Green Chemistry:
Teaching & Research

Green Chemistry & Engineering Education
National Academies' Chemical Sciences Roundtable

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Washington, D.C.
United States of America

*Teaching is the grindstone on which research skills are sharpened.*

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Outline:

**Part I Green Chemistry at York (CHEM 3070)**
- Course content, teaching strategies and resources
- Sample problems and exercises
- Student feedback

**Part II Green Metrics Analysis**
- RME master equation and visual depiction
- Synthesis tree analysis
- Material, energy, and cost optimization
Resources & Strategies

**Resources**
- Research journal articles
- Society news magazines
- Patent literature/databases
- Books
- Campus colloquia
- Course website

**Strategies**
- Inter-disciplinary problems based approach
- Decision making
- Quantitative reasoning and evaluation
- Encourage self-discovery and independent learning

**Pre-requisites**
- 2nd year organic chemistry with minimum C grade + brush-up quiz
- Science library resource workshop and quiz

**Evaluation**
- Biweekly quizzes
- 4 Problem Sets
- Written assignment + oral
- Final Exam (5th problem set)

**Written Assignment**
- Journalistic style
- Choice of topic
- Rigorous critiquing of synthesis or manufacture of target product or process according to “green” criteria
Chemistry & Society

Development of Organic Chemistry
* chronology
* genealogy
* connections with world events

Development of Industrial Chemistry
* chronology
* genealogy
* connections with world events
* accidents
* Responsible Care (CCPA)

Media vs. Chemical Scientists vs. Chemical Societies Relations

Business of Doing Chemistry
* economic impacts
* patents (Markush structures)
* confidentiality Agreements

Current News
* C&EN, ACCN
* CBC
* newspapers
* television

Career Development
* C&EN, ACCN
* CareerChem
* guest speakers (alumni)

Organic Name Reactions Timeline

Decade

Number of Reactions Discovered

Number of Reactions Named After People

Number of Reactions Not Named After People
Evol ution of Che mistry

Schreiber,
Nicolaou,
Whitesides
(1990s+)

Watson, Crick,
Pauling (1950s)

Pasteur, Michaelis,
Menten, Krebs (1880s-1930s)

Wohler, Liebig,
Bunsen, Kekule,
Hofmann (1860s)

Rouelle, Berard,
Lavoisier (1770s)

Chemical
Biology

Molecular
Biology

Chemistry

Pharmac

Biochemistry

Evolution of Paradigms in Organic Synthesis

Organic Synthesis

Target-oriented
Synthesis

Natural Products
(plants, marine and terrestrial organisms)

Designed Molecules
(rational drug design, combinatorial chemistry)

Methods-oriented
Synthesis

Reagents

Catalysts

Synthetic Strategies
and Tactics
(carbon skeleton framework, stereochemical control)

Diversity-oriented
Synthesis
( combinatorial
approaches; multi-
component reactions;
exploration of "chemical space"; computer assisted
synthesis; compound libraries)

Molecules
for material
science

Molecules
for biology

Molecules of
theoretical interest

Molecules
for medicine

Molecules
for molecular recognition
Synthesis Plan #1

Synthesis Plan #2

Concept Paradigms in (Organic) Chemistry

- Structure Determination
- Chemical Reaction
- Kinetic & Thermo-dynamic Analysis
- Optimization Metrics Analysis
- Synthesis Plan of Target
- Reaction Mechanism + Intermediates
Interconnections Between Chemical Industry Sectors

Survey of Modern Concerns

chirality

chemical function or property

\( (S)\)-thalidomide

\( (R)\)-thalidomide

\( \text{Pb} (\text{OE})_3 \)
Green Chemistry

Principles & Philosophy

Emerging Technologies

Reaction Paradigms

Reaction Metrics*

Linear Sequences

Convergent Sequences

Special Cases:
- isomeric products
- side reactions
- dynamic kinetic resolution (DKR)

Optimization of Parameters

Costs
- RMC
- energy

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Green Chemistry

Founded Green Chemistry Institute
http://www.chemistry.org/greenchemistry/institute/

Joseph Breen Green Chemistry Awards
http://www.chemistry.org/greenchemistry/institute/awards.html#breen

