The development of creative problem solving in chemistry

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Abstract: The object of this paper is to show how research has gone hand in hand with development to produce materials for teaching and learning which take problem solving well above the level of algorithmic manipulation and into the realm of creativity. To combat the common feature of school science and chemistry in particular, that problems have a unique solution, and to give students an appreciation of real science, problems of an open kind have been developed, which encourage the ingenuity, and idiosyncratic contribution of the students involved for their solution. In these, often there is no correct answer, only a 'best' answer, and there may be a variety of possible methods of finding it. Criteria for success are very different from the more common type of closed problems, but are much more difficult to define. The second strand of the work described here aims to make students aware of the benefits of group work and discussion by setting them objectives which are more likely to be achieved by groups of students working cooperatively together. Discussion is seen as of two types: task orientated discussion (how to solve the problem), and reflective discussion to consider in what ways their group was successful, and why; and in what ways it was less successful, and why. This helps students to realise that their success as a group is more than the sum of their individual contributions. [*Chem. Educ. Res. Pract*., 2006, **7** (2), 96-113]

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Introduction

In 1962, a document containing the so-called 'alternative' Chemistry syllabuses for use in Scottish schools was published (SED, 1962), covering O-grade (ordinary grade, age 15/16) and H-grade (higher grade, age 16/17) Alex Johnstone had made a major contribution to the development of these syllabuses, which were 'alternative' in the sense that teachers could adopt them or remain with the traditional syllabuses and examinations if they wished. However, they caught the mood of the moment, and most schools adopted them quickly, allowing the traditional syllabuses to be phased out. Later, Johnstone developed the groundbreaking Certificate of Sixth Year Studies (CSYS) syllabus for those post-H-grade students who opted to remain at school for a further year of secondary education. This was designed with deliberately low factual content to allow teachers to focus on wider skills of thinking (SEB, 1990). About one third of the marks for the assessment of this course were allocated to a project and practical work. These projects were organised and marked in a way similar to that of a final year university degree project, with an external assessor coming in to examine the students both in the practical work and the projects.

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Teachers found that this increased students' maturity and self-confidence, easing the transition to university or work.

Research on problem solving and on why students find it such a problem was ongoing at the Centre, with publications starting in 1979. A series of teaching units was developed by Reid for school pupils (described in Johnstone and Reid, 1979, 1981b). Some of these were in problem format while many involved the use of small groups. They were designed, among other things, to take chemistry out of the classroom in a realistic way, and to foster thinking skills. However, the main aim was the development of positive attitudes to chemistry and to show pupils that chemistry requires critical thinking and risk taking (Johnstone and Reid, 1981a, 1981b).

Further work resulted in the publication, by the Royal Society of Chemistry, of five booklets written by school teachers (Johnstone, 1982), designed as an integral part of the Certificate of Sixth Year Studies course for ages 17/18. These were largely based round industrial processes (fertiliser production, drug design, zinc uses and extraction, titanium uses and extraction and properties of oxygen-containing organic liquids). Similar research and development produced problem-solving materials for students taking standard grade (replacing O-grade; GCSE equivalent) at 15/16 years of age. These problems were entirely based upon laboratory work. They were designed to complement normal laboratory work and most of them were intended to occupy the last twenty minutes of a laboratory period. The clues for their solution were to be found in the preceding conventional laboratory. The effect was to supplement and reinforce the main points of the conventional work and to give the students room to exercise their own ideas. The output from this research was the book '*Practical Problem Solving for Standard Grade Chemistry*' which was circulated to all schools in Scotland (Hadden, 1989).

All this represented the starting point of this project. What was new was using group dynamics as a means of encouraging creativity. The aims agreed with the Royal Society of Chemistry reflected this. These were refined as work progressed and eventually became the following.

- To improve students' ability to work and communicate with others, and to develop an awareness and control over their own thinking processes;
- to give students the opportunity to develop their problem solving skills;
- to give students the opportunity to be creative and use divergent or lateral thinking;
- to show students that science is more than 'getting the right answer', and that it can involve using one's judgement, being creative and using lateral or divergent thinking.

We intended to meet these aims by

- presenting problems with a variety of possible solutions;
- getting the young people to work in groups to discuss their solutions critically and present their agreed solution to their peer group in the form of a mini lecture.

Thirty problems (seventeen of them lab based) were designed to meet these criteria. They were trialled by 16/17-year-old school students in Central Scotland. Before the problems were attempted, it was found to be important to explain to students the purposes of these new learning experiences. They were told that these materials were designed to enhance their ability to solve new or unusual problems and to give them opportunities to communicate and co-operate with others in a small group.

