Curriculum Units by Fellows of the National Initiative
2009 Volume V: Green Chemistry

Using Green to Catalyze the Changing of The World

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Introduction

Green Chemistry is defined as the invention, design, and application of chemical products and processes to reduce or eliminate the use and generation of hazardous substances; in laymen's terms, Green Chemistry is about inventing, designing, and creating products and systems that will be sustainable into the future. Green Chemistry's goal is to make sure that every atom that you put into a reaction ends up in your product.

Green Chemistry takes an amazing view on the world of science. The concept of Green Chemistry and sustainability is so simple, it is brilliant. I must admit that when I first heard of this seminar, I was under the impression that Green Chemistry dealt with 'recycling and cleaning up the messes left by earlier generations', a thought that excited me as much as watching paint dry. As I grew to understand that Green Chemistry focused on the development of a sustainable future, I became excited. I realized that I could have an impact on the future world, based on MY actions. As I made this connection, I realized that this could be THE connection that my students could make as well. Creating an awareness of Green Chemistry and sustainability has endless possibilities. Paul Anastas' anecdote [1] of 'the consumer products company and the supplier' brings to light the power of this new way of thinking.

> A consumer products company, after grasping the 12 principles of Green Chemistry, began looking at the contents of their cleaning products. They noticed a chemical that they wanted changed in one particular product. They went to their supplier and explained that the chemical needed to be removed; the supplier had one year to make the change in order for them to purchase from the supplier again. The supplier responded "we can have the chemical out next week, why didn't you ask?"

This anecdote exemplifies the change that can occur when we as a society are aware of Green Chemistry and what it means; my goal is to teach this awareness while combining applicable Chemistry methodologies that my students can use to learn the fundamentals.

As a Chemistry teacher, I have observed certain commonalities amongst my students. Students want to know: 1.) why they have to learn Chemistry, 2.) how does Chemistry apply to their world now, and 3.) how will Chemistry help them in the future. My answer usually is that Chemistry is the 'connecting science', a gateway that can open their eyes to what exists around them now, and to what possibilities can await them. As I explain this, I see the blank look on some faces, the look of excitement on a few, and for the majority, the look of "here we go again - a teacher that thinks we've got to love this subject because they do". I look forward to using this unit of Green Chemistry as THE connector to help catalyze students into becoming the future stewards of our world.

This Unit is designed for High School Chemistry students, which usually includes 10 th through 12 th graders. The Unit has been designed to be taught after the first three weeks of school; it should last 4 weeks and, because of the activities, would ideally be done during a block schedule.

Background and Rationale

I teach in a Title I High School that has a demographic population of 98% African-American, 1% Hispanic and 1% Caucasian. My typical student is in the 10 th to 12 th grade, enrolled in Algebra II, and has difficulty applying Math to real world problems. Most of my students perceive Math as a dreaded subject, and Science as irrelevant to their lives. They are motivated by finding paths to success. They perceive success as having money and the freedom to pursue opportunities that money can provide.

I originally intended to relate Green Chemistry to the amount of money (green) that my students could earn by 'Going Green'; I originally thought that if they knew how profitable being a Green Chemist could be, then my students would participate in the 'Sustainability Revolution'. As my knowledge and scope of Green Chemistry increased, I went through a transformation and certain realizations became absurdly obvious; we as a society ARE on a collision course; we are creating more waste than we are recycling, and even when creating new products, the amount of toxic waste created is more than the amount of products created. Sustainability is no longer an option, it is a requirement for our existence. President Obama acknowledges that to improve the quality of life for all Americans, we need to renew our commitment to science, technology, and innovation;[2] I believe this to be true. We need stewards of the future who will understand the needs of our society and earth; these stewards need to be advocates of Science, and in particular Chemistry, for the future will belong to those who are able to apply unique, new, innovative solutions to solve our energy crisis.

I intend to spark my students' passion in Science and in their ability to Change The World. The lessons have been designed to show them the collision course we are on and the disparity of our environmentally unconscious society. The lessons will then show my students the opportunities that can be had to Change The World using Green Chemistry. Rather than advocating 'Green' to my students by telling them to be 'Green', I will teach my students how to interpret the facts, and allow them to come up with their own conclusions. I will teach them about new 'Green' initiatives, and have them interpret the facts of those initiatives, coming up with their own conclusions. By teaching them how to apply the principles of Green Chemistry in their lives, and understanding how they can have an impact on their future, I believe they can find a successful space to create and be creative. My goal will be to have students experience what has been, and to create what can be. All of these experiences will be wrapped around the 12 main principles of Green Chemistry (see appendix A).

Scaffolding is a pedagogical approach that uses consecutive skill sets to teach something. The skill sets are taught in an order such that skill 3 needs skill 2, and skill 2 needs skill 1. Thus, if you wanted to teach someone how to balance their checkbook, you would first teach them how to identify and count money, then how to add and subtract money, and finally how to balance their checkbook.

Objectives

The unit will be taught over a four week period at the beginning of the year. Prior to the unit, the following items will have already been covered:

1. The 12 principles of Green Chemistry - What are they, and what do they mean? Let's talk about sustainability.
2. The Periodic Table - How to read and interpret atoms, protons, electrons, neutrons, and charges.
3. Reactions - Reactants, and products makeup reactions. There are 6 main types of reactions.

The Unit will teach the following objectives:

1. Multiple Step Reactions - Everyday products that we use are usually synthesized with multiple step reactions.
2. Reaction Types - The reaction types generally fall into 6 categories (Table A).
3. Basic Stoichiometric Dimensional Analysis - This methodology (often called stoichiometry) allows amounts and units to be converted based on commonalities.
4. Law of Conservation of Mass - Mass in neither created nor destroyed. The mass of the reactants must always equal to the mass of the products.
5. Atom Economy - This is the determination of the efficiency (at an atomic level) of the product being created.
6. E-Factor - This is the environmental factor that calculates the amount of waste by the amount of product created. It gives an overall ratio as to the impact that a product can have.
7. Case Study - Ibuprofen will be used as a case study to determine how multiple step processes were optimized to increase atom economy and yield.

Strategies & Activities

Lesson 1: Background and Approach

As we develop the scaffold of knowledge for our students, there are key concepts that are vital to their success in Chemistry. Being able to identify reactants, products, and the reaction type are critical; understanding how to calculate the Gram Formula Mass (GFM) for a single atom or complex molecule is also a necessity. In conceptual order, the recommended scaffolding approach is Reaction Concepts → Reaction Types → Atom Count in molecules → Law of Conservation of Mass → GFM → Atom Economy.

