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Chemistry Education Fostering Creativity in the Digital Era

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This article is dedicated to Professor Rafael Luque Alvarez de Sotomayor, University of Cordoba, for all he has done to educate and mentor chemistry students in the course of the last decade.

Abstract: Renewing undergraduate education in the chemical sciences to foster creativity using research, visualization and connectivity resources has substantial benefits, but requires changes in the curriculum and teaching methodology as well as in academic teaching and human resource conventional policies.

Keywords: chemistry education · digital era · scientific skills · creativity in chemistry

1. Introduction

Numerous problems affect today's science and technology education across the world, including the declining number of students enrolling in science and technology,[1] the unsatisfactory status of education in solar energy,[2] the declining interest in an academic career of Ph.D. students in chemistry, physics, engineering, life and computer science,[3] and the difficulty in communicating science to the public.[4]

Chemistry, furthermore, is experiencing a declining share of public spending on research when compared to other disciplines.[5]

Paradoxically, while schools and universities are reported to find it difficult to interest young people in studying science, technology and engineering subjects, industries relying on science, technology and engineering suffer from "a skill crisis" with companies "across all branches struggling to recruit new entrants into technical and research roles".[6]

In 2010, the percentage of Ph.D. chemistry students in the U.S. interested in an academic career, found to be the lowest (60 %) amongst all scientific disciplines likely due to the existence of the chemical industry, halved to 30 % after only three years of doctorate.[3]

A recent survey of a representative sample of chemistry professionals from academia and industry found that "chemistry has an image problem",[6] with 78 percent of the sample believing that the decline in chemistry students was attributable to "chemistry's perceived lack of 'newsworthy' innovations compared to other sciences".[7]

This is surprising considering, for example, the essential role that innovation in chemistry is already playing by making available low cost hydrogen fuel cells and Li-ion batteries,[8] namely the energy storage technologies crucial to solve the energy and environmental related crises.

Key to tackling the chemistry "image problem" mentioned above,[6] and to unleashing the full innovative potential of chemistry in the digital era, we argue in this study, are changes in undergraduate education in the chemical sciences to foster creativity using recent research findings, visualization and digital connectivity tools.

Universities, furthermore, are called to change their conventional human resource policies which almost invariably have valued and benefited research over teaching.

Drawing examples from different areas of chemistry, we show in the following how chemistry education can be actually enhanced using recent research outcomes, visualization and digital connectivity tools. Numerous other research areas where chemistry always had and will continue to have a determining role, such as health and the environment, have not been included among the examples. The conclusions, however, concern all areas of chemistry.

2. Changes in Chemistry Education

Studying the effects of research and development funding on scientific productivity in academic chemistry between 1990 and 2009, Rosenbloom and co-workers identified rapid growth in knowledge production in chemistry which "cannot be explained by any of the measurable input variables including financial expenditure".[9]

The team, in other words, discovered "a departure from past experience" which points to fundamental changes in the way chemical research started to be practiced in the early 1990s.

This shift in the practice of academic research in chemistry has been due to the fact that research has become multidisciplinary and collaborative beyond national borders. Collaboration with scholars from other disciplines and from other

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countries has become the norm rather then the exception, with a large percentage of today's research papers in chemistry including authors from different scientific backgrounds and nations.

Yet, as the former chair of the committee on chemistry education at International Union of Pure and Applied Chemistry (IUPAC)[10] has lately emphasized "many of our textbooks and teaching approaches are stuck in the past and haven't changed much in the past 30–50 years. So much of the growth of chemical knowledge in cutting edge areas that cross disciplines is therefore lost to our students".[11]

The findings of fifty years of research in chemistry education,[12] suggest a number of changes in undergraduate chemistry curricula, educational materials and teaching methodologies. However, to quote the same scholar in chemistry education research, change in the practice of chemistry education has been "glacially slow".[13]

One way to promote change is to incorporate in chemistry education the outcomes of contemporary research. Another, as mentioned above, is to use new visualization tools

Figure 1. Work on green and conventional natural product extraction techniques for Master students at Avignon University. [Reproduced from Ref. 14, with kind permission].

2.1 Research-Enhanced Education

To teach the fundamental concepts of today's green natural product extraction Professor Farid Chemat at the University of Avignon, France, asks his students to use new microwave hydrodiffusion and gravity technology to extract essential oils, vitamins, dyes, biophenol antioxidants and other bioproducts (Figure 1).[14]

Students compare directly in the laboratory the new extraction method with older processes such as conventional hydrodistillation or Soxhlet extraction with *n*-hexane.

