Future of the Chemical Sciences

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Foreword

As we celebrate the Royal Society of Chemistry's 175th anniversary year, our mission to advance excellence in the chemical sciences is as relevant as ever.

At the same time, chemistry and the environment in which chemists work are evolving all the time. We need to prepare for and influence these changes, so that we can continue to support our community.

We ran the Future of the Chemical Science initiative to help us understand how chemistry and chemists might evolve in the next ten to twenty years.

The idea was not to gaze into a crystal ball and make predictions, but to find out what some of the best minds in our community think about where the chemical sciences are going.

Based on these discussions, we have developed four surprising, but plausible scenarios, which we are using to inform our strategic planning.

Take the issue of education and training. As the professional body for UK chemists, we want to secure a strong pipeline of people with the chemical skills that our society will need in the future. To do that, we need to influence the way chemistry is taught now.

We encourage other organisations to use the scenarios to challenge their thinking and to share with us how they are preparing for an uncertain future.

In this way, we hope the report will not be the end of this process, but instead the beginning of a conversation with our community. And that, together, we can make sure the chemical sciences fulfil their potential to improve the lives of people around the world.

Chief Executive

Executive summary

The Royal Society of Chemistry wanted to understand how the chemical sciences may evolve to improve the everyday lives of people in the next ten to twenty years. We used scenario planning as a methodology for understanding uncertainty and challenging conventional thinking.

Analysing the present: seven key themes

First we identified **seven key themes** that may shape the future of the chemical sciences.

1. The role of the chemical sciences – essential and connected

Chemistry may need to be increasingly interdisciplinary and there could be a significant shift from blue-skies to problem-driven research. There is a risk of chemistry turning into a "follower" discipline in discovery.

2. Future demand – chemistry for impact

It is likely the chemical sciences will be increasingly required to solve challenges in energy and climate change, food production and clean water. Chemistry might have an increased role in biochemistry and the pharmaceutical industry, as well as in the maintenance and development of infrastructure.

3. Funding structures, institutions and education – the need for change

There may be a need for change in government funding, towards more and better directed investment in chemistry. Chemistry education might need a more integrated approach that is increasingly hands-on and interdisciplinary.

4. Globalisation – collaboration and competition

There is likely to be global growth in demand for the chemical sciences, which might not necessarily result in a significant shift of chemistry to low-cost economies. It might be challenging for the UK to remain in the top tier of leading chemistry countries.

5. Technology – efficiency and innovation

Advances in technology are likely to remain a major trend, with far-reaching implications for the future of the chemical sciences. The nature of chemistry research, organisational structures and chemistry careers might need to change in response to these radical changes.

6. Openness – disruptive, inevitable and uncertain

Open data, open access and open content might drive collaboration, specialisation and increased transparency, but the consequences are not fully understood.

7. Social change – changing workforce and public attitudes

Strong growth in demand for medicine for age-related conditions and changing demographics might lead to competition for talent and a new definition of talent that is more diverse and inclusive. There may be an increased public appetite for chemistry-related challenges with greater public intervention on how public money is spent.

Looking to the future: four plausible scenarios

We then conducted scenario planning workshops with people from across the chemical sciences, exploring how these seven themes might develop and interact. As a result of these discussions, we developed **four plausible but unexpected scenarios** for chemistry ten to twenty years from now.

1. Chemistry saves the world

The chemical sciences have the potential to solve many of the world's greatest challenges. What effect would this have on chemists and the chemical sciences?

2. Push-button chemistry

As the world becomes more connected, science and technology may become decentralised. How would automated, remote and modular chemistry change the world?

3. A world without chemists

Without the chemical sciences as a clear discipline and distinct university subject, the pipeline of future chemists could dry up. What would happen in a world without chemists?

4. Free market chemistry

If austerity measures continue in the world's biggest economies, public funding for research could be withdrawn entirely. How would chemists adapt to a world where scientific discovery is driven by the priorities of private funders?

These scenarios are **not** designed to predict the future, make a case for a preferred outcome, or offer an exhaustive list of possibilities. Rather, they are tools to challenge assumptions and prompt strategic conversations, to help leaders in the chemical science community prepare for an uncertain future, and take proactive decisions to shape that future for the benefit of people around the world.

Contents

Introduction

We exist in a rapidly changing and turbulent world. Developments in technology, science and society have caused major changes to traditional systems, structures and ways of working and exciting new opportunities are emerging.

These trends are changing the nature of chemistry as a discipline, the role of chemists and the landscape within which we work. The future of the chemical sciences is unclear. Our current response to changes may no longer be adequate. It is essential for organisations to look ahead, anticipate future developments and adapt to stay relevant.

The Royal Society of Chemistry wanted to understand how the chemical sciences may evolve to improve the everyday lives of people in the next ten to twenty years. So in spring 2015 we launched the multi-stage Future of the Chemical Sciences initiative, involving leaders from across the chemical sciences.

We used scenario planning as a methodology to understand uncertainty and challenge conventional thinking. Scenario planning is based on the understanding that many factors can influence the future context. These different factors can interact and combine in complex and unpredictable ways to create surprising outcomes. These can be shifts that directly impact the immediate environment, for example the automatisation of chemical processes, or in developments in the wider context, such as an ageing population or changes in societal values.

First, we identified seven key themes. We then considered how these themes might evolve and interact to create unexpected situations and challenges. In this way, we developed four plausible but unexpected scenarios for chemistry ten to twenty years from now.

These scenarios are not designed to predict the future, make a case for a preferred outcome, or offer an exhaustive list of possibilities. Rather, they are tools to challenge assumptions and prompt strategic conversations about the future.

The aim of planning for the future is to transform the turbulent environment into one which can be managed. Strategic scenario planning has a unique role in this regard by considering multiple outcomes. Understanding how existing trends may develop and interact can help organisations manage and monitor risk and make flexible long-term plans for the future.

