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**Contributions of Educational Research to**
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# THE FUTURE SHAPE OF CHEMISTRY EDUCATION [1]

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**ABSTRACT:** Diverse forces shape the teaching and learning of chemistry at the beginning of the 21st Century. These include fundamental changes in the contours of chemistry as defined by new interfaces and research areas; changes in our understanding of how students learn, and how that applies to chemistry education; the wide-spread implementation of computer and information technologies to visualize complex scientific phenomena; and external forces, such as global concerns about energy and water resources and the environment, and the level of chemical literacy and public understanding of science. In responding to those forces, new dimensions to learning chemistry must be emphasized. Tetrahedral chemistry education is a new metaphor that emphasizes these dimensions, stressing the importance both of the human learner and the web of human connections for chemical reactions and processes. Examples of ways to build on this metaphor in five areas of the chemistry curriculum are outlined. [*Chem. Educ. Res. Pract.*: 2004, *5*, 229-245]

**KEY WORDS:** *tetrahedral chemistry education; macroscopic-molecular-symbolic levels of chemistry; energy; environment; synthesis; visualization; chemistry of life*

## INTRODUCTION: SHAPES IN CHEMISTRY AND CHEMISTRY EDUCATION

Shapes are fundamentally important in chemistry. The alpha helix and tetrahedron are recognized instantly as shaping countless compounds found in nature and synthesized in laboratories. At the beginning of the 20th Century, Jacobus van't Hoff, recipient of Chemistry's first Nobel Prize, acquired fame for his early work that led to the prominence of the tetrahedral shape in chemistry.

At the beginning of the 21st Century, many forces shape the teaching and learning of chemistry. In this paper we will trace the shape of some of those forces, and their potential to transform chemistry education as we know it. I will illustrate with examples from my own classroom and laboratory, and work done by IUPAC's Committee on Chemistry Education, some practical ways for chemistry education to respond to those shaping forces, which include:

(a) fundamental changes in the contours of chemistry as defined by new interfaces and research areas,
(b) changes in our understanding of how students learn and how that applies to chemistry education,

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[1] Based on Plenary Lecture given to the *18th International Conference on Chemical Education*, Istanbul, Turkey, August 6, 2004

(c) the wide-spread implementation of computer and information technologies to visualize complex scientific phenomena, and
(d) external forces, such as global concerns about energy and water resources and the environment, and the level of chemical literacy and public understanding of science.

To frame our view of the future shape of chemistry education, I will suggest that we consider van't Hoff's tetrahedral shape as a helpful metaphor to enrich our description of different dimensions to successfully learning chemistry. A more familiar geometrical figure to chemistry educators is the planar triangle (Figure 1), which has been used effectively in the last decade to describe what we value in teaching and learning about the world of atoms and molecules. The familiarity of this metaphor is due in large part to the seminal work of Johnstone (1991), Gabel (1992, 1993), and others, who have helped us see that three learning levels, (the symbolic, macroscopic and sub-microscopic, or molecular) are needed for students to make sense of chemistry.

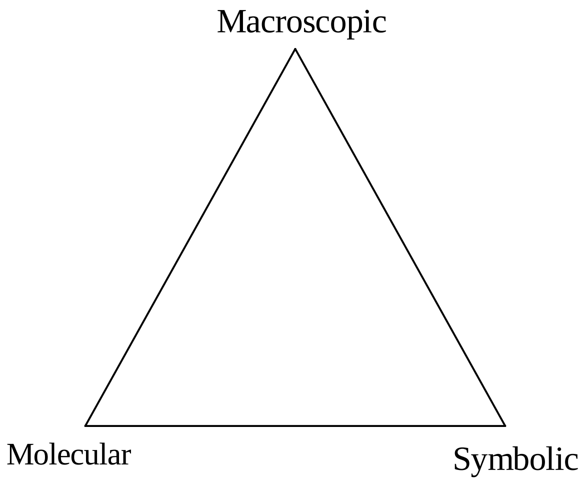

**FIGURE 1.** *Triangle of learning levels in chemistry education.*

The planar triangle of understanding has proven to be of great value, shaping the design of secondary and post-secondary curriculum, including textbooks, lab manuals and visualizations. It is featured at the beginning of the "Note to Students" in the preface to the textbook first year chemistry students use at my university (Kotz & Treichel, 2003, p xxviii). This triangle has even shaped benchmarks for national science education standards in the US (NRC, 1996).

