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The Future of Work: a Chemistry Perspective

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Abstract

In this text of a lecture given by the President of the Australian Academy of Science, the history of scientific advancement is captured in the evolution of modern chemistry. The rapid increase in the ability to make discoveries in chemistry, since, say, the founding of the Australian Academy of Science in 1954, rests on the consequences of the other great discovery of that year, the silicon transistor. The throughput of a research chemist in 2015 is much greater than could have been envisaged in the middle of the 20th century, largely due to modern analytical and computational instrumentation. The pace of change challenges education, from the earliest schooling to postgraduate degrees. A researcher must now move out of a narrow specialisation and be prepared to apply her skills wherever needed. Additional training for postgraduate research students, beyond the traditional 'learning by doing, is needed and nine dot points of desiderata for a doctoral program are offered. The lecture ends with the uplifting words of Max Perutz, who in 1962 offered his principles for success of a research laboratory.

Introduction

In 1954, two events occurred that would have been of some general interest to the membership of the Royal Society of New South Wales, under whose auspices we meet today. One was the founding of the Australian Academy of Science, an organization of learned Fellows dedicated to the advancement of science in Australia, which I am proud to lead.[1] Although it might not have been clear at the time, perhaps the more important event was the invention of the silicon transistor (Riordan, 2004). This discovery, in combination with the efforts of others to develop techniques to mass produce and miniaturize them, has brought the information technology revolution into being by allowing the development of high-speed computers.

The technological developments enabled by this single device have completely changed the way that we live and work in every field. More importantly, it has vastly opened up the realms of possibility in science and research, making realities of concepts that could once have only been the domain of the most fantastic imagination. The concept of doing science by computer – such as computer modelling of molecular interactions, or the climate system, or using computers to investigate inaccessible domains in space or inside the human body – has arisen in its entirety in the last sixty years.

[1] See About Us, Australian Academy of Science, 2015, http://www.science.org.au/about-us, Accessed 13/10/2015.

The speed of this transformation is almost beyond comprehension. Sixty years is not even a single average lifetime, certainly well short of Keynes's century of change. In this period, the annual output of scientific knowledge will have grown over 100 times, yet the total population of the world has increased by about 2.7-fold.[2] Undoubtedly, the advent of the computer is responsible in no small measure for this remarkable increase in scientific productivity.

In my own field of chemistry, the laboratory of today would be seem a little odd to the founding fellows of the Academy. There would be some familiar elements certainly; students conducting reactions in scientific glassware, the business of preparing results for scientific journals or conferences and the alternate frustration and joy of research. Yet the speed at which chemical investigation can be conducted today would be unthinkable for these fellows. With the assistance of computerized instrumental techniques, a novel chemical compound can be identified and characterized in a morning; the same analysis would have required several weeks' or months' patient and careful experiments in the 1950s. The structure of DNA, which took eighty-four years to be determined after its isolation, can today be quickly analysed by computer-aided x-ray diffraction crystallography. Combinatorial drug discovery technology allows for new pharmaceutical leads to be revealed entirely automatically, allowing scientists to target their research efforts on refining and developing promising drug leads, rather than laboriously creating and testing individual molecules.

[2] Over the period, the annual rate of scientific output is estimated to have increased by 8-9% per annum. See Bornmann and Mutz, 2015.

Clearly, the Keynesian dream of a fifteen hour working week has not yet arrived. However, because scientists (and society more generally) can now do much, much more with the time they do spend working, the amount that we can achieve in fifteen hours today would most likely dwarf a week's work from Keynes's day. The acceleration in scientific output, combined with an ever-increasing sophistication of scientific discovery, ensures that science will make significant progress towards solving some of the most challenging problems of our time. However, the pathway to capitalizing upon these discoveries is less clear – we know where we want to go, but how will we get there?

Of course, science is already responding to the problems facing the world currently, and there are some exciting developments that we *can* foresee. For example, although climate change is a significant challenge, the science community is discovering innovative ways to reduce greenhouse gas emissions, especially those from energy production. I am particularly encouraged by the advances being made in flexible plastic photovoltaic solar materials. These materials, which could even be sewn into clothing, might soon allow solar cells to be installed not just on roofs, but almost everywhere – allowing a truly ponderous amount of solar power to be generated for our use.

