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Chemical education: theory and practice

Review

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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]

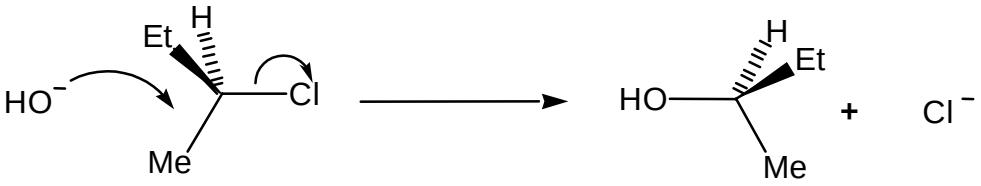
"…each of us receives some signal from the environment through one of our sensory organs, and that signal is then interpreted according to some 'schema' or pattern that we have previously built, and then incorporated in modified form as new knowledge." (Herron)[31]

*"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

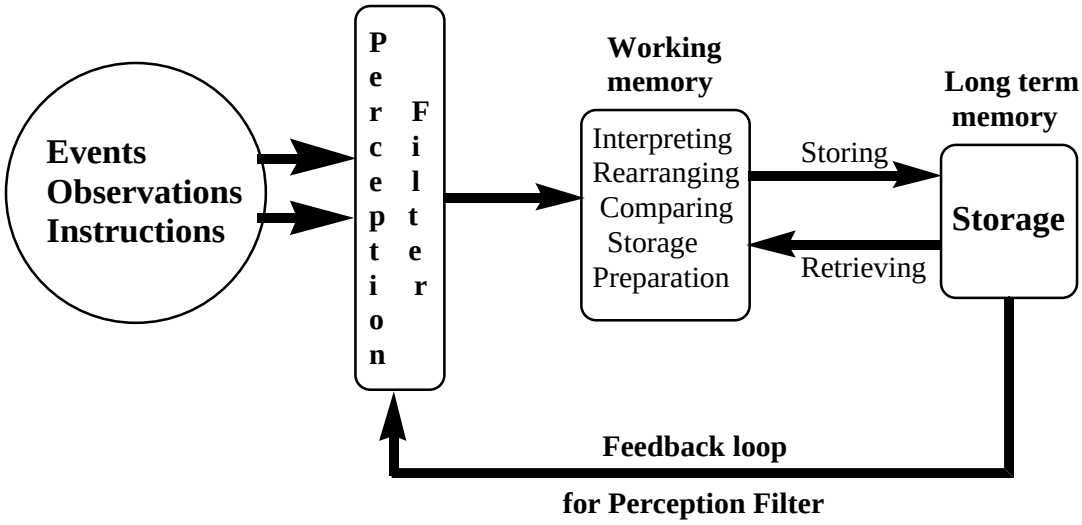
so that they got a 'real understanding' for the processes (still a model, anyway!), and only then being introduced to the more frequently used models as simplifications of this. We should remember that many students would neither want nor need to go beyond the incomplete models provided by Stages 2 or 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]

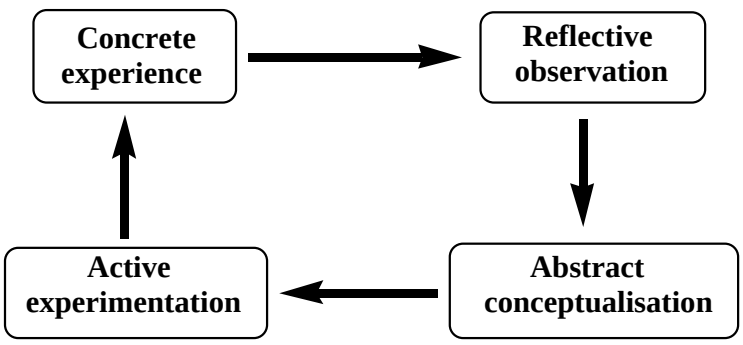
i) Stimulus-response approach

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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Proceedings

Laboratory work provides only one of many skills needed by the experimental scientist.•

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Introduction

I graduated as a Biochemist in 1959. Of course a lot has changed since then. One change that ought to have persuaded us to re-evaluate the way we teach science in general and chemistry in particular is the enormously increased need for a scientifically literate population – a population capable of understanding, discussing, and influencing those major issues of the day that are based on science. It seems to me to be absolutely right for a meeting about chemistry and education to think about the issues and questions that are important for our society. Of course many of these have only tenuous connections with science; issues to do with war, with terrorism, with refugees and such like. But lots of today's serious moral and economic issues are a consequence of advances in science; genetic engineering, cloning, and climate change come to mind immediately. General issues like these generate more specific questions; some relate to risk (is it safe to immunise children with MMR vaccine? to eat meat from cows with BSE? to continue to burn fossil fuels without constraint?); some relate to control measures (is a vaccination policy an effective method of controlling an outbreak of foot and mouth disease?); some relate to the availability of resources (what sort of resources is it reasonable to commit to a particular genetically deformed baby? to providing impotent men with Viagra? to keeping unhealthy pensioners like me alive?). Each of us will have our own examples of questions desperately needing an answer based on an understanding of the scientific process and of the nature of evidence. But in addition to having a scientific basis, any answer has to be applied in the context of a complex society with its own history, culture and conventions. It really is extremely important for everyone, including those not trained in science, to understand and debate these issues.

To meet this need for a scientifically literate population we need to review our responsibilities as teachers. When I graduated I thought that academics were supposed to educate an elite to **extend** our knowledge of the World. Now I know it is more than that. About ten years ago, at a meeting to debate 'should higher education address business needs?' I said that University graduates should "*know their subject, and be able to **ex**plain, **ex**ploit and **ex**tend their knowledge*". My choice of 'explain' was deliberate; it emphasises our role as evangelists of public understanding of science. Today I would amplify what I then called "*the triple X Experience*" by saying that our role as teachers is to educate scientifically literate evangelists. A truly scientifically literate evangelist will recognise that 'Laboratory work provides only one of many skills needed by the experimental scientist'.

Of course I agree that laboratory work is a defining feature of a natural science, though not of course exclusive to chemistry. That doesn't mean that I think we should therefore describe chemistry as a laboratory-based subject, since I don't believe this does justice to what we actually do. I suggest that a better description of science (including chemistry, of course) is:
'a discipline which is based on the logical and imaginative interpretation of purposeful observation'.

Making Purposeful Observations

I chose 'purposeful observations' carefully to distinguish them from what I call 'chance observations'. I call something a chance observation when it is commonplace enough to be made, but not noticed, by other scientists. Pasteur and Fleming famously made chance observations; they were such commonplace observations that they were made by dozens of others (including to my certain knowledge the uncle of my first lab technician). What distinguished Pasteur and Fleming was that they converted their chance observation into a purposeful one by imaginative and logical interpretation.

Of course there are other examples in history, but they get rarer because the kind of chance observations that can be turned into purposeful ones (even by the most creative thinkers) have mostly been made. New observations that contribute to our understanding of the world are hard to make. Nowadays purposeful observations (even if they are unexpected) are made under very special and unusual conditions. This gives us a clue about the way scientists work. I suggest that our work involves the following six steps:

i) decide what observations we would like to make,
ii) imagine the conditions in which such an observation might be made,
iii) plan how best to create these conditions,
iv) create the conditions to the best of our ability (usually in a laboratory),
v) observe carefully to see whether our imagination and our planning were effective,

• This is an edited version of the Galen Lecture delivered at the 4th Variety in Irish Chemistry Teaching on 27.3.2002.

vi) interpret the observations with a mix of logic and imagination.

We often use the phrase 'doing and experiment' to describe steps (iv) and (v), and may overlook the fact that these two steps are a part of a larger (seamless) process. Most chemists (but not all scientists) 'do their experiments' in a laboratory. That is why laboratory work is central to chemistry. But we need to put it into context by also emphasising the creative thought that goes into planning the conditions in which a purposeful observation might be made and into the imaginative interpretation of observations so that they expand our knowledge of the world. Doing laboratory work is necessary for the advancement of scientific knowledge and understanding, but it is not sufficient. Laboratory work is also difficult and expensive, so it is wasteful to do experiments before we have thought as carefully as possible about how to make the observations we want. In other words, real scientists put off their experiment until they have thought it through; minimising the need for laboratory work is, I suggest, a sensible principle for scientists. Of course, it turns out that laboratory work is so slow, and the need for purposeful observations is so great, that experimental scientists spend a great deal of time in the laboratory.

Here is my list of the things we think about before doing an experiment, which subsumes steps (i), (ii), (iii), and (vi).

- What question(s) are we trying to answer (what idea(s) are we testing?)
- What observations (data) would provide an answer to the question(s) (would be consistent with or refute the hypothesis)?
- How can we best create conditions for making the desired observation(s) (collect the data)?
- How will we process and evaluate the observations (data)? Note that this includes taking account of error and uncertainty in any observation (measurement) made.
- What will we do next – why did we bother?

I stress that **all** these are things we think about **before** doing the experiment (and therefore often things that we do outside the laboratory, with a consequence that our students may not associate them with laboratory work). The 'what next' point is an important one. The scientist is like a chess player; always thinking several moves ahead, even though the result of the next step is uncertain; in other words we predict but not rely on the result of the previous step. Without this element of the planning process, an experiment is not real science but becomes mere 'stamp collecting'. I don't think this is an insult to philatelists since they know they are not engaged in a pursuit designed to lead to the discovery of the secrets of the world through "*the systematic study of nature"* (a phrase borrowed from the Canadian novelist Robertson Davies).

I contend that in our teaching we over-emphasise laboratory work at the expense of planning and interpretation, and consequently we devise laboratory exercises that encourage a 'stamp collecting' approach to science. The laboratory exercises we give to our students actually discourage them from thinking scientifically about the process of science in which I include

- the nature of evidence and proof,
- the design of investigations,
- the limitations to knowledge imposed by the available procedures for obtaining it.

Let me illustrate what I mean with an example from a lab manual I picked up recently when I happened to visit a friend. This is a good and well thought out exercise; it's worth including in any undergraduate chemistry course. One thing that really impressed me was the clear and honest list of objectives heading the instructions in the lab manual. Here they are.

- To gain experience of monitoring reaction progress using spectrophotometry;
- To learn about pseudo-first-order kinetics;
- To compare manual and automated methods for data acquisition and analysis;
- To determine an activation energy.

Clearly someone has thought carefully about what the student is supposed to learn. All of them are important. The lab manual also contained a recipe with details of

- the concentrations of reagents to use,
- the temperatures at which to measure the rate of reaction,
- the method to use to measure this rate,
- the way to process the data to obtain the required activation energy.

Because this exercise involves following a well-tried recipe designed to give a result that is already known, it cannot really be described as 'doing an experiment'; the students have no need to think at all about the scientific process. I have always maintained that these recipe-following exercises are a necessary part of the process of learning about experimental work, but they are not sufficient.[1] The exercise I have just described is (like most other lab exercises) an excellent example of how to 'collect a new stamp'.

What such exercises do not do is provide any opportunity for the student to learn how to make a purposeful observation. It does not help the student to learn

- why anyone wants to know the value of an activation energy (when you have measured it, what are you going to do with it? what makes this measurement part of science rather than just stamp collecting?);
- how to formulate an hypothesis ;
- how to design an experiment to test that hypothesis.

Understanding how to test an hypothesis is a particularly important part of scientific literacy.

In our book *A Question of Chemistry*[2] we provide one of my favourite examples of the muddled attitudes to the criteria of proof. It concerns the safety of Rabbit Calicivirus as a way

to control the rabbit plague in Australia. The extract below was taken from an article in the New Scientist.

"…to justify releasing the virus in the first place, the Australian government ***should have first obtained clear proof that it infects just one species****, the rabbit. Researchers claim to have done just that. They exposed 31 species of native and domestic animals to the virus. They measured the amount of antibodies and virus in the blood and organs of these animals, and looked for signs of sickness. Those tests showed that the virus did not replicate or cause disease in any test animal.* ***'Our testing of rabbit calicivirus is the most comprehensive study that we know of into the host range of an animal virus',*** *says Murray."*

In the book we ask students to consider whether the criteria specified for releasing the virus can be achieved, and whether Murray's statement is consistent with the supposed need for clear proof.

This passage illustrates that the nature of proof is often poorly presented by scientists, and so it is unsurprising that the public misunderstand the limits to scientific enquiry. Leading from this, I propose two key principles that scientific evangelists need to impress on the public.

- It is theoretically and philosophically impossible to prove the absence of something (an effect, a substance, etc).
- The ability to detect something positive depends on the precision of the method in use (the level of random error) as much as it does on its sensitivity.

I have plenty of anecdotal evidence to support the suggestion that neither point is intuitively obvious. I even have real evidence from a small study we carried out into what we called 'the language of error'.[3] We found that most of a sample of first year chemistry undergraduates believed that 'a qualitative method can be used to **prove** that a constituent is absent from a substance'. Few of them recognised that that the limits of detection of the analytical method merely set the upper limit of the amount of substance that can be detected. This, and other misconceptions we uncovered, hinder their ability to design convincing investigations. I will illustrate this point with some previously unpublished data.

Investigating Factors Affecting the Time of a Pendulum Swing

In this study, first year science students used a computer simulation called pendulumLAB (created by Jane Tomlinson). This allows the investigation of factors affecting the length of time a pendulum takes to swing. The user can choose the length of the pendulum, the mass of the bob, and the angle to which the bob is raised, and is asked to investigate the effect each of these has on the time of the swing. Before discussing the results from our volunteer students, I will suggest how the investigation might be carried out by someone who adopts the principle of minimising laboratory work.

