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Chemistry lessons for universities?: a review of constructivist ideas

REVIEW

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Research in science education has identified a vast catalogue of misconceptions, or 'alternative conceptions': beliefs held by students which are at odds with orthodox science. These ideas are often held tenaciously in the face of teaching, and while many are idiosyncratic, some are found to be widely held. Alternative conceptions have been uncovered in all areas of science, and have been elicited from learners at all levels, from primary school through to graduates. University teachers need to appreciate the strength of these alternative conceptions, and the barriers they create for meaningful learning. No matter how skilfully university chemistry is explained, many students will build their new knowledge on shaky foundations. The 'constructivist' research programme seeks to explain the origins of students' alternative ideas, and to use this information to inform more effective teaching approaches. According to this perspective, knowledge is constructed in the mind of the learner, and therefore learning builds on the existing ideas in the students' minds, even if these are far from matching the (presumably 'more scientific') ideas the teacher had in mind. This review of the constructivist literature summarises the implications for teaching and learning chemistry in universities.

Introduction: student misconceptions in chemistry.

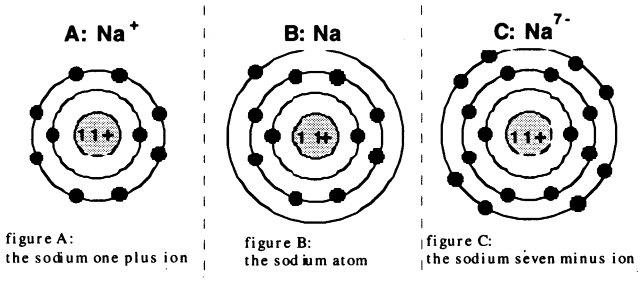
A group of science graduates, training to be teachers, was asked to compare the stability of three chemical species, represented by the simple 'Bohr-type' diagrams shown in Figure 1. A number of the respondents suggested that C, a highly charged anion of sodium, would be more stable than the neutral atom (B). Na^{7-} is not found naturally, and has such a high charge that it could only be held together under extreme conditions. One might wonder how graduates, about to embark on a career teaching science, could possibly think Na^{7-} was a stable chemical entity. One of the trainee teachers explained that "C has a full [sic] outer shell of electrons and so is less likely to give e^- up than B, which will want [sic] to give away an e^- to get a full outer shell." This is just one piece of evidence for a common misconception that *any* species with an octet, or a full outer shell of electrons, is stable, and that atoms actively seek to fill their shells[1].

Such misconceptions are very widespread, and not just among weak or lazy students. The literature reports a wide range of areas where pupils commonly misconceive the chemistry they are taught. For example, readers may recognise the following common 'errors':

- A reaction between an acid and a base *always* produces a neutral solution[2].
- In ionic bonding the ions can *only* bond with counter-ions with which they have exchanged electrons, rather than with *any* adjacent oppositely charged ions[3,4].
- To be isomers, compounds *must* belong to the same class (so, for example, CH_3CH_2OH, an alcohol, and CH_3OCH_3, an ether, cannot be isomers)[5].

Because of the widespread nature of such misconceptions, and their perceived significance for teaching and learning, there has been a great deal of research into their incidence, and some considerable theorising about why they arise, and how teaching should best respond to them. This review considers how this literature can inform chemistry teaching in universities.

Figure 1: three chemical species



The constructivist approach

A wide range of terms has been used for these 'misconceptions'. Here the term *alternative conception* will be used, but some authors refer to *intuitive theories*, *naive theories*, *preconceptions*, *alternative frameworks* or *children's science* [6]. Although there are sometimes good reasons for preferring different terms, there is no consensus, and so in effect these labels are often synonymous. The research programme is sometimes referred to as the 'alternative conceptions movement', but is also commonly labelled 'constructivism'.

Constructivism draws upon ideas from key thinkers from the psychology of learning (eg [7–10]), but since the late 1970s the theoretical base of the research programme has been developed within the context of a vast canon of empirical data collected from studies into learning in science (eg [11–17]). A number of popular books discuss constructivist ideas in science teaching[18–23]. Research into learners' ideas has produced evidence of alternative conceptions in all aspects of science that have been studied, and the findings relating to secondary level science are summarised for teachers in a much cited book[24].

Much of the work has focused on the school sectors, where there have been major projects such as LISP (Learning in Science Project) in New Zealand[20], and in the U.K., CLISP (Children's Learning in Science Project), and SPACE (Science Processes and Concept Exploration). These projects have examined a range of topics: for example SPACE (focusing on primary school science) has produced a report on pupils' ideas about materials[25] and CLISP (focusing on secondary school science) has looked at the understanding of elementary ideas in chemistry[26]. Although less research has been carried out with university students than in schools, there is considerable evidence that alternative conceptions continue to be a problem at this level[27–29]. Indeed it would be surprising if this were *not* the case, since alternative conceptions cannot be expected to disappear spontaneously, and the importance of research into this area at university level is increasingly recognised (eg [30]). Findings within chemistry at all levels have been reviewed[31, 32] and a number of topics have been identified as common sources of alternative conceptions (see Table 1). University teachers who are aware of the nature and extent of alternative conceptions and who understand how they might have arisen are best able to help students to learn effectively. Rather than being irritated or puzzled by learners' responses in assignments and examinations, lecturers may use their knowledge of why these ideas arise to develop more effective teaching strategies.

Students' alternative ideas are sometimes so ingenious that their invention would seem to involve much more effort than simply learning the conventional ideas taught in class. Other responses may be so implausible from a chemical viewpoint (such as the stability of the Na^{7-} ion discussed above) that it is difficult to conceive how students thinking along such lines could possibly believe that they had understood their lectures. The key to this apparent paradox is to appreciate something of the way learning and memory works. To a first approximation we can consider learning to be two separate processes: *adding* new information to existing frameworks of ideas, and *restructuring* these conceptual frameworks (eg [33, 34]). In order to better facilitate the student's learning, it is therefore useful to consider the nature of their prior knowledge, their assimilation of new knowledge, and the restructuring of their conceptual frameworks.

