploads/2018/04/StateOfTheGlobalPaperIndustry2018_FullReport-Final-1.pdf>
* Bruce Lipshutz:
  + Lipshutz, B., Current Opinion in Green and Sustainable Chemistry, 2018, 11: 1-8 <https://www.sciencedirect.com/science/article/pii/S2452223617300780>
  + Lipshutz, B., J. Org. Chem., 2017, 82, 2806-2816 <https://pubs.acs.org/doi/ipdf/10.1021/acs.joc.7b00010>
  + Lipshutz, B., ACS Sustainable Chem. Eng., 2016, 4, 5838 – 5849 <https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.6b01810>
* Archer Daniels Midland and Novozymes, NovaLipidTM:
  + Additional information about trans fats and health effects: Mayo Clinic, <https://www.mayoclinic.org/diseases-conditions/high-blood-cholesterol/in-depth/trans-fat/art-20046114>
* Pfizer:
  + Taber, G.P., Pfisterer, D.M., and Colberg, J., Organic Process Research & Development, 2004, 8, 385-388 <https://pubs.acs.org/doi/10.1021/op0341465>
* Dow Chemical Company (Rohm and Haas):
  + Additional educational modules by Michael Cann, University of Scranton, <http://www.scranton.edu/faculty/cannm/green-chemistry/english/environmental.shtml>
  + Additional information on Marine anti-foulants: International Marine Organization: <http://www.imo.org/en/OurWork/Environment/Anti-foulingSystems/Documents/FOULING2003.pdf>

**Class Exercise:** Real-World Cases in Green Chemistry Exercise

**Videos:** [Newlight Technologies](https://www.youtube.com/watch?v=s3mEbSSDaNk) [Buckman Maximyze® Technology](https://www.youtube.com/watch?time_continue=2&v=42H7SsCX7zI) [SiGNa Technologies](http://www.signachem.com/resources/?fwp_languages=english&fwp_categories=videos)

**Lecture 14:** Designing for Recycling & Degradation

**Required Readings:**

* “Designing Small Molecules for Biodegradation” R. S Boethling, Chem. Rev. 2007, 107, 2207-2227. https://pubs.acs.org/doi/10.1021/cr050952t

**Optional/Supplemental Readings:** none

**Class Exercise:** Biodegradation Activity using BIOWIN, Estimating Biodegradation of Organic Molecules, and Design for Biodegradability

**Videos:** [Introduction to Biodegradation](https://youtu.be/k4Vk5zPPMxA)

**Homework #3:** Estimating Biodegradation of Organic Molecules

**Lecture 15:** Catalysis

**Required Readings:** none

**Optional/Supplemental Readings:**

* Lancaster, Mike; “Green Chemistry An Introductory Text”; 2002, Ch.4, 84-129 (Editions 1, 2, or 3).
* Clark, James; “Catalysis and Green Chemistry”, Pure Appl. Chem., Vol. 73, No. 1, pp. 103–111, 2001.
* “Introduction to Green Chemistry”, Albert S. Matlack, CRC Press, Ch. 5 & 6 2nd Edition, 2010.

**Class Exercise:** none

**Videos:** [Catalysis Introduction and Life Cycle](https://www.youtube.com/watch?v=jH7RInRDJPY&feature=youtu.be)  Catalysts (in Powerpoint)

**Lecture 16:** Solvents: Understanding Their Role

**Required Readings:**

* “Green Chemistry: Theory and Practice”, Anastas and Warner, Oxford University Press, Ch. 4 Section 5

**Optional/Supplemental Readings:**

* “CHEM21 selection guide of classical and less classical solvents” Denis Prat and et. Al, Green Chem., 2016, 18, 288 <https://pubs.rsc.org/en/content/articlelanding/2016/gc/c5gc01008j#!divAbstract>
* “Chemistry in Context”, 8th Edition, McGraw Hill Education. Ch. 5

**Videos:** [Solvents: Introduction](https://www.youtube.com/watch?v=cFOenexaNSw&feature=youtu.be)  [Why Use Solvents](https://www.youtube.com/watch?v=QrtNiMMCMt8&feature=youtu.be)  [Solvents: Applications](https://www.youtube.com/watch?v=s292eRxhmms&feature=youtu.be)  Solvents video (in PowerPoint)

**Lecture 17:** Working without Solvents

**Required Readings:** “Green Chemistry: Theory and Practice”, Anastas and Warner, Oxford University Press, Ch. 4 Section 5

