Review

Chemical education: theory and practice

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Introduction

We intend that this review should help the conscientious and caring teacher of degree-level chemistry to build on the tested experience of researchers into teaching and learning. There is a huge literature on this aspect of academic scholarship, much of it unfamiliar (and often incomprehensible) to practicing teachers, but which is potentially useful since it can provide short cuts to discovering how to improve our students' learning. Our intention is to select those findings from educational research that are most relevant to chemistry, and translate them into an accessible language so that the educational theory can more easily contribute to the design and delivery of effective chemistry courses. This translation is necessary because, as pointed out by de Jong,[1] education research has been strongly influenced by general psychological theories, and these are largely inaccessible to most chemists. It is perhaps unsurprising, therefore, that many teachers are unaware of underlying educational theory that is embedded in literature which is unfamiliar in style and language. Indeed de Jong, in his plea for closer links between educational research and teaching, suggests that there is only a weak relationship between general educational theories and specific teaching practices. The establishment of the ILT and associated Subject Centres, and journals such as *University Chemistry Education*, should help to strengthen this relationship.

With the benefit of hindsight, most established theories of learning appear obvious. Nevertheless, it takes most of us a lifetime to rediscover them for ourselves. The results of educational research can help us to use the experiences of those who have thought deeply about teaching and learning in developing our own individual approach to teaching. Our main driving force in writing this review is our belief that most academics will welcome the opportunity to do just that because they are conscientious about their teaching, and are looking for ways to improve it. Nevertheless, we recognise that there are other, often externally imposed, pressures on us to consider the need for change in teaching activities. These include the demands of the quality assurance and assessment processes, and the increasingly common requirement for all lecturers to gain some qualification in teaching. These external pressures may help to persuade academics that this review could be helpful.

We have one other reason for writing this review. We are not satisfied that those who have a particular interest in and aptitude for the scholarship of teaching and learning receive their rightful recognition in terms of a satisfactory career structure. One contributory factor to this unfortunate state of affairs is that, at least until recently, there have been few opportunities to publish the results of successful innovations in the design and delivery of chemistry courses to students, yet publication is a key aspect of true scholarship. This journal aims to help to fill this gap, and we hope that this review will help colleagues both as readers and contributors.

What do we want our students to learn?

Until quite recently, this heading would have dealt almost exclusively with the **content** of a degree course. Of course content is crucial, though it is worth reminding ourselves that most of us are not really satisfied with the learning of facts for regurgitation; we expect our students not just to learn facts but to learn them in such a way as to be able to **use** them. Hodson[2] reports that Gagne[3] made this point in 1963 when he proposed that the overarching purpose of science education is to enable students *"to employ inquiry in the manner so well known to scientists"*, and that this overall goal had the three sub-goals of ensuring that students acquire attitudes of inquiry, methods of inquiry, and understanding of inquiry. Some years ago, Garratt[4] put this point in a way which drew attention to the need to communicate science as well as to do it: "our graduates need to know their subject so that they can **ex**plain**, ex**ploit and **ex**tend it; universities need to provide a triple X experience." The Dearing Report[5] and the Chemistry Benchmarking document[6, 7] both amplify this by drawing attention to the need for students to develop **skills**, only some of which are subject-specific. Of course, the history of skills-development goes back much further than Dearing. For example, Haldane[8] wrote in 1924 that "*it is the sole purpose of the university teacher to induce people to think*". de Bono[9] stated that *"it must be more important to be skilled in thinking than to be stuffed with facts"*. More recently, Arons[10] claimed (in our view rather dubiously) that *"No curricular recommendation, reform, or proposed structure has ever been made without some obeisance to the generic term 'critical thinking' or one of its synonyms*". Occasionally, thoughtful scientists have suggested that failure to take these ideas seriously has disadvantaged science as a worthwhile course of study. Thus Finster[11] complains that science is all too often taught as though right answers to everything exist (and are already known) and that this leads to public misconceptions about what science can and cannot do. According to Fry et al.[12], this is still believed by many of our students: "*one of the greatest misconceptions on the part of many students is their belief that a subject consists of large amounts of factual knowledge and, to become the expert, all one needs do is to add this knowledge to one's existing store."* Perhaps for this reason, Kuhn[13] argues that *"…the mastery of any particular body of scientific knowledge (is) an unwieldy and unsatisfactory educational goal. More promising is the concept of science education as promoting a way of thinking."*

Generalisations such as these do not provide much guidance on exactly what we might want our students to learn. Dearing[5] and the Chemistry Benchmarking document[6, 7] provide some more useful detail. Thus the Dearing Report (paragraph 38) stated that:

"There is much evidence of support for the further development of a range of skills during higher education, including what we term the key skills of communication, both oral and written, numeracy, the use of communications and information technology and learning how to learn. We see these as necessary outcomes of all higher education programmes."

Underpinning this is recommendation 21, which requires all degrees to have a 'programme specification', which *"gives the intended outcomes of the programme in terms of:*

i. Knowledge/understanding of subject (syllabus)
ii. Special subject skills (e.g. lab work)
iii. Cognitive skills (methodology, critical analysis)
iv. Key skills"

These four aspects of learning are effectively identical to the four headings listed in the programme specification proposed by the chemistry benchmark document. The first three of them would surely be included in any list of 'what we want our students to learn'. This does not mean that there is universal agreement about how they should be interpreted, and there is plenty of room for hugely different interpretations. For example, what is the desirable balance between the acquisition of knowledge (content) and the gaining of the understanding needed to exploit and extend this knowledge (process)? Does traditional laboratory work teach all the skills needed by an experimentalist – including the design of investigations and the making and imaginative interpretation of observations; do students learn effective critical analysis without being provided with explicit and specific opportunities to practice it within the course structure? The debate about this interpretation is important, and it is our view that it is not currently a sufficiently vigorous debate to provide a secure future for chemistry. The fourth area, that of Key Skills, is even more problematical, since many teachers regard themselves as inadequately qualified to teach these skills, and some profess not to understand what they are.

The Chemistry Benchmarking document lists eight such skills:

- Communication (written and oral)
- Numeracy and computing
- IT skills
- Problem-solving (and critical thinking)
- Information retrieval
- Interpersonal skills
- Organisational skills (including time management)
- Skills for continuing professional development

The first three of these are also listed by Dearing, who includes 'learning to learn' as a fourth, which more or less corresponds to 'skills for continuing professional development'. Earlier, Coldstream[14] had proposed four very similar skills as *"abilities for the exploitation of knowledge*"; his list was: 'communication', 'numeracy', 'teamwork' (which must overlap strongly with 'interpersonal skills'), and 'lifelong learning'.

These views of what a chemistry graduate should be able to do are mirrored by the views of employers, as reported by Mason.[15] Recent graduates also selected several of these areas from a list of 'action statements' as ones where they felt that their university training had been inadequate.[16] Interestingly, they specifically selected 'contributing to discussion', 'understanding/evaluating the views of others' and 'talking/writing persuasively to non-specialists', all of which could come within the heading of 'communication', but which may often be overlooked. These action statements, identified by Duckett et al.,[16] may usefully highlight the fact that a difficulty with the lists of general skills is that they leave a great deal of room for interpretation. A particular area of concern is 'problem solving', which (in its fullest sense) involves a great deal more mental flexibility than is required to solve the algorithmic type of problems that comprise most of the problem activities set to our students. Bodner and Domin[17] discuss this in more detail, and we suggest that most of us would do well to analyse the problems set for students against the framework suggested by Johnstone,[18] which divides problems into eight types according to whether the **data** are 'given' or 'incomplete', the **method** is 'familiar' or 'unknown', and the **output** or **goal** is 'defined' or 'open'. Bennett[19] has concluded that in examinations the vast majority are of Johnstone's 'type 1' in which the data are given, the method is familiar, and the goal is defined. In contrast, most problems faced by experimentalists are closer to 'type 8' (incomplete data, unfamiliar method, undefined goal), and we believe that we should give our students more opportunities to practice this type of problem. Various suggestions have been made[20-27] for ways in which this might be done.