Pedagogical pendula have swung back and forth between descriptive and theoretical chemistry in university courses and programs for several decades. The triangle reminds us that balanced coverage of both the macroscopic and symbolic levels of learning chemistry is needed to cover the scope of the subject and adequately address the needs of learners. Information and computer technologies have been used to develop computer animations, simulations, and dynamic molecular models, transforming our ability to visualize molecules and chemical changes at the molecular level.

Chemistry education research has made considerable progress in identifying student misconceptions in chemistry ("Student preconceptions", 2001). The triangle of thinking levels highlights the importance of directing further research toward student conceptions and misconceptions that occur at all three of those vertices.

## TETRAHEDRAL CHEMISTRY EDUCATION

But, as outlined elsewhere (Mahaffy, 2003), educators need to emphasize new dimensions to learning chemistry to address concerns about scientific literacy and limited public understanding of the role of chemistry in everyday life. To capture these new emphases in an image deeply grounded in the history of chemistry, I have proposed that we extend our planar triangle of learning levels into a tetrahedron (Mahaffy, in press), where the fourth vertex represents the web of human contexts for learning chemistry – the human element (Figure 2).

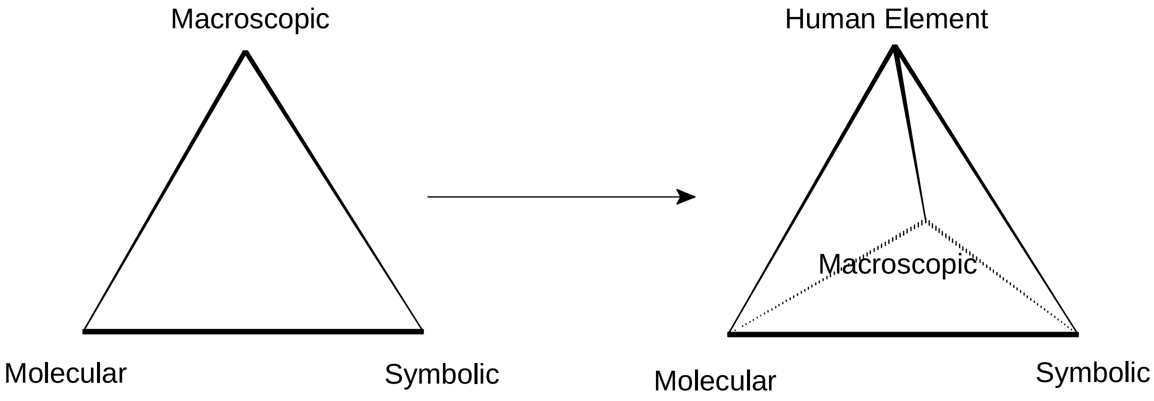

**FIGURE 2.** *Tetrahedral chemistry education: A new emphasis on the human element.*

Tetrahedral chemistry education could serve as an apt metaphor for describing what we value in chemistry education, highlighting the human element by placing new emphasis on two dimensions of learning chemistry:

(1) The rich web of economic, political, environmental, social, historical and philosophical considerations, woven into our understanding of the chemical concepts, reactions, and processes that we teach our students and the general public.
(2) The human learner. Tetrahedral chemistry education emphasizes case studies, investigative projects, problem solving strategies, active learning, and matching pedagogical strategies to the learning styles of students. It maps pedagogical strategies for introducing the chemical world at the symbolic, macroscopic, and molecular level, onto knowledge of student conceptions and misconceptions.

While the metaphor of tetrahedral chemistry education is new, the underlying emphasis on the human element is not. Emil Fischer, recipient of the second Nobel Prize in Chemistry (1902), was quoted as saying: Chemistry is “inseparably bound up with the fortunes of those who dedicate themselves to it.” (Fischer cited in Read, 1947). A poignant comment from a student whose father permitted him to study science, because he was considered “too stupid” for business (Frängsmyr, 1966).

Echoing Fischer’s sentiment, 1981 Nobel Laureate Roald Hoffmann’s book, The Same and Not the Same (1985), is introduced by:

> Positioned at the crossroads of the physical and biological sciences, chemistry deals with neither the infinitely small, nor the infinitely large, nor directly with life. So it is sometimes thought of as dull, the way things in the middle often are. But this middle ground is precisely where human beings exist, and…the world at the molecular level is complex and agitated, like the emotions of the supposedly dispassionate scientists who explore it.

Successful chemistry teachers already practice tetrahedral chemistry education, by situating chemical concepts, symbolic representations, and chemical substances and processes in the authentic contexts of the human beings who create substances, the culture that uses them, and the students who try to understand them (Mahaffy, in-press). The tetrahedral metaphor may help us integrate content and context, instead of emphasizing one at the expense of the other.