Green Chemistry Network (Canada)
http://www.greenchemistry.ca

12 Principles of Green Chemistry

1. Prevention
2. Atomeconomy
3. Less hazardous chemical syntheses
4. Designing safer chemicals
5. Safer solvents and auxiliaries
6. Design for energy efficiency
7. Use of renewable feedstocks
8. Reduce derivatives
9. Catalysis
10. Design for degradation
11. Real-time analysis for pollution prevention
12. Inherently safer chemistry for accident prevention
Green Chemistry Paradigms

**REACTION MEDIUM**
- Ionic Liquids
- Water
- Supercritical \( \text{CO}_2 \)
- Solvent Free (solid supports)

**REACTION METHOD OR STRATEGY**
- Ultrasound (Sonochemistry)
- Microwave Irradiation
- Grindstone chemistry
- Biocatalysis using Enzymes
- Organic Synthesis by Multi-component Approach
- Microstructured reactors
- Renewable feedstocks as starting materials

Evolution of Depiction of Organic Reactions
Baeyer, A. Ann. Chem. 1863 127 199

\[ \text{N}_3\text{C}_4\text{O}_4\text{H}_3 + 2 \text{H}_2\text{S} = \text{N}_2\text{C}_4\text{O}_3\text{H}_4(\text{NH}_2) + \text{H}_2\text{O} + \text{S}_2 \]

**Old Paradigm**
- Balanced chemical equations
- Functional group identification tests
- Structure determination by melting point derivatives, index of refraction, degradation to known compounds
- Purification by distillation, recrystallization

**Modern Paradigm**
- Juxtaposition of substrate and product structures only in chemical equations
- Structure determination by spectroscopic methods, total synthesis
- Purification by chromatographic methods
Evaluation of a Chemical Reaction

Economic feasibility based on raw material costs and availability
Technical feasibility based on energy demands
Potential for unwanted side, runaway, and hazardous reactions
Environmental impact of all materials used

Quantification of reaction metrics:
• % conversion of substrate to product
• % yield of product based on conversion of limiting reagent
• atom economy (Trost AE)
• reaction mass efficiency (RME)
• environmental impact factor (Sheldon E)
• stoichiometric factor (SF)
• process energy metric
• solvent recovery metric

Toxicity parameters for all materials used (LD50)
Sample Problem #1

Two industrial routes to m-chlorostyrene from m-chloroethylbenzene are shown.
(a) Account for all byproducts and identify catalysts in each step.
(b) For each route write out a set of balanced chemical equations for the transformations.
(c) For each route determine the overall yield, overall RME, and overall mass of waste per kg of m-chlorostyrene product. As some each step in both routes is run under stoichiometric conditions.
(d) Determine the raw material costs (RMC) to produce 1 kg of m-chlorostyrene from each route using the market values for various starting materials given in the table below.
(e) Identify byproducts that may pose toxicity concerns and those that pose hazards upon scale-up.
(f) Identify recycling potential of waste products.
(g) Identify processes that may pose equipment corrosion problems.
(h) Identify reactions that are energy demanding (high temperature/ high pressure).
Taking all factors together decide which route is better economically and environmentally.

Sample Problem #2

The Wittig reaction produces triphenylphosphine oxide as a waste byproduct.

Given the three recycling reactions shown below that convert O=PPh₃ back to PPh₃, assess which option is best according to the combined RME values for the Wittig and recycling reactions.
(1) O=PPh₃ + H₂O + HSiCl₃ → PPh₃ + 3 HCl + SiO₂  90 %
(2) O=PPh₃ + O=CBr₂ → 2/3 Al₂ → PPh₃ + 2/3 AlCl₃ + CO₂  90 %
(3) O=PPh₃ + HCl + 1/4 Ti(1-OPr) → PPh₃ + H₂O + O=C(CH₃)₂ + 1/4 TiCl₄  90 %
Sample Problem #3

Four different routes to a generalized γ-lactone are given. For each route provide an overall balanced chemical equation and determine values for AE(min) and E(max). If the RME for each route is to be above a threshold value of α = 0.5 determine the range of permissible reaction yield values when AE = AE(min) and the probability of achieving such a threshold in each case.