We are also struck by the fact that these lists of skills do not make any specific mention of the need to develop an understanding of the 'scientific method' and in particular the need to appreciate the nature of scientific evidence and proof which limits *"to what extent things are known (for nothing is known absolutely)"*.[28] Arons and Arons[10] discuss some aspects of this, and they list ten "*thinking and reasoning processes that underlie analysis and enquiry. These are processes which teachers rarely articulate or point out to students"*. From their list, we pick out as being of special importance the process of "*discriminating between observation and inference, between established fact and subsequent conjecture"*. As an example of failure to do this, they quote an experience with a group of teachers heating copper in a crucible and watching it turn black. When asked what they observed, many replied that they observed oxygen combining with copper, and it took a *"a sequence of Socratic questioning"* before they recognised that this was an inference rather than an observation. It is our view that we should help our students to learn to appreciate this and other aspects of the nature of science. However, we agree with Hodson[29] that the distinction is not always obvious since "*all scientific observations, except the most trivial**, include** theoretical inferences*".

The skills listed by various authorities are quite unexceptional, as are the additional ones we would like to see in the list. Indeed, most of them are exactly the skills which most of us would expect (or at least hope for) in a top class post-doc in our research group. If we are honest, we know that these skills do not develop spontaneously during the PhD programme, and so the foundations need to be laid during the undergraduate course. Thus we conclude that we should define what we want our students to learn in terms of what we recognise as the characteristics of a researcher capable of managing an imaginative research programme. "*We should put less emphasis on the teaching of chemistry and more emphasis on learning how to be chemists because being a chemist involves knowing chemistry, but knowing chemistry (alone) does not make a chemist*".[30] Alas, this does not help us to know how to teach them!

Our view is that one of the key principles to effective teaching is the need to consider the student's position, and in particular to appreciate how students learn. Herron has argued that we need to be aware that "*our students have a very different view of the world from our own! Because of this, we often have difficulty conveying our view of the world by telling"*.[31] Moreover, Fry et al.[12] point out that "*…some academics teach students without having much formal knowledge of how students learn. Many lecturers know how* they *learn best, but do not necessarily consider how* their students *learn and if the way they teach is predicated on enabling learning to happen.*" Because we need to get into the mind of the learner, and think about how they will receive our teaching, our next section deals with aspects of how students learn.

How do students learn?

a) Constructivism

One of the most accessible summaries of constructivism is by Bodner,[32] and his paper includes the oft-quoted assertion from Ausubel: *"The most important single factor influencing learning is what the learner already knows"*.[33] When we teach, we need to remember that the new facts and ideas that we propound do not become incorporated directly into the mind of the student without processing; they have to be fitted into the existing structures and schemes already in the mind. The origin of the aphorism that "*knowledge is never transmitted intact from one individual to another*",[31] can be attributed to Piaget,[34, 35] who studied the intellectual development of children; his influential ideas formed the basis of many of the theories of how people learn, and led to the development of the concept now known as constructivism. Although there are other theories of learning, constructivism is one which readily strikes chords with scientists; thus, Resnick[36] emphasised its importance to education in science in the 1980s, whilst Fry et al.[12] described it as "*the most prominent theory about how learning takes place*." For those interested in reading more about the application of Piaget's ideas to the teaching of chemistry, the paper by Craig is recommended,[37] whilst Herron[31] has listed references to fourteen relevant papers published in the *Journal of Chemical Education* in the decade up to 1983, and Novak has presented an alternative link between educational psychology and learning in science.[38] The relevance of constructivism to the teaching and learning of chemistry has been reviewed by Bodner,[32] and more recently in this journal by Taber,[39] whilst Clow's paper about computers in chemistry teaching also has a useful section on 'how students learn'.[40] We refer readers to these excellent reviews, and restrict ourselves here to some brief comments supported by quotations which we regard as particularly apt. Bodner[32] summarised constructivism in the phrase: "*Knowledge is constructed in the mind of the learner*." We have selected three other quotations that amplify this summary a little.

*"… learners **construct** understanding. They do not simply mirror and reflect what they are told or what they read. Learners look for meaning and will try to find regularity and order in the events of the world, even in the absence of full or complete information."* (Von Glasersfeld)[41]

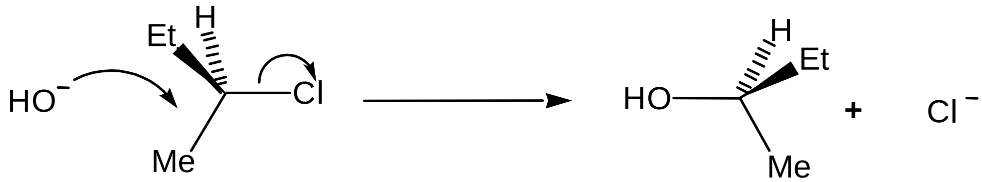
"…each of us receives some signal from the environment through one of our sensory organs, and that signal is then interpreted according to some 'schema' or pattern that we have previously built, and then incorporated in modified form as new knowledge." (Herron)[31]

*"When learners have a **different** theoretical framework from that assumed by the teacher, they may look in a different (wrong?) place, in a different/wrong way, and make different/wrong interpretations, sometimes even vehemently denying observational evidence that conflicts with their existing views."* (Gunstone)[42]

According to the constructivist model, we therefore have to discard the traditional view that knowledge corresponds to or matches reality. Rather, we have to accept that, for the learner faced with new information "*the only thing that matters is whether the knowledge we construct from this information functions satisfactorily in the context in which it arises*" (Bodner).[32] Thus, individuals may construct different images of reality from the same new information, since each is incorporating the new information into a unique existing set of mental images or schema. As Hodson[2] puts it, with reference to laboratory work, "*because predictions, perceptions and explanations are all strongly influenced by prior conceptual understanding, students who hold different frameworks of meaning essentially conduct different investigations, with correspondingly different learning outcomes.*" For teachers, this concept of how knowledge is constructed helps to explain the frequency with which students seem to misunderstand completely or fail to remember new chemical concepts to which we introduce them; it may even encourage us to find out more about what students already understand so that we can build on it, though this is made more difficult by the fact that each of them will have different starting points! In any case, knowing what students understand is only the first step towards making *"connections between what we are doing and what is understood."* (Herron)[31]

The adoption of the constructivist model requires us to accept that we cannot brilliantly transfer into the minds of our students, what we have in our own minds. Our own minds do not contain reality itself but models of reality that we have painstakingly constructed for ourselves. It is a convenient shorthand to treat these models as though they were reality, and we frequently do so. A resulting problem is that many of our students appear unaware that their concepts of (for example) atoms and molecules are actually only models. Typically, models develop in stages from simple beginnings to complex concepts. The mechanism of nucleophilic substitution reactions provides a simple example that spans inorganic, organic, and physical chemistry. Almost all the stages in developing our current understanding of this type of reaction have involved intense controversy amongst the leading chemists of the time. It often seems logical to an experienced chemist who has already (painstakingly) constructed this knowledge in their own mind that the most up-to-date model will be

Figure 1. Mechanistic representation of an S_N2 process.



instantly understood by students. This is frequently not the case because the students do not have a suitable framework onto which such a complex model can be built. They need to be provided with what Taber[39] describes as a 'scaffold'. It may well be more easily assimilated if the model is developed gradually, giving time for the assimilation of each stage before showing how it needs to be modified in order to account for more observations. Here is a series of stages through which the mechanism of substitution reactions might be developed.