## ILLUSTRATING TETRAHEDRAL CHEMISTRY EDUCATION

Through that lens of tetrahedral chemistry education, let's examine a few of the many ways in which chemistry education should be shaped by new interfaces and research areas, and new understandings of how students learn. Each of the four vertices of the tetrahedron (and the corresponding faces connecting those vertices) should be emphasized at different points of the curriculum, and in different ways for majors and non-majors. Perhaps chemistry majors should encounter overt connections to the top vertex (the human element) more frequently, especially in advanced courses. To motivate further study, non-science majors encountering chemistry need to start by seeing its relevance to their lives. Once motivated, students not majoring in science often need a great deal of help with the symbolic/ quantitative/ representational vertex of the tetrahedron.

In illustrating tetrahedral chemistry education below, I've drawn on three sources. The first is a visionary report commissioned by the National Academies of Science in the US, Beyond the Molecular Frontier: Challenges for Chemistry and Chemical Engineering (NRC, 2003). The second also represents visions about the way chemistry shapes modern life – but this time by children from around the world reflecting on what it means to "live in a chemical world." Several of those student visualizations are used as illustrations, selected from 402 submissions to the recent competition organized by IUPAC's Committee on Chemistry Education (CCE), in partnership with Science Across the World (SAW), (Schoen, 2003). Finally, I will illustrate from my own research and "practice" in the classroom and laboratory, five concrete examples of what tetrahedral chemistry education might look like:

- Chemistry Fuelling Modern Life
- Chemistry of our Planetary Support System
- Chemist-Creators
- Seeing and Understanding the Chemical World
- Chemistry of Life

**Chemistry fuelling modern life**

81.9. Up from 67.9 just a few months ago. That's the price (in cents) of a liter of gasoline in Edmonton this fall, as the global market value for a barrel of oil skyrockets. When my students are asked to think about how chemical reactions fuel modern life, they often think first of the combustion of fossil fuels. The study of combustion reactions presents rich opportunities to address the symbolic, macroscopic, and molecular levels of chemistry in contexts that matter for my Canadian students, who burn the refined products of Alberta's tar sands as they make their way to and sit in a warm classroom. In the region of the world where this 18th ICCE is being held, students know well the economic, political, and environmental dimensions of oil and gas resource development.

Perhaps a chemistry educators' perspective on fossil fuels should also include the insights of Mendeleev, who felt that the potential for chemical transformation of these materials far exceeds the value obtained from their combustion. When visiting the oil fields of Pennsylvania and Azerbaijan, Mendeleyev described burning petroleum as a fuel as "akin to firing up a kitchen stove with banknotes" (Stanitsky, Eubanks, Middlecamp & Pienta, 2003). His perspective provides a classroom transition into other uses for petroleum and non-renewable feedstocks, and an introduction to polymers and plastics.

Chemistry majors often come to university adept at working out empirical formulas from combustion analyses, and can usually "see" molecular level pictures of fossil fuels like natural gas. Many will learn to understand representations of the molecular orbitals for methane and its combustion product, carbon dioxide. But some increasingly important forms of methane ("ice on fire") and carbon dioxide can light new sparks of interest in our students. At high pressures and low temperatures, methane and carbon dioxide molecules can become enclosed in cages of water molecules, forming non-stoichiometric hydrates. In the case of methane, these clathrates are found in vast quantities in the deep ocean and in the arctic tundra, with estimates for total reserves varying wildly, but likely on the order of magnitude of other total coal, oil, and natural gas reserves (Suess, Bohrmann, Greinert, & Lausch, 1999; Kleinberg & Brewer, 2001).

An entire tetrahedral chemistry course could be built around methane hydrates, including the history of their discovery, the lore associated with the release of giant methane bubbles in marine disasters, the extent of marine and terrestrial resources, challenges of extraction, climate change implications, structural dimensions, and thermodynamics of hydrate formation.

Humans have recently exploited reactions involving more exotic fuels and oxidants, such as hydrazine and nitrogen tetroxide, refined kerosene and liquid oxygen, ammonium perchlorate and aluminium, and hydroxyl-terminated polybutadiene, to begin to answer fundamental questions about our solar system ("Mars Exploration Rover," 2004). Much of the world has watched stunning images of the Rover on Mars in the past two years, made possible by the propulsion of spacecraft to the red planet some 150 million km away from earth.

We know, too, that we will need to move beyond fossil fuels during the lifetime of our students, and issues such as global climate change will push ahead alternatives such as fuel cells and nuclear fission and fusion, in addition to renewable resources. A discussion of nuclear energy serves well to introduce ideas of risk assessment and perception, and to balance the risks of using fissionable materials with those of increased combustion of fossil fuels.