Appendix 1 outlines how the problems were to be used while Appendix 2 gives two examples of the problems.

Problem solving

A problem is sometimes defined as a situation where at present the answer or goal is not known. For the problems normally encountered in educational situations, the way to that goal is not known initially. This, of course, assumes that a goal has been specified: 'find the volume of'; 'how many ...?'; 'show that ...'. Some problems of this kind can be reduced to routines or algorithms in which students can be drilled, meaning that they can eventually become exercises where one set of numbers is substituted for another. For the student who can recall the method of tackling the problem, no problem remains.

However, in real life, problems may have quite different shapes which are not amenable to algorithmic manipulation and which demand a degree of lateral thinking for their solution. Criteria for success are very different from the more common closed problems. Teachers and students are so used to getting 'the correct answer' in academic problems, that they can be misled into thinking that in science, there is a unique answer for every problem. There is a danger of cultivating within our students an 'all is known' view of science: a discipline to which students can make no personal contribution. All too often examination questions are of this type, reinforcing even more this distorted view of science.

This paper describes problems of an open kind, which invite the ingenuity, and idiosyncratic contribution of students to their solution. Sometimes there is no correct answer, only a 'best' answer judged against the criteria set by the students themselves. Students may end up with their best answer being within an order of magnitude, realising this is only a useful 'guesstimate'. Sometimes, there is a correct answer but a variety of possible methods. Success in others may lie with economy of time, cost or scale.

The problems attempt to foster process skills such as data seeking and selection, choice of method, balance of criteria, and awareness of error as well as discussion and presentation skills. Underpinning our approach is the Information Processing Model of learning. According to this model, the process of problem solving will more or less cease if too many 'chunks' of information are competing for the students' attention. Chunks are pieces of information coming into the mind's 'working space'. However, if there are too many of these, there is no space left to process the information and the problem solving process grinds to a halt. An upper limit of about five chunks is normal for comfortable manipulation.

The Information Processing Model as outlined by A H Johnstone in Wood (1993) acted as a theoretical basis for developing the strategies recommended to students attempting to find solutions to the problems. For example:

- The problems were designed to minimise overload by the way they were structured, and by using discussion to help students break the problem into processable chunks. Consider 'Hair' as an example (Appendix 2). Students are asked to estimate the approximate rate of growth of human hair, and to use this figure to estimate the number of amino acid molecules which are incorporated in the growing hair every second.
- The initial instruction to the students points out that for many problems the search for an exact answer may be a distraction, and tells them that they will have to make approximations on their way to devising a solution. This initial discussion can focus on familiar words in the problem like 'hair', 'rate of growth', 'units', helping to define the problem and providing the important framework ('perception') of the problem. The importance of the language used in framing the problems cannot be overemphasised (Johnstone and Cassels, 1980; Talbi, 1990).

- Such discussion often initiated key ideas, which led to a solution of the problem. In this case, it was words like 'haircut', 'hairdresser' or phrases like 'about once a month', 'about 1 cm cut off' that led to a solution.
- Students are encouraged to 'brainstorm' the problem thus giving access to the long-term memories of several people and their associated mental patterns and chains (Kempa and Nicolls, 1981; Reid and Yang, 2002).

Types of problem

Originally we saw problems as of four different types -

Type	Data	Goal
1	specified	specified
2	insufficient	specified
3	specified	not specified
4	not specified	specified

As work progressed, this classification evolved and expanded into the following (Wood and Sleet, 1993):

Type	Data	Methods	Outcomes/goals	Skills bonus
1	Given	Familiar	Given	Recall of algorithm
2	Given	Unfamiliar	Given	Looking for parallels to known methods
3	Incomplete	Familiar	Given	Analysis of problems to decide what further data are required
4	Incomplete	Unfamiliar	Given	Weighing up possible methods and deciding on data required
5	Given	Familiar	Open	Decision about appropriate goals; exploration of knowledge networks
6	Given	Unfamiliar	Open	Decision about goals and choice of appropriate methods; exploration of knowledge and technique networks
7	Incomplete	Familiar	Open	Once goals have been specified by the student, they are seen to be incomplete
8	Incomplete	Unfamiliar	Open	Suggestions of goals and methods to get there

The 'normal' problems usually encountered are of types 1 and 2. Types 3 to 8 represent much more the skills required for investigative work. Goals may not be absolutely clear at the beginning, and methods may be unfamiliar. Data may be incomplete and the student will then have to generate them from experimental work and/or by literature search.