Stage 1. In order to develop an explanation of how/why substitution reactions occur, we would expect some prior understanding of the concept that **opposite (partial) charges are attracted to one another**, and some notion of **bonding**. The simple model of substitution reactions involves the idea that **electron-rich nucleophiles** attack **electron-deficient electrophiles**, and a **leaving group** is ultimately displaced; all this terminology needs to be learned and understood by the student because it provides part of the framework with which new ideas must be integrated. Stage 1 helps the learner to retain and rationalise a substantial knowledge base, and it provides a foundation from which the model can be developed.

Stage 2. Stage 1 offers no explanation for the very different reaction rates that can be observed for reactions of this general type. It can be effective to alert students to this limitation after they are comfortable with Stage 1, and to indicate that this shows that the model is incomplete. Note that this does not mean that the Stage 1 model is *wrong*, but that the explanation is somewhat shallow as there is no detail at all concerning how the bonds are made/broken. At this stage, new experimental data can be introduced which leads to the concept that the same overall mechanism can take place in different ways; for example, a study of the reaction rates, and dependence on substrate concentrations, can lead to the possibility of the following three processes:

a) Y + A–X → Y–A–X → Y–A + X (add X, then lose Y)

b) Y + A–X → Y---A---X → Y–A + X (add X and lose Y synchronously)

c) Y + A–X → Y + A + X → Y–A + X (lose X, then add Y)

Stage 3. Bright students will quickly realise that Stage 2 is also limited because it addresses neither the issue of stereochemistry, nor the question of why different reactants follow different pathways. We can produce a more detailed mechanistic explanation by using the 'arrow pushing' symbolism, but we should be well aware that this too is only a model. It bears an uncertain relation to reality, and individual learners will perceive the model in different ways. Using a specific example (Figure 1), we might express mechanism b) by the following S_N2 process:

This mechanism provides enough detail to allow a plausible explanation of why the example shown follows pathway b), and similar 'arrow pushing' (combined with electron counting and steric considerations) can be used to justify why pathways a) or c) may be followed in other examples.

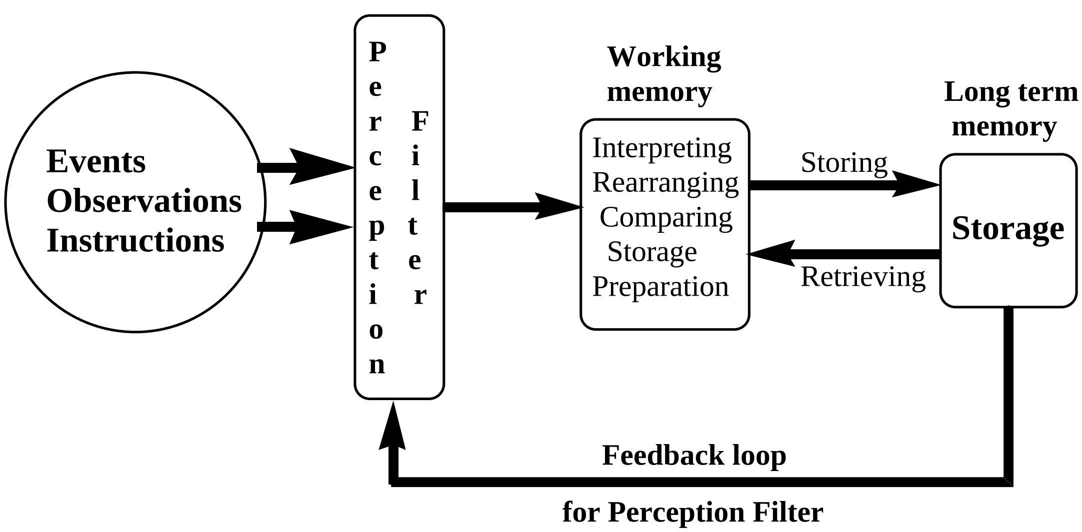
Stages 4, 5…The Stage 3 model will provide reasonable explanations for most substitution reactions. Some students will feel that this is indeed a complete explanation, and that this is really what happens. But brighter students will perceive that the model is still incomplete, and there are experimental data that demonstrate the deficiencies. The Stage 3 model can be refined by a consideration of the molecular orbitals (another symbolic model!), which helps explain why some S_N2 processes are favoured over others that are apparently similar,[43] and also provides a more rigorous (and perhaps more convincing) explanation for the stereochemistry of substitution reactions.[44] Thereafter, we can add more and more detail to how we believe the reaction takes place, and we can add yet further refinements when experimental data cannot be fully matched against each new model. However, it is doubtful that our students would benefit from **starting** with an MM2 molecular dynamics quantum/relativistic calculation so that they got a 'real understanding' for the processes (still a model, anyway!), and only then being introduced to the more frequently used models as simplifications of this. We should remember that many students would neither want nor need to go beyond the incomplete models provided by Stages 2 or 3, and furthermore that these simpler models are often far more useful to the practising professional chemist. For example, a simple model is likely to be preferred to a more rigorous analysis in considering the practical question 'how do I change the reaction conditions so that I can get a good yield in the lab tomorrow', since the more rigorous model might take weeks to compute. So we need to have some awareness of how our students will construct their evolving model at each level that we teach them, and that some students will need extra help when the intellectual level is getting beyond them. It is just as important to accept that there are different ways of helping students to construct an understanding of the topic, and that other teachers might develop the model using different stages that are just as valid.

We also need to be aware that new information must be interpreted and organised so that it can be integrated with the information in the *long term memory*,[45] and this processing must take place in the *short term (working) memory*, which has space for only a limited number of pieces of information.[46] Johnstone has notably developed this model for learning (see Figure 2), and has discussed it in a very accessible way.[47] Experienced chemists can use tricks to hold larger amounts of information in the working memory,[39] and can take short-cuts when performing calculations,[48] or writing mechanisms. A complex formula may comprise a single chunk[49] of information for an experienced chemist, but may overload the working space of a novice who does not share the same conceptual frameworks,[50] and tutors need to avoid overloading the working memory in their teaching.

The approach of first teaching a simple model allows the student to build a strong framework on which to incorporate new ideas and so to construct a more complex model; a key point is to avoid creating the impression that the simple model is **wrong**. This approach has the added benefit that it approaches more closely the way science is done. Scientific discovery is based on identifying patterns, proposing theories that explain these observations, and then refining the model in the light of more detailed data or of exceptions that 'prove' (i.e. 'test') the rule or model. It is small wonder that students do not know how to design experiments or construct arguments, if we always teach them only the most complete explanation.

Constructivism needs to be developed considerably from this basic description before it can be fully used by teachers to develop a theory of teaching, which Bodner points out, is subtly different from a theory of learning.[51] In particular, we need to decide what assumptions to make about the students' prior knowledge and how best to take account of the fact that the students' mental models may not coincide with our own. Many educational researchers give these some euphemistic name like 'alternative conceptions'. We prefer Hodson's view[2] that it is better to use 'misconceptions' to demonstrate

Figure 2. Model for learning developed by Johnstone.[47]



"opposition to the relativism that is a prominent feature of much contemporary writing dealing with constructivist approaches to teaching." We will not here go into details of the misconceptions that have been found to be common, but Taber,[39] Barker,[52] and Johnstone[48] have analysed some of the problems of misconceptions. We simply want to point out that all students have them as a result of their previous experience, and so they don't always have the foundation we assume when we plan our teaching (or, as Boothroyd[53] would prefer, when we plan our students' learning). We should therefore not be surprised that students develop new misconceptions based on what we tell them, however brilliantly clear our telling is. We suggest that the only way of minimising this problem is to be aware of it, to try to discover the nature of any new misconceptions, and to deal with them sympathetically rather than blaming the students.