Over the next decade we should introduce our chemistry students to key chemical challenges related to energy, such as the following (NRC, 2003, p. 160-170):

- Fuel cell chemistry and technologies
- Materials for solar energy capture and storage
- High-energy-density, rechargeable storage batteries
- Biomass as a renewable fuel source
- Superconducting materials for energy distribution
- Technologies and catalysts for coal as a fuel
- Carbon dioxide sequestration
- Lower cost, lighter weight, more durable, recyclable polymers for vehicles.

Finally, we need to help our students understand and address the energy crisis that exists in many parts of our globe today – the challenge of finding sufficient food to meet daily caloric requirements for our body's internal combustion engines and sufficient fuel to prepare that food.

### Chemistry of our planetary support system

The on-going intense search for water on Mars highlights the critical function of that triatomic molecule in sustaining life on our own planet earth. A second example of tetrahedral chemistry education can be found in investigating the chemistry involved in the support systems of our own and other planets. Education for chemists and citizens in atmospheric and environmental chemistry should include concepts (NRC, 2003, p. 148-159) such as:

- How an understanding of the complex chemical interactions of our biosphere can help design sustainable materials and processes for modern life.
- Green chemistry in design of products, including catalysts
- New processes for generation and distribution of energy that address air & water quality and climate change.

First year university science students can be introduced to a spectrum of concepts from physical properties to phase diagrams by asking them to mentally transport a cup of liquid water to the surface of Mars, and think about what phase changes would be possible under the combination of low temperature and the planet's very thin atmosphere. Researchers think that the water which carved the Martian gullies may have boiled explosively at very low temperatures soon after it erupted from underground (“Making a Splash,” 2000).

The role water plays in sustaining human life is emphasized by predictions that "fierce national competition over water resources…contain the seeds of violent conflict” (Annan, 2002). In the region where this ICCE conference is held, examples like the dramatic degradation of the Aral Sea illustrate starkly the need to pay careful attention to this molecule of life. The students in our classrooms now will need to play a key role in providing clean water to the world’s population, and also in dehydrating conflicts that result from competition over fresh water resources.

Considerable pedagogical value can be found in encouraging students to create their own visualizations of chemical processes important in their lives. One imaginative visualization of the chemistry of our own planet, drawn by 10 year old Macicj Tomela from Poland is shown in Figure 3 (Schoen, 2003).

**FIGURE 3.** *“A World of Chemicals.” Submission by 10-year old Maciej Tomela from Poland, to the IUPAC/SAW 2003 “It’s a Chemical World” poster competition.*

The descriptive term, calcareous ooze, intrigues chemistry students as they try to understand the ultimate environmental fate of another triatomic molecule vital to earth’s support systems, carbon dioxide. Thirteen-year old Tudor Bumbak from Romania, puts a whimsical human face on carbon dioxide at the molecular level in Figure 4 (Schoen, 2003).
Investigating the nature of electromagnetic radiation, and the interaction of electromagnetic radiation with molecules such as carbon dioxide can build on accessible images such as Bumbak’s. To make sense of the science behind current models and data on global climate change, students need to understand radiative forcing by carbon dioxide and other less well known trace atmospheric gases.

In my chemistry course for arts and social science students, accessing the symbolic/ numeric vertex of the tetrahedron is particularly challenging, and making connections to everyday life of students is critical. So we hold a lab in a grocery store to identify topics of

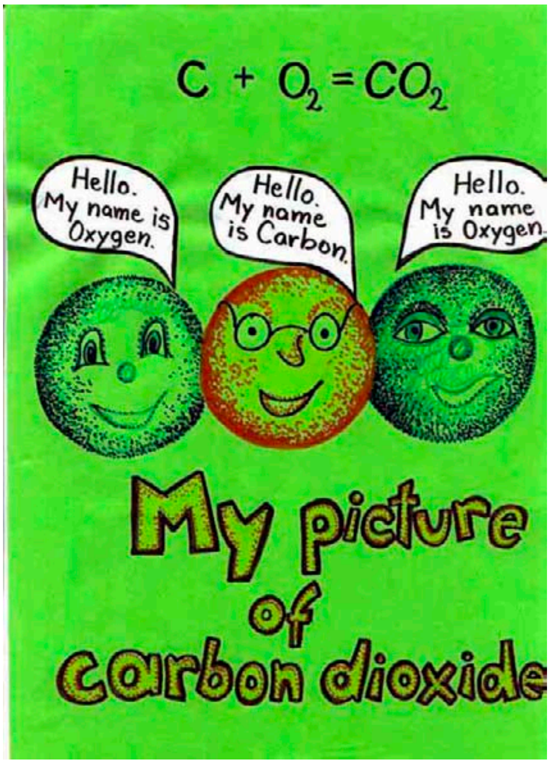

**FIGURE 4.** *"My Picture of Carbon Dioxide." Submission by 13-year old Tudor Bumbac from Romania, to the IUPAC/SAW 2003 "It's a Chemical World" poster competition.*

