MICROSCIENCE IN THE IYPT AND THE ANTHROPOCENE EPOCH

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ABSTRACT

The International Year of the Periodic Table of the Chemical Elements recognizes the development of the Table as one of the most significant achievements in science. The development was achieved by a hands-on, minds-on approach to chemistry, an approach to learning that can be facilitated today with microscale chemistry. The development yielded a cornucopia of benefits, but the global population is now getting so large that we have gradually moved into the Anthropocene Epoch. In this Epoch we have to learn how to live for sustainability, and chemistry education must be part of this learning. The importance of microscale chemistry is increased in this context and, acknowledging the need for systems thinking, it should evolve into One-World Microscience. *[African Journal of Chemical Education—AJCE 9(3), November 2019]*

INTRODUCTION

Microscale practical activities have been propagated for several years in the teaching of chemistry [1]. The continued attention to microchemistry in education reflected the aim of providing access to hands-on activities for learners at low cost, whilst minimizing hazards and environmental impact. The minimizing of hazards and environmental impact is of special concern in chemistry, and the use of microscale experimentation has often been seen as an aspect of green chemistry practice [2].

In this International Year of the Periodic Table of the Chemical Elements (IYPT) the importance of the aim which has been behind the propagation of microscale chemistry can be seen. The Periodic Table emerged as a result of hands-on, minds-on activities over an 80-year period and this achievement had spectacular consequences. Furthermore, it can be argued that microscale practical activities deserve wider attention in the natural sciences now that it is generally acknowledged that we have entered the Anthropocence Epoch – one in which human activity measurably impacts Earth's life support systems [3].

In this paper, we reflect on the development of the Periodic Table and its consequences for human activity in the past two centuries and the emergence of the new epoch, and discuss the implications for Microscience.

THE CHEMISTRY BIG BANG I: BASIC CONCEPTS FOR THE PERIODIC TABLE [4]

Before the middle of the 18th century one might say there was no chemistry. There was much practical activity, but there was no successful theoretical framework to guide or interpret it. The concepts of element and atom had been around for two thousand years, but they were not defined in the way we would today. Speculative lists of elements of the fire, earth, air and water variety provided no guidance for practitioners trying to make sense of the properties of materials.

Lavoisier (1743-1794) changed all this by the use of mass measurements. He established a law of conservation of mass in chemical changes, and relied upon this in arriving at a definition of elements. The definition of elements, as substances that cannot be broken down to simpler substances by chemical practice, meant that there was a technique for identifying elements (elementary substances) and distinguishing them from compounds (compound substances). The breaking down was achieved by heating, because in his time current electricity had not been discovered. Hence some very refractory substances like silica and alumina were initially not recognized as compounds.

As a result of such experimentation Lavoisier published the first list of chemical elements in his book - Traité Elémentaire de Chimie - published in 1789. We could well recognize the IYPT as also marking the 230th anniversary of this first listing!

In parallel with this breakthrough, he joined de Morveau, Berthollet and Fourcroy in 1787 in proposing a systematic nomenclature of compounds based upon their qualitative elemental composition. Thus salt became sodium chloride. He knew nothing about the stoichiometry of compounds and so calcium chloride was so-named, instead of the more systematic calcium dichloride. Their so-called binary nomenclature remains one of the principal nomenclatures of chemistry.

Lavoisier is sometimes referred to as the “father of chemistry” and surely he deserves this accolade. Doubtless he would have earned yet more recognition by further experimentation, if he had escaped the guillotine in the reign of terror during the French revolution.

Lavoisier’s breakthrough was the start of the chemistry Big Bang. Twenty years later Dalton introduced a new atomic theory. He saw a possible implication of the new chemical element concept in atomic terms. Elements were made of atoms that are all the same; different elements had different atoms, especially as regards their weight. Atoms of different elements combined in forming compounds; he did not countenance the possibility of like atoms combining. He pushed these basic ideas further by determining atomic weights by experiment. He assumed that atoms combined in 1:1 ratio unless otherwise indicated: therefore, when a binary compound was decomposed the ratio of the weights of the products was deemed to be the ratio of the atomic weights. He recognized of course that these were relative values, and set the value of H as 1 as it proved the lightest of all he could test. Thus the atomic theory now assumed a quantitative aspect, experimentally based upon the use of mass measurements, as pioneered by Lavoisier. Once again the publication (1808) of a book – A New System of Chemical Philosophy – marked this next phase of the Big Bang.