The nature of prior knowledge

By the time students enrol on a university chemistry course, they have been learning for (at least) almost two decades. During this time they have been constructing a complex set of understandings about the world. This structure of beliefs and ideas is sometimes called 'cognitive structure'[35–37]. At each point in this process, new learning has been channelled by the existing cognitive structure, so learning is something of a 'boot-strapping' operation[38]. As a person matures, their cognitive structure develops: their knowledge base increases, and – in general – becomes better integrated and more sophisticated[39]. University teachers with some understanding of how this knowledge base has developed are best able to help students to build on it effectively.

Even at birth the brain should not be considered as a blank slate upon which anything could be written. The human brain has evolved so that it is 'pre-programmed' to develop in certain ways[40]. The precise extent of this genetic input is subject to research and debate[41], but there is no doubt that the baby has predispositions to learn certain types of information, and 'chunk' information from its surroundings in specific ways[42]. The child is programmed to interact with its physical environment and to learn from that experience. Children are constantly bombarded by information from a variety of sources: parents, siblings, friends, television and so forth[43]. They make sense of what they hear and see in terms of their developing conceptual frameworks. In everyday use, language tends to be weakly defined, allowing increased scope for misinterpreting what is heard[44,45]. Even when the interpretation is accurate, much of the source information may be unclear, confused or just plain wrong[46]. The child is *then* exposed to formal schooling.

Some of the child's early learning about its surroundings provide the 'intuitive theories' that can later interfere with the learning of formal science [47,48]. For example, one of the most common and tenacious alternative conceptions uncovered by research is the erroneous belief that a force must be

Table 1: chemistry topics identified as leading to alternative conceptions.

Griffiths 1994 [31]	Garnett et al 1995 [32]
chemical equilibrium	chemical equilibrium
acids and bases	acids and bases
stoichiometry	balancing and interpreting chemical equations
electrochemistry	oxidation-reduction and electrochemistry
the nature of matter	the particulate nature of matter
bonding	covalent bonding, molecules and intermolecular forces
physical and chemical change	
dissolving and solutions	
combustion	

continuously applied to keep an object moving at a steady velocity[49]. Orthodox science holds that any net force will *accelerate* the object. The young child does not know about the frictional forces that are ubiquitous in everyday life, and falsely infers that the constant push or pull commonly needed to work against friction is *inherently* required to maintain a body's momentum. Once this alternative conception is established it tends to be retained and applied, at least until – and often well after – Newton's law of inertia is met in school physics. Many other alternative conceptions are believed to derive, at least in part, from such interpretations of early experience[50] and it should be no surprise that pupils often come away from class with a different sense than that intended[1].

Learning from teaching, then, relies on the learners perceiving *connections* between the curriculum content introduced by the lecturer and their existing cognitive structure. Effective learning depends as much on the student's existing knowledge as on the quality of the presentation. Any mismatch between the expected and actual prior knowledge can act as 'bugs' in the system, i.e. impediments to learning[51]. As Sirhan and colleagues have pointed out in this journal, we need to 'prepare the mind of the learner'[52].

Assimilating new knowledge

Although we each have enormous *long term* memory capacity, our working memories are very restricted[53]. When subjects are asked to remember nonsense information their processing capacity is extremely limited. In this kind of *rote* learning exercise, the typical person can only cope with between 5 and 9 bits of information. The number 102202216302311 (15 digits) would exceed most people's capacities. Yet, in practice, we all remember much more complicated information than this, because we impose meaning on the information, in terms of existing knowledge. It is easier to recall 102202216302311 *if* it is recognised as a representation of the ground state electronic configuration for aluminium (10[=s]^2, 20[=s]^2, 21[=p]^6, 30[=s]^2, 31[=p]^1). Complex information may be learnt if it can be processed into manageable chunks, and this processing involves spotting patterns in the information, by relating it to existing knowledge. For example, a complex structural formula may comprise a single chunk of information for an experienced chemist, but may overload the working space of a novice who does not share the same conceptual frameworks[54].

The human brain will automatically *construct meaning* from what is heard and seen, by relating it to whatever is already known (or, at least, already *believed*). In this way the information is altered into a form that can be assimilated into existing conceptual structures. Although this introduces distortions, it is a much more effective means of data processing than 'total recall'[55]. Ausubel used the term *meaningful* learning to distinguish this process from rote learning. By *making sense* of information we can learn it more effectively[56]. This characteristic of learning emphasises the need for teachers to offer students 'anchors' which help them to make meaningful connections with prior knowledge.

Restructuring conceptual frameworks

As people are so successful at interpreting most data in a way that fits their expectations, radical conceptual change is considered to be rare[57]. Learning usually involves refinement of, or minor amendments to, existing frameworks, and it takes time to develop a new, coherent, way of organising knowledge about a complex topic. It seems that learners start to construct alternative 'versions' of their understanding in the background: versions that may come to be more coherent and so in time become the preferred way of thinking about the topic[34,57]. Clearly, then, it is not unusual for learners to hold 'multiple frameworks' for the same topic in mind[37]. An important role for the teacher is to reinforce the reasoning that justifies the scientific preference for accepted theories, and so help provide a 'scaffold' by which the student can make the transition from an entrenched alternative conception to take up the preferred framework[58,59].

Individuals are believed to compare their manifold conceptions subconsciously using the same types of criteria that scientists might use to decide between competing theories: simplicity, degree of match with empirical data, scope of explanatory power, etc.[60, 61]. The decision as to which set of ideas to apply is often dependent on the perceived context[62]. Indeed learners may access one set of ideas in a context such as a test, and a different set in more everyday contexts[63,64]. Researchers have been able to elicit different responses when presenting individuals with several versions of what is formally the same question, by embedding one version in an everyday setting, and presenting the other as a more typical abstract 'academic' question[65–67]. Thus it is important to provide contexts for the students in which the alternative conception is clearly inadequate, but which are consistent with the preferred framework.

