NYHOLM LECTURE*

Solving Chemical Problems

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1 Introduction

Chemists spend much of their time solving, or attempting to solve, problems! This review is about how they do it, why they succeed and why they fail; and what lessons we can learn so that we can help all those studying chemistry or working as chemists to improve their ability to solve chemical problems.

In the next section, the nature and extent of chemical problem solving is explained. Then in sections 3 and 4 the research methods for investigating problem solving and the main findings as they apply to chemical problems are described. Experience with teaching chemical problem solving is the subject of section 5.

There is a vast literature on problem solving in general and it would not be possible to include references to it all in this review. Therefore the paper is comprehensive about chemical problem solving, but only key references are given to research into general problem solving.

Many authors,[1-4] most recently Guy[5] writing about university chemistry courses, have provided opinion and sometimes research evidence that students, teachers, and employers are dissatisfied with the ability of chemistry students at all levels to identify† and to solve problems. What do they mean by solving problems in chemistry?

2 What is Chemical Problem Solving?

No problems exist in isolation—a problem is perceived by an individual. This is illustrated by Figure 1 and by the illustrative examples (Problems 1—7 which appear in this text).‡ These statements or questions have been problems to at least one individual at some time.

*First delivered at a RSC Education Division Meeting on 23 February 1982, at the Scientific Societies' Lecture Theatre, Savile Row, London W1.
†In fact this review is as much about identifying and recognizing problems as it is about solving problems.
‡The Nyholm lecture was illustrated with 20 examples provided in a separate booklet.

[1] A. H. Johnstone, F. Percival, and N. Reid, *Stud. Higher Educ.*, 1981, **6**, 77.
[2] H. L. Youmans, *J. Chem. Educ.*, 1971, **48**, 387.
[3] G. L. Gilbert, *J. Chem. Educ.*, 1980, **57**, 79.
[4] M. J. Frazer, C. R. Palmer, and R. J. Sleet. *Educ. Chem.*. 1976. **13**, 44.
[5] J. G. Guy. *Chem. Br.*. 1982, **18**, 44.

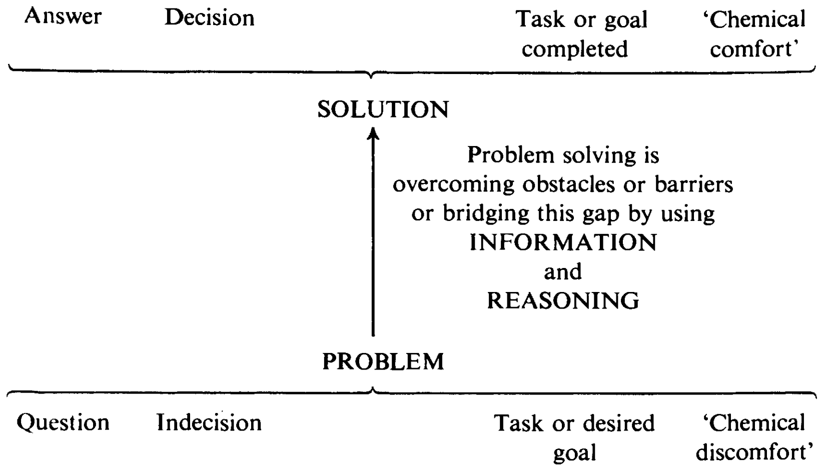


Figure 1 *The transition from problem to solution requires* (a) *information and* (b) *reasoning*

There are many times when a pupil at school, a student in higher education, or a professional chemist is faced: (*a*) with a question to which he does not immediately know the answer, and/or (*b*) with indecision and cannot immediately make a decision, and/or (*c*) with a task or a goal that he cannot accomplish or reach immediately and/or (*d*) with a feeling of 'chemical discomfort' (*e.g.* Problem 1) and cannot immediately feel 'chemically comfortable'.

Problem 1
(*a*) *A red solid of composition* PBr_7 *exists*
(*b*) *There is an oxide of carbon* $C_{12}O_9$

All these situations can be summarized by the statement that the individual has a problem for which he cannot immediately find a solution. There is an obstacle or barrier in the path from problem to solution. In general, problem solving is bridging this gap, or is overcoming the obstacle or barrier. To a greater or lesser extent, every problem requires the individual (*a*) to possess information and (*b*) to reason with this information in order to progress from the state of having a problem to the state of having a solution. Chemical problem solving is the process of using chemical knowledge and chemical skills to bridge the gap between problem and solution.

It is important for the problem solver to recognize that the required knowledge and skills do not depend on him alone. Memory is one source of information for bridging the gap, but other sources are: (*a*) the problem statement itself; (*b*) experts in the problem area (*e.g.* consider the best way of solving Problem 2); (*c*) the literature; and (*d*) observation and experiment (Problem 3 was solved by laboratory simulation).

Problem 2
How can I find the composition of a 1981 50 pence piece?

Problem 3
What was the cause of explosions on two separate occasions when crude oil from Qatar was in the early stages of being discharged at a port in Thailand?

In order to emphasize the nature and extent of chemical problems it is worth attempting a classification (Table 1). This classification was developed at a recent seminar on chemical problem solving.[6] Many problems, indeed most problems outside the classroom, do not have unique, unambiguously correct solutions—these can be called 'open problems'. On the other hand, problems that have

Table 1 *A classification of chemical problems—context and 'closed' or 'open'*

Artificial Problems	*Real Problems*
(i) The solution is known at least to the person (teacher, textbook author) who has presented the problem. Such problems are used in teaching for two purposes (*a*) helping students to learn by applying their knowledge, and (*b*) preparing students to solve real problems.	(i) The solution is not known to anyone. There may not even be a solution; or on the other hand, there may be several reasonable courses of action and the problem then becomes one of selecting the best solution.
(ii) Artificial problems may be further classified according to the nature of the solution (closed or open).	(ii) Real problems may be further classified according to the context (mission directed or not mission directed).
Closed problems: There is a single unique solution (*e.g.* numerical problems, identification of a compound either by experiment or from given data).	*Mission directed:* The solution is of consequence to industry, some other enterprise, or to society.
Open problems: There are a number of possible solutions (*e.g.* alternative synthetic routes, alternative experimental designs for a practical exercise, alternative courses of action in a simulation exercise concerning chemistry and its impact on society).	*Not mission directed:* The solution is of no immediate consequence to anyone except to the problem solver.