Problems of type 3 would involve the student saying '*If you want me to do this, I shall need the following ...*'.

Type 4 could be exemplified by *"How many copper atoms are there in a 2p coin?"*. This would involve a reasoning chain like: *"If I knew the mass of the coin and if I assumed that it was pure copper and if I had the atomic mass of copper and Avogadro's number, I could get an answer, but it would only be approximate. But if I have no balance and only a ruler, I could get* *its volume (approximately) and if I knew the density of copper, I could get a good estimate"*. This is very different reasoning from that in types 1 and 2.

Type 5 is much more open and is left to the judgement of the student as to what would constitute a reasonable answer. For example: 'Given the formula [$Co(NH_3)_4Cl_2$] deduce from it as much as you can'. This could yield a range of responses, including the oxidation state of the cobalt ion and its 'd'-electron configuration, the name of the complex, its percentage composition, its isomers, its likely reactions, and so on.

Type 7 would require the students to specify the goals, but to achieve these, extra data would have to be requested.

Type 8 might be of the kind where the students were given a substance and asked to suggest uses for it. The students would have to ask for, or find out experimentally, its properties before deciding upon uses.

Type 6 would be similar to type 8 but the given substance would be familiar to the students.

Types 1 and 2 problems have their place, but students are short-changed if they are not also exposed to the other types. In all the types, thinking skills are exercised, and flexibility, branching, open-mindedness and creativity are encouraged. Students who perceive chemistry as a developing, changing and intellectual adventure with room for individual thought and contribution will be those who are potentially the creative thinkers we hope to encourage.

All thirty problems in the book were trialled in schools at senior levels (17-19). The behaviour of the students was observed carefully. All the problems stimulated discussion and/or promoted the skills previously mentioned. Researchers involved in the trials were pleasantly surprised by the ability of students to argue and defend their presentations to their peer group and to the researchers who were total strangers to them.

The aim was to foster the development of the following process skills:

- Lateral thinking
- Balance of criteria
- Choice of method
- Data seeking and selection
- Awareness of error
- Discussion and presentation skills.

Discussion groups

"*The importance of problem solving for individual pupils has been widely emphasised ... However, it is also the case that scientific investigation, as it is practised in the wider scientific community ... involves teams or groups of workers. Co-operation and teamwork as well as effective leadership are likely to be qualities important among scientists. If we are to prepare the next generation of scientists for this, it will be necessary for schools to teach with these points in mind and not to leave it to chance.*" (Gayford, 1992).

A recent article "*Graduates unfit for work, say top firms'* reports that Britain's biggest companies are finding that 'many [UK] graduates lack the basic skills needed for employment. They "*are being let down by the [university] system … last year 598 positions were left unfilled as a third of employers said that they could not find candidates of sufficient quality*" (The Times, 2006).

Managers cited a series of shortcomings in potential recruits. These include:

- Too much time spent working on degrees and not enough joining clubs and societies, where students might work in teams;
- Not enough time spent on giving presentations in tutorials, leaving new graduates unable to communicate ideas in the workplace.

Discussion and presentation skills are important in all walks of life. They are not only important in their own right but are highly regarded by employers, and indeed in the community at large. Unfortunately, most students have to have these consciously taught, not necessarily by formal means, but by example, gentle encouragement and opportunity. Initially, students have to be encouraged to share tasks in groups, to pool their gathered information, to brainstorm, to listen, to criticise positively and to accept criticism as being constructive. Once they see the utility of group methods, even the most diffident of students make contributions in a peer group. There is a fine judgement needed on the part of the teacher as to when to intervene and when to remain silent, when to encourage and when to act as a consultant.

The importance of discussion

Discussion in schools

The traditional emphasis on content arising from examination constraints perhaps can mean that pupils tend to see science as an impersonal body of knowledge to be learned rather than as a co-operative activity where their knowledge, their skills and their value judgements are important and relevant. Such a content-driven approach to chemistry learning may well lead students to miss out on the excitement of chemistry and they may well see their studies merely as an experience to be endured on their way to some other area of study.

Primary pupils are accustomed to group work and to the associated project planning and allocation of different tasks within the group. The excitement and enthusiasm with which they approach the problems can be a great motivating force. This can continue at secondary stages. Extension material can build upon the success of group work in primary schools and can encourage groups of pupils to devise solutions to novel problems. They can see their learning as something generated, at least in part, from within the group rather than being imposed from outside.

Discussion in higher education

Group projects and presentations are becoming more common (Bell et al., 2002) in university and college courses, with the marks obtained contributing to the final degree classification. In addition to assessment by the responsible lecturer, students can assess one another using specific criteria set by the department concerned.