The normally subconscious processes of coming to see the inadequacies in our ways of thinking may be accelerated by having to justify our ideas to our peers[68]. Both new connections and unexpected inconsistencies may come to light when talking through ideas[69]. Discussion between learners may therefore both utilise the social imperative to reach consensus, and also provide opportunities to elicit and explore their ideas[70].

It has been argued that learners can become much more effective by being more aware of their own study habits, and thought processes (an area referred to as metacognition)[71–74]. This may be of particular interest in chemistry, where it has been suggested that many difficulties experienced by students result from 'model confusion': not recognising how much of chemical knowledge is based around alternative models that have different ranges of application[75]. For example, it is not 'wrong' to equate oxidation with addition of oxygen, or to see acids as proton donors: but these are not the only definitions we use. Similarly, the bond between carbon and chlorine could be better labelled either covalent *or* polar, depending on the particular context[76]. Academics can cause confusion by assuming that the context alone is sufficient to make it clear which model is being used and is most appropriate; in fact students usually need help in developing the ability to select the appropriate model from the context.

A student who conceptualises scientific knowledge as a series of models of varying applicability, and who appreciates something about the way their brain analyses, stores and accesses information could be a more flexible and successful learner. Such a learner would be able to recognise their own alternative conceptions as partial models that may not always apply[37].

Applying the constructivist approach to teaching chemistry

According to the constructivist perspective each individual learner has to construct their own personal knowledge system piecemeal, whilst at each stage interpreting any new information in terms of their understanding at that point. So students come to class with a range of ideas, from various sources, which seldom come close to matching the prior knowledge suggested by the curriculum they have followed. Recognition of this perspective is of practical value to the extent that it can inform teaching practice. Suggestions have been made about what a 'constructivist' teaching programme might look like[77].

A basic tenet is that the curriculum should be a programme of activities that encourage learners to (re)construct scientific knowledge. The teacher's role is to be a "facilitator" who will provide the appropriate opportunities for the learners to undertake the construction. The focus is on the learners' thinking about scientific ideas: the elicitation of existing ideas, and their subsequent restructuring – including exposure to conflict situations and the development and evaluation of new ('more scientific') ideas. An example of the effectiveness of this approach is given by Johnston and Driver[78] who devised a constructivist scheme for teaching particle theory to pupils at age 13-14. They reported that both learners and teachers were generally positive about the approach, although there were reservations. Pupils seemed to enjoy the lessons, and being required to "think…a lot" (p.175), but showed a concern with not immediately being told the 'right' answers. Some teachers, being used to prescriptive schemes of work, found the need for a flexible response to pupils' ideas rather challenging. The emphasis on discussion and argument intended to develop *understanding* made demands on learners' concentration that were noted by both pupils and teachers. However, teachers did report that they felt pupils were more actively involved in learning during lessons, and there was evidence that significant conceptual restructuring had occurred.

'Constructivist' schemes designed for use *in schools* involve activities that engage the students in the learning process – brainstorming, designing posters, circuses of simple experiments, debates about the merits of alternative ideas. These may not readily transfer wholesale to *undergraduate* courses[79]. Millar, however, has pointed out that constructivism – as a theoretical perspective on learning – does not imply a *particular* teaching methodology[80]. Effective learning occurs whenever the teacher is able to help facilitate the students' construction of something closely resembling orthodox scientific understanding. It has been suggested that in secondary schools "animated talk and argument are likely to be the hallmark of fruitful science lessons"[24]. This might sound a more desirable prescription for a research colloquium where new and challenging ideas are being explored, than for a lecture course designed to teach established principles. Yet it is important to realise that for the undergraduate audience the ideas being presented *are* novel and challenging, and do need to be explored, and justified, and made familiar. A skilled teacher *can* achieve a great deal through talking. However, the traditional lecture, based on the assumption that knowledge is simply *transmitted* as a unidirectional stream of data flowing from lecturer to student, is unlikely to be an effective mode of teaching[81, 82].

In order to apply these principles to university teaching it is useful to consider three factors

- The students' prior knowledge;
- The selection and organisation of content;
- The choice of appropriate teaching methods.

Eliciting prior knowledge

It has long been considered as good practice when planning courses and preparing lectures to bear in mind what might traditionally be labelled as '*assumed* prior knowledge'[83]. In an ideal world the lecturer might consider the question of whether students hold the expected prior knowledge as somebody else's responsibility: the students themselves, their previous teachers, or the department admissions officer! In practice, universities enrol large numbers of students with a limited understanding of that basic chemical knowledge that might be considered as the foundation for undergraduate study[84–86]. It therefore becomes necessary for the lecturer to ensure that students are in a position to understand the material included in a lecture. One of the key features of the constructivist approach is that it takes further the common-sense view that the teacher needs to make clear (and realistic) assumptions about students' prior knowledge. In the constructivist perspective these assumptions must be made explicitly clear to the students and alternative conceptions must be taken into account.

Various techniques have been used to elicit learners' ideas in science (eg[87,88]), and some instruments have been published, for example to diagnose alternative conceptions about ionic bonding[4] and about the factors influencing ionisation energy[89]. As restructuring can be encouraged through learners trying to explore and justify their ideas, some element of interaction between students can be valuable. One way of doing this is through the technique of 'concept mapping'. This involves producing a graphical representation of ideas about a particular topic: often writing the key concepts in boxes connected with lines or arrows labelled with the relevant propositions (see figure 2). The technique can be readily learnt by students, who may appreciate its value as a study and revision technique[91, 92]. Asking small groups of students to produce joint concept maps is one way of producing in-depth discussion of their ideas.