[6] M. J. Frazer, Report of a Seminar on Chemical Problem Solving, University of East Anglia. 1981. (Available from the author).

a unique answer may be described as 'closed problems'. We offer our students plenty of experience with closed problems but hardly prepare them at all for dealing with open problems.

It should now be clear that chemical problem solving involves one or more of the skills of analysis, selection, pattern recognition, experimental design, synthesis, process design, *etc.* Faced with such a wide range of types of chemical problem, some may ask is there any hope of being able to teach chemical problem solving? Would it not be better to concentrate on imparting chemical knowledge and letting the individual learn to cope with problems of particular types when first he meets them? It is the purpose of this review to show that it is both desirable and possible to help students become better at problem solving. But in order to achieve this our teaching needs to be based on the results of research on problem solving.

3 Research Methods for Investigating Problem Solving

A. Overview.—In order to appreciate the results of research on problem solving. it is worth reviewing briefly the methods that have been used. The motives for this kind of research are varied. For some, the studies are fundamental and are firmly placed in cognitive or developmental psychology and are moves in the attempt to answer the questions: 'How do we think?' 'How does the brain work?' Others are much more pragmatic and are simply trying to discover the strategies that lead to success and the reasons for failure in problem solving with the ultimate aim of developing better teaching methods. Although it is not possible to classify each study unambiguously, roughly we can label research with these two motives as 'descriptive' and 'prescriptive' respectively. Basically, in the descriptive approach the researcher records the behaviour of individuals in defined problem situations with the intention of describing as far as possible the mental processes that are occurring during problem solving. Often the intention is to fit the description into one of the theories or models of cognition. For example Simon and Newell[7] in a major, and now classical, study fit their observation and recordings of individuals solving problems into an 'information processing theory' in which the human problem solver is likened to a computer. Both are examples of information processing systems and are characterized by having an input and output for symbol structures, a processor including a short term memory, and a long term memory capable of storing and retaining symbol structures.

The prescriptive approach is aimed at generating advice to pass on to others. Such advice if followed is likely to lead to success in solving problems. Such advice may be general, may be related to a particular subject, or may refer to a particular type of problem (*e.g.* balancing a redox reaction, interpreting an n.m.r. spectrum) within a subject.

In order to concentrate on the 'reasoning' component and to reduce the 'information' component of bridging the gap from problem to solution, most

[7] A. Newell and H. A. Simon, 'Human Problem Solving', Prentice Hall. New Jersey. 1972.

studies have been in a context that is subject free. Researchers have confronted individuals with the Towers of Hanoi, with computer variations of the popular 'Dungeons and Dragons' game, with numerous combinations of missionaries, cannibals, domestic animals, and wild beasts crossing and recrossing rivers, and with many other ingenious situations in which previously learnt knowledge is of little use in reaching a solution.

Problem solving research in a subject context has been mainly in mathematics[8–10] and engineering.[11] In fact very little has been published on problem solving in chemistry. Part of the discussion at a recent conference on problem solving research[12] centred on the question of the relative merits of subject-free and subject-based studies.

With our present state of knowledge in this field all types of research (prescriptive and descriptive, as well as subject-free and subject-based) are needed and will contribute to understanding. The choice is very much a question of the personal interests and priorities of the researcher. Because of the urgent need to improve the teaching of chemical problem solving and because, ultimately, real people have to solve real problems, the reviewer gives priority to research that can be described broadly as 'chemical and prescriptive' and so this review will be biased in this way.

Research concerned with finding ways to overcome students' learning difficulties and misconceptions in chemistry is often relevant in attempts to improve chemical problem solving abilities. Examples of this type of research were described in the last Nyholm lecture by Johnstone.[13]

Four main methods for research into problem solving can be identified.

B. Empirical Methods.—Included here are the numerous publications usually written in the form of advice about strategies based on the analysis by an expert of his accumulated experiences of problem solving. There are several books[7,14–18] describing general strategies for problem solving. The background of the authors is so varied, and yet the recommended strategies are so similar in their essentials that we can be confident that the approach is correct. A summary is given in section 4B. Purists might not accept these publications as research reports because there are no pre-planned experiments, no testing of hypotheses, no controls, and no statistical data. On the other hand, critical

[8] G. Polya, 'How to Solve It', Doubleday Anchor Books, New York, 1957.
[9] M. P. Cohen and J. E. Bernard. *Int. J. Math. Educ. Sci. Technol.*, 1981, **12**, 169.
[10] D. J. Goldberg, *Int. J. Math. Educ. Sci. Technol.*, 1981, **12**, 211.
[11] D. R. Woods, J. D. Wright, T. W. Hoffman, R. K. Swartman, and I. D. Doig, *Ann. Eng. Educ.*, 1975, **1**, 238.
[12] Problem Solving and Education: issues in teaching and research, (Proceedings of a conference), ed. D. T. Tuma and F. Reif, Lawrence Erlbaum Associates, New Jersey, 1980.
[13] A. H. Johnstone, *Chem. Soc. Rev.*, 1980, **9**, 365.
[14] K. Raaheim, 'Problem Solving and Intelligence', Universitetsforlaget, Bergen. 1978.
[15] K. F. Jackson, 'The art of solving problems', Heinemann, London, 1975.
[16] F. H. George, 'Problem Solving', Duckworth, London, 1980.
[17] R. W. Samson, 'Problem Solving Improvement', McGraw Hill. New York. 1970.
[18] W. A. Wickelgren. 'How to solve problems'. Freeman. 1974.

reflection about experiences is an approach to research and, if the different authors are in broad agreement, their views cannot be ignored.

