I O C D

International Organization
for
Chemical Sciences in Development

Chemistry Education for the 21st Century

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I would like to add my own words of welcome to those of Alain Krief and to thank you all for coming to participate in this meeting on Chemistry Education for the 21st Century, organized by the International Organization for Chemical Sciences in Development (IOCD). I want to use the opportunity of this opening session to cover three things – first, I will provide a brief introduction to IOCD for those of you who are not too familiar with our organization; second, I will try to set the scene for the discussions we will be having over the next couple of days about Chemistry Education; and third, I will set out our ambition for the goals of this meeting and what we hope will be some of the key outcomes.

1. Introduction to IOCD

Let me begin with a brief introduction to IOCD, which was the first international NGO specifically devoted to enhancing the role of the chemical sciences in development. IOCD was founded in 1981 by Pierre Crabbé, a Belgian chemist with wide experience in academia and industry and in development programmes. Crabbé was a humanitarian with a vision that sciences like chemistry could help to narrow the development gaps between richer and poorer countries. In many ways he anticipated an approach to development based on cooperation that was eventually to become the global paradigm in the 21st Century. He was very clear that development was not a matter of charity but of mutual assistance and mutual benefit. In his book with Léon Cardyn he says: *“One does not go to a country to "assist" people, but to work with them. We should keep in mind that in cooperative programmes we learn more than we teach and receive more than we give.”*

In the first phase of IOCD’s work, through to the mid-1990s, IOCD moved away from UNESCO where it had been created in 1981, becoming registered in Belgium as a non-governmental organization in 1983 and establishing a Secretariat in Mexico City with the support of the Mexican government in 1985. IOCD quickly established a series of working groups in aspects of medicinal chemistry and the utilization of natural products and created some analytical service centres at universities in Europe, Mexico and the USA, to support chemists in low- and middle-income countries by provided spectra free of charge. In the 1990s, this was followed on by assisting in the creation of the Network for Analytical and Bioassays Services in Africa – developed under the leadership of Berhanu Abegaz based at the University of Botswana. Very early on, IOCD also established a panel for chemical education that was linked to the International Centre for Chemical Studies in Ljubljana; and meetings of the panel were held in Ljubljana in 1982 and Montpellier in 1983. The panel decided that IOCD should concentrate on programmes involving interactions between universities and the industrial sector; and that it should createan International Network for Chemical Education (INCE) to implement the panel's programmes. As far as I can determine, the INCE operated as a global network for a few years, but the seems to have wound up.

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IOCD’s initial aims included scientific engagement in research projects, research facilitation and capacity building – which at the beginning was mainly at the level of the individual. IOCD has been fortunate to attract some very prominent and brilliant scientists to its cause – including the first President, the Nobel Laureate Glen Seaborg; the current President, the Nobel Laureate Jean-Marie Lehn; and members of the Senior Advisory Council including the Nobel Laureates Norman Borlaug (father of the ‘green revolution’), Roald Hoffmann, Sune Bergstrom and Ryoji Noyori; as well as prominent scientists from low- and middle-income countries including Ethiopia, India and Pakistan.

Following Pierre Crabbé’s tragic death in a traffic accident in 1987, IOCD appointed its second Executive Director, Robert Maybury, a chemist who had worked on science and development with UNESCO and the World Bank. The 1990s saw many changes in the development sphere, with on the one hand rising capacities for science in a number of countries but on the other hand a series of financial crisis and a severe ‘donor fatigue’ which meant that there was much less money available for development work. IOCD moved into the second phase of its existence, developing new Working Groups and programmes but shifting its approach from running research projects to organizing meetings, seminars and workshops. The capacity building aspect also underwent substantial change, expanding its focus from the individual to institutional and working more with LMIC networks and on aspects of policy.

By 2011, IOCD’s portfolio encompassed 9 Working Groups and Programmes. I don’t have time to go into any detail about these, but information about all the Working Groups can be found on IOCD’s website. You will note that the last four activities on this list are all directly related to the field of chemistry education.

