CERP editorial for April 2018

Representations and visualisation in teaching and learning chemistry

[This is an editorial, so there is no abstract]

The 2019 special issue of *Chemistry Education Research and Practice* has been announced and will have the theme 'Visualisations and representations in chemistry education'. The call from the theme guest editors, Resa Kelly and Sevil Akaygün, for submissions to be considered for the theme is available on the journal's blog (http://blogs.rsc.org/rp/2018/02/23/visualisations-and-representations-in-chemistry-education/). This is both an especially interesting topic in chemistry education, and one of considerable importance to the practice of chemistry teaching.

Representation may be understood as one thing standing for another and this is especially important in teaching where the teacher often seeks to make the unfamiliar familiar. Sometimes we do not need to represent - as we make the unfamiliar familiar directly through immediate experience. As one example, students are sometimes expected to learn about flame tests - that is, identifying the presence of certain element in compounds by heating small samples in a flame. Certain elements, sodium, copper, potassium, among others, give 'characteristic' flame colours. It does not make sense to teach about this by representing the colours when it is possible to actually present the colours directly by showing students the flames. If a student is to to appreciate what is meant by a flame being described as lilac or brick red, then clearly actually seeing the colours (to which these labels have become associated) produced in the flame test is superior to a photograph reproduced in a book, and - even more so - than simply a verbal description. Indeed, we would normally want students to not only see, but carry out, the tests - as science is a practice, not just a body of knowledge; as learning tends to be more effective when multimodal; and as much of the knowledge of laboratory work is tacit in nature (Polanyi, 1962) - vicarious experience is never a perfect substitute for personal experience.

The nature of concepts and conceptual learning

Yet much that is taught and learnt in schools and colleges cannot be directly demonstrated so readily. In particular, so called 'academic' subjects, such as chemistry, have as a stock-in-trade a store of conceptual knowledge that they seek to make available to learners. Concepts are abstractions, and can act as categories. So a person who has acquired concepts of, say metal, liquid, and flask, could apply those concepts to making discriminations as part of organising and structuring their experience. William James famously pointed out that a newborn is faced with a blooming, buzzing confusion - their perceptual experience largely comprises patches of illumination, in different colours and shapes; and noises of different pitch, loudness, and duration; and so forth. Somehow that neonate has to develop into a sophisticated organiser and discriminator of their environment in order to survive in it. In time they can perceive objects rather than noises and patches of colour and so act in the environment - such as when they want to cross a road. Of course interpreting the environment in order to safely cross the road involves more than conceptualising (the pavement, the road, the vehicles, etc.) but also a degree of theorising. The person often has to draw inferences about other people's motives and likely behaviour. Each time we assume that it is safe to cross because we can reach the other side at a reasonable walking speed before approaching vehicles get to our position we are (usually without being aware) making assumptions that cannot be certain. We often cross a road in a situation where a visible car could easily accelerate sufficiently to collide with us before we get across (or where one that has just passed by could potentially make a U-turn and hit us), but even when that is physically feasible we apply what we know about normal behaviour and typical human psychology to evaluate that this is unlikely to happen (despite such pathological behaviour being over-represented in some genres of drama).

This is analogous to how scientists use concepts. Popper (1934/1959) argued that induction (the process by which we can draw general conclusions about classes - e.g., copper is an electrical conductor - from a ‘sufficient’ sampling of observations) was not sound as a logical basis for knowledge. We can not assume a particular copper wire will conduct electricity because scientists have already tested all copper wires that exist (or will exist), in order to check their conductivity. That clearly is not so. Nor should we conclude by induction that this copper wire will conduct, because scientists have sampled quite an array of cooper wires, and so far they all been found to conduct. In practice, that is how many of us do think much of the time, but such an inference is not logically certain. Rather, from a scientific perspective, we can assume that the next copper wire we encounter will conduct because is it made of copper, and we have theories of the structure of copper and of the nature of conductivity which allow us to deduce (providing our theories are sound) the properties of some copper wire that neither we nor any other scientist has previously tested. This is a logical deduction, and so depends upon the truth of the assumptions being made (that is, how good the theory is).

The metaphorical nature of human cognition

It has been suggested that our concepts are directly or indirectly based on abstraction from direct experience of the world (Lakoff & Johnson, 1980). That is, we form a set of concepts that link directly to perception by abstracting from events or objects that are perceived as somehow similar to each other. Then we use these concepts grounded in direct experience (such as hot, big, top, left, inside, underneath, etc) metaphorically to build more abstract notions: the hot date, the big boss, the top athlete, the left-field idea, the inner circle, and so forth. The hot date could take place in a sauna, and the big boss might be obese, but we know that is not what such terms are intended to convey. We do not all independently invent such second order concepts, rather their usage becomes common practice through sharing; but often when we meet a new term of this kind we appreciate the metaphor.