Discussion can help cultivate critical thinking skills

Engaging in discussion with others develops critical thinking. This can show students that they do have the ability, and even the obligation, to think critically. Resolving a difficulty, understanding a difficult topic, a flash of insight: these can and should be satisfying experiences. (Byrne and Johnstone, 1986a, 1986b, 1986c, 1987).

Discussion can help clarify ideas

Discussion can promote active learning because, in effective discussion, students can:

- express in their own words what they have learned;
- think critically about new knowledge and ideas;
- justify any decisions they make which are based upon the new knowledge and ideas;
- be prepared to admit to uncertainty and lack of knowledge;
- be prepared to admit to incorrect thinking and the superiority of another's ideas without loss of self-esteem.

Discussion groups can improve self-esteem

Schools are trying to get pupils to accept more responsibility and become 'managers of their own learning'. They are encouraged to become aware of their own learning processes, and as far as possible to be in control of them. At best this can be successful in helping young people to grow in self-esteem, to feel good about themselves as learners, and therefore to become more successful as learners (Higher Still Subject Guide: Chemistry, 1997).

Discussion can utilise group dynamics

Several minds working jointly on a problem can produce solutions that each on its own could not manage. As the group as a whole comes to realise this, it sees the necessity for encouraging the shy and the uncertain, stimulating the lazy and restraining the over-talkative.

Types of discussion

Two types of discussion are involved, both of which need a supportive and non-adversarial atmosphere. The first focuses upon the task itself and the second upon the factors, which contribute to effective group discussion and teamwork.

1. Task related discussion

a. Discussion before and during the problem

The problems are designed to increase problem-solving skills and to encourage co-operative working in small groups. In some, students can treat the initial group discussion as a 'brainstorming' session where all ideas are encouraged no matter how trivial or unrealistic they may appear at first sight. Divergent thinking is encouraged, as an apparently unrealistic idea from one group member can initiate a train of thought in other group members that could lead to the problem being solved.

Spending sufficient time on this initial discussion can save much time and effort during the problem itself.

b. Group presentations

In order to allow sufficient time for discussion, it can be better to give one problem to two groups of students rather than increasing the number of problems beyond the two or three recommended (Appendix 1). Each group makes its presentation to the whole class, and then discusses its findings with the class. This worked best when the teacher exercised informal control as required.

c. The teacher's role

The teacher's role during the problems is to provide sufficient support to ensure that the problem solving is at least partially successful. Students should be allowed to make mistakes and explore blind alleys provided that this leaves sufficient time for them to accomplish enough to feel some degree of success. They should be continually reviewing their solutions. Questions such as, *"What are you doing?" "Why are you doing it?" "How will it help you solve the problem?"* help focus the students' minds and can improve their problem solving performance dramatically. They also need encouragement: *"That sounds like a good idea, but have you thought about ... ?"*

2. Reflective discussion

Once the group have completed the problem, each student and the group as a whole are encouraged to be introspective and asked to consider -

- in what ways their group was successful, and why;
- in what ways it was less successful, and why.

This discussion follows on from the presentation and the ensuing discussion about the problem and the chemistry involved. Students are encouraged to look at what they achieved, and how they achieved their solution. This could give the participants valuable insight into themselves and could allow them to start to identify some of the elements that make for successful teamwork.

The aim of this discussion includes encouraging the ability to

- give and accept constructive criticism;
- value one another's contributions;
- be introspective and to consider one's own feelings and those of other group members.

Suggested approach to reflective discussion

People are often reticent when talking about factors that affect them on a personal level, and are more likely to enter into this type of discussion when in small groups. It was suggested that only a few minutes be spent on this type of discussion when it is first attempted, starting in a low-key way by asking a small number of questions and building upon success each time it is tried. The teacher should move the discussion imperceptibly on from task-related discussion to reflective discussion. Not too much should be expected at the first or even the second attempt.

As the students gain experience of such discussion, they start to realise that they are developing the skills and the abilities needed for successful teamwork, and that these are useful when devising solutions to the task in hand. The teacher can assist this process by asking questions regularly, usually resisting the temptation to offer answers. When asked a question by a group member the teacher should encourage another member of the group to answer it. The reply "*that's an interesting question*" is much used by leaders of team building courses!

Note that the teacher's role here is quite different from that during the problem-solving itself where he/she should give enough help to ensure success in tackling the problem concerned.