THE CHEMISTRY BIG BANG II: DEVELOPMENT OF THE PERIODIC TABLE

The hands-on, minds-on activities of Lavoisier and Dalton initiated a long drawn out period of clarification and amplification. The discovery of current electricity by Volta (1800) led to another tool in the breaking down of refractory compounds – and hence the identifying of several further elements. Furthermore, quantitative studies of electrolysis by Faraday implied that the forces between atoms might be electrical and these forces could be linked with the property of valency (or combining capacity). In parallel with these electrical developments, the quantitative study of gases and their reactions led Avogadro to propose (1811) that equal volumes of all gases at the same temperature and pressure contain the same number of molecules. Avogadro distinguished between atoms and molecules and proposed that like atoms could also combine to make molecules.

By the middle of the 19th century then, the big bang had generated a sense of impending breakthrough in understanding how the nature of substances might be understood in terms of their atoms and their molecules. The breakthrough was however frustrated by contradictions in the values of atomic weights deduced from different sources. The 1st International Congress of Chemists held in Karlsruhe in 1860 was convened in this context and the most helpful proposals came from Cannizzaro and were based upon Avogadro's reports which had been largely overlooked. Within a short time, the majority of chemists came to see how a consistent set of atomic weights could be agreed. Mendeleev was the one who first capitalized on the outcomes from the Congress, publishing his Periodic Table of the Chemical Elements in 1869. He was able to state:

"Elements show a periodicity of properties if listed in order of their atomic weights."

And, as he explained:

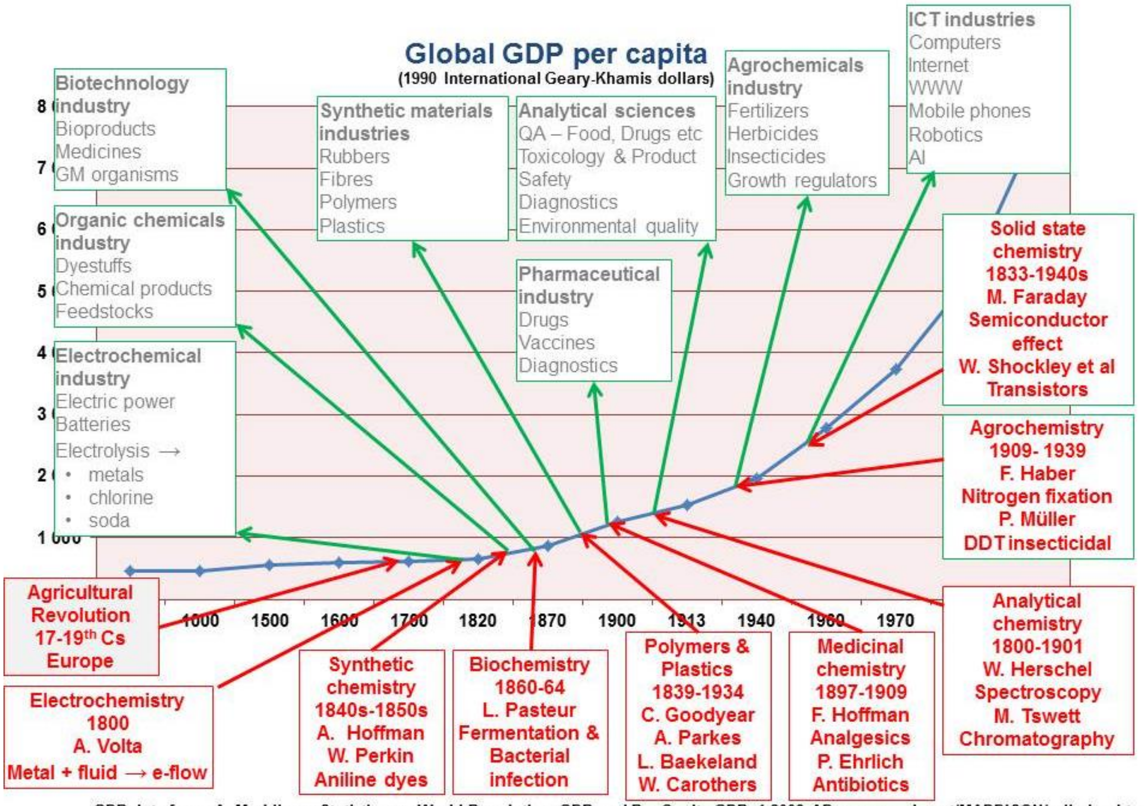
"The arrangement of the elements corresponds to their valency, and somewhat according to their chemical properties (eg Li, Be, B, C, N, O, F)."

