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Proceedings

Problem solving: the difference between what we do and what we tell students to do[*]

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Introduction

It is slightly over 30 years since I was first asked to teach something known as 'general chemistry' at the University of Illinois. Without any idea of what went into that course, the order in which topics should be taught, or the amount of time that should be devoted to each topic, I asked a couple of senior colleagues what they did when they taught this course and tried to do the same.

During the course of that first semester, I found that I enjoyed teaching and that the students enjoyed having me as their instructor. Everything was going well until I made the mistake of analyzing the students' answers to the exams I gave them. I was shocked; or, in the language of Jean Piaget, utterly disequilibrated. In spite of clear, concise, well-organized, and well-delivered lectures, I found that bright, hardworking science and engineering majors couldn't solve 'simple' problems on topics that had been taught — and taught well![1] Thus, it shouldn't be surprising that one of the topics I became interested in as a beginning researcher in chemical education was problem solving.

Over the course of about 20 years, the author has worked with roughly a dozen graduate students pursuing M.S. or Ph.D. degrees in chemical education whose studies focused on different aspects of problem solving. It is the results of these students' work that serves as the basis for this paper.

Problem-solving research

Virtually all of our insight into problem solving has come from research that uses qualitative methods, in which we interview people struggling to solve problems and ask them to 'think aloud' — to talk about what they are doing, or what they are thinking, while they are involved in the problem-solving process. We've worked in a variety of courses, from general chemistry through the sophomore organic and inorganic courses, to physical chemistry, and even advanced organic chemistry courses taken by graduate students.

A few samples of the kinds of questions we have given to participants in our interviews are shown below. The first question is from an early study of problem solving by science and engineering majors enrolled in a general chemistry course at Purdue; the second is from a study of undergraduates, graduate students, and faculty trying to predict the product of an inorganic reaction; the third comes from a study of students enrolled in a graduate-level organic chemistry course; and the fourth is from a study of graduate students' understanding of aspects of 2D FT NMR.

- Uranium reacts with fluorine to produce a compound, which is a gas at 57°C. The density of this gas is 13.0 g/L at 57°C and 1 atm pressure. Is the molecular formula of this compound (a) UF_2, (b) UF_3, (c), UF_4, (d) UF_5 or (e) UF_6?
- Predict the products of the following reactions:

  $Na + H_2O \rightarrow$ $NaOH + Cl_2 \rightarrow$
  $MgO + H_2O \rightarrow$ $H_2S + Cl_2 \rightarrow$
  $Ba_3N_2 + H_2O \rightarrow$ $NaOH + SO_2 \rightarrow$
  $XeF_2 + D_2O \rightarrow$ $NO_2 + H_2O \rightarrow$
- Explain the following reaction (Figure 1).

Figure 1
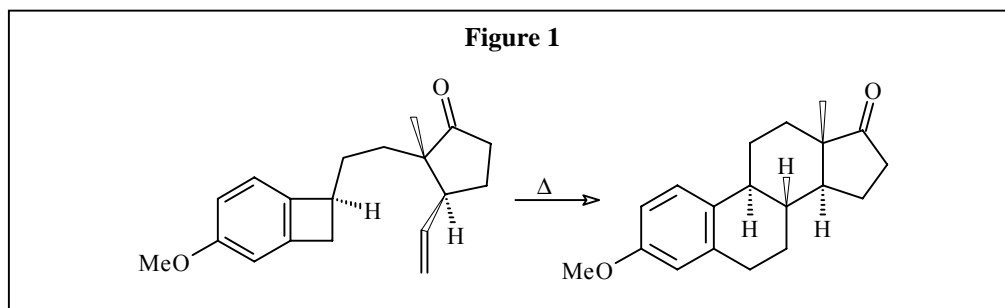
- Starting from thermal equilibrium (with M° aligned along the Z axis) and assuming no delays between pulses, predict in which plane the magnetization vector M will lay after experiencing the following pulse sequence. Assume the RF transmitter is aligned along the +X axis. $90°_x$, $90°_x$, $180°_{x'}$, $90°_{x'}$, $270°_{x'}$, $90°_{x'}$, $90°_x$.

Problems versus exercises

Chemists, who are used to differentiating between metals and nonmetals, between ionic and covalent bonds, between acids and bases, between polar and non-polar solvents, and so on, should be particularly sensitive to the role that duality can play in describing a phenomenon. Thus, they shouldn't be surprised that early research on problem solving was driven, in part, by attempts to distinguish between the way subject-matter experts and novices approached certain tasks.[2] Our work has led us to question the value of comparing the work of experts and novices because we don't believe a given task means the same thing to both groups.[3] To illustrate this, consider a problem we have given to hundreds, if not quite thousands, of industrial chemists participating in workshops on problem solving or graduate students participating in a training program for teaching assistants.

> Two trains are stopped on adjacent tracks. The engine of one train is 1000 yards ahead of the engine of the other. The end of the caboose of the first train is 400 yards ahead of the end of the caboose of the other. The first train is three times as long as the second. How long are the trains?

Let's assume, for the sake of convenience, that the two trains are headed in the same direction. Let's also remind ourselves of the definition of a *caboose* — the car that used to be placed at the end of a train, which was used by the crew on the train.

We've found that industrial chemists invariably start with a drawing, using some convention to identify the engine versus the caboose — such as the wavy line indicating smoke escaping from the engine of the trains in the following drawing. So far, without exception, they have all labeled the length of one train as 'x' and the other as '3x' They have also labeled the distance between the engine of one train and the engine of the other, and between the caboose on one train and the caboose on the other, as shown in Figure 2.
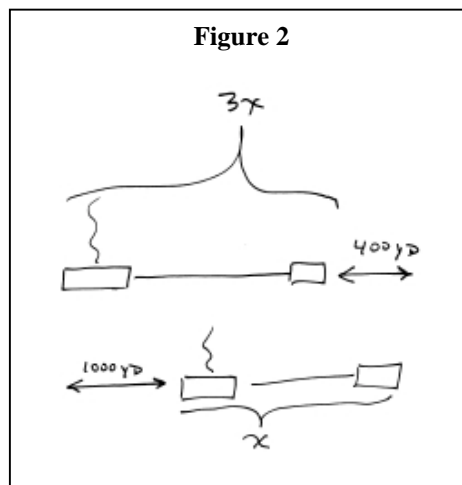

Figure 2

They then write an equation in one unknown and solve for 'x.'

$3x + 400 = x + 1000$

$2x = 600$

$x = 300$

The teaching assistants do virtually the same things. The only fundamental difference between the two groups is the tendency for those in industry to write 'x = 300' and for those in academia to write 'x = 300 yd.'

When the industrial chemists are told that there is no partial credit in this course, and they therefore get a zero, they get mad. They get a zero for the obvious reason — they haven't answered the question! When told that they are going to receive no credit for their answer, the graduate students shrug this off. They're

use to not getting the credit they feel they deserve on exams.

For now, let's focus on two observations about this problem. First, when faced with a novel problem, practicing chemists almost always start with a drawing of some kind, and frequently annotate the drawing with relevant information. Second, practicing chemists stop their problem solving activities when they get to the point that they fully understand the problem; not when they get the 'answer'.

Now let's consider another question:
> What is the molarity of an acetic acid solution, if 34.57 mL of this solution is needed to neutralize 25.19 mL of 0.1025 M sodium hydroxide.[4]
> $CH_3CO_2H(aq) + NaOH(aq) \rightarrow$
> $Na^+(aq) + CH_3CO_2^-(aq) + H_2O(l)$
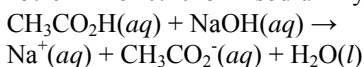
What would you expect practicing chemists to do? Would they start with an equation or formula, such as: $n = M$ x V? or with a drawing such as Figure 3?

Figure 3

CH$_3$CO$_2$H

34.57 mL

25.19 mL
0.1025M
NaOH
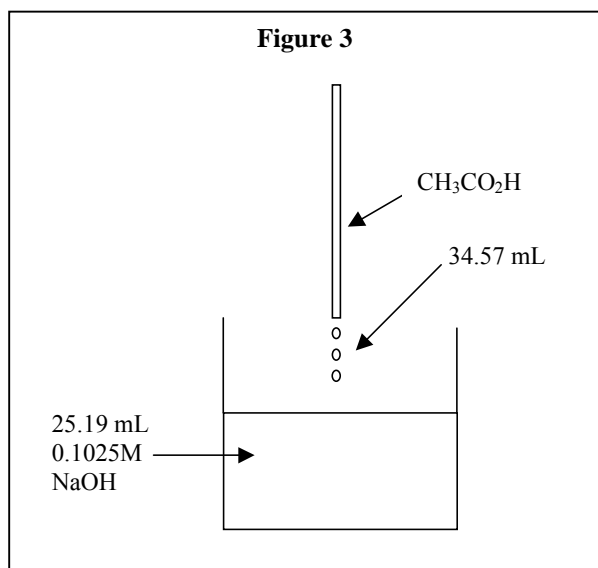
The answer should be obvious — in the absence of explicit instruction to do so, no practicing chemist would draw a picture when doing this routine exercise. They would all start by feeding numbers into an equation.