The following was suggested to encourage reflective discussion;

a. The group sits roughly in a circle with the teacher acting as informal chairman.
b. Reflective discussion can be started by asking a simple question such as *"How did you feel about the discussion?"* perhaps following this with *"Did it go well?"*, and *"Why do you think it went well?"*

An alternative is to start from the teacher's observations of the various groups' earlier discussions where the teacher has some idea of the more successful and less successful aspects. One of the successes could be used as a starting point, for example by asking direct questions such as *"John, would you agree that your group was successful in your discussion of ... ?", "Why do you think it was successful?", "What made it successful?", "What do the rest of the group think?"*

Once discussion is under way the teacher should ensure that some time is spent focusing on the feelings of the individuals in the group. This could be done by asking who felt that their contribution was never made (why?), or didn't have much heed paid to it, and what their feelings were at the time. An alternative is to choose a point in the earlier discussion where someone's point got lost in the discussion and asking something like *"Sheila, did you feel that your point about ... got sufficient attention?"*

c. At the end of the discussion, it is worth re-emphasising to the group the importance of teamwork and the interpersonal skills needed to work effectively in groups, and how important these are in industry, commerce and research. Most decisions are made, if not by committees, on the recommendation of committees.

Reflective discussion is designed to make students aware of their own feelings and emotions and of those of their peer group, and to make them realise how important these are in group work. This can boost students' self-confidence and increase their ability to contribute positively to group work.

Teamwork

The ability of each individual to function as a team member is a necessary but not sufficient condition for successful teamwork. Members of a particular team must be able to work effectively together. While there are certain attributes for all team members that increase the chances of this happening, members of successful teams usually have both different skills and different personalities.

1. Different skills

Different skills/ abilities should be represented in a team or in a committee, for example:

- a rugby team, where different balances of skills are required for forwards and for backs;
- a committee to plan a new chemical plant should include engineers, chemists, accountants and lawyers.

Students with a background in biology can have a different perspective from those who have studied only physical sciences.

2. Different personalities

Successful teams are likely to include a mixture of personality types. There are many ways of categorising people. One system (discussed by Johnstone and Al-Naeme, 1991, 1995) that works well in the science domain categorises by motivational trait -

- The ACHIEVER - sets out to do well, to be top of the class, is competitive, prefers expository methods of teaching and learning, dislikes being held back by slower students;
- The CONSCIENTIOUS - wishes to do well, content to please teachers or parents or whoever by working conscientiously within clear cut guide-lines, gains satisfaction from work duly performed;

- The CURIOUS - keeps asking questions, enjoys exploring, is the divergent thinker, the creative person;
- The SOCIAL - enjoys learning cooperatively and is not competitive.

There is overlap between the traits, but many of us show predominantly one or two of them. Most successful teams have an appropriate mix of these personality types, with some individuals moving flexibly between roles.

Discussion is a central part of the problem solving process and this suits the ‘social’ learner. The ‘conscientious’ are often hesitant when tacking the problems initially because no secure framework of thought is provided and because of the variety of possible methods and/or answers. Research findings (Johnstone, 1998, 2001) confirm the observations made during the trials that even this latter group is stimulated by the problems once the initial uncertainty has passed.

Analyses of school science courses (Johnstone and Al-Naeme, 1995) show that they generally provide opportunities for the achiever, for the conscientious and for the social learner, but provide little opportunity for the ‘curious’ pupil. Some ‘curious’ pupils consider that there is little in science for them because they perceive it as only about ‘getting the right answer’. Yet the ‘curious’ person can be the creative thinker, playing a key role in teams designing new products or devising new solutions to problems. Many of these pupils may gravitate to non-science courses in senior school and/or college/university; this is great loss to the scientific community.

Continuing work

This work on creative problem solving is not the end of the story. The Certificate of Sixth Year Studies Chemistry was the second most popular subject in the Scottish Sixth Year (17-18), coming second only to mathematics. While the projects were never intended to be original research (although that was done on occasion), it had to be *original to the pupil*; but the large number of pupils presented a challenge to teachers to devise valid projects for them all. This presented a clear logistical problem for teachers to find new problems for the projects and so an innovative series of ‘Starter Projects’ were devised by final year university chemistry students working with Johnstone. These were published as small booklets in two sets (Johnstone, 1993, 1995). They provided sufficient information for the pupils to get started on a project. If the pupil was making little progress, then further information was provided. As a last resort, fairly detailed instructions were available. The assessment of these projects allowed credit for initiative and resourcefulness, but students who needed a lot of support were not given this credit.