Of course it takes time to discover the extent of students' alternative conceptions, and many teachers will argue that the syllabus is so full that they cannot afford to be distracted from teaching the curriculum. However, it is important to balance the cost of spending time on this step against the potential benefits of ensuring that students build new knowledge onto a strong foundation. In constructivist teaching schemes, the elicitation of prior knowledge is an essential part of the curriculum process. The old joke that ‘I taught it, they just didn’t learn it’ is telling here – “the verb to cover and the noun information are responsible for much mischief”[93]. The lecturer’s role in the modern university is not just to cover the subject matter, but to ensure that it is learned.

Selecting and organising content

Where the students hold alternative conceptions they are unlikely to be erased by simply pointing out that they are wrong. Students will often need to be given time to understand *why* their ideas are wrong, and why the orthodox scientific viewpoint is more sensible. As their ideas may be well integrated into their frameworks of thinking this is not an easy task[94]. However, once identified, the lecturer can plan to challenge alternative conceptions at various points in the lecture course, by providing counter-examples (for example, through data exercises), pointing out self-contradiction, and developing critical thought-experiments[95, 96].

When selecting content to prepare lecture courses it is important to make sure both that the material is closely related to the students’ prior knowledge, and that the content is broken down into small manageable chunks that can be logically related and sequenced[97–99]. As discussed above, the ‘size of chunk’ will depend upon the prior knowledge of the learners. For the students to access the intended meaning they should only be asked to consider one new idea at a time. Each new concept or association should be explored in relation to the learners’ existing knowledge before moving on.

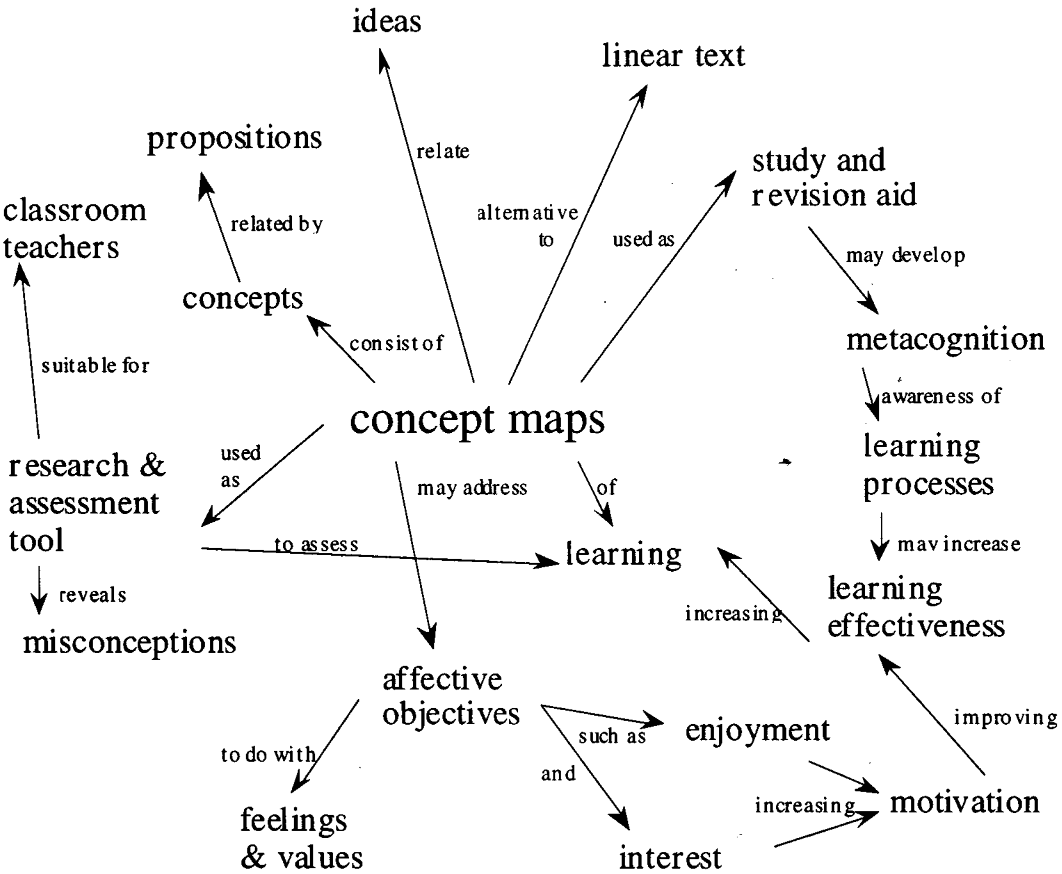
Where there is no obvious source of relevant prior knowledge – for example, some aspects of quantum theory[100] – it is important to provide the students with something familiar to which they can ‘anchor’ the new ideas[101]. This may be in the form of imagery[102], analogy[103–105] or metaphor[105–107].

Appropriate Teaching Methods

Lecture Style

Assuming that most university teaching will continue to be based on lecture courses, there are ways to make these more inter*active*, and therefore keep students’ minds actively engaged. As learning involves relating new material to old, a brief review of the relevant background should always be part of the introduction to any new teaching episode.

Figure 2: A concept map for the concept ‘concept map’.



From: Taber K S 1994 Student reaction on being introduced to concept mapping *Physics Education* 29 (5) 276-281.

It is also useful for the lecturer to provide an outline of where the lecture is heading, so that the students have an overview of the material. A rough idea of the 'shape of the territory' provides a template, which prepares the student to organise the material. (This is analogous to a jig-saw puzzle, which may be completed much more easily when the target picture is known.) Students will have different learning styles, and the logical progression of ideas is paramount to some, but an initial overview is more essential for others[58, 108]. Ideally a good presentation includes both an initial 'route map', and a careful logical exposition of the fine detail.