When we plan our students' learning we should, as well as considering student misconceptions, also recognise that we need to think about their different intellectual attitudes.

b) Stages of intellectual development

Attitudes to learning are influenced by the level of intellectual development that the individual has reached. Two particularly useful models of intellectual development are those developed by Piaget[34, 35] and by Perry.[54] Piaget's work was primarily with young children, but the final stages of intellectual development in his scheme are relevant to higher education. According to this, children aged about 7 are able to progress from 'pre-operational thought' to 'concrete operational thought', and then approximately coincidentally with the school leaving age they become capable of 'formal operational thought'. In summary, concrete operational thinkers argue from concrete examples; typically, they can describe without explaining, give examples but not general definitions derived from these examples, and are comfortable with anecdotal evidence whilst finding it difficult to test hypotheses in a rigorous way; they are able to deal generally with macroscopic events but find it difficult to see how to interpret these at a hypothetical level. Herron[55] quotes an example of the limitations of concrete thinkers taken from Copes.[56] Copes set a question to (young) students which gives the distances which a turtle and a rabbit can fly in different times, and the students are asked which can fly the faster. She found some students could not answer the question because they know that neither animal can fly – a finding that Herron suggests "*represents a rather profound inability to divorce oneself from experience and operate in the realm of possibility"*. Although Herron recognises that most college students are beyond this point, Greer[57] has made a strong case that substantial numbers of college students are concrete thinkers and that they therefore have difficulty following the abstract formalism in which much of our chemistry is presented; they compensate for this by rote learning.

Formal operational thinkers, in contrast, can follow a formal argument, can set up and test hypotheses, and are at home with hypothetical-deductive reasoning. Herron discusses the practical implications of this for teachers. Importantly, as he reminds us, Piaget argues that *"everyone reverts to concrete operational or pre-operational thought whenever they encounter a new area. Before one can reason with hypotheses and deductions based on experience, there must be a sound descriptive base which has been put in order"*. We would do well to remember that we are frequently expounding to our students new topics with which we are very familiar (and therefore operate in formal operational mode) whereas our students struggle (and fail) to understand them in concrete operational mode, and consequently revert to learning by rote what we tell them. A consequence of rote learning, as argued by Johnstone,[48] is that the ideas never get properly attached to existing learning in the long term memory, and so are soon forgotten. It may be that our concerns that students learn by rote what we want them to understand, and forget what we want them to remember, could be overcome by giving more consideration to the problems associated with operating at the concrete level. A rather different objection to rote learning is was made by Biggs,[58] who says: "*Rote learning scientific formulae may be one of the things scientists do, but it is not the way scientists think.*"

Perry conceived intellectual development in rather different terms (see Table 1). His different stages or positions have been paraphrased by Phillips and Pennington,[59] and an accessible account of his ideas is given by Finster,[11, 60] whilst Perry himself has written a chatty and useful summary of his findings.[61] Essentially, Perry sees the level of intellectual maturity progressing from 'dualism' (everything is either right or wrong, good or bad, etc), through 'multiplicity' where there is a danger that confusion reigns because it begins to be recognised that knowledge is uncertain (this position is closely related to post-modernism which cynics may say is characterised by the view that 'my opinion is as good as anyone else's), and finally reaches a position of 'relativism' in which it is recognised that knowledge is relative and contextual. Almost all of us will be able to identify occasions when we have commented

Table 1. Summary of the 'Perry' positions of educational development, adapted from references.[61, 59]

Position 1	There are correct answers to everything. If I work hard, I can learn (memorise) all of the knowledge that I need.
Position 3	There are some uncertainties, but there are nevertheless 'right' answers to everything, which can be found. The experts will sort out any gaps in our knowledge in due course.
Position 6	There are no definitive explanations, and everyone's opinion is equally valid. Everything is uncertain (both in my studies and in my life) ….. HELP!
Position 9	Whilst I'm aware of uncertainty, working frameworks allow me to tackle many questions confidently, whilst being aware of dilemmas or assumptions.

adversely on student attitude or performance for reasons which we could (with hindsight) attribute to them being too far down in Perry's positions. If we assume that the students we are teaching are in different positions, it may help us to develop ways of teaching which will help all of them to engage with the material more effectively.

We referred above to 'rote learning' which Ausubel[33] contrasted with 'meaningful learning' in which *"new information is attached to existing learning, making it richer, more interconnected and accessible through many cross references"*. A similar distinction between 'surface' and 'deep' learning was drawn by Marton,[62, 63] Entwistle,[64] and Ramsden.[65] Most of us will have observed that some students (usually classified as the weaker ones) learn their topics superficially, whereas others consider the subject more deeply. It is therefore not surprising that this characteristic has been documented by research. Statements that identify deep learners are exemplified by "*I try to grasp the key principles, and check back on earlier parts of the topic to see how it holds together*", whilst a surface learner might "*read about a topic from start to finish, trying to remember as much as possible*". Marton's group in Sweden found that students who were assessed as deep processors were able to summarise concisely the key results from a short article, whilst the surface learners were not.[66] Other studies have found it harder to classify the students convincingly, since the majority seem to be somewhere in between the two limiting descriptions, but the general observations have nevertheless been verified elsewhere.[67] However, one really important observation is that students can vary the depth of their studying. We suggested above that some students may adopt rote learning because they are unprepared for the level of formal operational thinking which is required by the way the subject is presented. This ability of the same individual to adopt different approaches to learning has been noted in several contexts. For example Finster[11] reports that *"students do not uniformly approach all aspects of their life from the same [Perry] position"*, and Beard and Hartley[67] report Laurillard's conclusions[68] that students can vary the depth of their study. Thus students tackling a topic because it genuinely interests them are more likely to study it deeply, but if the aim is (for example) to pass an exam (as distinct from understanding the topic), then the learning is likely to be surface in nature. It follows that, even if the stated aim of a course or module is 'to develop an understanding of this topic', one might as well state the aim as 'to do well in the exam' if the 'ability' of students at the end of the tuition is assessed in this way! One should also note that students might interpret lectures in different ways, depending on the depth of their approach. For example, consider presenting three mechanisms for substitution reactions. The surface learner, who is essentially near the start of the Perry scale of progress, will expect the lecturer to identify which method is 'correct' or might decide which is the right one, and learn it; the 'intermediate' learner (near the middle of the Perry scale, and hoping for definitive answers) might simply be confused by the choice of mechanisms, and could muddle them all up; the deep learner, who uses theories flexibly, will be receptive to the lecturer. According to Ramsden,[69] *"The ubiquity of surface approaches in HE is a very disturbing phenomenon indeed"*. In support of this he quotes Whitehead[70] who said as long ago as 1929: *"I have been much struck by the paralysis of thought induced in pupils by the aimless accumulation of precise knowledge, inert and unutilised... The details of knowledge which are important will be picked up* ad hoc *in each avocation of life, but the habit of the active utilisation of well understood principles is the final possession of wisdom."*