Such a person might draw up a strategy along the following lines.

- First establish which of the variables has a detectable effect.
- Set up the pendulum and make replicate measurements with all variables constant to determine the precision of measurement.
- Change one of the variables (a lot) and make a similar set of replicate measurements.
- Now change another (a lot) and repeat.
- Now change the third variable (a lot), and repeat.
- If necessary investigate further with more measurements

Table 1. Data to show the effect of angle, mass and length on the time of a pendulum swing

Data to show the effect of	Angle	Mass	Length
Length	150	150	20
Mass	20	100	100
Angle	80	20	20
Readings	27.7	24.5	24.8	9.2
	27.7	24.8	24.9	9.0
	27.9	24.8	24.8	9.3
	27.1	24.5	24.5	9.3
	27.3	25.1	24.3	8.9
Mean	27.54	24.94	24.66	9.14
S.D.	0.29	0.24	0.22	0.16

- Big changes in each variable would be achieved with angles of 80 and 20, mass of 20 and 100 g and length of 150 and 20 cm (fairly arbitrary values chosen by common sense and for convenience).

Table 1 shows data obtained by using these principles. These illustrate that, on the basis of these 20 measurements, we can easily draw the conclusions that

- There is a clear effect of angle
- Any effect of mass is too small to be shown with this set of data
- There is a huge effect of length.

Of course it is now quite easy to add more data. One might do this to try to establish the shape of the relationship between angle and time or length and time, or to test whether an effect of mass could be detected by collecting more data at the same values of angle and length, or (preferably) with a larger range of values for the mass of the bob.

The data in Table 2 illustrates how difficult it can be to detect an effect if one makes the wrong choice of variables. Columns 4 and 5 show this with different angles, where the two angles chosen are close together, and columns 1-3 show the similar problem that arises if the length of the pendulum is so short that the time of the swing is difficult to measure with precision. This illustrates that careful thought makes the difference between a successful investigation from which unambiguous conclusions can be drawn and the collection of data that may be misleading.

Table 2. Data to show the effect of angle when the length is short and the angle variation is small

Length	20	20	20	100	100
Mass	100	100	100	100	100
Angle	40	20	80	20	40
Readings	9.3	9.2	10.1	20.2	20.4
	9.2	9.0	10.1	20.0	20.5
	9.2	9.3	9.9	20.3	20.7
	9.4	9.3	10.0	20.4	20.5
	8.9	8.9	9.9	20.1	20.6
Mean	9.20	9.14	10.0	20.2	20.5
S.D.	0.19	0.16	0.1	0.16	0.11

Investigations by Students

Turning to the data collected by students, an encouraging fact is that all of them carried out 'fair tests' in the sense

that they studied the effect of one variable at a time, whilst keeping the other two constant. However, only four of them had a clear policy of making replicate measurements. One of these took five replicate readings, and did so at each of the fifteen chosen of conditions; another took twelve sets of triplicate readings which made up about a third of the total; the other two took a single set of replicates (one of eight and one of ten). That left ten students who had essentially no information about the reproducibility of their data. I say 'essentially no information' because the data collected by nine of them did actually include one or two sets of duplicate or triplicate readings, but these look as though they were obtained by chance rather than by design since the separate values were obtained whilst systematically changing different variables, and it is doubtful whether the students noticed.

As part of the study, we had asked the students to predict the effect of each variable before starting their investigation, since this might help them to focus on what they were testing. Their predictions are summarised in Table 3. Note that any prediction that there will be no effect can **in principle** be refuted by demonstrating an effect. In contrast, any prediction that there will be an effect cannot **in principle** be refuted. The latter prediction can be confirmed by observing an effect. In contrast, failure to observe an effect may simply mean that the method in use is not sufficiently sensitive or precise to detect one. There is little to say about the effect of length. Only two students made the incorrect prediction that it would have no effect, and both changed their minds as a result of their investigation.

As we have seen, the effect of the angle is much smaller. Even so, one might have expected that the eight students who correctly predicted an effect would confirm their expectations; in fact only half did so. One (who measured the time of swing at 17 angles from 2-60 degrees, and at a length of 10 cm) concluded that the effect of angle is 'variable, increasing and decreasing the time taken'. Since this student made no replicate measurements, it is not possible to say whether he gave any consideration to the effect of error on the data. The other three students actually changed their minds and concluded that angle has **no** effect. None of them based this on what could be described as an exhaustive study; one took 9 readings, another took 10 and the third took 24 (including 10 replicates with all parameters constant). I believe that these students failed to detect an effect simply because they made a poor choice of conditions – all of them used a pendulum length of only 10 cm, which makes the effect hard to detect, and one of them made the task almost impossible by restricting the range of angles to 30-60 degrees. It seems that they changed their minds without good justification, and in a direction that is **in principle** dangerous, and they showed a fine disregard for the principle that the absence of an effect cannot be proved.

The other six students made a prediction that, as Table 1 shows, can be refuted quite easily. However, only three of them changed their minds. A fourth thought that there is probably an effect, but was not confident of the significance of this in the absence of statistical analysis. This conclusion was based on a two-minute study involving only 19 measurements (including a single replicate). Had the student made (say) 6 replicates at each of three different angles (18 readings instead of 19), the data would have convincingly demonstrated an effect without the need for statistical analysis. That leaves two students of these six who confirmed to their satisfaction that there is no effect of angle. Perhaps these two were so committed to their prediction that they failed to test it adequately; this is a practice that we may deplore, but which we are all too aware happens.

Student conclusions about the effect of the Mass of the bob lead us to similar conclusions. The one student, who predicted there would be no effect, confirmed this prediction on the basis of single measurements made at each of four masses ranging only from 10 g to 40 g. All thirteen students who made the incorrect prediction that Mass would have an effect, changed their mind. One actually concluded that the time of swing decreases as Mass increases – the opposite of the prediction. This was a remarkable conclusion to draw from 8 measurements each made at a

Table 3 Student predictions for the effect of variables on the time of swing for a pendulum

VARIABLE	LENGTH	ANGLE	MASS
NO. PREDICTING:			
NO EFFECT	2	6	1
EFFECT	12	8	13

different Mass and giving a range of values for the time of 14.1 – 14.8 s, since to test the reproducibility of the method, this student earlier made 10 replicate measurements, the results of which varied from 6.1 to 6.9 s. The remaining eleven all concluded that Mass has no effect, which is in accordance with the current state of physical knowledge. This would be a satisfying result, if the students had reached their conclusion after an exhaustive investigation. Unfortunately this was not the case, as is obvious from the simple observation that few of them had sufficient results to estimate the level of uncertainty (or error) in their data. Table 4 shows the number of results obtained by each of the students that give information about the effect of Mass. Only two of them could possibly be described as having carried out an exhaustive investigation. Far from being comforting that they drew a correct conclusion, this result can only mean that these students (like many of the others) have a very poor appreciation of the nature of evidence and, in particular, of the philosophical impossibility of proving the absence of an effect. Furthermore, the students generally seem to have little concept of the most efficient way of testing whether an effect can be observed, or of the problems created by experimental error.

Table 4 Data related to the effect of Mass on the time taken by one swing

Number of OBSERVATIONS	No. of students	RANGE of masses	No. of students	LENGTH used	No. of students
> 25	2	90	8	≥ 100	5
8 - 13	9	50 -70	2	20 - 50	4
3 or 4	3	30 - 40	4	10	5

I do not wish to give the impression that I think the students have demonstrated incompetence, since the outcome was very similar when we asked academic scientists to carry out the investigation.[4] One may excuse both groups on the grounds that they were put in a position that discouraged thought, and strongly encouraged them to do an experiment while they still had things to think about. But I also think that we do too little to provide opportunities for students to develop the kind of thinking which might help them both to design better investigations themselves, and also to recognise flaws in the design of other investigations. A scientifically literate evangelist needs this latter skill as much as any other.

Possible Remedies for Shortcomings in Laboratory Investigations

This conveniently brings us back to the point that most laboratory exercises we give to our students actually discourage them from thinking scientifically about investigations. The example mentioned earlier illustrates this. The exercise requires the students to determine the activation energy of a reaction. The following list summarises key aspects of experimental work missing from this exercise.

- The exercise gives no clue about the reasons why a chemist might need to measure the activation energy of a reaction; what makes the measurement a purposeful observation and not a piece of stamp collecting?
- The students have no opportunity to think about how to choose the conditions under which to make measurements in order to ensure that suitable data are collected.
- The only guidance given on the treatment of experimental error is an instruction to estimate the largest and smallest values that could fit the data, thus students are not encouraged to consider why literature values of activation energies (and other measured values) rarely offer a range of values.
- The determination of a value for the activation energy does not provide an opportunity to test an hypothesis.

How can we remedy these shortcomings? I have three suggestions

- Incorporate additional tasks into the lab manual;
- Introduce (or enhance) pre-lab and post-lab work;
- Integrate computer simulations with a lab exercise.

When we published our study of student understanding of the language of error,[3] we suggested that teaching in this area needs to be radically rethought and restructured. We proposed that lab manuals for work involving quantitative measurements should include instructions such as 'give evidence of the random error in your data', 'indicate precautions you took to avoid systematic error', 'comment on the comparability of data collected by different individuals (and whether differences are significant)', and so on. Of course these tasks would be difficult for students since most of them are unfamiliar with the relevant concepts. One way to overcome this problem would be to provide all students with a 'Glossary of terms used to deal with error and uncertainty in experimental data'. This would be more or less equivalent to a Data Book that many departments provide for students to use at all times including in examinations. Such a Glossary would provide much more than mere definitions of words and phrases, and in many cases would provide a substantial paragraph explaining a term and showing how chemists (scientists) have adopted a specific technical meaning for a word that may have a rather different emphasis in common usage; the use of 'accuracy' and 'precision' provides an obvious example. A well-written Glossary of this sort could be a valuable asset for most graduate chemists, and the careful design of questions incorporated into lab scripts would encourage them to become familiar with it and perhaps to continue to use it for many years after graduation.

This general concept of including small additional tasks into the lab manual for incorporation into the lab write up could, with advantage, be extended to non-quantitative lab work such as synthesis. For example, students could be asked to comment on the purity of their product (what impurities are

most likely to be present, what is the maximum level at which they might be present?), or to comment on yield (was their yield of product satisfactory for a method intended to provide enough material for further testing, or for commercial exploitation on a kilogram scale, or on a multi-tonne scale). I believe that imaginative questions would benefit from the existence of a well-written Concepts book, which would have similar benefits to those perceived for the Glossary.

I believe that this sort of additional task would help to focus students' attention on factors which experimentalists need to take into account when interpreting their observations, and in this way could bring a formal exercise one step closer to the making of a purposeful observation. But there is a limit to what we can do in this way. For example, these tasks cannot bring students any closer to realising that one of the key things to think about before resorting to laboratory work is 'what will we do next?' One way to do this is by studying a relevant published paper in a pre-lab session. This was an idea I developed with Brian Mattinson at York.[1, 5] I think we have not previously seen this as a piece of pre-lab work deliberately linked to a specific piece of lab work to enhance understanding of purposeful observations. One of the papers we used happened to deal with the measurement of rate constants (not a million miles away from my exemplar lab exercise of determining an activation energy). The authors of this paper wished to determine the rate constant for the reaction between OH and NO in order to better understand possible effects on the stratosphere of an increase in supersonic air travel (a matter of concern at the time the paper was written). Imagine using this paper as a pre-lab exercise before students tackle the determination of an activation energy. It would surely be easy to convince them that the determination of rate constants and activation energies is not a piece of stamp collecting but is a purposeful observation. They could appreciate that the investigation, which forms the subject of the paper, is too complex to be carried out in an undergraduate laboratory, but that it is worth practising their laboratory skills on a simpler system. Thus this paper exercise, if carried out in conjunction with a lab exercise, should help students to appreciate the place of laboratory work in the broader canvas of experimental science.

The third approach that I advocate is the use of computer simulations. There are many ways of using these to complement and enhance laboratory work. Here I want to limit my discussion to two of these. One is illustrated by enzymeLAB, the first simulation I planned and used. Its purpose was to provide students with an opportunity to plan their own investigation of an enzyme.[6] It would be easy to design an analogous simulation dealing with the determination of an activation energy. This could simply involve using the Arrhenius equation and assigning a value for A and E_a to an imaginary reaction (A + B → P). With such a simulation, students could decide for themselves on the conditions under which to measure k_{obs} in order to determine the activation energy. The exercise could be carried out before or after the laboratory exercise to illustrate the point that careful thought about the design of an investigation can usefully lead to the minimisation of time and effort spent in the laboratory. However, my experience shows the importance of both providing careful preparation, and also sensitive feedback, if students are to get maximum benefit from the use of simulations like this.