C. Studying Individuals Attempting to Solve Problems.—In this type of research, analysis is made of data collected about the behaviour of individual subjects attempting to solve problems. The subjects may be either novices or experts. However, there are obvious dangers in expecting to be able to transfer the skills and strategies used by an expert directly to the novice. Various methods of data collection have been used:

(*a*) Recording on audio-tape, the subject's comments after he has been invited to 'think aloud' during problem solving (subsequent analysis of the transcript of the subject's comments is called protocol analysis);

(*b*) Observing the subject during problem solving either directly or by television;

(*c*) Obtaining the subject's written solution and notes;

(*d*) Interviewing the subject immediately after he has attempted the problem;

(*e*) Testing the subject either before or after problem solving to investigate whether he has the requisite chemical knowledge and skills ('information' in Figure 1) to solve the problem;

(*f*) A variation of (*e*) is to provide the subject with a highly structured problem in order to investigate which part of the problem (*e.g.* item of chemical knowledge, chemical skill, reasoning step) causes the difficulty;

(*g*) Providing the subject with an opportunity to ask for more information as he attempts the problem—this information can be provided directly by the observer/researcher, by card selection, or by selection from a computer memory.

Most often a combination of these data collection methods is used. There are various ways of recording and analysing the data. Sometimes a simple record showing the sequence of behaviour or a transcript is felt to be sufficient, but where possible the researcher will try to probe deeper and produce a map or network purporting to show the connections between the words, concepts, and actions used by the subject. At the University of East Anglia we have been attempting to develop the use of problem solving networks[19,20] as a method of both recording and analysing individual subjects' attempts at chemical problem solving.

These methods of data collection and analysis do not lend themselves to dealing with large groups and most research in this area is of the type sometimes described as 'clinical'. For example, in recent research into solving problems in

[19] A. D. Ashmore, M. J. Frazer, and R. J. Casey, *J. Chem. Educ.*, 1979, **56**, 377

[20] M. J. Frazer, J. Morris, M. P. B. A. Pereira, M. E. M. Pestana, A. V. Powell, and T. F. Wallace, Higher degree theses at the University of East Anglia. Details available from the author.

physics[21,22] the 'think aloud' protocols of only one expert and one novice were compared. Nevertheless some useful insights were gained.

D. Evaluation of Courses and Activities that claim to Teach Problem Solving.— There are so few courses concerned principally with problem solving that it is not surprising that there are very few published evaluations. If we are to improve the problem solving abilities of our students we shall need to develop more courses and activities with this specific aim. It is to be hoped that such courses will be evaluated. A course in general problem solving techniques for post-graduate students[23] and problem solving courses in mathematics[9] and engineering[11] have been evaluated.

E. Systematic Collection of Teachers' Views.—Teachers spend a considerable amount of time marking, watching, and correcting students' attempts at problem solving. Few, if any, attempts have been made to tap this potentially rich source of information about students' strategies, difficulties, and reactions to various approaches.

In the next section the results obtained by these various research methods, particularly as they apply to problems in chemistry, are brought together.

4 Results of Research into Chemical Problem Solving

A. The Stages of Problem Solving.—Several authors[8,15,19,24–28] have taken an overview of the problem solving process and have described the stages that an individual must pass through in order to progress from problem to solution. In Table 2 a summary of the views of different authors is displayed and, although the words are different, a clear pattern emerges. However Table 2 is not altogether satisfactory because, with the exception of the scheme due to Jackson, emphasis is on the class-room type of problem in which a well defined problem with a unique answer is presented to students. A scheme, adapted from one first presented by Casey,[24] is more suitable for describing the stages for real chemical problems. This scheme, which is still related to Table 2 by the three main phases, is shown in Figure 2. Important features are: (*a*) recognizing that a problem exists is an important stage that is often overlooked, (*b*) all the stages are interrelated and the problem solver may return to each stage several times clarifying and refining each time, (*c*) arriving at the best solution often leads to

21 J. H. Larkin, J. McDermott, D. P. Simon, and H. A. Simon. *Science*, 1980, **208**, 1335.
22 J. H. Larkin and F. Reif, *Eur. J. Sci. Educ.*, 1979, **1**, 191.
23 M. F. Rubinstein in 'Problem Solving and Education: issues in teaching and research, ed. D. T. Tuma and F. Reif, Lawrence Erlbaum Associates, New Jersey, 1980, p. 25.
24 R. J. Casey, personal communication, 1980.
25 D. P. Ausubel, 'Educational Psychology—a cognitive view', Holt, Rinehart, and Winston, New York, 1970.
26 R. M. Gagné. 'The Conditions of Learning', Holt, Rinehart, and Winston, New York, 1970.
27 J. P. Guilford and R. Hoepfner, 'The Analysis of Intelligence,' McGraw Hill, New York, 1971, 104.
28 C. T. C. W. Mettes. A. Pilot, H. J. Roossink. and H. Kramers-Pals, *J. Chem. Educ.*, 1980, **57**, 882.