Reaction Types can generally be broken into six types (make sure to let your students know two more types of reactions, dissociation and nuclear, will be covered later in the year). Please note that in the examples given for Table A below, A, B, C and D represent a 'placeholder' for Elements from the Periodic Table of Elements in the first four reaction types, while H represents Hydrogen, O Oxygen, C Carbon, A Acid and B Base in the

Combustion and Acid-Base reactions:

Table A - Reaction Types

Reaction Types	**Algebraic Representation**
Synthesis	A + B -> C
Decomposition	AB -> A + B
Single-Replacement	A + BC -> AC + B
Double Replacement	AB + CD -> AD + CB
Combustion	(C + H) + O_2 -> CO_2 + H_2O
Acid-Base	HA + BOH -> BA (salt) + H_2O

Recognizing the number of atoms within a molecule is also an essential understanding for Chemistry. Numbers in front of the molecule (i.e., 3 in 3NaCl) are called coefficients; subscripts follow the particular atom or molecule that they coincide with (i.e., 2 in H_2O). If a molecule is made up of one element, than variations of texts may refer to it as an atom or a molecule. Table B gives an example of six numerical variations that commonly occur when counting atoms:

Table B - Six Numerical Variations for Counting Atoms

C *Means there is 1 Carbon Atom(no number next to atom means that there is 1 atom)*	**3C** *Means that there are 3 Carbon Atoms (3*1)*	**$4H_2$** *Means that there are 8 Hydrogen Atoms (4*2)*
NO_3 *Means that there are 3 Oxygen Atoms and 1 Nitrogen Atom*	**$2NO_3$** *Means that there are 6 Oxygen Atoms (2*3) and 2 N Atoms (2*1)*	**$4(NO_3)_2$** *Means that there are 24 Oxygen Atoms (4*3*2) and 8 Nitrogen Atoms (4*1*2)*

The Gram Formula Mass (GFM), also commonly referred to as molecular mass, molecular weight, or formula weight, is determined by adding the atomic mass units (amu) found on the periodic table of all the atoms in a molecular compound. This GFM is the amount of grams of substance in one mole; thus, the units will be in grams per mole, or annotated as g/mol. When calculating the GFM, you add the total mass for all the atoms within the molecule. Using the six variations from Table B, Table C below shows the calculation of Gram Formula Mass for each molecule:

Table C - Gram Formula Mass Variations

C = 12 g/mol *C – 12 amu x 1 atom*	**3C = 36 g/mol** *C – 12 amu x 3 atoms*	**$4H_2$ = 8 g/mol** *H – 1 amu x 4x2 atoms*
NO_3 = 62 g/mol *N –14 amu x 1 atom* *N = 14 g/mol* *O_3 –16 amu x 3 atoms* *O = 48 g/mol*	**$2NO_3$ = 124 g/mol** *N –14 amu x 2x1 atoms* *N = 28 g/mol* *O_3 –16 amu x 2x3 atoms* *O = 96 g/mol*	**$4(NO_3)_2$ = 496 g/mol** *N –14 amu x 4x1x2 atoms* *N = 112 g/mol* *O_3 –16 amu x 4x3x2 atoms* *O = 384 g/mol*

Once you understand reactions, reaction types, how to count atoms within molecules, and how to calculate the GFM, you have the scaffold knowledge to understand and calculate the Percent Atom Economy. The Percent Atom Economy is the percent "of what you put into your pot [that] ends up in your product." [3] The formula for calculating the Percent Atom Economy is:

$$\text{Percent Atom Economy (\%)} = (\text{GFM of desired product} \div \text{GFM of all products}) \times 100$$

This lesson will teach 4 objectives and review 4 topics. Multiple Step Reactions, Gram Formula Mass, Atom Economy, and E-factors will be taught. Reaction types, some basic laboratory safety techniques, Law of Conservation of Mass, and vocabulary will be reviewed. Before handing out the 'Analysis of Acetic Acid Production Sheet', pour 5 mL of vinegar into each of 5 test tubes (make sure not to let the students see you pour it). Review with the students how to properly sniff from an unknown substance (wave hand over the test tube opening and waft towards your nose), as well as how to hold a test tube (using test tube tongs). Ask them what they think is in the test tube. Use words that are easily identifiable with acids so that you can scaffold their understanding of acids and bases as the year progresses. Have them write down quantitative and qualitative properties of the liquid. Have the students classify those properties as physical or chemical. If needed, use a pH paper to test the pH (which should be well below 7.0 since it is an acid). Mention that acetic acid is known in the Chemistry world as ethanoic acid, and is with the carboxylic acid family; it is used to wash medicines such as ibuprofen, used in soft drink bottles, and is commonly found in wood glue. Acetic acid can be made synthetically from petrochemical feedstocks, or from biological sources. After some discussion, let the students know that the substance in the test tube is vinegar, and that it is a biologically sourced form of diluted acetic acid. [4] With this information covered, have the students look at Table E and while you describe the multiple steps that it takes to make Acetic Acid, emphasize that the stick and ball diagrams represent the same thing as the stick diagrams, and that both represent the molecular abbreviations. Hand out a modified version of Table D (Table D has the answers filled in for your convenience, but remove as necessary for your students) and have the students complete the sheets individually or in pre-selected groups of two.

Table D - An Analysis of Acetic Acid Production

An Analysis of Acetic Acid Production – Instructions(Multiple Step Reaction and Reaction Types)*Fill out the table below with the step#, reaction type, reactants, catalysts (if any), products, what chemicals we are keeping, and which we are wasting. Then, calculate the Gram Formula Mass (GFM) for each molecule (don't forget your units!). Proceed to calculate the total GFM of your reactants, products, and wasted molecules for each step. Finally, complete the atom economy calculation.*

Step #	**ReactionType**	**Reactant Molecules**	**Catalyst**	**Product Molecules**	**Atoms Kept**	**Atoms Wasted**
1	**Single Repl.**	**C, FeS_2**		**CS_2, Fe**	**CS_2**	**Fe**
2	**Single Repl.**	**CS_2, Cl_2**		**CCl_4, S**	**CCl_4**	**(2)S**
3	**Decomp.**	**CCl_4**	**Heat**	**C_2Cl_4, Cl_2**	**C_2Cl_4**	**(2)Cl_2**
4	**Single Repl. & Dbl Repl.**	**C_2Cl_4, Cl_2, H_2O**		**C_2Cl_3OOH, HCl**	**C_2Cl_3OOH**	**(3)HCl**
5	**Single Repl.**	**C_2Cl_3OOH, H_2**		**CH_3COOH, HCl**	**CH_3COOH**	**(3)HCl**