These examples suggest that a given individual might exhibit fundamentally different behaviors on different problem-solving tasks. To help the reader understand the source of these differences, we need to define the terms *problem* and *problem solving*. We'll start with John Hayes' definition of the term *problem*.[5]

Whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross that gap, you have a problem.

According to Hayes, the presence of a gap between where you are and where you want to be is a necessary — but not sufficient — criterion to classify a task as problem. There also has to be an element of uncertainty or confusion, if not downright ignorance, about how one is going to cross that gap.

Almost 20 years ago, Wheatley proposed a definition of *problem solving* that is consistent with Hayes' definition of a problem. Wheatley argued that problem solving is "*what you do, when you don't know what to do*".[6]

If the definitions proposed by Hayes and Wheatley are accepted, it should be easy to understand why we stress the difference between tasks that are *routine exercises* and those that are *novel problems*. When people first encounter these terms, they often assume that the difference between an exercise and a problem is based on difficulty, or complexity. Our work has shown that problems are neither inherently more difficult nor more complex. The only difference between an exercise and a problem is the element of familiarity.

Consider the following question from a general chemistry exam.
> What weight of oxygen is required to burn 10.0 grams of magnesium?
> $2 Mg(s) + O_2(g) \rightarrow 2 MgO(s)$
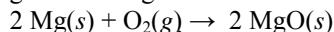
This is a routine exercise for a practicing chemist, but a novel problem for students who encounter chemistry for the first time.

Another example of this phenomenon can be found in the following question from a sophomore organic chemistry course.
> Robinson annulation reactions involve two steps: Michael addition and aldol condensation. Assume that Michael addition leads to the following intermediate.
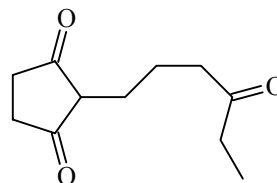
What would be produced when this intermediate undergoes aldol condensation?

This is a problem for most chemists, but a routine exercise for those who either teach or do organic chemistry. Not because they're any brighter, but because they are so familiar with similar tasks.

The distinction between exercises and problems is important because it is a potential source of miscommunication between instructors and their students. We tend to put a content expert in the classroom for whom tasks that arise during the semester are routine exercises, and expect that individual to 'teach' students for whom these tasks are novel problems. Consider what would happen if we asked organic chemists to teach physical chemistry, or vice versa. The approach they would take to 'teaching' students how to solve problems would be different, not simply because of differences in the way they think about chemistry, but because of differences in their familiarity with these tasks.

The difference between the way exercises and problems are worked is particularly well illustrated by the examples that appear in so many textbooks. These examples have several characteristics.
- They are logical sequences of steps.
- They string together in a linear fashion.
- They proceed from the initial information to the solution.

These textbook solutions, which are often mirrored by instructors in the classroom, are examples of a phenomenon that can be called 'forward-chaining' or 'forward-working'. They are examples of how routine exercises are worked by individuals with many years of experience with similar tasks. However, they have little, if any, similarity to the approach successful problem solvers use when they encounter novel problems.

As Herron once noted:[7]
> "The solutions given by authors in textbooks bear little resemblance to what experts do when they work unfamiliar problems. (Textbook solutions ... describe the most efficient pathway to a solution and probably represent how an expert who solves such problems routinely would approach the task.)"

Herron and coworkers have argued that:[8]
> "... [textbook] examples must convey to the students an unrealistic idea about how problems are actually attacked. The examples provide no indication of the false starts, dead ends, and illogical attempts that characterize problem solving in its early stages, nor do they reveal the substantial time and effort expended to construct a useful representation of a problem before the systematic solution shown in examples is possible."

Instead of comparing the work of experts working on routine exercises with novices struggling with novel problems, we have chosen a different duality. We prefer contrasting the work of successful problem solvers (of any age) with the behavior of those who are less successful when these individuals encounter problems that are outside of their area of expertise.

Models of problem solving
One of the goals of our work is the development of a model of problem solving that has two characteristics. First, and foremost, it must fit our experimental data from interviews with successful problem solvers working on what is, for them, a novel problem. Second, it must be 'teachable'; it must be a model that can be given to students that can improve their problem solving performance in chemistry.

Let's therefore look at several models of problem solving that have been proposed, starting with Polya's model that consists of four stages:[9]
- Understand the problem
- Devise a plan
- Carry out the plan
- Look back

This model makes sense. It seems logical that we would start by understanding the problem, then devising a plan, then carrying out the plan, and then looking back to check our work and consolidate our gains.

Unfortunately, Polya's model is not consistent with our work. To try to convince the reader of this, consider the following problem which is based on the experimental data collected when one of the first xenon fluoride compounds was analyzed.[10]
> A sample of a compound of xenon and fluorine was confined in a bulb with a pressure of 24 torr. Hydrogen was added to the bulb until the pressure was 96 torr. Passage of an electric spark through the mixture produced Xe and HF. After

the HF was removed by reaction with solid KOH, the final pressure of xenon and unreacted hydrogen in the bulb was 48 torr. What is the empirical formula of the xenon fluoride in the original sample?

We've given this problem to practicing chemists who do not teach general chemistry. They inevitably get the correct answer, but analysis of what they say when we ask them to work this problem out loud suggests that they do not follow the four stages of Polya's model. Indeed, a common comment heard when they finally get to the answer — XeF_4 — is: "*Oh, its an empirical formula problem!*" In other words, our experience with this problem — like the 'two trains' problem cited earlier — suggests that the process of problem solving is over when one gets to the point that they understand the problem.

Several other models of problem solving that are logical extensions of Polya's model have been discussed elsewhere.[11] They all have the disadvantage of not being consistent with the patterns we've observed for successful problem solvers working on novel problems. Let's therefore turn to a model proposed by Alex Johnstone and co-workers.[12] This model assumes that each learner has a working-memory capacity (X) and that each problem has a working-memory demand (Z), which is defined as the maximum number of steps activated by the least able individual.

The Johnstone-El Banna model assumes that when the working-memory capacity of the individual is equal to or larger than the demand on working memory $(X \geq Z)$, we have a necessary, but not sufficient, condition for success. It isn't sufficient because success also depends on prior knowledge; on whether the prior knowledge is easily accessible; on the student's motivation (inclination, interest, etc.); and so on.

This model assumes that students won't be successful when the demand on working memory exceeds the capacity of working memory $(Z > X)$, unless the student can organize the demand on working memory so that it is smaller than his or her working-memory capacity. Johnstone and co-workers note that when the demand of the problem exceeds capacity, there is a sharp drop in performance. But, some students ($\approx 10\%$) seem to be able to solve problems for which the demand exceeds capacity $(Z > X)$ because of chunking devices that reduce the demand on working

memory.

Let's assume, for the moment, that the Johnstone-El-Banna model is correct when it is applied to situations that meet the six criteria proposed by Tsaparlis.[13] Furthermore, let's assume that Niaz is correct when he concludes that: "*Teachers can facilitate success by decreasing the amount of information required for processing, and thereby avoiding working memory overload*".[14] Now what? From the perspective of this model, there isn't much we can do to improve student performance in our classes — other than helping them learn how to 'chunk' information. We simply have to accept the limitations our students bring to the classroom, and conclude that the only way we can improve their performance is to lower the intellectual rigor of the tasks we give them.

We believe that we can do more than this. Based on research on problem solving in mathematics, Wheatley proposed an anarchistic model of problem solving that describes what successful problem solvers do when they work on novel problems.[6] As noted most recently by Calimsiz,[15] this model is consistent with the results of our problem-solving interviews.

An Anarchistic Model of Problem Solving

- Read the problem
- Now read the problem again
- Write down what you hope is the relevant information
- Draw a picture, make a list, or write an equation or formula to help you begin to understand the problem
- Try something
- Try something else
- See where this gets you
- Read the problem again
- Try something else
- See where this gets you
- Test intermediate results to see whether you are making any progress toward an answer
- Read the problem again
- When appropriate, strike your forehead and say, "son of a ..."
- Write down 'an' answer (not necessarily 'the answer')
- Test the answer to see if it makes sense
- Start over if you have to, celebrate if you don't

"Draw a Picture"

There are several stages in this model that deserve explicit attention. In the 'two trains' problem, we saw the role that a drawing that is annotated with relevant information can play in solving a novel problem. We've also seen, in the calculation of the molarity of the acetic acid solution, that drawings aren't done when people encounter a routine exercise.

Over the years, several of the author's colleagues have noted how difficult it is to get their students to "draw something" while working on problems in organic chemistry. We've encountered a similar resistance among juniors taking physical chemistry, often because they can't visualize the system they are working with.

In a study of problem solving by graduate students and early career faculty within the context of combined spectra interpretation, Cartrette[16] noted that successful problem solvers in this study were much more likely to draw out molecular fragments as they were deduced in the problem solving process — in other words, to "draw something."