Table 2 *Words used by various authors to describe the stages of problem solving*

	Ashmore, Casey, and Frazer[a]	Ausubel[b]	Gagné[c]	Guilford and Hoepfner[d]	Jackson[e]	Mettes, Pilot, Roossnik, and Kramers-Pals[f]	Polya[g]
PHASE I RECOGNIZING	1. Defining	1. Setting 2. Defining	1. Presenting 2. Defining	1. Preparing 2. Analysing	1. Formulating 2. Interpreting	1. Analysing	1. Understanding
PHASE II SOLVING	2. Collecting information 3. Reasoning	3. Gap filling	3. Formulating hypotheses	3. Producing	3. Constructing courses of action	2. Planning the process	2. Devising a plan
PHASE III CHECKING AND IMPLEMENTING	4. Checking	4. Verifying	4. Verifying hypotheses	4. Verifying 5. Reapplying	4. Making decisions 5. Implementing and reviewing	3. Executing and checking	3. Executing a plan 4. Reviewing the solution

[a]Ref. 19; [b]ref. 25; [c]ref. 26; [d]ref. 27; [e]ref. 15; [f]ref. 28; [g]ref. 8

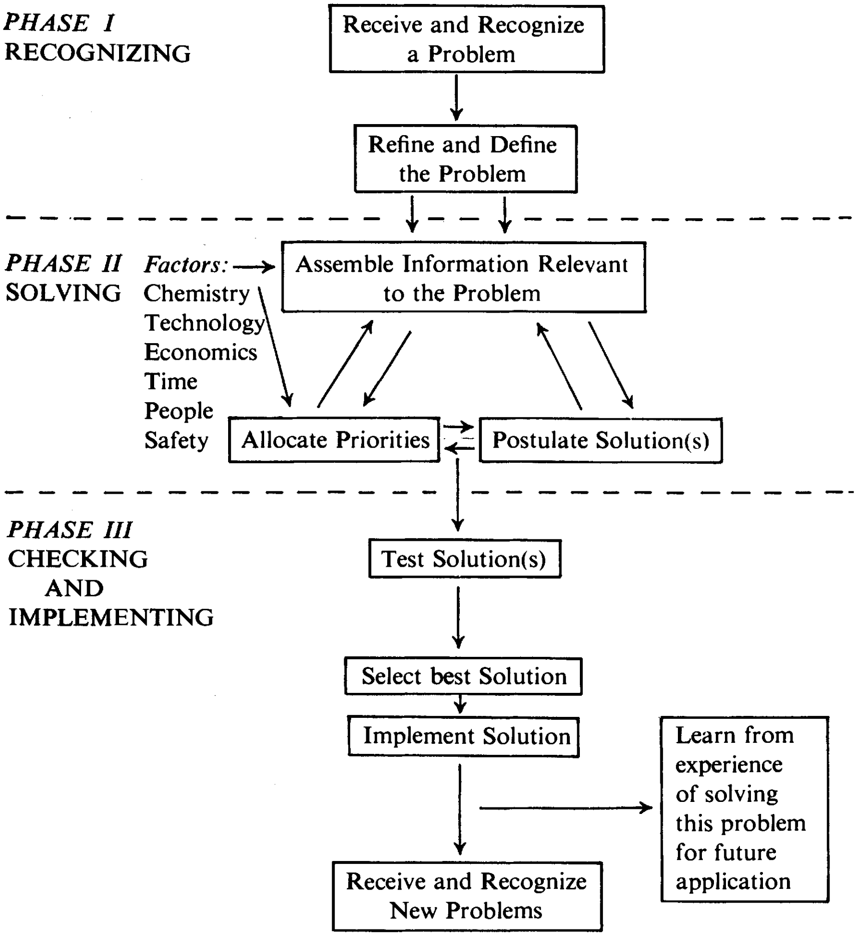


Figure 2 *A model of the phases in real chemical problem solving*

action and to the recognition of further problems, and (*d*) people should learn from the experience of solving a problem.

We can never know how may times the failure to recognize a problem has delayed the advance of knowledge or has led to inefficiency in industry. The importance of problem recognition cannot therefore be overemphasized. Furthermore, team work and providing opportunities for contact between individuals with different backgrounds and outlooks is important. It is unlikely that all stages of a complex chemical problem could be completed by one individual. Someone with the experience to recognize a problem may not have the experience and knowledge to solve it and *vice versa*. This is one of the strong arguments in favour of co-operation between higher education and industry. In some cases the problem may not be recognized until all the chemistry of the solution has been worked out (*e.g.* Problem 4—here was a 'solution' waiting for a problem.)

> *Problem 4*
> *Can the compound* $AlPO_4.HCl.(EtOH)_4$ *which was discovered by chance at the Mond Division of ICI in the early* 1970's *be exploited? Its* X-*ray crystal structure was determined, it is soluble in water, and decomposes at about* 70 °C *to give the inert* $AlPO_4$

B. General Strategies of Problem Solving.—Research methods described in 3B and 3C have led to the formulation of a number of general strategies to be adopted when faced with a problem. They are listed in Table 3. They are

Table 3 *General strategies or advice to problem solvers*

(1) Work backwards from the goal not forwards from the given information.
(2) Break down the problem into sub-goals and work at each separately. Do not try to cope with too much information at any one time.
(3) Convert an unfamiliar problem into a familiar problem and then apply an already learnt procedure.
(4) Make a guess at the solution and work backwards to see if the guessed solution is consistent with all the information available.
(5) Check that all the information stated in the problem has been used and that all other sources of information (memory, literature, experts, experiment) have been exhausted.
(6) Check that all the stages of problem solving (Table 2 and Figure 2) have been used.
(7) Check whether there are any guidelines (4C) or algorithms (4D) applicable to this problem.
(8) Try to see the problem as a whole.
(9) Draw diagrams, verbalize the problem, convert a statement into a question, convert statements into mathematical expressions.
(10) 'Brainstorm' *i.e.* write down all the ideas that come to you however foolish or irrelevant they seem.
(11) Rest to allow time for 'incubation' of the problem.

applicable to all problems whatever the subject content but are not all necessarily appropriate for every particular problem. Indeed some are contradictory. They are best seen as advice or ideas to try if the problem solver is not making progress and does not know what to do next in order to proceed from problem to solution.