interest, including food additives and methods of preservation, trace contaminants, and the link between food and energy. We calculate the fossil fuel cost of bringing a banana from Ecuador to Edmonton in February, comparing the mass of carbon dioxide produced in the transportation chain to the mass of the banana consumed in Northern Alberta. That same banana is also a source of exposure to radioactivity. We calculate the annual exposure to radiation from the beta-emitting radioisotope $^{40}K$ found in bananas, and compare this annual exposure to radiation doses from other activities, such as radon gas, medical x-rays, smoke detectors, and the nuclear power industry.

Connections to fundamental chemistry of our planetary support systems can be extended to senior courses. Tapping into wide-spread concern about the health effects of recent massive forest fires in Western Canada, students in our 3rd year environmental chemistry course have looked at particulate matter and trace by-products of combustion reactions. In the past year those students teamed up with Environment Canada scientists to study particulate matter formed in prescribed forest burns in Banff National Park. Using GC-MS, they contributed to understanding the production of polycyclic aromatic hydrocarbons (PAH) such as benzo[a]pyrene and chrysene in particulate matter from burns. Carrying out small controlled burns in our laboratories, they helped design and test a protocol to determine whether the needles, stems, or forest duff are responsible for PAH formation ("Science research on fire," 2004).

**Chemist-Creators**

> I want to praise chemical synthesis, the making of molecules. Synthesis is a remarkable activity at the heart of chemistry, that puts chemistry close to art, and yet has so much logic that people try to teach computers to design strategies for making molecules... [Chemical syntheses] are shaped by scientific needs, economic considerations, traditions, and aesthetics." (Hoffmann, 1985, p. 95)

Often chemists try to mimic in the laboratory what is done so well in the creation of valuable molecules such as Taxol in nature. Materials such as pharmaceuticals (Figure 5) and polymers are among the most beneficial substances chemistry has brought to the human race, along with countless other substances (Figure 6) that make life enjoyable.

**FIGURE 5.** *"The Power of Chemistry." Submission by 16-year old Byung-Chan Kang from Korea to the IUPAC/SAW 2003 "It's a Chemical World" poster competition.*

**FIGURE 6.** *"Magic Cosmetics." Submission by 13-year old Tania Bancila from Romania, to the IUPAC/SAW 2003 "It's a Chemical World" poster competition.*

The promise for chemical contributions through synthesis to highlight new interfaces in the curriculum is suggested in the examples given below (NRC, 2003, p. 22-40, 123-147)

- Biomimetic approaches
- Catalysts with selectivities of enzymes
- Combinatorial methods
- Understanding chemistry of surfaces, especially catalysts
- Methods for microstructured materials, like nanoparticles
- Synthesis of substances that spontaneously self-assemble into organized systems with important properties
- Green chemistry and environmental fate incorporated into design, including the development of procedures for atom efficiency in industrial processes, and reaction cascades, where the products of one reaction feed the next.

It is estimated that over one million new compounds are synthesized each year (NRC, 2003). The creation of those new molecules, their destruction at the end of their useful life cycle, and their ultimate environmental fate are all activities "at the heart of chemistry," presenting opportunities to weave content and context together in tetrahedral chemistry education.

One example. Tetraethyl lead was a miracle molecule (Detwyler, 2001) introduced about 75 years ago by Thomas Midgley, showing exceptional success in improving the efficiency of the internal combustion engine. But that gain came at the cost of distributing small amounts of lead around our globe, with some serious effects on the health of young children (Mahaffy et. al., 1998).

Undergraduate student laboratories at both introductory (Mahaffy, Newman & Bestman, 1993) and advanced levels can focus on the analysis of trace substances like lead that affect the health of our planet in subtle ways. Our environmental chemistry students worked recently with our local health authority to develop new screening matrices for environmental lead in the home. The analysis of lead in laundry dryer lint provided an educationally-rich example of the surprising potential for applying analytical chemistry to some very ordinary waste materials (Mahaffy, et. al., 1998) to help address a health concern.