So when a colleague tells you that they recently got their fingers burnt, you probably do not expect this to be meant literally (at least, not unless you already consider them to be irresponsible when it comes to laboratory risk assessment). Using a term like this as a metaphor to communicate an idea relies upon people having direct experience of fingers and burns, but also access to a repertoire of nuanced social/economic experiences that they can reflect on. To know what someone means by this term one has to be able to relate it to situations (experienced, or capable of being imaged based on actual experiences) that are in a sense like having got one’s finger’s burned: that is when getting too close (metaphorically) to a (metaphorically) hot situation.

In the first half of the last century Lev Vygotsky discussed two sources of our conceptual knowledge (Vygotsky, 1934/1994). Spontaneous concepts are the abstractions we make from everyday experience. Scientific (or academic) concepts are those that are acquired through formal teaching. One of Vygotsky’s great insights was to realise how these these two systems interacted in conceptual development. Spontaneous concepts can be directly, indeed automatically, applied, but are not suitable for use in sophisticated thinking. Academic concepts are represented through formal symbol systems (language being the most obvious) and can potentially remain ‘rote’ learning. Vygotsky used a metaphor of these two types of concepts growing towards each other. Formal instruction provides a language with definitions and the like that can allow spontaneous concepts to move from the intuitive level so that they can be used in deliberation, conversation, and discourse in general - so they become open to analytical critique for example. Spontaneous concepts provide the grounding for making sense of formal academic concepts. A formal definition of combustion can only be understood by relating it to direct experience of phenomena: and an implicit concept of fire or burning abstracted from direct experience can be theorised in terms of the taught formal concept. In effect our functional concepts are neither one kind or the other, but melded concepts that develop from the interplay of spontaneous and academic concepts (Taber, 2013).

Representing concepts

Language is one of the key representational systems used in teaching, and indeed in much human activity. It has a key role when teaching canonical concepts, even those that relate directly to phenomena we can demonstrate. So combustion is a theoretical concept that can be understood to encompass a variety of actual experienced events - but if we want different students to develop the same theoretical understanding we rely on shortcutting the historical development of the concept (which in any case will be contingent - so it cannot be assumed that re-running history would lead to the same set of concepts understood in precisely the same way) and guide learners towards the canonical understanding that has developed. [1]

We can also use language to 'share' concepts which have less potential for direct abstraction from experience - examples (and in chemistry there are a great many) might be resonance, d-level splitting, ideal gas, homolytic fission, or transition state, where what can actually be directly experienced is unlikely to be abstracted into the formal concept without considerable mediation. Even in a case like neutralisation, where it is relatively easy for students to have close experience with many examples of the class of reaction, the argument used to abstract these examples under a common concept is theoretical, and/or instrumental (indicators, pH meters, etc.), and not based on what can be directly perceived. Often our concepts in chemistry do not relate to phenomena (directly observed events) in themselves, but rather these are seen as signs of something not directly observable. So the explanandum that act as phenomena are often the inscriptions produced by complex apparatus (such as a Fourier n.m.r. spectrum) that are taken to indicate some aspect of nature that can be usefully conceptualised (Latour & Woolgar, 1986). Here both instrumentation and the explanations of a more knowledgable other are involved in mediating the acquisition of the formal concept. For example, the teacher not only has to explain the concept of hydrogen bonding but also why a certain reading on a thermometer or the particular details of a peak on a spectrum provide something that needs to be explained with the help of this concept.

Chemistry has many important concepts that are primary about, or at least primarily or partially understood in terms of, entities that are not accessible to direct experience: molecules, ions, electrons, orbitals, and so forth (Johnstone, 1982). Here students learn about a world of theoretical entities at a scale far from their direct experience. It should not be surprising that we find common learning difficulties such as confusing the explanandum and explanans (e.g., copper conducts because it is made up of copper atoms which conduct) and teachers offering to make the unfamiliar familiar by calling upon human motivations (as when atoms are said to want to achieve full electron shells). A little thought shows just what an achievement it is when there is some kind of alignment in how learners conceptualise chemistry compared to how their teachers were intending.

The notion of sharing our concepts is itself metaphorical. We share divisible objects. We can share a bag of peanuts by having some each. If the teacher shares peanuts with her class she then has less peanuts herself. If the teacher shares her concepts, then something rather different is going on. Teaching was once commonly thought of in terms less of sharing than of copying - copying ideas from the teacher to the learners (although the common metaphor of the transmission of knowledge might imply translocation rather than replication), but we know of no mechanism that allows ideas to be directly copied. Rather learners have to construct their own understandings, which under skilled guidance will hopefully become sufficiently similar to that intended to allow meaningful communication and some level of engagement in the practices of the discipline. All of this depends upon teaches being able to represent their thinking in ways that students can interpret.