This brief description of theories of how students learn leads to the obvious conclusion that the differences between students means that there can be no single perfect method of teaching a topic in a way that gives maximum opportunity to **all** of them to gain both knowledge and understanding. It is for this reason that Fry et al.[12] conclude that "*an awareness of learning styles is important for the teacher planning a course module, as a variety of strategies to promote learning should be considered*." This makes the job of the teacher much harder than it otherwise might be, but also means that we are unlikely to be made redundant because someone has produced 'the perfect teaching package'! This simple conclusion is reinforced by considering not just the different stages of intellectual development of students, but also some of their underlying characteristics.

c) Characteristics of students

Various attempts have been made to classify students according to some general (possibly innate) characteristic which is believed to have an effect on their ability to learn; particularly readable and useful books that have covered this topic have been written by Beard & Hartley,[67] and by Ramsden.[71] Beard and Hartley, for example, discuss the terms 'extrovert' and 'introvert' coined by Eysenck.[72, 73] These terms have been used (somewhat dubiously in our view) to indicate that some (the extroverts) interact with peers, tutors etc better than do others (the introverts). Eysenck concluded that extroverts are distracted from study by other social activities, whereas introverts tend to display better study habits. In a later study, he also concluded that extroverts are better at responding immediately to verbal tasks, whilst introverts tended to demonstrate better long-term memory. Thus we should expect students with the behavioural characteristics of extroverts or introverts to respond differently to the same learning environment. Extroverts may do best in situations that benefit from interaction and argument, and these will help them to develop their skills in expressing coherent arguments. Situations which require long periods of undisturbed concentration are likely to be better understood by introverts, but they may be less good at presenting or defending a particular scientific viewpoint than those students who interact better with their peers. Tutors may wish to encourage students to learn to develop an interactive approach to their learning, even if it is contrary to their introvert nature. In the first place, most would accept that outgoing students provide a more stimulating learning environment from which all can benefit and the presence of one or two such individuals may help to explain why some cohorts of students do better than others when all available measures indicate that their average ability is similar. In the second place, employers expect modern graduates to be able to interact effectively with others, and the conscientious tutor will wish to encourage this characteristic. The teaching strategies need to take this into account.

Beard and Hartley also discuss the concept of 'convergent' and 'divergent' thinkers which was developed, particularly by Butcher, in the 1960s.[74] According to this model, divergent thinkers are readily able to see how ideas can be developed and used in many ways, can see correlations between one piece of information and another, and respond well to open-ended questions which appear to require creativity. Convergent thinkers, on the other hand, tend to focus specifically on the task in hand and like to identify specific outcomes at the end of their studies; whilst admirable in many ways, the implication is that this is rather less imaginative. Rather unfortunately for scientists, as pointed out by Beard and Hartley,[75] it was discovered that arts students tended to be more divergent in their thinking, whilst scientists were more convergent, and the scientific community found it somewhat unpalatable to suggest that their subject areas required less creativity. It has transpired however, that convergent and divergent thinking do not seem to correlate well with the more generally accepted views of creativity, so scientists were perhaps worrying unnecessarily! What does seem clear is that scientific research and learning almost certainly benefit from a high degree of focussing, and identifying specific questions that one wishes to answer. Scientific discovery depends on a rigorous and focussed approach, but of course the most influential scientific discoveries almost certainly depend also on imagination and creativity on the part of the scientists. From an educational standpoint it is important to realise that some students will naturally have more focussed approaches to their studying of science. Students such as these tend to be easy to teach, for it is simple to see how they are progressing in their understanding of the topic. However, they will less readily see connections between different topics, or wish to explore the topics in more open-ended ways, which is unlikely to please those academics, who complain that students study their topics in isolation and fail to see the link from one area of their subject to another. As teachers, we need to be aware of the different way that divergent learners will develop their understanding, **and** we need to positively encourage this approach in those who are convergent learners.

Another way of categorising learners is as 'serialist' or 'holist'.[76-78] This differentiates between students who address topics or problems in a step-by-step fashion and those who look first at the big picture. Serialists are likely to be convergent thinkers, and holists are likely to be divergent thinkers, but there are subtle, although important, distinctions. Divergent thinkers are able to take the knowledge that they have constructed and apply it widely, whereas holists construct their knowledge by using a wide diversity of information and input in order to generate a working model. One might therefore expect divergent thinkers to be better at problem solving and to be well equipped to apply their understanding to a wide range of situations; the holistic learner, on the other hand, utilises a wide range of experience and knowledge in order to construct an understanding of a topic.

In our view the main value of these attempts at classification is that they provide a formal structure by which we can recognise that each student is unique and will therefore respond differently to the same input. We have already discussed how the constructivist model of learning leads us to this conclusion. The different stages of intellectual development and the different general characteristics of each individual simply amplify the differences by pointing to additional levels of variety.

Of the many characteristics of students that have been studied, the one that is most widely recognised as relevant to their capacity to learn is their innate ability. Unfortunately, educationalists have been unable to agree on a single appropriate measure of 'innate ability' because it comprises so many skills (e.g. memory, logical reasoning, abstract thought, data manipulation, communication skills), and all of us have experience of very able students who have specific weaknesses, and weak students who have specific strengths. Gould[79] has provided a readable account of some of the early arguments about whether 'intelligence' is a multivariate or a two-factor characteristic. But most of us, whilst recognising the concept of 'intelligence', would not necessarily equate it directly with 'ability'. This view is compounded by studies which have been made of the correlation between the performance before attending university (e.g. 'A' level scores or IQ test results), and the degree classification obtained at the end of an undergraduate course.[80, 81] In general, the correlation coefficients based on 'A' levels or aptitude tests are regarded as insignificantly different from zero, thus providing no evidence for a relationship. Most of these analyses were carried out when a significantly smaller percentage of the population in the UK went into higher education, and it is not known whether the conclusion would be changed if carried out now that students with a wider range of A level scores attend universities. However, the lack of correlation may simply reflect the difficulty of defining the term 'ability', the vexed question of the comparability of degree classification from different institutions, and the possibility that the skills required to obtain high scores at 'A' level and in IQ tests are different from those required for a university degree. We know of no evidence that this last point is true, though it might plausibly be argued that topics dealt with at university tend to be more abstract than those encountered at A level, which can be more readily related to observations in the world around us. Whether such abstract topics create a more demanding learning environment must depend (if Piaget and Perry are correct) on how successfully each student has developed an ability to think in a formal operational mode and progressed to a relativist position. If we subscribe to the view that a university environment requires higher order cognitive skills than are required by A level, then it must surely be incumbent on us to ensure that our teaching is designed to foster the development of the intellect. We cannot simply rely on the native 'ability' of the students, but must recognise that the different abilities of each student need different kinds of stimulation and contexts if they are to be fully developed.

Moreover, the range of characteristics (ability, style of learning, motivation) for each student dramatically affects the way they perceive their tuition, as expressed by Perry[61]:
"*Every student who came to us for counselling seemed, if we listened long enough, to be attending a different college; each student enrolled in a given course was in a different course, and the instructor was an angel, a dud, and a devil*."

How might we teach?

