International Organization
for
Chemical Sciences in Development

One-World Chemistry: Implications for Education[1,2]

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1. Introduction

Chemistry has been outstandingly successful during the last two centuries – as a pure science, making fundamental advances in its own domain and underpinning the establishment and growth of adjacent molecular sciences such as biochemistry, biology and materials science; and as an applied science, contributing products and materials that impact on virtually every aspect of human existence.[4]

However, in the 21st century, there are many new challenges that chemistry faces:

- As mature science, chemistry has acquired much historical baggage, including some that has tarnished its image and reputation with the general public, some of whom have come to associate chemicals only with pollution and toxicity. Furthermore, some scientists have come to regard chemistry as no longer exciting or at the cutting edge of scientific breakthroughs, but more as a service science for newer and more fashionable areas like molecular biology and nanoscience.[5,6]
- But there are also external challenges that chemistry faces – in particular, how best to contribute to solving the major global problems that the world now faces, such as sustainability, clean energy production, combatting global warming, and challenges in food, water and medicine.[7,8,9]
- And there are challenges in adapting how chemistry is taught and how best to achieve a chemistry literacy in the general population that is appropriate for contemporary living in the Anthropocene epoch.[10]

These challenges led a group of us working with the International Organization for Chemical Sciences in Development (IOCD) to write a series of articles on the future of chemistry. One of these, published in Nature Chemistry in 2015, discussed the need for chemistry to make pivotal contributions to help realize the ambitious UN Sustainable Development Goals. We argued that to do so, chemistry needs to reposition its priorities, approaches and practices.[11]

In a further paper in 2016, we proposed that this repositioning might be ‘one-world’ chemistry, a new orientation which offers a framework for how to achieve the required reform. This new orientation recognises that human and animal health and the environment are intimately inter-connected systems; and it aims to reposition chemistry as a science for the benefit of society, which requires, among other things, that the teaching and practice of chemistry adopts systems thinking and cross-disciplinary ways of working.[12]

This proposal has major implications for chemistry education, concerning reframing the ‘idea’ of chemistry as a discipline. One-world chemistry emphasises that chemistry should be taught and practiced in the context of its applications, such as in health, nutrition, energy and materials for structure and function – and, as a new imperative for chemistry, that it helps to meet the challenges of multiple global crises that we now see unfolding. Beyond applications, it also recognises the need to teach chemistry in the context of its impacts. One-world chemistry presents the idea of chemistry as a science that is vibrant and creative, that is useful and that is concerned centrally with sustainability and with ethical principles and practice.[13]

Understanding chemistry in the context of its impacts requires acknowledging its negative as well as positive potentials. While pointing to all the good things that chemistry has done for health, wealth, wellbeing and quality of life, it is vital to also acknowledge the damage that has been done and the misuses to which the products of chemistry have been applied– whether it results toxicity to people or animals, general pollution of the environment, or deliberate harm such as that caused by chemical weapons. It must be openly recognised that all chemistry knowledge and products can be applied for good or bad: and that it is people of all kinds, in every part of society, (including scientists, policy-makers, industrialists and the public) who decide. One-world chemistry stresses needs to understand how these dimensions of chemistry that relate to human and animal health and wellbeing and the biological and physical environments of the planet are all intimately connected and link up in the real world.

Chemistry literacy is about acquiring the capacity to make informed choices, and all choices have implications beyond the immediate setting, so that systems thinking is essential – which means that chemistry literacy must be taught in the context of real-world applications.

2. Systems thinking in chemistry education

Background

An important implication of learning chemistry in a broader context of its connections with and impacts on the world is the recognition that chemistry needs to be learned in a way that develops the capacity of thinking about systems and how they function and interact. This also means looking beyond the field of chemistry itself and bringing in cross-disciplinary approaches.