Similarly, we are discovering new ways of combating and treating a range of diseases, such as cancer. Increasingly, personalised medicine will be important in effectively treating cancer, where we tailor the treatment depending on an individual's genetic makeup, using advances in analytical chemistry, bioinformatics and biostatistics. We are also developing new ways of delivering treatments by using novel polymers to encapsulate the toxic chemotherapy agents, so that they are delivered directly to where they are needed.

These sorts of developments are relatively predictable if we extrapolate from current activities. They are, if you like, the 'known unknowns' – those advances that seem likely to arrive in the near term. Yet for a young person today, their lifetime will be filled to a much greater extent with the 'unknown unknowns' – discoveries that we cannot today foresee, nor have any hope of predicting how they might change society and work in the future.

I would not for a moment attempt the folly of predicting what the future will be like, or what the workers of the future will do. History has shown time and time again that scientific progress can have the most profoundly unforeseen impacts upon all facets of society. In fact, we tend to not be very good at predicting what might occur, even with discoveries already in hand. A panel of eminent experts assembled by US President Roosevelt in 1937, charged with advising him on the likely developments in science and technology, failed to divine the importance of antibiotics and fax machines. Both of these had been initially discovered in the preceding decade, and have both made profound changes to the world in the second half of the twentieth century (Thomas, 2014).

My background is Chemistry, and I have spent all my working life in academic teaching and research. Apart from a couple of vacation jobs I have had little experience working in the "real world" and therefore I feel ill qualified to comment on the topic in hand. I would rather talk about my own experiences as a research scientist and share some of the ideas that I have developed in adapting to jobs of the future.

Chemistry is one of the fundamental scientific disciplines and is broadly applicable to aspects of materials science and biology. Jobs in pure chemistry in Australia are rather limited. The greatest opportunities are in academia, publicly funded research institutes and a very few companies. Whereas in the post second world war years in Australia chemical research and chemical manufacturing were core business activities, in recent years these have largely moved offshore to locations where markets are larger or where labour costs are lower. It is the very fact that chemistry impinges on so many related disciplines that means chemists can gain employment in allied industries such as analytical and public health laboratories, biotechnology companies, medical research institutes and small manufacturing companies.

It is with dismay that I observe that a chemist is not rated sufficiently highly to be on the skilled occupations list for entry to Australia as a preferred permanent resident. There is one small crack letting in some light on all this - chemical engineers are listed as group having desirable skills. This list clearly looks only at the immediate skills shortages in the labour market, rather than giving consideration to preparing Australia to be an economy prospering through innovation in the future. For example, although taxation accountants are included on the skilled occupations list, there is a high probability that much of their work will be automated over the coming decades (Frey and Osborne, 2013). We should be using our skilled migration program not only to solve current skills shortages, but also strategically to boost our future innovation capacity.

Returning to chemistry I believe that it is still essential that any scientist is properly trained in the core discipline. History has shown that a well-trained chemist, whether it be at

Bachelor's, Master's or doctoral level, has sufficient analytical skills to be useful in a variety of professions, and is usually capable of acquiring new skills on the basis of the early training. By completion of the PhD degree the graduate should be able to demonstrate a capacity for independent and original thinking, and should exhibit problem-solving skills for a variety of tasks. In considering jobs of the future a crucial question to ask is "What is the best training to reach these outcomes?"

How will scientists be trained to be ready for jobs in the future? What should be the core aspect of training of scientists in general (and chemists in particular)? Ultimately our success as a nation will depend on education in preparation for jobs of the future. The Rt. Hon. Tony Blair said in launching the Labour party education manifesto on 23rd May 2001 at the University of Southampton "Our top priority was, is and always will be education, education, education". This statement is as relevant today in 21st century Australia as it was for Britain at the start of the century.

Alarmingly, the concept of having a "feeling for science" amongst younger people appears to be on the decline. A survey conducted on behalf of the Academy of Science in 2010 and again in 2013, which asked respondents a number of relatively basic science questions, found that the greatest decline in correct responses came from those aged between 18-24 years (Auspoll, 2013). A report completed by the Academy for the Office of the Chief Scientist found a worrying and significant decline in the number of senior secondary students studying science – showing a decline from more than 60 per cent of Australian year 12 students studying science in 2004 to only 51.4 per cent taking a science subject in 2010 (Goodrum et al., 2012). This report also makes it clear that a student's decision to take science subjects at a senior level is greatly influenced by their experiences of science at more junior levels.