Our experience suggests that one cannot get students to draw a picture as a routine part of their problem solving process by telling them that *they should do* this. We've found that students are more receptive to including this step when we tell them that this is something that *we do.*

"Try Something"

We've often described the steps "try something" and "try something else" as 'playing with the problem'. Unfortunately, far too many of our students — particularly those who are struggling with the course — believe you can't 'play' with a problem. They believe that 'trial and error' is not a legitimate strategy for problem solving — often because they haven't seen any of THEIR instructors use this strategy in class. This is unfortunate because trial and error seems to be one of the most powerful strategies that our successful problem solvers own.

There is abundant evidence in our data that successful problem solvers routinely encounter a cue during problem solving that causes them to ask: Am I getting anywhere? Many beginners forget to do this. They exhibit a 'garden-path syndrome', working the problem the way they might walk through a garden — smelling the roses along the way, but not noticing that they aren't getting anywhere. Successful problem solvers tend to start over when they find that they aren't making any progress toward the answer; beginners often fail to do this.

"Does the Answer Make Sense?"

The penultimate step in this model is particularly important. We have found that beginners seldom test their answers to see if they make sense for several reasons. First, they've never seen anyone do this when they've watched their instructors work out the solutions to tasks that are exercises for the instructors. Second, they are seldom given the information they would need to do this.

Whenever we think about the penultimate stage in this model we are reminded of the phenomenon known as a Fermi calculation or Fermi estimate. Enrico Fermi had a reputation for asking students at the University of Chicago questions that seemed impossible and then showing them how to use common knowledge to estimate the answer. (For our purposes, "to test the answer to see if it makes sense.")

The most oft-cited example of a Fermi calculation involves asking students to estimate the number of piano tuners in Chicago. One starts with an estimate of the population of Chicago, the fraction of this population who are likely to own pianos, the frequency with which pianos are tuned, and so on.

Fermi calculations can be relatively simple, such as estimating how long it would take to eat your weight in food (about a month), or how much trash produced in a typical house each year (about 1000 pounds). But they can also be considerably more challenging, such as estimating the fraction of the continental U.S. covered by automobiles.

The Difference Between Exercises and Problems

In summary, we would like to argue that Polya's model is an ideal approach to working a routine exercise. One reads the question, understands the task, devises a plan, and so on. We might go so far as to argue that one of the characteristic tests of whether a task is an exercise is to ask: How is the solution found? Exercises are worked in a linear, forward-chaining, rational manner. Our model suggests that problem solving is cyclic, reflective, and can appear irrational. Experts who watch students struggle with a problem are tempted to intervene; to show the

'correct' way of obtaining the answer. This makes the expert feel good, but it doesn't necessarily help the individual who is struggling with the problem for the first time.

Our experience suggests that the anarchistic model can be taught to students and that students who pick up this approach to problem solving often do better in the course than those who do not. Teaching this model involves presenting it to the students at the beginning of the semester and then explicitly using it, over and over again, throughout the course.

We've found that this model is equally productive in introductory courses taken by freshman from the various schools that require a year of general chemistry and in physical chemistry courses taken by junior chemistry and biology majors. In a recent study of sophomores taking a year-long course in organic chemistry, Calimsiz[15] found that this model most closely reflected the process by which successful students worked problems that asked them to propose a set of reactions that would transform a given starting material into a given product.

Implications for teaching

For some time, we've been recommending that instructors who teach introductory chemistry courses draw a picture for every task they work in class from the beginning of the Fall semester until the end of the Spring semester. We find that when this is done, the number of 'C'-s in the class goes down and the number of 'B'-s and 'A'-s goes up. An example of this phenomenon is shown below:

Question: Use the K_{sp} for calcium fluoride to calculate its solubility in grams per liter.

Figure 4 contains the information extracted from the statement of the problem, as well as information that
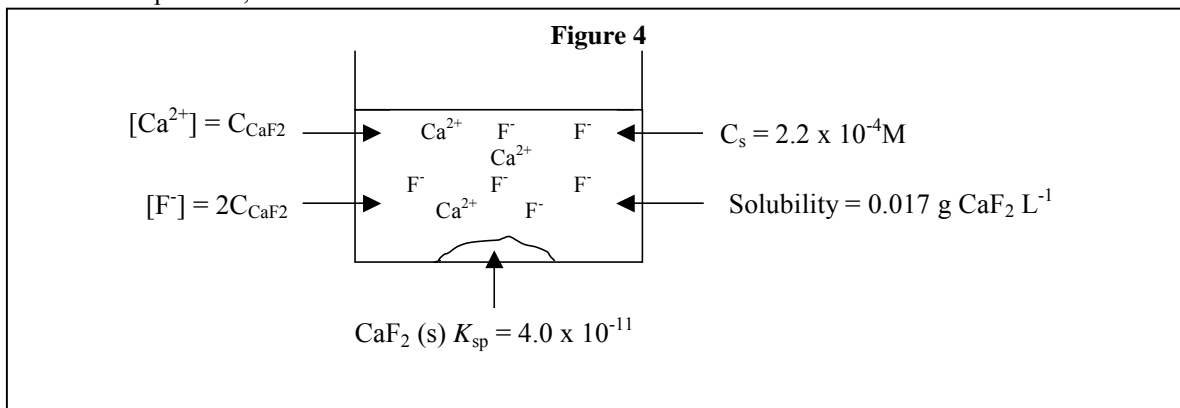
is derived while one proceeds toward the answer. Part of its power comes from the fact that it is a symbolic representation. Part comes from the fact that it is a second representation, which often brings to the students' attention details that are not always as obvious as we might expect. (Such as the fact that there are twice as many F^- ions as Ca^{2+} ions in the solution.) It is also important to recognize that this diagram is a chunking device, as called for in the Johnstone-El-Banna model. It brings together information, thereby reducing the demand on working memory.

In a prior publication in this journal[17] we looked at the implications of this idea when it is applied to the kind of descriptive chemistry one finds in modules on inorganic chemistry. The example we used in that paper was based on years of watching what happens when TA's try to explain the reaction between the triiodide ion and thiosulfate.

$$I_3^-(aq) + 2S_2O_3^{2-}(aq) \rightleftharpoons 3\,I^-(aq) + S_4O_6^{2-}(aq)$$
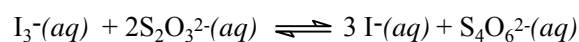
Transfer of learning

Gage and Berliner argue that "*the transfer of skills, knowledge, learning strategies, etc., is a fundamental goal of all levels of education*".[18] Transfer has been defined as the "*use of information or skills characteristic of one domain or context in some new domain or context*".[19] Transfer can occur from one problem to another within a course; from one class to another; from one year to another; from school to home; and from school to work.[20]

For years, one of the Author's goals has been building problem solving skills that transfer to other courses and, eventually, to improvements in on-the-job performance. It is for that reason that he includes

Figure 4

$[Ca^{2+}] = C_{CaF2}$

$[F^-] = 2C_{CaF2}$

$C_s = 2.2 \times 10^{-4}\,M$

Solubility $= 0.017$ g CaF_2 L^{-1}

CaF_2 (s) $K_{sp} = 4.0 \times 10^{-11}$

questions such as the following in his textbooks because he believes that these questions provide the basis for practising the anarchistic model of problem solving he incorporates into his classes.

In 1773 Benjamin Franklin observed that one teaspoon of oil spilled on a pond near London spread out to form a film that covered an area of about 22,000 square feet. If a teaspoon of oil has a volume of about 5 cm^3 and the oil spread out to form a film roughly 1 molecule tall, what is the average height of an oil molecule?[4]

It is also the reason that he collects questions such as the following, which was proposed for a course on environmental problem solving.

In a remote area in Nepal, the concentration of aluminium in outdoor air at ground level averages 9.4 x 10^{-8} μg/cm^3. (It is much higher inside the Sherpa dwellings because of wood and yak dung burning). At the same site, the Al concentration in the top 1 cm of fresh snow averages 0.12 μg/g, while in the top 1 cm of three-day-old snow it averages 0.20 μg/g. Calculate the average deposition velocity of the Al falling to the ground when it is not snowing.[21]

For many years, a family of problems has circulated that were the primary concern of individuals doing research on problem solving and the limited number of people who collected puzzles for shear intellectual excitement. Consider the following problem, for example (Figure 5).

Each of the following cards has a letter on one side and a number on the other. Which card or cards would you have to turn over in order to find out whether the following rule is true or false: If a card has a vowel on one side, it has an even number on the other side.[22]

Figure 5

| A | D | 4 | 7 |
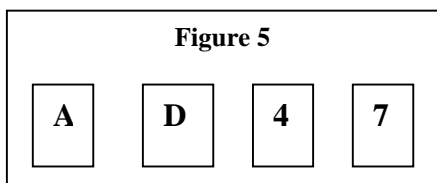
It is possible that someone might get the answer to this question without creating one of the drawings discussed in this paper, but it is not likely. Most people assume that the card with the 'A' on it must be turned over, and they are correct. What is surprising is the relatively small number of people who assume that one also has to turn over the card with the '7' on it, to make sure that there is no vowel on the other side. The author is convinced that people who get this wrong would do better if they didn't try to solve the problem in their heads. If they were forced to keep records of their thought process while they thought about each card, one at a time; if they were forced to draw a picture or make a list to help them understand the problem.