"Education in this way", Chemat suggests, "materializes the concepts and principles of green chemistry and engineering, whereas further education in the classroom instructs tomorrow's chemistry practitioners on the need to effectively communicate the benefits of a greener product for the final consumer".[14]

At Marshall University in the U.S., the students in organic chemistry taught by Professor Kenneth J. O'Connor use a new solid palladium catalyst to practice and more closely understand today's green synthetic organic chemistry.[15]

The catalyst successfully mediates the main carbon-carbon cross-coupling reactions and is also an highly selective hydrogenation mediator affording the saturation of a wide variety of alkenes and alkynes with experimental yields ranging from 60–95 % under mild conditions.

In detail, students are given the catalyst and one of three alkenes (dimethyl fumarate, *trans*-cinnamic acid and methyl *trans*-cinnamate), and are requested to carry out the hydrogenation reaction in 2-methyltetrahydrofuran under H_2 balloon conditions (Figure 2).

2-Methyltetrahydrofuran, they are further taught, is a green solvent[16] with higher boiling point than commonly employed methanol, which would lead to higher solvent recovery on an industrial level.

At the end of the experiment, the solution is filtered and the solvent evaporated to yield the saturated ester. Spectroscopy is used to confirm the product's structure by comparing the NMR and IR taken to the literature spectra.

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Figure 2. Progress of methyl *trans*-cinnamate hydrogenation mediated by Silia*Cat* Pd(0) followed by thin layer chromatography. [Image courtesy of Prof. Kenneth O'Connor, Marshall University].

Students learn through a single experiment how to use spectroscopy methods coupled to qualitative thin layer chromatography (TLC) to follow the course of a reaction.

Eventually, they calculate the green chemistry metrics E factor (the mass ratio of waste to desired product) and assess the atom economy of the reaction, thereby learning how to translate the green chemistry principles (Table 1) into practically useful numbers.

Table 1. Hydrogenation of methyl *trans*-cinnamate mediated by Silia*Cat* Pd(0). Questions to organic chemistry students at Marshall University after laboratory hydrogenation led by Professor Kenneth J. O'Connor.[15]

$$C_6H_5CH=CHCO_2CH_3 \xrightarrow[\text{Silia}\textit{Cat}\ \text{Pd(0)}]{H_2\text{(1 atm),r.t.}} C_6H_5CH_2{-}CH_2CO_2CH_3$$

1. How did you know that your reaction went to completion?
2. Assuming your yield is not 100%, where do you think the biggest losses occurred in this experiment?
3. What is the mechanism typically proposed for the hydrogenation of an alkene using a transition metal catalyst?
4. Which reagent has the largest effect on the E factor in this experiment? If this reaction were conducted in an industrial setting where solvent recovery was much higher than in your experiment, what would happen to the E factor?
5. How can you determine spectroscopically that the reaction has gone to completion after isolating your product?
6. Calculate the yield, atom economy, and E factor for your reaction. Explain what these values mean for each calculation.

2.2 Visualization-Enhanced Education

"Now I am going to look at molecules in a different way. There is no sharp distinction between symmetry and no symmetry – there are a lot of levels in the middle"[17] commented in 2010 a chemistry high-school teacher in Israel after using the Molecular Symmetry Online online visualization tool to view molecules and their symmetry elements in three-dimensions (Figure 3).

Along with a group of experienced chemistry teachers, the school chemistry educator performed online calculations of continuous symmetry measure (CSM, a number between zero and 100 providing a quantitative description of the distance a particular structure has from perfect symmetry)[18] with emphasis on the chemistry rather than on the mathematics.[17]

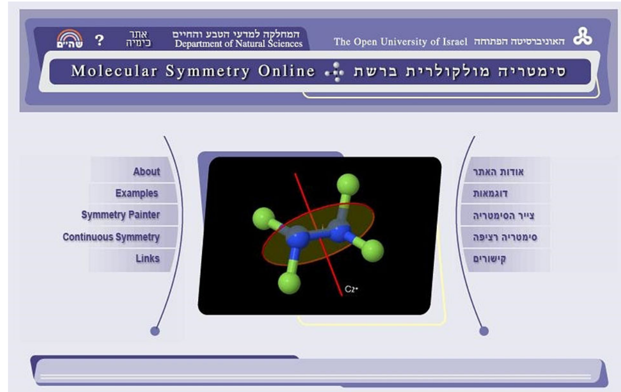

Figure 3. Home page of the Molecular Symmetry Online website managed by The Open University of Israel at the URL: http://telem.openu.ac.il/symmetry.