We hope this report, and our four scenarios, will stimulate dialogue within our field about how best to prepare for an uncertain future, so that we can shape the future of the chemical sciences for the benefit of people around the world.

Approach

Our Future of the Chemical Sciences initiative brought together leading chemistry minds from around the world. Together, we challenged and tested emerging trends in the chemical sciences and beyond.

1. Engaging thought leaders

We engaged with thought leaders in the chemical sciences from industry, government and academia to gain insights into big trends that are shaping our field and the wider environment. These insights were complemented by comprehensive landscape research and analysis.

2a. Defining future themes of change in chemical sciences and society

Based on our initial findings, we developed hypotheses and conducted targeted interviews with key leaders in our field, as well as further analysis of the landscape in which chemical scientists operate. This enabled us to identify seven key themes that may influence the future of the chemical sciences.

2b. Mapping weak signals of future change

Building on the seven themes we identified a range of "weak signals" – drivers of issues that might not be highly influential in the present, but that could become important catalysts of change in the future. These weak signals included a variety of case studies and examples, such as personalised healthcare and DIY micro-engineering, distributed energy grids, batteries of the future, catapult centres and the extreme longevity movement. These case studies illustrated the drivers of change in the sector, how they might evolve and the questions that need to be answered.

3. Developing plausible scenarios

Following the research on themes and the associated weak signals, we held three workshops (two in London, UK and one in Boston, USA) to develop scenarios for the future of the chemical sciences. The workshops were attended by leading thinkers from academia, government and industry.

Building on the seven themes, each group debated the drivers, consequences and likelihood of future changes. We developed four plausible but unexpected scenarios as a result of these discussions.

Scenario development – a multi-stage process

What do we think?	What does it mean?	What are the early signals of this?	What could happen?
Phase 1 Engagement	**Phase 2a** Synthesis	**Phase 2b** Weak Signals	**Phase 3** Scenarios
Capture big trends shaping the world that could affect the chemical sciences and society in the future **Approach** • Engagement with global opinion leaders • Internal workshop • Landscape research	Define themes that may imply future change in chemical sciences and society **Approach** • Hypothesis development and testing • Targeted interviews: remarkable people • More targeted landscape analysis	Identify weak signals to challenge conventional thinking **Approach** • Develop illustrative examples of emerging trends for all themes • Determine underlying forces and cross cutting implications	Develop plausible scenarios and understand possible implications for the future of the discipline and society **Approach** • Workshop with key opinion leaders • Scenario mapping and development • Strategic conversations

Analysing the present: seven key themes

Overview

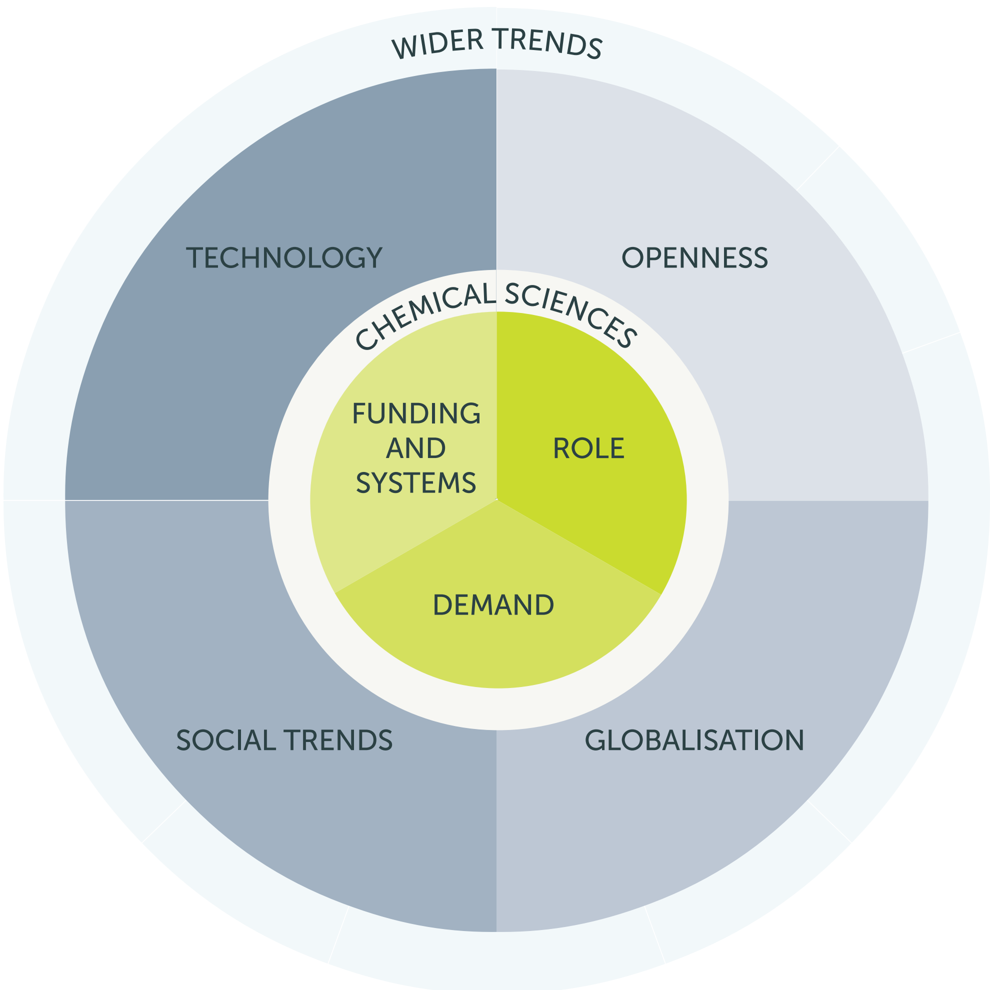
Based on our interviews with key stakeholders, landscape research and further focused-dialogue with the community, we identified seven major themes that may drive change in the chemical sciences.