But the world has changed since 1981: economically, politically and socially. And the field of international development has changed. It has moved from ‘international aid’ (which some people describe as ‘redistribution’ or ‘charity’) to ‘development cooperation’; from a focus on the Millennium Development Goals (MDGs)’ which were seen to be of concern to the poorest countries to emphasis on global sustainable development, which is everybody’s business; and from a concept of ‘developed’ and ‘developing’ countries, which is now seen as inappropriate in a word where China, Brazil and India all feature in the list of the world’s 10 biggest economies, to a classification according to the annually updated World Bank rankings of ‘high-income’ and ‘low- and middle-income’ countries, (HICs and LMICs), based on assessments of GDP per capita. These changes in perspective are associated with recognition of:

- The need to have recipient countries in greater control of aid and for aid to be more focused on impact.
- Shared responsibility
- Inclusion of all the stakeholders in the process
- Co-development and opportunities for “reverse innovation” in which HICs have much to learn from innovations created in and by LMICs
- “South-South“ cooperation among LMICs themselves
- and an increasing phenomenon is “triangular“ cooperation, involving a traditional donor (HIC) an emerging (LMIC), and a beneficiary country (LMIC).

IOCD’s third phase began with the appointment of Prof. Alain Krief as IOCD Executive Director in 2010 and recognition that, in a changing world, IOCD must renew its strategy, methods and membership. The new strategy for this decade has three Strategic Priorities:

1. Chemistry for better health
2. Chemistry for a better environment
3. Capacity building in chemical education

IOCD’s strategy is to support ownership, partnership and capacity building for the use of the chemical sciences in and for the benefit of LMICs. Our approach involves going beyond scientific aid for LMICs to fostering science applied to equitable global development. And our function is increasingly to serve as an umbrella and facilitator for programmes and funding for research, education and capacity building in the chemical sciences.

2. Chemistry Education

Let’s begin with a reflection on the value of education in chemistry; and I would like to make the point that the chemical sciences have been good for wealth and health– but only up to a point, and only for some.

Let’s look overall at how human wealth has changed over time. This graph plots global Gross Domestic Product per capita, expressed in constant dollars, over the last 2000 years. As you can see, global GDP per capita remained relatively unchanged for over the first three quarters of this whole period, but then began to rise increasingly steeply. An important precursor to this rise was the Agricultural Revolution, which took place in the 17-19th centuries in Europe. By greatly increasing agricultural output, it liberated large numbers of people from the business of growing food and they flocked to the towns and cities, where the industrial revolution was able to benefit from their labour.

The chemical sciences have made a major contribution to this growing global wealth:

- In 1800 Alessandro Volta established the beginnings of the field of electrochemistry, laying the foundations for the electrochemical industry, including the generation of electrical power, its storage in portable forms in batteries, and electrolysis processes that have provided many important industrial materials.
- Synthetic chemistry had its origins in the 1840s and 50s with work on the aniline dyes. The scale-up and commercialization of synthesis processes led to major growth in organic chemicals industries in several European countries.
- Work by Pasteur in the 1860s founded the field of biochemistry and paved the way for the development of the biotechnology industry.
- Over the course of a century from the 1830s to the 1930s, work by several scientists, including the Belgian Leo Baekeland, created a new set of industries manufacturing materials such as rubbers, fibres, polymers and plastics.
- Studies by Felix Hoffman on aspirin and by Paul Ehrlich on antibiotics in the period 1897-1909 provided the basis for medicinal chemistry and gave rise to the modern pharmaceutical industry, whose sales now approach a trillion dollars a year.
- William Herschel’s work laid the foundations of spectroscopy in 1800, while the basis of chromatography was established a century later by Michael Tswett. The combination of powerful techniques for the separation and structure elucidation of chemical species provided the basis of a whole range of important analytical sciences with applications that include food, medicine and the environment.
- The second agricultural revolution had its origins in work in the early 20th century by Fritz Haber on nitrogen fixation and later by Paul Müller on the insecticidal properties of DDT. These were precursors to a wide range of agrochemical industry products.
- The demonstration by Michael Faraday of the first semiconductor effect in 1833 and work on transistors by William Shockley and a group of physicists and chemists at the Bell Laboratories in the late 1940s were important milestones in solid state chemistry. We are still seeing the expansion of information and communications technology industries based on this field today, with a host of applications of computer microchips that are transforming our lives.