There is a risk that teaching might begin to look like an impossible task once we begin to recognise that we have to deal with students at different levels of intellectual development and with different behavioural characteristics, which affect both the way they learn and their attitude to learning. If this is the way it seems to us, spare a thought for the school teacher, who faces the same variety but does not have the privilege of setting a minimum standard for entrance. The situation is as it is; the better we recognise and understand it, the better chance we have of teaching effectively. In this section we therefore discuss whether there are general principles of teaching that are worth applying regardless of the variation between our students. However, before we do this, we consider the importance of motivation first to the learning process, and then (briefly) to assessment, and finally to the overall teaching approaches that educationalists have identified.

a) Motivation

Motivation has been classified as being 'intrinsic', 'extrinsic', or 'achievement driven'. According to Newstead and Hoskins,[82] "*intrinsically motivated students enjoy a challenge, want to master the subject, are curious and want to learn; whilst extrinsically motivated students are concerned with the grades they get, external rewards and whether they will gain approval from others*." An achievement driven student "*is concerned primarily with achieving a successful outcome at the end of his or her studies*" and "*both extrinsically and intrinsically motivated students can be high or low in achievement motivation*." Much of the theory behind motivational teaching is based on "need for achievement" (often abbreviated to "N'ach"), a concept that was developed in particular by McClelland and co-workers.[83] One might expect that highly motivated students would achieve higher grades, but there is little evidence to support this expectation. One reason may be that the methods of determining whether students are highly motivated seem to provide little correlation with the way that they will actually carry out their studies at degree level.[84-86] In this connection it may be relevant that Entwistle et al.[80] discovered a much stronger correlation when students retrospectively assessed their levels of motivation at the end of their degree course. Newstead and Hoskins[82] suggest that another reason why motivation and achievement do not correlate well is that "*intrinsic motivation, while valued by lecturers, is not necessarily rewarded in the assessments they give students*". In spite of the lack of evidence that well motivated students perform well, there are good reasons for encouraging motivation. One is that studies of schoolchildren indicate that lower achieving pupils who appear poorly motivated receive less attention from their teachers.[87] It seems likely that the same is true at university level and consequently the atmosphere created by highly motivated students enthuses other students (and the tutor), and this is likely to affect whole cohorts or groups of students as much as the performance of individuals. Another powerful reason for wishing to improve motivation is the general agreement that the absence of motivation is a real bar to achievement. In this connection Newstead and Hoskins report that well motivated students often felt there was no relationship between the amount of work they put into writing an essay and the mark obtained for it. This quickly led to a lack of incentive for students to put in more effort than what they had discovered would readily achieve a second class mark. Although this may not seem especially important in a chemistry course where essay writing is typically a small component, their conclusion is relevant to all teaching; it is that providing appropriate feedback (as well as a mark) is essential if students are to remain motivated.

The ideal provision of 'full and appropriate feedback' is an under-rated aspect of much of our teaching, but it can require substantial amounts of time that are generally unavailable. It follows that imaginative new ideas are needed which allow effective feedback to be provided at low cost. One example of such an idea is the procedure described by Denton for laboratory work,[88] and the same strategy might be adapted for use with any kind of written work. Denton's approach provides what we might call 'pseudo-individual' feedback, in that it generates an individual report by selecting the most appropriate comments from a bank of common statements. Genuinely individual feedback may be preferable in principle, but, in our view, this is only going to be worthwhile if the students have engaged fully in the two-way process by submitting work that has been carried out thoughtfully. In similar vein, small group tutorials (or appropriately organized workshops) can provide an opportunity to respond to the needs of different students, and to ensure that they participate in active learning; large group teaching is likely to involve little active involvement of students, and it is tempting for the tutor to simply provide the 'right answer' (a format which is likely to be appreciated by students, even if it encourages a surface or rote learning approach to their studies).

A feature of effective feedback is that it will improve the student's confidence (and hence their motivation), not only in the quality of work being produced but also in their ability to progress. It follows that we need to take care not to undermine student confidence. Two particular practices are worth actively striving for in the way we teach, since both can encourage confidence and motivation. One is that we should seek to respond positively to student answers to questions or contributions to discussion by picking out those aspects which can be treated as partially correct; it is easy to fall to the temptation of pronouncing them wrong when they may be merely incomplete or muddled. All students (not just the one who has made a contribution) are likely to be motivated to continue to make contributions by a tutor saying 'that is a good (or interesting or sensible) thing to say' but then leading the discussion towards a better response. To do this demands that one listens carefully to a student response in order to find something positive to say about it. There is an important benefit of doing this; it often helps us to discover why the student has a particular misconception, and therefore helps us to start to correct it by showing how it is inconsistent with known observations.

The other common undermining action has some similarities; it involves telling students that what they have learned previously about some topic is 'completely wrong' and instructing them to forget it and start again. Such a suggestion is not only extremely demotivating, but it cannot be reconciled with the constructivist model of learning, which would make it impossible to ignore the mental images already stored in the mind. In any case, it is most unlikely to be true that previously taught simplifications are totally wrong. A much more effective approach is to understand the (sometimes limited) virtues of the simple model, to demonstrate that it does not adequately explain all observations, and thus to introduce a more complete model which the students can construct into their existing framework.

It would be useful to comment not only on what **not** to do, but also on what methods of teaching might improve motivation. Unfortunately, we have to agree with Newstead and Hoskins[82] (in their interesting article on 'Encouraging Student Motivation') that *"there is no quick fix"*. They go on to conclude that *"students' approaches to study and their motives are determined by a number of aspects of the higher education system… Trying to change students' motives by changing the way one module or group of modules is taught is unlikely to be effective, since all the other aspects will be working against this change."* Much as we recognise the value of a concerted departmental commitment to teaching approaches based on good educational theory, we think this conclusion is unduly pessimistic; we have all come across particular teachers who seem to have the knack of stimulating and enthusing their students, and we can observe their methods and attempt to adopt those of their practices which fit our own style. More specifically, it is generally observed that almost any novel approach is a sufficient stimulus to increase the motivation to learn, which is a reason for always trying to pick up new ideas for teaching even if one does not really see any pedagogic advantages.

We are particularly aware of the common view that one of the most important aspects of chemistry is laboratory work, and this is frequently used to argue for more of this kind of work. We argue that the unthinking adoption of any such general principle is dangerous, and we draw attention to Byers'[89] comment on laboratory work:

"Unfortunately, all too often students see laboratory work as a form of assessment rather than as an opportunity to learn, and because they are required to do something different each time they go into a laboratory they never feel comfortable with what they are doing and tend to believe that they are poor practical workers. Thus, far from being motivated by practical work, many students actively dislike it and are at best motivated only by the marks they might obtain from doing it."

The final point we wish to make about motivation is that possibly the most influential motivating factor under our control is the assessment system we adopt. Here we can only deal very briefly with this complex and far-reaching topic.

b) Assessment

A readable and practical summary of many aspects of assessment is provided in Ramsden's book,[90] whilst one of the most comprehensive books on the topic was written by Rowntree;[91] Race[92] has provided valuable tips on assessment procedures. Pirsig[93] makes a convincing case in favour of a subjective element in the assessment process, which makes refreshing reading for scientists who regard 'objectivity' as the Holy Grail of assessment.

The motivation provided by an assessment system is the wish to obtain a high mark. Of course this would be a particular benefit if our assessment procedures prompted the students to develop the skills that we value. Unfortunately, questions that assess many of the skills we look for at HE level (e.g. essay-type questions, or advanced problem-solving that do not have one 'correct answer') are hard to mark with precision.[94] The point was developed by Beard & Hartley,[67] who suggest that tutors would like to assume that the students' primary aim is to learn about their subject, with the tutor providing the right environment and encouragement to do so – whereas the primary aim of students is 'to get a good degree'.

Certainly one of the objectives of assessment is to generate marks towards degree classification (or progression) and so meet the expectations of employers who wish to see some 'objective' measure of the ability of prospective employees. However, we should remember that this is only one of several objectives; Hodson[29] suggests four in all, which he then discusses in more detail. They are

- A summative function. It should provide some description of a student's levels of attainment in all aspects of the course at the end of the course.

- A formative function. It should enable teachers to diagnose strengths and weaknesses, learning gains and misconceptions, in order to plan more effectively for the further learning of each student.
- An evaluative function. It should provide teachers with information about the effectiveness of the curriculum experiences provided, in order to assist curriculum decision making and planning.
- An educative function. It should enhance and promote learning by engaging students in interesting, challenging and significant experiences aimed at developing further insights and understanding.