Three of these trends may directly impact the chemical sciences:

- Role of chemical sciences
- Demand for chemical sciences
- Funding structures, institutions and education

And four of the themes may fundamentally change the world in which the chemical sciences exist.

- Technology
- Openness
- Social trends
- Globalisation



The role of chemical sciences

Essential and connected

Chemistry may need to be increasingly interdisciplinary, which will result in opportunities for innovation. There is likely to be a shift from blue-skies to problem-driven research. There is a risk of chemistry turning into a "follower" discipline in discovery.

Increasing interaction between chemistry and other sciences, most notably the biological sciences, but also fields such as mathematics, engineering, and computer and materials sciences, was identified as the single most important theme for the chemical sciences over the next ten to twenty years.

It is recognised that, over the last two decades, innovation has most often arisen at the boundaries of traditional subjects. Interdisciplinarity is essential for tackling major challenges and driving new approaches to research. Advances in carbon capture and photovoltaics will involve further collaboration between chemistry and engineering, for example, while silicon technology is an exciting area at the interface of chemistry and technology.

Engagement with arts and social science subjects may also play a role in changing attitudes to design and consumption, with implications for future manufacturing processes and use of natural resources.

There is a shift from blue-skies to problem-driven research. Although already an important focus over the past decade, there is a sense that the future challenges posed by interdisciplinarity must be addressed with greater urgency if chemistry is to remain an influential subject.

The perception is that chemistry might turn into a "follower" discipline, whilst other sciences lead on discoveries. This implied threat demands changes in curricula, funding, culture and perhaps even the definition of the subject.

Weak signal: popular science culture

There is increasing public interest in and popularisation of the sciences, with scientific broadcasters such as Sir David Attenborough, Brian Cox and Stephen Hawking becoming "science celebrities". Science is also becoming increasingly present in social media. An example of this is the Facebook group "I f**king love science" which started in March 2012 and has nearly 25 million likes.

Here's what some of the leading figures from the chemical science community had to say...

"The definition of chemistry needs to become broader. You can't keep steering back to very purist chemistry, or it will become embedded in the past, the scientific equivalent of Latin. Something you learn before you learn something else."

"If you look around the modern world and the challenges we are facing, it is going to be about resource efficiency, climate change, health, constrained resources... and chemistry is at the heart of that."

"The most important trend of all is the relationship of chemistry to biology. More and more biology is taking a fundamental approach – understanding what's going on at a molecular level – and as it does so it gets closer and closer to chemistry."

"The reality is that in the last century chemistry was involved in inventing a lot of new molecules and substances... This century will be different... [Chemistry] is going to be involved in combinations of molecules into new substrates and structures and formulations... Key strands going forward are going to be the bioscience strand and performance molecules and linking into computational power. Being able to model, simulate and predict chemistry outcomes and biotech outcomes, and material outcomes. It is a world of multidisciplinarity not discipline isolation."

Demand

Chemistry for impact

The chemical sciences will likely be increasingly required to solve challenges in health, energy and climate change, water and food production. Chemistry might have a greater role in biochemistry and the pharmaceutical industry, as well as in the maintenance and development of infrastructure.

The world faces major challenges that demand a response from chemistry. Partnerships are needed between countries, disciplines – including social sciences – and the public and private sectors.

There are a number of areas where there is likely to be an increased demand for chemistry. Advances in personalised medicine, mutational drugs, sequencing, vaccines to deal with global health issues and treatments linked to an ageing population are important developments where chemistry will play a role.

Chemistry is also expected to play a key role in tackling major challenges associated with energy and climate change, particularly in green solutions to generate and store energy. Carbon capture, renewables, energy storage, recycling (in materials and processes) and battery technology are research areas that will grow in importance in the future.

In the next ten to twenty years, the current infrastructure of the chemical industries could be unfit for purpose and, more widely, infrastructure may be degrading. Chemists can play an important role in developing processes and products to repair, replace and protect future equipment. They will be able to contribute through producing more durable and sustainable materials, for example.

The further development of the "Internet of Things" (IoT) is expected to affect local services, healthcare, communications and commerce. The IoT could make a difference in managing challenges linked to dense urban populations. There are opportunities for chemistry, for example, in the development and maintenance of sensors for air quality and safe sustainable lighting.

For some of our participants, the role of chemistry in these sectors, and in interdisciplinary teams, is not yet well understood by the wider public, policymakers, funders and even some members of the chemistry community itself.

Weak signal: distributed energy grids

From 2006 to 2011, Iran privatised all electricity production and distribution companies, with the exception of the main grids and transmission lines. This changed a monopoly into an open market with different companies managing electricity generation, transmission and distribution. As a result, interest in a distributed grid developed. Various distributed generation plants in Iran now use renewable energy sources, including photovoltaic cells, wind turbines, biomass generation and fuel cells.

Most regions that are interested in distributed grids have frequent power failures in their existing network. There are many more examples for "off the grid" distributed energy generation, including:

- SolarKiosk, designed by Graft architects to provide a "portable autonomous business unit" that doesn't need electricity access, but can sell energy, products, tools and services. The first one opened in Ethiopia.
- Juabar, a company that operates a network of solar charging kiosks in Tanzania to enable people without access to electricity to charge mobile devices.

Here's what some of the leading figures from the chemical science community had to say…

"There will be pressure on chemists to supply the chemistry to address the serious problems facing humanity, particularly with climate change, more efficient ways of producing materials, chemicals for the rising population, as well as the more obvious health related issues. [To address this] there will be a focus on chemists being part of interdisciplinary teams working to address problems around the world."

"I have some sympathy with the idea that chemistry needs to redefine itself, but this is an evolution not a revolution. In all areas [of the discussion], I could cite examples where change is already happening. It's really about shifting the centres of gravity. At the same time, we're probably all agreed that the organic, inorganic, physical split is less and less relevant."

"[There is an] idea of linking chemistry and physics, geo-engineering and agri-economics. You see a lot of that already with some of these biotech initiatives and projects… I think agriculture is particularly crucial because the pressure is around nutrition, food security and an expanding population. [There is a] need for a second kind of green revolution."