A limitation of this way of using simulations is that it can emphasise the stamp collecting approach to science, since it does nothing to show the importance of **purposeful observations**. To deal with this aspect we need a simulation that requires some form of hypothesis testing, such as pendulumLAB. What makes this particularly suitable is that one of the three variables to study has a very clear effect on the measurement, one has an effect that can be tricky to detect, and the third has no effect. Nevertheless, pendulumLAB is not suitable for inclusion in an undergraduate chemistry course, because the topic does not link with the knowledge base of the subject. One possibility would be to adopt the principle of a simulation that we called unknownLAB in which the subject of study is not given, but the user is asked to investigate the effects of three variables. The abstract quality has the questionable virtue that it does not obviously relate to a different discipline. I would make two changes to our original version of unknownLAB before recommending it for trial. First, I would increase the flexibility by having different versions of the basic relationship between dependent and independent variables, and these could be randomly assigned to different students. Secondly, I would provide background notes indicating that previous observations on the system provided an indication of the likely findings. I would do this partly because it is more realistic (Galileo would have known quite a lot about pendulums before attempting to carry out a definitive investigation), and partly because it would encourage users to think carefully about how to test an hypothesis.

The other real system, which I would consider simulating, is the solubility of alcohols in water (or may be the partition of alcohols between oil and water). I like this system because most students (and a surprising number of academics) are unfamiliar with it; they usually think that the solubility of straight chain alcohols (say C_3 to C_6) in water increases as the temperature is raised, whereas, of course, the reverse is true. This trivial observation can be converted into a purposeful one by using it to calculate ΔH and ΔS for the transfer of a CH_2 group from water to oil. Now that many chemists are aspiring molecular biologists, this is an important measurement, since it is the basis of an understanding of hydrophobic interactions. It also happens to fit my criteria for a useful simulation, in that ΔH is very small and therefore difficult to determine, whereas ΔS is large and negative. Because the system is unfamiliar to most students of chemistry, it seems a suitable one to ask them to investigate; they would do so with some expectations of what result they would find, and many of them would be surprised by their findings. This would provide useful opportunities for discussion of the process of science that go far beyond the narrower field of hydrophobic interactions.

Concluding remarks

In this paper I have argued that our practical courses typically over-emphasise laboratory work at the expense of the planning of investigations and the interpretation of data. A consequence is that our students are not taught the true meaning of scientific literacy and frequently have only a poor appreciation of some basic principles of the nature of evidence and proof that contribute to the scientific method (whatever this is). I provide some evidence from previously unpublished results, which supports my concerns and conclude by making some suggestions for teaching strategies that I believe could lead to improvements.

Readers convinced of my first point may be encouraged to introduce changes to their teaching strategies, some of which may even be based on the suggestions I have outlined. Bodner et al.[7] argue that when we introduce changes it is because we have "*perceived weaknesses in the current situation*", that we have "*formulated an hypothesis that a particular change will lead to a particular improvement*" and that we will "*wish to test or evaluate our hypothesis*". Alas, those who have introduced imaginative changes in their teaching know how difficult it is to evaluate their success; a likely outcome is that the students neither enjoy nor appear to learn from the experience. Neither finding should persuade us that the idea should be dropped, but both should be matters for some concern.

I do not believe that student 'enjoyment' of a learning experience is a good measure of its potential value, even though it often appears high up on course evaluation forms. Adverse feedback from students need not be taken at its face value, and we should heed the advice of Bodner et al.[7] that our evaluation should "*look behind the façade of answers to the question 'do the students like it?' toward deeper questions such as 'what do students learn that they were not learning before?'*". However, I do believe that negative student feedback provides evidence that the teacher's intentions have not been fulfilled; it may not be the idea that is at fault so much as the detail of its execution. It may simply be that the students are unaware of what we are trying to achieve – that we are so convinced of the need for change that we have forgotten that the students have both different starting points and different objectives. We need to try to get into their minds and change our presentation accordingly, remembering the tenet of Constructivism that new knowledge needs to be constructed in the mind of the learner, and built into the individual's existing framework of knowledge.

The question of whether the students learn has been addressed somewhat enigmatically by Bodner in his comment that "*we can teach – and teach well – without having the students learn*".[8] When challenged about this, he explained that he was pointing out that the criteria used by unbiased onlookers to assess teaching quality do not usually include that of student learning. This point was brought home to me when the use of scientific papers as a teaching aid, which I outlined above, was picked out by the TQA exercise as of particular merit even though I have no evidence at all that the students learned anything from the experience. My conclusion from the negative nature of the student feedback from the scientific paper exercises makes a good general conclusion to this paper. It is that the piecemeal introduction of innovations made by individual enthusiasts is always likely to produce disappointing results because the impact is too small in relation to the course as a whole. If we are serious about the need for increased scientific literacy amongst our students, then this must be reflected in a change in attitude of the whole department; it is no use any one member thinking that it is an issue that can be left to one or two enthusiasts.

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A problem based learning approach to analytical and applied chemistry

Paper

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Abstract
Problem based learning (PBL) and extended problem solving activities are increasingly being used in many disciplines. The effectiveness of these approaches suggests that there is a need for such resources for use in chemistry education. A problem-based approach can produce students who are well-motivated, independent learners, effective problem solvers and who have a broad range of interpersonal and professional skills. This paper describes the development of problem solving case studies as an approach to PBL in chemistry. The case studies present a 'real' problem or scenario which students solve by application of prior knowledge, acquisition of new knowledge and by developing a problem solving strategy. The case study described here is based on an investigation of a (fictitious) suspicious death. The activities involved cover areas of analytical chemistry and forensic science. The case study is designed to be flexible, allowing it to be tailored to a particular course. There is no unique correct solution to the case study, and students must use judgement in order to come to an acceptable conclusion. The nature of the activities involved ensures that, in order to complete the case study, students must use a variety of scientific and transferable skills.

Introduction

Employers have long urged the Higher Education sector to produce graduates with a range of transferable skills that would make them more immediately effective in the world of work. Several reports[1-3] have identified, in particular, communication skills, team working, numeracy, use of IT and learning to learn as highly desirable qualities in a graduate. This view has also been highlighted as being particularly important in analytical chemistry.[4] The comprehensive survey[5] by the LGC in 1993 reported that employers' overwhelming concern was with graduates' ability to apply appropriate theory and laboratory techniques to practical problems. Good interpersonal skills were identified as being crucial to allow analysts to work effectively in a team and to evaluate problems jointly with clients. Most, if not all of these qualities would be highly regarded by any employer of science graduates, but unfortunately, those employers questioned in the survey felt that very few graduates possessed them.

The United Kingdom Analytical Partnership (UKAP) recently carried out a survey of ten university chemistry courses that contained a significant amount of analytical science. The report[6] identified several skills gaps in the undergraduate provision. These related to the acquisition of analytical problem solving skills, working with others, method selection and handling data.

To produce graduates, who can operate in the workplace professionally, we need to go much further than just ensuring that they have a sound knowledge of chemistry, adequate practical abilities and rudimentary problem solving skills. We must produce graduates who have the scientific skills of critical thinking with an analytical approach, are able to interpret data and information, can tackle unfamiliar and/or open-ended problems and thus, are able to apply their chemical knowledge. In addition, the modern graduate must master a range of 'professional' or transferable skills including communication, team working, time management, information management, independent learning and the use of information technology.

Many disciplines have used problem based learning (PBL) to achieve this balance of knowledge, qualities and skills.[7] In this, problems act as the context and the driving force for learning[8] and the acquisition of new knowledge is done within these contexts. PBL differs from problem solving in that here the problems are encountered before all the relevant knowledge has been acquired and, therefore, necessitates both the acquisition of knowledge and the application of problem-solving skills. In some cases, defining the problem itself forms part of the PBL approach. In problem solving, the knowledge acquisition has usually already taken place and the problems serve as a means to explore or enhance that knowledge.

Boud and Felleti[8] claim that a PBL approach produces more motivated students with a deeper subject understanding, encourages independent and collaborative learning, develops higher order cognitive skills as well as a range of transferable skills including problem solving, group working, critical analysis and communication. Problems that are used for PBL should address curriculum objectives, be real and engaging, be 'fuzzy' and place the group in a professional role, i.e. as scientists. Students should be required to develop a problem solving strategy, to acquire new knowledge

and to make judgements, approximations and deal with omitted/excess information.[9]

A report[10] from the USA has recommended that PBL methods should be used to teach analytical science. Wenzel has commented[11] on the lack of PBL resources available and indicated the types of resources that would be needed by analytical chemistry educators. These include real-world problem based case studies, collaborative learning problems and laboratory PBL activities.

The development of effective problems is not a trivial task. However, from our experience, the effort is well rewarded when problems are based upon real contexts and scenarios. From these, students are able to see the relevance of their discipline and so approach such activities with enthusiasm and interest. Chemistry is a discipline that provides a rich source of contexts in, for example, forensic science, pharmaceuticals, environmental science, and industrial chemistry. Of the traditional 'branches' of chemistry, analytical chemistry is, by its very nature, the most applied. The scope for producing 'real' problems for students to solve is great.

Our Approach

Our approach is to use the principles of PBL to develop problem-solving case studies. These provide extended problems that are related to applications or real contexts with incomplete or excessive data, require independent learning, evaluation of data and information and do not lead to a single 'correct' answer.

Case studies have a long history in many subject areas and their value within chemistry has long been recognised.[12-20] From our perspective, a case study should

- involve the learning of chemistry by requiring students to learn independently
- be active in style
- involve a work-related context
- involve the development of transferable skills
- encourage reflective learning
- have clear learning objectives

We have chosen contexts within environmental, industrial, forensic and pharmaceutical chemistry to provide 'real' scenarios for the application of analytical chemistry. Six case studies have been developed to cover different aspects of analytical chemistry and each has been designed to encourage the development of different transferable skills. Although they require students to apply new knowledge in order to solve the problem, our case studies are perhaps more structured than the traditional PBL approach, where a problem may be presented as a single statement or short paragraph. Ours extend over several sessions and provide students with different activities at each stage of the problem. They are all flexible enough to be used in a variety of different teaching situations. One of them is described here.

The Pale Horse

Overview

This case study sets analytical chemistry within the context of a forensic investigation of a (fictitious) suspicious death. The case study begins by setting the scene as follows: On the 10th February 2001, Brigitte Barberi found her mother, Maria Barberi, dead in her home. After an initial search of the crime scene by the scene of crimes officer (SOCO), the body was taken to the morgue. Door-to-door enquiries revealed evidence of a boundary dispute between the Barberis and their neighbours and that Maria's mother had just died leaving her a farm. Her husband, Martin, did not return from fishing until later that evening. A few days later both Brigitte and Martin Barberi were admitted to hospital with suspected heavy metal poisoning.

Each group of students is told that they are investigating the suspicious death of Maria Barberi. The tutor may also discuss the intended outcomes of the case study in terms of subject specific knowledge as well as scientific and transferable skills.

The case study operates by gradually supplying information in the form of reports from various official agencies, including the police, a pathologist and a forensic laboratory. The students request analysis on the evidence collected in order to determine the cause of death (poisoning), the poison's identity and mode of administration. Results from the analysis of evidence collected are available in the form of over 120 result cards covering the three possible types of evidence that could be collected:

- Physical evidence (e.g. fingerprints on a wine bottle (see Figure 1), phone records, contents of medicine cabinet),
- Chemical evidence (e.g. graphite furnace AAS for heavy metals in food (Figure 2), FT-IR of a white powder, identity of suspected blood stain, comparison of different wines etc.),
- Toxicological evidence (e.g. XRF for heavy metals in hair samples from Maria (Figure 3), head space GC for alcohol in blood, ICP-MS for heavy metals in blood from Martin and ICP-OES for heavy metals in the blood of Brigitte.)

The requests for analysis on the evidence collected are made at three stages (see Figure 4). From the results supplied, the students should be able to determine that the poison used was thallium, which was administered in some gooseberry wine given to the Barberis by their neighbours. This was also used to make a chicken chasseur dinner eaten by Maria, Martin and Brigitte Barberi. If suitable toxicological requests are made, the students should also be able to determine that Maria died of chronic thallium poisoning over about a period of a month and other members of the family experienced acute thallium poisoning. The motives and opportunity of the various suspects are determined from the anecdotal evidence.

Figure 1. Example of physical evidence result cards

B2	**FP**	**Fingerprint request**		
Evidence No.:		10-02-0071-B2 Chateau de la Graville 1999 (white) bottle (part full)		
Prints		Powder and fixed print then photographed.		
Prints				
		Print from Mr Barberi.		Print from unknown person
Notes		The unidentified set is probably male due to their size.		

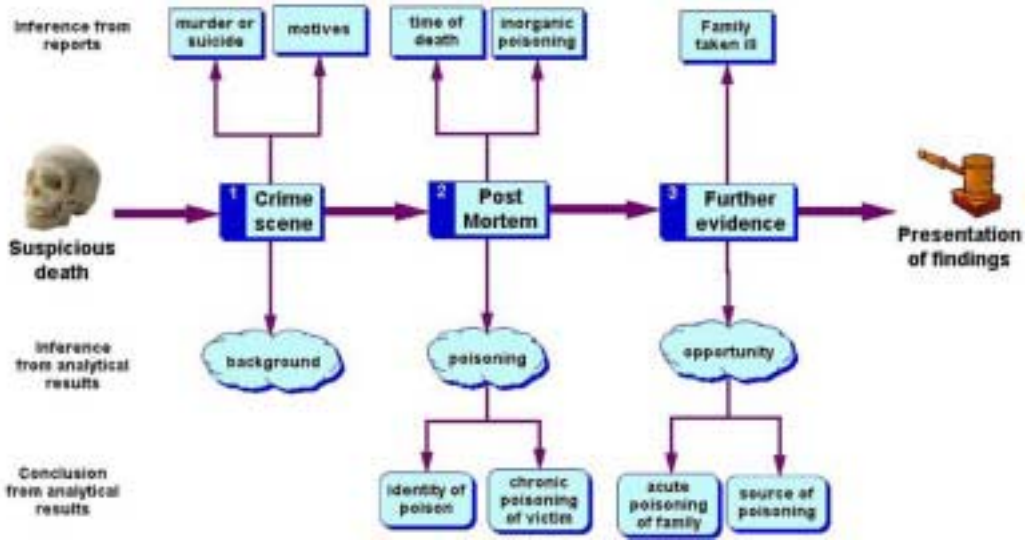
Figure 2. Example of chemical evidence result cards

H5	**GF**	**Graphite Furnace AAS of food**				
Evidence No.:		10-02-0071-H5 Part eaten plate of food.				
Test		Microwave acid digestion with 5 ml of nitric acid to 1g of sample then Graphite Furnace AAS				
Results			**Blank** **w/v**	**H5a potato w/w**	**H5b White sauce w/w**	**H5c Chicken w/w**
		Tl	< 5 ppb	0.6 ppm	26.7 ppm	3.4 ppm
Notes		Remnants of the chicken chasseur meal. GFAAS is a very sensitive quantitative method of analysis. 1000 times more sensitive than Flame AAS.				