In 1997, the Certificate of Sixth Year Studies was replaced by Advanced Higher (Higher Still Development Unit, 1997). This course was more prescriptive than its predecessor, with much more content (similar to that in English A level) and unfortunately, this left less time for investigative and problem solving work. However, the project in a shortened form was retained with fewer marks being available for it, and the use of an external examiner, although retained initially, has been regrettably discontinued.

When these latest reforms were first proposed, The Royal Society of Chemistry (Scottish Education Committee) was concerned that the project work and its associated learning experiences would be marginalised or disappear, and it persuaded the Higher Still Development Unit to commission (along with The Royal Society of Chemistry) the two original authors of the Starter Projects along with the author of this paper to update the previous starters and write new ones. This built upon the knowledge and experience that had been gained when trialling the problems on creative problem solving described above. These were published jointly by the

Royal Society of Chemistry and Learning and Teaching Scotland (Support Materials, 2000, 2002) and were circulated to all Scottish secondary schools.

These materials were written specifically for the Scottish system, but demand from outside Scotland showed that they were of more general interest and usefulness. A new introduction was written and the material republished by The Royal Society of Chemistry (Education Division) (Robertson, Gray and Wood, 2001).

This paper has attempted to show how research and development can go hand in hand, with support from a Learned Society (RSC) and the chemical industry, to make a difference to the way in which chemistry is taught. “Education in chemistry” can be successfully linked with “Education through chemistry” to transform the subject from a largely passive experience to be accepted, into an exciting, demanding and participative experience to be enjoyed.

Epilogue

One Head of Chemistry wrote to the author after trialling some of the projects with his 17-year old pupils – *“I spoke to the pupils informally after the trial and everyone remarked how much they enjoyed the double period and how quickly the time had passed. Another comment was that you really had to know what you were talking about before you tried to explain it to a group. They all felt that it was much more demanding than simply answering an exam paper question. I thought that the material was excellent and intend to use it next year after the appropriate section of work.*

”There is no doubt that it is useful revision but that is secondary. The group discussion, team work and experience of presenting conclusions/ findings to their peers were invaluable.”

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Appendix 1: Using the problems

General

The problems are designed to improve problem solving skills, and to encourage cooperative working in small groups. A brief introduction by the teacher is required so that students know the objectives of the learning experience and realise what is expected of them.

Format of the problems

For flexibility of use each problem is set out in two parts, as a statement of the problem and as a teacher's guide, including a suggested approach.

Each of the problems starts on a new page. When the problems were trialled the statement of the problem and the suggested approach were photocopied and given to students; this approach worked well and is recommended to teachers. However, teachers are encouraged to modify the problems to suit their particular circumstances. It is unlikely that the suggested approaches will suit all circumstances, and the extended discussion may not always be necessary.

The practical work in some of the practical problems is small and could be carried out in advance if access to a laboratory is not possible for the main problem solving session; some of the non-practical problems have extensions which do involve laboratory work, and could be incorporated into the main problem solving session.

Objectives

During the trials it was found to be most important to explain the objectives of the learning experience to the students before they attempted the problems. These include:

- to improve students‘ ability to work and communicate with others and to develop an awareness and control over their own thinking processes;
- to give students the opportunity to develop their problem solving skills;
- to show students that science is more than ‘getting the right answer’, and that it can involve using one’s judgement, being creative and using lateral or divergent thinking.

Students should know that these skills are not only important in themselves but are highly regarded by employers and the community.

The chemistry underpinning many of the problems is relevant to senior school courses and can be readily integrated into class teaching. In addition, during trialling it was found that group discussion to find solutions, and the preparation of a presentation to the peer group, helped to clarify concepts, deepen understanding and correct misconceptions.

Student groupings and duration of problems

During the trialling of these problems, discussions within groups of students were found to be effective. The size of the class will determine how many groups there are and how many different problems are in use at one time. For classes of about twenty, two or perhaps three different problems might be used; whilst for classes of twelve or less, one or two different problems would be more suitable. To allow more time for discussion it may be better to give one problem to two different groups of students rather than increasing the number of problems beyond the number recommended.

Each group should make a presentation to the rest of the class and then answer questions and discuss their findings with the rest of the class.

It is not possible to give definitive time allocations for each problem, as this depends upon many factors including:

- the problem itself;
- the number of students;
- the ability of the students and their previous experience of these problems; and

- the importance the teacher attaches to different parts of the problem (tackling the problem, its presentation and the discussion following the presentation). In practice, the reverse may apply – the time available dictates the number of stages tackled.

When the lesson lasts for about 100 minutes or more it is possible to complete some of the problems along with the associated presentation and discussion in one day, otherwise the presentation and/or discussion will have to be left until later. The presentation and associated discussion is sufficiently important to warrant the extra time.