"The big issue facing healthcare is the access to medicines… Affordability becomes everything. Chemists have a role to play here. With good synthetic routes, the access question can be solved at a price point the world can afford. Proteins, cell-based therapies all have an important place. The role of chemistry in these platforms shouldn't be underestimated."

Funding structures, institutions and education

The need for change

Governments may need to change their funding approach, towards more and better directed investment in chemistry. Chemistry education might need a more integrated approach that is more hands-on and interdisciplinary.

We are seeing growing pressures for change in two areas of the chemical sciences: the total funding and the structures used to allocate that funding; and how education in the chemical sciences should develop.

UK Government funding for science is unlikely to grow and an exit from the European Union by the UK would bring further uncertainty over funding. If the Government continues its current direction, characterised by low investment in chemistry and directed by non-specialists that do not have an understanding of where the money is most needed, there is the possibility that the UK will become a second-tier player in the global chemistry community.

Concentrating skills and research in (fewer) specialist centres can limit "disruptive thinking" and diversity in research. There should be further investment in world-leading centres. It is important to understand that the future of chemistry may be more interdisciplinary and that funding will need to be allocated to reflect this. Private sector and crowd-sourced funding is likely to become increasingly important.

In education, there is a call for a more integrated approach. Universities may continue to produce chemistry undergraduates with core training in chemistry, but with an increasing focus on interdisciplinary skills and approaches. Improvements in technology, computer modelling and automation are likely to significantly impact early-career researchers. The traditional model of a principal lead investigator, leading a team of post docs is likely to change significantly, driven by funding pressures, changes in technology and access to open data.

Weak signal: interdisciplinarity

There is increasing interest in chemistry-based projects from other disciplines of science and technology, and from commercial organisations. This multi-stakeholder demand is driving a shift towards problem-led science.

23andMe, a genomics and biotechnology company, sells a personal genome test to consumers in the US, Canada and UK. The DNA sequencing results can give an individual information about their ancestry, genetic traits, inherited conditions, genetic drug response and genetic risk factors.

The greatest commercial value however, is in the genetic database of sequenced DNA. 23andMe data has been sold to Genentech for research on Parkinson's disease and to Pfizer for research on Inflammatory Bowel Disease.

Here's what some of the leading figures from the chemical science community had to say...

"We are in a [period of] progressive change [from when] funding and universities were almost completely provided by central government. This change started some time ago and it is going to continue. Institutions and professions need to become more sophisticated and advanced in their thinking and have a variety of funding sources."

"The most pressing question is the separation of scientific discipline by Funding Council. It's hard, under these structures, to get to the most exciting science... Funding doesn't recognise the interdisciplinary nature of discovery. We don't have the structural components we need."

"I think everybody has accepted that you cannot have every person who is teaching chemistry in a university running a research group. What we haven't worked out is what academics ought to be doing. They ought to be, in my view, aware of what is happening in research, probably associated with some of the big successful research groups – maybe spending some months there in the summer. The word scholarship is sometimes used, so you can be a scholar without being a hands-on researcher... and a translator because industry doesn't have as many people on their own books with time to look at the literature. And there needs to be a bridge between what happens in academic research and what happens in industry."

"It seems obvious, but we need to develop some useful pedagogic standards for multidisciplinary working."

Globalisation

Collaboration and competition

There is likely to be global growth in demand for the chemical sciences, which might not necessarily result in a significant shift of chemistry research to emerging economies. It may be challenging for the UK to remain in the top tier of leading chemistry countries.

As for all sectors, the global landscape for the chemical sciences is shifting rapidly, driven by technological, economic, political, social and demographic factors. Emerging economies are investing in research and development, and new economies have recently grown to rival traditional bases of chemistry in both scale and skills.

While growth in the demand for chemical products comes mainly from emerging economies, growth in supply is coming from wherever the advantaged feedstock is. This may not necessarily result in massive global shifts of commodity activity to low-cost economies, as the production of commodity chemicals is capital intensive and demand could be local or national.

The UK is currently recognised as a leading scientific country and could continue as a global leader, especially in research and innovation. Capitalising on this excellence remains an issue, and there is concern about the country's ability to remain in the top tier over the next ten years. International collaboration is essential to tackling global challenges, but the UK will need to secure its role in future global partnerships.

There is also the possibility that globalisation will peak in the next decade, with increasing political pressure for protectionist measures in some countries. This could mean that multinational companies no longer see significant savings from investing elsewhere might return to the UK and US, drawn by excellence offered by their institutions and workforce. However, it is also possible that companies will shift research and development to emerging economies, to support expansion in these markets.

The UK needs to maintain alliances with established markets and strengthen relationships with emerging economies. The growing trend for international partnerships in research, driven by new technologies and open data, is expected to continue.

Weak signal: borderless networks

Future Earth is a major international research platform that aims to provide knowledge and support to accelerate transformations to a sustainable world. This hub is an open network for scientists of all disciplines, natural and social, as well as engineering, the humanities and law and it coordinates new, interdisciplinary approaches to research on three themes: Dynamic Planet, Global Sustainable Development and Transformations towards Sustainability.

Future Earth was announced in 2012 at the UN Conference on Sustainable Development (Rio+20) and the network was launched in 2015. It is sponsored by the Science and Technology Alliance for Global Sustainability, the International Council for Science and UNESCO, among others.

Here's what some of the leading figures from the chemical science community had to say…

"Research activity will increasingly be focused on what people call challenges, or bandwagons – around things the politicians think they can sell to the public… And I think it is a big danger for advanced economies, because they are going to get wiped out by other economies that are more able to accommodate the sort of creativity that leads to step change… Politicians and civil servants now build their careers around micromanaging the research agenda at levels far beyond their expertise."