Note for multi-step sequences assume the reaction yield refers to the combined steps.

\[
\begin{align*}
\text{(1)} & & \text{NaOEt} & + \text{EtOH} & \rightarrow & \text{EtOOC} & + \text{Na}^+ \\
\text{(2)} & & \text{HO} & + \text{COOH} & \rightarrow & \text{HO} & + \text{MnO}_4^- \\
\text{(3)} & & \text{R} & + \text{CH}_3 & \text{O} & + \text{MnO}_4 & \rightarrow & \text{Mn(O(CO)CH}_3^2 & \\
\text{(4)} & & \text{R} & + \text{Br} & \text{COOEt} & \rightarrow & \text{HO} & \text{R} & \text{COOH} \\
\end{align*}
\]

Student Feedback & Comments

“This course promotes thinking on real-life practical chemical problems rather than mindlessly memorizing facts and spilling the beans on an exam. Biweekly quizzes kept us on the ball.”

“I enjoyed the course because the instructor allowed his students to experience the material with a positive feeling even though the industry is quite negative at times.”

“I liked that we were introduced to the chemical literature.”

“The course gives a good sense of the type of work you’ll be involved in as a chemist.”

“I liked reading material about current issues in chemistry. This is the only way students can make the transition from school to work.”

“I had a better appreciation of chemistry after learning about how the subject evolved.”

“I was motivated to learn chemistry by this course. I liked the exercise of coming up with as many synthetic routes as possible to a given compound. My negative feelings about the subject disappeared!”
“This course provided a good insight of the “real world” of chemistry. It introduced a number of topics that are important to chemistry but never mentioned in other courses. We were introduced to chemical industries and what they are all about. The instructor encouraged us to attend public lectures to get a better sense of the chemistry that is evolving. He got back to us the very next lecture and answered any questions that he was unable to answer in the last lecture. I learned more about organic chemistry in this class than from previous chemistry courses. I also learned a lot more about the chemical industry.”

Part II

Green Metrics Analysis

RME master equation and visual depiction
Synthesis tree analysis
Material, energy, and cost optimization
Reaction Mass Efficiency Master Equation

\[
RME = \left( \varepsilon \right) (AE) \left( \frac{1}{SF} \right) (MRP) = \left( \varepsilon \right) (AE) \left( \frac{1}{SF} \right) \left( \frac{1}{1 + \frac{\varepsilon (AE) [c + s + \omega]}{(SF) (m_p)}} \right)
\]

Parameters:
- \( \varepsilon \): reaction yield
- \( AE \): atom economy
- \( SF \): stoichiometric factor; \( SF = 1 \) implies no excess reagents
  \( SF > 1 \) implies excess reagents used
- \( MRP \): materials recovery parameter

Recall: Lavoisier’s law of conservation of mass for balanced chemical reaction/equation.
**REACTION METRICS FORM**

**DATE:** May 31, 2005

**NAME OF TARGET PRODUCT:** trans-Benzal acetophenone

**REACTION CLASSIFICATION:** Carbon-carbon bond forming

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**BALANCED CHEMICAL EQUATIONS:**

\[
\text{Ph} = \text{Ph} + \text{H}_2\text{O}
\]

---

**PART 1: RAW MATERIALS USAGE**

**(i) REAGENTS**

<table>
<thead>
<tr>
<th>MW (g/mol)</th>
<th>Density (g/mL)</th>
<th>Volume (mL)</th>
<th>Moles</th>
<th>Mass (g)</th>
<th>Cost ($/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetophenone</td>
<td>120</td>
<td>1.03</td>
<td>3</td>
<td>0.02575</td>
<td>3.09</td>
</tr>
<tr>
<td>benzaldehyde</td>
<td>106</td>
<td>1.046</td>
<td>2.5</td>
<td>0.0247</td>
<td>2.615</td>
</tr>
</tbody>
</table>

**TOTAL REAGENTS**

Add lines 12 to 15

226 g

5.705

**(ii) CATALYSTS**

<table>
<thead>
<tr>
<th>MW (g/mol)</th>
<th>Density (g/mL)</th>
<th>Volume (mL)</th>
<th>Moles</th>
<th>Mass (g)</th>
<th>Cost ($/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 M NaOH (12 %)</td>
<td>40</td>
<td>1.1309</td>
<td>12.5</td>
<td>0.35340625</td>
<td>14.13625</td>
</tr>
</tbody>
</table>