This question surfaced recently because it is being used by companies such as Microsoft as part of the process by which potential employees are screened.[23] Other questions that are asked during these interviews include:

There are three ants at the three corners of a regular triangle. Each ant starts moving in a straight line toward another, randomly chosen corner. What is the probability that none of the ants collide?

Once again, it might be possible to get the right answer (one in four) without a drawing, but most people would have to start by translating the problem into a drawing.

One of the more popular questions in the Microsoft collection is the following:

Suppose you have eight billiard balls (or jars of pills, etc.). One of them is defective — it weighs more than the others. How do you tell, using a two-pan balance, which ball is defective in two weighings?

Many people to whom we've given this question conclude that either it can't be done or at least they can't do it. Everyone we've watched get the right answer has taken the approach of 'playing with the problem'. If you start by trying to put four balls on each pan of the balance you find that it can't be done in two weighings. So try putting three balls on each pan. If the pans balance, the defective ball is among the two you didn't weigh, and you can determine which one it is in a single weighing. If the pans don't balance, select the three balls that are heavier. Now try something else. Pick two of these three balls and put one of them on each pan. If one is heavier, it is the defective one. If the pans are in balance, then the ball that wasn't chosen must be defective.

The anarchistic model of problem solving presented in this paper was based on interview data on

mathematically oriented problems. As we have continued our work, we've found that it applies just as well to non-mathematical problems such as organic synthesis or spectral interpretation. More recently, we've found that it applies to problems that extend beyond the domain of chemistry, and might therefore involve skills that are worth building and transferring.

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Paper

The classic HCl experiment: how long is the hydrogen–chlorine bond?

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The analysis of the rotational-vibrational spectra of hydrogen chloride has been utilised over many years to provide valuable learning experience for chemistry students. This paper describes a physical chemistry laboratory mini-project based on the classic HCl experiment as an example of enquiry-based learning aiming to achieve a better understanding of molecular spectroscopy by the students and to enhance their problem solving and independent learning skills. The experiment itself has been extended to the preparation of HCl and DCl, handling of the gaseous samples and analysis of both the fundamental and the first overtone bands in the infrared spectra. Working in small groups, students develop their own research strategy, carry out the experiment, analyse the data and make conclusions about the effect of isotopic substitution on the bond length and the bond force constant of hydrogen chloride. A number of mini-projects have now been introduced to our spectroscopy and physical chemistry courses. In addition to improving students' knowledge of the subject, problem solving and team working skills, they also bridge the gap between scripted practicals in the first year teaching laboratory and the research projects conducted by our students in their final year at Keele.

Introduction

Over the last forty years, the analysis of the rotational-vibrational spectra of hydrogen chloride has become a classic experiment in physical chemistry laboratories.[1, 2, 3, 4, 5] Indeed, a number of molecular and vibrational parameters can be obtained from such measurements with a high degree of precision, and a clear link between the quantum chemistry theory and spectroscopic experiments can be established. Some more recent developments of this experiment include the use of more sophisticated analysis routines, the investigation of deuterium chloride and computer modelling of the rotational-vibrational spectra of diatomic molecules.[6, 7, 8, 9] At Keele, we have recently introduced a number of physical chemistry laboratory mini-projects for our undergraduate students in order to enhance their skill base, problem solving and independent learning.[10] In general, a mini-project commences with setting a problem related to studied topics: to investigate the effect of isotopic substitution on the bond length and the bond force constant, to construct a quantitative Jablonski diagram for an aromatic molecule, etc. In the following step, students need to develop their own research strategy that outlines how they are going to conduct the experiment, obtain the required information and analyse the data. In the course of the practical work carried out in small groups, students need to reflect on the approach, make improvements to the experimental design and learn from their own mistakes. Finally, an individual or a group report for each experiment is submitted; in the latter case, a self-evaluation of the teamwork has to be included. It should be noted that despite all the modifications, the practical work still does not require the use of expensive chemicals, sophisticated equipment or highly specialised instrumentation. Following this approach, four experimental mini-projects on various topics in vibrational and electronic spectroscopy have now been incorporated into the laboratory classes for our second year chemistry students. This paper describes one of the projects, a modified HCl experiment, as an example of enquiry based learning, which is aiming to ensure a better understanding of molecular spectroscopy by the students and to stimulate their active involvement in the learning process.

Experimental Procedures and Background Theory

The HCl mini-project was undertaken over three 2-hour sessions including planning the work and carrying out the experiment and data analysis. In addition, about the same amount of private study time was necessary for background reading, information retrieval and writing the final report. Access to standard teaching laboratory facilities and information resources was also required. The classic HCl experiment has been substantially extended to include the preparation of both HCl and DCl, handling of the gaseous samples for spectroscopic measurements and analysis of both the fundamental and the first overtone bands in the infrared spectra. FTIR transmittance measurements were performed using a Thermo Nicolet Avatar 320 and a Perkin-Elmer Paragon 100 instruments, both of which are entry level FTIR spectrometers commonly available in the undergraduate chemistry laboratories. The details of the sample preparation, spectra collection and data processing are described in the available supplementary information.[11]

Laboratory Class: Day One

Instead of a traditional style detailed laboratory script describing the background theory, experimental procedures and data analysis over many pages, students receive a one-page summary of the task.

"Studying chemistry we are routinely considering detailed structural features of organic and inorganic compounds. Have you ever wondered where all this information came from? Who determined bond lengths, geometry and composition for thousands and thousands of molecules, when and how? Well, here is your chance to follow the footsteps of many distinguished researchers.

Your aim in this experiment is to determine the hydrogen–chlorine bond length for four isotopic analogues $H^{35}Cl$, $H^{37}Cl$, $D^{35}Cl$ and $D^{37}Cl$ to ±2 pm. In addition, you need to determine the hydrogen–chlorine bond force constant for these molecules. Based on your data, you need to draw conclusions about the effect of isotopic substitution on the bond length and on the bond force constant.

In this mini-project you are expected to demonstrate practical skills in experimental chemistry and data analysis as well as the ability to plan your work and to manage your time and team effort.

You should work in groups of 3 or 4. First of all, you need to develop a plan outlining your research strategy: how you are going to conduct the experiment, analyse the data and obtain the required information. Keep in mind the resources available in the laboratory when planning your work. Before commencing the experimental work, you must discuss your plan with a demonstrator who may provide additional instruction sets and assigned exercises.

Following the discussion, you will need to complete a risk assessment, carry out the experimental work, analyse your data and calculate the required values for bond lengths and bond force constants in order to achieve the aim of the experiment, and produce a report."

When the initial perplexing reaction subsides and the students proudly reject the offer of a one-meter wooden ruler for the bond length measurements the teamwork begins. By the end of the first lab period, detailed plans of actions are drawn up and discussed, and the preparations for the experimental work are underway.

Making It with Spectroscopy

Before long students realise that their molecular spectroscopy course provides a solid theoretical foundation for the analysis of molecular structures and that the FTIR spectrometers available in the teaching laboratory can provide good quality rotational-vibrational spectra of simple molecules in the gas phase. They also discover that the sample of hydrogen chloride is not supplied but must be prepared first, which requires some revision of first year chemistry. Since they are required to obtain four isotopic varieties of hydrogen chloride, students need to appreciate that ^{35}Cl and ^{37}Cl isotopes are naturally found in the 3:1 ratio (75.8% and 24.2%, respectively), whereas the abundance of deuterium is far below 1% (99.98% of ^{1}H and 0.02% of D) and the use of deuterated reagents is necessary.[12] It is also pointed out by the demonstrator that in order to produce an approximately 50:50 ratio of HCl to DCl in the isotopic mixture, one has to work with a 10:90 mixture of H_2SO_4 and D_2SO_4. This should lead to the discussion of the zero point energy and the effect of isotopic substitution on the dissociation energy and the reaction rates; if it does not, the instructor initiates it.