"What each country has to ask itself is 'What part of the value chain are we going to excel at? In which institutions do we place our bets, or do we spread our money around? Do we have political will to invest in a few centres that will be genuinely world class? Do we want to compete at the top internationally or do we want to keep the home market happy?' If you look at Shanghai, Boston, San Francisco, internationally there are a few centres emerging. In the AstraZeneca move to Cambridge [UK], the implication is clear. They are going where the action is. This sort of thing matters."

"What is changing, of course, is the huge impact of China. The number of very good papers coming out of China is phenomenal, so it is bound to change the balance. It won't be just America and Europe leading the way."

Technology

Efficiency and innovation

Advances in technology and the rapid adoption of innovation have far-reaching implications for the future of the chemical sciences. The nature of chemistry research, organisational forms and chemistry careers are likely to change.

Technology is likely to drive radical improvements in efficiency, processes, computational modelling and metrology. This is likely to further impel interdisciplinary working and change the nature of research, the character of academic and professional careers, organisational forms and industrial structures. For example, there may be more start-ups, specialists and niche players.

Experimentation is expected to become radically more efficient. This will impact research, who is able to conduct this work and the necessary infrastructure. Computational developments, combined with advances in real-time and high-throughput experimentation, may radically reduce the time required for modelling and to "get stuff out of the lab".

Approaches to research on organic synthesis, general catalytic chemistry and testing the physical properties of models will see changes, and chemists are expected to become even more focused on thermodynamics. The production of "molecules on demand" may follow, although this development probably sits beyond our ten to twenty year time horizon. Chemists may be able to produce models on demand for specific clients and to develop a product without extensive testing.

New technologies are likely to enable an increasingly diverse audience to identify problems and take part remotely in experiments to develop solutions.

Weak signal: learning computers

IBM's artificially intelligent computer system Watson can answer questions. It is built to apply advanced natural language processing, information retrieval, knowledge representation, automated reasoning and machine learning technologies to the field of open domain question answering.

According to IBM more than 100 different techniques are used to analyse natural language, identify sources, find and generate hypothesis, find and score evidence, and merge and rank hypotheses.

In February 2013 IBM announced that Watson's first commercial application would be to provide clinicians with evidence-based treatment options for lung cancer treatment at Memorial Sloan-Kettering Cancer Center in New York.

Here's what some of the leading figures from the chemical science community had to say...

"If you imagine how computers are developing and expanding all the time in terms of their capabilities, give us ten or fifteen years and they will be able do phenomenal things. The ratio will change – you will have [proportionally] more people calling themselves chemists who are sitting in front of a computer all day, than in front of a fume cupboard."

"Science can learn a lot from technology. We see a lot of leap-frogging taking place in technology... This [access] is driven by people's ability to see how they can instrumentalise it in their lives. There is a lot of entrepreneurial interest [and] potential to monetise it [and] apply it for various public goods. Its outcomes are very transparent and quite clear. You would think technology might be quite difficult to find in countries like Kenya or Nigeria or Ghana. But if they can access technological resources there you would think they would be able to do the same thing with certain bits of scientific infrastructure or apparatus. The challenge is to think about how we can do the same things and think through opportunities for instrumentalising, for opening up scientific practice for communities in different ways."

"Much of the work [of chemists in universities] is influenced by metrics used to judge success. At the moment it isn't always considered terribly good to do rather applied and less glamorous research, for example making chemicals out of sewage. But in the future people will get recognition for these things... People will win Royal Society of Chemistry prizes for doing it because it is considered important."

Openness

Disruptive, inevitable and uncertain

Open data, open access and open content might drive collaboration, specialisation and increased transparency, but the real consequences of this openness are not fully understood.

Allied to technological change, the general trend towards openness will be disruptive. There is likely to be more real-time collaboration between universities in the UK and beyond, facilitated by open data. However, increased access to data does not automatically translate into better chemistry.

The way that people share and access information may be radically different. The extent to which all data can be open is likely to be shaped by market needs. Chemists and companies employing them will probably continue to be driven by incentives, rewards and intellectual property rights.

Open access will grow with significant implications for publishing, and it is possible that in ten to twenty years all journals will be open-access and interested readers will expect free access. This would fundamentally change the business model for commercial and not-for-profit publishers.

Increasing access to old research would enable chemists to apply recent developments in knowledge and technology to previous findings. In this case, there would be growing challenges linked to sharing and managing content, including data transparency, accountability and ethics issues.

These developments might drive collaboration and specialisation, and threaten established institutions such as funders, businesses and publishers. Increased transparency, wider access to information, improved functionality and interoperability might also offer huge opportunities.

Weak signal: mass input to scientific investigation

World Community Grid enables anyone with a computer, smartphone or tablet to donate their unused computing power to advance cutting-edge scientific research on topics related to health, poverty and sustainability. Through the contributions of over 650,000 individuals and 460 organisations, World Community Grid has supported 24 research projects to date, including searches for more effective treatments for cancer, HIV/AIDS and neglected tropical diseases. 35 articles have been published in peer-reviewed scientific journals based on research conducted via the grid.

Here's what some of the leading figures from the chemical science community had to say...

"Open data and open access are absolutely essential. Everyone benefits from an open system. You'll see a much more mature attitude across sectors, where secrecy is being replaced by collaboration. You need to understand where you compete in the value chain. The counterpoint to openness is that we have to know how we add value."

"The key challenge [in data access] becomes not whether I find this out, but which information do I trust?"

"Publishing is not [just] about publications and a lot of people make that mistake. Publishing is about information dissemination. Big trends [in publishing] at the moment have to do with new affordances that we gain from the internet... What has happened is the traditional scientific publication, the traditional journal article, has moved online. It has gained some extra functionality but fundamentally it hasn't changed a great deal. Scientists are more and more sharing their underlying data... Increasingly the data itself is being published on its own with some annotation and explanation, but not necessarily with an accompanying scientific paper. The other thing that is happening, still at an early stage is the sharing of not just data, but also software and algorithms."