**TOTAL CATALYSTS**

Add lines 19 to 20

14.13625

**(iii) SOLVENTS**

<table>
<thead>
<tr>
<th>Density (g/mL)</th>
<th>Volume (mL)</th>
<th>Mass (g)</th>
<th>Cost ($/g)</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% EtOH</td>
<td>0.816</td>
<td>7.5</td>
<td>6.1200</td>
<td>0.0422</td>
</tr>
</tbody>
</table>

---

**Diels-Alder**

- Complete Reclaiming
- Partial Reclaiming
- No Reclaiming
- Ideal

**Grignard**

- Complete Reclaiming
- Partial Reclaiming
- No Reclaiming
- Ideal

**Friedel-Crafts**

- Complete Reclaiming
- Partial Reclaiming
- No Reclaiming
- Ideal

**Aldol condensation**

- Complete Reclaiming
- Partial Reclaiming
- No Reclaiming
- Ideal
Atom Economy/Reaction Mass Efficiency - E-factor
Connecting Relationships

\[ AE = \frac{1}{1 + E_{mw}} \quad RME = \frac{1}{1 + E_m} \]

Criteria for “green” reactions:
(1) \( AE \geq 61.8 \% \) so that \( AE > E_{mw} \)
(2) \( RME \geq 61.8 \% \) so that \( RME > E_m \)
(3) Reaction solvents and all post-reaction materials used in work-up and purification stages must be reclaimed and/or eliminated.
PROFILE OF ORGANIC REACTIONS ABOVE GOLDEN ATOM ECONOMY (%AE > 60%)

CUMULATIVE GROWTH OF ORGANIC REACTIONS: BELOW AND ABOVE GOLDEN ATOM ECONOMY THRESHOLD
**Triclosan Synthesis**

Reaction conditions:
(i) acetyl chloride, AlCl₃ catalyst (94.3%);
(ii) 2 Cl₂, (81%);
(iii) 1/2 K₂CO₃, CuCl catalyst, xylenes (48.3%);
(iv) 62.5% H₂O₂, 1/2 maleic anhydride, CH₂Cl₂ (91.3%);
(v) MeOH, 35% HCl catalyst (94.5%).

**Synthesis Tree**

(32) CH₃OH
(49) 1/2 C₃H₂O₃
(69) 1/2 K₂CO₃
(141.8) 2 Cl₂
(94) AlCl₃
(133.35) CH₃COCl
(78.45) S₁
(146.9) S₂
(34) H₂O₂
(289.35) P
Kernel RME function

\[ RME = \frac{289.35 \times}{S} \]

\[ S = \left[ \frac{32}{\varepsilon_4} + \frac{49 + 34}{\varepsilon_3 \varepsilon_4} + \frac{69}{\varepsilon_2 \varepsilon_3 \varepsilon_4} + \frac{133.35 + 78.45 + 146.9}{\varepsilon_1 \varepsilon_2 \varepsilon_3 \varepsilon_4} + \frac{94 + 141.8}{\varepsilon_1 \varepsilon_2 \varepsilon_3 \varepsilon_4} \right] \]

\[ = \left[ \frac{32}{\varepsilon_4} + \frac{83}{\varepsilon_3 \varepsilon_4} + \frac{69}{\varepsilon_2 \varepsilon_3 \varepsilon_4} + \frac{358.7}{\varepsilon_1 \varepsilon_2 \varepsilon_3 \varepsilon_4} + \frac{235.8}{\varepsilon_1 \varepsilon_2 \varepsilon_3 \varepsilon_4} \right] \]

RME = 0.1517 (about 15%), \( E_m = 5.59 \)

AE = 0.3717 (about 37%), \( E_{mw} = 1.69 \)
Kernel RMC function

\[ RMC = \left[ \frac{32\text{MeOH}}{\varepsilon_4} + \frac{49\text{MA} + 34\text{H}_2\text{O}}{\varepsilon_3\varepsilon_4} + \frac{69\text{K}_2\text{CO}_3}{\varepsilon_2\varepsilon_3\varepsilon_4} + \frac{141.8\text{Cl}_2 + 94\text{PhOH}}{\varepsilon_1\varepsilon_2\varepsilon_3\varepsilon_4} + \frac{133.35\text{AlCl}_3 + 78.45\text{AC} + 146.9\text{1,4-DCB}}{\varepsilon_1\varepsilon_2\varepsilon_3\varepsilon_4} \right] \]

\[ RMC = \$ 333.61 \text{ per mole} = \$ 1.15 \text{ per gram} \]
Fractional RMC by Reaction Stage for Triclosan Synthesis

