Teaching, Learning, and Computing

A REVIEW

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Introduction

Chemistry teachers want to improve their students' learning. They have been encouraged in this desire by the Dearing Report[1] which stresses the need for students to 'learn to learn'. Teaching with the aid of computers is often vaunted as a way to improve students' learning. This review argues that in order to use computers to improve students' learning, it is necessary to apply the work that people have already done on understanding how students learn. In the previous issue of this journal, Johnstone's review[2] discussed the process which goes on in students' minds when they learn. Here, I wish to review the work on learning with a view to its application to the use of computers in teaching chemistry.

In the first section, I discuss how students learn in general terms; in the second, I deal with research on learning in Chemistry; and in the final section, I show how this work has been applied to computers in teaching.

How do students learn?

General points

An understanding of how students learn can help teachers to devise effective strategies for teaching. This requires that research into the learning process is made accessible. Books such as those edited by Entwistle[3] or Bigge and Shermis[4] aim to show how such theory can be applied to real situations. Borg's critical review of the educational research literature[5] has useful sections on recommended reading. The excellent books by Laurillard[6] and Ramsden[7] are particularly accessible to the practising teacher.

A central strand in much of this literature concerns the development of students' views of knowledge. This strand is founded in the work of people like Piaget, Bruner, and perhaps most pertinently to higher education, Perry (whose model is summarised for chemists in[8]; an illustrated account of how his model affects students can be found in[9]). Such views of student development see the aim of education as moving students from a simple to a more complex position. In the first state, students tend to see facts as absolute, accept the view of authority uncritically, think of knowledge as a collection of facts to learn, and believe that all questions have a single right answer. The aim is to help them to espouse a more relativistic view of knowledge, find out for themselves, see how evidence can be interpreted in different ways, and construct integrating models into which such interpretations can be fitted. These writers emphasise that to facilitate such development, students need to be supported at the appropriate level: a student who strongly believes that there is one right answer will find an exercise which shows a multiplicity of possible interpretations confusing and unhelpful.

Constructivism

Constructivism is a theory about how students learn, and has at its centre the idea that knowledge is not transmitted intact from teacher to student, but is actively constructed in the mind of the learner. The origins of constructivism lie in the work of Piaget and Ausubel in the 1960s, but more recent works[10-16] are more useful for practical applications to university chemistry education; Bodner's paper[17] has precisely this as its focus.

According to constructivists, the most important single factor influencing learning is what the learner already knows. The teacher needs to be aware that this prior knowledge will have a profound influence on the way students construct new knowledge, and needs to take account of this in planning the delivery of new ideas. Furthermore, because students bring different prior knowledge and expectations to new experiences, they will learn different things from the same experience.

To summarise the implications of constructivist theory rather starkly:

- Education in chemistry needs to help students to understand how chemical knowledge is created/ discovered.
- When there is conflict between students' existing (possibly mistaken) ideas and those being presented by the teacher, students will have problems. Teachers need to recognise when this occurs, and provide effective support.
- True learning only occurs when students create their own understanding; but teachers are needed to create the environment in which this can happen.
- Learning is not the simple transmission of facts from teacher to student, but a continuous and active process on both sides.

One aspect of how students' pre-existing ideas influence what they learn is discussed by Edmundson and Novak.[18] Students have different views of how 'facts' come to be known (epistemology), and this affects their learning strategies. Students who firmly believe that there are accessible 'right answers' to all reasonable questions are more likely to try to learn by memorising facts; those who think that 'facts' are constructed by social processes are more likely to try to understand the material being presented.

Context, motivation, and learning strategies

Students' learning strategies are affected by many other factors besides their epistemology.

Students approach learning in different ways, and their approach to a particular course or activity exercise is affected by its context and by their motivation.To help students learn in the strongest sense, teachers of chemistry will want to encourage them to try to understand the material at a deep level.

Ausubel[19] identified a difference between 'meaningful' and 'rote' learning; he maintained that students' motivation was an important factor for inducing meaningful learning. This is similar to (but not the same as) the difference between 'deep' and 'surface' learning, which is discussed in the works edited by Marton *et al*[20] and Schmeck.[21] In a chapter of the latter collection, Entwistle identifies three possible approaches:[22]

- a surface approach, where the students' aim is to simply reproduce the material necessary to complete their course;
- a deep approach, where the students' aim is to reach a personal understanding of the material; and
- a strategic approach, where the students' aim is to be successful by whatever means are necessary.