Social trends

Changing workforce and public attitudes

There will be strong growth in demand for medicine for age-related conditions, and changing demographics might lead to competition for talent and a new definition of talent which is diverse and inclusive. There may be an increased public appetite for chemistry-related challenges with greater intervention from the public on how public money is spent.

There are a number of broader social trends shaping the chemical sciences. An ageing population, for example, means growth in demand for medicines to prevent, treat and control age-related conditions will be a key future focus for chemistry.

In the future chemists may develop personalised medicine to tackle diseases like Alzheimer's and dementia. These developments may in turn impact the workforce profile of the chemistry community itself. In a world of longer life expectancies, career lengths are likely to increase and "talent" will be sought among both the young and the old.

Changing demographics and an increasingly mobile workforce, especially in countries such as Japan, South Korea and Germany, are likely to result in increased competition for talent. Gender parity remains a challenge for chemistry beyond undergraduate level. The need for a more diverse workforce may increase in the future, but concerted efforts may be required to improve its gender balance and attract people from diverse backgrounds.

Behavioural and attitudinal patterns among the wider public are likely to impact on the sector, including growing public engagement with environmental issues and a determination to mitigate against future damage. There may be a greater public appetite for objective and quality information on and possible solutions to these issues. Chemists may have a role to play here and stand to enjoy greater recognition for their contribution to issues of broad public concern.

Weak signal: increasing human longevity

The Human Connectome Project is constructing a map of the complete structural and functional neural connections in vivo within and across individuals. The aim of this "connectomics" project is to allow chemo-preservation by informing us about neural structures to the degree, scale, and level of accuracy required to properly preserve a brain. In the future this could allow preservation of the patterns that make up a brain and therefore a person.

Here's what some of the leading figures from the chemical science community had to say…

"Chemistry is one of those areas where gender parity is particularly low. The stats are shocking and I think we are in danger of focusing on other kinds of innovation when it comes to education when there is still a pretty fundamental gap. When you look from the perspective of developing countries – two out of three girls drop out before they graduate from high school in rural Kenya. And then participation in STEM education drops precipitously even within that… It has very real implications for the kind of science that is done, the way it is done and applied… It is not just an abstract political idea. It is a real area of concern."

"Some of the things that [chemists] deal with are conceptually difficult. It's hard impress upon a generation and subsequent generations that have become used to almost instant gratification in terms of the acquisition of facts, the idea that in order to acquire concepts you need to sit and think about them, perhaps for days on end at times. Before you get people to that point, you need to do something to excite them."

"The media, especially the broadcast media, tends to be dominated by people who are not scientists and tend to think, if they're not overtly negative about science, 'well that won't interest the audience'. They are beginning to realise that people do [have an interest in science]… That may be part of a long term process arising from better public education. It's a gradual virtuous circle."

Looking to the future: four plausible scenarios

Overview

In this turbulent and changing world, the future of the chemical sciences is unclear and cannot be defined in a single frame.

We have developed four plausible future scenarios, exploring how some of our seven themes might play out and interact in different ways. Each is set in the next ten to twenty years and depicts a plausible and challenging future world under a particular set of assumptions about how the context of the chemical sciences might evolve.

These scenarios are not designed to make a case for a preferred future, nor to offer an exhaustive list of possibilities. Rather, they aim to challenge leaders in the chemical sciences in their assumptions and their thinking and to stimulate strategic conversations about the future. Ultimately, they are intended to help the chemistry community and the Royal Society of Chemistry to take more proactive decisions today to shape the future for the benefit of people around the world.

The scenarios are:

Scenario 1: Chemistry saves the world

The chemical sciences have the potential to solve many of the world's greatest challenges. What effect would this have on chemists and the chemical sciences?

Scenario 2: Push-button chemistry

As the world becomes more connected, science and technology may become decentralised. How would automated, remote and modular chemistry change the world?

Scenario 3: A world without chemists

Without the chemical sciences as a clear discipline and distinct university subject, the pipeline of future chemists could dry up. What would happen in a world without chemists?

Scenario 4: Free market chemistry

If austerity measures continue in the world's biggest economies, public funding for research could be withdrawn entirely. How would chemists adapt to a world where scientific discovery is driven by the priorities of private funders?

Scenario 1: Chemistry saves the world

Chemistry discoveries have been a key enabler of the world we live in, though many went unrecognised. Today, the world faces many challenges, from climate change, water shortages and natural resource scarcity, to providing healthcare for an ageing population. In this scenario we assume that the chemical sciences provide answers to many of these questions and explore what would happen to the chemical sciences if chemists solve some of the world's greatest challenges.

This is a world that has been shocked by the challenges facing society and has reacted accordingly.

Major threats to humanity and our environment have focused research efforts and resources on issues of food, water, health, climate change and energy. Governments, philanthropists, industry and academia have come together to address these challenges through huge joint initiatives.

Chemists are recognised for taking a leading role in addressing major global issues such as climate change, pandemics, water shortages and the exhaustion of rare mineral supplies. As a result, chemistry is seen as a discipline with strong core values and it now exists in the cultural space.

Chemistry is an everyday topic of conversation for most people. Major films with scientific plots inspire a generation of chemists. Media connects the public to chemistry and famous chemists explain concepts to the public in popular and accessible ways. The elderly are particularly willing to participate. They own much of society's wealth and face complex health problems, and look to science for solutions.