Molecules like tetraethyl lead, taxol, nitrous oxide, CFCs, antibiotics, and thalidomide are just molecules. But their creation, destruction, health effects, and environmental fate should raise challenging questions in the chemistry curriculum, including issues of how to create new materials without depleting the earth's scarce raw materials or contaminating the biosphere with synthetic by-products and used materials. Hoffmann (1985, p. 139-140) puts forward a very provocative statement of the social and ethical responsibility of chemists, which we use as a discussion starter in our senior seminar course for chemistry majors:

> Molecules are molecules. Chemists and engineers make new ones, transform old ones. Still others in the economic chain sell them, and we all want them and use them. Each of us has a role in the use and misuse of chemicals… At the same time, I believe that scientists have absolute responsibility for thinking about the uses of their creations, even the abuses by others. And they must do everything possible to bring those dangers and abuses before the public. If not I, then who? … It is this duty that makes them actors in a tragedy and not comic heroes on a pedestal. It is this responsibility to humanity that makes them human.

Tetrahedral chemistry education could remind our students of their responsibility as chemists and citizens to humanity, perhaps most clearly evident in the creation of molecules used for warfare, such as those being addressed by United Nations Organization for the Prevention of Chemical Weapons, one of the sponsors of this ICCE conference.

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|  | **Seeing and understanding the chemical world** |  |

Student-generated visualizations, such as in Figures 3-6 and the two in the section header above, give a revealing glimpse into the thought processes and conceptions students have of the macroscopic and molecular levels dimensions to seeing and understanding chemistry. That glimpse can reveal students' mental models, including long-standing misconceptions such as the nature of the electronic structure of the nucleus, often represented by students in pictures such as that shown on the right.

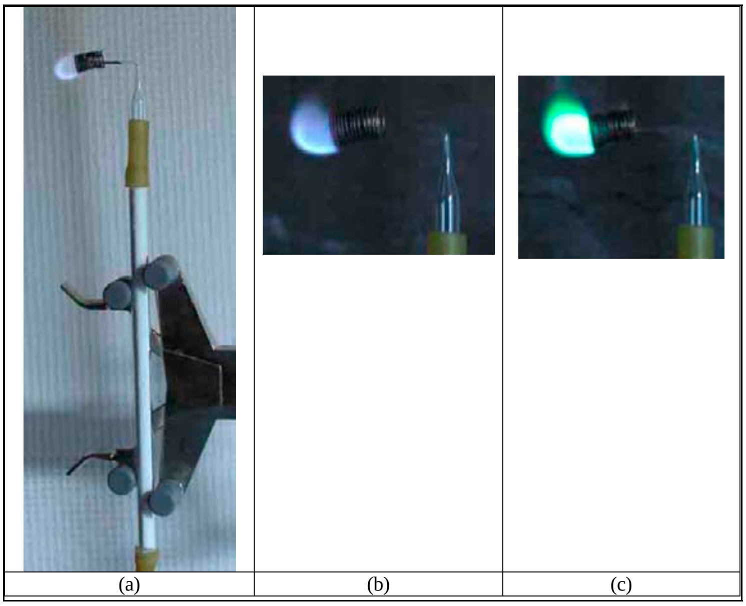
Tetrahedral chemistry education reminds us of the need to pay careful attention to learner differences and conceptions as we introduce different levels of "seeing" chemistry to our students.

At the macroscopic point of the tetrahedron, we use very simple laboratory experiments to introduce the world of polymers and also to take instruments out of their black boxes.

Figure 7 shows a polystyrene cast of a watch glass, produced by evaporating a solvent such as toluene or acetone from a solution made by dissolving pieces of a Styrofoam coffee cup (Silberman, 1994).

**FIGURE 7.** *Polystyrene cast peeled off of a watch glass (right) after evaporating the toluene or acetone solution (centre) of a Styrofoam cup (left).*

Figure 8 shows a simple, 2-Euro gas chromatograph (Thompson, 1990; Slupsky, Mahaffy, Strom & Newman, 2004), constructed by first year university students from a glass tube filled with laundry detergent. The gas chromatograph uses methane as a carrier gas, and the combustion of methane over a copper wire at the end of the “column” to detect the presence of chlorinated hydrocarbons, such as CFCs.



(a) (b) (c)

**FIGURE 8.** *Demystifying gas chromatography. (a) A home-made gas chromatograph showing the colour of the flame (b) prior to and (c) after injection of a CFC. Peak width and retention time is measured with a stop watch.*

A revolution in computer based visualizations in chemistry in the past decade has the potential to give students around the globe dynamic mental images of molecular-level processes that can help them understand structure and reactivity.