As is generally recognized he arrived at this breakthrough by supposing that some elements had yet to be discovered and that some atomic weights were inaccurate.

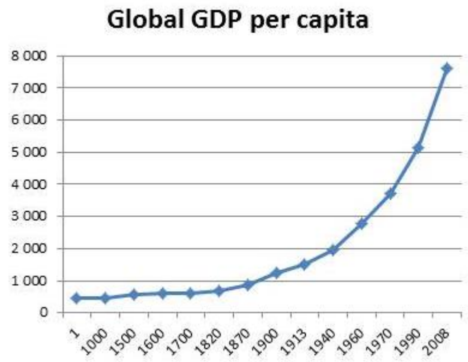
The later developments to the Periodic Table have embellished the basic construct. Knowledge of the sub-atomic particles has resulted in atomic number replacing atomic weight and the frequent use of descriptors such as s-block and p-block, whilst "valency" has disappeared from many chemistry textbooks, being replaced by "valence electrons". But if Mendeleev were alive today he would recognize that he was the father of the present-day Periodic Table. Chemistry textbooks and educators today teach some of the features of the present day version, but usually spend little time on its roots. As a result, the Big Bang is reduced to a whisper and its significance in the evolution of one of the Big Ideas in Science [5], namely "All matter in the Universe is made of very small particles", is lost. Also missing in most treatments is that it represents in one grand structure, the macroscopic, microscopic (sub-microscopic), and symbolic aspects of chemistry that permeate its entire discourse. [6]

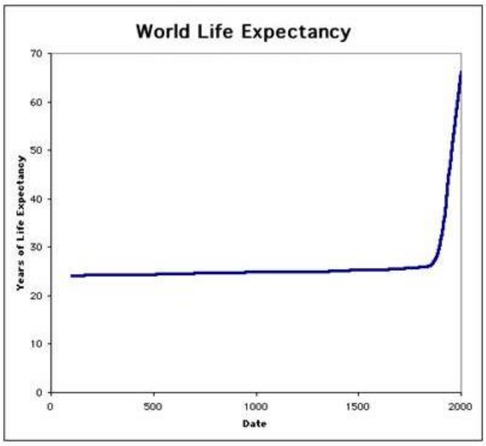
AFTER THE BIG BANG – THE BENEFITS OF CHEMISTRY

In the decades following the chemistry Big Bang, there was an unleashing of creative developments. As the press release by IUPAC (2017), following the UN proclamation of the IYPT, emphasizes [7], it proved to be a unique tool for not only deepening understanding of chemistry, but in developing applications of chemistry for the benefit of humanity. There was an astonishing growth in global GDP per capita, which has been sustained until present times. The following graph, created by Matlin [8], shows this growth and links it with the opening up of new areas of chemical knowledge and their industrial applications. The steepening of the curve over time (especially if one notes the timescale is not linear) becomes marked after 1870, suggesting the impact of the chemistry Big Bang on this global indicator.



The same message is suggested by the graph showing world life expectancy [8]. Here the timescale is linear so we see more clearly the astonishing acceleration of life expectancy in the wake of the Big Bang (taken to have been completed in 1870).





GDP data from:
A. Maddison, Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD. www.ggdc.net/MADDISON/oriindex.htm

Life expectancy graph from:
http://www.j-bradford-delong.net/movable_type/images2/Life_Expect_Long.gif

Once again let us not fail to acknowledge that, behind these indicators of benefits, there has been a vast human creative activity which may be characterized as hands-on and minds-on.