An overhead projector with an acetate transparency per group speeds up the presentations because each group can prepare their visual aids simultaneously; otherwise several groups can be competing for the use of the blackboard at the same time.

The teacher's role

The teacher's role during the problems is to provide sufficient support to ensure that the students are at least partially successful. Students should be allowed to make mistakes and explore blind alleys provided that this does not take up so much time that it jeopardises success. They should be made to think, but given sufficient help, not by giving them answers but by encouragement ('that sounds like a good idea'), by asking appropriate questions or by pointing them in the direction of a suitable textbook. In some of the problems, an old inorganic textbook like Parkes and Mellor proved more useful than a more up-to-date book like Cotton and Wilkinson.

After presentation of the problems the group is asked to consider how well they accomplished the task, and discussion becomes more reflective.

Notes

1. 'Communication and interpersonal skills ... are considered to need the greatest development at the commencement of ... employment' from CASupdate no. 1, published by the Careers and Appointments Service of the University of Technology, Sydney, Australia.

2. Some projects have been used for examination revision. Here too, much useful learning took place during discussion. On occasion a misconception would persist through to the presentation, but further discussion, with teacher input as required, would remedy the problem.

Appendix 2: Two sample problems

Problem 1: Hair

The problem as issued to students

i) Estimate the approximate rate of growth of human hair in ms^{-1}.

ii) Use this figure to estimate the number of amino acid molecules which are incorporated in a growing hair every second.

Many real-life problems do not need exact answers. Often an exact numerical answer would be misleading.

In science, it is useful to be able to make estimates. This can be important when checking whether an answer makes sense, for example in deciding whether an injection of 10 cm^3 of a drug solution is a reasonable dose.

In this pencil and paper exercise you will need to make approximations to get answers.

You should refer to any sources of information that you think might help such as your notebooks textbooks and data books. Ask for assistance if you get stuck.

Teachers' guide

Introduction

Teachers who have not used the problems before should read the section 'Using the problems' before starting.

Prior knowledge

Concept of bond length and knowledge of amino acids. A detailed knowledge is unnecessary as students are encouraged to consult textbooks and data books during the exercise.

Resources

Scientific calculators, tables of bond lengths and access to suitable textbooks in which to find the structures of amino acids should be made available for reference.

Group size: 3 or 4

Possible methods

Question (i)

One method is: 'I go to the barber every six weeks and he cuts off about 3 cm of hair' or 'I get my hair dyed: after about 2 weeks there is about 1 cm undyed.'

Therefore 1 cm (0.01 m) of hair grows in 2 x 7 x 24 x 60 x 60 seconds

or

1 m of hair grows in 2 x 7 x 24 x 60 x 60 x 100 seconds

This equals a growth rate of 8.3×10^{-9} ms^{-1}. Given the accuracy of the data, the growth rate of hair can be taken as about 10^{-8} ms^{-1}. The approximations have made mean that the answer is no more than a general indication of the value.

Question (ii)

The size of an amino acid molecule has to be estimated in order to calculate the approximate number of amino acids joining a hair per second. Most amino acid molecules have similar structures H_2N-CHX-COOH where X is different for each amino acid.

To get an idea of the length of a molecule, the bond lengths in the chain can be added together: this approximates to 0.5 x 10^{-9} m (0.5 nm). The number of molecules joining each chain per second is calculated by dividing this figure into the growth rate figure calculated in question (i):

10^{-8} ms^{-1}/ 0.5 x 10^{-9} m = 20 molecules joining each chain per second.

This is only the first stage: the number of chains growing along each hair have to be taken into account.

A reasonable guess for the cross section of a hair is 0.01 mm, 10^{-5} m. This equates to an area of about 10^{-11} m^2.

A reasonable guess for the cross section of a typical amino acid molecule is that it is about the same as the length calculated above of 0.5 x 10^{-9} m. This indicates a cross section area of about 10^{-19} m^2.

Therefore there are about 108 amino acid chains per hair. Using this figure, along with the 20 molecules joining each chain per second gives an estimate of 2 x 10^9 molecules joining each hair per second.

Suggested approach

During trialling the following instructions were given to students and proved to be effective:

1. Working as a group, discuss the first question and try the calculation.
2. Discussion can play a vital role in working out possible solutions to such problems. Several minds working on a problem together can stimulate the production of ideas that one on its own could not manage. About 10 minutes should be spent on this initially, with further discussion as required.
3. Because exact answers are not possible, you will have to use your judgement to make sensible estimates.
4. Write up what you did in note form. You should explain how you decided upon the estimates you had to make.
5. Repeat steps 1 and 2 for the second question.
6. Working as a group, prepare a short (ca 5-minute maximum) presentation to give to the rest of the class. If possible all group members should take part: any method of presentation, such as a blackboard, overhead projector, etc., can be used.

