



**Goverdhan Mehta**

Prof. Goverdhan Mehta is an organic chemist who has worked for many years at the University of Hyderabad, where he was a Professor, Founder Dean and Vice-Chancellor. He was also Director of the Indian Institute of Science in Bangalore and has held chairs, visiting and honorary positions in India, Belgium, France, Germany and USA. He is a Fellow of the Indian National Science Academy, serving as President in 1999 – 2001, and a Fellow of the Royal Society, London and of numerous other societies. He is distinguished for his work in organic synthesis, for which he has received many awards and prizes. He is currently University Distinguished Professor and Dr. Kallam Anji Reddy Chair in the School of Chemistry at the University of Hyderabad.



**Alain Krief**

Prof Alain Krief is widely known for his contributions to organic synthesis, including work on organo-selenium chemistry. He is currently also pursuing work in chemical informatics. For many years he was Director of the Laboratory of Organic Chemistry at the University Notre Dame de la Paix in Namur, Belgium and subsequently an Emeritus Professor there. A French citizen born in Tunisia, he studied in France, the UK and USA and has been a visiting professor at more than 15 universities worldwide. He has been the recipient of many prizes and medals, including the Prize of the French Academy of Sciences. In 2009- 2020 he has held the position of Executive Director of the International Organization for Chemical Sciences in Development.



# Chemistry in a post-Covid-19 world

The long-term impacts of global upheaval unleashed by Covid-19 on economic, political, social configurations, trade, everyday life in general and broader planetary sustainability issues are still unfolding and a full assessment will take some time. However, in the short term, the disruptive effects of the pandemic on health, education and behaviours and on science and education have already manifested themselves profoundly – and the chemistry arena is also deeply affected. There will be ramifications for many facets of chemistry's ambit, including how it repositions itself and how it is taught, researched, practiced and resourced within the rapidly shifting post-Covid-19 contexts. The implications for chemistry are discussed here under three broad headings, relating to trends (a) within the field of knowledge transfer; (b) in knowledge application and translational research; and (c) affecting academic/professional life.

*“Historically, pandemics have forced humans to break with the past and imagine their world anew. This one is no different. It is a portal, a gateway between one world and the next.”*

— Arundhati Roy<sup>1</sup>



**Henning Hopf**

Prof. Henning Hopf is an organic chemist who studied in Germany and USA. He became professor in Würzburg and was then appointed to the Chair of Organic Chemistry of the Technical University of Braunschweig (TUB), where he was Managing Director of the Institute of Organic Chemistry until his retirement. He was President of the German Chemical Society and a member of the Göttingen, North Rhine-Westphalian and Norwegian Academies of Sciences. His work has been concerned with cyclophanes, highly unsaturated hydrocarbons and aromatic compounds. He has been awarded many prizes and medals, including the Chemistry Prize of the Göttingen Academy of Sciences and the Max Planck Research Award. He is currently an Emeritus Professor in the TUB.