C. Guidelines for Chemical Problem Solving.—These refer to procedures that are more specific than general strategies but more general than algorithms (see 4D). Many teachers and students find general strategies of little help when they are immersed in a chemical problem or at a 'dead-end'. The dangers of relying on specific algorithms will be outlined in the next section.

There is therefore a need to generate guidelines, based on research, for chemical problem solving. Not much has been published yet, but a start has been made with problems in the areas of (*a*) synthesis of organic compounds,[29,30] (*b*) identifying organic compounds from given analytical and spectral data,[29] (*c*) elementary thermodynamics,[31,32] (*d*) numerical problems in general chemistry,[33] and (*e*) simple stoicheiometric problems.[34,35]

The guidelines for organic problems developed by the groups at the Universities of East Anglia and Leuven[29,30] are shown in Table 4. The approaches developed by the group at Twente University of Technology[28,31,35,36] and by Selvaratnam and Frazer[33] for solving numerical problems in general chemistry are similar and are shown in Figure 3 and Table 5 respectively. Five simple steps for solving stoicheiometric problems[34] are shown in Table 6. It is surprising, however, how many students are either unaware of this approach or are unable to apply it.

D. Algorithms in Chemical Problem Solving.—An algorithm is a set of rules which are to be learnt and which if applied correctly to an appropriate standard problem will lead automatically to a solution of the problem. Most authors would consider that once a problem has been reduced to the stage of only needing the application of an algorithm then there is no longer a problem. The obvious danger of teaching problem solving by using algorithms is that a student is lulled into a false sense of security and is completely unable to cope when meeting a novel situation. Students trained to use $V_1N_1 = V_2N_2$ to solve titration problems have difficulties when faced with titrations using all of a solution made by weighing out a solid into an unknown volume of water.

Some algorithms may be useful (*e.g.* converting % composition figures into

[29] L. Brandt, H. Fierens, R. A. Y. Jones, and P. J. Slootmaekers, Paper given at International Conference on Chemical Education, Dublin, 1979.
[30] P. J. Slootmaekers, L. Brandt, H. Fierens, R. A. Y. Jones, and M. J. Frazer, Paper given at 6th International Conference on Chemical Education, Maryland, U.S.A., 1981.
[31] C. T. C. W. Mettes, A. Pilot, H. J. Roosink, and H. Kramers-Pals, *J. Chem. Educ.*, 1981, **58**, 51.
[32] C. T. C. W. Mettes, A. Pilot, and H. J. Roosink, *Instruct. Sci.*, 1981, **10**, 333.
[33] M. Selvaratnam and M. J. Frazer, 'Problem Solving in Chemistry', Heinemann Educational Books, 1982.
[34] M. J. Frazer and D. Servant, unpublished.
[35] H. Kramers-Pals, J. Lambrechts, and P. J. Wolff, 'Conversion of Quantitative Problems in General Chemistry to Standard Problems', personal communication, 1981.
[36] H. Kramers-Pals, J. Lambrechts, and P. J. Wolff, 'Recurrent Difficulties of Students in Solving Quantitative Problems in General Chemistry'. *J. Chem. Educ.*, 1982, **59**, (June issue).

Table 4 *Guidelines for solving some problems in organic structure analysis and synthesis*

Organic structure analysis

(1) Set out the problem in the form of a flow-scheme.

(2) Calculate the 'unsaturation index' of each compound and interpret this in terms of possible combinations of rings and multiple bonds.

(3) Write down possible explanations for each step in the flow-scheme, and exclude any contradictions in these explanations.

(4) Work through the scheme, starting from the part where there is most information and using the explanations derived in (3).

(5) Check for alternative solutions, and check that the proposed solution is chemically correct and fits all the information in the problem statement.

Organic synthesis

(1) Write out in full the formula for the target molecule.

(2) Examine target molecule for its main features.

(3) Select 'equivalent molecules' (*i.e.* the same carbon skeleton) to target molecule.

(4) Split up equivalent molecule into possible precursors.

(5) Combine possible starting molecules into these precursors.

(6) Select synthetic route.

an empirical formula), but in general it is not recommended to teach students algorithms for solving chemical problems.

E. Reasons for Failure to Solve Chemical Problems.—In sections A—D emphasis was on what leads to success. We now turn to the results of research that indicate reasons for failing to solve problems. It is assumed in this section that a problem has been recognized because it is hardly meaningful to refer to failure when the individual is unaware that he has a problem. Let us then assume that someone has recognized a chemical problem but fails to bridge the gap to obtain a satisfactory solution. There can be three reasons: (*a*) failing to start, (*b*) starting but not finishing, and (*c*) finishing but with a 'solution' that is incorrect, or that is not a solution to the original problem. We take each of these in turn.

(i) *Not starting.* This may be due to: (*a*) lack of confidence, (*b*) lack of motivation, (*c*) having too much information, (*d*) not obtaining an overview of the problem and thus not identifying goals and sub-goals.

Problem 5 is a good example for illustrating failure to identify the goal.