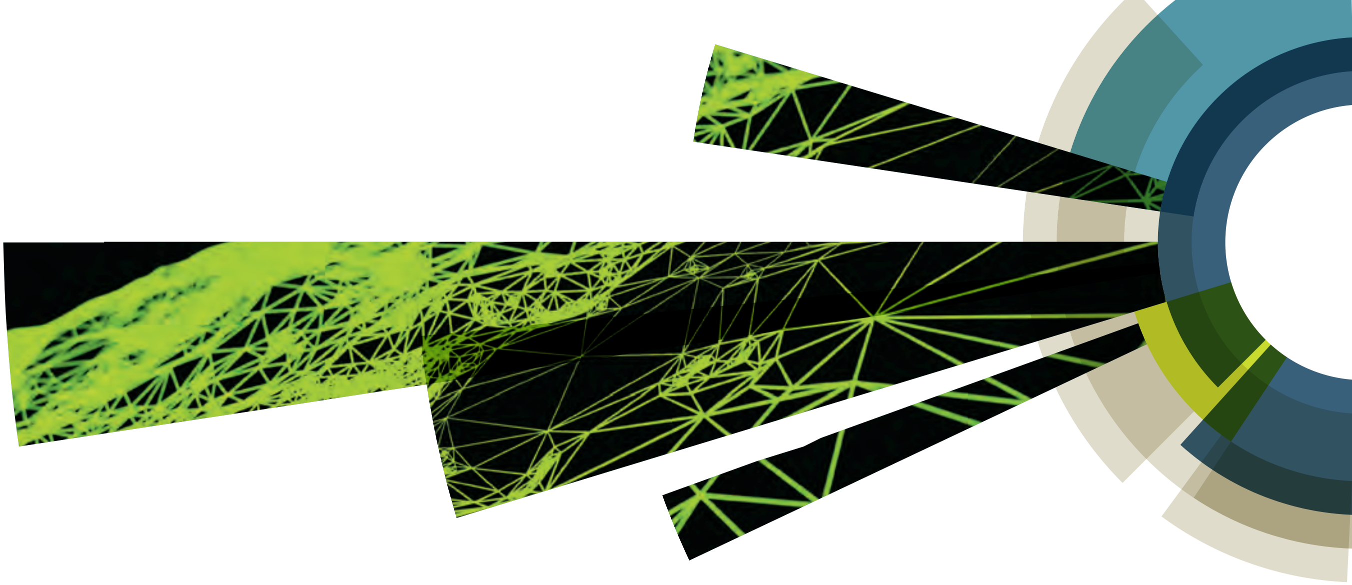
Companies have a greater interest in chemistry and sponsor applied research in their fields. Non-traditional chemistry employers take more chemists into their workforce and the reach of chemists grows. Funding for basic research becomes rarer so funding from charities and capturing the wealth of philanthropists becomes more important. As a consequence of the emerging funding model, there are more incremental and problem-solving discoveries, but fewer breakthrough ones.

The number of chemists in science policy and government around the world has increased. Academics have multiple roles, beyond their scientific research and teaching. Chemists need to apply their skills and knowledge across multiple disciplines, so professional skills, such as IT and communications, are essential.

A new qualification, recognising impact and interdisciplinary working, rather than specialisation, is prestigious and sought after. New interdisciplinary chemistry courses are the most popular undergraduate and postgraduate courses among students.

There is also much more chemistry education for other specialisations, for example chemistry for aeronautical engineering. Undergraduate degrees still exist in chemistry, but with more modular and specialist topics. Chemistry remains part of core science throughout children's education.

A flourishing ecosystem of chemistry start-ups exists, supported by close industry partnerships. Like the large community of citizen scientists, most of the start-ups' work is done on a computer, and conducted in closely monitored cloud labs. New forms and models of regulation emerge to support these communities.



Scenario 2: Push-button chemistry

Developments in technology and communications have changed the way organisations are structured and collaborate with each other. In many sectors, such as manufacturing, traditional business models have broken down and value chains are being decentralised to create a more diverse marketplace. At the same time, there is growing demand for personalised goods and services. A more entrepreneurial culture of chemistry has developed. This scenario explores a world where the chemical sciences are automated and decentralised.

This is a world shaped by the extraordinary developments in science and technology, enabling more do-it-yourself and entrepreneurial chemistry.

Developments in science and technology have made laboratory equipment easier to use, and it can normally be accessed remotely. Most lab time is rented and the majority of experimental work is automated. Most chemical processes are stored in computers and no experiment starts without an initial computer model. People can easily run experiments from home, using off-the-shelf software to conduct early planning and modelling.

Anyone can buy contract experiments from largely automated "lab factories" paying on a per-experiment basis. Providers are a mix of large central services and small contractors. There is a large community of small, entrepreneurial custom synthesis firms. New platforms for brokering access to contract experiments and renting lab time emerge. These businesses are valuable, and grow from start-ups. Access to low-cost, on-demand experimentation and computer modelling has created a more entrepreneurial culture in chemistry.

With lower barriers to entry and wider participation in chemistry, ideas can come from anywhere. New crowdfunding mechanisms and venture capital funds have emerged to find these ideas and scale them, challenging traditional firms.

The low cost and accessibility of experimentation has allowed a greater degree of personalisation in lifestyle and personal care chemical products. Chemistry goes underground. Car enthusiasts design their own custom fuel additives and gardeners make fertilisers customised to local conditions and preferences. There is a large online community of people synthesising and sharing their own personal brands.

A world of push-button chemistry is increasingly difficult to regulate, especially in areas like pharmaceuticals. People attempt to make their own drugs, to synthesise compounds they cannot access using public health services. There is an unregulated black market for advice on how to make your own generic treatments. New models for quality assurance emerge, brands become more important and there are small retail quality assurance labs on the high street.

Chemistry education is also more entrepreneurial. Chemists fund and customise their own education. This continues throughout their lives and comes from a broader range of sources. Only a small number of global teaching institutions remain. They offer virtual education on how to navigate the molecular space. Practical training is increasingly specialised, and is delivered through industry partnerships. A chemist is likely to be self-employed and working mainly in the virtual space.

Scenario 3: A world without chemists

In the past, the chemical sciences existed both as a collection of sub-disciplines and as a community of chemists. Today, chemistry has broadened its horizons even further and separated entirely into sub-disciplines. Without the chemical sciences as a distinct discipline and university subject, the pipeline of future chemists starts to dry up. In this scenario we explore a world without chemists.

This is a world where chemists have become increasingly less influential and productive, and other disciplines have taken the lead on discovery.

