Can problem solving be taught?

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Introduction

There has been a strong movement over the past few years to consider Transferable Skills as part of the education process at all levels. Among these skills Problem Solving has had a prominent part; but is Problem Solving a Transferable Skill and can it be taught?

It could be argued that all human beings exist because they are already competent problem solvers. Daily we solve quite complex problems such as crossing a busy road, driving a car, feeding a family and maintaining a home with all its interpersonal and practical needs. From time to time we deal with difficult problems such as buying a house, moving house, planning a vacation, changing career or choosing a course of study. Despite occasional mistakes, people on the whole are pretty good problem solvers and survivors. The range of problems we can tackle is remarkably wide.

However, in the academic sphere, we complain that our students are poor problem solvers. Presumably we mean that they are not good at solving *our* kind of problems. This points up the fact that problem solving is very context dependent. A person who can solve complex everyday problems may seem to be hopeless when confronted with a chemistry problem even though the basic thinking processes may be very similar.

The nature of problems

Before we go any further in our attempt to answer the question that is the title for this paper, we need to look more closely at the nature of problems. They can be thought of as having three parts: some starting information, a goal or desired outcome, and a method of getting from where we are to where we want to be. If one or more of these three components is missing or incomplete or fuzzy, we have a problem. To clear our minds, we can set up a classification of problems as shown in Table 1.[1] There are eight possible permutations of the three components of a problem, but the first of these is not really a problem if we accept the definition above, that one component must be missing or incomplete to constitute a problem.

Table 1 Classification of problems

TYPE	DATA	METHOD	GOAL
1	Complete	Familiar	Clear
2	Complete	Unfamiliar	Clear
3	Incomplete	Familiar	Clear
4	Complete	Familiar	Unclear
5	Incomplete	Unfamiliar	Clear
6	Complete	Unfamiliar	Unclear
7	Incomplete	Familiar	Unclear
8	Incomplete	Unfamiliar	Unclear

However, the situation designated as Type 1 is what **we** commonly call a problem. Many academic ‘problems’ are of this kind: all the necessary data is given, the method is familiar, and the goal is explicitly stated. Standard stoichiometric problems, physical chemistry exercises in thermodynamics and kinetics, synthetic pathways in organic and inorganic chemistry and general spectroscopic questions tend to be of Type 1. They are algorithmic, following well-trodden paths, using familiar formulae and common mathematical techniques. Students, with practice, should be able to solve these, but often fail to do so. In almost every case an explanation for this failure can be found in information overload, which has been discussed elsewhere.[2]

Let us return to the other seven types of problem set out in Table 1. In each case something is missing or incomplete and the solver is obliged to recognise what is missing and to find some way of supplying it. This involves skills that require insight and an ability to see things in new ways. A degree of creativity is needed to tackle these successfully.

Problem-solving strategies

Coming back to the title of this paper, it is recognised that problem solving as applied to Type 1 situations can indeed be taught by routines repeated many times. However, for the other seven types, the answer to the question is much less clear. When we move into the realm of insight and creativity, we are unable to reduce the problem solving process to any kind of routine. There are general principles that can be applied to turn the problems into a form which make the application of insight easier, but which do not, in themselves, provide the solutions.

Here is an example of the advice given by an examination board to its high school chemistry pupils who are about to do a practical project.

> Make sure you understand what is wanted
> Plan the route
> Carry out the plan
> Check that the result is reasonable

This is all good advice for tackling the problem, but it does not really provide the solution! Problem solving can be thought of as filling gaps between 'certainties'. We can teach ways of narrowing the gap, but I am sure that we cannot teach the last step: the bridging of the gap. This last step needs knowledge (both know-what and know-how), experience, confidence, and the mental flexibility to 'see' new things.

Let us look at the gap-reducing techniques that are teachable.

Knowledge has to be in place because problem solving is very context dependent.

Let the mind 'hang loose'. If you are getting nowhere in one channel, take a break and look for another approach. Brainstorming in a group is just this.

Break down the field that may lead you into a fixed way of thinking by pulling the problem apart. This removes distracting things and reduces the load on mental Working Space.[3]

If possible make your problem visible by converting words into pictures, diagrams or graphs. (This is recognising that most of us are visual thinkers.)

Work *backwards* from the goal, if need be. At the end, go back over how you did it to establish and reinforce any new technique you may have 'invented'. This will also confirm new linkages you have made in your mind. It is possible to illustrate these guidelines by use of crossword clues. The structure of cryptic clues is that they have two parts, each of which supports or confirms the other. With that in mind, let us look at some mini-problems provided by crossword clues.