To reach the final destination and to obtain the required bond lengths and bond force constants students need to have a good grasp of the background theory, which provides a direct link to the lecture material and tutorials. Subsequent step-by-step analysis of the experimental data offers an opportunity to consider the experimental design and the underlying principles of molecular spectroscopy. For instance, the provided 'detailed' instruction tells students to collect infrared spectra using the highest available resolution. Which one is it, 1 cm^{-1} or 32 cm^{-1}? To keep students on the right track during their practical work and data handling, four sets of instructions are available, but not before students' working plans are finalised. A typical set of instructions describes a selected topic, e.g. sample preparation or data acquisition and processing, as it would in a comprehensive lab script, but with some key points missing or with additional compulsory questions initiating further discussion and testing the level of understanding of the background theory. In some cases students can gain 'bonus marks' (up to 10-15%) for being able to work out the difficult bits by themselves. Our instructions for the HCl mini-project cover the preparation of an isotopic mixture of $H^{35}Cl$, $H^{37}Cl$, $D^{35}Cl$ and $D^{37}Cl$, the measurement of the rotational constants B_1 and B_0 by the method of combination differences, the calculation of the rotational constant B_e, and the determination of the equilibrium vibrational frequency.[11]

The data treatment, although based on a rather simple model, is quite extensive, as results for all the isotopic variants of HCl have to be analysed. There is room here for the students to demonstrate their organisational skills and teamwork (each group of students can submit a joint account of their work which would have to include a self-assessment of the group's performance). IT competence and a reasonable background in math are also among important assets for this mini-project. Table 1 gives a summary of the subject specific and generic skills students are expected to demonstrate and enhance in this mini-project.

Table 1. Theoretical issues, experimental work and generic skills addressed in the HCl mini-project.

Subject specific knowledge	Practical work	Generic skills
Molecular spectroscopy of diatomic molecules	Sample preparation using isotopically substituted compounds	Working efficiently as a team
Rotational and vibrational energy levels, population of energy levels	Risk assessment	Planning and managing own work and time
Rotational and vibrational absorption spectra	Practical work with FTIR instrumentation	Designing and planning an experiment
Isotopic substitution, bond length and bond force constant	Handling of gaseous samples for infrared analysis	Critical evaluation of own work
Fundamental transitions and overtones	Work with specialised spectroscopic software	Information retrieval from on-line resources and research papers
Harmonic and unharmonic oscillator		Plotting graphs and obtaining statistical information
Method of combination differences		
Preparation and properties of hydrogen chloride		
Isotopes, their properties and abundance		
Kinetic isotope effect		

Finally, a conclusion should be reached whether isotopic substitution has any effect on the bond length and on the bond force constant. Accurate results for all four molecules, which usually agree with the literature data[5, 13, 14, 15] to ±1% (e.g. the bond length measurements are within 1 pm of the published values) greatly facilitate the decision making. Interestingly, students are often surprised to discover during discussions with the instructor that these data constitute some of the most accurate measurements they obtain in the undergraduate laboratory classes.

Concluding Remarks

Overall, students appreciate the challenge of this practical course that provides a clear link between the theory of quantum mechanics, spectroscopic analysis and everyday chemistry. They acknowledge difficulties encountered in their work and value the sense of achievement when the final conclusions are made, as well as the opportunity to develop critical thinking and ability to tackle unfamiliar and open-ended problems, which is clearly seen from their comments. To quote some of the responses, "*problem solving and team work provide an effective way of understanding course material and learning useful transferable skills*", "*new*

style makes lab more interesting", "*labs enable you to use your own initiative and to apply your knowledge*", "*this is good experience for later in the course, i.e. research*", "*good practice in using team work – a vital skill*". In the module evaluation questionnaires, students emphasise that the mini-projects have helped them to enhance their skill base, to understand the background theory, to put the lecture material into context and to improve their team working. In addition, we are now accumulating more quantitative information, including the results for Spectroscopic Methods and related modules, marks for the exam questions on molecular spectroscopy, and of the students' performance in the final year projects, to assure successful learning outcomes of this approach.

Notwithstanding our generally positive experience with mini-projects, the following points should be kept in mind. Detailed planning and adequate resourcing of chemical laboratory mini-projects call for careful consideration. Some weaker students are likely to require additional attention and help to overcome the 'activation barrier'. It is worth noting that the current Internet culture encourages students to commence their enquiry based learning by hitting the Google search button, and they may be 'lucky' to find detailed

answers on the web pages of some universities. To overcome this problem, the emphasis is placed on the students' explanation and understanding rather than on their ability to find the information. It has also become clear that students greatly appreciate the importance of teamwork, and they are now requesting additional training in team building and management techniques. This will be provided jointly with our Education Department as part of the key skills training for the second year students starting with the next academic session. In addition, a number of students have pointed out the demanding nature of the mini-projects ("*more time should be given to research the project*", "*thrown in the deep end*", "*it would help for a bit more background information, clues [to be given]*") and asked for more guidance and explanations at the beginning of the laboratory work to ensure smooth running-in for the molecular spectroscopy practicals.

Mini-projects are now becoming a common feature of our spectroscopy, inorganic chemistry and physical chemistry courses with around ten different experiments available in this format. These include four topics on molecular spectroscopy (*How long is the hydrogen-chlorine bond, The structure of acetylene, Conquering the spectrum of iodine,* and *The Jablonski diagram of anthracene*), two mini-projects on the chemistry of transition metal complexes and another four on electrochemistry and kinetics. In addition to boosting students' understanding of the subject, their generic and teamwork skills, the mini-projects serve as an important transition from scripted practicals in the first year to the research projects carried out by the chemistry finalists in their third year at Keele.

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Evaluation of higher *vs.* lower-order cognitive skills-type examinations in chemistry: implications for university in-class assessment and examinations

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The absence of sufficient, convincing, research-based documentation is often quoted as an argument against any change in the currently dominant lower-order cognitive skills (LOCS)-type examinations. Our aim with this paper is the fostering of higher-order cognitive skills (HOCS) learning, based on three relevant research studies: two conducted in Greece, and one in Israel. A different pattern of students' performance was revealed on examination questions requiring HOCS compared with that on questions requiring LOCS. A high performance on the latter does not necessarily guarantee a high performance on the former, and the reverse may also be the case. A 'high-stake' examination, used for entry into higher education in Greece, was found to select the best LOCS-performing students! Alternative forms of examination, such as the 'take-home exam', proved to be useful mainly for the enhancement of university students' active participation in courses, their self-directed, independent study, and the cultivation of their HOCS through the inclusion of questions requiring HOCS, dealing with material not covered in class. In a related Israeli study, conducted within an introductory freshman general and inorganic chemistry course, it was found that, given a free choice between HOCS- and LOCS-type questions, the top performing students preferred to answer questions requiring LOCS, in spite of proclaiming their preference of those requiring HOCS.

Introduction

The almost compulsive need for extensive testing and assessment in science education within contemporary educational systems at all levels may result in stagnation, if not regression, in attaining the newly emerging educational-instructional goals worldwide.[1] Yet, the absence of sufficient, convincing, relevant, research-based findings is often quoted as a strong argument against any change in the currently dominant lower-order cognitive skills-type examinations.[2] In this work, we briefly describe and critically analyze research work which examines the two types (lower- and higher-) cognitive skills (LOCS and HOCS), and has direct bearing on the issue at point. Three relevant studies, the first two conducted in Greece, and the third in Israel, are reviewed and discussed further for this purpose. These are:

1. A comparison of one examination, the Panhellenic Chemistry Competition (PCC), analyzed for LOCS vs. HOCS-type questions, with a second examination, the General Examination (GE), used for entrance into higher education in Greece.[3] In a directly connected study, the student performance patterns in science/chemistry examinations which require HOCS or LOCS were examined.[4]

2. The use of take-home examinations to promote students' participation, collaboration and the development of their HOCS.[5]

3. A study focusing on students' LOCS/HOCS declared preference, compared with their actual performance within a freshman introductory general and inorganic chemistry course at an Israeli university, targeted at promoting HOCS-learning.[6, 7]

The work here presented is complementary to related research studies,[4, 6-10] and is guided by the following rationale:

- Examinations should not only be consistent with the teaching/instructional goals, but also, meaningfully, contribute towards their attainment.[2, 6, 8, 11, 12]

- The development/acquisition of HOCS by our students should be a major instructional goal in both disciplinary (e.g., chemistry) and interdisciplinary science teaching at all levels.[2, 4, 8-15]

- Appropriately designed HOCS-oriented examinations in science/chemistry teaching should be used to (a) foster and develop students' HOCS capabilities, and targeted at HOCS learning;[2] (b) reveal their misconceptions (followed by their remediation) and distinguish between students' misconceptions, misunderstandings and 'no conceptions'[8] for appropriate teaching-learning strategies to be applied accordingly in line with 'HOCS *learning*';[2, 11, 14] (c) foster a shift from concentrating on the dominant algorithmic exercise solving ability to meaningful problem solving, requiring conceptual understanding[14-16] /'HOCS *learning*';[11-15] and (d) identify (not label), within context, students who are fitting or close to the HOCS-type (henceforth HOCS-students), and students who are fitting or close to the LOCS-type (henceforth LOCS-students), in science courses for improving course-teaching and assessment strategies, regardless of whether the related teaching was LOCS- or HOCS-oriented.[4-11] [A word of caution: as with any human quality, the distinction between HOCS and LOCS cannot be dichotomous; instead, HOCS and LOCS are 'classified' within the edges of a continuum. The categorization we use here is just for the purpose of the study, not for labeling students.]