Calculate the Gram Formula Mass

C: **12 g/mol** Fe: **56 g/mol** S: **32 g/mol** H_2: **2 g/mol** CS_2: **76 g/mol** Cl_2: **70 g/mol** CCl_4: **152 g/mol**

FeS_2: **120 g/mol** C_2Cl_4: **164 g/mol** H_2O: **18 g/mol** HCl: **36 g/mol** C_2Cl_3OOH: **162 g/mol** CH_3COOH: **60 g/mol**

Calculate Total Gram Formula Mass

Step 1:	Reactants: **132 g/mol**	Products: **132 g/mol**	Products Wasted: **Fe**
Step 2:	Reactants: **216 g/mol**	Products: **216 g/mol**	Products Wasted: **2S**
Step 3:	Reactants: **304 g/mol**	Products: **304 g/mol**	Products Wasted: **2Cl_2**

Step 4: Reactants: **270 g/mol** Products: **270 g/mol** Products Wasted: **3HCl**

Step 5: Reactants: **168 g/mol** Products: **168 g/mol** Products Wasted: **3HCl**

What pattern(s) do you notice? **The reactants weigh the same as the products (Law of Conservation of Mass).**

Calculate Atom Economy

Final Product Formula: **CH_3COOH** Final Product GFM: **60 g/mol**

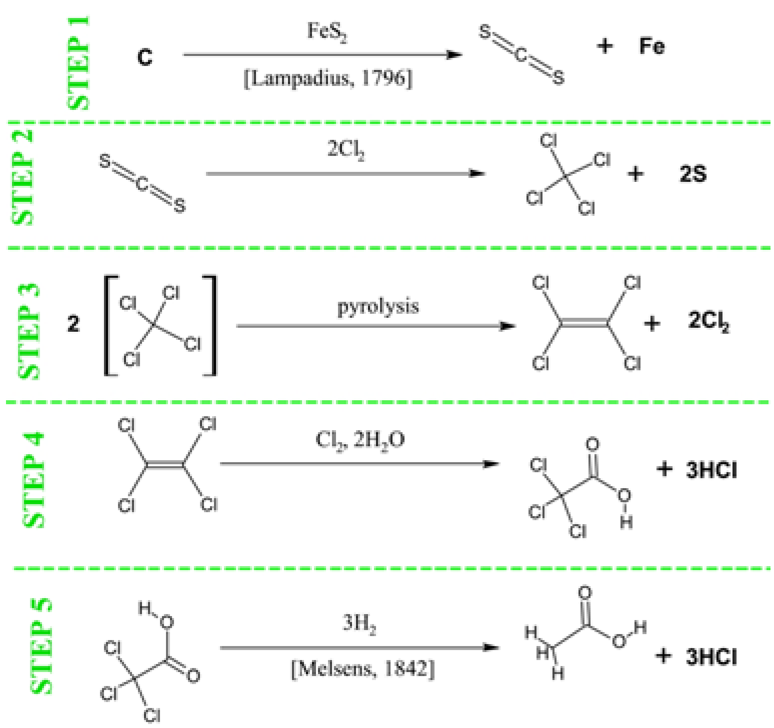
Total GFM of all products: **1090 g/mol** Atoms Wasted: **Fe, (2)S, (2)Cl_2, (6)HCl**

Atom Economy Formula Inputs: **(Final Product GFM÷(Total GFM of final product + wasted products))x100 = (60÷(60+476))x100 = (60÷536)x100 = 11.2 %**

Atom Economy (%): **11.2 %**

Table E - Acetic Acid Production - Stick Diagram

An Analysis of Acetic Acid Production (Multiple Step Reaction, Reaction Types, E-factor and Atom Economy)



Lesson 2: Background and Approach

Basic Stoichiometric Dimensional Analysis is an essential survival skill in Chemistry. It allows us to use physical and chemical properties of chemistry to mathematically manipulate numbers and units to solve simple and complex problems. Although stoichiometry is one of the fundamental skills in Chemistry, it is an essential math skill as well that, if mastered, can carry on with our students through their lifetime; unfortunately, getting our students to make that transference can sometimes be difficult.

To understand stoichiometry, there are 5 essential understandings that you need to have. First, numbers and units do not necessarily follow each other, yet both are always needed to properly express something; 4 quarters is 1 dollar, but 4 dollars is not 1 quarter, and 4 or dollars by itself means nothing. Second, any number over 1 is still that number. Third, a quantity divided by itself is equal to one, including units and numbers; 4 quarters divided by 1 dollar is equal to 1. Fourth, any quantity multiplied by 1 is itself. Finally, it is important to conceptualize that units units = 1, and that units units = units.[2] Knowing how to combine and dissociate numbers and their respective units to find answers in secondary numbers and units will allow you to complete this lesson, and develop a good fundamental understanding for the process and understanding of stoichiometry that will be used through Chemistry and beyond.

Table F below has 5 examples of stoichiometric conversions, as well as numerical descriptions of the description from the paragraph above.

Table F - Stoichiometric Conversion Examples

$$\frac{10\ \text{dimes}}{1} = 10\ \text{dimes} \quad \frac{10\ \text{dimes}}{1\ \text{dollar}} = 1 = \frac{4\ \text{quarters}}{1\ \text{dollar}} = \frac{1\ \text{dollar}}{4\ \text{quarters}}$$

To convert $\$$ to quarters: *(but it is still the same amount in dollars)*

$$1{,}000{,}000\ \cancel{\text{dollars}} \times \frac{4\ \text{quarters}}{1\ \cancel{\text{dollars}}} = 4{,}000{,}000\ \text{quarters} = \$\ 1{,}000{,}000$$

While the goal of this lesson is to teach the fundamentals of stoichiometry, the heart of this lesson is in the shock factor impact that I want the students to have. Real world examples of the amounts of pollutants that we have created will be used and sourced. Rather than telling the students that we are on a collision course, I will allow them to come to the conclusion that there is a problem (i.e., Based on these variables, how many gallons of plastic bottles are thrown in our dumps in 2 weeks? 5 months? 1 year?) To allow the students to visualize how the impact will affect them, the space requirements of the waste generated will also be calculated. (i.e., Based on these variables, how much space in landfills will be needed in the next 10 years? How many times could you cover the surface area of the earth with this waste? [5] Conversions will be utilized throughout these questions so that students can grasp the concepts of converting, and overcome the 'memorization'/'calculator only' process of converting.