This phenomenal rise in global GDP per capita during the last few centuries is mirrored by another spectacular rise in the same period. Global average life expectancy remained below 30 years of age right up to the end of the 19th century, but in the last 100 years it has more than doubled and is still increasing.

But like average wealth, average life expectancy is not evenly distributed around the world among different countries. As this map shows, national average life expectancies for some countries now exceed 80 years, while for others, national average life expectancies can be less than half that - including for some of the poorest countries such as those in parts of Africa and Central Asia.

But increasing life expectancy is not simply a matter of economic development. So, let us take a closer look at the relationship between wealth and health. A plot of average national life expectancy against GDP per capita is known as a Preston curve (after Samuel Preston).

The relationship is clearly not a straightforward linear one – beyond a certain national wealth, more money does not buy greater average life expectancy, but below this point it does seem that having more money makes a big difference.

Economics is clearly not the only factor involved in the dramatic increases we have seen in average life expectancies during the last hundred years. If you plot a set of Preston curves for the last century covering different time periods, you find something very interesting. In any one time period, there is a similar trend for the relationship between life expectancy and GDP per capita – but between each succeeding time period there is an overall increase in life expectancy. So in constant dollars, the same amount of national wealth buys more life in a later period. Economists like Easterlin have concluded that the steep decline in mortality during the 20th century had its origin not directly in wealth but in technical progress – where 'technical progress' refers to a combination of technological advances and their diffusion and uptake in different countries and the capacities of the countries themselves to conduct and apply research.

Ismail Serageldin, Founding Director the new Library of Alexandria in Egypt, has commented that "developing countries cannot do without home-grown capacity for scientific research and technological know-how. Increasingly, a nation's wealth will depend on the knowledge it accrues and how it applies it, rather than the resources it controls. The 'haves' and the 'have-nots' will be synonymous with the 'knows' and the 'know-nots'." And clearly, for the poorer countries, not acquiring and using new knowledge is not only a matter of economics – it is also a question of life and death. To put it simply – "ignorance is fatal".

It is not surprising, therefore, that among the targets of the MDGs for 2015 are the achievement of universal primary education and a global increase in the rates of adult literacy. But there are still more than three quarters of a billion adults in the world who are illiterate, and three quarters of these are concentrated in just 10 of the largest countries. Globally, the average literacy rate is around 85%, but there is a large gender imbalance with two thirds of the adult illiterates being female. The gender parity index for adult literacy is at its worst in the Arab states, Sub-Saharan Africa and South-West Asia, and it is these same countries that are furthest from meeting the 2015 targets.

More specifically in the field of science, this map illustrates the density of research workers in different countries, with lowest densities again being found in Africa and parts of Asia and Latin America.

Not surprising, low densities of skilled human resources for research correlate with low levels of scientific output. Indeed, if you scale a map of the world according to scientific papers published by citizens of each country, it provides a vivid illustration of the so-called 'north-south divide'.

So, what needs to be done about science literacy? Over 50 years ago, Paul DeHart Hurd wrote about 'Scientific literacy as a goal of science education'. Forty years later, Hurd observed that 'Although 350 years have now elapsed since it was first proposed that a purpose of science education ought to be the contributions that science makes to public life and the common good, the appropriate curricula have yet to emerge. He urged that 'Science curricula need to be reinvented to harmonize with changes in the practice of science/technology, an information age, and the quality of life.'

Of course, all of us who have worked in education know that curriculum reform is an extremely difficult business to achieve in practice. I am reminded of a comment I first heard from the Vice-Chancellor of a university in Africa: The curriculum is like a graveyard: it's full of dead bodies, but they have lots of friends who are still alive.