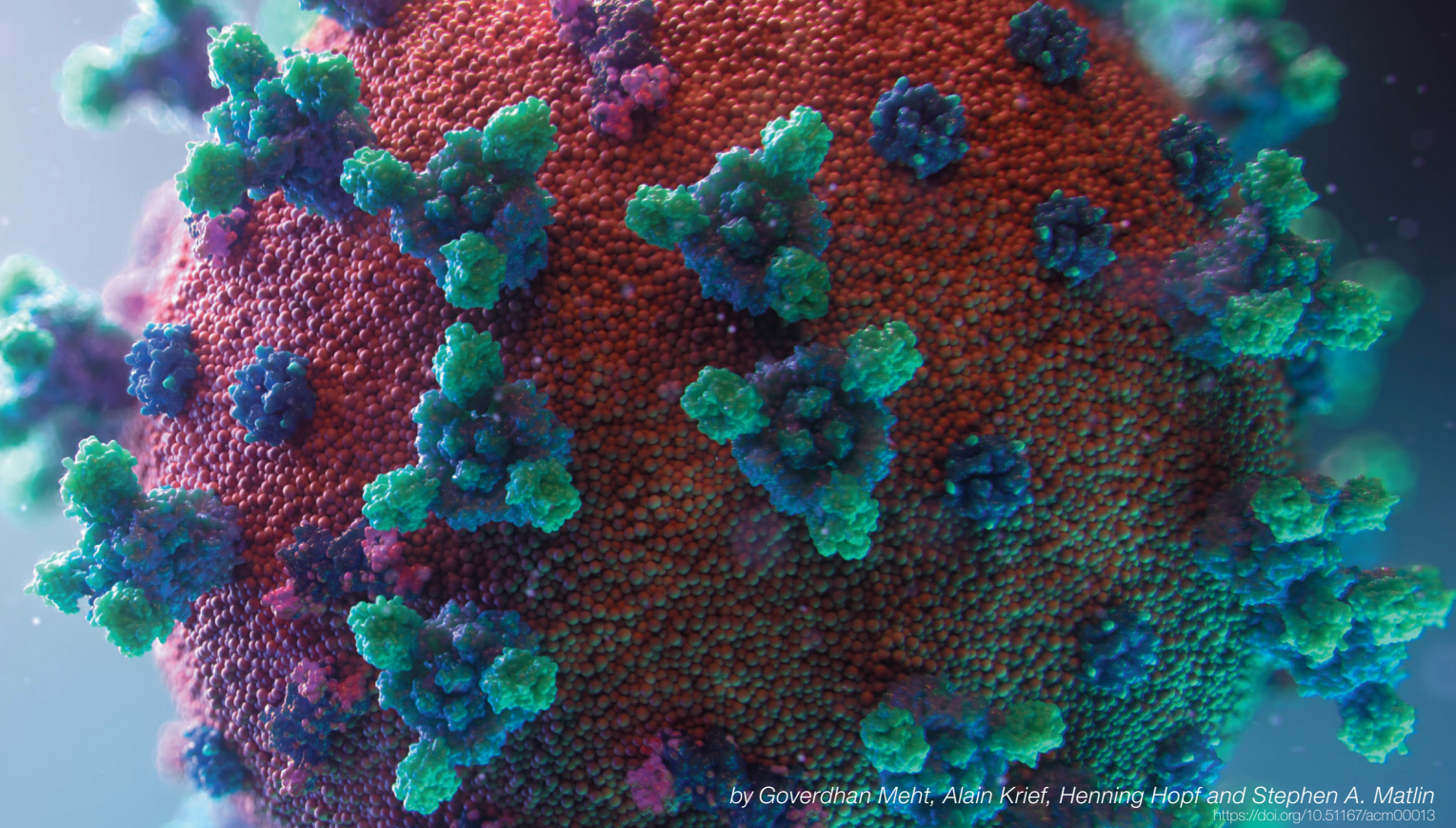
**Stephen A. Matlin**

Prof. Stephen Matlin is an organic chemist who served as Professor in Biological Chemistry in City University, London and Warwick University. He then worked in international development, appointed as Director of the health and education division of the Commonwealth Secretariat, Chief Education Adviser in the UK Department for International Development and Executive Director of the Global Forum for Health Research in Geneva. His awards include the Edmund White Prize at Imperial College London and Kelvin Lectureship of the British Association for the Advancement of Science. He is currently a Visiting Professor in the Institute of Global Health Innovation at Imperial College London and Senior Fellow in the Global Health Centre at the Graduate Institute, Geneva.



**THE WORLD IN** general will not be same after Covid-19<sup>2</sup>. The new disease, first recognised in late 2019, was the direct cause of more than 45 million recorded cases and 1.1 million deaths by November 2020<sup>3</sup> and many more could be expected before the pandemic abated. In addition, there is ongoing debate<sup>4</sup> about the possible and probable magnitude of the impacts of the pandemic on economics (including short-term dramatic declines in GDP and increases in poverty), employment, the environment,

international development and cooperation, politics and society. The whole of science<sup>5</sup> and the domains of universities<sup>6,7</sup>, and industry<sup>8</sup> in which it operates are being greatly affected. *Numerous areas of human affairs, including the world of science, are likely to become differentiated as 'before' and 'after' Covid-19.* Chemistry is no exception – and is of particular importance as its capacities are central to combatting such global threats as Covid-19 and protecting lives and the planetary environment.



by Goverdhan Meht, Alain Krief, Henning Hopf and Stephen A. Matlin  
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## The emerging landscape of chemistry

This article attempts to capture some of the main trends and directions for the field of chemistry in this pivotal period – to signpost possibilities, opportunities and challenges in a rapidly evolving landscape. Kekulé (the 19th century chemistry icon and discoverer of the structure of benzene) is often quoted<sup>9</sup> for his articulation of the character of chemistry as “the science of the metamorphosis of matter. Its real subject is not the existing matter, but its past and its future. The relationship of a compound to its past and what can become of it, is the true essence of chemistry.” Complementing this insight, it must also be recognised that the subject and practice of chemistry itself changes over time – and that it is presently passing through a period of considerable and diverse metamorphoses.

Many of the changes currently underway are being accelerated or reoriented by the global upheavals resulting from the Covid-19 pandemic, so that even though this event may not be the original cause of most of the changes in chemistry it can be seen as an exceptionally powerful accelerator.