Once students begin grasping the severity to our planet that the facts represent, we will focus on learning how to express this information. What does this mean? What can be done to solve this problem? Is money going to be the limiting factor in the years to come, or is water, air, oil, gas, fuel, or electricity? [6] This stoichiometry lesson will end with reviewing and having the students quantify the energy requirements of our planet and various existing solutions. The students will begin understanding that there is a whole world of opportunity in the future for people involved in the harnessing of Energy; harnessing the world's energy will bring opportunities to Change The World. After the lesson, we will review the 12 principles of Green Chemistry.

As an interim between Lessons 2 and 3, not covered in this unit, students should be exposed to the concepts of balancing equations numerically and using visual diagrams. Students should be proficient in mathematically balancing more complex reactions. The Law of Conservation of Mass should be reviewed and taught as a method to tell if 'something is missing' when the students are calculating their own products. A website which is an excellent resource for these concepts is http://www.explorelearning.com and is highly recommended.

Lesson 3: Background and approach

At this point, the foundation for atom economy has been covered, although it is conceivable that the students will not yet have a good conceptual grasp of the concept. Lesson 3 will reinforce the concept of Atom

Economy and introduce the concept of E-Factor using Pfizer's 'Economizing with the Atom' exercise (appendix B). The Environmental Factor (E-Factor) is a generic metric that can be used to measure the environmental effectiveness of the production of a substance. Roger Sheldon is recognized as the one who introduced this formula which is:

$$\text{E-Factor} = \text{Total Waste (kg)} \div \text{Total Product (kg)}$$

The 'Economizing with the Atom' exercise will help students visualize atom economy and the E-Factor. As an extension to the lesson, have students generate a list of "Life's Products We Use". Have the students break down the list into the 4 categories from the exercise.

Category	**E-Factor**	**Life's Products We Use**
Petrochemicals	0.1	**Nail Polish**
Bulk Chemicals	1-10	**Plastic Water Bottles**
Fine Chemicals	100	**iPOD Touch Screen**
Pharmaceuticals	250	**Antibiotics**

Then have the students consider the life cycle of those products. Have the students answer the following question - Does the E-Factor of 'Life's Products We Use' change over the life cycle of the products? Explain your answer (Sample Answer: Yes, the E-factor changes over the life cycle of a product. After manufacturing, the product needs to be shipped, which adds to the waste. The product is transported with packaging that may also get thrown away after use.). [7] This exercise will be used to express and help students conceptualize how much waste is created by the various products they use on a daily basis, AFTER production of the item. Discussions will occur as to the impact that the consumer driven society we live in is having on our world, its resources, and our existence.

Lesson 4: Background and Approach

A Case Study will be done on Ibuprofen, and the innovative way in which it is now being produced. [8] The pedagogy of the case study will be unique in that it integrates an interactive 'whodunnit' lesson to teach the students how to analyze the wasted chemicals that the original process created, while looking at other properties. Then, a straightforward analysis will be conducted as to the new methodology and its impact on the world.

Ibuprofen was first patented and introduced in 1969 by the Boot Pure Drug Company, who developed a six step process of developing this 'wonder drug' originally named Brufen. They started with a petroleum based compound known as 2-methylpropylbenzene, and through this six step process created Brufen (also known as 2-(p-Isobutylphenyl)propionic acid). [9] Table H below shows this original process, which became known as the Boot Process. Unfortunately, the Atom Economy was less than 40%, which meant that for every 40 grams made, 60 grams was ending up as toxic waste. In 1997, the BHC Company (now BASF Global) received the 1997 EPA's Presidential Green Chemistry Challenge Award for a new method of synthesizing Ibuprofen. The new method, called the Hoechst Process (see Table I), makes ibuprofen in three steps, and achieves a Percent Atom Economy of greater than 77%, meaning that for every 77 grams of ibuprofen that is produced, now only 23 grams is made up of waste (and the acetic acid wasted from step one can actually be recycled to make more ibuprofen, bringing the actual Percent Atom Economy closer to 90%). [10]

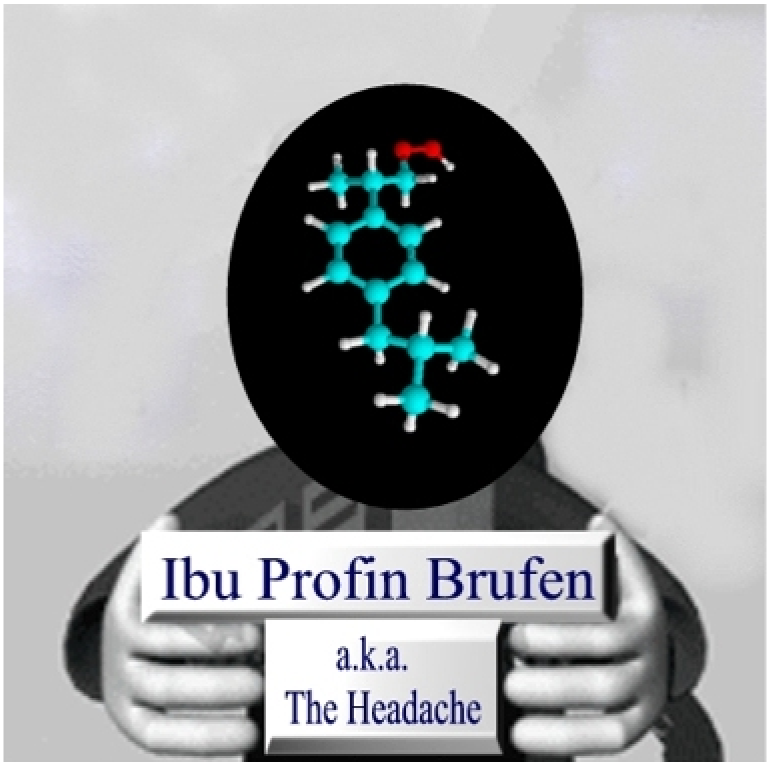
The lesson is jumpstarted with the activity 'A Murder Most Foul'. Student instructions for this activity are described in Table G1; the known facts about 'The Headache' are all accurate statements about Ibuprofen. The only paper evidence found on 'The Headache' is his 'formula book' which is Table H. Table G2 has 14 "wasted chemicals" that have clues as to what step in the Boot Process they came from. Table G2 has the answers in the conclusion section that the students will fill out. The Forensic Scientist Data Sheets are accurate, and provide plenty of opportunities to review concepts such as chemical/physical properties, Diatomic Molecules, GFM, and naming conventions. [11] I suggest finding some manipulative elements and creating 'stations' in your room outlined in tape to emphasize what happened to the 14 elements. The purpose of this exercise is two fold. First, this exercise should help the students conceptualize the ibuprofen formation process (via the older Boot Process). While reviewing elemental properties, the students should then be able to isolate the wasted elements and correlate them to the correct step that they were 'wasted' in, and be able to calculate the final atom economy. When this activity is complete, go over the Boot Process in detail, stopping to describe which elements are wasted in each step (see Table H). Have the students verify their answers. Discuss the following: Since 30 million pounds of ibuprofen are produced each year, how much waste is produced by this method? (Answer: % Economy Calculates to 40.2 %, so the amount wasted using this process equates to 59.8%. [30,000,000 lbs./yr. 0.598 = 17,940,000 lbs. of waste generated per year]) Discuss the implications of this, and allow students time to absorb the enormity of the problem.