Yet we can't assume that seeing leads automatically to understanding. Nor can we assume that students around the world in different cultural contexts see the same visualizations or animations in the same way. The technologies and use of animations and visualizations are advancing much more rapidly than our knowledge of the perceptual and cognitive processes that they engage. Designers of visualizations still too readily embrace the naïve theory that any visual representation will be transparently understood. Better theories and practices require sustained interaction among visualization practitioners and researchers in vision science, cognitive psychology and neuroscience, assessment, physical and biological sciences, and education.

The creation of a multi-disciplinary research community on science visualization is beginning to address these questions, with one important forum and driving force being the Gordon Conferences on Visualization in Science and Education ("Gordon Conference," 2005).

One example of addressing "one-size fits all" approaches to visualizations is the launching of a collaborative research project to determine the effects that different cultural settings have on the way students perceive and understand visualizations. We plan to study how visualizations affect the learning and understanding of chemistry in students from different cultural backgrounds, including high schools in Chicago, Puerto Rico, and South Africa. Some teachers will use expert-generated computer visualizations. Other teachers will have the students develop their own visualizations using art, dance, music, drama, and so on. The third group of teachers will teach chemistry in the way they always have. Outcomes will guide understanding into how and when to most effectively use sophisticated, computer-based animations. We also hope to learn when very simple things that students do or teachers do with students may be more effective ways of conveying concepts in chemistry and physics (Henry, 2004).

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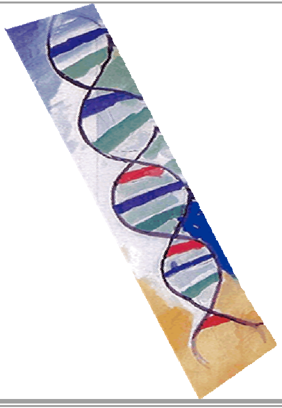
| **Chemistry of life** |  |

Emil Fischer's 1902 Nobel lecture traces the challenges in elucidating the nature of chemical processes by the "one-sided" study of carbon compounds. He extends an urgent call for "the reversion of organic chemistry to the great problems of biology." (Frangsmyr, 1996). The formal secondary and undergraduate post-secondary chemistry curriculum has only inched toward that interface with the chemistry of life over the intervening century. Yet the profession knows that formal educational programs will not be sustainable, and chemistry will not meet the needs of an aging society, unless chemistry educators support that interface from within chemistry programs much more effectively. Topics that might be worked into the chemistry curriculum to more fully equip students to understand the chemistry of life (and bring chemistry to life for students) include (NRC, 2003, p 95-122):

- The overall goal of understanding the chemical mechanisms by which biological processes occur.
- A focus on the chemistry of the brain and memory
- New antiviral and antibiotic compounds for drug resistant pathogens
- Genetic variation in responses to medicines
- Better ways to deliver drugs to targets
- Biocompatible materials for organ replacements
- Global production and availability of pharmaceutical products, including products derived from indigenous materials.

Working at this interface, undergraduate students in my laboratory are currently working on improving techniques to facilitate identification of biologically active substances in complex natural product mixtures. Dual goals are to provide tools that can be used with collaborators investigating indigenous medicinal plants in East Africa, while also developing laboratory experiments that can bring the chemistry of life more fully into organic or advanced organic chemistry courses in universities.

One example is the use of two-dimensional thin layer chromatography (2D-TLC) bioautography techniques to assay natural product mixtures for biological activity, such as anti-microbial or anti-fungal activity (Aradi, Zondervan, Strom, & Mahaffy, 2004). Figure 9 shows the spatial resolution obtained by 2D-TLC on a synthetic mixture of commercial antibiotics. The antibiotic mixture is spotted on a TLC plate and developed in a non-polar solvent. After rotation by 90 degrees, the plate is then developed in a more polar solvent and