Within the continuously evolving landscape of chemistry, while fundamental breakthroughs in this mature discipline are now quite sporadic, major advances that go beyond incremental accretion of knowledge in this central science are primarily driven by contemporaneous developments in adjacent fields and its role as ‘quality of life’ science. This is an inevitable consequence of chemistry’s dual character as a science that, in dealing with the material basis of the world, both pursues knowledge and seeks applications. Three particular sources of stimulus for developments in chemistry as a discipline are notable:

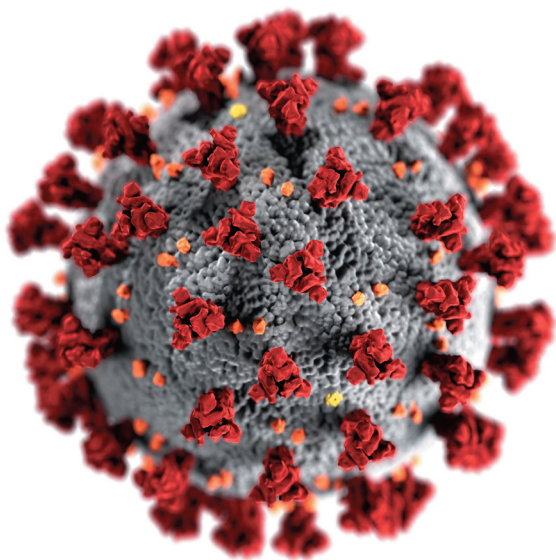
- (a) Advances in theory or practice in other disciplines (e.g. physics breakthroughs in quantum mechanics and various spectroscopic techniques) and availability of advanced computing and visualization tools for simulation and modelling, which chemists have been very successful in adopting and applying to their own challenges, have provided fresh insights into atomic and molecular structure and properties;
- (b) New approaches to analytical tools and structural analysis, including advanced separation protocols (from fractional distillation and chromatography to use of membranes, supercritical extraction and centrifugal/cyclonic methods) and tools for structure determination (from early UV,

IR, NMR and MS to advanced methods like electron microscopy, atomic force microscopy and hyphenated techniques such as LC-NMR, LC-MS, LC-QTOF MS, synchrotron-microcrystallography) have enabled chemists to analyse complex materials and isolate and identify novel structures with increasing rapidity. Concurrently capacities have been developed to operate at smaller scales (milli- to pico-molar) and faster time scales (milli- to femto-second), enabling real-time observations at atomic and molecular levels.

- (c) In cross-disciplinary work, cutting edge breakthroughs at the interfaces with other disciplines (e.g. biological and solid-state sciences) have synergistically advanced understanding and driven practical applications of chemistry in areas like engineering and medicine that aim to satisfy present and potential future societal needs or desires.

## Integrating knowledge and the quest for 21st Century dimensionalities in chemistry

A notable feature in chemistry in recent years has been a desire to advance beyond reductionist approaches, both to within the subject itself and across its interfaces with other disciplines. **One important facet of this move towards integrationism and the exploration of new dimensionalities in chemistry has been the effort to enhance directionality, purpose or societal goals, for example to strengthen the contribution of chemistry to achieving the UN Sustainable Development Goals (SDGs) or tackle environmental challenges,**



### **emphasising chemistry's potential as a core sustainability science.**

The changes that are being observed can be classified and analysed in a number of different ways. Here, they have been grouped into three areas – reflecting trends (a) within the field of knowledge transfer; (b) in knowledge application and translational research; and (c) affecting academic/professional life. Of course, all of these are highly interactive and inter-dependent areas and all are situated within the rapidly shifting contexts of 21st Century global affairs including the post Covid -19 scenario.

### **Chemistry knowledge transfer**

*“Changing a curriculum is like moving a graveyard - you never know how many friends the dead have until you try to move them.”*  
— Adage ascribed to Woodrow Wilson or Calvin Coolidge

The approach to teaching chemistry that evolved in the 19th-20th Centuries predominantly focused on explaining the fundamental pillars of the subject through lectures, textbooks and laboratory exercises, with some limited attention given to practical applications such as the sources, processes and uses of some selected products. However, the teaching of chemistry has been on an evolutionary trajectory, undergoing major changes involving the content of courses, the nature of knowledge and skills required and how they are assessed, and the process of delivery. Transformations in these areas are being

driven by two cross-cutting, interactive factors, discussed below.