Next, explain the 'Green' method of making Ibuprofen, showing the students the Hoechst Process (Table I). Calculate the atom efficiency of this process. Using the same 30 million pounds per year example, calculate the amount of waste produced each year using the new process; the figure is huge, but significantly smaller than the Boot Method. (Answer: % Economy Calculates to 77.4 %, so the amount wasted using this process equates to 22.6%. [30,000,000 lbs./yr. 0.226 = 6,780,000 lbs. of waste generated per year]) Also, make sure to mention that using this new process, the acetic acid generated from Step 1 of the reaction can actually be recycled over and over again to create more ibuprofen. [12]

Table G1 - A Murder Most Foul Activity

A Murder Most Foul

The District Attorney's Office Needs Your Help to convict the Head of the Brufen Family, Ibu Profin Brufen, a.k.a., "The Headache". The Headache is an organized, synthesized chemical drug boss that MURDERED many chemicals in his rise to the top. We have the broken families of chemicals (or what's left of their bodies, in most cases). We have some qualitative and quantitative evidence that the CSI forensic scientists have gathered. Your mission is to: 1.) Decipher the only paper evidence found on "The Headache" (from Table H), 2.) Conduct autopsy forensic research to prove quantitatively and without a doubt what chemicals were killed and in what step, 3.) Present this information to Judge Teacher to see if there is enough quantitative evidence to get a conviction, and 4.) Calculate "The Headache's" murder ratio, known as atom economy, so that we can accurately describe how murderous he was. Use the evidence given below to guide you:



Known Facts

- Born 1969, England
- Resides in Bishop, Texas (since 1992)
- Known for: Drug Production 30 million pounds per year
- Street Names (a.k.a.'s) Advil, Motrin, Nuprin, Proflex, RD13621
- Weight: Needs to be figured out
- What makes him melt: 77-78 ?C
- Stable Drug KingPin

Table G2 - A Murder Most Foul: Forensic Scientist Data Sheets

Forensic Scientist Data Sheets

Item No.: 1 **Date Found:** 8/15 **Partial/Full Body:** Partial

Location Found: High Gases Lane **GFM (g/mol):** 1

Other: **Est. Original GFM (g/mol):**

Chemical Properties: Flammable

Physical Properties: Gas @ 77 ËšF, No Color

Qualitative Observations: We suspect this atom was cut off from ‘The Headache’ himself in an attempt to give him a bonding connection on his rise to power.

Conclusion: Molecule is H from Step 1. GFM = 1 g/mol. Hydrogen is high on the Periodic Table, and is a Gas @ 77 ËšF, has no color, and is extremely flammable. The ibuprofen process starts off with a $C_{10}H_{14}$ molecule that releases this Hydrogren Atom to begin the synthesis. Also, the date is indicative of the first step of the process.

Item No.: 2 **Date Found:** 8/15 **Partial/Full Body:** Partial

Location Found: Acetic Anhydride Circle **GFM (g/mol):** 59

Other: **Est. Original GFM (g/mol):**

Chemical/Physical Properties:

Qualitative Observations: 1 Double Bond amongst the mutilated atoms

Conclusion: Molecule is $C_2H_3O_2$ from Step 1.GFM = 59 g/mol. The 'mutilated double bond' came from the $C_4H_6O_3$, and this molecule is called Acetic Anhydride. Also, the date is indicative of the first step of the process.

Item No.: 3 **Date Found:** 8/16 **Partial/Full Body:** Full

Location Found: Luv Carbonyl Lane **GFM (g/mol):** 68

Other: **Est. Original GFM (g/mol):** 68

Chemical Properties: Likes to take H's from alpha Carbons & Inflammable

Physical Properties: Inorganic Salt

Qualitative Observations: The Drug Boss didn't even try to hide this chemical body… he just left it used and wasted into 9 atoms lying on the streets.

Conclusion: Molecule is $NaOC_2H_5$ from Step 2. GFM = 68 g/mol. It is an inorganic salt called a Carbonyl. The 9 atoms are 1-Na, 1-O, 2-C, and 5-H. It is the only molecule that gets used 100% in the Boots Process. The date (one day later than the previous items) indicates the second step of the process.

Item No.: 4 **Date Found:** 8/16 **Partial/Full Body:** Partial

Location Found: Light Gas Vista **GFM (g/mol):** 1

Other: **Est. Original GFM (g/mol):**

Chemical Properties: Flammable **Physical Properties:** Density: 0.082 g/liter

Qualitative Observations: Found trying to connect its one electron to an atom with 7 valence electrons in its outer shell

Conclusion: Molecule is H from Step 2. GFM = 1 g/mol. Hydrogen is a light flammable Gas that has a density of 0.082 g/liter. The H is 'cut off' along with the Cl (which has 7 valence electrons in its outer shell). The date indicates Step 2.

Item No.: 5 **Date Found:** 8/16 **Partial/Full Body:** Partial

Location Found: Halogen Circle **GFM (g/mol):** 35

Other: Halogen **Est. Original GFM (g/mol):**

Chemical Properties: Melting Point: -150.7 F

Physical Properties: Green

Qualitative Observations: Watch out with this one, when scientist #3 sniffed it slightly, he got very ill.

Conclusion: Molecule is Cl from Step 2. GFM = 35 g/mol. Chlorine is a green Halogen Gas that has a melting point of -150.7 ËšF. Chlorine gas is poisonous and even sniffing small quantities can make you ill. The date indicates Step 2.