Figure 3. Example of toxicological evidence result cards

C2	**XRF**	**XRF of Maria's hair**			
Evidence No.:		10-02-0071-C2: Hair sample from the body.			
Test		XRF is a non-destructive method requiring short sample preparation			
Result		Element	ppm (w/w)	Element	ppm (w/w)
		As Cd Cu Hg	1.2 1.1 27.5 1.8	Mn Pb Se Tl	1.2 19.4 1.0 1.2
Notes		It is difficult to distinguish between environmental deposition of metals and that from ingested sources.			

Figure 4. Overview of the case



The nature of the activities involved ensures that, in order to complete the case study, students must develop a variety of scientific (Table 1) and transferable skills (Table 2). The minimum contact time is 4-5 hours and the students are required to spend approximately 12 hours in associated independent study depending upon their experience and background. It is recommended that they work in randomised groups of 3-6 so that each group has a range of abilities and skills. One member of the group takes on the role of Chief Investigating Officer and is responsible for the overseeing of information gathering, compilation of reports, note-taking, reporting etc. So far, the case study has been successfully trialled in analytical chemistry, forensic science and professional skills modules at five universities in the UK. The Pale Horse case study has also been written so that it may be implemented flexibly over a different number of sessions of varying lengths as described in the tutors guide. For brevity, we will describe only the format where it was run over five one-hour sessions.

Introducing the case

Depending upon the background of the students and the module, a preliminary introduction may be required in order to introduce the role of forensic science. A series of overheads are provided, entitled the 'The Place of Forensic Science', that cover the various stages of an investigation from the scene of crime to forensic laboratory and, finally, to court.

Scene of Crime

In the first one-hour session, the students are given reports from the first attending officer and the investigating officer detailing the initial actions of the police officers, the police surgeon and the SOCO. After the students have discussed the information, two crime scene photos are provided that show the room before and after the body was removed. Once these have been studied, the students are given transcripts of the door-to-door interviews with the neighbours. The students are prompted to consider the types of physical evidence that they would ideally want to collect from the scene of crime.

Table 1. Summary of scientific skills developed

SCIENTIFIC SKILLS	
Disciplines covered	Analytical chemistry, toxicology, forensic science, forensic pathology.
Scientific knowledge	Matching analytical techniques to the application. Organic analysis (e.g. identification of white powder, alcohol in blood.), inorganic analysis (determination of heavy metals by AAS) and forensic science (fingerprinting, DNA, and serology)
Handling information	Manipulation and evaluation of information and data to make realistic decisions on the evidence available.
Problem Solving	Tackling unfamiliar problems, using judgement, evaluating information, formulating hypotheses, analytical and critical thinking.

Table 2. Summary of transferable skills developed

TRANSFERABLE SKILLS	
Communication skills	Oral presentations and report writing.
Improving learning and performance	Using feedback to reflect upon group and individual performance. Drawing the experience within the group.
Information technology	Word processing reports and preparing material for presentations.
Planning and organisation	Managing an investigation, individual judgement, taking responsibility for decision making and time management.
Working with others	Brainstorming, discussion, division of tasks and reporting back to the group.

When the students have completed these considerations, they are given the SOCO report that details the evidence that was actually collected. The students make a limited number of requests for analysis of this physical evidence, which may include, for example, fingerprints on a wineglass, contents of a wine bottle, telephone records, identification of a white powder on a table, etc. From these results, the students should be able to determine the background of the case, and develop some theories concerning how and why Maria Barberi died.

Post-mortem

At the start of the second one hour session, the students are given the results of their requests in the form of result cards and are given a little time to look over these before being given the next police report. This states that Maria Barberi was pronounced dead at the scene by the police surgeon before being taken to the morgue for the post-mortem. Photographs and some background notes on the persons involved are then distributed. This normally promotes some interesting discussion among the students about the appearances of the witnesses, their background and possible motives.

Finally, the students are given the pathologist's post-mortem report. From the information contained in this report, they should realise that they ought to be looking for heavy metal poisoning, although some students do not always realise this at this stage. The students are then invited to request chemical analysis of the urine, blood, kidney, liver and hair samples taken at the post mortem. They are provided with a list of samples that have been collected and must identify the analyte and preferred analytical method. The requests are submitted to the tutor before the next session. In our trials, students spent about 3-6 hours in independent study in order to decide which pieces of evidence to analyse and select the most appropriate analytical technique for their chosen analyte.

Additional Evidence

At the start of the third one-hour session, the students are given the results of their requests for analysis of the samples taken from the dead body. They should be able to determine whether a poison was used and, if so, what it was and when it was administered.

The students are then given the final set of reports from the investigating officer. From these they are able to discover that additional evidence was collected from the scene of crime a few days later after both Martin and Brigitte were admitted to hospital with suspected acute heavy metal poisoning. The evidence collected included the chicken chasseur that Martin had been eating before he was taken ill, wine from the kitchen and blood and hair samples from the family. The students are able to make further requests for chemical analysis on this or on any previous piece of evidence. The requests are submitted before the next session. Again, the students had to spend time in independent study in order to select the appropriate analytical technique for their chosen analyte, especially if they did not receive useful results from their previous requests.

At the start of the fourth one-hour session, the results are returned to the students. At this stage the students should have sufficient evidence to start preparing a short presentation and a written report that consider the following.

- The state of Maria Barberi's mind at the time of death.
- Whether the death of Maria Barberi was suicide, murder, accidental death or death by misadventure.
- The cause of death.
- The identification of any poison used and how it was administered
- Whether the illnesses of Martin and Brigitte Barberi could be linked to each other and/or to the death of Maria Barberi.
- How might the poison have been obtained
- Whether further evidence is required and if a warrant should be obtained to search for this evidence
- The suspect(s) motive and opportunity.
- Whether the person the students suspect could be charged on the evidence they have gathered so far.

When students have made their presentations and/or handed in their reports in the final one-hour session, the tutor leads a review or debriefing session. This is an

essential feature within the PBL framework. It is especially important when the case is relatively complex, and is an opportunity to discuss the details of the case from a number of different perspectives. The role of analytical science in solving the case can be emphasised and students can be encouraged to reflect on their own development in terms of knowledge and skills. It can also provide an opportunity to allow those students who have missed some of the essential points to re-group if necessary.

Requesting Analysis

Students make requests to the forensic laboratory on 'Evidence Request Forms' and must specify clearly the analytical technique required. By making sensible requests, students should be able to identify the cause of death, the poison used and the method of administration. The number of requests permitted is limited to encourage critical thinking and avoid an excessive number of requests being made. This forces the students into asking sensible questions and thinking carefully about choosing the correct analytical technique. It is made clear to the students that a rule of the case is that no useful results will be obtained if they do not specify a suitable method of analysis for the desired analyte. It is for the tutor to decide how rigorously this rule is enforced and this may depend on the desired learning objectives.

Submitted requests are useful in charting the changes in the student's attitude towards the case. They also indicate issues on which the tutor may wish to comment. For example, it may be helpful to remind students that while certain techniques are often considered to be extremely 'powerful' (e.g. NMR spectroscopy and ICP-MS), they are not necessarily always the most appropriate methods for all analytical problems.

When making requests, students are encouraged to consider (amongst other things) the following:

- What samples they want analysed
- What they are looking for (specifically) from each analysis
- What analytical techniques are most appropriate
- What detection limits can be achieved by each method
- What would constitute a 'normal' concentrations
- Whether the sample is likely to be a mixture of components
- If qualitative analysis is required
- If quantitative data is required
- What the meaning of a negative result might be

Results of analyses are given back to the students on prepared 'Result Cards', examples of which are shown in Figures 1-3. There are over 120 such cards contained in the case study, including blank 'Results Cards' that are provided for any other responses that have not already been covered. This also allows the tutor to assist the students however he/she chooses, perhaps in indicating why the results from a particular chosen method of analysis would not be useful and thus, suggest the selection of another method. The degree of assistance given would depend on the background of the students and the aims of the module.

The students are expected to make clear how the analytical data they have received has informed their judgement and whether any of their conclusions are based upon the anecdotal evidence. Criminal law requires proof beyond reasonable doubt and as there should still be a considerable amount of doubt at the end of the case, students should be able to make recommendations for further investigations that should be carried out by the police and the forensic science service.

Assessment

The Pale Horse case study offers a number of opportunities for assessment depending on the learning outcomes set by the tutor; a couple of assessment schemes that have been employed successfully are shown in Table 3.

Table 3. Example assessment schemes

Case summary	20%
Summary of results	20%
Oral presentation	30%
Contribution to group	30%
Total	100%
Or	
Written report	60%
Oral presentation	40%
Total	100%

The 'case summary' provided with the case study is a series of questions about the case that could be completed and submitted instead of a full report or used to focus the students' ideas before they produce oral presentations. The one-page results summary should outline the evidence that has been gathered by the group from their requests for analysis. This is useful for the tutor who can easily see on what evidence the assumptions have been based without referring back to the evidence request forms. The written report may be either group or individual and could be as short as one page. The duration and focus of the oral presentation can be varied at the discretion of the tutor and could be peer assessed. Marks for the contribution to the group could be awarded by the students for each team member to give an indication of each individual student's contribution.

Observations

As the Pale Horse case study has been piloted at five institutions and with over 250 students with varying backgrounds taking analytical chemistry, forensic science and professional skills modules, we have been able to gather a significant amount of feedback. As

shown in Table 4, the student feedback has been very positive.

Table 4. Student feedback for the Pale Horse (n = 45)

1=disagree and 5=strongly agree.	Response (1-5)
By taking part in this case study, I feel I have developed the following skills:	
• Solving unfamiliar problems	3.8
• Working with others	3.9
• Thinking logically / critically	4.2
• Communicating my ideas	4.0
• Link between theory and practice	3.8
I have enjoyed taking part in this activity?	4.3

The case study presents a novel way of working for the majority of students and staff involved. It is noteworthy, that the enthusiasm and engagement of students swiftly increases throughout the activity as they become more involved in the decision-making processes and engaged with the story. The following comments were given by students when asked "*What did you like best about the case study?*"

"*Something different and interesting."*
"The way you were given evidence to draw conclusions from and not all at once."
"Getting new evidence and forming them into new ideas."
"It was different to normal modules and was very interesting."
"Putting all the evidence together to solve problems."
"Being able to choose your own evidence rather than simply being handed it."
"The challenge of solving an un-solvable problem."
"The idea of there being no correct answer but based upon the evidence alone."
"Preparing the talk and drawing conclusions."
"How each time there was something new introduced. We still had to work at it. It was never all given away and thus kept us curious."

Initially, many of the students seemed surprised that they were not given meaningful results when they had not specified a suitable method of analysis, assuming that the tutor would offer some flexibility. This was especially true amongst the students whose main subject area was outside of analytical chemistry. However, students quickly improved in this regard and carried out independent learning (where necessary) about analytical techniques in order to specify the appropriate analytical methods. The formal assessment of each component of the case study helped in overcoming the students' initial reluctance to work outside the classroom sessions.

Additional feedback from the students showed that the case study had not only provided them with the opportunity to develop their knowledge of analytical and forensic chemistry, but had increased their transferable skills capabilities. Examples of their responses to the request: "*Describe one thing that you have learnt about yourself from this activity*" are given below: -

"I lack the ability to defend my arguments and know when to compromise."
"It is good to discuss things with other people, to get lots of different ideas about things."
"Improved my time management skills."
"I can put forward my case well but must also listen to others."
"I can work well within a group."
"Group participation is essential to ensure all group members benefit as well as myself."
"I didn't think I would be so nervous about speaking."
"I can think logically sometimes. My time management is better than I thought."
"I didn't have as much of a problem public speaking as others do."

We believe that using this case study achieves the initial objective of using problem solving to develop subject knowledge in analytical chemistry and forensic science as well as a range of other scientific and transferable skills. Students are required to use a range of skills in order to achieve a satisfactory outcome, and the applied, 'real' context engenders enthusiasm and motivation towards solving problems.