We note that this list does not explicitly include the function of providing feedback to students concerning their understanding of a topic (see cognitive theory, below).

It is probably impossible to devise an assessment procedure that meets all these functions, but it is clear from this list that the assessment process must be two way; students must tackle a topic with genuine commitment, and come to tutorials/workshops wishing to contribute to the learning process. When that happens, time will be well spent in providing detailed feedback to each student. But if written work is done superficially, and students are more interested in marks than in understanding, then the assessment process can become a huge burden for the tutors and has limited educational benefit.

It is our view that these issues need to be addressed in some detail by discussing more rigorously what we really wish and intend to achieve through assessment, and what (changes in) procedures and strategies are most likely to help us to achieve our objectives. Of course, an individual or institution concluding that the sole purpose is to generate a mark that can be defended (in a court of law if necessary) is likely to come to a decision that differs from one with broader aims.

c) Teaching theories

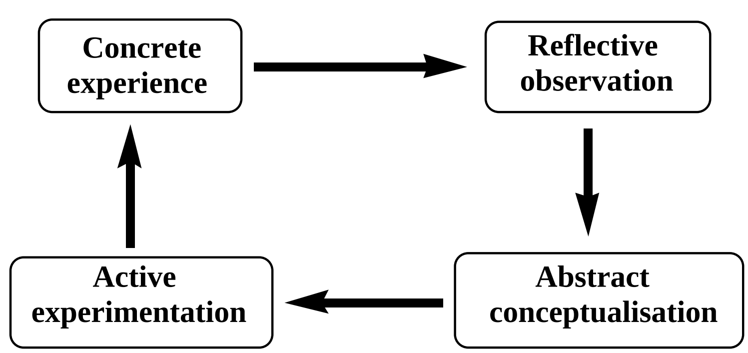
We now turn to more general theories of teaching. We have had some difficulty in classifying these in a consistent way because of the overlap between the concepts, but we (tentatively) identify four main approaches, guided largely by the ideas of Hartley & Beard,[67] and by Hilgard & Bower.[95]

i) Stimulus-response approach

The 'stimulus-response theory' of teaching can be summarised as: activity, practice, reinforcement (with rewards).[95] Thus students are actively involved in the learning process (e.g. in a lecture, being asked questions, or being required to tackle short problems); they are then expected to practice their developing skills, and this is driven by feedback in the form of rewards (marks, or peer acclaim) or punishments which reinforce the learning process. Importantly, the underpinning principle is that it is the response (reward or punishment) that drives the learning process, and is in some ways one of the oldest educational concepts. However, embedded within it are active learning (see below) and assessment (see above), both of which are now regarded as central to modern educational methods.

ii) Active learning approach

The driving force for this approach is that you learn something by doing it. Hodson[2] suggests that this approach was pre-eminent in the 1960s, and became known as 'discovery learning'. He summarises discovery learning as follows: *"Because scientists achieve their goals largely through observation and experiment, it was assumed the learning of science is also best achieved in this way. In other words, it was assumed that the best way of learning science is through activities based on a model of scientific inquiry."* He goes on to expose the limitations of this naïve idea. Today, the most extreme claims of discovery learning are no longer widely accepted, but 'learning by doing' or 'experiential learning' is still such a strongly stated principle of most modern teaching that it is sometimes forgotten that this was not always an accepted approach. Beaty[96] points out that experience does not always lead to learning and theories of experiential learning have focussed on the importance of reflection. The most well known model is based on Kolb's learning cycle, which has the following four stages:



Although this cycle is widely recognised by theorists as a valuable model for learning, for a variety of

reasons we do not always encourage our students either to **reflect** or to **do** as much as perhaps we should. The importance of reflection has been touched on both by Boothroyd[53] and Johnstone,[97] and we believe that the relentless pressure of assessment in HE is providing less and less opportunity for this important aspect of learning.[98] Interesting accounts on how to create opportunities for active participation in lectures and in small group teaching have been written by Horgan,[99] by Griffiths,[100] and by Hutchinson.[101] The term 'active learning' is often used in association with 'student centred learning' to describe the shift away from the traditional lecture towards an approach to teaching which puts more responsibility on the student to participate actively in the learning process.[102] We do not see how it can be literally possible for learning of any kind to take place without active participation of the student! But we accept the useful distinction between the kind of teaching which encourages 'deep' or 'meaningful' learning rather than 'surface' or 'rote' learning. Garratt[102] has pointed out that providing opportunities for student-centred learning "*involves shifting the tutor's role from that of 'authority' towards that of 'facilitator' or 'manager of learning'. The loss of control which this implies can be difficult to adapt to.*" However, there is a strong case[53] for adopting teaching methods which put more responsibility on students to gain knowledge and so leave the teacher more time to concentrate on higher order activities like understanding and application. Perhaps the best known classification of levels of learning (or competence) is that described by Bloom,[103, 104] who defined six 'cognitive levels' which, starting at the lowest level, are:
Knowledge, Comprehension, Application, Analysis, Synthesis, Evaluation.

iii) Cognitive theory
When a lecturer focuses on finding ways to help the learner to construct a working understanding of a topic, the approach is driven by cognitive theory. Because the starting point must be 'what does the learner already know?'[33] the teacher must clearly identify this, and (ideally) develop a well-organised course in which the key concepts are logically linked. The use of 'pre-labs'[105, 106] and 'pre-lects'[107, 108] help to establish the starting point for an educational process, whilst feedback to the teacher is essential to demonstrate that students have understood (rather than rote learned) a topic, and 'post-labs'[109] are an example of this. It may seem that this approach is little different from the two previous approaches, and of course they can overlap as much as the lecturer chooses. But the cognitive approach is based on the teacher helping the student to understand a topic, whereas the preceding approaches assume that the understanding is driven by student participation and/or practice of the subject matter.

iv) Behavioural theory
This theory makes three assumptions about students: that they naturally want to learn, that they have the ability to understand the topic being taught, and that the right social environment and motivation can be created in order to allow them to learn successfully. There are two crucial elements to the theory. The first is that learning is not an isolated activity; it takes place from or with other people, often through the use of group activities. The second is that the topic has to be personally relevant in order that individuals accept their responsibilities, and are motivated to learn. It is generally accepted that the success of an approach based on this theory depends on (almost) everyone contributing to the learning experience and so the learning environment must be non-threatening if it is be effective.

In summary, the four approaches are driven by the following general principles:

- Feedback motivates learning.
- Active participation aids understanding.
- Teaching must focus on how students construct their understanding and this involves having time to reflect and fit the new knowledge into an existing framework.
- The learning environment is crucial.

If we were to strip these down to just four words, they would be: feedback, participation, constructivism and environment. But are the above classifications helpful to practising teachers? We believe they represent very important aspects of high quality teaching. But this does not mean that all teaching activities will give equal emphasis to all four aspects. We suggest it is useful to identify which one (or maybe two) of these principles is dominating each specific aspect of teaching, and ensuring that this is properly addressed. For lectures, it might be constructivism (and participation?); for tutorials, environment and feedback; for labs and workshops, participation. Whilst professional experience and intuition probably dominate the content and delivery of most course material, many of us would benefit from applying some of the more formal classifications to our teaching methods, in order to help us identify ways in which we could improve them.