Even university students will not be able to focus fully on a talk for fifty minutes or more[109]. Few academics can hold their audience spell-bound for that long, and it is therefore beneficial to break lectures into short segments by varying the activity. The more *active* the students' minds, the greater the amount of learning that is likely to occur, and so it is important for the students to have to *process* the new information. However this will not be effective unless students are given time and incentive to carry out the necessary processing.

Ideally the lecturer could intersperse the presentation of material with short question and answer sessions, which check that members of the group understand key points before moving on. As Edwards and Mercer point out, teacher's questions are usually designed to teach, and can be a useful way of reinforcing ideas[110]. This may be a difficult approach with large cohorts, especially where most of the students are not known by name and cannot easily be identified in a lecture context. However, interaction between peers can be equally effective at reinforcing new ideas[111]. After each chunk of material is presented, the students could be asked to complete some simple questions – and discuss and explain their answers with the person next to them. As an alternative, students can be asked to *produce* questions for their neighbours to answer, based on what they think they understand.

Anything that might seem to 'interrupt the flow' (sic) of material in a lecture course can be criticised on the grounds that it will reduce the amount of chemistry 'taught'. However, it is well recognised that most students are unable to effectively learn all of the material in their lectures (as demonstrated in final examinations!). It makes sense to be more selective in choosing the material presented if this results in students understanding, retaining and applying that core material better. Hutchinson, for example, reports how a focus on "active intellectual engagement" can enhance retention of concepts, analytical and study skills, and indeed overall success in studying undergraduate chemistry[111].

Continuity and progression

One lesson from the constructivist approach is the importance of making sure that the student has an overview of the subject, and appreciates the *interconnections* within and between different topics. When ideas are presented in different lecture courses, there is even more chance of the learner failing to make connections, especially where different terminology is used by different teachers. (As a personal anecdote, I was told by one A level student that different types of chemical bonds were studied in organic and in inorganic chemistry – the former used single and double bonds, and the latter ionic and covalent bonds.) As learners tend to 'compartmentalise' their knowledge, they will have difficulty accessing knowledge when they do not realise that the context requires it[112, 113].

In the school system in England, in common with many other countries, there is now a National Curriculum, which has been designed so that major topics are met at several different stages of schooling, and with links to other parts of the curriculum detailed in margin notes[114]. This helps the teacher see how a particular topic fits into a coherent curriculum. Universities can help their students by providing a similar structure, so that their course does not seem to be a disjointed set of experiences.

Tutorial work

Learners will most easily come to use scientific versions of concepts in place of their alternative conceptions when they are given the opportunity to rehearse the new ideas, and appreciate their superiority. Even if the alternative conceptions make little sense from a *conventional* viewpoint, they have presumably been fruitful for the student. For example, some learners believe that the nucleus of an atom gives rise to a certain amount of attractive force that depends upon its charge, and that this is *shared* between however many electrons are present. Although this is not good science, it enables students to make correct predictions about some aspects of the patterns observed when atoms are ionised. So, for example, students will explain that a second ionisation requires more energy than the first (true), because once one electron has been removed the others receive a greater share of the nuclear attraction (false)[113].

The student needs to be given sufficient experience of working with the scientific models, to come to appreciate their greater explanatory power. It is important, then, that the student can be *successful* in applying the new ideas. This means that the problems set have to be structured to ensure that the student is both able to achieve success, *and* to develop their skills by applying the scientific principles in increasingly difficult cases and in ever-widening contexts. Ideally, the students are provided with support and advice that is gradually reduced until they have mastered the material – an approach known as 'scaffolding'[59]. As alternative frameworks tend to be idiosyncratic, and as students have different strengths and work rates, it is difficult for the necessary experiences to be provided by including activities in lecture courses alone.

Tutorial work may play a key role, although cost implications may require this to be supplemented with other modes of delivery. In principle this could be through programmed learning *if* high-quality materials are available. Peer tutoring may also be very valuable, if other students are willing and able to help. This can take place within a large examples class, where students who have successfully completed problems help others[52]. Another approach would be schemes using, for example, students in the final year to work with first years – something that may provide experiences of benefit to both in constructing and developing chemical knowledge[115].

Practical work

The constructivist approach emphasises how experiences can only lead to meaningful learning when they can be related to existing knowledge. The need to timetable sessions to utilise available staff and laboratory resources, the time consuming nature of some practical work, and the need to employ rotas to use expensive equipment, all make it difficult to schedule undergraduate practical sessions adjacent to the most relevant lectures.

Practicals can sometimes be undertaken six months in advance of, or behind, the presentation of the relevant theory. This is a worry if we want practical work to provide the evidence for, or demonstrate, scientific principles. Work in schools has shown that even when practical work is integrated with theory within science lessons, the learner's spontaneous tendency is often to interpret observations in terms of alternative conceptions. Indeed, it is not unknown for pupils and teachers to report *seeing* different results[18]!

It is not sufficient, then, to assume that a student who has at different times been taught an aspect of theory, and undertaken the course experiment that is intended to reinforce the theory, will automatically make the connection and relate the two episodes. Clearly some students will, and some good students will put in the preparation to ensure they have a coherent experience of the overall course. The constructivist approach suggests that the two episodes can be mutually reinforcing, but that the connections need to be made explicit, and that most students will need to be provided with a framework to draw their attention to the salient features of the practical. This may mean an appropriate input from the supervisor or demonstrator during the lab sessions (which may be difficult when a wide range of practicals is occurring in the same lab), or – at least – carefully designed textual materials to accompany the laboratory session[116, 117]. At the moment students are not always provided with such resources.

Conclusion

The vast literature into learners' ideas in science suggests that whenever a science teacher sets out to teach a topic there are likely to be students in the class who hold ideas that are inconsistent with the material that is to be presented. Sometimes the learner will make little sense of the presentation, but on other occasions learners will make their own, *alternative*, sense by constructing a meaning that matches their existing ideas. This is, at least in part, an explanation for intelligent, motivated, and hard-working students commonly failing to learn the intended curriculum.