Other case studies

To date, we have developed six problem-solving case studies (Table 5), each with a focus on analytical science within environmental, forensic, industrial and pharmaceutical chemical contexts. These have been piloted with students representing all three stages of

Table 5. Titles and contexts of case studies developed

Level 1/2	**Context**
New Drugs for Old	Drug discovery and organic spectroscopic analysis
The Titan Project	Industrial inorganic chemistry and statistics
Level 2/3	
A Dip in the Dribble	Investigation of the environmental impact of a fire
Launch-a-Lab	Setting up industrial contract analysis
Tales of the Riverbank	Investigation of pollution of a river
The Pale Horse	Investigation of a suspicious death.

undergraduate study, and in some cases, at post-graduate level. In our experience, these types of activities work equally well with students at all levels of their development and within many chemistry-related disciplines. The level of support given by the tutor may be greater in the early stages of academic development or with students who are tackling a case study that is outside of their area of specialism. Further accounts of the remaining five case studies will appear in future publications. A copy of 'The Pale Horse' can be obtained from Dr. Tina Overton, Department of Chemistry, University of Hull, Hull, HU6 7RX or e-mail T.L.Overton@Hull.ac.uk

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Paper

Turkish chemistry undergraduate students' misunderstandings of Gibbs free energy

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Abstract

This study is aimed at identifying and classifying Turkish chemistry undergraduates' misunderstandings of Gibbs free energy. In order to fulfill this aim, open-ended diagnostic questions and semi-structured interviews were used, conducted both before and after the topic was taught. Diagnostic questions were answered as pre-tests and post-tests by about forty-five students who took physical chemistry courses from two different chemistry education departments in two different universities in Turkey. Twenty-two 'pre-interviews' and five 'post-interviews' were carried out just after the administration of the tests. Seven different misunderstandings were identified. Although some of the findings of this study confirm the previous research findings, it goes beyond them by identifying new misunderstandings and suggests places where these misunderstandings may originate. The results have implications for tertiary level teaching, suggesting that a substantial review of teaching strategies is needed.

Introduction

Ever since the classical studies of Piaget, there has been an interest in the conceptions of physical science held by young children.[1] Even a casual observer of the field of science education over the last two decades knows that this has been a period of unprecedented exposure of the ideas held by children, adolescents, and adults, about a wide range of scientific phenomena.[2, 3] Research in this domain has attempted to answer questions such as, which misunderstandings occur, what are their origins, how extensive are they and, of course, what can be done about them?[4] It is quite understandable why students' ideas concerning chemical phenomena have become a research focus. Many students both at secondary level and at university struggle to learn chemistry and many do not succeed.[5] Research now shows that many students do not understand fundamental concepts correctly[2] and also many of the scientifically incorrect ideas held by the students go unchanged from the early years of the schooling to university, even up to adulthood.[4] By not fully and appropriately understanding fundamental concepts, many students have trouble understanding the more advanced concepts that build on them.[6]

The constructivist theory of learning suggests that knowledge is constructed through a process of interaction between an outside stimulus and conceptions that already exist in the learner's head. During this process, some of the existing conceptions are modified and some new ones created. Different views on the nature of students' understanding, and differences in the methodologies employed to discover students' conceptions led researchers to make different claims. One of the widely discussed theories in science learning is that 'children's conceptions are genuinely 'theory-like', that is having a coherent internal structure and being used consistently in different contexts'.[7] This notion is articulated by McCloskey,[8] and supported by Engel Clough and Driver.[9] McCloskey argues that people develop well-articulated naive theories on the basis of their everyday experiences. Furthermore, he argues that these naive theories are consistent across individuals. On the other hand, diSessa[10] raises issues to do with the nature of misunderstandings. He questions the views of McCloskey and argues that people hold loosely connected, fragmented ideas, some of which reinforce each other but none of which have the rigour of theory. In diSessa's words, students have 'knowledge in pieces'. diSessa goes on to suggest that there is evidence in his work of students making up explanations spontaneously at the point which they are faced with a question, drawing where they can on core intuitions based on everyday experience. (He calls these notions phenomenological primitives, or p-prims.) Later work, for example that of Southerland et al.,[11] provides additional support for the notion that students make up explanations spontaneously. Therefore, students' explanations may not be misunderstandings; rather they are spontaneous constructions that might be scientifically correct or incorrect. Southerland et al.[11] also argue that, if it is accepted that some students reason from core intuition, a great deal of variability in students' explanations is to be expected.

Many high school and university students experience difficulties with fundamental thermodynamics ideas in chemistry.[12] Despite the importance of thermodynamics as one of the foundations of chemistry, most students emerge from introductory courses with only very limited understanding of this subject.[13] Gibbs free energy is thought by students as one of the most difficult ideas in chemistry. There have been a limited number of researches carried out upper secondary level[14] and university.[6, 12, 15, 16,]

Johnstone et al.[14] observed that A-level students had some serious misunderstandings about Gibbs free energy. It was found that nearly a quarter of the subjects thought that if a reaction had a large Gibbs free energy change it would occur rapidly. The researchers also thought that there was a misunderstanding, which was not tested, that the net rate of the reaction in a system tends to zero as equilibrium is approached. They suggested that this was because of the fact that the value of ΔG tends to zero. It was also suggested that the reason misunderstandings of thermodynamics ideas arose among high school students was because of the fact that they are not mature enough to appreciate the conceptual subtleties of the subject. The remedies for these kinds of misunderstandings might include the suggestions[14] that students should avoid using too much mathematics during the learning of the ideas of thermodynamics, and also that students should be helped to make the correct connections with their existing knowledge.

Banerjee[12] carried out a research with sixty third-semester college students (B.Sc. Ed.) in order to find out their ideas of chemical equilibrium and thermodynamics. An achievement test on thermodynamics and equilibrium was developed and given after 12 weeks to assess the conceptual understanding and problem-solving abilities of the students. Many widespread misunderstandings were revealed. One of those was that in an equilibrium reaction, a high negative value of ΔH and positive value of $T\Delta S$, make the right-hand side of the equation negative. Hence, ΔG is negative and the reaction is spontaneous. In this explanation, the problem lies behind the interpretation, although the logic is correct. The tendency to lower Gibbs free energy is solely a tendency toward greater overall entropy. Systems change spontaneously solely because that increases the entropy of the universe, not because they tend to lower energy. ΔG is a measure of the change in the entropy of the universe caused by the reaction. The equation: $\Delta G = \Delta H - T\,\Delta S$ gives the impression that systems favour lower energy, but this is misleading. ΔS is the entropy of the system and, $\Delta H/T$ is the entropy change of the surroundings. Total entropy tends toward maximum for spontaneous reactions.[12] The second misunderstanding was identified from the question: '*Draw a graph of Gibbs free energy versus the extent of the reaction: A → B*'. Students thought that Gibbs free energy would increase or decrease linearly to make the reaction spontaneous either in the direction A → B or B → A depending on whether A (reactant) or B (product) initially had more Gibbs free energy. Bannerjee comments that students were not able to conceptualise that Gibbs free energy has the lowest value at the equilibrium position. The researcher also argues that these kinds of misunderstandings should not be thought of being confined to this sample, they might be widespread among students and even teachers.

Carson and Watson[15] conducted a qualitative research with twenty first-year undergraduates drawn from a cohort of 100 students attending a university chemistry department in England. Their results suggest that students found Gibbs free energy an obscure concept even after the lecture course. Students were familiar with the concept but showed no understanding. The only aspect students knew was that it had to be negative for a reaction to be possible. In a study, carried out by Selepe and Bradley[16] with student teachers in South Africa, it was reported that students' understanding of Gibbs free energy was rather superficial. Six out of ten students said that Gibbs free energy is the energy taken out or lost by the system during a reaction. In addition, two out of ten argued that Gibbs free energy is the energy that has not been used to make the reaction to occur and that Gibbs free energy is the internal energy that makes substances react.

In a recent study Thomas[6] studied students' misunderstandings in thermodynamic concepts in physical chemistry. It was reported that students considered that ΔG^{θ} is the same as ΔG except that ΔG^{θ} is measured at a standard temperature (298K) and standard pressure (1 bar), whereas, ΔG is measured at any particular temperature and pressure. It was also reported that students confused ΔG (the change in Gibbs free energy between two states) with Gibbs free energy itself so that the Gibbs free energy of the system either asymptotically approaches zero or goes to zero at equilibrium. In another study it was reported that students perceived Gibbs free energy as the thermal energy transferred into or out of the system.[17]

The purpose of the study

This study is aimed at identifying and classifying Turkish chemistry undergraduates' misunderstandings of Gibbs free energy

In order to fulfill this aim, open-ended diagnostic questions and semi-structured interviews were used, conducted both before and after the topic was

taught. Although some of the findings here confirm those reported previously, it goes beyond them by identifying new misunderstandings and suggests places where these misunderstandings may originate. This is particularly important in order to be able to take corrective action.

Methodology

This study is part of a continuing research project.[18] A diagnostic questionnaire consisting of open-ended questions on key chemical ideas in thermodynamics, including three questions on Gibbs free energy, was developed and applied twice as 'pre-test' and 'post-test' with seven months interval to a total of about forty five students who followed physical chemistry courses in two Chemistry Education Departments in two different universities in Turkey. Physical Chemistry is introduced in the third year and the course contents were similar in both departments. One of the participating universities is situated in western and the other is situated in eastern Turkey. The administration of the diagnostic questionnaires was carried out by the researcher in a lecture hour (50 minute). Students were not permitted to take the diagnostic questionnaires out of classroom or discuss it with their friends and their lecturers.

In this study it was accepted that a good diagnostic question is one that generates information that accesses respondents' thinking about the ideas being explored (Sozbilir[18]; p.331). The three diagnostic questions used in this study tested the following ideas related to Gibbs free energy:

- The magnitude of $\Delta_r G$ indicates how far the reaction is from equilibrium at a given composition but it does not give any information about the rate of a reaction.
- A more negative value of $\Delta_r G$ indicates the greater the probability that the reaction will occur, and also the more negative value of $\Delta_r G^0$, the larger positive value of the reaction equilibrium constant, K.
- The Gibbs energy change tends to become zero when the system approaches equilibrium and is zero at equilibrium.
- Thermodynamic quantities tell us nothing about rates of reactions.

A sample question can be seen in Appendix showing the ideas are being tested and the expected answer (For the complete diagnostic questionnaire see Sozbilir[18] pp. 385-405). The first analysis of the students' responses to the diagnostic questions identified a set of misunderstandings about Gibbs free energy. Following this, frequencies of the misunderstandings were determined and tabled.

A number of interviews were carried out just after the pre-test and the post-test in order to support the data obtained from the questionnaires. The interviews held after the pre-test (twenty-two interviews) sought to reveal the students' understanding of all the key ideas that were investigated in the entire study, including Gibbs free energy. Five post-interviews sought to explore the students' understanding of Gibbs free energy in detail. Therefore, there are more pre-interviews than post-interviews. The interviewees were all volunteers and the interviews took place in a staff office on one-to-one basis. Each interview was tape recorded and then transcribed fully. Students' permission to tape-record the interview was sought in each case. Interview times varied between half an hour and 45 minutes. Students were not told about the content before the interviews, but they were aware that they would be covering the same topics as the questionnaire. The interviews were not carried out as a free-standing study and so were not subjected to rigorous analysis. Selected extracts from these interviews are reported here to illustrate and support the evidence found from the questionnaire data.

Results

An overview of the undergraduates' misunderstandings before and after teaching is given below, followed by detailed examination of some of the students' responses. Table 1 shows the percentages of the misunderstandings identified before and after teaching. The percentages in the tables may be seen as reasonable low. However,

Table 1. Common misunderstandings about Gibbs free energy

No	Misunderstandings Identified	Pre-test n=46	Post-test n=44
1	The slower the reaction, the smaller change in Gibbs energy	6%	13%
2	The bigger the Gibbs energy change, the faster a reaction occurs.	6%	<5%
3	The smaller $\Delta_r G^\theta$, the faster the reaction occurs.	<5%	34%
4	The bigger $\Delta_r G^\theta$, the faster the reaction occurs.	20%	11%
5	The reaction with bigger $\Delta_r G^\theta$ goes towards full completion.	<5%	6%
6	If a reaction occurs fast, it goes towards full completion.	<5%	11%
7	Incorrect drawings	16%	23%

the percentage of blank responses was as high as 50% for some of the questions, indicating that students have almost no knowledge of Gibbs free energy. This high blank response rate lowers the percentages of misunderstandings revealed. In the quotations from students' responses such as ($OT_2/E/S_{13}$); **OT** and **ST** stand for the pre-test and the post-test respectively, **E** and **B** stand for the institutions where the data collected and **S** stands for the student. In the quotations from the interviews such as ($SI/B/S_1$); **OI** and **SI** stand for pre-interview and post-interview respectively, **E** and **B** stand for the institutions where the date collected and **S** stands for the student. In addition, **R** and **I** stand for the researcher and the interviewee respectively.

The slower the reaction the smaller change in Gibbs free energy:

This misunderstanding increased from 6% in the pre-test to 13% in the post-test. Students simply argued that if a reaction takes place very slowly, the change in Gibbs free energy must be less indicating a belief that there is a relationship between the reaction rate and magnitude of Gibbs free energy change in the students' mind. This misunderstanding suggests that students cannot differentiate between the kinetics and the thermodynamics of a chemical reaction.

Some of the responses quoted below reflect the students' views.

"Since the reaction proceeds slowly, Gibbs free energy change must be negative and close to zero ($ST_1/E/S_{11}$)".