And then there is the question of chemistry literacy. Some have taken this in a very narrow sense, to mean, for example, the capacity to balance a chemical equation. But John Gilbert has emphasised a much wider approach, taking chemistry literacy to encompass a number of procedural competences:

- Understanding the nature of chemistry, its norms and methods
- Understanding the key theories, concepts and models of chemistry
- Understanding how chemistry and chemistry-based technologies relate to each other
- Appreciating the impact of chemistry and chemistry-based technologies on society

… and Gilber also identifies a number of degrees of chemical literacy:

- Practical or functional chemical literacy: that is needed for a person to function normally in respect of food, health and shelter in everyday life
- Civic literacy: that is needed for an informed debate about matters with a chemistry or chemical technology-related dimension
- Cultural chemical literacy: being able to appreciate chemistry as a major aspect of scientific endeavour: implies an ability to enter into professional-level dialogue with a chemist

Gilbert also notes that the substance of chemistry as a field of scientific enquiry is made up of four components:
- The processes used to obtain (discover or create) chemical knowledge
- The general concepts and specific facts so produced
- The applications of that knowledge in understanding and changing the world
- The implications of that understanding and change for individuals and societies

In the digital age, we are seeing increasing concern by countries to improve their 'e-literacy' – and just to take a snapshot of one country: I have just returned a few days ago from a three week visit to southern India, and while there I was reading the Indian daily newspapers. One interesting article was about a school in Gujarat that is eliminating paper from the classroom and going over completely to the use of tablet computers. The Prime Minister, Manmohan Singh, was also visiting the state of Kerala while I was there, and one of his tasks was to launch an e-Literacy Programme in the state which is aiming to achieve 100% e-literacy within 33 months. But the extent to which the new digital technologies are penetrating even to some of the most remote rural areas of India is perhaps best summed up by this photo that I took in northern India a couple of years ago…

So, if the chemical sciences have been good for wealth and health, for some, one of the challenges we now face is how to make good quality, relevant chemistry education available, accessible and affordable to all? And of course the whole field of education is itself changing rapidly – so how must chemistry education also change, with regard to modes of teaching and learning; and with regard to its relevance not only to the latest scientific knowledge and theories, but also to the wider world of work in general and to the need to support and enable social responsibility by all people? And running through all of these challenges is the often neglected question of how to address a range of gender issues in teaching and learning.

With regard to modes of teaching and learning, the most common approach that has been used since antiquity has involved direct interactions in real time between teachers and learners – i.e. the age of the classroom & textbook. Going beyond this model, open and distance learning (ODL) approaches were developed in the last hundred years or so. Distance education traditionally first used postal services to provide materials for students enrolled in correspondence courses, but it entered a new era of using broadcast media (in particular TV broadcasts) in 1971 when the UK's Open University began enrolling students. We are now in the third era of ODL – the age of computer-based learning with web-based supporting materials. The new technologies have enabled the establishment of massive open online courses (MOOCs), variously making claims to be "education for everyone" and "education at scale", with large programmes like Udacity, Corsera and edX being accessed by millions of students.

And the evolution continues as new technologies become available. We are now living in the era of the mobile telephony and the smartphone, and I think we will be hearing from Mei-Hung Chiu about some of the potential to exploit this technology for learning chemistry.

One common thread running through all these modes of education, whether it is the textbook in the classroom or texts that can be mailed in the post or downloaded from the internet, is the need for materials to support teachers and learners, to provide them with reliable, up-to-date knowledge, explanations, examples and illustrations. I will return to that point shortly…

Another challenge concerning the way that chemistry education must change is in the content of courses and in particular their scope, depth and relevance. Peter Mahaffy has noted that diverse forces are shaping teaching and learning of chemistry at beginning of 21st Century, including:
- 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;

- widespread implementation of computer and information technologies to visualize complex scientific phenomena;
- external forces, such as
  - global concerns about energy and water resources and the environment
  - the level of chemical literacy and public understanding of science

In responding to those forces, new dimensions to learning chemistry must be emphasized. Mahaffy proposes that the traditional ‘triangular’ metaphor of learning in chemistry which focuses on macroscopic, sub-microscopic (or molecular) and symbolic aspects of the subject, should be replaced by a ‘tetrahedral’ metaphor that emphasizes also the human element of learning. This additional dimension stresses the importance both of the human learner and the web of human connections for chemical reactions and processes. Mahaffy notes that each of the four vertices (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; and that the human element is concerned with 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.