We also must acknowledge that the benefits of chemistry have increasingly been associated with some negative indicators. We have been alerted to these aspects during recent decades, and the alarm bells have been ringing ever more loudly in the last few years. Chemistry is frequently identified as associated with these negative indicators. For example, in the 6th UNEP Global Environmental Outlook (GEO-6) (2019) [9] it is stated:

> *"Modern society is living in the most chemical-intensive era in human history: the pace of production of new chemicals largely surpasses the capacity to fully assess their potential adverse impacts on human health and ecosystems."*

It is estimated in the report that 9 million people per annum are killed by pollution (80% aerial), but of course the life expectancy graph shows that globally this has still a small impact on the total population of the planet.

More widely realized now is the evidence of climate change. The UN Forum on Climate Change recently (2019) [10] reported:

"Climate change presents the single biggest threat to sustainable development everywhere and its widespread, unprecedented impacts disproportionately burden the poorest and most vulnerable…. Urgent action to halt climate change and deal with its impacts is integral to the successful implementation of the Sustainable Development Goals."

Such observations make it obvious: the question 'what are the benefits of chemistry?' must in future become 'what are the sustainable benefits of chemistry?' That is the right question as we recognize the Anthropocene Epoch has begun.

CHEMISTRY EDUCATION FOR THE ANTHROPOCENE EPOCH

230 years after Lavoisier's first list of chemical elements and 150 years after Mendeleev's Periodic Table we face a "crisis of sustainability". Yet "we still educate at all levels as if no crisis existed" [11]. Nevertheless, discussion has begun, and hopefully this will translate into action. Insofar as chemistry education is concerned, a number of organizations and individuals have put forward views. One of the organizations to do so has been the International Organisation for Chemical Sciences in Development (IOCD). In a paper entitled 'One-World Chemistry and Systems Thinking' [12], it is argued:

'Chemistry cannot be separated from the context in which it is conducted and its practice must be considered in relation to its impacts on many interconnected systems'

'Chemistry – the "central science" – must become a "central sustainability science"'

'Both teaching and practice must be informed by systems thinking and consequently embrace approaches that cross disciplinary boundaries'.

Such views may be accepted by many chemistry educators, but there will be uncertainty about their implications. IOCD has tried to provide some clarification in this regard, explaining what the implications of the concept of one-world chemistry are [13].

It is not arguing for the abandonment of teaching individual sciences in favour of an undifferentiated 'general science'. Rather is it arguing for stressing the unity of scientific principles and thought processes from the earliest stages of science education. It also argues for embedding in chemistry education from a very early stage, a growing awareness of the ways that chemistry interconnects with other disciplines.

The way forward for curriculum developers, that is indicated by the above views and clarifications, seems to align with two current science curriculum concepts particularly, namely that of Big Ideas of Science and about Science and that of Inquiry-Based Science Education. I look rather briefly at these in the following sections.

Big Ideas of Science and about Science

This vision of a science curriculum for our times emanates from significant organizations representing both teachers and researchers at all levels of education – the Association for Science Education (UK) (mostly concerned with primary and secondary education), the Inter-Academies Project (representing the views of several national Academies of Science) and the National Academy of Sciences (USA). As Harlen explains, they conceive the goals of science education [5][14]:

> *'not in terms of a body of facts and theories, but as a progression towards understanding key ideas of relevance to students' lives during and beyond their school years'*

They go on to identify 10 Big Ideas of Science that represent the traditional domains of chemistry, physics, biology and geology. As an example, one Big Idea of Science with strong relevance to chemistry educators is:

‘All material in the Universe is made of very small particles’

A paragraph of elaboration helps to understand their thinking:

> *‘Atoms are the building blocks of all matter, living and non-living. The behaviour and arrangement of the atoms explains the properties of different materials. In chemical reactions atoms are rearranged to form new substances. Each atom has a nucleus containing neutrons and protons, surrounded by electrons. The opposite electric charges of protons and electrons attract each other, keeping atoms together and accounting for the formation of some compounds.’ [14]*

The foregoing paragraph is expanded upon and aligned with the typical age ranges at which the progression of understanding might be anticipated.