Figure 3 *Principal phases of the programme of actions and methods for systematic problem solving in science (PAM)*

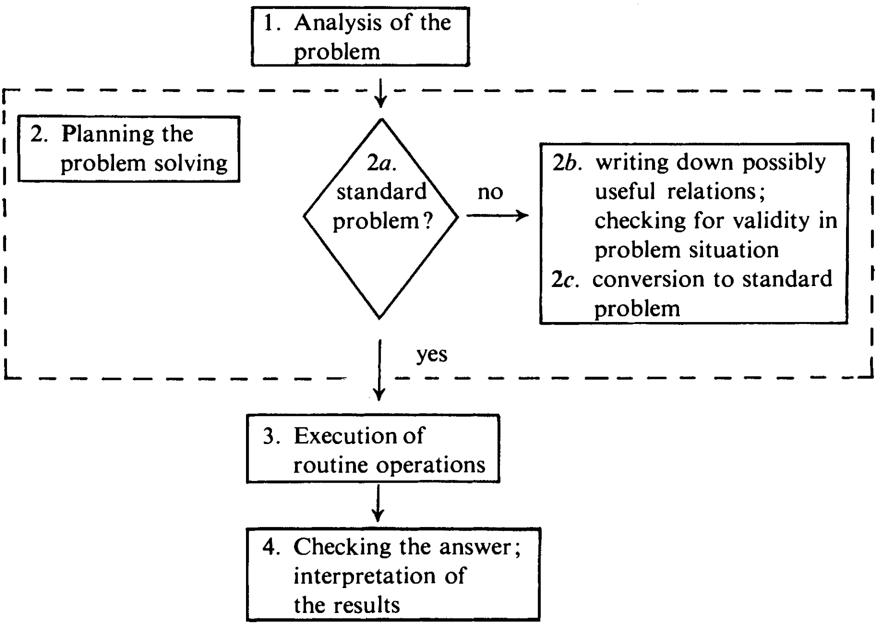


Table 5 *Guidelines for solving numerical problems in general chemistry*

Step 1 Clarify and define the problem

Step 2 Select the key equation
This relates the required physical quantity to some or all of the physical quantities available from the data given in the problem.

Step 3 Derive the equation for the calculation
This is derived from the key equation and is in the form of the required physical quantity on the left hand side and only known physical quantities on the right hand side.

Step 4 Collect the data, check the units, and calculate

Step 5 Review, check, and learn from the solution

Problem 5
3.00 g *of phosphorus pentachloride (vapour) are heated in a closed* 1.00 dm^3 *vessel at* 300 °C. *The degree of dissociation according to the equation:*

$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$

is then 0.300. *Calculate the density of the equilibrium mixture*

Table 6 *Guidelines for solving stoicheiometric problems*

(1) Write balanced equations for all the processes.
(2) Hence find the stoicheiometric ratio of the unknown to the known species.
(3) Convert all the given quantities (masses, volumes, concentrations *etc.*) into moles of specified chemical species.
(4) Find the moles of the specified unknown species.
(5) Convert moles of the unknown species into the required quantity (mass, volume, concentration *etc.*)

The problem was first suggested by Selvaratnam[37] and has since been used by him and the author to bewilder chemists at all levels. Experienced chemists have been found to cover a page or so of algebra based on

$$K = \frac{\alpha^2}{1 - \alpha}$$

before they realized that the goal was to find the density of a stated mass of gas in a closed container of fixed and stated volume. It is a common mistake to assume, on the basis of a superficial reading of the problem statement, that here is a problem of a particular type and then to embark on some known procedure (*e.g.* in numerical problems this may take the form of writing down a known equation). The successful problem solver, on the other hand, obtains an overview of the problem and identifies the goal.

One of the major differences between the novice and the expert is the greater amount of information the expert can handle.[21,22] Through greater knowledge and experience the expert sees patterns ('chunks') in the given information. He is able to work with these chunks as if they are single items of information. On the other hand, the novice does not see the pattern and tries to cope with considerably more items of information. The question of processing chemical information by 'chunking' has been discussed by Johnstone.[13,38]

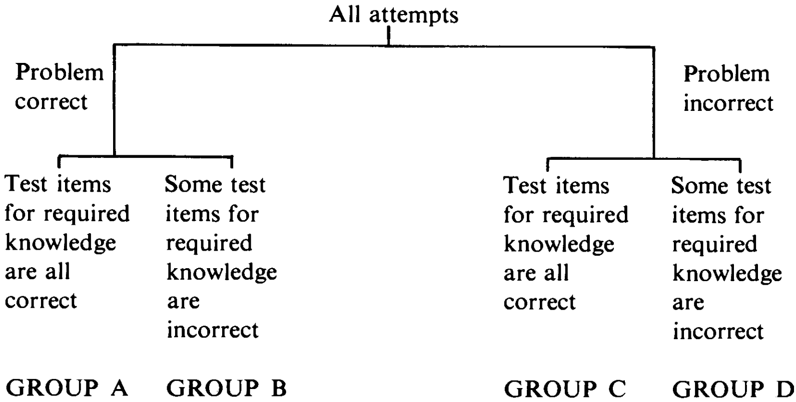
(ii) *Starting but not Finishing*. This may be due to: (*a*) any of the reasons for not starting, (*b*) absence of, or failure to recall, required knowledge, (*c*) knowledge incorrectly recalled or applied, (*d*) failure to use items of knowledge that are available to the individual (*e.g.* information given in the problem statement), (*e*) failure to make approximations, (*f*) becoming 'set' (*i.e.* fixed in a particular mode of thought) as a result of either failing to make a guess or of imposing unnecessary constraints.

Of these, (*b*) is the most important. The author and co-workers[20,34,39] have now tested many secondary school and university level chemistry students with a range of problems. The subjects' written attempts were analysed using the

[37] M. Selvaratnam, *Educ. Chem.*, 1974, **11**, 201.
[38] A. H. Johnstone and N. C. Kellett, *Eur. J. Sci. Educ.*, 1980, **2**, 175.
[39] M. J. Frazer and R. McCabe, 'Students' difficulties with chemical problem solving', Paper presented at the international seminar: Chemical Education in the Coming Decades—Problems and Challenges. Ljubljana. 1977.

network method[19] (see section 3C). Subjects were interviewed and also took a test, which included items to see whether or not they possessed the knowledge and skills required to solve the problem. It is then possible to divide the subjects into four groups as shown in Figure. 4.