Based on selected relevant research results and the related evolving implications for science/chemistry teaching, this paper is directed at the fostering of HOCS learning. There are chemistry teachers who subscribe to the view that mastery of computational, LOCS-type exercises (traditionally referred to as 'problems') is 'equivalent' to conceptual understanding of chemistry. A series of studies and articles have demonstrated that this wide-spread notion is unfounded.[15-27] Of particular relevant interest is the connection of performance in algorithmic and conceptual items to psychometric variables.[28-31] Since this paper is about assessment and examinations, particularly the HOCS-type, these will constitute its focus.

LOCS and HOCS examination items

LOCS and HOCS examination items (an item being a question, or a group of questions, or an exercise or a problem, or a 'scenario' to relate to) are operationally defined as follows:[4, 15]

LOCS items: These are knowledge questions that require simple recall of information or a simple application of known theory or knowledge to familiar situations and context. They can also include the so called 'problems', mostly computational exercises, solvable by the application of taught/recalled/known algorithms, not necessarily understood by the 'solver', which are already familiar to the learner through previous specific directives, or long-term practice, or both.

HOCS items: These are quantitative or qualitative, ill-defined/structured, or open-ended questions, mostly unfamiliar to the student, which require for their 'solution' much more than just knowledge and/or application of known algorithms; they may require analysis, synthesis, system thinking, decision making, problem-solving capabilities, but mostly the making of connections, and critical evaluative thinking.[2, 15, 32] This includes the application of known theory or knowledge to unfamiliar situations or situations with an unusual element or dimension.[33] In this respect, HOCS extend far beyond the skills of analysis, synthesis, and evaluation to those of critical-, system (lateral) evaluative thinking, requiring the synergistic interaction/integration of these and related skills in different situations and contexts.[2, 14, 32]

Examples of HOCS and LOCS questions in chemistry examinations are provided later in this paper, as well as in previous publications.[4, 8, 10, 14-16]

Greek Study I: The Use of One Examination for the Evaluation of Another Examination

In this study, we compared the General Examination (GE) with the Panhellenic Chemistry Competition (PCC) exam, both held in Greece in 1991 for high school graduates (N = 1352). The second examination offered a 'golden' opportunity to carry out such an evaluation, by being used as a frame of reference or measuring stick. The two examinations have quite different features: PCC is informal, and places the emphasis on items that require HOCS;[11] GE is formal, and consists of questions that require simple recall of knowledge and algorithmic exercise solving; that is, of questions that require just LOCS.

The GE was targeted at secondary education graduates (age 17-18) who competed for admission to higher education in Greek institutions. The chemistry section consisted of four major items. Two of these were knowledge questions (LOCS-type), the answers to which could be found in the standard chemistry textbook, with no need for any cognitive processing other than simple recall. The other two items were algorithmic computational 'problems'. Because of the severe competition, students preparing for the exam study hard, solving a large number of computational 'problems'. In this way, problems are treated by the application of

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Table 1. *Student performance (means; standard deviations in parentheses) in the Panhellenic Chemistry Competition (PCC), the Chemistry General Examination (GE), and on the HOCS and LOCS components of the PCC.* [4]

	Group/Subgroup	N	PCC	PCC_{HOCS}	PCC_{LOCS}	GE
1.	All students	1352	24.4 (18.6)	-	-	-
2.	Students with marks $\geq$ 50 in PCC	146	61.8 (8.8)	54.3 (12.1)	72.2 (13.4)	92.5 (6.9)
3.	Students with marks $\geq$ 68 in PCC	42	73.3 (4.4)	66.8 (6.6)	82.2 (9.8)	95.4 (5.9)
4.	Students with marks $\geq$ 35 in PCC and marks 98.8-100 in GE	40	62.9 (13.2)	-	-	99.3 (0.5)
5.	Students with 35, 36, or 37 in PCC*	43	35.7 (0.5)	-	-	84.1 (10.9)
6.	Students with marks $\geq$ 70 in PCC_{HOCS}	16	74.6 (6.4)	74.1 (3.1)	75.3 (14.6)	94.4 (6.0)
7.	Students with marks $\geq$ 90 in PCC_{LOCS}	16	73.9 (7.1)	59.8 (11.5)	93.4 (2.3)	94.7 (4.7)

* Note that about half (21) of these students had a very high mean performance in GE (93.5).

known and well-practiced algorithms, thus turning them into 'exercises'. Operationally, we categorized all GE questions as questions that required LOCS for their solution, i.e., LOCS items. This is in line with the perception of the GE by all involved (State, news media, teachers, parents and students) as a test that requires just rote learning, not critical thinking or other related HOCS.

The Panhellenic Chemistry Competition (PCC), on the other hand, is aimed at the annual selection of the students who represent Greece in the International Chemistry Olympics. Although the chemistry dealt with in the PCC is, as a rule, known to the students from their high school chemistry courses, a considerable number of questions require the application of theory, known or acquired by the students, to novel situations, i.e., HOCS. Consequently, we categorized the questions of the PCC into HOCS-type questions (for which we will use the notation PCC_{HOCS}) and LOCS-type questions (for which we will use the notation PCC_{LOCS}). The 1991 PCC examination consisted of 22 (58%) HOCS and 16 (42%) LOCS questions. Table 1 provides the summary of student performance data for the two examinations. [4]

Discriminating power of the two examinations
A main feature of the PCC, which is due to its more demanding questions, with less time available to answer them, is its capacity to effectively classify 'good' students, that is, to discriminate between the 'good' and the 'very good' ones. The values of the standard deviations (SD) demonstrate this power. Thus, for the 42 best performing students on the PCC, the SDs are 4.4 for the PCC and 5.9 for the GE. On the other hand, for the 40 best students on the GE, the corresponding SDs are 13.2 and 0.5

respectively. As we move down the scale of performance, the PCC is losing this discriminating power. In contrast, the GE, although failed to discriminate among 'good' students, had a sufficiently good discriminating power as we move to the lower performance levels. Thus, the 43 students of our study, with the lowest marks in PCC - 35, 36 and 37 (out of 100) - had a SD of 0.5 on the PCC and 10.9 on the GE. It follows that performance on the PCC is a poor predictor of performance on the GE.

Student performance patterns on questions requiring HOCS and LOCS
By comparing the performances on the PCC_{HOCS} and PCC_{LOCS} items of the 146 students who achieved at least the 50% level in the PCC, we found that the performance on the items requiring LOCS was much higher (17.9 points on a 0-100 scale) than that on the items requiring HOCS. This finding could have been expected and was corroborated in other related studies. [7, 15, 16] Indeed, the correlation between performance on PCC_{LOCS} and GE was higher (Spearman rho = 0.32) than that (0.25) between PCC_{HOCS} and GE (Table 2).

Table 2. *Spearman correlation matrix for the Panhellenic Chemistry Competition (PCC),* the Chemistry General Examination (GE), and the HOCS and LOCS components of the PCC.* [4]

	PCC	GE	PCC_{HOCS}	PCC_{LOCS}
PCC	1			
GE	0.39	1		
PCC_{HOCS}	0.77	0.25	1	
PCC_{LOCS}	0.59	0.32	-0.01	1

*Students with marks $\geq$ 50% in the PCC (N = 146).

Surprisingly, no correlation (Spearman rho = -0.01) was found between students' scores on PCC_{HOCS} and PCC_{LOCS}. The fact that students who did very well on PCC_{HOCS} (entry 6 in Table 1) did not score higher on PCC_{LOCS}, explains this lack of correlation. This fact is surprising in view of the expectation that HOCS students should, in principle, be able to deal successfully with items requiring just LOCS. According to Bloom's taxonomy, the possession of LOCS is taken for granted as a prerequisite for having the HOCS capacity, thus assuming that we can have LOCS-only students but not HOCS-only students. On the other hand, the overall correlation between PCC and PCC_{LOCS} (0.59 see Table 2) was found to be statistically significant, apparently for the students who must have taken the PCC with very good preparation.

A possible explanation for the lack of correlation between students' scores on PCC_{HOCS} and PCC_{LOCS} is the extent of the students' pre-examination preparation; that is, practically speaking, many PCC participating students failed to prepare for it. One cannot exclude, however, the involvement of affective factors, such as motivation and personal preference for particular types of questions[7] as being important contributors to the above finding.

What is the effect of the extent of pre-exam preparation on performance, and what are the implications of our relevant findings for in-class assessment? Clearly, students with varying amount of preparation have taken the PCC exam. Our findings suggest that the difference in preparation has affected the performance on the questions requiring LOCS (PCC_{LOCS}) but not necessarily on the questions requiring HOCS (PCC_{HOCS}). Students who did poorly on the PCC_{LOCS} but did relatively well on the PCC_{HOCS} have probably had only a little preparation for the PCC. That the lack of, or an inadequate preparation is, indeed, the reason for the latter 'no difference' can also be inferred from essentially the same mean PCC_{LOCS} mark of these 'HOCS students' as that of the whole 146 student sample.