Summary

This review summarises what we judge to be the most useful theories about how students learn, and how their learning is affected by their intellectual development and their individual characteristics. We are aware that this is only indirectly related to the needs of academics whose concern is how to improve their own teaching. We made no attempt to deal with these needs more directly because we do not believe that it is possible to draw up a set of simple guidelines that guarantee good teaching. Rather, we believe that good teaching results from individuals interpreting educational theory for themselves. We suggest that the kind of teaching to which we aspire is that which provides students with a foundation on which they can build, and which inspires them to learn for themselves and to use their knowledge creatively and imaginatively in pursuit of their chosen goal. To achieve this, teachers need to take the maximum advantage of their own experiences and strengths, and be aware of their own weaknesses. It would be inconsistent in a review that promotes the constructivist approach to learning to attempt to describe the right way to teach; to do so would be to treat academics as though they were in Perry's position 1 in which they believe that 'there are right answers to everything' (including the best way to teach). Furthermore we have both observed some of the problems which arise when individuals use a style of teaching which does not come naturally because they feel that they should attempt to follow the advice or the example of a successful or popular or charismatic teacher. Moreover, wonderful teaching materials (e.g. hand-outs or Web graphics) are not sufficient to create a good learning experience, and "… *some brilliantly articulated and beautifully illustrated course texts … can leave the student with a feeling of inadequacy in the face of such perfection, or (even worse) uncritical contentment with having been 'enlightened'.*"[110]

Rather than try to provide a simplistic set of guidelines, we have tried to show the importance of adapting one's personal strengths (and weaknesses) to the fundamental needs of our students, and this means getting as far as possible into their minds (and not just trying to stand in their shoes). Educational theory can help us to do this, and yet we fear that educational theory is too often overlooked in planning a teaching strategy. Indeed, we go further than this and argue that departments and individuals pay too little attention to educational theory when they draw up the intended learning outcomes of courses and when they devise the assessments used to determine how far these intended learning outcomes have been achieved. We fear that much of the laudable concern with the identification of course outcomes fails to take sufficient account of qualities which are desirable but are difficult to quantify. All too often the roles of a course or a teacher are defined in terms of tightly specified course objectives, learning outcomes, and principles of good teaching practice. The great advantage of this is that it is comparatively easy to assess whether these tightly defined criteria have been met. We have been led to this position by the pressures imposed by quality assessment, by the need for accountability, and (increasingly) by the fear of litigation. Unfortunately these assessable criteria are not necessarily those which best meet the educational needs of our students. Furthermore, they can all too easily act as a straightjacket to the teacher who has the gift of inspiring students to learn for themselves a subject they have come to love. We are aware that this is a dangerous line to take, since there is only a fine line between extolling creative teaching and concluding that inspirational teaching is stifled by over-preparation – an argument that we have heard used to excuse a casual approach to preparation, which we cannot condone. We accept that it is possible to 'over-prepare' for teaching when the time is spent on the minutiae of meeting learning outcomes by spoon-feeding students with 'right answers to everything'. Teachers who know their subject well may not need much preparation time in order to ensure that they 'cover the ground', but they need to remember the quotation that *"the verb to cover and the noun information are responsible for much mischief"*.[102] This should remind us that the better we know our subject, the more time we need to spend in preparation in order to get into the minds of our students.

Unfortunately, addressing the fundamental needs of the students is not necessarily a passport to success as a teacher (at least not if judged by conventional criteria). Students are likely to give the most positive feedback about teachers who provide them with what they think they want (taking a short term view of obtaining a degree), and this is not always the same as what they need (taking a long term view of education for life). Furthermore, we see little evidence that the Teaching Quality Assessment exercises have been able to grapple with the difficult problem of recognising those learning experiences which have the most beneficial long-term effect on the students, nor do we see any evidence that innovative teachers will be rewarded by their institutions for publishing their ideas, principles and teaching strategies.

Our personal view is that the most useful principles that we can glean from educational theory are the following.

a) We gain understanding through constructing more and more advanced models from the information available to us. This constructivist approach cannot be short-circuited by the brilliance of the lecturer – it is an integral part of the learning process, and teaching methods must take this into account. The starting point for constructivist teaching is: 'what do the students already know/understand?'

b) Students learn through widely differing approaches. All go through a series of developmental stages, identified originally by Piaget in children, and subsequently by Perry in HE (hopefully at a higher level and a more rapidly evolving rate). These stages start from an expectation by the learner that there are right and wrong answers to everything, and develop to the level where the learner can appreciate that problems need to be tackled in a variety of ways, and that they sometimes lack a unique answer. The way that students study depends on their motivation, ability, and character, and tutors need to take account of this in their teaching methods. However, there is remarkably poor correlation between any of these characteristics at university intake, and final degree performance. Students can be trained to change their style of study if an appropriate environment and encouragement are provided.

c) Learning is driven by feedback, participation, constructivism, and environment. In practice, teachers place a different emphasis on each of these at different times, with each teaching activity often dominated by one or two of them. It can be useful to bear these driving forces in mind when designing course material, or when trying to identify the strengths or weaknesses of a programme.

d) Over-assessment can reduce the motivation for students to understand topics, and encourage them to rote-learn material.

e) The individual characters of students influence the way they learn, so it helps them when we provide opportunities for them to influence the learning process (e.g. through small group tutorials, although there are other ways).

f) Students need time to reflect on their work; we therefore need to find ways of motivating them to do so and to provide them with the necessary time by avoiding curriculum overload.

In this review, we did not set out to provide a comprehensive survey of how educational theory has influenced the teaching of chemistry. Nor (fortunately!) did we expect to discern a definitive set of guidelines for high quality teaching. But we did hope to identify some of the accepted wisdom, and we particularly recommend the following sources of information and guidance as excellent starting points:

- Beard & Hartley's excellent and readable book on educational theory in HE.[67]
- Ramsden's good, practical advice on all aspects of teaching in HE.[71]
- Johnstone's paper on key principles that underpin (chemical) education, including his 'Ten Educational Commandments' (*cf.* points a–f above).[97]
- Bodner's summary[32] and Taber's review[39] of constructivism.
- The wealth of useful advice in the handbook edited by Fry, Ketteridge and Marshall,[111] and developed further by Ketteridge, Marshall and Fry.[112]
- A bibliography of educational material compiled by Reid for the Physical Sciences Centre of the LTSN.[113]

Chemistry students need a knowledge base, an understanding of the key principles, some special subject-specific skills (e.g. lab skills), an ability to solve problems and think critically, and a range of transferable skills. The Dearing Report[5] and the Benchmarking document[6, 7] are in close agreement about what they expect of a (chemistry) graduate, and most academics would agree with those expectations (but with differing emphasis on the various components). However, whilst most HEIs claim to teach transferable skills, it is these that are identified as most lacking by employees and employers. We would suggest that more opportunities for active learning of these skills, and greater incentives for those doing well, are the major ways in which this could be addressed.

Teaching at any level is a difficult task. At HE level, students come to us with a range of abilities, characteristics, motivation, and aims. They have differing expectations of us as teachers, and construct their understanding in their own individual ways. It sometimes seems that most of them would prefer us to simply teach them 'the truth about chemistry', and to tell them how to do well at exams. When they behave like this, we need to remember that they, like us, have many legitimate calls on their time and therefore look for short cuts to essential work. Given time to reflect, few would deny that general (or transferable) skills as well as knowledge are essential for their future careers. For many of them (especially those who have already made up their minds not to pursue a career in chemistry), these skills are likely to be perceived as more important than subject knowledge. We have a responsibility to show them that these key skills can be developed through the learning of chemistry, and we believe that we need some understanding of educational theory to help us to meet these responsibilities. Ultimately, our aim must surely be to motivate our students in a way that encourages them to learn about chemistry, to learn how to do chemistry, and to learn how to think like scientists.

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