A system is an interconnected set of elements that is coherently organized in a way to achieve a function or purpose.[14] One definition of systems thinking, adapted from the Waters Foundation,[15] is that it uses strategies to develop understanding of the interdependent components of dynamic systems. Another way of expressing this is that systems thinking is about seeing and understanding systems as wholes rather than as collections of parts. It should be noted that, in practice, systems relating to the planet are rarely at equilibrium, but are dynamic and show changing patterns of behaviour all the time.

There are a number of strategies available for bringing systems thinking into chemistry education. These include looking beyond the trees to engage in 'forest thinking'; considering change over time; contextualizing data and concepts; and making use of causal loop diagrams, concept mapping and dynamic systems modelling.[16]

Entry points and strategies

Entry points for introducing systems thinking into education can include taking very broad global perspectives – for example, pointing to the way that, in the last two hundred years, the impact of human activities on the planet has become so far-reaching that it has come to define a new geological age – the Anthropocene. Another entry point is to talk about the concept of planetary boundaries[17] and the realization that, in some critical areas, the capacity of some planetary systems to cope with the results of human activities have already been exceeded. Or, some specific global challenges can be considered, such as those encapsulated in the UN Sustainable Development Goals and that relate to areas like water, food, energy and health;[18] or the interactions between human, animal and environmental systems that are at the heart of the development and spread of antimicrobial resistance;[19] or the impacts of atmospheric carbon dioxide on the oceans, which include the destruction of entire ecosystems such as coral reefs.[20]

Bringing systems thinking in chemistry education can make use of strategies such as learning from rich contexts and using case-based and problem-based approaches to learning;[21,22] taking the approach of the Next Generation Science Standards,[23] which aim at 'three-dimensional' learning and especially emphasize cross-cutting concepts that help students explore connections across different domains of science; drawing on work by Sevian and Talanquer[24] on learning progressions in chemical thinking, which provides insights into pathways in the evolution of students' chemical thinking and how these link with efforts to teach theory, relevance, applications and consequences; and undertaking life cycle analysis such as product life cycles.[25,26]

Some particular aspects of a couple of these approaches are highlighted, concerning cross-disciplinary concepts and life cycle analysis.

Cross-disciplinary approaches

There is a tendency is for disciplines like chemistry to be taught and to work separately in their own silos. The subjects are typically kept on parallel tracks, with little real cross-over or effort to integrate different facets of the whole system.

Cross-disciplinary engagements can involve a number of different modes:[27]

