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Do We Expect Too Much? Reflection on Chemistry Content in Higher Education†

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Learning Science

Education research in the 1970s, like other related areas, was dominated by quantitative work¹ during an era for which *social sciences* sought to draw upon the successful *scientific* approach typically used in the physical sciences (in particular) to investigate teaching and learning.^{1,2} So if we felt a cohort of students did not understand some concept, we tried to find out whether or not a different teaching approach could *fix* their misconceptions.³ But how to do this? Well, drawing on a scientific approach, we would divide the class or classes up, teach one cohort the same way we always had, and the other cohort in our new way, and evaluate any differences in conceptual understanding using, *e.g.* a standardized topic test. Differences would be examined for statistical significance of evidence that our new approach to teaching had worked. And this is the way much research was done at the time. Control of variables, randomized sampling, and so on, were all embedded in such an approach to educational research.

At about this time, however, key research – some of it NZ-based – suggested teaching and learning was rather more complex. Investigation into how students arrive at their own views of scientific concepts, focused on student misconceptions, or alternative conceptions, *viz.* students' views that are at variance with the accepted scientific viewpoint. Perhaps it is not that surprising that students harbour misconceptions for abstract concepts such as the kinetic theory, electricity, and force. But some student views of more common concepts are less easily understood and it is likely that they are influenced by other factors such as cultural background. There are some unusual examples reported in the literature. For example, one study of misconceptions of Papua-New Guinean students found some to believe that pregnancy occurs when a spirit child enters a woman rather than as a result of sexual intercourse.⁴ A Caribbean-based study found that some students believed that hair would grow more rapidly if it was cut during the full moon.⁵ Other researchers have suggested that some student misconceptions may arise as

a result of the learning process itself.⁶ These studies might seem curious or odd but, overall, such studies suggested that factors other than the school environment and the teaching processes used were also influential in student learning. There are now huge bibliographies of student alternative conceptions compiled, some with several thousand studies detailed.⁷

What is perhaps of more concern is the *remarkable tenacity of many student misconceptions*. Students in many cases seem unwilling to give up their prior beliefs even after instruction.⁸⁻¹⁰ Similarly, early research by Osborne and colleagues¹⁰ suggested that even very able students, *i.e.* those who passed exams with high marks, did not actually understand fundamental scientific concepts in ways we would desire.

What might be the overall origins of such problems, and what might we do about it? Let me consider this by looking at what I think is a key factor; high, *perhaps unrealistic*, expectations of our students.

Learning Chemistry in Higher Education

As mentioned above, considerable concern has been expressed in the literature about the high incidence, and remarkable tenacity, of common student misconceptions. The vast bulk of this research is concerned with school students, but similar issues are reported also for students of advanced chemistry from the higher education sector. Some higher education research reports give a real sense of frustration experienced by teachers or lecturers as they struggle to deal with student misconceptions.¹¹⁻¹⁶ While there are a number of concepts that students traditionally find difficult such as aspects of physical chemistry, like thermodynamics and electrochemistry,¹¹ researchers seem more concerned at the prevalence of student misconceptions for *even very simple concepts*.^{12,15,16} For example Heron¹⁶ comments that for his first-year chemistry students *fewer than 50% of the students seemed to comprehend that it was Cl⁻ that was in table salt and not Cl₂ or that*

there was a difference between the two (see p.146).

There is a general feeling expressed in the literature that such student misconceptions are related to prior learning experiences (or lack thereof!), although some authors suggest that it may be more related to the students' level of cognitive development.¹⁵⁻¹⁷ One key factor I suggest may be *the large amount of factual material that students are expected to memorise* when developing understanding of a complex body of knowledge like chemistry.^{14,18}

A brief review of course material for any one of many chemistry courses shows that we expect students to memorise a large amount of material, and often at the same time demand advanced problem-solving skills. An abridged course outline for third-year analytical chemistry I once taught is given as Fig. 1.

Advanced Analytical Chemistry

Isotope chemistry. Methods of detection, measurement, safe handling and application of isotopes to Chemistry, Biology and the Earth Sciences. Stable isotopes. Interfacing of analytical instruments with computers. Experimental design. Statistical treatment of data. Quality control. Chromatography. Atomic absorption spectroscopy. Mass spectrometry. X-ray diffraction. Electrochemical analysis.

Fig 1. Topics for advanced analytical chemistry course

High-level understanding of other related disciplines typically is also presumed, particularly at advanced levels of study. For example, in advanced postgraduate level structural chemistry courses we require advanced mathematical ability and a thorough understanding of many advanced physics concepts.

Consider the following extract from a small portion of one lecture on single-crystal X-ray diffraction delivered to an advanced level chemistry class (Fig. 2).

The interaction of X-rays with the planes of a crystalline lattice is dependent upon the position of the individual atoms, or more correctly elements of electron density, present in or close to the crystal planes. Assuming discrete (i.e. atomic) scattering sources, the problem becomes one of the superposition of waves of different amplitudes and phases. Thus upon interaction with a given set of crystal planes a wave of total amplitude F , has X and Y components,

$$X = \sum f_j \cos \delta_j \text{ and } Y = \sum f_j \sin \delta_j$$

where f_j is the atomic scattering factor for the j^{th} atom, and δ_j is the phase for j^{th} atom.