**Optional/Supplemental Readings:**

* “Introduction to Green Chemistry”, Albert S. Matlack, CRC Press, Ch. 8, 2nd Edition, 2010.
* Andrew P. Dicks (2009) Solvent-free reactivity in the undergraduate organic laboratory, Green Chemistry Letters and Reviews, 2:2, 87-100, DOI: 10.1080/17518250903164549 <https://www.tandfonline.com/doi/full/10.1080/17518250903164549?scroll=top&needAccess=true>
* Andrew P. Dicks (2009) A review of aqueous organic reactions for the

undergraduate teaching laboratory, Green Chemistry Letters and Reviews, 2:1, 9-21, DOI: 10.1080/17518250902820182 <https://www.tandfonline.com/doi/full/10.1080/17518250902820182>

**Class Exercise:** none

**Videos:** none

**Homework #4:**

* Solvent Substitution: CHEM21 Solvent Selection Guide
  + More information available on the Guide here: (<http://learning.chem21.eu/methods-of-facilitating-change/tools-and-guides/>)

**Lecture 18:** Exam #2

**Lecture 19: Green Chemistry and Energy**

**Required Readings:** none

**Optional/Supplemental Readings:**

* Energy Independence, Transcript of the Testimony of Richard E. Smalley to the Senate Committee on Energy and Natural Resources —April 27, 2004: http://www.americanenergyindependence.com/energychallenge.aspx
* For more information about biodiesel and fact sheets see BDI Biodiesel: Biodiesel Fact Sheets: https://www.biodiesel.org/what-is-biodiesel/biodiesel-fact-sheets
* Open-access article on dye-sensitized solar cells: Efficient Dye-Sensitized Solar Cells for Direct Conversion of Sunlight to Electricity, Gratzel, M., Kalyanasundaram, K., Material Matters, 2009, 4.4, 88, https://www.sigmaaldrich.com/technical-documents/articles/material-matters/efficient-dye-sensitized.html
* For more information about microwave synthesis: Nuchter, M., Ondruschka, B., Bonrath, W., Gum, A., [Green Chem.](https://doi.org/10.1039/1463-9270/1999), 2004, **6**, 128-141https://pubs.rsc.org/en/content/articlehtml/2004/gc/b310502d - DOI: [10.1039/B310502D](https://doi.org/10.1039/B310502D)
* For more information on Smart Grids and systems: Smarter planet: Energy and Utilities, Slideshare, IBM, 2011,https://www.slideshare.net/gmattathil/smarter-planet-energy-and-utilities

**Class Exercise:** Synthesis of Biodiesel, and Dye-sensitized Blackberry Solar Cell

**Videos:** none

**Lecture 20:** Green Analytical Chemistry

**Required Readings:** none

**Optional/Supplemental Readings:**

* Green Analytical Chemistry articles:
  + Vanhoenacker, G., Sandra, P., David, F., Sandra, K., Pereira, A., 2010, Green chromatography (Part 1): Introduction and liquid chromatography, LC-GC Europe, 23, 242-259 <http://www.chromatographyonline.com/green-chromatography-part-1-introduction-and-liquid-chromatography>
  + “Green Analytical Chemistry” by Paul Ferguson and Douglas Raynie, in Green Techniques for Organic Synthesis and Medicinal Chemistry, 2nd Edition, Zhang, W. and Cue, B. W., Eds., Wiley, 2018, pp. 43-66
  + M. Koel, M. Kaljurand, *Crit. Rev. Anal. Chem.*, **42**, 192-195 (2012). <https://pubs.acs.org/doi/abs/10.1021/cr068359e>
  + Galuszka, A., Migaszewski, Z., Namiesnik, J., 2013, The 12 principles of green analytical chemistry and the SIGNIFICANCE mnemonic of green analytical practices, Trends Anal. Chem., 50, 78-84
  + Galuszka, A., Konieczka, P., Migaszewski, Z. Namiesnik, J., 2012, Analytical eco-scale for assessing the greenness of analytical procedures, Trends Anal. Chem., 37, 61-72
  + Tobiszewski, M., Namiesnik, J., 2015, Scoring of solvents used in analytical laboratories by their toxicological and exposure hazards, Ecotox. Environ. Safety, 120, 169-173
  + Chem. Rev., 2007, 106, 6, 2695-2708
  + National Environmental Methods Index (NEMI): <https://www.nemi.gov/about/> (searchable database for analytical methods, includes a greenness metric)
  + R. Helmy, R. Hartman, C. J. Welch, and M. Al-Sayah, *Green Chem.,* 2011, **13**, (934-939)
* Solvent Selection articles:
  + Dunn and Perry, et. al., Green Chem., 2008, 10, 31-36
  + Henderson, R.K., et. al., Green Chem., 2011, 13, 854
  + American Chemical Society’s Green Chemistry Institute Pharmaceutical Roundtable, <http://www.acs.org/content/acs/en/greenchemistry/industry-business/pharmaceutical.html>
  + Solvent replacements for chromatography: Taygerly, J.P., Peterson, E.A., *et. al*., Green Chemistry, 2012, 14, 3020-3025
* Additional background information:
* For more information on X-ray fluorescence: ThermoFisher, <https://www.thermofisher.com/us/en/home/industrial/spectroscopy-elemental-isotope-analysis/spectroscopy-elemental-isotope-analysis-learning-center/elemental-analysis-information/xrf-technology.html>
* For more information on IR spectroscopy: Compound Interest, <https://www.compoundchem.com/2015/02/05/irspectroscopy/>
* For more information on Raman Spectroscopy: NanoPhoton, <https://www.nanophoton.net/raman/raman-spectroscopy.html>