Item No.: 6 **Date Found:** 8/17 **Partial/Full Body:** Partial

Location Found: Hydronium Lane **GFM (g/mol):** 1

Other: Was attracting my negativity **Est. Original GFM (g/mol):**

Chemical/Physical Properties:

Qualitative Observations: Diatomic Tendencies

Conclusion: The H ion from Step 3. GFM = 1 g/mol. Hydrogen ion is usually associated with H_3O^+ , a hydronium ion. H has diatomic tendencies, and because it has a positive charge, it tends to attract negative particles. The date indicates Step 3.

Item No.: 7 **Date Found:** 8/17 **Partial/Full Body:** Partial

Location Found: Evian Lane **GFM (g/mol):** 16

Chemical Properties: Density = 1.308 g/liter **Est. Original GFM (g/mol):**

Physical Properties: Gas at room temperature

Qualitative Observations: Diatomic Tendencies

Conclusion: The Atom is O from Step 3. GFM = 16 g/mol. Evian is a type of water, hinting that the O came off the water molecule. Oxygen's density is 1.308 g/liter, is a diatomic molecule, and is a gas at room temperature. The date indicates Step 3.

Item No.: 8 **Date Found:** 8/17 **Partial/Full Body:** Partial

Location Found: Ethyl Formate Lane **GFM (g/mol):** 73

Other: 10 atoms had one bonding point **Est. Original GFM (g/mol):**

Chemical/Physical Properties:

Qualitative Observations: Had a piece of paper on 1 atom which read "I'm on top of the world, ma!"

Conclusion: The Molecule is $COOC_2H_5$ from Step 3. GFM = 73 g/mol. This molecule is known as an Ethyl Formate, and is often written as COOEt, where Et represents C_2H_5. The 10 atoms that form this molecule with single bonds are 3-C, 2-O, and 5-H. The 'on top of the world' comment is due to the COOEt which looks like it is on top of a pyramid (albeit sideways). The date indicates Step 3.

Item No.: 9 **Date Found:** 8/18 **Partial/Full Body:** Partial

Location Found: Hydroxylamine Drive **GFM (g/mol):** 2

Other: 2 atoms - identical **Est. Original GFM (g/mol):** 33

Chemical/Physical Properties:

Qualitative Observations: White, crystalline residue near site where found

Conclusion: The atoms are 2 H's (note: not H_2) from Step 4. GFM = 2 g/mol. These 2 identical Hydrogen atoms come from a molecule known as a Hydroxylamine, which is a white crystalline residue. The date indicates Step 4.

Item No.: 10 **Date Found:** 8/18 **Partial/Full Body:** Partial

Location Found: Ibu Swamp Lane **GFM (g/mol):** 16

Other: **Est. Original GFM (g/mol):**

Chemical/Physical Properties:

Qualitative Observations: Signs of a previous double bond

Conclusion: The atom is O from Step 4. GFM = 16 g/mol. This atom came off of $C_{13}H_{18}O$, where it had a double bond. TheIbu Swamp Laneis a clue, since the O comes off of the big molecule that is forming Ibuprofen. The date indicates Step 4.

Item No.: 11 **Date Found:** 8/19 **Partial/Full Body:** Partial

Location Found: 1 block from Double Bond Lane **GFM (g/mol):** 1

Other: **Est. Original GFM (g/mol):**

Chemical/Physical Properties & Qualitative Observations:

Conclusion: The atom is H from Step 5. GFM = 1 g/mol. This atom came off of the C==N double bond, and item no. 12 is also '1 block from Double Bond Lane'; this is the clue to recognize that this H came from Step 5. The date also indicates Step 5.

Item No.: 12 **Date Found:** 8/19 **Partial/Full Body:** Partial

Location Found: 1 block from Double Bond Lane **GFM (g/mol):** 17

Chemical Properties: Has a negative charge lingering

Physical Properties:

Qualitative Observations: Had a tattoo ~Attach yourself to those that are a gas of laughs and you will live on the edge~

Conclusion: The molecule is OH from Step 5. GFM = 17 g/mol. This molecule came off of the C==N double bond, and item no. 11 is also '1 block from Double Bond Lane' as a clue. OH as an ion is called Hydroxide and has a negative charge. The 'attach yourself to' tattoo is referring to the Nitrogen the OH was attached to; Nitrogen is also known as laughing gas. The date indicates Step 5.

Item No.: 13 **Date Found:** 8/20 **Partial/Full Body:** Partial

Location Found: Triple Bond Lane **GFM (g/mol):** 14

Other: **Est. Original GFM (g/mol):**

Physical Properties: Nonmetallic

Qualitative Observations:

Conclusion: The atom is Nitrogen (N) from Step 6. GFM = 14 g/mol. This nonmetallic atom came off of the only triple bond in the process. The date indicates Step 6.

Item No.: 14 **Date Found:** 8/20 **Partial/Full Body:** Partial

Location Found: Rain Lane **GFM (g/mol):** 3

Other: 3 separate atoms **Est. Original GFM (g/mol):**

Chemical/Physical Properties:

Qualitative Observations: 3 similar atoms appear to have been passing by connected to their original molecule (estimated at 18 g/mol) when 'The Headache' wasted them.

Conclusion: The atoms are 3 Hydrogens (H) in Step 6. Total GFM = 3 g/mol. They all came off of water (H_2O) molecules whose GFM is 18 g/mol. The Rain Lane is a clue to lead the students to think 'water molecules'. The date also indicates Step 6.