Education starts with children and progresses through adulthood. To ensure that Australia has a continuing cohort of talented adult scientists, it is important that we attempt to engage students with science from the beginning.

The Australian Academy of Science has recognized school education as its core business for over a decade. *Primary Connections* is an inquiry-based program (generously supported by successive Federal governments) that empowers primary school teachers not formally trained in science teaching to inspire young children in the discipline. [3] Through its active teacher training and mentoring and extensive course modules aligned to the National Curriculum *Primary Connections* reaches about two-thirds of all Australian primary schools, and is mandatory in South Australia. It is truly inspirational. I saw it in action at an ACT primary school. There a teacher was introducing the concept of Venn diagrams to six year olds. There were two overlapping large hoops. In one hoop there were toys that could be pushed while in another hoop there were toys that could be pulled and in the overlapping sector there were toys that could both be pushed and pulled. I have to confess that for the first time I really understood a Venn diagram from that experience. Now the focus of the program is the development to reach remote rural and indigenous communities, and the hope is that the whole project will be financially sustainable.

[3] See Primary connections, Linking Science with Literacy, Australian Academy of Science, 2015 http://primaryconnections.org.au/, Accessed 13/10/2015.

In the area of secondary education the Academy (again with Federal government support) is developing *Science by Doing*, a comprehensive online science program for Years 7 to 10 available free to all Australian students and teachers and supported by award winning professional learning modules and a research based professional learning approach. [4] The Australian Academy of Technological Sciences and Engineering is actively engaged in a hands-on inquiry-based program of education in maths and science, called Science and Technology Education Leveraging Relevance (wisely abbreviated to STELR), that importantly 'provides career profiles which highlight the study pathways necessary for jobs in STEM – related industries'.[5]

The abovementioned educational programs have as their aims the development of a community of people who have "a feeling for science." Importantly they should demonstrate how we should be educated not only the jobs of the present, as mentioned for STELR, but also for jobs of the future. It is this latter task that we are addressing today, and it is virtually impossible to make detailed predictions, so I shall stick closely to the basic core training.

Much has been written about the most desirable aspects of tertiary education and training. For chemists we must not abandon training in the core elements of the discipline. I remember when the TV program *Crime Scene Investigation* appeared on television there was a huge demand for courses in forensic science. Graduates were produced in droves, far too many for employment in the field. However, most knew very little general science and many had difficulty finding employment in other areas.

In undergraduate courses there is a developing emphasis on active learning, essentially learning through problem-solving (Waldrop, 2015; Kober 2012). In undergraduate Chemistry courses we must teach the core skills of chemistry. Problem-solving can then be very effective. However, there still remains the problem of motivating chemistry lecturers to be innovative in their teaching practice. Rewarding teachers for application of such approaches in tertiary institutions is not well developed.

Similarly, science graduates in Australia are unlikely to gain experience of their discipline in the wider world. A broad educational experience makes better scientists; students with a range of educational experiences will better be able to make connections between disparate areas of knowledge, and hence be become better problem-solvers. Scientists who can forge connections can make important inventions – for example, one scientist's curiosity-driven research in electrochemistry, a branch of chemistry not then associated closely with medical research, led to the discovery of the blood glucose sensor that is now an essential tool used by millions of diabetics every day to manage their condition (Thomas, 2014). The Office of the Chief Scientist has recently highlighted the low levels of work-integrated learning opportunities available to undergraduate science students in Australian universities, and argued that lack of incentive, and a want of resources for academics to facilitate industry placements for the students were significant barriers to achieving meaningful educational experiences outside the lecture theatre

[4] See Science by Doing, Australian Academy of Science, 2015 http://www.science.org.au/science-by-doing, Accessed 13/10/2015.
[5] See STELR, Innovative Science Teaching, STELR-ATSE 2015 http://www.stelr.org.au/, Accessed 13/10/2015.

(Prinsley and Baranyai, 2015).