Figure 4 *Division of students into four groups according to problem and test results*



Students in groups A and D need not concern us at present. It is students in group C who are of most interest. They fail to solve the problem, yet they possess all the required knowledge. In a typical result[20] taken for Problem 6, 54% of the students were in group C. There is always a small number of students in group B. This is not surprising since the test is unlikely to be 100% reliable; the context of the problem may prompt the student to recall the information whereas the test item did not prompt him; and most likely, the student was able to obtain the solution either by guessing, or by assuming, the missing required knowledge.

> *Problem 6*
>
> *The haemoglobin from the red corpuscles of most mammals contains approximately* 0.33% *iron by mass. Physical measurements indicate that haemoglobin has a relative molecular mass (molecular weight) of* 68×10^3.
>
> *How many iron atoms are there in* one *haemoglobin molecule?*

Examples of all the other causes of starting but failing to finish have been identified by the work at East Anglia.[20,39]

(iii) *Finishing but with an Incorrect Solution*. This may be due to: (*a*) any of the reasons for not starting or failing to finish, (*b*) errors in arithmetic, (*c*) failure to check final answer (*e.g.* for orders of magnitude, for correct number of decimal places, for correct units, for 'pentavalent' carbon for a chosen reagent that will attack. or be attacked by, some other part of the system, *etc.*).

5 Teaching Chemical Problem Solving

A. General Considerations.—If, as seems generally agreed, we want to improve the chemical problem solving abilities of our students, then the conditions listed below need to be followed as far as possible.

(i) *Practice*. Students must be given opportunities to practise solving problems. Not much will be learnt about problem solving by reading about it or by listening to someone talk about it or demonstrate it. More time in courses needs to be allocated for students to experience at first hand the deployment of their chemical knowledge and skills in order to move from the problem state to the solution state. Testing recall of knowledge and testing the ability of students to substitute numbers into an equation or to follow an algorithm is problem solving at the lowest level.

(ii) *Develop Confidence*. It is important to develop the student's confidence that he can solve problems. A number of points are worth noting.

(*a*) The student needs to be confronted as far as possible with problems carefully selected to provide tasks which are not beyond his knowledge and level of skill. All too often the problems presented to students require the use of some obscure piece of knowledge or the application of an only recently acquired concept that is still insecure in the student's framework of knowledge. Problem solving is not something to be met by the student for the first time in an examination. The teacher must select from the literature chemical situations that will be real problems to the student because the solution(s) will not be obvious and yet the necessary information and reasoning is likely to be well within his grasp. In the course at UEA described in section B problems of this type have been used. For example Problem 7 does not require any great depth of knowledge or skill and yet the compounds X, Y, and Z are unlikely ever to have been met by the second year students taking the course.

> *Problem 7*
> *Sulphur tetrafluoride and ammonia react at* $-95\,^{\circ}\mathrm{C}$ *to give nitrogen, ammonium fluoride, and a yellow solid* X (N, 30.4%; S, 69.5%; *relative molecular mass* 184). *Reduction of* X *with sodium dithionite gives a white solid* Y (N, 29.8%; S, 68.1%; H, 2.1%; *relative molecular mass* 188). X *reacts with chlorine to give* Z (N, 17.2%; S, 39.3%; Cl, 43.6%; *relative molecular mass* 245). *What are the formulae of* X, Y, *and* Z? *The infrared spectrum of* Y *shows bands at* 3320 *and* 3285 cm^{-1}. *Complete reduction of* X *using hydrogen iodide gives quantitatively hydrogen sulphide* (*infrared bands at* 2684 *and* 1290 cm^{-1}) *and ammonia* (*infrared bands at* 3336, 1628, *and* 950 cm^{-1}). *Using this information what can you deduce about the structures of* X, Y, *and* Z?

(*b*) The intention should be for students to succeed and not to fail. Of course problems should be challenging, and teachers must be constantly pressing their students, but unless students quite frequently experience the pleasure of bridging the gap and reaching a solution, they will lose confidence and interest.

(*c*) There is a tendency for teachers to ignore the students who have obtained a correct solution, just putting a tick at the end. This does not help. Teaching problem solving is about teaching the processes of problem solving. The student with a correct answer needs guidance, comment, and encouragement about his approach and the strategies used, just as much as the student with no solution or with an incorrect one. The suggestion in step 5 of the guidelines shown in Table 5 is an important one. It is check and *learn from the solution*. Teachers should try to inculcate this habit in their students, with the hope that it might then stay with them for life. Certainly, successful researchers and industrial chemists are those who are constantly examining, and learning, from their own experiences. Students need to be shown what they have achieved by their solutions or attempted solutions.

(*d*) One of the most common ways of developing confidence in problem solving is to use small groups and peer teaching.[10,11,40–43] Students are more willing to make guesses, and to try trial and error methods in the absence of their teacher. They are likely to be patient as they explain to each other their ideas and learn from one another as they try to bridge the gap from problem to solution. The expert who has crossed the gap and is 'looking back' from the solution is likely to be less able to explain the problem and to see the student's difficulties.

(*e*) Presenting a complete solution in the form of a network[19] allows the student to see the many possible routes from problem to solution. Some students lose confidence if the route they chose does not correspond to the one presented in a linear fashion in a text book or by the teacher.

(iii) *Use Guidelines.* In the early stages of teaching problem solving it is necessary to provide the student with some general guidelines (see 4C). The group at Twente University of Technology proposes the use by students of a key-relations chart,[35] which is a summary of the major equations relating the various physical quantities in the topic area.

(iv) *Limit the Amount of Information.* In the early stages, the teacher should as far as possible present problems in which the amount of information the student has to handle at any one time is not too large[44] (three or four separate items at the most). Later, with experience, the student will see patterns in data and will be able to handle more and more information as a consequence.