Table H - Original Boot Process

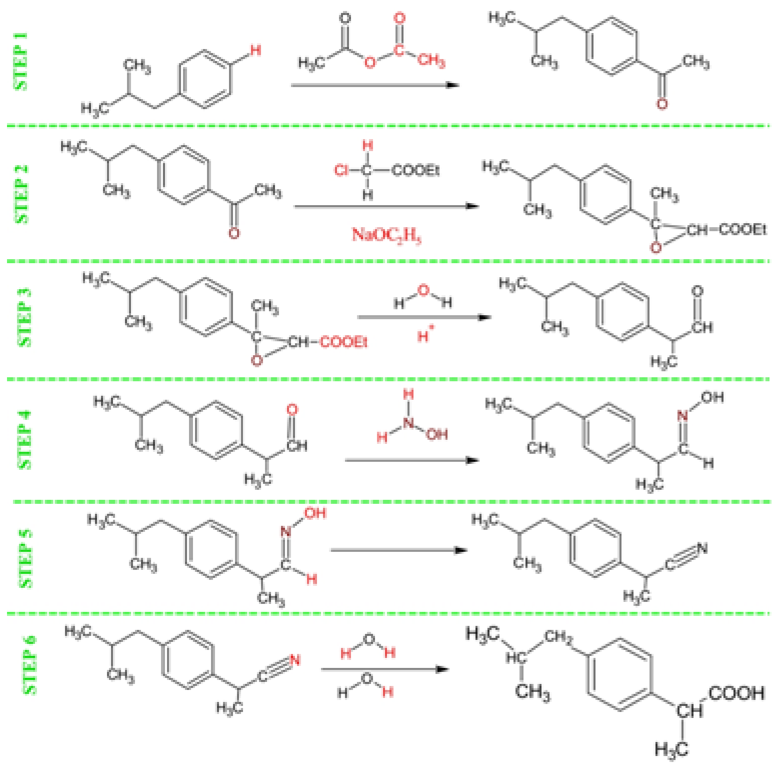
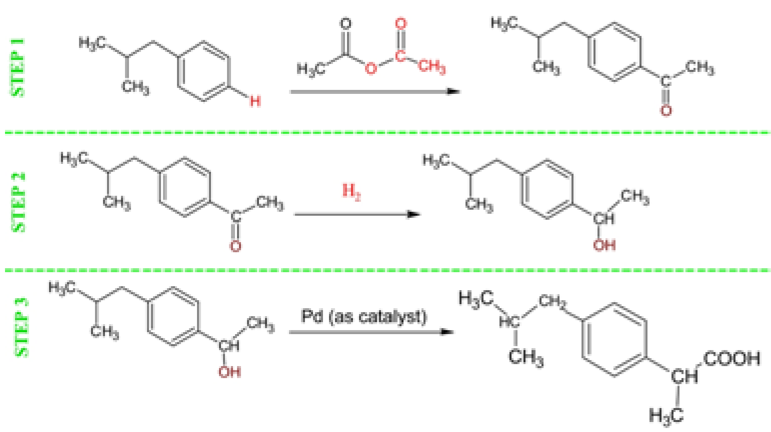


Table I - New "Greener" Ibuprofen Process



Conclusion of Unit

As the unit ends, discuss the various branches of Chemistry and the opportunities (lookup local jobs in your area) that are available. The students should be able to answer questions such as who are innovators in the field today? What opportunities exist for the future? What products could you make better? What companies hire chemists? What industries can apply the concepts of "sustainability"? [13]

The unit will end with a report (2-5 pages typed, or 15 PowerPoint Slides, both written and verbally presented) in which the students will choose at least one green product in use on the market and show how the product is (or is not) applying the Twelve Principles of Green Chemistry. The student should be prepared to defend their position and explain how the principle(s) can be applied to their GREEN life now; they will conclude their presentation/report with how they perceive their new knowledge will help them Change Their World in the future.

Resource List 1: Bibliography for teachers

Allen, David T., and David R. Shonnard. Green Engineering: Environmentally Conscious Design of Chemical Processes. Upper Saddle River: Prentice Hall PTR, 2001.

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Montagnon, Tamsyn, and K. C. Nicolaou. Molecules That Changed the World. Weinheim: WILEY-VCH, 2008.

Obama, Barrack. "Science Issues." Barack Obama's Official Website. www.barackobama.com/pdf/issues/FactSheetScience (accessed July 1, 2009).

"Pfizers Atom Economy." Atom Economy. www.beyondbenign.org/K12education/hs_lesson_plans_en/atom%20economy.doc (accessed July 7, 2009).

Timpson, William M.. 147 Tips for Teaching Sustainability: Connecting the Environment, the Economy, and Society. Chicago: Atwood Pub, 2006.

Benign by Design: Alternative Synthetic Design for Pollution Prevention (ACS Symposium Series). New York: An American Chemical Society Publication, 1994.

Green Chemistry Education: Changing the Course of Chemistry (ACS Symposium Series). New York: Oxford University Press, USA, 2009.

Green Chemistry: Designing Chemistry for the Environment (ACS Symposium Series). New York: An American Chemical Society Publication, 1996.

Green Engineering (ACS Symposium Series, 766). New York: An American Chemical Society Publication, 2000.

Resource List 2: Student Reading List

Criddle, Craig, and Larry Gonick. The Cartoon Guide to Chemistry (Cartoon Guide To...). London: Collins, 2005.

Green Chemistry: Real World Cases in Green Chemistry: Avoiding Waste (Acs Symposium Series). New York: An American Chemical Society Publication, 2000.

Reading List 3: Materials for classroom use

Lesson 1:

(5) 20 mL Test Tubes

(5) Test Tube Tongs

(1) Test Tube Rack

50 mL Vinegar

Appendix

A.The 12 Principles of Green Chemistry

1. It is better to prevent waste than to treat or clean up waste after it is formed.
2. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Chemical products should be designed to preserve the efficacy of function while reducing toxicity.
5. The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. 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. A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable.
8. Unnecessary derivatization (blocking group, protection/de-protection, and temporary modification of physical/chemical processes) should be avoided whenever possible.
9. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.
11. 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. 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.

B. Pfizer's Economizing with the Atom Activity

Economizing with the Atom

Based upon the E-factor Lesson developed by Irv Levy

Educational Goal: To provide an understanding of atom economy and how it is used in chemical processes and how it can be applied to everyday life.

Student Objectives: Students will…

- Understand principle 2 of green chemistry
- Perform an exercise which has them practice atom economy
- Relate the exercise to chemical processes

Materials (for a class of 32):

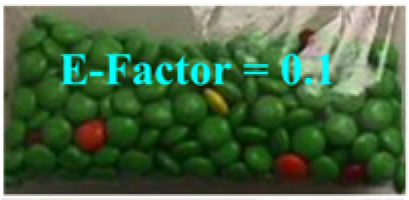
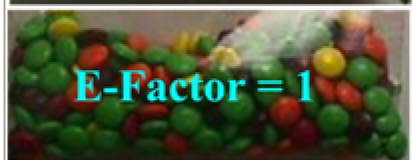
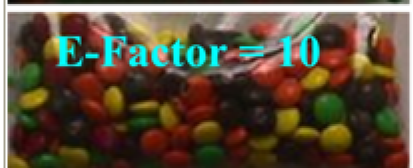
- One large bag of M&Ms
- Digital scale
- Package of individually wrapped potato chip portions
- Optional: plastic gloves

Time Required: 45-60 minute class period

Standards Met: S1, S2, S5, S6, S7

Green Chemistry Principles Addressed: 2

Prep: Prepare five baggies of M&Ms as shown below.