In doctoral training there is much room for improvement. While Masters courses in many institutions in Australia incorporate significant course work, this is far less common at the doctoral training level. Doctoral training requires the ability to frame a research problem, to think inductively and creatively, to design experiments and solve a problem and to write discursively about the evidence supporting the conclusions arising from observations. The topic is less important than the process. If I reflect on my own personal experiences and those acquired through different doctoral training programs in different countries, I would wish to include the following into a program.

- Share the concept of serendipity as captured by Horace Walpole – 'making discoveries by accident and sagacity of things they were not in quest of' (Oxford Dictionaries, 2015).
- Remind people of Pasteur's comment - 'In the fields of observation chance favours only the prepared mind' (Pasteur, 1854).
- Practise the art of asking incisive questions (Kinaret, 2015).
- Expose doctoral students to a series of inspirational speakers; provide Master Classes; begin early in thinking of careers outside academic life (Nurse, 2015).
- Provide engagement with industrial partners.
- Train researchers in general business skills, such as reading a balance sheet and principles of governance.
- Teach research leadership techniques (Leiserson and McVinney, 2015).
- Build a culture that strives for excellence.
- Develop entrepreneurial skills.

Above all in the doctoral process we must be exposed to ideas and thinking that are outside the normal range of experience. This can be managed in a variety of ways, most of them emerging from imaginative and creative research leadership by research mentors. From such a process will emerge the ideas and opportunities that will lead to the jobs of the future.

Most importantly, the challenges and opportunities of the future will require thinkers and workers that are eminently agile and adaptable. Increasingly, disciplines are converging to create new fields of knowledge. As a report prepared for the Australian College of Learned Academies points out, many of today's jobs in STEM fields did not exist a decade ago (Bell et al. 2014). There is no reason to believe that the exponential increase in scientific advances will run out of steam so it is likely new fields will continue to arise with increasing rapidity. Collaboration and interdisciplinary research will become ever more important, and the advances afforded by science will rely on scientists from different areas working together, and also in concert with non-scientists. A quote widely attributed to Niels Bohr, who pioneered the modern interpretation of the structure of the atom, says that an expert is 'someone who has made all the mistakes that can be made in a very narrow field'. However, the days of the very narrow field are probably numbered. I think the expert of tomorrow will be someone who sees the importance of not only their own mistakes, but also the mistakes in the fields of others. Of course, this is not to suggest that the chemists and scientists of tomorrow will not be specialists in their field – it will simply be increasingly important for scientists to be aware of developments beyond their immediate sphere, so as to adapt to developments as they arise.

Despite the rapid rate at which the science and the world generally will evolve in the future, I think that the practical business of science and research will retain considerable continuity with the past. The ability for scientists to be inspired by curiosity and to be challenged and stimulated by their peers will remain crucial elements of scientific endeavour. The only proper currency in the conduct of science will continue to be good ideas that withstand rigorous investigation. Comfortingly to those founding fellows that I invoked earlier, I think the place of the student conducting good experimental work in science, and chemistry in particular, is assured.

And most importantly, in considering how we will approach the future, I think we can still learn from the successful ideas of the past. The philosophy of Sir David Rivett, founding fellow of the Academy of Science and Professor of Chemistry at the University of Melbourne, when setting up CSIRO was simple but effective: 'Determine the field that you want to study, find the best person to lead the group, get them money and give them their head.' (Moyal, 1994).

I might finish with Dr Max Perutz, who won the 1962 Chemistry Nobel Prize with John Kendrew for 'their studies of the structures of globular proteins' and founded the MRC Laboratory of Molecular Biology in Cambridge. He was asked about the secret of success that subsequently resulted in the award (so far) of ten Nobel prizes for work carried out at that institution. 'The principles he used were: choose outstanding people and give them intellectual freedom; show genuine interest in everyone's work, and give younger colleagues public credit; enlist skilled support staff who can design and build sophisticated and advanced new apparatus and instruments; facilitate the interchange of ideas, in the canteen as much as in seminars; have no secrecy; be in the laboratory most of the time and accessible to everybody where possible; and engender a happy environment where people's morale is kept high' (Thomas, 2002). This is not a bad recipe to start with.

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