Find rare new frequencies below the visible range (8 letters)
Since clues have two complementary parts, it is necessary to find where the clue splits. This one divides into 'find rare new' and 'frequencies below the visible range'. Chemists will *know* (importance of knowledge in problem solving) that frequencies below the visible are infrared or below. Can the other half of the clue clinch the answer? 'Find rare' can be rearranged to give INFRARED and so the problem is solved. Finding an anagram is made easier if the present order of the letters (the field) is broken down to help new associations to be formed. For example,

FIND RARE written as

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      F  I
   N        R
   A        R
      E  D
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makes it easier to see new arrangements because the original sense has been removed.
This simple example has illustrated three principles of problem solving: break the problem down; break the 'linear field' to allow for new associations; apply existing knowledge.

Let us look at a few more clues to illustrate other points.

Hide from an aquatic creature (8 letters)
The way it is presented is trying to mislead with the word 'hide'. The mind has to explore possible meanings: 'hide' to 'conceal' or 'hide' is 'skin'. The solution of this one depends upon other cross clues and the fact that 8 letters are required. In other words, data is missing and has

to be found in other ways. This involves working backwards from the requirement of 8 letters. The answer is SEALSKIN.

Follows orders, orders about the end of day (5 letters)

This breaks at the comma. 'Follows orders' can be OBEYS. Is this confirmed by the second part of the clue, 'orders about the end of day'? Here we have to let the mind 'hang loose' to explore the word 'orders'. Orders can be decorations, medals, etc. The end of 'day' can be 'night' or just the letter 'y'. Decorations can be O.B.E.-s, and adding in 'y' we get OBEYS. This confirms our previous deduction from the first half of the clue and fits the requirement for 5 letters.

Again basic problem solving techniques are illustrated: divide the information, use knowledge, look for the unusual, and finally use the evidence to corroborate.

One last clue shows how easily the mind can become stuck in one channel.

Man on board has right to consume seafood (5 letters)

'Seafood' and 'on board' have a nautical link, which may be misleading. What seafoods do we know with 5 letters? 'Prawn' is a possibility. Does it fit with the first part of the clue 'man on board has right'? Is there any other way of thinking of 'man on board'? It could be a 'piece in a board game': a PAWN. Include R to stand for 'right' and we have PRAWN. This solution has drawn on knowledge, on the ability to think laterally and on breaking out of the obvious association and looking for something new.

Now let us apply these ideas to some chemical examples.

Given that it shows two signals in NMR, what is the structure of SF_4?
What additional information would you need to be able to decide between the various possibilities?

This is a problem of Type 3, in which the data are incomplete. Students seeing the formula SF_4 might be misled into thinking of tetrahedral, square planar or square pyramidal structures. However, the other part of the clue (two NMR signals) does not fit with any of these. This needs a new thought. Does a Gillespie-Nyholm (VSEPR) approach help? Sulfur has six outer electrons and each fluorine provides an electron, giving a total of ten (or five pairs). This leads to a trigonal bipyramid with four bonding pairs and one lone pair. But how are they arranged round the sulfur? If three bonding pairs are equatorial and one is axial, we would get two signals with intensity ratios of three to one. If, however, two were equatorial and two axial, we would get two signals of equal intensity. This is the missing part: are the signals of equal intensity or not?

This is parallel to the thinking involved in the crossword clues. Readers might have found the crossword examples uncomfortable even though their structures and problem solving requirements were very similar to chemical examples. This serves to illustrate the context dependence of problem solving and the difficulty of transferring problem solving skills.

The supervisor leaves a note for his student to keep the reaction mixture at a certain temperature. The student phones him to ask if it is Fahrenheit or Centigrade and the supervisor says it doesn't matter. What is the temperature?

This was given to a class of eighty final year honours students, but fewer than ten were able to solve it completely. The responses were interesting in that they threw light on the different problem solving strategies used. They all recognised that there must be a temperature that is the same on both scales. Most said that there was a formula linking the scales, but that they could not remember it. The problem was therefore impossible to solve.

A few recalled the formula and solved the simple algebra. Some remembered the fixed-point values for the boiling and freezing points of water, but could go no further. Very few used this information to draw a graph and find the equivalence point of the two scales. Some recognised the lack of data and suggested a method if the data had been available, but these were in the minority. By far the majority tried to solve it as a Type 1 problem, but finding that the data (given or recalled) was missing, they just gave up.