### **Chemistry's content, context and interconnections**

Chemistry was traditionally taught by a reductionist approach in which, for presumed clarity and ease of learning, topics were broken down into the most basic, 'fundamental' elements possible, to be studied one-at-a-time and with 'context' such as applications or implications for more complex settings dealt with, if at all, as a brief post-script. There have been increasing moves to reorient the teaching of chemistry towards more integrated approaches.<sup>10</sup>

- Alternative approaches, such as problem-based/inquiry-based learning and context-based learning, became more popular<sup>11</sup> in the late 20th and early 21st Centuries, encouraged in part by research-led advances in understanding of learning and pedagogy and of the need to make better connections between facts, concepts and symbols, as well as recognition of the need to reinvigorate chemistry education and make it more relevant to everyday living.<sup>12</sup>
- The traditional approach of learning 'fundamentals' has tended to lead to severe fragmentation in which topics are sub-divided and taught separately and learners find it difficult to make connections between isolated pieces of knowledge, perceive the discipline in an integrated way and apply the understanding gained across sub-areas within chemistry and other disciplines. The evolving emphasis on cross-disciplinary approaches, imparting ability to tackle complex, system-wide problems – such as climate change, waste, clean water and planetary sustainability – has led to a growing desire for a more integrative approach to learning chemistry, that will build competence in such

crucial skills as systems thinking.<sup>13</sup> Many universities have already moved to offering courses and research programmes that traverse disciplinary boundaries. These include ones that bridge interfaces between chemistry and other disciplines (such as biology, engineering and medicine), as well as dealing with challenges (e.g. involving systems science, engineering and social and policy connections) such as waste management, water processing and recycling.

- A group of chemists committed to promoting sustainability has presented the concept of 'one-world chemistry', an approach that incorporates cross-disciplinary working and systems thinking.<sup>14</sup> Systems thinking has been identified as one of five key competencies that are essential for a sustainable future<sup>15</sup> and consequently a vital skill to be acquired by chemists. Through participation in a project of the International Union of Pure and Applied Chemistry (IUPAC), the roles of system thinking in enhancing the understanding and integration of chemistry and of developing its role in sustainability have been elaborated.<sup>13</sup> Furthermore, the systems-oriented concept map extension (SOCME) has been developed as a tool that aids the understanding and visualization of interactions within and between systems.<sup>16</sup>
- Concerns about global challenges, UN SDGs, etc, and the overall sustainability of the planetary environment require more than adding information/footnotes to existing chemistry texts. Typical school and undergraduate textbooks carry a historical legacy which is rooted in the idea that the planet has an effectively inexhaustible supply of natural resources. This has been reflected in the way that sources, transformations and applications of inorganic compounds derived from minerals and organic compounds derived from carbon-based fossil deposits have been presented. Chemistry is central to achieving the SDGs and now needs to be repositioned for a sustainable future.<sup>17</sup> To take organic chemistry as an example, the ready availability of unfunctionalized aliphatic and aromatic hydrocarbons, downstream from fossil fuels, has conditioned many generations of chemists to emphasize the importance of functionalising C-H bonds and oxidative transformations. A shift to sustainable use of renewable feedstocks, predominantly oxidised and highly functionalised materials, e.g. based on cellulose and lignin, should be mirrored by a re-orientation in the teaching of functional group chemistry and a much greater emphasis on C-O bond manipulations and reductive transformations.<sup>18</sup> Overall, there is a distinct trend towards teaching chemistry within a sustainability framework, positioning chemistry as a core sustainability science.<sup>19,20</sup> Cross-disciplinary lecture courses have emerged that aim not only to interface or



integrate chemistry with physical and biological sciences, but also to broaden the horizon and usher-in societal connections with arts and humanities, including philosophy, psychology and sociology.

- Chemistry learning is important for citizens in general, who need to have sufficient knowledge about the nature of the materials they handle in every-day life to make informed judgements about claims and about risks and benefits of particular products and processes. ***The threats to health and life that Covid-19 has brought have vividly highlighted the need for every citizen to be able to navigate a safe course and to protect themselves and their families and communities by understanding, evaluating, prioritising and applying information with a science/chemistry angle.***

### Access and delivery

The approach to transfer of chemistry knowledge that evolved in the 19th-20th Centuries predominantly focused on explaining the fundamental pillars of the subject through face-to-face lectures, tutorials and seminars, complemented by textbooks and laboratory exercises. Transitions towards online/distance learning have been assisted by advances in information and communications technologies (ICTs) and now greatly accelerated by the lock-downs imposed during the Covid-19 pandemic, with major implications for chemistry education.

- In recent years new platforms and pedagogies exploring the potential of 'edutech' and online teaching have surfaced. Expanding ICT capacities have encouraged many universities to begin developing on-line elements to their courses and to incorporate augmented/virtual reality<sup>21</sup> and visualization elements to assist learners to increase their conceptual understanding, including in areas such as structure, bonding and reactivity.
- A prominent impact of Covid-19 in many places has been to accelerate or precipitate a move from face-to-face to virtual ways of engaging and induction of many more people into the work-from-home (WFH) or work from anywhere (WFA) and learn-from-home (LFH) era. This move has necessitated overcoming resistance to change and acquisition of new skills by both teachers and learners. Post-Covid-19, university education is likely to operate increasingly on a hybrid model, with both face-to-face and WFH/WFA/LFH virtual modalities operating in parallel or 'blended' modes as the future normal. The hybrid system will need to be contextually and geographically specific, sensitive to the economic and social circumstances and living conditions of teachers and students while ensuring high-quality educational outcomes.