The first step in a constructivist learning approach is to make the teacher and student aware of the learner's current ideas. Teaching can then be planned that challenges alternative conceptions, and provides students with the opportunities and rationale for conceptual restructuring.

In secondary education constructivist approaches have been claimed to produce more effective science learning. Teachers are being trained to begin a topic by finding out what the pupils think they already know, and to start from that point, rather than simply assuming that the learners know what they 'should' at that stage of their education[118]. Less time is wasted repeating the over-familiar, or relying on non-existent prerequisite knowledge, and teachers are aware of where they could easily be misinterpreted through the pupils' alternative frameworks. The same approach could also pay dividends in university teaching.

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References

1. Taber KS 1998 An alternative conceptual framework from chemistry education *International Journal of Science Education* 20 597–608
2. Schmidt H-J 1997 Students' misconceptions – looking for a pattern *Science Education* 81 123–135
3. Taber KS 1994 Misunderstanding the Ionic Bond *Education in Chemistry* 31 100–103
4. Taber KS 1997 Student understanding of ionic bonding: molecular versus electrostatic thinking? *School Science Review* 78 85–95
5. Schmidt H-J 1992 Conceptual difficulties with isomerism *Journal of Research in Science Teaching* 29 995–1003
6. Abimbola IO 1988 The problem of terminology in the study of student conceptions in science *Science Education* 72 175–184
7. Piaget J 1973 *The Child's Conception of The World* St. Albans, U.K.: Granada (first published in Great Britain by Routledge & Kegan Paul, 1929)
8. Novak JD 1978 An alternative to Piagetian psychology for science and mathematics education *Studies in Science Education* 5 1–30
9. Vygotsky LS 1978 *Mind in Society: The development of higher psychological processes* edited by Cole M, John-Steiner V, Scribner S & Souberman E, Cambridge, Massachusetts: Harvard University Press
10. Bruner J & Haste H (Eds.) 1987 *Making sense: the child's construction of the world* London: Routledge
11. Driver R & Easley J 1978 Pupils and paradigms: a review of literature related to concept development in adolescent science students *Studies in Science Education* 5 61–84
12. Driver R & Erickson G 1983 Theories-in-action: some theoretical and empirical issues in the study of students'

conceptual frameworks in science *Studies in Science Education* 10 37–60

13. Gilbert JK & Watts DM 1983 Concepts, misconceptions and alternative conceptions: changing perspectives in science education *Studies in Science Education* 10 61–98
14. Pope M & Gilbert J 1983 Personal experience and the construction of knowledge in science *Science Education* 67 193–203
15. Bodner GM 1986 Constructivism: a theory of knowledge *Journal of Chemical Education* 63 873–78
16. Driver R 1989 Students' conceptions and the learning of science *International Journal of Science Education* 11 481–490
17. Watts M & Jofili Z 1998 Towards critical constructivist teaching *International Journal of Science Education* 20 173–185
18. Driver R 1983 *The Pupil as Scientist?* Milton Keynes: Open University Press
19. Driver R, Guesne E & Tiberghien A (Eds) 1985 *Children's Ideas in Science* Milton Keynes: Open University Press
20. Osborne R & Freyberg P 1985 *Learning in Science: The implications of children's science* Auckland: Heinemann.
21. Black PJ & Lucas AM (Eds) 1993 *Children's Informal Ideas in Science* London: Routledge
22. Fensham PJ, Gunstone RF & White RT (Eds) 1994 *The Content of Science: a constructivist approach to its teaching and learning* London: Falmer Press
23. Mintzes JJ, Wandersee, James H & Novak JD. (Eds) 1997 *Teaching Science for Understanding: A human constructivist view* San Diego, California: Academic Press
24. Driver R, Squires A, Rushworth, P & Wood-Robinson V 1994 *Making Sense of Secondary Science: research into children's ideas* London: Routledge
25. Russell T, Longden K & McGuigan L 1991 *Materials* SPACE Project Research Report, Liverpool: Liverpool University Press
26. Briggs H & Holding B 1986 *Aspects of Secondary Students' Understanding of Elementary Ideas in Chemistry: Full Report* Children's Learning in Science Project, Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds
27. Cros D, Amouroux R, Chastrette M, Fayol M, Leber J & Maurin M 1986 Conceptions of first year university students of the constitution of matter and the notions of acids and bases *European Journal of Science Education* 8 305–313
28. Cros D, Chastrette M & Fayol M 1988 Conceptions of second year university students of some fundamental notions in chemistry *International Journal of Science Education* 10 331–336
29. Zoller U 1990 Students' misunderstandings and misconceptions in college freshman chemistry (general and inorganic) *Journal of Research in Science Teaching* 27 1053–1065
30. Carson EM & Watson JR 1999 Undergraduate students' understanding of enthalpy change *University Chemistry Education* 3 46–51
31. Griffiths AK 1994 A critical analysis and synthesis of research on students' chemistry misconceptions, in Schmidt H-J Proceedings of the 1994 International Symposium *Problem Solving and Misconceptions in Chemistry and Physics*, ICASE [The International Council of Associations for Science Education] Publications 70–99
32. Garnett PJ, Garnett PJ & Hackling MW 1995 Students' alternative conceptions in chemistry: A review of research and implication for teaching and learning *Studies in Science Education* 25 69–95
33. Duschl RA, Hamilton RJ & Grandy RE 1992 Psychology and epistemology: match or mismatch when applied to science education, chapter 1 of Duschl R & Hamilton R (Eds) *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice* Albany, NY: State University of New York Press 19–47
34. Vosniadou S 1994 Capturing and modeling the process of conceptual change *Learning and Instruction* 4 45–69.
35. Ausubel DP & Robinson FG 1971 *School Learning: An Introduction to Educational Psychology* London: Holt International Edition (first published by Holt, Rinehart and Winston, 1969)
36. White RT 1985 Interview protocols and dimensions of cognitive structure, chapter 4 of West LHT & Pines AL (Eds) *Cognitive Structure and Conceptual Change* London: Academic Press 51–59
37. Taber KS 2000 Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure *International Journal of Science Education* 22 399–417
38. de Bono E 1969 *The Mechanism of Mind* London: Penguin Books (first published by Jonathan Cape)
39. Novak JD & Musonda D 1991 A twelve-year longitudinal study of science concept learning *American Educational Research Journal* 28 117–153
40. Gazzaniga MS 1992 *Nature's Mind: the biological roots of thinking, emotions, sexuality, language and intelligence* London: Penguin
41. Preece PFW 1984 Intuitive science: learned or triggered? *European Journal of Science Education* 6 7–10
42. Pinker S 1995 *The Language Instinct* London: Penguin
43. Lucas A 1993 Constructing knowledge from fragments of learning?, chapter 8, in Black PJ & Lucas AM (Eds) *Children's Informal Ideas in Science* London: Routledge 134–147
44. Watts DM & Gilbert J 1983 Enigmas in school science: students' conceptions for scientifically associated words *Research in Science and Technological Education* 1 161–171
45. Bruner J 1987 The transactional self, Chapter 4 of Bruner J & Haste H (Eds) *Making sense: the child's construction of the world* London: Routledge 81–96
46. Claxton G 1993 Minitheories: a preliminary model for learning science, Chapter 3 of Black P J & Lucas AM (Eds) *Children's Informal Ideas in Science* London: Routledge 45–61
47. Piaget J 1964 Development and learning *Journal of Research in Science Teaching* 2 176–186