These results suggest that both HOCS- and LOCS-type questions ought to be used in class assessment.

This will not only promote HOCS learning,[2, 12, 32] but also identify and distinguish between HOCS- and LOCS-type students. This approach can be applied in both formative and summary evaluations, as well as in designing the course teaching and remediation.

We conclude, that the PCC_{HOCS} and PCC_{LOCS} parts of the PCC measure quite different skills, i.e., HOCS versus LOCS. This can also be deduced directly through an appropriate statistical factor analysis in which the performances of the 146-student sample on the PCC, the PCC_{HOCS} and PCC_{LOCS} parts of the PCC as well as on the GE were taken as entry data.[4] Two factors were thus extracted, one loading on PCC and PCC_{HOCS}, the second on GE, PCC and PCC_{LOCS}. We find that our conclusion regarding the difference between HOCS and LOCS is supported by this analysis. (Note that factor analysis considers the correlation of a number of observed variables to be a result of their sharing of common sources or *factors*, and not as a result of one being a direct cause of the others.)

Greek study II: the take-home, open-book examination as a means to promote students' participation, collaboration and HOCS

Many university science and chemistry educators are concerned about the poor lecture attendances by students in university lecture-based courses. There are countries, such as Greece, where it is not mandatory for students in universities to attend lectures. As a result, attendance at lectures is low, and students do not participate actively in the learning process. However, these students attend examinations, often without adequate preparation, their preparation being largely textbooks-based. What is worse is that there is a little chance that they will develop their HOCS.

One easy means that may be very effective in increasing student participation and collaboration in the learning process, particularly with respect to their HOCS development, is the take-home, open-book examination.[34] This 'method' has been applied in Greece and the results were very encouraging.[35] The participation and involvement of the students was widespread and enthusiastic.

Table 3. Students' ($N = 85$) mean performance (standard deviations in parentheses) in the take-home examination.[35]

	Questions based on material taught in class			Questions outside of material taught in class		
	LOCS in knowledge (3 questions)	LOCS in application (2 questions)	Total (5 questions)	HOCS (4 questions)	LOCS in exercise (1 question)	Total (5 questions)
M	88.0	74.0	82.4	35.2	81.7	44.5
(SD)	(6.1)	(15.5)	(7.4)	(20.6)	(28.9)	(19.9)

Almost all students handed in their papers on time, after dealing, seriously and extensively, with all the questions posed. Most papers were carefully worked out and nicely written.

Table 3 summarizes the students' performance on the take-home examination. Students performed very well on the knowledge and application questions that could be found directly in, or with the aid of the course textbook. They performed equally well on a question that required LOCS (a stoichiometric calculation: Do 10 g of PCl_3 contain more, the same, or fewer atoms of chlorine than the number of bromine atoms in 10 g of PBr_3?) However, their performance dropped dramatically on the HOCS questions that dealt with material outside that taught or discussed in class, in spite of their use of several textbooks and the intra-student collaboration that took place. An example of such a question is given below (for more examples, see Zoller et al. [10]):

> One of the best ways of checking the purity of PCl_3, which is used in the manufacture of saccharine, is to compare the mass spectrum of a sample with that of pure PCl_3. Given that chlorine has two naturally occurring isotopes (^{35}Cl and ^{37}Cl, relative isotopic abundance ~ 75:25, respectively), whereas phosphorus has just one (^{31}P), in your opinion, is the given relative isotopic abundance for the chlorine atom (75:25) relevant to the method here presented for checking the purity of PCl_3? [This question is not only different in kind, in that it clearly requires HOCS, but also is a much more difficult question than the previous, LOCS, one. It is hardly surprising that the marks were lower.]

Table 4 shows student performance on the January 1995 end-of-semester examination, as well as previous years' results in the same course, taught by the same instructor. Although no direct inference could be made concerning the effect of the take-home exam procedures on the students' performance, clearly it had a substantial effect on student participation in the exam: the latter climbed to 94% in the year of the take-home exams,

compared with 76% and 80% in the two previous years. (Taking an exam is optional in Greece.)

The Israeli study: students' performance versus selected LOCS/HOCS questions

A study was conducted within a freshman introductory general and inorganic chemistry course for biology majors ($N = 22$) at an Israeli university that compared the students' stated preferences regarding LOCS- and HOCS-type questions with their actual choices made in examinations.[7] The study involved a mid-term take-home examination which consisted of a set of ten questions categorized as algorithmic (A), LOCS (L), HOCS (H), or mixed-order (MOCS) [i.e. consisting of algorithmic and LOCS parts (A/L), algorithmic and HOCS parts (A/H), algorithmic and LOCS and HOCS parts (A/L/H), etc.]. The students, who had been exposed to HOCS-promoting teaching for half a term,[11] were asked to choose just two questions (out of ten); to work them out at home on their own while taking their time; to use any material they might need; and to submit their final answers for grading as a substitute for an ordinary mid-term examination. This meant that the students could choose (if so they wished) two algorithmic or LOCS questions only, and avoid HOCS questions altogether. Questions 2, 3 and 5 - categorized by a panel of experts as algorithmic (A), LOCS (L), and HOCS (H) respectively - are given below as representative examples:

Question 2 (A). When $CaCO_3$ is heated, CaO and CO_2 are obtained. What will be the weight of the remaining solid mixture if 25 grams of $CaCO_3$ are heated in an open container until half of the $CaCO_3$ is decomposed?

Question 3 (L). Which is the oxidizing agent and which is the reducing agent in the following reactions?

i. $F_2 + 2Cl^- \rightarrow 2F^- + Cl_2$
ii. $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$
iii. $2Cu^{2+} + 4I^- \rightarrow 2CuI + I_2$
iv. $H^+ + OH^- \rightarrow H_2O$

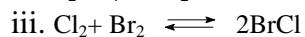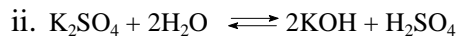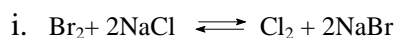**Table 4.** Freshman students' performance on the end-of-semester formal elementary physical chemistry examination.[35]

Year	1992	1993	1994	1995
N [a]	43	61	64	75
Participation [b]	54%	76%	80%	94%
Successful among all exam participants	44.2%	65.6%	46.9%	56.0%
Successful among all freshman students	24.0%	50.0%	37.5%	52.5%

[a] Freshmen only who took the exams.
[b] An estimate of student participation in each exam, based on an average total of 80 students per year.

Question 5 (H). The following are three balanced reactions and yet, the chances for the first two to actually take place are very small, whereas the third would occur under appropriate conditions. Why? Rationalize!

i. $Br_2 + 2NaCl \rightleftharpoons Cl_2 + 2NaBr$
ii. $K_2SO_4 + 2H_2O \rightleftharpoons 2KOH + H_2SO_4$
iii. $Cl_2 + Br_2 \rightleftharpoons 2BrCl$

We hypothesized (or hoped...), that the good 'HOCS-students' in the class—after being exposed to 'HOCS-teaching'[12] —would prefer HOCS-type questions, given a free choice on examination situations. The students' performance distribution, versus their selected two out of ten take-home exam questions (LOCS, or HOCS, or 'mixed') to respond to is given in Table 5.[7, 36]

The top performing students, six out of 22 (27%), preferred to select and respond to LOCS-type questions. This clear-cut selection of only LOCS-type questions by these students can easily be rationalized by the 'student-proof' approach to grading in examination situations; that is, students prefer to choose what they perceive to be the *easiest* possible way to get a high grade without taking any risk, regardless of their preference of HOCS/conceptual understanding-type questions, and/or whether or not a much more *challenging* (and meaningful) alternative is available. Since these students could get away without the need to respond to HOCS (or even MOCS) questions, we do not know (based on the given results only) if they were 'LOCS' or 'HOCS' (or 'MOCS') students. The pattern change in the 'profile' of the questions selected by the freshman students from top to bottom in the LEVEL column (i.e., LOCS → LOCS plus MOCS → MOCS ... → MOCS plus HOCS) suggests that the HOCS-oriented instruction during the two months period preceding the examination was not sufficient to change students' 'exam-attitudes/behavior' as far as the hoped for shift in preference from LOCS to HOCS learning is concerned.

Summary, Conclusions and Implications

It was found in the Greek Study I, that there is a different pattern of students' performance on examination questions requiring HOCS, compared with that on questions requiring LOCS. A high performance on the latter does not necessarily guarantee a high performance on the former. On the other hand, many 'HOCS students' in our study performed no better on the supposedly easier questions requiring just LOCS, compared with their performance on questions requiring HOCS. Based on the analysis of the data, we have attributed this finding to insufficient pre-examination preparation/study. Alternative interpretations, such as low interest in, motivation by, and/or disposition towards the traditional rote-type and algorithmic examination items, cannot be excluded. Nevertheless, our results may suggest that the 'linearity' assumed/implied in Bloom's taxonomy, that the possession of LOCS is taken for granted as a prerequisite for having the HOCS capacity is questionable, at least with respect to a certain segment of the student body.