Representational systems used in chemistry

Learning chemistry does not only rely on a reasonable competence in a language such as English. Chemistry also draws on a wide range of other symbolic representations (Taber, 2009). Intimately linked to the theoretical structure of the subject is the system of chemical symbols and equations that can be used to summarise, posit, explore, quantify, etc., real or conjectured chemical reactions. This system also has the useful ambiguity of often potentially standing at the same time for something at the bench (macroscopic, observable) level and something at the submicroscopic (theoretical models of matter many order of magnitude smaller) level. Other special forms of symbols are used to reflect compound structure and reaction mechanisms in organic chemistry. As a science, chemistry uses general forms of graphical representation common in many subjects, but sometimes with discipline-specific features (such as the common representation of reaction profiles). It also has its particular representations, such as the periodic table which summarises a great deal of chemical knowledge - for those who can interpret it.

Non-verbal forms of representation are extremely valuable in teaching and learning, not simply because 'a picture can paint a thousand words' (i.e., that sometimes an image can succinctly represent what would require a long verbal description) but also because the human cognitive architecture tends to use imagery and words as complementary - so working memory is considered to have distinct buffers for visual and verbal information for example (Baddeley, 2003). Much imaginative thinking is visual in nature, and this is considered to have made major contributions to scientific work (Miller, 1986).

Affordances of technology

Once classroom use of these non-verbal forms of representation were limited by what could be achieved in a printed book page or by what a teacher might draw on the board - perhaps supplemented by some gestural hand-waving (Kress, Jewitt, Ogborn, & Tsatsarelis, 2001). However improvements in educational technology mean that many previous restrictions no longer apply. Animations, stop motion video, computer generated simulations, virtual reality - are all becoming increasingly widely available.

This offers many advantages. Images can be much more sophisticated. They can be generated to illustrate what could be seen from different angles and at different scales. Not only is shifting scale or changing perspective possible, but so is following the progression of a system over time. This is important in that the scientific imagination often works by forming a mental model that evolves over time, and this process can now be represented in what seems a continuous flow of action. This raises areas of research interest (Gilbert, 2005) - for example exploring people's (scientists, learners') actual mental visualisations and simulations; and developing tools to support students' in forming productive visualisations of chemical entities and systems.

It is also easy with modern technology to present alternatives. A long-standing problem in science education is the tendency for many learners to assume that the models they meet are meant to be realistic representations of aspects of nature. That may sometimes be so (although if it is a model, it will have some differences, and in particular simplifications), but by no means always. There is a range of models of the atom which can be useful to the chemistry learner - but when they meet different, and apparently incongruent, models of the 'same' target in different contexts this can give the impression that we are free to tweak our models arbitrarily (that is, regardless of the strength of empirical backing) as needs arise. At a click of a button a teacher can present a range of relevant alternatives (of models, or of different representations based on the same model) and explore the relative strengths and weaknesses of the alternatives. This may be especially valuable in situations where there is no single representation that is unambiguously preferred - but can also be used as a basis for discussion in those topics where learners commonly reproduce canonical versions incorrectly.

Learners are doing it for themselves

Another important theme here is shifting the role of the learner from being just a receiver and interpreter of representations, to being a generator of representations (Tytler, Prain, Hubber, & Waldrip, 2013). Clearly, given how canonical learning depends upon on appropriate mediation by the teacher who guides the learners' constructions of knowledge, learners are unlikely to spontaneously re-invent the canonical representations of a discipline. Those students who suggest that the benzene molecule has a kind of electron reservoir in the centre of the ring, because that's how they interpret the symbolism of the circle drawn within a hexagon in the symbol commonly used to denote an aromatic ring, would be unlikely to invent the canonical symbol. For them, the circle inside the hexagon is read more iconically than symbolically, and represents a container inside the sigma framework of the ring.

It would clearly not make sense to set learners the tasks of making up their own symbols to use in class to denote standard conditions, enthalpy change, electrode potential, radicals, and the rest. Students can get confused enough when we try to get them to all work with the same set of symbols and formalisms. However there are some good arguments for engaging in such activities, at least some of the time. Developing representations is an important part of scientific work. All those canonical systems and conventions we use, both those that can seem fairly arbitrary, and those where there is some kind of iconic logic - as when drawing open vessels such as conical flasks and test tubes cross-sectionally to show where materials may be added or removed - were creations of human imagination. Education in the sciences tends to focus heavily on the logical thinking required to do science, but usually puts much less emphasis on the equally important role of imagination (Taber, 2011). In some countries this is especially so at school level, where learners are given little reason to consider science as a creative activity. Getting students to occasionally develop their own representations can give them a flavour of this aspect of the scientific enterprise, and may engage some students who normally prefer other areas of the curriculum.