## Chemistry and health

An example of a field of chemistry teaching and research where revival and reimagination in content, focus and integration are now all timely is that which has been branded for decades as 'medicinal chemistry'. Traditionally, degree programmes in 'medicinal chemistry' have centred on the preparation of sets of compounds (ranging from a handful of examples derived from individual syntheses to extensive libraries generated by combinatorial methods) and on developing an understanding of how structure and physico-chemical characteristics relate to performance at stages such as formulation, absorption, distribution, active-site binding, metabolism and clearance.

It is important that 'medicinal chemistry' embraces related areas like pharmacology and biology, as well as the emerging capacities of AI and in silico methods, to help steer drug discovery efforts and avoid being regarded as a service tool; but also that there is recognition of the potential for contributions of chemistry to health to go very much wider than these medicinal/pharmaceutical/drug-discovery areas. The birth of the rapidly advancing arena of 'molecular medicine' owes its origin substantially to progress in opportunities opened by medicinal chemistry. The understanding of health itself has broadened from a restricted biomedical view of disease to a much more open model in which other determinants such as environmental, economic, political and social factors also play significant roles.<sup>30</sup>

A second example that illustrates the importance and value of a unified approach that integrates knowledge and practice within and beyond chemistry is provided by the critical current challenge of sustainability (see below). As a leading sustainability science, chemistry education and research needs to help introduce, build competencies and spearhead innovations in a range of techniques, skills and approaches including life cycle assessment, circularity of materials and systems thinking.

## Chemistry and sustainability – working towards material circularity

The evolution from 'environmental' to 'green' to 'sustainable' chemistry<sup>31</sup> has reflected the development of an increasingly broad perspective on the nature of the challenges to the planet and of the deep-seated roles that the chemical sciences must play in responding.

The International Year of the Periodic Table in 2019 provided an opportunity for reflection on the material sustainability,<sup>32</sup> and brought into clear focus the recognition that dealing with waste by radical improvements in material circularity represents the underlying challenge for sustainability. The need has been emphasised for a comprehensive approach in which chemistry is at the core efforts to clean up, catch up and smarten up in minimising waste in all its forms, as a key enabler of a sustainable post-trash age.<sup>33</sup>

As an example, case studies have focused on aluminium, plastics and textiles.<sup>34</sup> In each case, the challenges for chemistry were highlighted in relation to all stages from the sourcing of feedstocks to the disposal or return to some form of use of the primary material – but also in relation to the comprehensive consideration of all reagents and solid, liquid and gaseous by-products and waste products. The case study on aluminium illustrates the magnitude of many of the challenges that need to be tackled by chemists: while aluminium is one of the most extensively recycled materials on the planet and is often quoted as a model of sustainability and circularity, the large carbon footprint associated with its extraction, refining, applications and recovery, together with the production of massive quantities of by-products during processing (especially Red Mud from the refining of bauxite ore) have major impacts on the environment.

What links these two examples from very different fields is recognition that (a) ***chemistry itself must be understood as taking a comprehensive and unified view of matter, in which everything is accounted for, rather than focusing exclusively on the desired 'product'*** (as an entity whose use is someone else's concern) and ignoring the 'by-products' (which are viewed as worthless waste); (b) ***chemistry can and must be central to understanding and helping determine the subsequent fate of all materials involved in the processes adopted***, whether it is the creation of a substance for use in a pharmaceutical or medical device or in the delivery of a functional product for any other application; and (c) ***chemistry's central contributions are increasingly at and across its interfaces with a host of other disciplines*** and chemists need to nurture and expand their proficiency in conducting collaborative research in these complex domains.