The modulus of the scattered X-ray beam is given by,

$$|F| = \sqrt{(X^2 + Y^2)},$$

and the phase is given by the arctangent of the ratio of the Y and X components *i.e.*,

$$\alpha = \arctan(Y/X).$$

The periodic nature of the unit cell restricts the allowed values for δ_j such that,

$$\delta_j = 2\pi(hx_j + ky_j + lz_j)$$

where h , k , and l are the Miller Indices for a given set of crystal planes, and x_j , y_j , and z_j are the atomic co-ordinates for the j^{th} atom expressed as fractions of the unit cell lengths.

We can write,

$$A_{hkl} = \sum f_j \cos 2\pi(hx_j + ky_j + lz_j) \text{ and,}$$

$$B_{hkl} = \sum f_j \sin 2\pi(hx_j + ky_j + lz_j).$$

Thus the total phase and amplitude for the wave becomes,

$$\alpha = \arctan(B/A) \text{ and,}$$

$$|F_{hkl}| = \sqrt{(A^2 + B^2)}.$$

It is convenient to express the above using complex numbers as,

$$F_{hkl} = A + iB.$$

The complex quantity F_{hkl} is known as the structure factor.

Since $\exp(ix) = \cos(x) + i\sin(x)$, the structure factor can be written as a complex exponential term,

$$F_{hkl} = \sum f_j \exp[2\pi i\theta],$$

where θ is $hx + ky + lz$.

Assuming infinitesimally small elements of electron density rather than discrete atomic scattering sources, we express F_{hkl} as an integral rather than a summation thus,

$$F_{hkl} = \int_V \rho(xyz) \exp 2\pi i\theta \cdot dv,$$

where $\rho(xyz)$ is the electron density at point xyz .

Fourier transformation yields an expression for $\rho(xyz)$ in terms of the structure factor F_{hkl} ,

$$\rho(xyz) = \sum_h \sum_k \sum_l F_{hkl} \exp(-2\pi i\theta).$$

From this expression we can calculate an electron density map for the entire contents of the unit cell and this will reveal regions of high electron density corresponding to atomic positions giving the molecular structure for the material under study. In principle the Fourier series should be evaluated for all values of hkl from $-\infty$ to $+\infty$. Bravais lattice restrictions and symmetry constraints do not allow this, however, and the result is small ripples in the calculated electron density map, particularly around the heavy atom positions.

Fig. 2. Portion of an advanced level lecture on X-ray crystallography.

Even a cursory examination of this brief portion of just one lecture clearly shows how much we expect from our students. We expect knowledge and expertise in trigonometry, differential and integral calculus, complex number theory, wave theory, atomic theory, electricity and magnetism, symmetry, and so on. This list is by no means exhaustive but it is immediately evident that we assume a remarkable in-depth knowledge of a number of highly abstract concepts.

There was a widely-held view amongst departmental staff in the institution where I worked when I taught such topics that this is exactly as it should be. The usual ratio-

nale of this is that it is important for us to maintain high academic standards in order to ensure the integrity and high reputation of our degree programs. In addition, it is viewed that such knowledge and skills are important for students engaging in postgraduate studies or research.

If we accept that such expectations are reasonable, the question remains as to whether we actually achieve the understanding and problem-solving skills we seek with our present instructional strategies? Despite reservations occasionally expressed about the students' abilities, once students reach the final year of the degree program they almost inevitably graduate. Hence, we are in effect indicating by virtue of their graduation that, in general, our students do meet these expectations. A simple illustration suggests that this may not be the case.

Third-Year Chemistry Student Understanding of Atomic Structure

A representative sample of third-year chemistry students at one institution was briefly surveyed on their understanding of a concept that most of the teaching staff would consider very simple, namely fundamental atomic structure. By comparison with the X-ray analysis of Fig. 2, the concept of atomic structure as presented here is almost trivial.

The students were asked to sketch an appropriate representation for the electronic structure of the hydrogen atom and the carbon atom (Fig. 3). It is important to bear in mind that this exercise was carried out with a group of students that had graduated with a BSc at the end of the year this activity was conducted. Furthermore, many of these students had already been awarded good grades for previous chemistry courses, *e.g.* A (80-85%) and A+ (85-90%). Despite this, the incidence of student misconception was high. Only two respondents gave an answer that could be considered consistent with the currently held scientific view. The naiveté of the answers was quite remarkable. It seems that most of these students (*ca.* 70% of respondents) still think of atomic structure in terms of the Bohr model while some gave answers that were difficult to attribute to any recognisable model of atomic structure. The results presented here are far from rigorous, but they indicate of a lack of understanding of a fundamental and comparatively simple scientific concept. Since the Bohr model is not taught in first-year chemistry, it seems likely that this model of the atom represents prior knowledge that our senior students are bringing to the classroom.¹⁹

ATOMIC STRUCTURE	
In the space below, please draw a sketch of what you understand to be an appropriate representation for the electronic structure for the:	
Hydrogen Atom:	
Carbon Atom:	

Fig. 3. Atomic structure questionnaire for third-year chemistry students.