Obviously, these approaches tend to lead to different learning strategies and hence different outcomes. A surface approach leads to rote learning; a deep approach can lead to the student examining evidence and relating it to their ideas in a constructive way;and a student with a strategic approach will use whichever strategy they perceive will result in the best marks. The strategies students use affect what they learn: rote learning at best results in a substantial knowledge of factual information, but a deep approach can result in a deep level of understanding.

High-quality learning requires a deep approach.[23] Most students employ a strategic approach: they will switch between a deep and a surface approach according to what they think will be most effective. (This is a very sensible approach; and indeed, the students who enter a chemistry department will have been selected by the education system to be those who are adept at picking the most effective approach.)

The key factors affecting students' approach to learning are their previous experience (as argued by constructivists), the style of learning they have previously employed, their perceptions of the activity, and its context.[24, 25]

Students' motivation to learn is also important, but does not necessarily determine whether they employ a deep or a surface approach. Aspects of students' motivation to learn can be classified as either intrinsic (*e.g.* wanting to know for its own sake) or extrinsic (*e.g.* wanting to learn what is on an exam syllabus).[26, 27] There is also a third class, called 'amotivational' learning, which covers the situation where students do things (like attending lectures) without any conscious belief that this will help them learn anything.[28, 29] It is hard to design a course to address students' intrinsic motivations, but university teachers have a great degree of control in respect of extrinsic motivations (they decide what is in the exam) and in respect of amotivational approaches (they decide what goes on in lectures and workshops).

In designing a teaching method which encourages students to employ a deep approach to learning, a number of factors should be considered. According to Ramsden,[24, 25] key features which facilitate a deep approach are:

- The activity should be perceived by the students as interesting and relevant. (It is almost always worth explaining the relevance of new material or activities in several different ways).
- Students should have a choice over their study methods; the more autonomy over their learning they have, the more likely they are to try to understand, rather than simply follow instructions.
- The workload should not be excessive; if there is too much to consider in a deep way, students are forced to use a surface approach .
- Students should not be anxious about the exercise.(This can be especially important when considering the use of computers, since computers can themselves be a potent source of anxieties.)
- Students should not feel threatened by the exercise in any way. (The assessment procedure is often seen as a threat, as discussed further later.)

Other authors have suggested the following additional features:

- Students should be actively involved in the exercise.[30]
- Students should interact with each other; peer learning can be very powerful.[30, 31]
- Students should have/take time to reflect on the exercise afterwards, to consider what they have learned, how they learned it, and how it fits with what else they know.[30]
- The context of the exercise should be similar to that where the subject material is relevant; there is evidence[32] that there is little transference of understanding from one context to another - a familiar phenomenon to chemistry teachers facing the 'modularisation' of a course!

No single teaching method or activity can hope to cover all these points effectively. Laurillard[6] and Ramsden[7] both maintain that no single teaching method can create an environment in which students adopt a deep approach to learning. A range of teaching styles is valuable. Different students will be attracted by and learn most effectively from different teaching styles.

Assessment

Assessment is a key factor affecting students' learning: students will try to learn what they think will be assessed. Useful discussions of assessment can be found in the books by Rowntree,[33] Kempa,[34] and Brown *et al*.[35, 36]

The purposes of assessment are generally agreed to be:

- to provide feedback for the student in order to reinforce their learning;
- to provide feedback to the teacher about the students' level of knowledge (summative assessment) and to indicate where further work is required;
- to act as a focus for an activity and motivation for the student.

Assessment defines the *de facto* curriculum.[33,37] Ramsden[25] explains further that assessment is the most important factor in improving teaching and learning, because most students do what they think will get them marks. The style and scope of assessment will determine the learning approach of the student, as discussed above: assessment of factual recall and the ability to solve simple 'algorithmic' problems leads to a surface approach to learning.

Elton[37] has argued that traditional examinations are unreliable because they assess little beyond factual recall and simple application of techniques to familiar problems. Bowden *et al*[38] showed that students can do well in such examinations while lacking understanding of basic concepts which are required for their later learning. Assessment can be an almost random process - Longmore and McRae[39] claim to find no significant difference between conventional examination marking and awarding marks on the basis of how far the script travels when all the papers are thrown down the stairs.