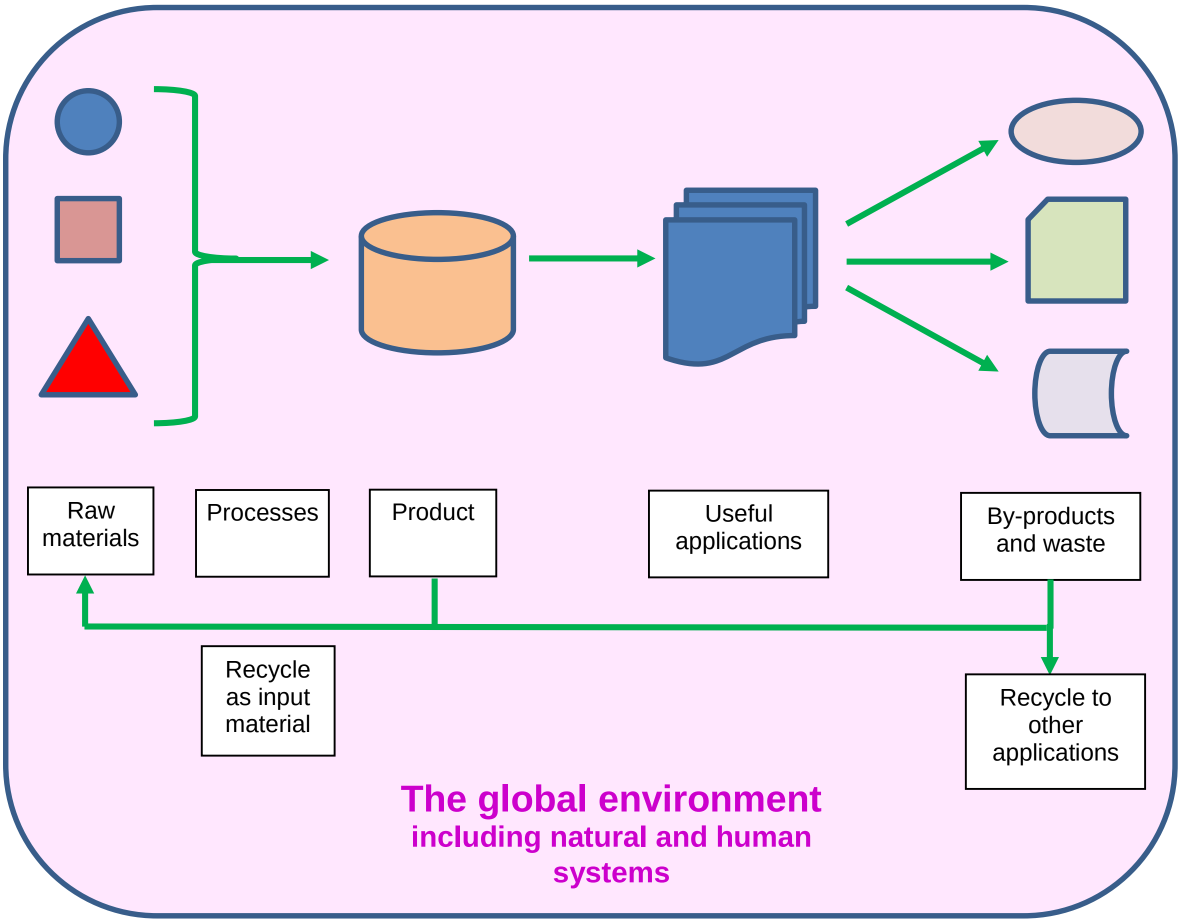
- **Multidisciplinary**– bringing together knowledge and problem-solving approaches from a host of fields that can each contribute, 'side-by-side', to different stages or aspects of problem-solving;
- **Interdisciplinary** – developing expertise in working across the boundaries between chemistry and other disciplines and transferring methods from one discipline to another. While the interdisciplinary mode still implies the autonomy of subjects working in cooperation,
- The **transdisciplinary** mode goes beyond this, creating a new synthesis of chemistry and other subjects in which knowledge, methods and solutions are developed holistically: recognizing that valuable knowledge can be found in the spaces between defined disciplines.

Cross-disciplinary concepts and approaches, are not only important for the application of chemistry to solving applied problems, but can also make the field of chemistry much more attractive to potential students.[28]

Life cycle analysis

The life-cycle of a typical product can be considered from the sourcing and extraction of raw materials through to the manufacture of a product, its distribution and use and the eventual disposal of the product, by-product and waste (Figure1).[13] This entire product life-cycle engages not only with the world's physical and biological systems but also with the complex human system. A useful starting point for this approach is the adoption of the ideas and principles of Green Chemistry, with its emphasis on reducing waste and toxicity in the practice of chemistry.[29,30]

Figure 1 Life cycle of a chemical product



Examples of chemistry-related systems thinking

Carbon dioxide in the atmosphere and oceans

The traditional approach to teaching about the dissolution of carbon dioxide gas in water examines aspects like the solubility product of CO_2, dissociation of the dibasic acid and equilibria among the various species present, the pH of the solution and the effect of adding ions that form carbonates. The thinking can be moved from the laboratory beaker to the global scale by looking at atmospheric CO_2 and its dissolution in seawater, the effects on pH in the oceans and the consequence of seawater acidification on the shells of sea creatures that are made of carbonates, and the effects on whole ecosystems like coral reefs. This approach to ocean acidification chemistry and its impact can be used to develop learner responsibility and understanding.[16,31,32,33]