**Class Exercise:** none

**Videos:** [Green Analytical Chemistry webinar](https://www.beyondbenign.org/webinar/implementing-green-chemistry-introductory-analytical-course/)

**Lecture 21:** Introduction to Toxicology

**Required Readings:** Anastas, Paul T.; Warner, John C.; “Green Chemistry: Theory and Practice”; Oxford University Press: Oxford, 1998, Chapter 5.

**Optional/Supplemental Readings:** none

**Class Exercise:**

* Relationship Between pKa and Skin Irritation Activity
* Module 1 Aqueous and Lipid Solubility (optional)

**Videos:** [Toxicology](https://www.youtube.com/watch?v=X5x-RXLoLNU&feature=youtu.be) [Toxicology: Toxic Substances](https://www.youtube.com/watch?v=aw0_neqg3Eo&feature=youtu.be) [Toxicology: Dose and Exposure](https://www.youtube.com/watch?v=LBk6y7aM7js&feature=youtu.be) [Toxicology: Toxicity Categories](https://www.youtube.com/watch?v=AJ9OvAqTjI0&feature=youtu.be) [Toxicology: Factors Affecting Toxicity](https://www.youtube.com/watch?v=ayOIWXTOheQ&feature=youtu.be)  [Toxicology: Chemical Interactions](https://www.youtube.com/watch?v=YhCD_FGFCXA&feature=youtu.be)  [Concepts in Toxicology (optional)](https://www.webpages.uidaho.edu/etox/lectures/lecture03/index.htm)

**Lecture 22:** Chemical Exposure and Dosage

**Required Readings:** Toxicology - Dose Response (see folder)

**Optional/Supplemental Readings:** none

**Class Exercise:**

* In-Class Discussion - Which Solvent Would You Use?
* Lettuce Seed Assay (optional)
* Daphnia Bioassay LD%) (optional)

**Videos:** [Toxicology - Dose Response](https://youtu.be/BukK1R3lCnU)

**Homework #5:** Chemistry for the Environment

**Lecture 23:** Molecular Toxicology

**Required Readings:**

* Zimmerman, J. B., & Anastas, P. T. “Toward designing safer chemicals”; *Science,* 2015a, *347*(6219), 215-215. doi: 10.1126/science.aaa6736 <http://science.sciencemag.org/content/347/6219/215.full>
* Zimmerman, J. B., & Anastas, P. T.; “Toward substitution with no regrets”; *Science*, 2015b, 347(6227), 1198-1199. doi: 10.1126/science.aaa0812

<http://science.sciencemag.org/content/347/6227/1198.full>

**Optional/Supplemental Readings:** none

**Class Exercise:**

* 5.B-D. Electrophilic Reactions in Toxicity (Optional)
* Module 8 ADME and Rational Chemical Design (Optional)

**Videos:** [Toxicology - ADME](https://youtu.be/v6sFdawERRU)

**Lecture 24:** Designing Future Products with Reduced Toxicity

**Required Readings:**

* Voutchkova, A. M., Osimitz, T. G., Anastas, P. T.; “Toward a Comprehensive Molecular Design Framework for Reduced Hazard*” Chem. Rev*, 2010, *110* (10), 5845-5882. doi: 10.1021/cr9003105

<https://pubs.acs.org/doi/abs/10.1021/cr9003105>

* National Academies Press “A Framework to Guide Selection of Chemical Alternatives”, 2014, Chapter 13.

**Optional/Supplemental Readings:** none

**Class Exercise:**

* Module 5 Glutathione as a Tool for Testing Gene Function (optional)
* Module 6 Crossroads of Computational Chemistry and Toxicology (optional)
* Module 7 Using ProTox (optional)

**Videos:** none

**Homework #6:** Toxicology

**Lecture 25 & 26:**

**Required Readings:**

* Mellor et al. (2018) The safer chemical design game. Gamification of green chemistry and safer chemical design concepts for high school and undergraduate students, Green Chemistry Letters and Reviews, 11:2, 103-110, DOI: 10.1080/17518253.2018.1434566

<https://www.tandfonline.com/doi/abs/10.1080/17518253.2018.1434566>

**Optional/Supplemental Readings:** none

**Class Exercise:** none

**Videos:** none

**Lecture 27:** Final Exam