Outline the problem, describe what you did and explain your solution and the approximations you had to make. After the presentation, be prepared to accept and answer questions and to discuss what you did with the rest of the class.

Possible extensions

1. Estimate the number of hairs on the human body and calculate the total number of amino acids used each day to keep human hair growing.
2. Estimate the total food intake for an adult and the proportion of protein in this, and hence calculate the approximate protein intake per day. Consider what happens to all of this. The possibilities include: hair salon floors; shaving in the morning if you are male; hair and skin debris down the bath plug; not to forget old skin, the main constituent of house dust and excretion as urea.

Note

Students can be reminded that making hair is only one of many uses of amino acids in our bodies - all the fleshy parts of our bodies are replaced at the molecular level every four years or so. Thus we are literally new people every four years or so because every soft part is demolished and rebuilt at the molecular level, usually with little or no change of shape.

Problem 2: Making copper

The problem as issued to students

Make some copper metal starting from copper(II) nitrate crystals. Normal laboratory apparatus and any other chemicals can be used provided that they do not contain any copper.

At least three different methods should be tested. Which method works best? You should refer to any sources of information that you think might help, such as your notebooks, textbooks and data books. Ask for assistance if you get stuck.

Safety

Normal safety procedures when handling chemicals should be adhered to and eye protection worn. There are particular hazards that could arise depending upon how you tackle the problem.

You must get your method checked for safety before starting on the practical work.

Teachers' guide

Introduction

Teachers who have not used the problems before should read the section 'Using the problems' before starting.

Prior knowledge

Reactivity series, interconversion of salts and the effect of heat on nitrates. A detailed knowledge is unnecessary as students are encouraged to consult textbooks and data books during the exercise.

Resources

The reactions should be carried out in test tubes or - in the case of the electrolysis - in small beakers.

Solid copper(II) nitrate should be provided at the start.

Students can request apparatus and chemicals during the practical session: these should be issued if they are safe to use. In particular, electrolysis apparatus will probably be required but should not be on view.

Group size: 2/3

Risk assessment

A risk assessment must be carried out.

Special safety requirements

If the nitrate is heated, note that poisonous nitrogen dioxide gas is produced; also the water released from the hydrated salt could run down and crack the hot glass.

There is a hazard of explosion with any gas reduction apparatus.

Possible methods

1. Dissolve the salt in water and electrolyse the solution.
2. Dissolve the salt in water and add a more reactive metal (preferably powdered) such as zinc or magnesium. It is usually necessary to stir the mixture with dilute acid after the reaction to remove excess displacing metal.
3. Heat the nitrate to get the oxide and reduce it with carbon or natural gas.
4. Dissolve the nitrate in water; add aqueous sodium carbonate; filter off and dry the copper(II) carbonate; heat to produce copper(II) oxide; and finally reduce this with carbon or natural gas.

If students do not think of the short methods (1 and 2), see if they are suggested in the final discussion. If they aren't, join in the discussion yourself!

NB. The thermite reaction is a possible method, but the inherent hazards mean that students must not carry it out. Teachers may wish to do so at their own discretion.

Suggested approach

During trialling the following instructions were given to students and proved to be effective:

1. Working as a group, discuss the problem and list as many different methods as you can. Ask for help if you can't think of at least three.
2. Discuss the advantages and disadvantages of each method.
3. Discussion can play a vital part in working out solutions to open-ended problems. Several minds working together on a problem can stimulate ideas that one on its own could not manage. About 10 minutes should be spent on this initially, coming together for further discussion as required.
4. Each person in the group should select a method and write it up in note form.
5. Get your method checked for safety and then carry out the practical work to find out how well it works.
6. Write a brief account of what you did; include discussions of the advantages and disadvantages of your method.
7. Working as a group, try and decide on the best method from all those tried.
8. Working as a group, prepare a short (ca 5-minute maximum) presentation to give to the rest of the class. If possible all group members should take part: any method of presentation such as a blackboard, overhead projector, etc, can be used. Outline the problem, describe what you did and explain your conclusion.

After the presentation, be prepared to accept and answer questions and to discuss what you did with the rest of tine class.

Note

Zinc powder can be a particular problem – some samples react well, others explosively, perhaps because different samples are oxidised to different extents.