Stage 1: 93.6%
Stage 2: 2.3%
Stage 3: 4.0%
Stage 4: 0.1%

Fractional Cost Distribution for Input Reagents on a Per Mole Basis for Triclosan Synthesis

- Hydrogen peroxide: 30%
- Potassium carbonate: 2%
- Chlorine: 47%
- Aluminum trichloride: 3%
- Methanol: 2%
- 1,4-dichlorobenzene (S1): 2%
- Phenol (S2): 3%
- Acetylchloride: 5%
- Maleic anhydride: 6%

6-Methoxylepidine Synthesis

<table>
<thead>
<tr>
<th>Method</th>
<th>Yield (%)</th>
<th>Atom Economy (%)</th>
<th>Kernel RME (%)</th>
<th>Kernel RMC ($/gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCl₃, ZnCl₂</td>
<td>52</td>
<td>46</td>
<td>24</td>
<td>0.62</td>
</tr>
<tr>
<td>InCl₃, microwave</td>
<td>85</td>
<td>42</td>
<td>35</td>
<td>8.22</td>
</tr>
</tbody>
</table>

B: *Tetrahedron Lett.* 2003, 59, 813

For method B to be cost competitive with method A, price of metal halide must not exceed $55 per mole.

- FeCl₃: $21
- ZnCl₂: $12
- InCl₃: $1147
\[ \mu_1 = -99.54 \text{ g/mol/reaction stage} \]
Fractions of Total Energy Input

\[ \Phi_{\text{product}} = FTE = \frac{\sum_j^M (RME)_j \Psi_j}{\sum_j^M \Psi_j} \]

\[ \Phi_{\text{waste}} = \frac{\sum_j^M \left[ 1 - (RME)_j \right] \Psi_j}{\sum_j^M \Psi_j} \]

\( \Psi_j \) = energy input for j\textsuperscript{th} reaction

\( M \) = number of reactions

\( (RME)_j \) = reaction mass efficiency for j\textsuperscript{th} reaction
<table>
<thead>
<tr>
<th>Kernel Reaction Metrics</th>
<th>Pictet-Gams</th>
<th>Decker Wahl</th>
<th>Rodd-Bouteville-Peschke-Pal</th>
<th>Dean</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE (%)</td>
<td>13.6</td>
<td>19.7</td>
<td><strong>31.7</strong></td>
<td>27.4</td>
</tr>
<tr>
<td>E_{max} (%)</td>
<td>6.37</td>
<td>4.03</td>
<td>2.15</td>
<td>2.65</td>
</tr>
<tr>
<td>RME (%)</td>
<td>0.52</td>
<td>2.8</td>
<td><strong>15.1</strong></td>
<td>8.0</td>
</tr>
<tr>
<td>E_{max}</td>
<td>101.12</td>
<td>35.37</td>
<td>23.75</td>
<td>5.63</td>
</tr>
<tr>
<td>E_{pseudo-max} (%)</td>
<td>3.8</td>
<td>13.8</td>
<td>12.7</td>
<td>40.0</td>
</tr>
<tr>
<td>(pseudo-max) (%)</td>
<td>(10.6)</td>
<td>(7.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of reaction inputs, ( I )</td>
<td>18</td>
<td>20 (13)</td>
<td><strong>11</strong></td>
<td>15</td>
</tr>
<tr>
<td>Number of reaction steps, ( M )</td>
<td>11</td>
<td>12 (9)</td>
<td><strong>8</strong></td>
<td>13</td>
</tr>
<tr>
<td>Number of reaction stages, ( N )</td>
<td>8</td>
<td>9 (9)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>( k ) (g per mole per reaction stage)</td>
<td>-163.57</td>
<td>-83.10</td>
<td><strong>-218.9</strong></td>
<td>-151.56</td>
</tr>
<tr>
<td>RMC $^a$ (CAD per gram)</td>
<td>29.04</td>
<td>4.72</td>
<td><strong>0.45</strong></td>
<td>22.05</td>
</tr>
</tbody>
</table>