The teacher team discovered that the visualization tool expanded their view of the three-dimensional structure of molecules, and improved their understanding of molecular internal motion (vibration and rotation) which opened up new ways of thinking about and looking at molecules.

Suggesting that their experience could shed light on curriculum choices for teachers' education, Tuvi-Arad and Blonder concluded that "results indicate that highly advanced content can influence the way teachers think, understand, and eventually teach."[17]

The chemical methodology guiding the creation of new and useful substances is indeed based on visualization and association of chemical building blocks, most notably atoms and molecules.[19]

Following the introduction of quantum mechanics in the 1920s, said methodology has been expanded by the use of incommensurable theories resulting from the interplay of quantum mechanics and heuristic chemical concepts.

The outcome are rules and models, such as those concerning chemical reactions based on rearrangement of electron pairs during reaction which are of great utility as predictive tools.[19]

In the digital era visualization, transforming data into graphical structures, is aided by the computer and becomes interactive.[20] The aim of producing visual representations of data, though, remains unvaried: to amplify the understanding of the phenomena being studied as "understanding often comes from seeing".[21]

"Computer-supported and not computer-based",[21] suggests Valle, since "visualization does not speak to machines, it speaks to humans" and is "useless without human pattern recognition and without our openness to creative and serendipitous discoveries".[21]

According to the same science visualization scholar, the main obstacle on the path to a more generalized use of visualization in (quantum) chemistry would be "considering visualization a way to produce nice images only and not a data understanding process".[21]

Such visualization process explains, for example, the success of the reaction mechanism approach to teach and learn organic chemistry proposed by Wentland in the early 1990s ("leading to a greater understanding and appreciation of organic chemistry as attested by the many students from several universities who have taken my courses")[22] and lately streamlined and expanded by Ogilvie and Flynn,[23] along with other organic chemistry professors in Canada.[24]

Successfully used since early 2012 at the University of Ottawa, the latter methodology allows students to predict the outcomes of reactions they do not yet know based on the ability to recognize reaction patterns on the basis of electron flow.

In this way, students do not have to memorize a large set of reactions while becoming, in Flynn's words, "fluent in organic chemistry's language".[25]

Rather than organizing the discipline around structure, the discipline gets organized around reactivity (Figure 4), progressing from simple reactions, such as that between acid and base, to more complex ones.[23]

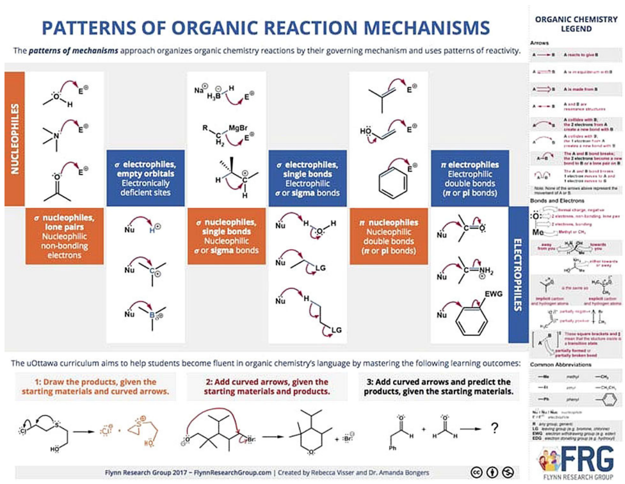

Figure 4. The educational approach developed by Flynn, Ogilvie and co-workers at the University of Ottawa organizes organic chemistry reactions by their governing mechanism and patterns of reactivity [Image reproduced from www.flynnresearchgroup.com/research, with kind permission].

Before students learned any reaction, the electron-pushing formalism mechanisms and the principles of reaction mechanisms are taught in a gradient of difficulty by teaching first the mechanistically simplest reactions and then the more complex ones during the first semester. The main organic chemistry reactions are then taught in the first and second semester of organic chemistry based on the pattern of their governing mechanism, rather than by functional group.[23]

The team authored a textbook[24] organized around the principles of reactivity, rather than on structures (alkanes, alkenes, alkynes and so on) including as a visualization tool a software (ChemWare) that allows students to visualize the dynamic mechanism of the main organic reaction mechanisms taught.

Studying the impact of the electron flow, mechanistic approach to teaching organic chemistry in action by analysing the student exam results, Flynn and Featherson recently reported that students actually attribute the correct meaning of electron-movement and bond formation/breakage to the curved arrows used in the formalism.[26]

2.3 Connectivity-Enhanced Education

Most today's leading chemistry scholars regularly update their research group websites and regularly use social networks to further disseminate their work, promote feedback and start new personal interactions and collaborations.