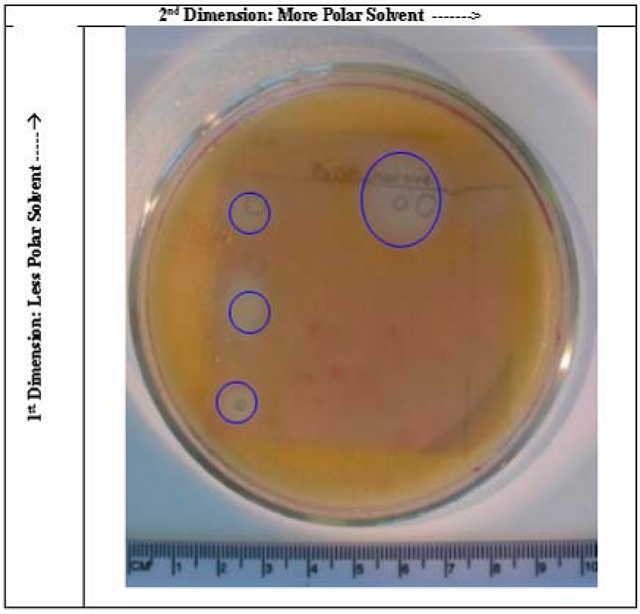


**FIGURE 9.** *Using 2D-TLC bioautography to show inhibition of Staphylococcus aureus by components in a mixture of commercial antibiotics. Zones of inhibition are clear and colourless, and outlined in blue. Compounds outlined in pencil on the TLC plate under the agar were visualized with ultraviolet light before pouring bacterially infused agar on top of the TLC plate. The initial antibiotic mixture (Gentimycin -12 mg, Ampicillin - 0.5 mg, Penicillin - 16 mg, Chloramphenicol - 5 mg, and Sulfisoxazole - 50 mg) was spotted in the bottom left circle on the plate.*

dried. Agar, infused with a bacterium such as *Staphylococcus aureus* is poured onto the plate, which is incubated for 24 hours. Visualization of bacterial growth is enhanced by lightly spraying the plate with a dye which the bacteria metabolize to produce a brightly coloured product. Clear, uncolored zones of inhibition by compounds with anti-microbial activity are then readily visualized.

We are presently developing a series of integrated undergraduate organic chemistry laboratory experiments based on the chemistry of garlic. Important techniques exploited in these experiments include the use of 2D-TLC bioautography to facilitate the identification and isolation of compounds responsible for garlic's anti-microbial and anti-fungal properties (Jackson, Strom, & Mahaffy, 2004).

## WHO WILL SHAPE THE FUTURE OF CHEMISTRY EDUCATION?

In the five areas described above, I've illustrated ways in which chemistry education practice can be shaped both by important new interfaces and by new understandings of how students learn - both important features of tetrahedral chemistry education.

The student visualizations illustrating each of the five section headers above remind us that the students currently in and soon to be in our classrooms are the ones who will truly determine the future shape of chemistry and chemistry education. Those visualizations are extracted from a brilliant water colour (Figure 10), created for our global IUPAC poster competition by one of those future-shapers, 14 year-old Can Etik from Istanbul.

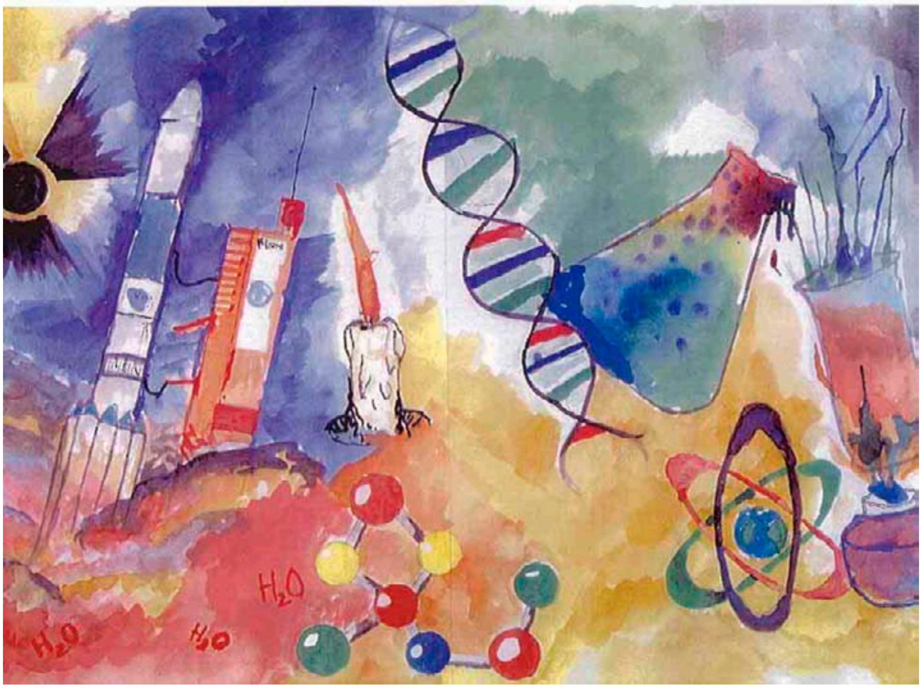


**FIGURE 10.** *"Chemistry is Everywhere." Submission by 13-year old Can Etik from Turkey to the IUPAC/SAW 2003 "It's a Chemical World" poster competition.*

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