How does your knowledge of hard and soft acids and bases help to explain the composition of seawater and of sedimentary rocks?

This problem was set following a course on bioinorganic chemistry. It required a reorganisation of knowledge, allowing the mind to 'hang loose'. Water had to be recognised as a hard base that would complex readily with hard acids from the ions in columns 1 and 2 of the Periodic Table. Carbonate ion was a competing hard base for ions such as Ca^{2+} and so on. Students whose knowledge was in a set of 'mental boxes' could make little of a question like this because they could not (or had not been shown how to) break down the field and change the context.

The organisation of knowledge

All these examples demonstrate the fact that problem solving often depends upon knowledge and experience laid down in memory in such a way as to allow new connections to be made. In contrast, much student learning is laid down either unattached to existing knowledge, or linearly or in a single context.

As an external examiner I interviewed a young lady who was analysing soap powders for their phosphate content. She chatted about tripolyphosphates and the fact that she had to boil them up in the first stage of her analysis. However, she had not seen the significance of the 'tripoly-' prefix. She thought that polymers occurred only in organic chemistry and could make no attempt to suggest a structure, although she had found the formula for the ion in a book. The boiling process did not link with hydrolysis in her mind. She then told me about doing a reaction with a molybdenum compound to get a coloured solution, but had not made any connection with the transition metal chemistry she had done. There was no recognition that a phosphate ion might be a ligand attached to a transition metal ion to give a coloured complex. The use of the Lambert-Beer Law in the photometric measurements that followed was in yet another detached box.

In my experience this case is not atypical. This student had a lot of knowledge, but it was stored in sealed boxes and so was not in a free enough state to allow for the creation of new configurations in new contexts. The way she had laid down her knowledge was firmly bound into fixed contexts. During the interview she constantly expressed surprise, and even pleasure, as she saw the new connections and saw her knowledge coming together. This may happen spontaneously for some students, but it could be facilitated by the way we teach.

I have been advocating pre-learning for a long time.[4] Pre-labs and pre-lectures are an ideal way to help students to see new connections by showing how their existing knowledge is going to help them to learn the new knowledge by forming new linkages. Post-labs and post-lectures serve the purpose of making sure that new linkages are evident and have been established in the minds of the students.

Knowledge laid down linearly can normally be accessed in that form only. The alphabet, and the sequence and electronic configuration of the first row transition elements are examples of linear learning. 'Boxed' learning is bound within itself and in a given context. Most teachers will have seen examples of student inability to transfer a well-known mathematical technique to a chemistry problem. Teachers have the responsibility not only to provide what to learn, but to help their students to revisit the same learning in different contexts and to make the linkages explicit. This is the essence of problem-based learning, which is being used to such good effect in medical schools. The branched learning that is needed for efficient problem solving can (but seldom does) happen spontaneously. In the same way as we do not leave students to find out all the content of a course for themselves but present what has to be learned, so also do we need to make a systematic effort to help students to form links between units of content.

Concluding thoughts

Returning to the question posed in the title of this paper, can problem solving be taught?

- We **can** teach techniques that will help to organise the problem solving process.
- We **can** help students to store and organise their knowledge in such a way as to facilitate problem solving.
- We **cannot** teach insight, which is the ultimate key to real problem solving.

How then have we, as teachers, become good problem solvers? How have we moved from stumbling novices to become experts?

Several studies in different disciplines have concluded that it takes about 10,000 hours of study and practice for a novice to become an expert and then only so in one narrow field.[5] Expertise in one field does not automatically transfer to another field unless it is very close. Transfer to other more distant fields is very poor as a generalised skill. There may be fairly good transfer between academic and industrial chemistry, less transfer between chemistry and biology and very poor transfer into everyday problem solving situations.

10,000 hours of study and experience is much longer than any undergraduate course, and so we should not be too surprised when our students lack expertise. We, as experts, have had the benefit of a long time to achieve our expertise and have had the luxury of developing it in some relatively narrow part of chemistry. We expect undergraduates to show expertise across the discipline during their undergraduate period, an expertise that we ourselves do not have! It is worth recalling how much we had to learn when we began to teach. This might provide us with a more realistic expectation of our students' problem solving abilities. It may be that, within our own narrow slot in a discipline, we have met clusters of similar problems so often that they have been reduced to Type 1 *for us* and no longer constitute a problem.

References

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