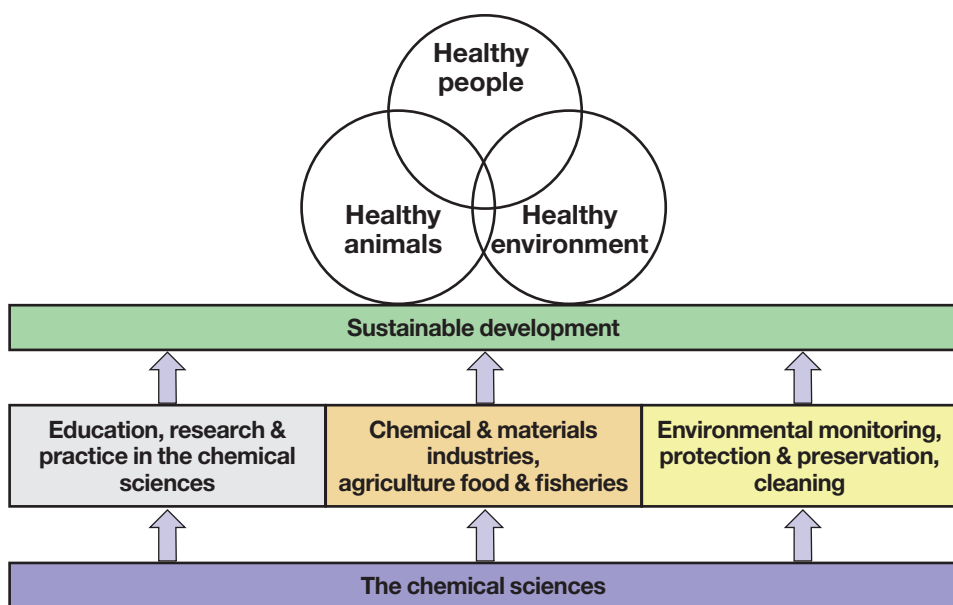


Figure 1 The chemical sciences support sustainable development

*The precipitate shifts by many institutions into the new modes of delivery, occasioned by Covid-19, should not be allowed to overshadow the need for fundamental revisions to the content of chemistry education.* As pointed out by Talanquer et al<sup>22</sup> in drawing lessons from the pandemic, “As chemistry educators, we cannot stand idly by and simply translate what we have done for more than 50 years into a virtual format to ensure its existence for 50 years more.”

### Knowledge application and translational research

“Nature also has her laboratory, which is the universe, and there she is incessantly employed in chemical operations.”  
— Jane Marcet<sup>23</sup> (1858)

### Trends in chemistry research

Both curiosity-driven scientific research and utility-driven endeavours are sometimes profoundly influenced by the trends/fashions of the day, which in turn are determined by the major breakthroughs of the time such as discovery of  $C_{60}$ , the birth of nanoscience and mapping of the human genome. Chemistry is no exception and the formulation of the Woodward-Hoffmann rules, advent of supramolecular chemistry, recognition of super-conducting perovskites and solar cell materials, metal organic frameworks (MOFs: as sensors and energy storage materials), asymmetric catalysis, enzyme engineering for directed evolution, insights into electronic

structures through ab-initio and density-functional theory (DFT) methods and single-molecule-spectroscopy are some examples of contemporary trends. There is also a profound influence of funding priorities in areas believed to be of strategic or economic importance (e.g.  $CO_2$  fixation, energy storage systems, conducting polymers, photo-electrolysis and  $H_2$  production to name a few). Emergence of new processes, equipment and techniques also define new trends e.g. metal-mediated coupling reactions, flow chemistry, digitisation, robotics, 3D printed chemistry vessels, reactions in or on water and ‘no work-up’ regimes for chemical transformations. Such fashions may appear in academia and/or industry (the latter being heavily influenced by potentials for value-creating applications in areas such as new materials related to health, energy or ICT). In addition, broader trends running across the areas of focus are sometimes evident – such as increasing attention to positioning chemistry research ‘closer to nature’ in an effort to reduce the energy and material requirements needed to make products.

Such concentration of effort in a trending field can boost its advancement and may lead to important breakthroughs and valuable applications, and this tendency will undoubtedly continue. However, there are also down-sides. For example, disproportionate fascination with the fashions of the day can distort funding trends, while other areas that might have made advances of fundamental and practical importance may be starved of resources and freedom to innovate constrained. ***The evolution of more balanced and open processes in resource allocations is now urgently needed to ensure that disciplines like chemistry remain agile, flexible and open to innovation,***

***while directing appropriate levels and proportions of resources to the most pressing priorities.***

### Refreshing chemistry: a unifying perspective

Strands of chemistry research engagement have always included studies of atomic and molecular structure, properties and dynamics of processes, synthesis and transformation of matter. Increasingly, as chemistry entities have found applications in newer smart materials and products across extremely diverse biological and everyday lifestyle materials, the focus of attention in chemistry research is transitioning towards utilitarian aspects and synthesis of properties rather than of structure *per se*.<sup>24</sup> In the emergent scenario, the traditional cubicalization of chemistry into components such as organic, inorganic, physical, analytical, etc appears increasingly redundant and must fade away.

Moreover, throughout its history, chemistry has engaged in both blue-sky research for knowledge advancement and research focused on useful applications. Divisions into ‘pure’ and ‘applied’ research are unhelpful, since the former inevitably leads (sooner or later) to the latter and many fundamental breakthroughs have emerged during the course of seeking solutions to specific problems. Nevertheless, funders (whether allocating government grants or making industrial investments) have placed increasing demands on the applicant to predict ‘impact’ as a key requirement, with direction of available resources towards strategic goals.

