Creating critical chemists

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PROCEEDINGS

Two kinds of exercise have been developed with the intention of stimulating groups of students to discuss chemical topics and to develop their thinking skills. The exercises have been used with undergraduate chemistry students at Hull, and appear to have met their objectives. The exercises which are described and illustrated here are four types of 'critical thinking exercise' (constructing argument, understanding argument, critical reading, and making judgements), and traditional logic problems which have been rewritten into a chemical context.

Introduction

Students on undergraduate chemistry courses are very well trained to memorise factual information and reproduce that information under examination conditions. The acquisition of this skill is one of the main ways of achieving academic success in Higher Education. This is not surprising if we consider the nature of most undergraduate chemistry curricula which encourage a 'skills and drills' approach to chemistry[1]. The subject is consequently reduced to a vast set of facts and a loosely associated set of problem solving skills. There is little or no chance for students to discuss the nature of scientific investigation, and reasoning and problem solving skills are often restricted to routines or algorithms on which students can be drilled. Johnstone[2] warns that this approach is in danger of cultivating a closed *all is known* view of chemistry as a discipline in which students can make no personal contribution. It has been demonstrated[3] that students who see scientific knowledge as a body of facts will generally follow a passive rote-learning strategy whilst those students who see science as an ongoing process of concept development will tend to think about new material and integrate it with other scientific knowledge. According to de Bono[4]

"the long years of education are mostly concerned with knowledge. Fact is piled upon fact and little if any time is spent thinking... On the whole it must be more important to be skilled in thinking than to be stuffed with facts."

Of course, there are many chemical facts which students need to learn, but we must also make time and provision for them to develop and practice their thinking skills.

My objectives in developing these exercises has been to provide students with the opportunity to discuss chemistry, to develop valid opinions which may differ from those of the tutor, to evaluate and criticise ideas, and to tackle new types of problems. The exercises I will discuss here are exercises in critical thinking and logic problems.

Critical thinking exercises

Some time ago John Garratt and I came across the work of the Meno Thinking Skills Service[5]. Their aim is to assess students' potential thinking skills. To be effective as assessment exercises, their exercises (or test questions) need to be context free. This contrasts with the view of Byrne and Johnstone[6] that critical thinking is a subject-related skill. It occurred to us that we could use the Meno approach to develop subject-related exercises in a similar style, and that these would create valuable opportunities for developing rather than assessing thinking skills. From the Meno style of exercise we have selected Constructing Argument and Understanding Argument and have also developed Critical Reading and Making Judgements[7,8,9].

Constructing argument

In these exercises students are presented with three statements which they must arrange in such a way that they constitute a logical argument when joined together by words such as *therefore, so,* or *it can be inferred that.* Students are always asked to justify their preferred order. Consider the following example:

(A) *For mononuclear oxoacids, the species with the greater number of oxogroups has the lower pKa and is the stronger acid.*

(B) *$HClO_4$ is a stronger acid than $HClO_3$.*

(C) *$HClO_4$ has more oxo groups than $HClO_3$.*

The order *A, C therefore B* or the order *B, C this illustrates the general principle that A* can both be justified. The first option illustrates the way in which we tend to teach chemistry. We present students with a 'rule' and expect them to use it to predict observations on which the rule may actually have been based. The second option is much closer to how chemistry actually evolves: evaluation of experimental observations leads us to postulate a general rule, although, obviously, more than two pieces of evidence would be required. Whenever I have used this example, with students or with academics, the group is usually split fairly evenly between these two options. This leads invariably to a discussion of the nature of scientific argument, logical reasoning etc. From this simple exercise you can see that students will be required to think carefully, to justify their reasoning, to defend an opinion and to discuss their opinion with other students. As the Meno problems are used for assessment they must be completely unambiguous and have a single correct answer. In contrast, if problems are to be used for learning, then the ambiguity apparent in this example is useful as it leads the students into justification of their responses.

Understanding argument

In this type of exercise students are given a passage of text which forms a coherent argument. Following the passage are several statements from which students must select the one which will, for example, express the flaw in argument, present the underlying assumption, strengthen the argument etc. Consider the following example:

Mono-nitration of methylbenzene results in a mixture of 2-substituted (60%) and 4-substituted (40%) product. This suggests that steric hindrance slows down the rate at the two position. This suggestion is supported by the observation that mono-nitration of t-butyl benzene yields only 10% of the 2-substituted product and 90% of the 4-substituted product.

Which of the following statements best expresses the underlying assumption in the above passage?

(A) The expected ratio for an unhindered reaction is 2/3 2-substituted and 1/3 4-substituted products.
(B) The expected ratio for an unhindered reaction is 50% 2-substituted and 50% 4-substituted.
(C) CH_3 is 2,4 directing.
(D) CH_3 causes no electronic difference between the 2 and 4 positions.

This problem requires careful thought in order to arrive at the best answer. Even groups of academics cannot immediately agree on what this is. The exercise, therefore, provides scope for discussion of the chemical problem, and of the thought processes involved in arriving at an answer to the question.

A is without question an underlying assumption, and I therefore suggest that it is the best selection to make. *B* would not be expected by any competent organic chemist and in that sense is untrue. C is true, but the data given in the passage demonstrate that CH_3 is 2,4 directing and so this is not an underlying assumption in the normal sense. *D* is a piece of theory which rests upon observations of many aromatic substitution reactions.