"... because Gibbs free energy change must be very small as the reaction occurs very slowly ($ST_1/B/S_{13}$). "

The bigger Gibbs free energy change means the faster the reaction occurs:

The students simply argued that if the Gibbs free energy change of a reaction is large, the reaction takes place faster; this is exemplified by one respondent's answer below.

"The bigger the Gibbs free energy change the faster the reaction occurs. Gibbs free energy changes must be small for the reaction [transformation of diamond to graphite] as the reaction occurs very slowly ($OT_1/E/S_{11}$)."

The student directly related the magnitude of Gibbs free energy to the rate of reaction. This misunderstanding was also highlighted by Johnstone et al.[14] who reported that one A-level student in four considered that a reaction for which the Gibbs free energy change is large occurs rapidly (p.249). It is apparent from the findings of this study that undergraduates in Turkey also hold the same misunderstanding. The above two misunderstandings possibly originated from an analogy with the macrophysical world that 'the further things fall, the faster they go', or even 'the more energy provided, the higher the velocity'. Undergraduates seemed to confuse the common sense ideas of physics with chemical thermodynamics, due to a poor understanding of Gibbs free energy and chemical thermodynamics.[14] The interviews that took place after teaching also provided evidence that students thought along similar lines, as shown by the responses to the diagnostic questions:

"R: ... could you tell me, can we make a guess about the rate of a reaction by looking at the magnitude of a reaction Gibbs free energy value?"

"I: if... one... If a reaction occurs spontaneously yes... rate of a reaction... I am telling what I think right now."

"R: OK, that's OK."

"I: If a reaction does not occur spontaneously, it means, it occurs at low rates."

"R: Can we decide (rate of a reaction) by looking at the Gibbs free energy value? Let's say we have two reactions, one has positive Gibbs free energy one has negative Gibbs free energy. What do you think in this case?"

"I: At first glance, It seems positive...because it has positive Gibbs free energy, it means it occurs more rapidly. The other one must be slower because it has negative Gibbs free energy."

"R: You are saying that if $\Delta G > 0$ it occurs faster! What about the case where both of them have negative ΔG. Let's say both of the reactions have negative ΔG, one of them has -20 KJ/mol and the other one has -40 KJ/mol. In this case which one do you think occurs more rapidly?"

"I: The one with a bigger magnitude."

"R: Which one, 40?"

"I: No, -20, because it is bigger than -40 mathematically. "

"R: Why that so?"

"I: Only because of the mathematical value of them. The bigger value is bigger, and the smaller value is small. I decided according to the mathematical value of them. I don't know any more about Gibbs free energy. Mathematically it (means -20) is bigger. ($SI/E/S_4$)"

As seen from the beginning of the preceding discussion, the interviewee was not aware of the spontaneity of a reaction. She argued that if a reaction does not occur spontaneously, it occurs at low rates. She may have had the misunderstanding that spontaneous reactions occur quickly. Selepe and Bradley[16] argued that students perceived 'spontaneous' as 'immediate or rapid action' and as a result it was thought that slow reactions were not spontaneous. Subsequently, the interviewee also showed no understanding of the positive and negative values of Gibbs free energy. This is interesting, because at the beginning of the

interview she displayed some knowledge about Gibbs free energy: stating that if $\Delta G > 0$ reaction does not occur, if $\Delta G = 0$ reaction is at equilibrium and, if $\Delta G < 0$ reaction occurs spontaneously. In answer to a subsequent question, the interviewee approached the problem from a solely mathematical standpoint and did not consider any chemical aspects. She simply compared the magnitudes of Gibbs free energy values mathematically. She also admitted that it was a guess, because the interviewee also declared that she did not know anything more about Gibbs free energy. This way of reasoning perhaps explains the source of the above misunderstandings in that students look at the mathematical values without an understanding of the underlying chemical ideas.

The smaller $\Delta_r G^0$, the faster the reaction occurs:
This particular misunderstanding was widely identified in the post-test responses. 34% of the students argued that the rate of the reaction is directly proportional to the magnitude of the Gibbs free energy change by stating that the smaller $\Delta_r G^0$, the faster the reaction occurs. The answers showed that there is a strong belief among the undergraduates, that the Gibbs free energy change of a reaction gives an indication of the rate of the reaction. Some of the responses are quoted below:
"We can compare the rate of the reactions. The reaction with small change in Gibbs free energy occurs faster... ($OT_2/B/S_1$)."
"To become spontaneous $\Delta_r G^0$ must be smaller than zero. The smaller the Gibbs free energy the faster the reaction happens. So, the second reaction occurs faster than the first one ($ST_2/B/S_5$)."

Although it was not clear why the respondents thought in this way, one can speculate from the nature of the students' responses. These showed two different approaches. The misunderstanding in the pre-test, that *the bigger $\Delta_r G^\theta$, the faster the reaction occurs* changed in the post-test to the misunderstanding that *the smaller $\Delta_r G^\theta$, the faster the reaction occurs*. This significant shift can be explained by examining the students' reasoning. In the pre-test, students tended to use their everyday experiences to explain phenomena such as the rusting of iron, whereas in the post-test they mostly tended to explain the phenomena in terms of phase changes occurring in the reaction and energy exchange accompanying the reaction. This shift suggests that teaching may replace particular misunderstandings with others rather than eliminating them. Hence, teachers and lecturers should be aware of this reality. Students developed a new way of approaching the problem as well as developing new misunderstandings.

The bigger $\Delta_r G^0$, the faster the reaction occurs:
This misunderstanding is the opposite of the above. However in contrast to the above, this was identified in 20% of the pre-test responses and dropped to 11% in the post-test. Students simply argued that if the Gibbs free energy change is bigger, then the reaction occurs faster as quoted below:
"The bigger the Gibbs free energy the faster the reaction happens ($OT_2/B/S_{11}$)."
"The first reaction $[CO_{(g)} + 2H_{2(g)} \rightarrow CH_3OH_{(l)}]$ *occurs fast. Since its $\Delta_r G^\theta$ is big. In addition, transformation from gas to liquid happens faster compared to solid ($ST_2/B/S_{16}$)".*
"The Gibbs free energy change of first reaction is bigger. Therefore the kinetic energy becomes more, I think, the first reaction occurs faster ($OT_2/E/S_{12}$)."

Students approached the problem from different points of view. Some approached it from a macrophysical point of view, as illustrated in the second quotation, by considering phase changes. In the first reaction the reactants are in the gaseous phase and the product is in the liquid phase, but in the second reaction $[4Fe_{(s)} + 3O_{2(g)} \rightarrow 2Fe_2O_{3(s)}]$ the product is in the solid phase. Perhaps they thought that making a solid from the gas must take more time compared to making a liquid from gas reactants. In addition, some of them related Gibbs free energy to kinetic energy, as in the third quotation above. Students seemed to be confused between kinetic energy and entropy. Perhaps they thought about the relationship between Gibbs free energy and entropy hence they ended with the above misunderstanding, as entropy contributes to Gibbs free energy, and so Gibbs free energy must have a close relationship with kinetic energy, according to students.

The reaction with bigger $\Delta_r G^0$ goes towards full completion:
This particular misunderstanding was not evident in the pre-test but 6% of the post-test responses contained this misunderstanding. Students simply argued that if the Gibbs free energy change of a reaction is larger, it goes towards full completion. One of the respondents explained that if the Gibbs free energy change becomes large the reaction occurs rapidly, so it goes towards full completion. This kind of response suggests that students did not adequately understand the difference between reaction kinetics, thermodynamics and chemical equilibrium.

If a reaction occurs fast it goes towards full completion:
"If a reaction happens faster it produces more products and goes toward full completion ($ST_2/B/S_9$)."

The above quotation and many similar others suggest that students have no understanding of reaction kinetics and of the equilibrium state, though every reaction has a different rate at different stages of the reaction. Students displayed the misunderstanding, that if a reaction occurs quickly, all the reactants will be converted into products. The probable origin of this misunderstanding is the assumption that all the reactions go to full completion. Perhaps students did not appreciate the fact that every reaction reaches an equilibrium point where the rates of the forward and reverse reactions are equal. That means that some of the products turn to reactants again. Alternatively, students may misunderstand the meaning of full completion of a reaction.

Incorrect drawings:

16% of respondents in the pre-test and 23% in the post test drew the incorrect representations shown in Figure 1 to reflect the Gibbs free energy change versus the extent of reaction for a hypothetical A → B reaction (see Appendix for the question).

In the post-test, one in four students drew the correct graph and provided a correct explanation. However, there were several incorrect drawings, as shown below. In a study conducted by Banerjee,[12] in response to a similar question undergraduates mostly drew the graph (d). The students argued that Gibbs free energy increases or decreases linearly to make the reaction spontaneous in either direction A → B or B→ A, depending on whether A (reactant) or B (product) had more Gibbs free energy to start with (p. 881). Banerjee[12] suggests that these incorrect ideas may originate from the fact that at equilibrium Gibbs free energy is at its lowest. The fact that the Gibbs free energy change tends to zero as the system approaches equilibrium and becomes zero at equilibrium, had not registered in the undergraduates' mind. A few respondents stated that Gibbs free energy becomes zero at equilibrium, indicating that students' confused Gibbs free energy change and Gibbs free energy itself because it is Gibbs free energy change that becomes zero at equilibrium.

The pre and post-interviews revealed some new misunderstandings about Gibbs free energy that were not identified through the diagnostic questions. In the pre-interviews, students were only asked what they knew about Gibbs free energy and why Gibbs energy is also known as 'free energy'. Students' responses showed either very little or no understanding of free energy. The only fact many students remembered was that it helps to estimate whether a chemical reaction occurs or not as illustrated below:

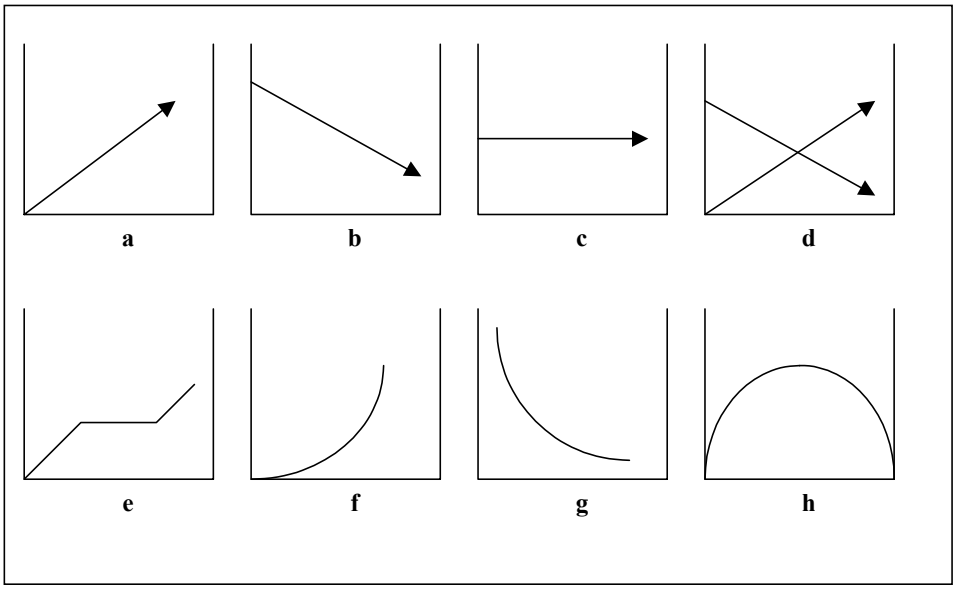
"R: Could you tell me what do you know about Gibbs free energy?"

"I: ...emm... it helps us to estimate whether a reaction happens or not. Enthalpy and entropy are used in calculation of Gibbs free energy. There is an equation.

$\Delta G = \Delta H - T\Delta S$. In this equation if $\Delta G < 0$, I think the reaction happens, if $\Delta G > 0$ it does not happen. If $\Delta G = 0$ it is in equilibrium (OI/E/S_1)"

A few of the interviewees demonstrated some knowledge of 'Gibbs free energy change' such as it is equal to 'maximum amount of work' without showing that they knew what is meant by

Figure 1. Incorrect drawings to reflect Gibbs free energy change versus extent of a hypothetical A → B reaction



'maximum amount of work' or 'non-expansion work'. These suggest only a superficial understanding of the idea. However, when students' were asked a question about the nature of Gibbs free energy, the responses were mainly composed of guesses and showed little scientific understanding as shown below:

"R: Gibbs energy is called as Gibbs free energy as you know. Could you tell me why it was called as Gibbs free energy? Where may it come from?"

"I: It is a kind of energy when molecules are stable, they don't move, or it has in it when it is free... (OI/B/S_5)."

In another interview, one of the interviewees responded to the same question as follows:

"I: free [long silence] *it may be energy of substances when they are free (OI/E/S_5)."*

The interviewees' responses reflect the everyday meaning of word 'free', unlike what is meant by 'Gibbs free energy' in chemistry. At this point it is important to note that the nature of the Gibbs free energy is missed out in most of the textbooks, and also linked to this, it is not included in many physical chemistry courses. Most of the courses follow the quantitative problem-solving strategy in presenting physical chemistry to the undergraduates. Textbooks often describe Gibbs free energy in terms of its quantitative aspects with no explanations about its meaning. Under these circumstances, it is understandable if students don't understand the philosophy behind the Gibbs free energy.