48. Andersson B 1986 The experiential gestalt of causation: a common core to pupils' preconceptions in science *European Journal of Science Education* 8 155–171
49. Gilbert JK & Zylbersztajn A 1985 A conceptual framework for science education: The case study of force and movement *European Journal of Science Education* 7 107–120
50. Watts M & Taber KS 1996 An explanatory gestalt of essence: students' conceptions of the 'natural' in physical phenomena *International Journal of Science Education* 18 939–954
51. Taber KS 1995 Prior learning as an epistemological block?: The octet rule – an example from science education, paper presented at the *European Conference on Educational Research*, University of Bath, September 1995, available via Education*-line*, at http://www.leeds.ac.uk/educol/
52. Sirhan G, Gray C, Johnstone AH & Reid N 1999 Preparing the Mind of the Learner *University Chemistry Education* 3 43–46
53. Eysenck MW & Keane MT 1990 *Cognitive Psychology: a student's handbook* Hove, East Sussex: Lawrence Erlbaum Associates Publishers
54. Bennett SW & O'Neale K 1998 Skills development and practical work in chemistry *University Chemistry Education* 2 58–62
55. Luria AR 1987 *The mind of a mnemonist* Cambridge, Massachusetts: Harvard University Press
56. Ausubel DP & Robinson FG 1971 *School Learning: An Introduction to Educational Psychology* London: Holt International Edition
57. Thagard P 1992 *Conceptual Revolutions* Oxford: Princeton University Press
58. Meadows S 1993 *The Child as Thinker: the development and acquisition of cognition in childhood* London: Routledge
59. Scott P 1998 Teacher talk and meaning making in science classrooms: a review of studies from a Vygotskian perspective *Studies in Science Education* 32 45–80
60. Strike KA & Posner GJ 1985 A conceptual change view of learning and understanding, Chapter 13 of West LHT & Pines AL (Eds) *Cognitive Structure and Conceptual Change* London: Academic Press Inc., 211–231
61. Strike KA & Posner GJ 1992 A revisionist theory of conceptual change, Chapter 5 of Duschl RA & Hamilton RJ *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice* Albany, N.Y.: State University of New York Press
62. Hennessy S 1993 Situated cognition and cognitive apprenticeship: implications for classroom learning *Studies in Science Education* 22 1–41
63. Gilbert JK, Osborne RJ & Fensham PJ 1982 Children's science and its consequences for teaching *Science Education* 66 623–633
64. Solomon J 1993 The social construction of children's scientific knowledge, Chapter 5, in Black PJ & Lucas AM (Eds) *Children's Informal Ideas in Science* London: Routledge 85–101
65. Viennot L 1979 Spontaneous reasoning in elementary dynamics *European Journal of Science Education* 1 205–222
66. Viennot L 1985 Analyzing students' reasoning: tendencies in interpretation *American Journal of Physics* 53 432–436
67. Bliss J, Morrison I & Ogborn J 1988 A longitudinal study of dynamics concepts *International Journal of Science Education* 10 99–110
68. Gilbert JK & Pope ML 1986 Small group discussions about conceptions in science: a case study *Research in Science & Technological Education* 4 61–6
69. Carr M, Barker M, Bell B, Biddulph F, Jones A, Kirkwood V, Pearson J & Symington D 1994 The constructivist paradigm and some implications for science content and pedagogy, chapter 11 of Fensham PJ, Gunstone RF. & White RT (Eds) *The Content of Science: a constructivist approach to its teaching and learning* London: Falmer Press 147–160
70. Newton P, Driver R & Osborne J 1999 The place of argumentation in the pedagogy of school science *International Journal of Science Education* 21 553–576
71. Novak JD 1985 Metalearning and metaknowledge strategies to help students learn how to learn, Chapter 12 of West LHT & Pines AL (Eds) *Cognitive Structure and Conceptual Change* London: Academic Press 189–209
72. Novak JD 1989 The use of metacognitive tools to facilitate meaningful learning, chapter 11.1, in Adey P Bliss J Head J & Shayer M (Eds) *Adolescent Development and School Science* Lewes (East Sussex): The Falmer Press 227–239
73. Wittrock MC 1994 Generative science teaching, chapter 3, in Fensham PJ, Gunstone RF & White RT (Eds) *The Content of Science: a constructivist approach to its teaching and learning* London: Falmer Press 29–38
74. White RT & Mitchell IJ 1994 Metacognition and the quality of learning *Studies in Science Education* 23 21–37
75. Carr M 1984 Model confusion in chemistry *Research in Science Education* 14 97–103
76. Taber KS 1995 An analogy for discussing progression in learning chemistry *School Science Review* 76 91–95
77. Driver R & Oldham V 1986 A constructivist approach to curriculum development in science *Studies in Science Education* 13 105–122
78. Johnston K & Driver R 1991 *A Case Study of Teaching and Learning about Particle Theory: a constructivist teaching scheme in action* Children's Learning in Science Project, Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds
79. Harlen W 1999 *Effective Teaching of Science: a review of research* Edinburgh: Scottish Council for research in Education
80. Millar R 1989 Constructive criticisms *International Journal of Science Education* 11 (special issue) 587–596
81. Fox D 1983 Personal theories of teaching *Studies in Higher Education* 8 151–163
82. Prosser M & Trigwell K 1999 Relational perspectives on higher education teaching and learning in the sciences *Studies in Science Education* 33 31–60