Critical reading

Another area in which students need to be encouraged to exercise judgement and analytical perception is in reading. They read from a wide variety of sources including textbooks, journals and papers and do not often question what they read or ask themselves whether they fully understand what they have read. Authors necessarily often have to assume that the reader already has specialised knowledge that the students may not yet have acquired. The example given here is typical of the sort of passage which students might reproduce word for word without fully understanding the context or assumed knowledge. They often do not bother to look back at previous chapters in order to fill in the gaps in their knowledge.

Scandium is as similar to aluminium as to yttrium and the lanthanides because of its small ionic radius. Scandium fluoride is insoluble in water but dissolves readily in an excess of HF to give fluoro complexes such as $[ScF_6]^{3-}$, and the similarity to Al is confirmed by the existence of a cryolite phase Na_3ScF_6. (from Cotton & Wilkinson, Advanced Inorganic Chemistry).

What extra piece of information would help you understand this passage?

(A) Scandium and aluminium have similar radii.
(B) Aluminium occurs naturally as cryolite.
(C) Cryolite is Na_3AlF_6.
(D) Cryolite is insoluble in water but dissolves in HF.
(E) The cryolite structure is adopted by many salts containing small cations and large anions.

The most obvious answer is C. All of the other statements are true and this fact often confuses students, who often choose the first factually correct statement they recognise rather than thinking about which one fits the given criterion. Different students feel they need different pieces of information in order to better understand the passage as they all bring different prior knowledge and experience with them to any task. Requiring students to explain their choice of answer helps them to clarify their own thought processes and to identify the gaps in their knowledge.

Making judgements

To many students *problem solving* involves manipulating or interpreting data in order to arrive at a correct answer already known to the tutor and *asking questions* involves an expectation that the tutor knows the answer. Students can be misled into thinking that in chemistry there is a unique answer for every problem. In contrast research chemists regularly face problems which may not have a single correct answer and so require judgements to be made in order to arrive at a sensible solution. Questions have to be asked by the researchers themselves before they can begin to build a context for the problem within which to propose an answer.

This next type of problem requires students to ask questions and provide a context for the problem before they can begin to propose solutions. The problems are designed to be of a general nature, open ended and to promote discussion. The best or most sensible answer depends entirely upon the context and for any context there may be a range of acceptable answers. Consider the following examples:

What do we mean by a pure compound?

or

What level of impurity is allowed in a compound before it is regarded as impure?

These appear to be very simple questions but they are not easily answered. For instance, if we begin by defining the context as being 'purity of water' we still have to define much more of the context before we can provide an answer. For example, 'purity' means different things to different people in different contexts and we might consider HPLC grade water, deionised water, tap water, spring water, ground water. As tutors we may be guilty of switching contexts quickly without defining the new context to our students. Questions of this type encourage students to explore concepts that they are familiar with but seldom give much thought to.

Logic problems

The final type of problem discussed here involves two chemists, Dr Beaker and Dr Gooch, who encourage students to think in many different ways and to exercise their powers of logical reasoning and deduction. The idea for these problems came from an engineering problem solving book, 'The Chicken from Minsk'.[10] The problems in this book are brain teasers which the authors claim motivated and enthused their students. It seemed likely that chemistry students would find the problems more relevant if they were set within a chemical context and so Dr Beaker and Dr Gooch were created[11].

An example of a Dr Beaker problem is given here:

Dr Beaker and Dr Gooch each want to prepare a batch of a new compound but both have insufficient starting material. Dr Beaker is 24 g short and Dr Gooch is 2 g short.

They decide to pool their material to make a single batch. When they do they find that they still do not have enough.

How much starting material does the preparation need?

Observing the way that students (and academics) tackle this problem is very interesting. They appear to tackle it in one of three ways. One group know the answer immediately, almost intuitively, but have great difficulty explaining how they arrive at the answer. Another group work out the answer by logical deduction and a third group will construct a set of equations and solve them. Even though there is a single solution to these problems they do encourage students to think creatively and they are encouraged to explain how they solved the problem. People use different strategies for solving the problems and, by thinking about how they think, they learn something about their own thinking processes and strategies for problem solving.

Conclusion

I have been using critical thinking exercises and logic problems with students for several years. I have used them with classes of up to 40 students organised into small groups of 3 or 4. The students work on the problems within the small groups but then engage in class discussion of their answers and are encouraged to explain and justify their answers. In my experience, students have become enthusiastically engaged with the exercises and are easily guided into class discussion. (The relative success of each problem can be judged from the degree of arm-waving and head-scratching that takes place).

There are many ways of encouraging students to think critically, to evaluate and analyse and to explore their own thinking skills. A few have been described here. Edward de Bono said in *The Five Day Course in Thinking*[4].

'...based on the three points of simplicity involvement and achievement, the book is intended to amuse the reader into developing an awareness of his own style of thinking, its strong points and weaknesses'.

The problems described in this presentation are simple, they involve the reader and enable them to achieve some success. Their value is not diminished if they are also able to amuse.

My observations of students tackling the exercises described here suggests that students are not very good at recognising the tools they have for solving problems, and even worse at selecting the most appropriate tool for a job. It is as though their thinking skills are like the tools in an untidy garden shed. When a problem arises, the temptation is to open the shed door a crack and take out the nearest tool with which to tackle the problem. This is inevitably the last tool which was used and so new tools are not experimented with. It is our job to encourage the student to throw open the shed door and learn how to use all the tools kept within.

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A collection of critical thinking problems is soon to be published; C J Garratt, T L Overton and T Threlfall, Addison-Wesley Longman, early 1998.

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