The post-interviews demonstrated some additional misunderstandings about the concepts related to Gibbs free energy. These misunderstandings gathered around spontaneity and Gibbs free energy, and reaction rate and the magnitude of Gibbs free energy change. Students' understanding of the spontaneity of a reaction was limited, as they argued that if there is no external interference in the reaction it is spontaneous. Scientifically, a spontaneous process is one that has a tendency to occur, as determined by a negative Gibbs free energy change.[16] Students' understanding of 'spontaneous' shows parallels with meanings used in everyday language, as Ochs[13] argues. This can be seen from the following dialogue:

"R: What do you mean by spontaneous?"

"I: Without an external influence, if the conditions are available a reaction can happen without an external help, it happens spontaneously."

"R: Can you give me an example?"

"I: Yes, rusting, rusting of iron..."

"R: Could you tell me how can you understand whether a chemical reaction occurs spontaneously or not? Is there a criterion? If yes, what is the criterion?"

"I: Of course there is, reaction heat, reaction enthalpy. At constant temperature, I mean, in a spontaneous reaction, reaction enthalpy should be smaller than zero."

"R: Do you mean the reaction should be exothermic?"

"I: ... emm... exothermic, endothermic in fact it is not conditional at the end. I think enthalpy should be considered, we know like this (SI/B/S_{10})."

The interviewee's understanding of spontaneity is different from the scientific one. In many similar responses students repeated the everyday meaning of spontaneous. It is also clear from the dialogue that the interviewee did not understand the criterion for a spontaneous reaction, which is a widespread misunderstanding amongst the undergraduates. They perceive enthalpy as a criterion for the spontaneity of a reaction instead of Gibbs free energy. Similar findings were also noted by Selepe and Bradley.[16] Ochs[13] argues that the word spontaneous, as used in the context of chemical thermodynamics, is inconsistent and often misleading. It is commonly used without definition and its meaning varies amongst authors using it. The dictionary definitions do not fit the strict chemical definition of a negative change in Gibbs free energy.

Discussion

The key findings of this study can be summarized as follows. Many students were unable to answer the questions testing their ideas related to Gibbs free energy, as the blank response rate was as high as 50% for some of the questions. It was also apparent that a large number of students, who responded to the questions, demonstrated no understanding or included misunderstandings. The study confirms the earlier studies that undergraduate chemistry students' have serious misunderstandings about Gibbs free energy and often confuse key chemical ideas such as energy, enthalpy and entropy in thermodynamics (Sozbilir[18], Selepe and Bradley[16]). These results confirm that many find it difficult to grasp the advanced thermodynamic ideas with no or little understanding of the key underlying chemical ideas. Some misunderstandings could be correlated with some of the prerequisite concepts. Some of the misunderstandings about Gibbs free energy seemed to originate from a lack of understanding or ignorance of related ideas, such as equilibrium and reaction dynamics, energy, energy transformations and the change in energy involving in chemical reactions. The lack of knowledge of fundamental concepts, as it is well known, may generate subsequent misunderstandings. Therefore, care has to be taken to establish a secure knowledge of fundamental chemical ideas before teaching

advanced ideas. For example, in this case, lecturers could check students' understanding of energy, the change in energy (i.e. establishing that the students are aware of the difference between G and ΔG, H and ΔH), enthalpy and entropy before teaching Gibbs free energy.

Very significant misunderstandings were concerned with using thermodynamic data to throw light on the kinetics of a reaction, since undergraduates failed to differentiate between kinetics and thermodynamics. There was also evidence that students had difficulty with the nature of Gibbs free energy itself. When students were faced with a question concerning the nature of Gibbs free energy, as discussed in the previous section, they failed to offer a meaningful explanation of it.

While it is difficult to be definite about the sources of misunderstandings, the following could play a significant part. As discussed earlier, some of the misunderstandings seemed to originate from the incorrect application of everyday experiences and definitions to chemical events and to the meanings of thermodynamic terms. In addition, some problems seemed also to have originated from the students' lack of mathematical knowledge since physical chemistry often involve a lot of complicated mathematics. A solution to this problem would be to teach the topics in a less mathematical way and to put more effort into the teaching of conceptual understanding. Moreover, application of algorithms without conceptual understanding could be a possible source of misunderstandings. In relying on memorization of scientific laws without understanding the underlying principles behind them is also another possible source for the misunderstandings. For example, the difficulty in recognizing the difference between 'Gibbs free energy' and 'Gibbs free energy change' is of this kind. This difficulty may also originate from the strategies applied during teaching. If no attempt has been made by the lecturers to help student to see the overall picture about the Gibbs free energy and related ideas, students would find difficult to conceptualize and differentiate the closely related ideas. The findings of this study suggest that lecturers should design these courses in such way that facilitates students to see clearly the difference between G and ΔG and also know that it is 'the change in Gibbs free energy' that becomes zero at equilibrium *not* Gibbs free energy.

The students' drawings also demonstrated a limited understanding of Gibbs free energy and displayed misunderstandings and confusions. Moreover, the results suggested that students were quite likely to develop new misunderstandings after teaching in some cases whereas some of the misunderstandings persist. The reinforcement of some of the misunderstandings rather than elimination of them after teaching deserves more consideration. As seen from Table 1, misunderstandings 1, 3, 6, and 7 increased after teaching rather than eliminated. This increase could in part be attributed to an increase in the number of responses after teaching. In the pre-test more than 50% of the responses were blank compared to the relatively fewer blank responses (less than 40%) in the post-test. For example, when 53% of the pre-test responses were blank, the misunderstanding that the smaller $\Delta_f G^\theta$, the faster the reaction occurs identified at less than 5% of the responses whereas it is identified in 34% of the responses in the post-test where only 30% of the responses were blank. As the number of responses increased, the possibility of revealing students' misunderstandings increased.

Finally, although some suggestions have been made about the possible sources of the misunderstandings, it should be borne in mind that tracing the origins of misunderstandings is a highly speculative enterprise. The origins of such conceptions are often hidden and therefore difficult to study using empirical methods.[20] The conceptual history of the individual should be traced in order to be able to produce strong evidence. However, the commonality of the misunderstandings across different cultures and populations suggest that outside effects such as instructional practices, textbooks and the excessive reliance on everyday language, should be considered as potential sources of misunderstandings.

Implications for teaching

Although the results of this study are based on a small sample in Turkey, it is likely that many of these misunderstandings would be found among physical chemistry students elsewhere. Therefore, these findings may provide some clues about the quality of student learning in typical physical chemistry classes. This study suggests that a substantial review of teaching strategies at tertiary level is essential. Physical chemistry instructors may sometimes overestimate students' understandings of the key chemical concepts and underestimate their difficulties in acquiring them. If instructors recognize the possibility of misunderstandings concerning basic concepts and difficulty of learning advanced level concepts on the basis of these misunderstandings they will be better able to teach difficult concepts. The research in this area suggests that attempts made in order to overcome students' misunderstandings should focus on 'identifying and modifying students' preconceptions' and 'teach students how to monitor and control their learning'.[20] Diagnostic questions

are among the most frequently used technique for identifying students' preconceptions together with interviews, concept mapping and classroom discussions. The diagnostic questions used in this study (an example is given in Appendix) were found to be successful in identifying some student' misunderstandings. Therefore, it could be useful in the light of the evidence gained from this research that a systematic simple diagnostic test be used prior to teaching the topic in order to identify students' existing misunderstandings. Similar open-ended diagnostic questions, as given in Appendix, would be useful in identifying whether students hold the unscientific ideas such as confusion of G and ΔG, thinking that ΔG decreases or increases linearly in equilibrium and G is equal to zero at equilibrium rather than ΔG. Moreover, the other questions used in the study (see Sozbilir[18] pp. 385-405) were successful in identifying students' misunderstandings, such as confusing reaction kinetics and thermodynamics, and also the state of reaction equilibrium and reaction thermodynamic values. A practical alternative to diagnostic questionnaire would be classroom discussions, which can provide a wealth of information about the students' existing knowledge. Once students' ideas have been identified, the task of modifying those ideas begins. Several different successful conceptual change and cooperative learning approaches, including (for example conflict and confrontation, problem based learning, context based learning strategies etc) have been reported in the literature so far.[20] Accomplishing meaningful learning may be facilitated by a combination of individual, small-group and whole-class activities in which alternative explanations and descriptions of scientific phenomena are verbalized, justified, debated, tested and applied to new situations as suggested by Wandersee et al.[20]

Another possibility might be to focus on the quality of students' learning rather than quantity of concepts covered during the course.[6] Students may require extensive help to revise their thinking about the concepts and acquire the correct scientific meanings. Otherwise, although students correctly answer the examination questions, they may still hold on to their misunderstandings. It is also important to recognize the importance of the examination questions. In physical chemistry exams, questions mostly require quantitative solutions rather than qualitative discussions. It is suggested by Carson and Watson[15] that questions need to be of a kind that required students to demonstrate an understanding of the concepts involved. Mathematical calculations promote algorithmic learning rather than conceptual understanding. In the same vein, it might be useful to consider presenting first the nature of Gibbs free energy, the conceptual hierarchy up to Gibbs free energy and the relationships between the concepts qualitatively and then follow this with the quantitative aspects, as suggested by Carson and Watson[15]. Gibbs free energy could be defined as 'the quantity that tells us what changes are possible'. It tells us how to fix the circumstances so that a change becomes possible - for example Haber noticing that hydrogen and nitrogen could combine to make ammonia at high temperatures only if the pressure was made suitably high, but not at low pressures.[21] Here it is important to note that students may quickly misunderstand this statement if it is not mentioned that Gibbs free energy changes inform us about the spontaneity of a reaction only in the cases where temperature and pressure are constant. Otherwise students may adopt it as a general criterion and apply it incorrectly to every case. 'For non-isothermal cases there is no generally useful relationship between spontaneity and the sign of ΔG'.[22] Finally, as Millar[19] argues, 'the process of eliciting, clarification and construction of new ideas takes places internally within the learner's own head,... science should be taught in whatever way is most likely to engage the active involvement of learners'. Conceptual learning can be fostered by providing students with a variety of learning experiences.

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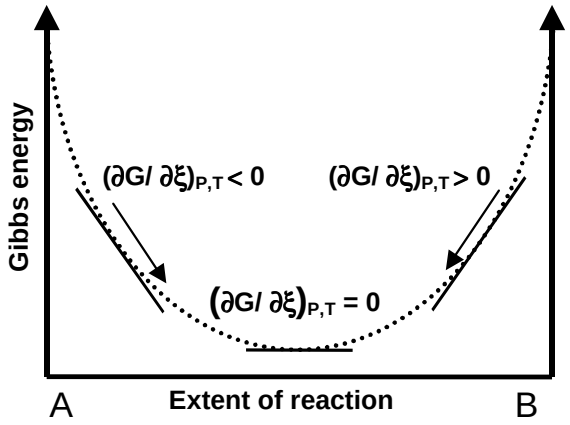
Appendix

Gibbs free energy

(This question is adopted from Banerjee[12])

Draw a graph of Gibbs free energy versus extent of reaction **A → B** on the diagram is shown here. Discuss and interpret the graph as carefully as you can.

The idea being tested is: The Gibbs free energy change tends to zero when the system approaches equilibrium and is zero at equilibrium.



The expected answer is: The following graph was expected to be drawn.
As indicated on the graph, chemical reactions spontaneously approach the equilibrium state from both directions; A → B or B → A. The equilibrium state always has a lower Gibbs free energy than that of either reactants or products. As the reaction approaches the equilibrium the Gibbs free energy change decreases, and at the equilibrium state the change in Gibbs free energy becomes zero. At equilibrium, the entropy of the universe attains a maximum level compared to minimum Gibbs free energy.

Perspective

Independent Learning for the Unwilling*

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1. What is learning?

He who has no philosophy is the prisoner of a false philosophy

Of course this was written by a philosopher – a philosopher of science in fact – but even so, it might be true. It applies no less to teaching than in its original context of the interpretation of quantum theory. It also matters. If, for example, we actually believe that the role of the instructor is 'not to fill empty vessels but to light candles', then we might just pause to reflect on how many candles our mode of teaching has lit recently. Of course, it helps if we not only recognise a candle once it is lit, but know how to go about lighting them. As Leamnson says: 'To do a good job of teaching it would help to have some notion of what's actually happening when learning is taking place'.[1] But I do not agree with Leamnson in his emphasis on the neurophysiological concomitants of learning. These are important, but it is not, or not just, as Plotkin would have it, that 'When we come to know something, we have performed an act that is as biological as when we digest something'.[2] So let us begin with my philosophy, which I want to describe by an analogy that is, in essence, really only an updated take on Dewey's view that students "*learn what they do, not what we tell them*".[3]

Think about artificial intelligence. The original grand plan of AI was the 'expert system'. This computer system would be programmed with the collective knowledge of the world's experts on some topic of interest – the diseases of the lower bowel, for example – and would therefore be superior to any single human expert. However, the results were disappointing; it turns out, that wisdom and understanding cannot be reduced to a database and a search algorithm. Following on from research in artificial life, we now believe that learning is what occurs in a system when an interaction with the environment produces a feedback to modify responses in the light of experience and an appropriate set of rewards.[4, 5] Note that I am not saying that an appropriate environment and a suitable reward regime enhance learning: everyone knows that. I am saying that this *is* learning and that it is a mistake to think it takes place in any other way.