Similarly, engaging students in learning in the digital era requires that professors use new ways to incorporate information and knowledge that students "acquire outside class in their digital lives" into lectures and discussion held in the classroom.[27]

Don't today's students pervasively use smartphones and their applications (apps) even during classes? Chemistry educators in Singapore then lately developed a method using Instagram and Snapchat social media for laboratory teaching purposes to strengthen the concepts learned during the curriculum and facilitate learning.[28]

A public account was created for both Instagram and Snapchat to facilitate the sharing of the real-time content with the students. Different images and videos of the week's experiment were captured and uploaded onto Snapchat and then onto Instagram. The instructor adds a caption to explain the main takeaway in the "snap", or pose a question for the students to think about.

The educators discovered that through instant sharing of images and videos on both platforms, information could be shared and disseminated to the students much more quickly, especially when the instructors were not able to attend to every student's question at the same time. Uploaded content helped for example to emphasize the correct execution of a certain procedural step that has been done incorrectly by previous groups of students, so that other students could learn and avoid to commit the same mistakes.

The mid-semester survey module of 75 students conducted five weeks after Instagram and Snapchat were incorporated into the teachings clearly showed that the majority of the students felt that the applications were helpful to them in several ways. For example, the images and videos uploaded helped the students to increase their retention of chemistry knowledge (88 %), increased their understanding of both theoretical and practical aspects after each experiment (80 %), and allowed them to correct their mistakes (89 %).

Similarly, Professor Hurst in Britain sends undergraduate students studying chemistry, biochemistry, and natural sciences a blend of annotated pictures and videos on Snapchat (Figure 5) to allow them to contextualize subject knowledge in the real world, enhance student engagement with chemistry, and provide insight into research environments and life as an academic in chemistry.[29]

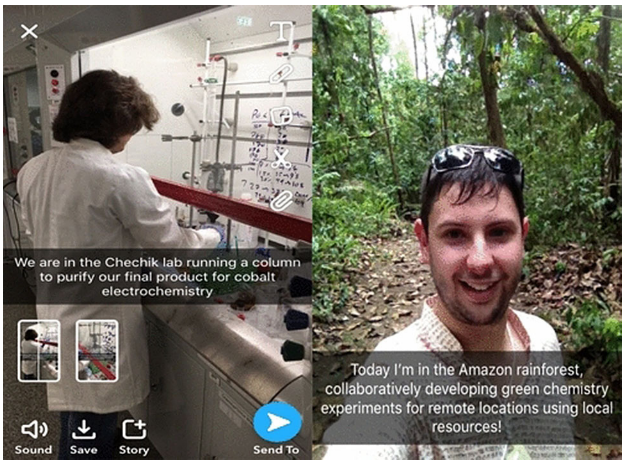

Figure 5. A Snapchat video screenshot of York University students demonstrating how to purify a product via column chromatography while their instructor, Prof. G. Hurst, provides them with a glimpse on green chemistry in remote locations using local resources. [Image reproduced from Ref.29, with kind permission].

Images and videos were shared using an account followed by 140 students. Survey of the students (43 % response rate) clearly showed (4.32/5.00) that trainees felt more engaged with chemistry when using the social media app. Said use, furthermore, was found by most students also a helpful tool to contextualize knowledge and understand how chemistry can be applied to affect their daily life.[29]

3. Conclusions

Trying to explain the dramatic growth in knowledge production in chemistry occurred between 1990 and 2009, one of the hypotheses made by Rosenbloom and co-workers ascribes the rise to the spread of automatic laboratory data collection, analysis using personal computers, and the internet.[9] In other words, new information and communication technology would be responsible for the increase in the productivity of academic chemistry.

A study of the content of this scholarly output would reveal its cross-disciplinary nature as boundaries that once defined the conventional domains of chemistry research (reflected in the "inorganic chemistry", "physical chemistry", and "organic chemistry" scholarly journals) broke down.[30]

Since the mid 1990s, enabled by the emerging World Wide Web and electronic mail Internet technologies, research chemists started to collaborate not only with colleagues from chemistry departments but also with scholars from biology, physics, computer science, engineering, medicine, archaeology, cultural heritage and many other formerly strictly separated disciplines.

Such widening of the scientific research practice had been anticipated around the same years by Lévy-Leblond,[31] calling for broadened scientific education aimed to shape scholars (and not ultra-specialized researchers) capable to carry out multidisciplinary research, and subsequently to teach the subject to tomorrow's science, technology and engineering students.