**Tree Parameters**

<table>
<thead>
<tr>
<th>Degree of convergence, ( \delta )</th>
<th>0.443</th>
<th>0.425</th>
<th><strong>0.450</strong></th>
<th>0.392</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.560)</td>
<td>(0.306)</td>
<td>(0.303)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative rate of convergence, ( \rho )</td>
<td>0.207</td>
<td>0.218</td>
<td><strong>0.200</strong></td>
<td>0.204</td>
</tr>
<tr>
<td>(0.199)</td>
<td>(0.186)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asymmetry, ( \beta )</td>
<td>0.813</td>
<td>0.861</td>
<td><strong>0.694</strong></td>
<td>0.630</td>
</tr>
<tr>
<td>(0.791)</td>
<td>(0.400)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Bupleurynol Synthesis

Organ, M.G. et al. Org. Lett. 2004, 6, 2913
\[(RME)_{\text{overall}} = \frac{184}{S}\]

\[S = \frac{44}{\varepsilon_7\varepsilon_8} + (28 + 6) \left( \frac{1}{\varepsilon_1\varepsilon_6\varepsilon_8} + \frac{3/2}{\varepsilon_1\varepsilon_2\varepsilon_3\varepsilon_4\varepsilon_5\varepsilon_6\varepsilon_8} \right) + \frac{161.8}{\varepsilon_6\varepsilon_7\varepsilon_8}\]

\[+ \frac{28}{\varepsilon_7\varepsilon_8} \left( \frac{2}{\varepsilon_6\varepsilon_5\varepsilon_6} + \frac{2}{\varepsilon_5\varepsilon_6} + \frac{1}{\varepsilon_2\varepsilon_3\varepsilon_4\varepsilon_5\varepsilon_6} \right)\]

\[+ \frac{46}{\varepsilon_6\varepsilon_7\varepsilon_8} + \frac{36}{\varepsilon_5\varepsilon_7\varepsilon_8} \left( \frac{1}{\varepsilon_6} + \frac{1}{\varepsilon_6} \right) + \frac{70.9}{\varepsilon_6\varepsilon_7\varepsilon_8} + \frac{65}{\varepsilon_6\varepsilon_7\varepsilon_8} \]

\[+ \frac{56}{\varepsilon_4\varepsilon_6\varepsilon_7\varepsilon_8} + \frac{52.45}{\varepsilon_2\varepsilon_3\varepsilon_4\varepsilon_5\varepsilon_6\varepsilon_7\varepsilon_8} + \frac{168}{\varepsilon_2\varepsilon_3\varepsilon_4\varepsilon_5\varepsilon_6\varepsilon_7\varepsilon_8}\]

\[RME = 0.083 \text{ (about 8 %)} \quad E_m = 11.09\]

\[AE = 0.1809 \text{ (about 18 %)} \quad E_{mw} = 4.53\]
Phthalic Anhydride

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Acknowledgements:

2002
Eric Cius (biology major)
Nikita Goussev (chemistry major, now at Torcan Ltd.)
Karen Lee (Chem. Tech. Dipl. At Seneca College; worked at BASF, Apotex, Inc.)
Sibel Ok (chemistry major, worked at GSK, Mississauga, MSc candidate, York)
Subukar Paramanathan (chemistry major, now at Dalton Chemical Ltd.)

2003
Ryan Bouchard (philosophy & chemistry)
Dragana Djokic (chemistry major, now at Ciba, Basel, Switzerland)
Hareem Ilyas (transfer from Seneca College)
Andreas Katsiapis (bioinformatics, computer science)
Jelena Loncar (chemistry major)
Maija Elina Lukkari (visiting from University of Helsinki, soil chemistry)**
Adriano Maida (Ph.D. candidate, U Toronto, biomedical science)

2004
Kelvin Chan (biotechnology major)
Neeshma Dave (atmospheric chemistry major, MSc candidate, York, surface science)
Rosa Park (chemistry major, Ph.D. candidate, UBC, chemistry)

2005
Julia Izhakova (biotechnology major)
Milos Markovic (chemistry major)
Jordan Schwarz (biotechnology major)
Murtazaali Sayed (biotechnology major)**