To be effective and reliable, assessment must be humane, and not perceived by the students as a threat. Most importantly, the students should be explicitly aware that the assessment not only covers the subject matter, but also rewards them for their understanding (and not merely rote learning).

Computers can be used to help in assessment. At a trivial level, word processors can help to ease the burden of marking by rendering all students' writing legible. Computers can also be used to present and automatically mark questions to students. Often such questions take the form of multiple-choice questions; there is, of course, a danger that students will infer from such an assessment that they need to memorise a set of discrete, testable facts - precisely the opposite of the deep approach discussed so far.[33]

Chemistry

General points

Some efforts have been made to apply educational research specifically to chemistry. Notably, Johnstone has applied an information-processing model of learning to chemical education.[40-5] Finster[46] has applied Perry's model of intellectual development to the design of a General Chemistry course. Garafalo and LoPresti[47] used educational research to devise an entire integrated science curriculum for freshmen. At a school level, Herron has applied educational philosophy and research, especially that of Piaget, and has written guidelines on how this can best be done.[48, 49]

At a smaller scale, many studies have focused on students' concepts and their inter-relation (their cognitive structure). Kempa and Nicholls[50] found that problem-solving ability above the algorithm level depends on the strength of concept-interlinking in students' minds. They also found that students' ability was dependent on context, such that individual students can do well in some areas and badly in others. Others[51-54] have found that when students' chemical concepts are examined by means of 'concept mapping' or similar exercises, large gaps in their understanding are revealed. They have also found that students have particular trouble relating chemical concepts to new contexts. This is in line with the general findings discussed in the previous section.

Much of the above work echoes general educational research. Chemistry is an experimental subject; this raises particular points which are perhaps not obviously covered by general principles.

Experimental work

Much has been written about the aims of laboratory work [55-58]. The skills and competencies required of chemists include familiarity with laboratory techniques, experimental design, data interpretation, summarising research findings and scientific report-writing. The main purpose of laboratory work is to provide students with the necessary technical skills; it is often hoped it will help to equip them with the other skills, and to reinforce the content of other parts of the course.

Effective laboratory work is difficult to plan. Laboratory experiments take up a great deal of staff, demonstrator and student time; the chemicals, equipment and laboratories are expensive and hazardous; results are unreliable because students are inexperienced. To reduce these problems, experiments carried out in teaching laboratories are usually very well researched, and the instructions given to the students are very prescriptive. As Garratt[59] points out, using such 'recipe labs' is an effective strategy for maximising both the quantity of practical experience gained by the students and the quality of their results. Such laboratory work is widespread[60] and there is good evidence that students learn technical skills from it.[41]

However, in a 'recipe lab' the practical becomes a demonstration, rather than a real experiment. Verdonk[61] coined the term 'bookification' to describe this move from 'fact-making' to 'fact-learning': instead of learning how to experiment, how to describe and how to explain, the students learn experiments, descriptions and explanations. Another drawback to such laboratory work is that students are all working towards the same answer and so can copy results from each other. Furthermore 'recipe labs' do not provide opportunities to learn about experimental design, investigation and critical analysis of results, and sources of error.[40,62] Hofstein[63] found no simple relationship between students' experiences in the laboratory and their learning. This is not surprising, given that students usually follow their instructions line-by-line without thinking about what they are doing[41] and only notice effects they have been told to observe.[64] Edmundson and Novak[18] found that most students gained little insight into the key science concepts involved in laboratory work. Johnstone *et al*[43,65] have discussed how overloading of students' working memory is a common cause of such problems.

Hofstein[63] asserts that, in order to remedy these failings, it is necessary to address factors such as the attitude of the staff, demonstrators and students, the aims of the experiments, the context in which the experiments are set, and the level of students' understanding. There are three overlapping ways in which this can be done: laboratory work can be made more open-ended; 'recipe' laboratory work can be carefully designed to mitigate its limitations; laboratory work can be supplemented with other teaching methods to cover its shortcomings.