The pace of change in the past ten to twenty years was so fast that chemists did not have time to reinvent themselves. Advances in artificial intelligence have replaced many traditional jobs and creativity has not been embedded in the education of the next generation of chemists.

The identity of chemistry as a distinct discipline has disappeared and has emerged as part of other cross-discipline subjects, such as the molecular sciences. The critical mass of chemists is dispersed into sub-groups. These sub-groups nurture specific parts of chemistry. Some sub-groups produce lots of research, while others are neglected. There are overlaps between the chemistry research topics in different sub-groups.

The general public does not understand what chemistry is and has no awareness of the impact that the discipline has made on the world. Celebrity biologists and physicists have attracted non-scientists to these fields, but there is no equivalent popular following for chemistry. Chemistry is still taught in schools, but most students choose to pursue their studies in areas that appear to be making more exciting discoveries and developments.

Young people do not see chemistry as a viable career option. The chemical industries are perceived to be in decline, there are fewer roles for chemists in governments and chemistry has a fragmented role in academia.

Universities no longer offer specific chemistry courses, although different aspects of chemistry are incorporated into other disciplines, such as the molecular basis of drug delivery. In the first generation there are enough people with the fundamental chemistry skills needed to teach these courses, but within two generations the skills to teach the fundamental chemistry aspects of the sub-group courses are lost.

The traditional boundaries for transferrable chemistry skills change. The connections between the different aspects of chemistry are lost. Chemistry still has a future, but there are multiple routes in. There are no chemists, but many people work on chemistry.

The world is effective at producing new chemistry research, for a while. Eventually research hits a wall. Fundamental chemistry skills are dying out and so there is no new basic research. This ultimately limits future opportunities for all chemistry research.

There is no specific research funding for chemistry per se, but there will still be funding for chemistry-type research with a clear outcome. Blue-skies chemistry research is much harder to fund. Fundamental discoveries will no longer come from specific chemistry research, but from within the framework of other disciplines.

Scenario 4: Free market chemistry

Historically, after the 1950s statutory bodies were the dominant source of funding for research, allowing research agendas to be set at a national level. However, population growth, austerity measures and public spending cuts have now reduced government spending on scientific research in many of the world's biggest economies. In this scenario we explore a future without public funding for the chemical sciences.

This is a world shaped by war, climate change and local social crises such as ageing populations. Governments struggle to deal with these mounting pressures, and have radically reduced their support for research.

In the absence of government funding, there is now a market for private research. The consumers of science become the funders. Most funders expect something out of the research. Industry funders invest where profit can be made and private institutes are driven by personal incentives. While industry wants to find a treatment for disease, private institutes want to eradicate it. These private institutes are the new version of philanthropy.

The world has more significant problems for chemistry to solve. There is a larger global population and most of the world is poor. There are food, water and energy shortages. In response to these challenges and the funding changes, researchers now frame their areas of focus in terms of solving these problems. As a result, most scientists focus on specific outcomes and few conduct fundamental research.

Chemistry departments have become private research institutes working on problems like healthcare solutions, energy, clean water and scarce resources. There is less basic research in this world of problem solving, but there are still fundamental discoveries in applied projects. Chemists are forced to "connect the dots"of research in a new way and this leads to discoveries.

Education is disconnected from research. Many research universities have closed and the academic institutions that remain are focused on teaching. All university labs become teaching labs. Teaching becomes more virtual and applied. The original meaning of university becomes redundant, but the focus on teaching enables greater creativity in the next generation. The value of a PhD has decreased so most scientists only have a Master's qualification. There are different requirements to start a career in research. Companies have to do more training in-house.

Chemists are no longer accountable to society. They now need to market themselves to receive industry or private funding. Few chemists work in a relatively insular way in a lab. Instead, they are consultants, helping organisations fix specific problems. They need to network, build their own personal brands and show strategic and commercial awareness.

There is a growing group of specialist marketing and publicity professionals who support chemists to tell their story and attract clients or funders. This focus on personal relationships means the chemical sciences are becoming increasingly elitist – it is important to know the right people to access funding.

Using the scenarios

Key considerations for the future

Our four scenarios raise important questions for the future.

- What will happen to the identity of chemistry as a distinct discipline?
- Who will hold the power to drive change in the chemical sciences?
- What will happen to the community of chemists – students, teachers, researchers in academia and industry, business, policymakers?
- What will be the funding priorities?
- What curricular changes might come about sooner than expected?
- Who will practice chemistry and where – at home, in universities, in companies?
- What skills will chemists need?

They also share some common features. These trends are already having an impact on the chemical sciences and they are likely to continue to grow in importance.

- Funding for basic research may decline, with a greater proportion allocated to solving specific problems.
- Chemists may need to tell their success stories better and justify their value to funders and society.
- Chemists may need to be more inclusive and work more closely with other disciplines and industries to be successful.
- The chemical sciences will need strong leadership to develop a positive reputation and impact on society.

How are we using the scenarios?

As the world's leading chemistry community, these questions are key for the Royal Society of Chemistry's long-term strategic planning. We are using the scenarios to sense-check our current strategy, and as a frame for considering the changing environment.

For example we have started two projects, one considering the potential evolution of professional bodies, the other focused on the implications of an open research environment.

We will revisit the scenarios regularly to reconsider and, if necessary, revise them in light of new developments, so that they remain useful tools. And we will continue to use them to make sure our strategy is fit for the future.

An ongoing dialogue

We believe that the chemical sciences can play an important role in solving the challenges facing our world and in improving the everyday lives of people today and in the future. If they are to fulfil this potential, leaders across the chemical sciences community need to be aware of and responsive to the changing environment.

We encourage organisations to use these scenarios to challenge their current thinking and consider how they might prepare for and shape the future of chemical sciences community.

These scenarios are not the end of this process, but instead the beginning of a strategic conversation with and within the chemical science community.

They are not written in stone – they need to be reframed to reflect new developments. We want to keep talking with our community and with other scientific organisations to keep the scenarios relevant and useful as the environment changes.

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