This is not to suggest that we stop teaching science and have a brief creative interlude as a form of light relief in our classes - far from it. The imaginative work of the scientist needs to married to the critical nature of scientific work. This can be an opportunity to employ a dialogic approach (Mortimer & Scott, 2003). Students can be asked to develop their own representation, and then compare with another student, and to explain their ideas to each other. The pair could decide which representation to take forward, or build some kind of hybrid. The process could be repeated by getting pairs into groups who discuss, argue, and bring forward a suggestion. The teacher can elicit group suggestions, and lead a class discussion on the different ideas. Then the canonical version can be introduced and students invited to comment on its strengths and limitations. This teaches something about the nature of representation, and the argumentation processes by which science encompasses the development, refinement, and selection, of conventions of representation, as well as hopefully getting learners to think about the canonical representations in more depth than when they are simply presented as a matter of fiat.

A teacher who is concerned that they might get their fingers burnt by risking students generating alternative representations that will not get credit in examinations might restrict the activity to representations lacking such official status. For example, students could be given outline periodic tables (perhaps showing element symbols and atomic numbers only) and asked to suggest helpful ways of visually representing key properties or trends. Even this brief discussion suggests there is great potential for work relating to representation and visualisation to be of interest to readers and inform chemistry education practices. This is clearly an exciting theme for a special issue, and the editorial team join the guest editors, Resa Kelly and Sevil Akaygün, in inviting contributions for consideration for the theme of 'Visualisations and representations in chemistry education'.

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References

Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829-839. Retrieved from http://dx.doi.org/10.1038/nrn1201
Gilbert, J. K. (Ed.) (2005). Visualization in Science Education. Dordecht: Kluwer.
Johnstone, A. H. (1982). Macro- and microchemistry. *School Science Review, 64*(227), 377-379.
Kress, G., Jewitt, C., Ogborn, J., & Tsatsarelis, C. (2001). Mulitmodal Teaching and Learning: The rhetorics of the science classroom. London: Continuum.
Kuhn, T. S. (1970). *The Structure of Scientific Revolutions* (2nd ed.). Chicago: University of Chicago.
Lakoff, G., & Johnson, M. (1980). The metaphorical structure of the human conceptual system. *Cognitive Science, 4*(2), 195-208.
Latour, B., & Woolgar, S. (1986). *Laboratory Life: The construction of scientific facts* (2nd ed.). Princeton, New Jersey: Princeton University Press.
Miller, A. I. (1986). *Imagery in Scientific Thought*. Cambridge, Massachusetts: MIT Press.
Mortimer, E. F., & Scott, P. H. (2003). Meaning Making in Secondary Science Classrooms. Maidenhead: Open University Press.
Polanyi, M. (1962). *Personal Knowledge: Towards a post-critical philosophy* (Corrected version ed.). Chicago: University of Chicago Press.
Popper, K. R. (1934/1959). The Logic of Scientific Discovery. London: Hutchinson.
Taber, K. S. (2009). Learning at the symbolic level. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple Representations in Chemical Education* (pp. 75-108). Dordrecht: Springer.
Taber, K. S. (2011). The natures of scientific thinking: creativity as the handmaiden to logic in the development of public and personal knowledge. In M. S. Khine (Ed.), *Advances in the Nature of Science Research - Concepts and Methodologies* (pp. 51-74). Dordrecht: Springer.
Taber, K. S. (2013). Modelling Learners and Learning in Science Education: Developing representations of concepts, conceptual structure and conceptual change to inform teaching and research. Dordrecht: Springer.
Tytler, R., Prain, V., Hubber, P., & Waldrip, B. G. (Eds.). (2013). *Constructing Representations to Learn in Science*. Rotterdam: Sense Publishers.
Vygotsky, L. S. (1934/1994). The development of academic concepts in school aged children. In R. van der Veer & J. Valsiner (Eds.), *The Vygotsky Reader* (pp. 355-370). Oxford: Blackwell.

[1] Some readers may note that this seems to imply a relativistic notion of science, such that different cultures develop different science and, as Kuhn (1970) pointed out, there is no independent standpoint from which to choose between them as any ‘judge’ would be encultured in one tradition or another. However, even if we see science as in principle progressive, that is in building accounts of the world that are incrementally closer to how nature actually is, different historical ‘runs’ are likely to take different routes even if we expect them to ultimately converge on the same accounts.