A widely-employed method for giving student chemists practice in designing and carrying out experiments and interpreting data for themselves is the research project. This is an "*important component in the education of a professional chemist*".[66] Ryder *et al*[67] report that tutors responsible for projects believe that they provide a unique opportunity to experience the actual practices of scientific research, which could not be achieved through other teaching contexts; they saw the project as an apprenticeship which introduces students to the culture of science. Analysis of the student view[68] showed that students do indeed gain valuable insight into the culture of science, but that peer support is needed to avoid students "*switching off [during] the boring bits*", and that students are inclined to worry excessively about not obtaining good results.

Project work is normally restricted to the final year of an undergraduate course. However, it is possible to make other laboratory work less recipe-based. For example, Johnstone[69] argues that tutors can design laboratory work to encourage the students to take more responsibility for their learning, without the need for much change in the amount of time or resources required. Laboratory worksheets can be improved.[70] It is possible to make laboratory work less recipe-driven. For instance, Merritt *et al*[71] found that one effective way of giving students practice in experimental design is to require them to prepare a plan of their experiment beforehand, and to encourage discussion. Verdonk[61] describes an investigation of ester synthesis designed to provide the students with some insight into the process of scientific research.

Johnstone *et al*[72] describe the results of a laboratory course which was designed to maximise the opportunity for the students to understand their work. The main features were the use of 'pre-labs' to give the students practice in the technical skills required and make the purpose of the exercise clear, and the minimisation of the amount of extraneous information presented. This resulted in a significant increase in the number of students who reported feeling able to concentrate on the chemistry involved. However, this work also showed that there is still considerable scope for providing more effective links between theory and practice.

Some of the limitations of recipe-driven laboratory work may be overcome by supplementing them with non-laboratory-based work. For instance, paper-based exercises can be used to teach critical skills (*e.g.* [42]) and experimental design (*e.g.* [73]), and whole courses have been designed to foster the development of such critical skills.[74] Another method of providing an effective link between laboratory work and theory is a carefully designed computer simulation exercise.[75]

Computers

In the last decade or so there have been many efforts to encourage the use of computers in teaching: most notably the Computers in Teaching Initiative[76] and the Teaching and Learning Technology Programme.[77-80] Two important reports on higher education published in this period (the MacFarlane Report[81] and the Dearing Report[1]) both prescribe the increased use of computers in teaching in the future.

There are many different ways in which computers can be used for teaching. They provide the following valuable features:

- hypertext, where text is presented with highlighted words, which when clicked provide further text, thus giving students an easy way to follow their own chosen route through a collection of information;[82]
- multimedia, where text is supplemented with high-quality graphics, animation, and sometimes sound;
- rapid feedback on answers to questions posed by the computer;
- Intelligent Tutoring Systems, which aim to provide complete artificial replacements for human tutors;
- computer-mediated communication, which can facilitate and enhance communication between teacher(s) and student(s), and between students;
- laboratory automation;
- simulations.

Many computer programs used for teaching combine two or more of the features described above. Examples in Chemistry include ChemiCAL[83] and the Chemistry Courseware Consortium's packages.[78, 84] Journals such as *Active Learning* and *Software Reviews, Journal of the CTI Centre for Chemistry* contain numerous other examples.

These features mean that computers allow new approaches to teaching to be developed. This automatically creates a potential benefit: as discussed above, a multiplicity of teaching methods can be very effective in promoting deep learning. However, any teaching method can be misused, and the use of computers has many unique potential problems. How can a tutor, keen to enhance their students' learning by use of computers, decide whether the benefits will outweigh the problems?

Are computers effective?

The Dearing Report maintains that "*the innovative exploitation of Communications and Information Technology holds out much promise for improving the quality, flexibility and effectiveness of higher education*"[1] (Chapter 13).

Computer-based material could be used to cope with increased student numbers. As Appendix 2 to the Dearing Report discusses, if resource-based learning is employed widely, the cost per course (in terms of staff time) need not increase as dramatically with increased student numbers as it would with more traditional course structures. For this to be achieved, the resource materials must be very well-designed, and capable of supporting a student working independently. It is worth noting that the benefits of this type apply mainly when resources are developed elsewhere and customised by a tutor for their own course. Developing one's own resource materials requires a large number of staff hours per hour of student learning time.

Decreasing the ratio of staff teaching hours to student hours of learning does not in itself show that using computers in teaching is worthwhile. The MacFarlane Report[81] found that:

"no general and comprehensive study exists which treats in detail the costs and benefits of applying innovation and using educational technology in higher education" (p. 80).