Content - Do We Want Depth or Coverage?

The latter half of the last century was characterised by enormous advances in science and technology that resulted in the demand for a more highly-skilled work-force. This demand has led to a large increase in students numbers studying science in high school and tertiary institutions,²⁰⁻²² and to a focus on more applied courses and vocationally-oriented degree programs.²¹ Whilst this shift may be appropriate, it does present some difficulties. For example, Bunting and co-workers, suggest that up to 50% of the intake of first-year science students lack understanding of key underpinning concepts.²² Further difficulty lies in the enormous number of applied science topics now available, and teaching staff are faced with the difficult task of deciding what topics to include in their courses.

Many lecturers are uneasy about leaving out topics that they see as interesting and relevant to students, and there is a tendency to want to include as many topics as possible. However, research into learning and instruction suggests that it may be more beneficial to teach a few topics in depth, instead of trying to give a superficial coverage of a large number of different topics.⁸ Moreover, it provides a deeper insight into how students acquire concept-knowledge and reasoning skills as suggested by Eylon and Linn.⁸

The argument here is that students need to develop their own concepts, see how to link new concepts with their existing concepts, and develop their own strategies for higher level activities such as problem-solving.²² This, it is suggested, is problematic if they are overloaded with factual material, or encounter too much material at once. There are a number of factors that educators need to take into account during instruction,¹² namely content, organization and presentation of material, the student's level of cognitive development, and the students' level of prior knowledge.

The instructional strategies suggested by Eylon and Linn⁸ are based on teaching by a more learner-centered or constructivist teaching approach. Interestingly, other educators have reported that less content is covered when teaching by a constructivist approach,²³ which fits in with reducing our emphasis on content coverage.²²

The view that teaching institutions should teach less material and instead focus on developing greater learning skills is gaining increasing attention at tertiary teaching institutions in this country.^{22,24} It also has been suggested that the increasing ease of access to sources of information such as the Internet means that fewer educators should place emphasis on the mere provision of factual material, and greater emphasis on higher-level cognitive skills.^{22,24}

The overall focus for us, as chemistry teachers, should be to have clear aims and objectives for individual courses and degree programs. In other words, what we need is a clear picture of what knowledge and skills we want our students to possess upon graduation, and what instructional strategies we need to implement in order to achieve those aims. Research into learning and instruction sug-

gests that this is best achieved by teaching less content in greater depth.

So What?

Articles such as this can be frustrating since they can highlight a problem many might agree with (to one extent or another), but struggle to provide solutions. I could argue that we first need to consider that we have a problem! You are of course welcome to disagree, but I challenge you to consider honestly whether or not you think your own students really understand fundamental chemistry in the way you want? I propose here that the literature (and some of my own prior work) suggests otherwise. I am not being critical of lecturing style or lecturers; to me, at least in part, the *problem* is the increasing diversity of our first-year intake. Bunting and co-workers²¹ found serious mismatch between the expectations of lectures of first-year biology with regard to student prior knowledge. Their careful analysis showed that even when staff said they had little expectation of prior knowledge, in fact they really did. Our first-year students are probably capable of *catching up*, with or without bridging programs. But Baddeley²⁵ argues that trying to do so may overload their working memory, that is to say the mental structures and processes used for temporarily storing and manipulating information. Some of our recent work has suggests that this is influential in a student's ability to learn complex science concepts.²⁶ The idea is that we all have a certain capacity to hold ideas temporarily in our minds, *working memory*, which we use to process ideas as we try to understand and link concepts. The argument here is that if we overload students with masses of facts, we *fill up* their working memory, making it hard for them to genuinely understand and link concepts.

Other recent work from our group²⁷ supports Fensham's notion that we need to carefully analyze the content of our courses (or papers) before we teach.²⁸ Fensham says we need to *treat content as problematic*. I do not mean that we think one concept or another to be difficult, but that we need to see that *the process of deciding what content should be taught* to students, at whatever level, is problematic in itself. Let me illustrate with an example. When writing a recent book chapter on chemical bonding,²⁹ Keith Taber (Cambridge University) and I got involved in a discussion about what constituted the *scientific model* for covalent bonding. Keith, writing from a secondary school teacher's perspective (in fact a trainer of secondary school teachers), was judging student understanding against a *scientific model* that was not the currently held model. We ended up realising that neither one of us was right or wrong. At each level of education we can only teach models (in this case of covalent bonding) at a level that is appropriate to our target student audience. This applies to secondary school, first-year, or masters-level students. So to treat *content as problematic* here would mean the teacher (or lecturer) making a careful analysis of the content to be taught (here models of covalent bonding) and deciding *purposefully* which model was appropriate. We might think we do this, and perhaps we do by instinct or based on experience. I would argue we need to engage in this to a much greater extent!

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