The triangular and teatrahedral models have been further extended by others, including Mei-Hung Chiu. She has added a further corner to form a pyramid and suggests the term meso rather than molecular to represent the linkage between the macroscopic and microscopic worlds; and the addition of language as another factor influencing students' understanding of complex science concepts.

Some of the other challenges in the changing world of chemistry education include:

- the need to optimise the role of the chemistry educator, whether as instructor, tutor, mentor or facilitator;
- the need to find improved ways to steach and support the learner’s acquision of skills in conceptiualization, visualization and modelling – all areas where computer-based technologies should be espcially helpful;
- the need to have effective, practical methods for setting standards and conducting assessment and accreditation, which must cover knowledge, both theoretical and practical skills and broader chemistry literacy;
- How to provide an education in experimentation, which many would argue is vital as a way of learning - seeing chemistry as an experimental science which uses observations to create and test theories and to help train the learner in deductive reasoning; and as a way of developing the practical skills of the future ‘chemist’ or ‘chemical technologist’. But problems in providing an education in experimental chemistry include: the poor availability of equipment, chemicals, laboratory facilities in some places; poor availability of practical teachers and laboratory technicians; and particular challenges in the case of distance learners. The Open University developed an approach to tackling this last challenge, providing home experimental kits and opportunitites for lab work in residential summer schools. Another approach has been the development of kits for microscale science, which we will be hearing about from John Bradley.
- And finally, there is the challenge which I mentioned earlier of providing materials supporting the teacher and learner. The traditional support material to provide a knowledge source for teachers and learners has literally taken the form of a ledge – a library shelf holding text books. The modern equivalent for the digital age must take the form of a knowledge base – a set of digital files and resources that can be accessed through computers and mobile devices using the internet and mobile networks. Alain Krief will be leading a discussion of IOCD’s plans to develop a Chemistry KnowBase on Wednesday morning.

To summarise, the question of chemistry education for the 21st century needs to consider key factors including the curriculum, teaching modes and delivery methods, experimentation and support materials. It needs to take account of the wider environment and global trends, including the use of the internet and mobile connectivity to make education accessible via computers and smartphones; it needs to work with new online programmes such as MOOCs to enable open access; and to enhance public understanding and broader chemical literacy; all the while maintaining its relevance in a rapidly changing world.

Chemistry education in the 21st century needs the engagement of five critical groups of stakeholders, with the learners of chemistry being supported by inputs from teachers, researchers, industry and policy makers – so here is another pyramidal model of chemistry education.

One particular problematic area in this model relates to research. It has been commented that far too little research is undertaken in the field of chemistry education, and that even when it is done it is often very difficult to get the results taken up and applied by teachers – so there is a persistent research-teaching gap. It is also often a challenge to get the results of research notice and utilised by policy-makers. Overall, therefore, there are substantial difficulties in translating the results of research into evidence-informed policy and practice. This phenomenon is by no means confined to the field of chemistry education and in other spheres has been referred to as the problem of research being 'lost in translation' and as the 'know/do gap'.

Part of the reason for this phenomenon is the fact that researchers and policy-makers often use language with different meanings and there is a need for the collective development of a shared non-technical language and a shared understanding about issues – especially those concerning questions of 'certainty' and 'risk'.

Having emphasised that these challenges in communication between different kinds of people, I will end this section with a very short story:

A man is out fishing one day when a hot air balloon drifts into view. One of the balloonists calls down to him: Where am I? The fisherman replies: You're 30 metres above the ground in a balloon. Oh, the balloonist says, you must be a researcher. The fisherman says, Yes, how did you know? The balloonist answers: Because what you told me is absolutely correct but completely useless. Ah, says the fisherman, and you must be a policy maker. The balloonist asks: Yes, how did you know? And the fisherman replies: Because you don't know where you are, you don't know where you're going and now you're blaming me.

3. Objectives

1. Reflect on recent, current and prospective changes in chemistry education
   - Inputs to a paper on *Education and chemistry: meeting the challenge of access for all*
2. Advise on the establishment of an *IOCD Working Group on Chemistry Education*
   - Consider the key characteristics for a *Chemistry KnowBase* to support teachers and learners
3. Consider the need for an *International Conference on Chemistry Education for the 21st Century*