"The tasks they are currently faced with in their profession as well as the social responsibilities they can no longer avoid" has written Lévy-Leblond, "demand that… we cannot go on behaving as if science…could be taught independently of its history".[31]

Hence, first, we need to train new professional chemists providing them with a basic understanding of the history as well as of philosophy, sociology and the economics of science.

Second, aware of evidence from chemistry education research on meaningful learning,[32] chemistry professors will teach topics explaining to students why they are learning that topic.[31]

Third, chemistry educators will convey to students a clear knowledge of the unique chemistry methodology to create new and useful substances based on mental visualization and association of chemical building blocks.[19]

Fourth, to face the chemists' difficulty in communicating with the general public (worsened by limited chemical knowledge of ordinary people),[33] educators will integrate science communication training into dedicated lectures focusing on how effectively communicating about their work with the general public.

As suggested by Steinman, science communication is "a difficult skill that many practicing scientists lack, likely due to the combination of increased specialization over time and the absence of formal training in science communication".[34]

As an instructive exercise, for instance, students will be asked to pick-up a recent scientific article and write an abstract in plain English of 100 words or less, using no jargon, aimed to the public as well as to journalists.[35]

Fifth, chemistry educators will teach the basics and the tools of open science, offering a critical overview of the changes occurred in knowledge creation via research and scientific collaboration and distribution driven by the Internet since the late 1990s,[36] including the recent emergence of preprints in chemistry.[37]

Laurillard has aptly argued that "academics work to the system in which they find themselves… Without such facilitation and reward, they will respond to what the system does reward, namely a professional approach to research only".[38]

If universities wish to support a professional teaching approach that mirrors the approach for research, "there has to be an acceptance that teachers must become reflective practitioners, and an intention by university management to create the conditions that foster and reward this rather different approach".[38]

In other words, universities willing to promote excellence in teaching will need to deploy a career and financial reward system targeting both research *and* teaching, in place of the system, thus far largely dominating across the world, which mostly rewards research achievements only.

Scholars in higher education studying teaching award-winning faculties in a research-intensive U.S. university, lately reported that the main suggestion of said leading faculty educators is to create teaching centers in each university to provide all scholars with training, mentorship, professional development, and opportunities for collaboration around teaching.[39]

This brings us again to Laurillard's call for the need of teachers to become "reflective practitioners".[38]

The percentage of chemistry professors and educators who received formal training in teaching is low in most world's countries. While this could be an acceptable feature of universities of the past, training a low number of chemistry students, this is no longer the case in today's academic organizations in which a significantly larger number of undergraduate students[40] attend different chemistry subjects as part of academic multidisciplinary courses significantly different from the past.

Finally, teaching in an organization (the university seen as a system), the purpose of which is defined from the customer's *(i. e.*, student's) perspective ('*provide me with all the facilities and help I need to achieve a positive outcome from my time at your university*')[41] educators will shape educational programmes and teaching methodologies around what matters to students.

Professor Chemat, for example, uses the old chalk and talk method of teaching (Figure 6), in a two-step learning process in which he first gives a conceptual and historical introduction of natural product extraction, and then offers the technical developments.[14] A quick glance to the public recognition of his former students published online on the World Wide Web and its social networks shows how this approach is actually appreciated by Avignon's chemistry students.

Figure 6. Picture from a lecture on natural product extration of Professor F. Chemat at the University of Avignon, 2009. [Image courtesy of Avignon University. The whole lecture (in French) is available online at the URL: goo.gl/PYSVsd].

Other educators use contextualized case studies to promote learning of key chemistry concepts and comprehension of their relevance to their lives. For example, scholars in the UK teaching introductory physical chemistry ask students to work in groups to examine and compare the combustion of fossil fuels and hydrogen to the use of H_2 in fuel cells, solar photovoltaic and geothermal energy to power an emerging city (Los Verdes) in the south-west region of the U.S.[42]

Students, the educators found out, welcome studying physical chemistry within an applied context, rapidly developing a subject knowledge, the societal relevance of which could now be clearly perceived.[42] These findings are particularly relevant as it will be the creativity of tomorrow's chemistry scholars that will play a crucial role in solving the energy and environmental related global crises,[43] by advancing the low cost clean electricity storage technologies mankind urgently needs to achieve the transition to renewable energy.[8]

Eventually, the guidelines suggested by this study building on relevant previous work of chemistry education scholars, will ease the work of chemistry professors and universities seeking new ways to improve chemistry teaching and learning thereby increasing its attractiveness for the vast number of students studying chemistry subjects in the digital era.

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