Fluorocarbons in the atmosphere
Teaching about the chemistry of the alkyl halides usually covers aspects such as synthesis and reactions and considers how the properties of the halogen elements affect the physical and chemical properties of the organic halides. A broader chemistry literacy requires asking how these substances fit in the real world and what kinds of roles people play in determining their use. An informative case study can examine refrigerants and, in particular, the use of the chlorofluorocarbons (CFCs). Chemically inert, non-toxic and non-flammable volatile liquids, CFCs such as CF_2Cl_2 (patented as 'Freon') were used in refrigerators from 1930 and by the 1960s members of this family of halogenated fluoroalkanes or 'halons' were also being widely used as propellants in aerosol cans and in fire-fighting as well as refrigeration, as they are non-flammable.

In 1974, Molina and Rowland (who subsequently shared the Nobel Prize) published their findings that the photolysis of atmospheric CFCs by sunlight releases chlorine atoms, which catalyse the breakdown of ozone. The chemistry of these processes involves the Chapman Cycle of oxygen and ozone photolysis and the catalytic effect of chlorine radicals in destroying ozone.

There was immediate public concern which focused both on the environmental damage itself and on the attendant increased risks of skin cancer. The interaction of chemistry, biology and environmental systems had reached a crisis point and public opinion demanded immediate, global action. In 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer[34] was signed. This protocol required the rapid phasing out of CFCs, which were temporarily replaced with hydrochlorofluorocarbons (HCFCs); and a slower phasing out by 2030 of the HCFCs, which are less damaging to the ozone layer but unfortunately are extremely powerful greenhouse gases.

It was remarkable that international agreement should be reached so quickly on such a major and contentious issue. Richard Benedick, who headed the US delegation in the ozone negotiations, commented[35] that there was *"a need to bridge traditional scientific disciplines and examine the earth as an interrelated system of physical, chemical, and biological processes, as well as the influence of human systems"*: a good example where systems thinking was central to understanding and responding to a global challenge that originated with chemistry.

Barriers systems thinking
While thinking about all the tools and strategies that can be applied to bring systems thinking into chemistry education, it is important to be realistic and recognise that there are also going to be a number of barriers to overcome.

Some of these relate to the learner and concern the readiness and capacities of students in particular settings. There is also the question of curricula that are often already overcrowded; the challenges of faculty inertia and whether the faculty has a sufficient knowledge base; and the need to develop appropriate assessments and accreditation standards. All of these factors can add up to resistance to changing the curriculum. The good news is that it has already been done in other disciplines: biology adopted systems thinking 30 years ago[36] and it is now time for chemistry to catch up.

3. IUPAC Project:

A project proposed by Peter Mahaffy and Stephen Matlin is been undertaken by IUPAC, with support from IOCD. Mahaffy and Matlin are serving as the Task Group Co-Chairs for this project and there are Task Group Members participating from around the world. The aim is to develop learning objectives and strategies for infusing systems thinking into general chemistry education. [37] The focus is on articulating learning objectives; and at the same time identifying barriers and developing strategies to overcome them, so that students are better equipped to address emerging global challenges.

An early phase of the project involves undertaking a literature review that will inform its development, identifying what is known and what experience and good practice can be adopted in the development of learning objectives and strategies for infusing systems thinking into chemistry education. It is intended to publish the review, to inform the chemistry education community about this emergent field, stimulate interest in adopting systems thinking approaches and highlight gaps that need to be filled through research.

We would very much welcome your inputs to the project, including your ideas on:
- What are good examples of how systems thinking is currently used in general chemistry to benefit student learning?
- What could be done better? What forms of systems thinking might help equip students to better understand the role of chemistry in addressing multiple emerging global challenges?

- What interdependent components of learner systems and chemistry learning could benefit from a systems perspective?
- What are the barriers to fuller implementation of systems thinking in general chemistry – and how can they be overcome?
- What positive and negative feedback loops for student learning might be identified through systems dynamics tools?

Please send any ideas or comments to:
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5. References and notes

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