(v) *Provide Realistic Problems.* Too often the problems presented to students are academic (closed problems with most of the required information given in the problem statement). This arises because of the false relationship between problem solving and assessment. The student is not given any experience of problem recognition or definition, gains no experience of deciding what

[40] M. Brewer, SIMIG, *Stud. Higher Educ.*, 1977, **2**, 33.
[41] K. G. Collier, *Stud. Higher Educ.*, 1980, **5**, 55.
[42] G. D. Moss and D. McMillen, *Stud. Higher Educ.*, 1980, **5**, 161.
[43] A. D. Ashmore and M. J. Frazer, 'The Evaluation of a Problem Solving Course', in *Research for the Classroom and Beyond*, The Chemical Society, 1977.
[44] A. E. Mihkelson. *Educ. Chem.*, 1982, **19**, 24.

information he should obtain from the literature or by experiment, and does not have to choose the best from a range of possible solutions. There is no shortage of books giving worked examples and exercises in closed academic type problems[33,45] but we need to give students more opportunities to experience problem solving as it really is outside the classroom. There is, however, a shortage of suitable examples and of experience on how best to use the material that is available. A set of fourteen case studies of problem solving in the chemical industry,*[46] examples of design,[47] the Scottish Chemistry Teaching Materials,[48] and the extension study to the S304 Open University Course[49] are some of the few examples of material available at the present time.

B. A Chemical Problem Solving Course.—The author has tried to include as many as possible of the principles listed in 5A in a course for second year B.Sc. honours chemists at the University of East Anglia. The chemical theme of the course is non-transition elements but the main aim is to help to develop the students' problem solving skills. The course is now in its eighth year and an early version has been described and evaluated.[43] The course is short, lasting for ten one hour sessions.

There are five components of the course.

(*a*) One lecture on strategies in chemical problem solving.

(*b*) Five sessions, described in more detail below, in which students attempt to solve problems (Problem 7 is a typical example).

(*c*) One session which takes the form of two games in which students experience problem recognition and working in a syndicate under pressures of time and finance (information to solve the problem has to be 'bought' with Monopoly money).

(*d*) The equivalent of two sessions spent at a computer terminal, solving problems in which no initial information is given and the student has to decide what information to request from the computer.

(*e*) One session, which is a course test consisting of three problems, for which there are course marks. No course marks are given for the other components of the course.

*Problems 3 and 4 are examples.

[45] M. C. V. Cane and M. J. Tomlinson, 'Organic Chemistry: A problem solving approach', Mills and Boon, London, 1977; G. C. Long and F. C. Hentz, 'Problem exercises for general chemistry', J. Wiley and Sons. New York, 1978; E. I. Peters. 'Problem Solving for Chemistry'. W. B. Saunders Co., Philadelphia, 1976; C. H. Sorum and R. S. Boikess, 'How to solve general chemistry problems', Prentice Hall. New Jersey, 1976; C. J. Willis, 'Problem solving in general chemistry,' Houghton Miffin Co., Boston, 1977.

[46] R. J. Casey and M. F. Frazer, 'Case studies of problem solving in industrial chemistry', to be published. Details from the author.

[47] C. J. Suckling, K. E. Suckling, and C. W. Suckling. 'Chemistry through models', Cambridge University Press, 1978.

[48] N. Reid, 'New Chemistry Teaching Materials', Scottish Council for Educational Technology. 1980.

[49] Extension Study 1, to the Course S304, The Open University. 1976.

The five sessions in which a single problem is presented take the following form. Each problem has a closed and an open part. The closed part should be possible to solve in about ten minutes. At the beginning of the session each student is presented with the problem and with carbonized paper. For the first twenty minutes the students work individually writing their solutions on the carbonized paper. They are encouraged to write down all their ideas and guesses as they work at the problem. At the end of twenty minutes they hand in one copy of their solution. These are marked by the tutor, who makes written comments about the chemistry and the problem solving strategies, and in due course returns them to the student. The students take the remaining copy of their solution into a peer group with three other students. For the next twenty minutes they then share and discuss their solutions in these groups. For the last twenty minutes, there is a plenary session during which a spokesman for each group presents the solutions for the closed and open parts of the problem. Finally, every student is given a handout showing the solution in network form.[19]

Although the course is short, students do seem to gain in confidence and in their ability to solve this type of problem. They also learn some non-transition element chemistry. Each year the formal and informal 'feedback' from the students is highly favourable. However, perhaps the best testimonial for the course comes from the number and quality of attempts at the inorganic problems included each year in the final examination.

6 Conclusion

It is widely accepted that professional chemists and chemistry students at all levels should be able to identify and solve problems. The nature of chemical problems and the skills needed to solve them are extremely varied.

Research into general, and chemical, problem solving is revealing not only successful strategies and guidelines but also the causes of difficulties. Results from this type of research are needed so that the teaching of chemical problem solving can be improved. There is no doubt that, with the right experiences, students can become better at solving problems. Furthermore, although there is no strong evidence, a problem solving approach to teaching may help with all aspects of learning chemistry.

Finally, it must be emphasized that a problem is something that an individual perceives. A given chemical situation may not be a problem at all for one individual, but may require high orders of creativity, or even serendipity (discovery by chance), for another. It was Louis Pasteur who wrote:

'. . . chance only favours the prepared mind.'

This quotation highlights one of the main points of this paper—chemical problem solving requires chemical knowledge. We must not allow the problem solving approach to teaching to cause our students to think that knowing and understanding the facts, concepts, and principles of chemistry is unimportant.

Acknowledgment. It is a great honour to have been awarded the Nyholm medal and I wish to express my gratitude to the Royal Society of Chemistry.

Sir Ronald Nyholm was a great inspiration to me, not only in my teaching and research in inorganic chemistry, but also because of his enthusiasm for efforts to improve the teaching and learning of chemistry. It was in no small part his encouragement that led me to commit myself professionally to chemical education.

I should also like to thank all my colleagues and students who have taught me so much during the last twenty-five years and I would particularly like to thank all those who have worked, or are working with me, on chemical problem solving.