The time is now ripe for a more unified view of chemistry to taken in the way the discipline is organized, practiced and resourced. An added important factor in support of this is the growing recognition and centre-staging of global 21st Century challenges to human security<sup>25,26</sup> and the planetary environment.<sup>27,28</sup> Finding credible, sustainable solutions requires concerted effort of the entire dimensionality of the discipline of chemistry, in concert with its sibling and overlapping disciplines.

This concept of a unified approach has found expression in the formulation of the mutually reinforcing SDGs, in the ‘one health’ movement which recognises the inter-dependence of the health/wellbeing of human beings, animals and the environment and in ‘one-world chemistry’ approach that was referred to in earlier. The chemical sciences underpin finding solutions to all these interconnected sustainable development challenges (Figure 1).

Changes in priorities for science and in the types and contents of research will necessarily have implications for research funding, which may need to be reoriented or repurposed. Inevitably, there will be a rebalancing of the roles of scientists and policy-makers in determining the priorities, with the influence of policy-makers likely to grow – and with it the

need for scientists to engage effectively in the debate. **This rebalancing may be framed as a 'loss of freedom' for science or, more productively, as an opportunity for science to gain importance and influence in national policy-making. Chemists should ensure that they are participants in the dialogue.**

An illustration of how a unified approach, where revival and reimagination in content, focus and integration in a field of chemistry are now all timely, is that area which has been branded for decades as 'medicinal chemistry'. This could be transformed into a broader, coherent field of 'chemistry and health' (see page XX). **The Covid-19 pandemic has highlighted the centrality of chemistry to health. Its disruptive effects may now help to provide the activation energy necessary to achieve deep-seated reforms to define 'chemistry and health' as a distinct field in both teaching and research.**<sup>29</sup>

### The digital transition and automation in chemistry

The impact of ICTs and the digital transition has increasingly been seen in many areas of chemistry. These include the screening and optimization of reaction conditions, selection of efficient synthetic pathways, automation of synthetic processes and identification of potential new drug molecules. The age of the 'robochemist' has been heralded<sup>35</sup> and process chemistry and chemical manufacturing are poised to go fully digital.<sup>36</sup> These rapidly-advancing developments necessitate a fundamental rethink about what chemistry researchers should do<sup>37</sup> and consequently what they must learn, including what kinds of experimental skills they need to acquire and how ingenuity and innovative talents in molecular level manipulations will be nurtured and assessed. Chemistry research supervisors and managers need to reflect rapidly on these questions and develop practical responses.

### Reconceptualising research collaborations

It has been increasingly recognised that no single discipline, sector or country will solve the challenges of sustainable development alone and that collaboration is the key.<sup>38</sup> Stern<sup>39</sup> has contended that internationalism is a critical force for driving sustainable development in the 21st century. In science generally, a trend towards multi-centre, often international research collaborations has been underway for many years and, at least in the short term, has been accentuated in the response to Covid-19.

Since the mid-20th Century, multilateral scientific collaborations led, among many positive fruits for humanity, to the global eradication or control of diseases, prevention of destruction of the stratospheric ozone layer and improved agricultural production that helped to feed the world's rapidly burgeoning population, as well as advances in many fundamental science



areas. While chemistry played a major role in all of these, in the past, chemistry engaged in large-scale, multi-centre collaborations to a much smaller extent than some other disciplines, such as physics and biology.<sup>40</sup> In the new post-Covid-19 times, there are substantial opportunities for chemistry to strengthen its position as a responsive solution provider for societal wellbeing, with increased emphasis on problem-oriented research.

### Research, development, innovations – Liebig's legacy and the industry connect

Among major trends that have been under way in chemical industries during the last few decades, increasing automation, greater attention to the 'greening' of chemicals production and heightened concerns about the management of effluents have been impacting on approaches within the factory gates. At a broader level, the nature of the field has been transformed by condensation of the entire industry through mergers and acquisitions since the 1990s, but also increased focusing on 'core business' by the new actors. There has been a shift to outsourcing of many components/feedstocks of supply chains and adoption of 'just in time' stock approaches; and the overall dis-integration of some major areas. This has been particularly visible in the pharmaceutical industry, with research, development and production being outsourced and new spaces created for the entry of research start-ups, contract research and development companies and clinical trials businesses and organizations.