<table>
<tr><th>M&M model</th><th>E-factor</th><th>Industry segment</th></tr>
<tr><td>
</td><td>0.1</td><td>Petrochemicals
A chemical derived from Petroleum or natural gas
Example: Solvents detergents, adhesives</td></tr>
<tr><td>
</td><td>1</td><td rowspan="2">Bulk Chemicals
plastics and polymers
Example: plastic bottles, grocery bags</td></tr>
<tr><td>
</td><td>10</td></tr>
<tr><td>
</td><td>100</td><td>Fine Chemicals
Chemicals used to make specific items
Example: coating on laptop screens, electronics parts</td></tr>
<tr><td>
</td><td>250</td><td>Pharmaceuticals
Example: antibiotics, blood thinners</td></tr>
</table>

Procedure:

- Project slide # 1
- E-factor ≡ mass of waste ÷ mass of product
- Ask the students for 4 volunteers who are ready for a snack.
- Ask the volunteers to come to the front of the class.
- Tell students that the goal of this experiment is to satisfy your need for a quick snack and to test out our equation using these individually packaged potato chips.
- Ask the students to unpack the potato chips and make a pile of chips and a pile of waste. You may want to have students use gloves at this stage so that they can eat the chips after.
- Ask the students to find the mass of the chips and then the mass of the packaging and record the totals on the board.
- Explain to the students that we are not finished yet as we haven't used a key component in green chemistry principle # 4 and tested to see if this product retains it's efficacy. Therefore the volunteers will need to eat the chips and tell us if they satisfy their craving for a snack.
- While they eat, have another student come up and solve the E-factor equation for the potato chips.

- Debrief with students as to how well the product performed in regards to it's e-factor. Make sure you include a discussion of why there was all that packaging and how that is what the person designing the product decided you needed in order to deliver the product you wanted.
- Ask students how the e-factor of this product might be improved.
- Ask students to get into groups of two or three.
- Tell the students that actually this formula is used by green chemists to evaluate chemical processes so at this point we would like to give you all a bag of chemicals.
- Hand out a small bag of M& Ms to each group of students.
- Explain that this bag of M&Ms is very special but that unfortunately the only ones that you can use are the green ones.
- Ask students to separate the green M&Ms from the other colors and make two piles. It turns out that green M& Ms have been discovered to be a key component in a revolutionary technology that helps to make hologram images come out of cell phones so that people can see each other when they chat.
- The green part is actually the chemical that you need.
- Ask students to calculate the e-factor for the bag of M&Ms
- Ask the students to tell you whether they are OK with having all this waste in order for them to have hologram images of their friends come out of their cell phones.
- Tell the students that you are going to give them another equation to help them be creative.
- Put the following equation on the board.
- E-factor = (mass of inputs - mass of outputs) ÷ mass of product
- Ask students to creatively come up with ways that they could reduce the e-factor.
- Discuss with students their possibilities, real or imagined.
- Show students the pre-prepared bags of M&Ms and explain how these bags represent chemical processes.
- Now tell the students that you know, they know that isn't real but that these techniques are really being used in industry.
- Ask students if any of them use Ibuprofen. You may have to prompt them with over-the-counter brand names of the drug.
- Project the slide of the Ibuprofen diagram number one on the accompanying PPT presentation.
- Talk through the process with the students.
- Explain that at the time Ibuprofen was invented it was a big breakthrough for people suffering from joint and muscle pain, it was originally invented to help arthritis patients. Sounds great right? Until you look at how much of the process created waste.
- Go to slide two where the graphic is highlighted with color
- Then highlight for the students that the green parts are the processes that are incorporated in the product and the brown is the waste.
- Put one ibuprofen pill on the desk (preferably green in color) and one brown ball that is roughly half the size again, and explain that this is the ratio.
- Ibuprofen was manufactured this way and sold over the counter between roughly 1980 and 1990 with around 46 tonnes of ibuprofen sold in the UK and Northern Ireland per year during that time.
- With the old method, that means that there would be 68.72 tonnes of waste = 69 female walruses of waste.
- Ask the students to tell you how many tonnes of waste that would be over 10 years.
- The process was changed in 1990 through the use of green chemistry techniques and specifically Atom Economy.
- Show the next slide with the new process. Ask the students to tell you what they immediately see as

being different.

- Talk the students through the new process. Point out that the acetic acid used in step one of the new process is recovered and used over again.
- Point out that the current and better method = 13.33 tonnes of waste, 13 female walruses. (show slide 5)
- The new method: If you count the recycling of the single main waste product, a mere 1% of the building block atoms result as waste. (show slide 6) The process also replaced a six-step by a three step process, aiding energy efficiency (principle 6) and simplifying real-time analysis for pollution prevention (principle 11).The waste before was mostly landfilled.
- Ask the students to refer back to the 12 principles and even though this is a green chemistry success story ask them to tell you why this process doesn't totally adhere to the 12 principles of green chemistry. Answer: Recycling is not really a green chemistry principle. It is better not to create waste in the first place.
- Explain that in the 60s when Ibuprofen was first synthesized, chemists weren't thinking about toxicity and lifecycle, so they just made a wonder drug and called it good. These days chemists are having to go back and fix a lot of these things. True green chemists, like us, look at the processes and materials through a green eye from the very beginning.
- Scientists are also looking at Bi-products as well. Chemicals that have been developed in the past have bi-products and scientists are looking at innovative ways to use those bi-products to make something else. It is just like when you have a Thanksgiving turkey. Try to imagine all the various foods you can make out of that one turkey.

Endnotes

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[1] Anastas, Paul. Interview by Mark Sommer. Green Chemistry: Better Living Through Nature. A World Of Possibilities. Internet, August 22, 2008.

[2] Obama, Barrack. "Science Issues." Barack Obama's Official Website www.barackobama.com/pdf/issues/FactSheetScience (accessed 1 July 2009).

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[9] Harrison, Karl. "Ibuprofen, What is Ibuprofen? About its Science, Chemistry and Structure." Chemistry, Structures & 3D Molecules 3Dchem.com - Home. http://www.3dchem.com/molecules.asp?ID=14 (accessed July 2, 2009).

[10] Montagnon, Tamsyn, and K. C. Nicolaou. Molecules That Changed the World. Weinheim: WILEY-VCH, 2008.

[11] Dingle, Adrian. The Periodic Table. New York: Kingfisher, 2007.

[12] " Green Chemistry | US EPA." U.S. Environmental Protection Agency. http://www.epa.gov/greenchemistry (accessed July 13, 2009).

[13] Green Chemistry Education: Changing the Course of Chemistry (Acs Symposium Series). New York: Oxford University Press, USA, 2009.