83. Curzon LB 1990 *Teaching in Further Education: An outline of principles and practice* (4th Edition), London: Cassell Educational Ltd
84. Cervellati R, Concialini V, Innorta G & Perugini D 1984 Chemical knowledge of students entering a first-year university chemistry course in Italy *European Journal of Science Education* 6 263–270
85. Assessment Subject Group of the Royal Society of Chemistry 1998 *Research in Assessment XIII: An updated report on the skills test survey of chemistry degree course entrants* The Royal Society of Chemistry Education Division, London.
86. Barker V & Bennett J 1999 The post-16 – university transition *Education in Chemistry* 36 101–104
87. White R & Gunstone R 1992 *Probing Understanding* London, The Falmer Press
88. Taber KS 1996 Chlorine is an oxide, heat causes molecules to melt, and sodium reacts badly in chlorine: a survey of the background knowledge of one A level chemistry class *School Science Review* 78 39–48
89. Taber KS 1990 The truth about ionisation energy: an instrument to diagnose common alternative conceptions *School Science Review* 81 97–104
91. Novak JD 1990 Concept mapping: a useful tool for science education *Journal of Research in Science Teaching* 27 937–949
92. Wandersee JH 1990 Concept mapping and the cartography of cognition *Journal of Research in Science Education* 27 923–936
93. Garratt J 1988 Inducing people to think *University Chemistry Education* 2 29–33
94. Chinn C & Brewer W 1993 The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction *Review of Educational Research* 36 1–49
95. Helm H & Gilbert J 1985 Thought experiments and physics education – part 1 *Physics Education* 20 124–131.
96. Helm H, Gilbert J & Watts DM 1985 Thought experiments and physics education – part 2 *Physics Education* 20 211–217
97. Heron JD et al 1977 Problems associated with concept analysis *Science Education* 61 185–199
98. Johnstone AH & Kellett NC 1980 Learning difficulties in school science – towards a working hypothesis *European Journal of Science Education* 2 175–181
99. Johnstone AH 2000 Teaching of Chemistry – logical or psychological? *Chemistry Education: Research and Practice in Europe* 1 9–15
100. Feynman RP 1985 *QED: The strange theory of light and matter* Princeton: Princeton University Press 9
101. Niedderer H, Bethge T & Cassens H 1990 A simplified quantum model: a teaching approach and evaluation of understanding, in Lijnse P L, Licht P, de Vos W & Waarlo A J (Eds) *Relating Macroscopic Phenomena to Microscopic Particles: a central problem in secondary science education* Utrecht: Centre for Science and Mathematics Education, University of Utrecht: CD-ß Press 67–80
102. Miller AI 1986 *Imagery in Scientific Thought* Cambridge, Massachusetts: M.I.T. Press
103. Vosniadou S & Brewer WF 1987 Theories of knowledge restructuring in development *Review of Educational Research* 57 51–67
104. Treagust DF, Harrison AG & Venville GJ 1996 Using an analogical teaching approach to engender conceptual change *International Journal of Science Education* 18 213–229
105. Duit R 1991 On the role of analogies and metaphors in learning science *Science Education* 75 649–672
106. Lakoff G & Johnson M 1980 The metaphorical structure of the human conceptual system *Cognitive Science* 4 195–208
107. Ritchie SM 1994 Metaphor as a tool for constructivist science teaching *International Journal of Science Education* 16 293–303
108. Child D 1986 *Psychology and the Teacher* (4th Edition) London: Cassell
109. Laws PM 1996 Undergraduate science education: a review of research *Studies in Science Education* 28 1–85
110. Edwards D & Mercer N 1987 *Common Knowledge: The development of understanding in the classroom* London: Routledge
111. Hutchinson JS 2000 Teaching introductory chemistry using concept development case studies: interactive and inductive learning *University Chemistry Education* 4 1–7
112. Karmiloff-Smith A 1994 Précis of Beyond Modularity: A developmental perspective on cognitive science *Behaviour and Brain Sciences* 17 693–745
113. Taber KS 1998 The sharing-out of nuclear attraction: or I can't think about Physics in Chemistry *International Journal of Science Education* 20 1001–1014
114. DFE/QCA 1999 *Science: The national curriculum for England key stages 1-4* Department for Education and Employment/Qualifications and Curriculum Authority
115. Coe EM, McDougall AO & McKeown NB. 1999 Is peer assisted learning of benefit to undergraduate chemists? *University Chemistry Education* 3 72–75
116. Johnstone AH 1997 "…And some fell on good ground" *University Chemistry Education* 1 8–13
117. Nicholls BS 1999 Pre-laboratory support using dedicated software *University Chemistry Education* 3 22–27
118. DfEE 1998 *Circular 4/98: Standards for the award of qualified teacher status: Annex A* Department for Education and Employment