Whether these developments have all been good for science, health and national economies has been the subject of much debate. What is evident is that Covid-19 has had a dramatic short-term impact on both the focus and functioning of chemical industries. Renewed

interest in vaccine development and in the repurposing of drugs<sup>41</sup> have been prominent features of the immediate industry response – along with heightened efforts to collaborate. For example, two front-runner drugs for Covid-19 management, favipiravir and remdesivir, have been out-licensed by the innovator companies to manufacturers in different parts of the world. AstraZeneca has demonstrated commitment to broad and equitable global access to the University of Oxford's potential Covid-19 vaccine, AZD1222, through agreements with the Coalition for Epidemic Preparedness Innovations (CEPI), Gavi the Vaccine Alliance, and the Serum Institute of India (SII). A number of supply chains are being built in parallel across the world to support global access at no profit during the pandemic.<sup>42</sup> As a harbinger of what may be anticipated in future disruptions caused by other pandemics or other major global events, **Covid-19 is likely to cause a serious rethink about the robustness of industry structures, the advantages of shortening supply chains and sourcing closer to home to increase resilience to future uncertainties.**<sup>43</sup>

### Academic/professional life

**“Every aspect of the world today – even politics and international relations – is affected by chemistry.”**  
Linus Pauling<sup>44</sup> (1984)

To Pauling's statement of the ubiquitous effects of chemistry on the world needs to be added the mirror image: everything in the world also impacts on chemistry. The practice of chemistry and the life of the professional chemist – whether in teaching, research or applied areas – take place within and are influenced by

global, national and local contexts that include competitiveness for position, resources, recognition and rewards, influenced by factors ranging from globalization to local politics and social attitudes.

### Values in chemistry

The sciences share a fundamental set of values resting on the foundation that honesty is paramount. In recent years, evidence of falsifications within science and the dissemination of fake science, exacerbated by misinformation about Covid-19 during the pandemic, have caused growing concern. In the age of the internet and social media, there has also growing publicity concerning cases of bias and poor professional conduct. Examples have been seen across science, including in the field of chemistry, involving negative attitudes of individuals, arrogance, aggressiveness, bullying, discrimination, unrealistic expectations and failure to allocate due credit to collaborators. Moreover, there have been systemic failures by institutions in dealing effectively, objectively and transparently with complaints.

It is important that institutions (including academia, industry, funders and publishers) now take a firmer, proactive lead in developing systems that can help to create a safe, congenial, fair and open environment in which scientists can work. At the same time, it is

important to ensure that there are spaces for a diversity of opinions to be aired, debated and considered and for everyone to become better educated in recognising the roots of inappropriate attitudes and actions and taking steps to correct them. As a leading discipline in science education, research and publishing, chemistry can play a major role in both improving its own performance and moving institutions in this direction.

Integrity, the scope of which encompasses personal attitudes and behaviour, ethical practices and research, is a key attribute that needs to be instilled in every scientist and its development should not be left to chance but achieved through training and incentives. Integrity in research must include not only the prevention of publication of fake science, but also earlier steps along the pathway in which hype and hypocrisy are increasingly prevalent and encouraged.<sup>45</sup> Integrity is not just a principle, but a practice which requires skill development and support by systematic approaches. Much can be learned from the systems of Good Laboratory Practice (GLP) and Good Manufacturing Practice (GMP) that have become norms in industry, are prerequisites for the registration of pharmaceuticals and are already familiar to many chemists. Such systems can be adapted and incorporated, discipline-wide, as a general basis for all scientific research.

A major example of an area which illustrates the need for reform of inappropriate attitudes and behaviour and where the discipline of chemistry can make a difference concerns equity, diversity and inclusion (EDI). In all areas of life, including the world of science, the impact of Covid-19 has been especially felt by groups that have long been subjected to discriminatory practices and barriers to diversity and inclusion. In addressing the challenge of EDI, experience shows that it is important to go beyond efforts that rely on brief exposure to 'sensitisation' or 'awareness raising' or formulaic processes that count numbers of individuals in a particular group as evidence of 'diversity'. Fundamental change requires training and the acquisition of skills and proficiency in 'cultural competence' to deal effectively with diversity and inclusion.<sup>46</sup>

### Conclusions

*“There can be no return to normal because normal was the problem in the first place”*  
— Graffiti in Hong Kong<sup>47</sup>

The extraordinary world-wide disruptions caused by the Covid-19 pandemic have caused a temporary halt or redesign in many professional activities, including in science and especially in experimental fields like chemistry where access to laboratories is required. There has been displacement of activities like teaching and conferencing into online, virtual channels. The pandemic has accelerated many movements and trends that were already in progress, forcing rapid decisions to be made and breaking down barriers and resistances to change.

As the central science that studies the metamorphosis of matter, chemistry offers a creative, exciting and rewarding career to professionals in academia and industry. And, as a science that also undergoes continuous change itself, chemistry is situated in the whirlwind of forces that is re-shaping the contemporary world. The discipline will undoubtedly be affected in major ways, both in the short and long terms, by Covid-19. Chemists should see this not just as a threat, but as an opportunity to seize the initiative, to take advantage of the increased fluidity of the times to drive the ongoing changes in the discipline towards better outcomes for science, for society and for the planet. ◆

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