Of equal importance in this vision of Big Ideas are those that are *about* Science. An example of one (of the four identified) is:

‘Science is about finding the cause or causes of phenomena in the natural world.’

which again has a paragraph of elaboration as:

> *‘Science is a search to explain and understand phenomena in the natural world. There is no single scientific method for doing this; the diversity of natural phenomena requires a diversity of methods and instruments to generate and test scientific explanations. Often an explanation is in terms of the factors that have to be present for an event to take place as shown by evidence from observations and experiments. In other cases, supporting evidence is based on correlations revealed by patterns in systematic observation.’*

It will be evident that the basic conception of the Big Ideas approach is consistent with the IOCD's argument for 'stressing the unity of scientific principles and thought processes' and by implication 'awareness of the ways that chemistry interconnects with other disciplines'. It should be evident that the Big Ideas are not the typical curriculum content sections devoted, for example, to chemical bonding or to chemical kinetics, although that content would receive attention as part of the progression.

Inquiry-based Science Education

Progressing the understanding of Big Ideas of Science may be seen as resulting from inquiring into the natural world. Scientists do this and so also may teachers and learners in a classroom. Hence, when teachers and learners inquire in this way, they teach and learn some of the Big Ideas *about* Science. This is not the kind of progression that is predominant in most school systems, when learners pass from a lower to a higher grade in each successive year. Such progression is typically like the deposition of a new layer of sediment in a lengthy geological process. Instead, this progression is a product of seeking answers to questions by collecting data, reasoning and reviewing evidence.

Inquiry does not necessarily imply practical activities although it often may do so. Data may be sourced from printed and electronic sources and modelling may feature too [15]. Inquiry-based teaching is demanding of teachers' skill and of time for teaching and learning. It can lead to greater depth in understanding but, as it takes more time, a sharper focus on a limited number of Big Ideas is a natural accompaniment.

School science curricula in most countries are far-removed from the principles embedded in the Big Ideas and IBSE concepts briefly reviewed above. Furthermore, a phrase like 'systems thinking' is likely to be new and evoke at least passive resistance. The case of the South African national curriculum for Physical Sciences (a grade 10-12 subject) exemplifies this very well. This secondary school subject has a curriculum that is 50% chemistry and 50% physics and hence basically is suited to some systems-thinking and interconnection of disciplines. Indeed, the US National Academy of Sciences explicitly endorses such a school subject:

> *"The historical division between the two subjects of physics and chemistry is transcended in modern science, as the same physical principles are seen to apply from subatomic scales to the scale of the universe itself." [16]*

However, the South African curriculum statement reveals absolutely no curricular linkages either internally between chemistry and physics or externally with Life Sciences. Furthermore, whereas 18,75% of curriculum time was allocated to a knowledge area called Chemical Systems in the curriculum introduced in 2003 [17], this was reduced to 4,5 % in the revision implemented in 2011! [18]

IMPLICATIONS FOR MICROSCALE CHEMISTRY

When we look back to the chemistry Big Bang and we look forward to the concepts of One-world Chemistry and Systems Thinking in chemistry education, what are the implications for microscale chemistry?

Firstly, looking back, we saw how the development of the Periodic Table of the Chemical Elements happened through hands-on, minds-on chemistry practical work. No period in history shows more clearly the impact of this approach on learning and applying chemistry. Inspired by this we may engage with inquiry-based science education with some confidence. Microscale chemistry fits within this framework by facilitating hands-on, minds-on practical work that is accessible to all.

Secondly looking forward, we see the writing on the wall – we cannot go on as before - either in our way of life or in our education. Chemistry education, and more generally science education, has a highly important responsibility to prepare learners at all levels, to confront the 'Earth Emergency' [19]. Curriculum change should be embarked on without delay, with the curricula preparing new teachers being an obvious priority. Microscale practical work must surely be an important component of the emerging new curricula. The scale of the equipment and chemicals used delivers its own tangible message to teachers and learners, whilst the low cost and convenience makes it use accessible to all in ordinary classrooms and in the field. Microscale chemistry has been a pioneer of practical work that demonstrates sensitivity to environmental impact and the experience gained should be incorporated into practical work in other experimental sciences. Microscale chemistry should promote its experiences and evolve into One-World Microscience.

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