There is, however, some evidence that computer-based teaching has a beneficial effect. Kulik *et al*[85-87] report that computer-based teaching gives a small but significant improvement in examination marks, and reduces the time required by the student to cover the same subject area to around 70%. However, the examinations in the studies which show these effects predominantly assess factual knowledge, rather than understanding. It is perhaps unsurprising that students absorb facts more efficiently when working at their own pace with computers than with lecturers.

The most common general finding in this area is that there is no significant difference in students' learning from different teaching media, including computer-assisted teaching. Russell[88] has collected around 250 research reports, summaries, and papers which support this view. In a specific chemical example, the comparison of a self-paced multimedia package with a conventional lecture course showed no significant difference in the test results of the two groups.[89]

So it is not possible to say in general whether a computer-based teaching exercise is effective or not; it will be necessary to examine it in its particular context.

How can we tell if an exercise is effective?

Obviously, for a computer-based exercise to work at all, the software and hardware involved must be useable. Whether or not the exercise is effective or not will depend on factors beyond the software itself. The educational principles discussed in the first section are a useful guide here: the exercise should build on what the students already know, and the context and assessment should be carefully designed in order to encourage the students to adopt a deep approach to the exercise.

Moyse[90] and Laurillard[6] have shown that deep learning is favoured if students engage with a computer exercise using 'structural' or 'formal' thought, where they have a model of what is going on and can apply their knowledge from other areas. If, on the other hand, they work only at a more 'functional' or 'operational' level, where they have only a fixed set of rules which they apply without understanding the basis for the rules, they tend to adopt a surface approach. Engaging in such structural or formal thought gives a greater scope for understanding, and makes it much easier for students to see the application of what they have learned to new contexts.

Jonassen[91] applying constructivist principles, argue that the computer should not be used as a mere conveyor of information (as is common). Instead, it should be employed as a tool to facilitate the construction of understanding by transcending mental limitations (such as finite working memory), and students should be given authentic tasks to carry out.

Perhaps the most useful way to examine the utility of a computer-based exercise is to apply the framework for the effective use of technology in teaching in higher education set out by Laurillard.[6] This framework is summarised in Figure 1. It is designed to encompass all aspects of the academic learning process, and encourage a deep approach to learning. Laurillard calls this model a conversational framework, because it stresses the importance of interaction between the student and the teacher.

The framework requires interaction at two levels: that of actions, and that of descriptions. Interaction at the level of actions concerns direct, experiential learning: actions on the world and their result. Interaction at the level of descriptions concerns adaptation and reflection: conversation about the world. An example of an activity which concerns the level of actions might be carrying out a preparation of an azo dye and seeing the vivid colour; at the level of descriptions, it would be considering the molecular orbitals, energy levels and photons which give rise to the effect. Laurillard uses the term 'intrinsic feedback' for the information the student can obtain at the level of actions, and 'extrinsic feedback' for information at the level of descriptions. Obviously, computers could conceivably be used to supply feedback of both types.

To learn in an academic sense, conversation (interaction) must occur at both levels. It is possible for students to learn even when such conversation is not fully supported by the teaching method employed. For instance, the role of the 'action-in-the-world' component could be played by considering reported or thought experiments; or the 'discussion-about-the-world' could take place solely in the mind of the student. However, providing support for all aspects of the framework encourages and facilitates deep learning.

A teaching exercise can be examined to see how it supports the activities of the Laurillard model: does it allow conversation between teacher and student at the level of descriptions (numbers 1 to 4 in the figure) *and* at the level of actions (numbers 6 to 9 in the figure)? Few single teaching methods address all aspects of the framework, so it is often valuable to combine complementary methods. Thus it is unlikely that an exercise which relies solely on a student working alone at a piece of software will support all of the elements necessary for deep learning; but it can be very effective to use a piece of software in conjunction with less technological teaching methods.