As we shall return to later, this explains a number of things. Most important of these is that students respond to the learning environment and reward system that they actually experience, which might not be the one we planned (if we did actually plan one). To take a trivial and well-known example, a reward system that focuses on the final (knowledge-based) examination encourages only shallow learning. According to a National Research Council report[6] "*appropriately designed assessments can help teachers realize the need to rethink their teaching practices. Many physics teachers have been surprised at their students' inabilities to answer seemingly obvious … questions…and this outcome has motivated them to revise their instructional practices.*"[7] Or to put it slightly more forcibly (and contentiously), there are no bad students, only bad course designs.

2. The learning environment

The first thing we deduce from this view of learning as the modification of response to environment is that teaching has to be approached collectively, because it is the combined programme that defines the student experience. This is not to denigrate the standard staff development programmes directed towards delivering a better lecture or a more relevant assessment. If we are going to drag students out of their beds for a 9.00 a.m. lecture, then we have a responsibility to be organised, audible and even, if possible, interesting. And we should not treat such an event as a mere token of our devotion to the ritual of teaching. But this individual approach to improved teaching can only go so far. The course that is entirely different from every other may occasionally be an inspiration, but is more usually a distraction and at worst an encouragement to students to treat education as a series of arbitrary hurdles. The different expectations induce what Sevin-Baden calls[8] disabling disjunctions – these are conflicts that inhibit learning rather than generating creative tensions. Let me emphasise that I am not saying I want boring sameness; what I am after is a coherent variety, and a prima-donna

* Written version of a talk prepared for the LTSN Physical Sciences workshops on Independent Learning.

approach to 'good' teaching, which ignores or even by implication diminishes the context in which it takes place, does not deliver this.

Traditionally, the design of a degree programme has meant the listing of the syllabus. It would be dangerous to dispense with this step, but it is also inadequate to end with it. Nowadays most programmes would rephrase the syllabus in terms of learning outcomes and add some transferable skills as intended (rather than accidental) learning outcomes. This is called course design. Now at this point the reader might be about to howl at my adoption of edu-speak, but I think of myself less as a course designer, more as a designer of learning environments. (Unfortunately this term is being appropriated to imply an association with the virtual learning environments of e-technology, but it should be clear that that is at most a small part of what we are talking about.)

So what is a learner environment? We can look at learning from the viewpoints of subject knowledge and skills, student prior experience and goals, the assessment regime and the community context. An overall learning environment is then is an alignment* of these knowledge-centred, learner-centred, assessment-centred and community centred foci.[6] Bransford et al. note the importance of alignment in this regard: "*Many schools have checklists of innovative practices…. Often, however, these activities are not coordinated with one another. …[P]roblem solving may be 'what we do on Fridays';…formative assessments may focus on skills that are totally disconnected from the rest of the students' curriculum. In these situations activities in the classroom are not aligned*." One might wish to extend the list beyond the classroom to apply this to University education, but the principle is the same.

3. Resource-based learning

New use for lectures

One might think naively then that the design of learning environments begins with a blank sheet of paper. Unfortunately, blank paper is often in short supply in university teaching. One has to start from where we are and what we have always done, and that is the traditional lecture course. That would seem to be the knowledge-centred environment sorted. However, here we appeal to a little test we have done in the physics department at Leicester, which was purely small-scale (a single class) and anecdotal, but which we found surprising and provoking. We took some examination questions that seem to have been answered particularly badly, in our case, as it happens, on the theory of relativity. Then we looked at the students' notes on this lecture material. In many cases we found that the poor examination answers were quite faithful reproductions of the students' notes. This may not be what we think we said or wrote, but it was what was heard and seen.

Of course, if our lectures merely repeat the material in a book then the outcome should be different: obviously we should get approximately what it says in the book – which might suggest a possible short-cut! The lecture course was invented to transmit information that was not readily available in printed form. It has survived because no-one believes that there is a book that treats their subject exactly right, because it is easier to be talked to than to read, and because it is an easy way of providing a community centred environment. The first is another example of perfection being the enemy of the good. The second is why students always prefer being taught to learning (which would be nice if it worked). And there are better ways of embodying a sense of community than simply sharing the same air supply.

We have, however, found that we can adapt the system by giving the lecture a useful role, while making print based media the main source of standard information. In effect we have introduced into our core physics courses at Leicester, mainly in years one and two, a form of resource-based learning (RBL), in which, unlike the original concept of RBL,[9] the relevant resources are rather closely defined and integrated with student activities. The course structure defines clear and varied roles for the lecture, which makes sense as the students move through each unit or topic on a fortnightly cycle. Each unit has an introductory lecture, which is intended to provide the motivation and explain the intended learning outcomes. It specifies the reading to be done by the students, which is subsequently checked by a short web-based multi-choice test. It also guides students in how to do the reading. The second lecture deals with the approach to problem solving in the topic area (or how you actually think of doing what is obvious after you've been told it). There is then a class session in which the students work in groups on set problems with the staff available for group consultation. "*Opportunities to work in groups increase the quality of the feedback available to students*."[10] It also provides a better opportunity to foster a sense of community and shared goals. This is helped by the team teaching approach in which the team of lecturers for each module share the lecturing but are all present to supervise the problems class. In the final lecture of each unit the lecturer can draw on the class experience to address the students' needs, which also, incidentally, can be used to inform the presentation of material in future years. Students then have time to complete an assignment for the unit, which they must hand in for marking and on which they receive feedback in small group sessions.

* The term 'alignment' is taken from Bransford; 'integration' might be better.

There are many technicalities of scheduling, variations in rates of progression and so on, the details of which need not detain us here. We can complete the picture simply by adding that this approach is used with a class of around 90 students for all the core teaching (i.e. the material that every student has to cover), which is almost the whole course in year one but becomes a decreasing part of the programme in each succeeding year, and disappears entirely by year four (for the M.Phys. cohort). It is replaced by specialist option courses and by a variety of project work that encourages independent learning, in order to reinforce core material and to take subjects to the research boundaries. The main question is, have we integrated the environments in a coordinated way and, if so, does it work? The answer, as one might guess, is yes and no. We have evaluated this in various ways, including peer review of various elements and focus groups of students meeting with us and with external consultants. We shall not give all the details here but summarise qualitatively some of the main points.

The learning environment

Let us start with the knowledge environment. It has to be admitted, despite what was said above, that the textbooks we use are not entirely suited to the purpose. For the first year the US compendium text is far too long (hence too heavy) not very interesting (despite the plentiful pages devoted to supposedly interesting asides) and rather too susceptible to pattern matching of formulae in place of problem solving. If the published literature is representative, then our second year students do not seem to be comparable with any anywhere else in the world. (My colleagues, and in some cases the students too, assure me that the books are either too hard, too easy, too long, too short, too boring, too mathematical, too descriptive…or, failing that, just too out of print.) This has made it difficult to dissuade some colleagues from relaxing back to the old, didactic style of lecturing. That said, the one thing this approach achieves above all else is to define the syllabus in terms of what can be reasonable absorbed in the time available, since core teams have to specify fortnightly assignments to cover the corresponding material and this, at least, is the first requirement of deep learning.

The student-centred environment is designed to lead to independent learning. Our greatest difficulty is to develop a work ethic that will enable this to take place. The idea is that we set students an example of how to work effectively by providing a lot of support in the core programme; by this means we hope to launch them on their optional courses needing much less direction. The first problem is that for many of our students their merely adequate entry grades can be put down to the fact that they were not really trying, and these students expect to get a satisfactory degree by continuing not to try very hard. In much the same group are those students whose entry grades were obtained for them by their teachers. It comes as a surprise that we are not going to get their degrees for them, especially when they compare their expected workloads with what they perceive to be required from students in other disciplines. The feeling of working hard was not what they were led to expect University life to be about, but it is in fact the most important experience we can give them. Against us it has also to be said that the transition from the highly directed core learning to the freedom of the options programme is not yet successful. The worst of it is that students have asked for further support for the option courses and that we have started to increase our provision. This seems to go against the attempt to develop independent learning. On the other hand, in our various focus groups, our final year students almost all volunteer the information that in retrospect they understand completely what we were trying to do, and for many their only regret is that we were unable to persuade them to participate more fully. In our defence it should also be said that the various independent projects in later years are often done very well.

An important feature of the student-centred environment is the inclusion of transferable skills as a natural and seamless part of the programme. For example, the first physics that students do involves working in groups, but it is not an exercise in group working. I think it also helps that they see us working as teams, which is where we probably have a natural advantage over many other disciplines. To many minds, the student-centred approach implies an entry test to determine what prior knowledge students bring. Having employed such a system, we have abandoned it in favour of variable pacing of progression through the programme. This means that students themselves determine the areas and topics to which they have to devote more time, rather than being categorized externally. I feel much more comfortable with the fact that we do not pick out students by exploring where they lack competence, but allow them to cover rapidly the areas in which they are confident; this comfort stems from the feeling that this is more in keeping with an independent learning approach.

Assessment

Perhaps the most difficult task is the design of the assessment regime. Despite the reservations about the mixing of support and evaluation that it entails, we have been driven to an environment in which everything that has to be done is (summatively) assessed. The driver here has been student attitudes: they demand that everything they do ‘counts’ and will not take seriously anything that generates purely formative feedback that does not ‘count’. Perhaps this should not be surprising, especially in view of what was said about assessment earlier, but it is. It is

surprising because many of our students will offer hours of their time to help with activities for schools and the general public, will volunteer to show prospective students round the Department in return for what, in the end, seems to be an egg sandwich and a biscuit of undistinguished provenance. They will offer to serve on student committees, organize conferences and all manner of helpful things without requiring that it 'count', but will not accept any other currency than marks as a reward for doing physics. What we do could be regarded as tests five-times a week, but by keeping the overall contribution to the degree small, students appear to see it as five-times a week distribution of the 'sweeties'. We do in fact maintain marks to the inherent accuracy of Excel spreadsheets, rounding only on the last day, so to speak, but none of these continuously assessed activities can affect any visible decimal places in the overall mark. There is clearly some strange psychology at work here, in which the mere thought of reward suppresses the students' numeracy systems.

On the other hand, we do keep a very strict record of attendance at all activities, apart from lectures (which are voluntary), and students receive a summons to come and explain any absence usually within hours of their absence being noted. I like to think this is not so much 'big-brother' as an obvious indication that someone cares. What happens is that after a couple of weeks all the students have learnt the rules and adopt a professional attitude to the eight hours a week of compulsory attendance: it becomes part of the community environment.

The community

One might think that the obvious approach to the community environment in a system that claims to produce independent learners is to 'leave students to get on with it'. However, on its own this would probably have the effect of producing what might be called a survival strategy, the symptoms of which are shallow learning and question spotting. Nor can an appropriate sense of community be generated by the occasional staff-student skittles evening or football match. Integration of the community environment means that it carries forward the student-centred approach, so that the way in which students work informally together matches the way that they have their formal classes, working either alone or in groups, in a physical space to which they belong and in which they have access to the knowledge environment – in the human version as academic staff, as well as the internet. Perhaps we are exceptionally fortunate in being able to provide this physical environment, with lecture theatres, laboratories, computer areas, workspace and communal social space and (most) staff offices all within the one building, but this good fortune did not come about by accident.

Conclusions

To conclude then, what about this unwillingness of staff and students to emerge from the comfort zone of traditional teaching methods and embrace innovation? This supposedly legendary reluctance is in fact mythical on both sides. Students are not experts on pedagogy, have very little interest in whether your teaching methods are innovative or not, and come prepared to engage in the game of getting a degree. It is our job to write the rules so that the game is worth playing. But writing the rules is also part of the game: the learning environment has two co-habitants, the staff as well as the students. And the knowledge-centred, teacher-centred, assessment-centred, community-centred environments have to be integrated for the staff also. My experience is that resistance to change occurs where it creates tension in this integration, often where innovation threatens to fracture the sense of community. Where innovation creates win-win situations, or at least offers the prospect of such, I have not experienced open antipathy to it. Of course, I am aware that the traditional mode of conduct of academic warfare is to agree to everything and do nothing, so opposition becomes covert rather than overt. But the principal weapon in politics is patience, and if your ideas are right, covert opposition can be changed without anyone having to be seen to climb down.

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Letter

Repeatability and reproducibility

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The recent contribution[1] on the language of error and the misconceptions held by students in the early stages of their undergraduate courses is to be welcomed; it should encourage a more positive approach to the whole area of error analysis in undergraduate experimental work. This is an important topic to which, for far too long, only lip-service has been given with the result that many chemistry students complete their degrees without any proper understanding of either the language or the principles of error analysis.

I would like to comment here on one of the terms frequently used in this area that in the last few years has been given a more precisely defined meaning. I refer to the term 'reproducibility', generally taken to be a measure of the consistency of replicate measurements of the same quantity. However, it has recently become common practice, particularly in the field of analytical science,[2] to make a distinction between what has been described[3] as 'within-run precision' and 'between-run precision'. The first of these refers to the 'reproducibility' obtained when the same method is used with the same materials by the same operator using the same apparatus in the same laboratory within a short period of time; this is now referred to as *repeatability*. The second is the 'reproducibility' obtained when the same method is used with the same materials but by a different operator using different apparatus in a different laboratory at a different time. The term *reproducibility* is now generally used for this second scenario. Thus, when an analyst is developing a new method for the determination of a given substance, the repeatability of the method will certainly be explored, but for the method to be accepted as one of general use, the reproducibility (as newly defined) will require determination and will need to compare favourably with the repeatability.

The distinction between the two terms is a useful one of which students should be made aware. Clearly the terms have important applications in a wide variety of quantitative determinations.

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