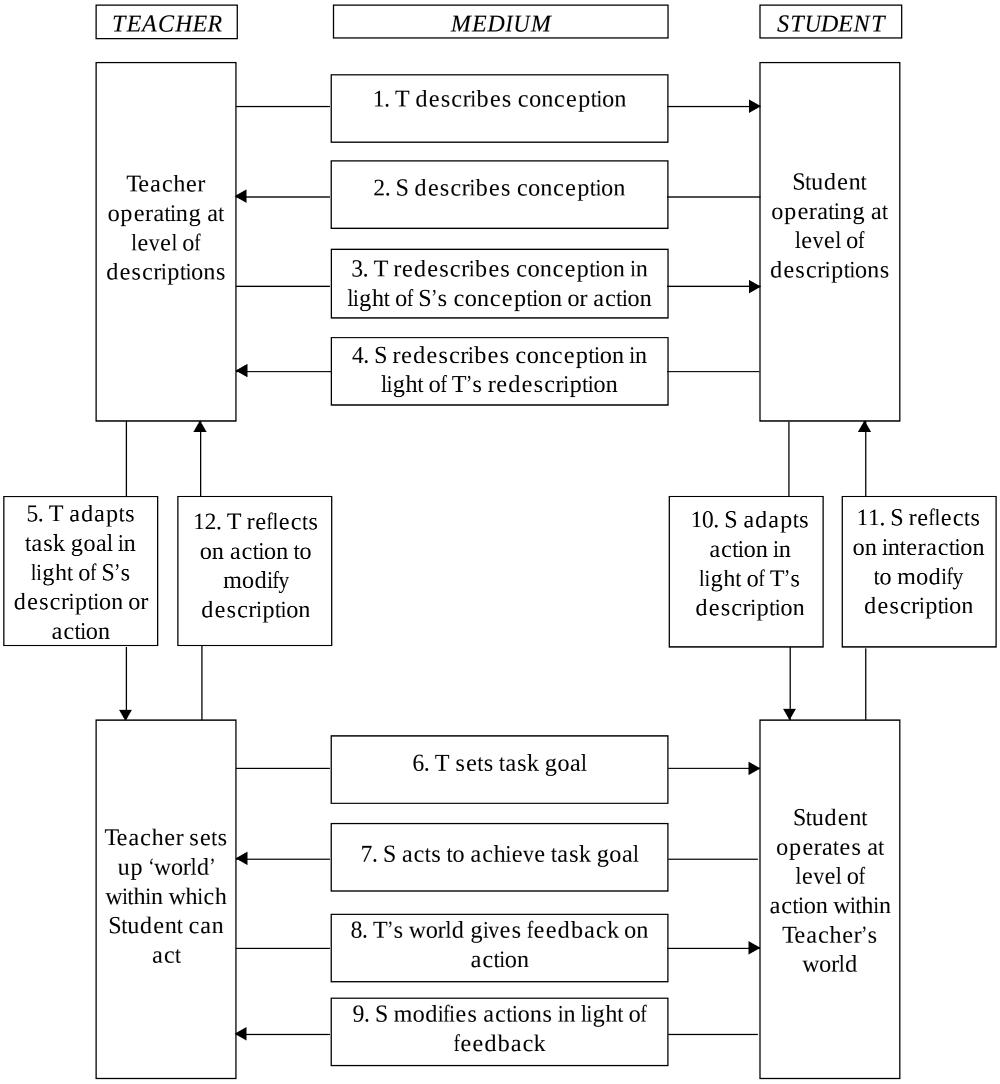
Conclusion

Computers are most effective when they offer a unique way of meeting a clearly identified educational need.

Existing courses are rarely perfect. Laurillard's framework and the work discussed in the first section of this review can help to identify defects; and few courses now take place without some form of evaluation taking place. Once identified, weaknesses can be addressed. Computers do not necessarily provide the best way to do this - but sometimes they do. Draper[92] calls this 'niche-based success'.

The effectiveness of a computer-based exercise lies mainly in the broader context - how the activities of the Laurillard framework are supported. Almost always, other forms of teaching will be required to facilitate students' deep learning.

Figure 1: Laurillard's conversational framework. Adapted from ref 6, *p.* 103.



Introducing computers to a course can often result in a boost to students' learning: there can be a novelty effect; and, less trivially, most chemistry teachers who introduce change do so after considering the purpose of the course, and how best to achieve it. The 'niche-based' approach, where an identified weakness in an existing course is addressed by the most appropriate method is the most reliable way to use computers to promote students' learning *powerfully*.

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