Table 5. Israeli students' performance distribution versus their selected LOCS, HOCS, and mixed-order (MOCS) questions.[36]

Score[a]	Number of students		%	Type of question[b]	Level[c]
96-100	4		18.2	A & L	LOCS
91-95	6	2	9.1	A & L	LOCS
		2	9.1	A & A/H	LOCS & MOCS
		2	9.1	A & L & L/H or A/L/H	LOCS & MOCS
80-90	4	2	9.1	A & A/L/H or A/H	LOCS & MOCS
		2	9.1	A/L/H & A/H or L/H	MOCS
60-79	5	1	4.5	A & A/L	LOCS
		1	4.5	A/L & A/L/H	LOCS & MOCS
		3	13.6	A/L/H & A/H A/L/H or A/H & H	MOCS MOCS & HOCS
<55	3		13.6	A or L or A/L & A/L/H or A/H	MOCS & HOCS

(a) Scale: 0-100
(b) Algorithmic – A; lower-order – L, higher-order – H
(c) LOCS: Including A, L & A/L as single items within the question;
     HOCS: Including A/H, L/H, A/L/H, and H as single items within the question;
     MOCS: (Mixed-order cognitive skills): Including both HOCS and LOCS within the question.

A major finding was that a formal examination that is decisive for students' future, such as the General Examination in chemistry (GE) of Greece, aiming at selecting the best students for higher education, was emphasizing LOCS. Consequently, it achieved the selection of the best LOCS-performing students! It is impossible to say, however, whether it concurrently succeeded in selecting, at least partly, the students who have had already acquired the HOCS capability.

The prevailing LOCS orientation in contemporary science and chemistry teaching versus the low prevalence of fostering students' development of HOCS structures are, most probably, responsible for the much lower performance of students on HOCS- than on LOCS-type examinations. One should also take into account the possibility that questions of the two kinds (requiring HOCS or LOCS) may differ in their degree of difficulty.

It has been suggested,[3] that there should be a scaling up of the difficulty and skills required of the questions set on the GE, in order to increase its discriminating power with respect to the very 'good' students. (By 'good' students we are implying those who have developed, at least in part, a HOCS capability.) At the same time, the good discriminating power of the GE with respect to the less able or less prepared students should be maintained. The above suggestion has, in part, been implemented in recent years in two ways: (a) initially, by increasing the complexity of the algorithmic GE problems, making them draw on more than one area of chemistry. (The increase in complexity was well received by the teachers, the media, and the Association of Greek Chemists.) (b) By a radical change from year 2000 onwards in the type of the questions, to include now a number of both open and objective (multiple-choice) type questions, some of which require conceptual understanding (but less often HOCS capability) to be demonstrated.

Greek Study II showed that alternative forms of examination, such as the take-home one, can be useful, particularly in encouraging students' active participation in the course, and their self-regulating, independent study. They provide the instructor with the opportunity to extend the range of topics beyond those that are formally covered in the lectures. The take-home exam provides students with practice of working out exam questions on their own, and provides a feedback mechanism with respect to students' progress and difficulties. It enforces students to consult other texts apart from the course textbook. Also, it encourages collaboration among students within the learning process. Last, but not least—though we have not

offered evidence—it is hoped that the HOCS-oriented parts in these exams will cultivate and foster students' HOCS.

The most significant result of the Israeli Study was that the top performing students, given a choice between HOCS- and LOCS-type questions, preferred to select and respond to the LOCS-type ones, suggesting that a short-term HOCS-oriented instruction is not sufficient for changing students' 'exam-attitudes/behavior' with respect to 'LOCS vs. HOCS learning'. Nevertheless, whether 'HOCS-students' prefer 'HOCS examinations', whereas 'LOCS students' prefer 'LOCS examinations', remains an open question that requires further research.

As far as science/chemistry class assessment practice is concerned, take-home examinations containing both HOCS and LOCS questions (such as those used in Greek Study II and the Israeli Study) can and should be used both for assessing student progress on HOCS (reflecting the effectiveness of the teaching strategies in HOCS-oriented science courses) and identifying or distinguishing between 'HOCS' and 'LOCS' students by comparing their performance on LOCS and HOCS-type questions, respectively. The latter should be primarily directed at modifying the teaching strategies as found necessary.

Taking the three studies together, and given that LOCS-type questions predominate in most traditional exams worldwide, and are therefore familiar, and recognized by the students as straightforwardly 'solvable' and by the teachers as easily gradable, it is no wonder that they are preferred even by the best students. On the other hand, HOCS questions cause problems to the majority of students. These trends are further supported by a recent study conducted in Turkey: while 96% of the questions in three types of upper-secondary schools were of LOCS-type, more than half of the questions asked in the university entrance examination were of the HOCS type.[37] As a consequence of this, students who had high academic achievement in science lessons in schools were not able to deal successfully with many questions at the university entrance exams. It seems that non-traditional teaching and learning methodologies, such as the take-home, open-book examination, offer a good opportunity for (a) employing HOCS-type questions and problems, (b) extending the scope and depth of material taught in class, and (c) encouraging true and meaningfully collaborative learning. If the development of students' HOCS capability is indeed a major objective in current reform of science and chemistry education, then HOCS-oriented teaching,

assessment methodologies, also exams and corresponding learning strategies, should become the focus of the teaching-learning process. Since the importance of enhancing the acquisition of HOCS by students is widely recognized, and was demonstrated to be feasible in chemistry/science courses, chemistry and science educators should address these and related issues, aiming at 'HOCS learning'. We believe that the LOCS to HOCS shift in chemistry and science teaching and learning not only *can* be done, but it *should* be done.

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Quantity algebra (calculus) – some observations

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I was first introduced to *Quantity Calculus* during the early 1950s in lectures given with absolute clarity, if somewhat dictatorially, by E. A. Guggenheim and Max McGlashan. I have been a devotee of the method ever since and thus welcomed the erudite account given by Joe Lee.[1] Although there is little in his account with which I would disagree, I thought it might be useful to comment on several facets that, when dealt with in a particular way, enhance student performance - they show a greater understanding of what they are doing and make fewer numerical and 'grammatical' mistakes.

The first hurdle is the name *Quantity Calculus*, which is frightening to students and causes many to close their minds to what is a simple and logical approach to handling physical quantities, their measures and their units. In any case it is difficult to see much similarity to what is normally understood as calculus. A less forbidding title is the alternative, *Quantity Algebra*. This name is a truer description of the processes involved and it is sensible to use it when introducing the method. Reference can be made to the more usual name subsequent to students carrying out examples to familiarise themselves with what the method is all about.

Other teaching strategies that I have found to be helpful are
- to encourage students to write down each step in a calculation involving units and when a change is made, to ensure that a note of the relationship used is included e.g. since $Pa = N\ m^{-2}$ and $J = N\ m$ then $Pa = J\ m^{-3}$. It is essential to ensure that students are fully conversant with basic definitions such as pressure, force, energy etc.
- to make extensive use of brackets to eliminate any doubt in calculations involving, for example, the conversion of units. It is better to use too many rather than too few brackets if they lead to a correct solution.
- to keep the measure and the unit together for each physical quantity when their values are substituting into an equation, rather than collect the units separately in a single composite term. This makes it much easier to check the units, a procedure which should always be a prerequisite to carrying out the final calculation.
- to ensure that 'dimensionally homogeneous' additive/subtractive equations are presented in the form illustrated by

$$V/cm^3 = 1.234 + (2.345 \times 10^{-4}\ t/^{o}C)$$

rather than in either of the other two alternative but correct forms given by Lee. Students are more comfortable handling such an equation in this form.
- to use exponents of ten whenever they are necessary in a calculation (a simple volumetric calculation is a possible exception where it is often simpler to use 1000 rather than 10^3). Thus in unit conversion e.g. $m^3 \rightarrow cm^3$ it is preferable to write $m^3 \rightarrow (10^2\ cm)^3$ - and the laws of indices applied - rather than $m^3 \rightarrow (100\ cm)^3$. Similarly, in labelling column / row headings in a table or in labelling the axes of a graph in which a repetitive power of ten multiplier arises, it is preferable to write for example, $T/10^3\ K$ rather than T/kK or $T/1000K$. The use of prefixes here is particularly dangerous. When the multiplier is a negative exponent of ten, less confusion and fewer errors occur if the multiplier and the unit are kept together. Thus although $V/(10^{-3}\ m^3)$ is more cumbersome and less aesthetically pleasing than $10^3\ V/m^3$; it is a much safer bet until a student is conversant and confident with the general approach.

To conclude, I turn to the name 'amount of substance' commonly used for the base physical quantity, symbol n, whose unit is the mole. This is the only three word name among those used for any of the seven base physical quantities and arose, not by choice from the English language but from the translation of the single German word 'Stoffmenge'.[2] It is a clumsy name particularly when used to refer to

a given chemical entity. 'The amount of substance of sodium hydroxide' i.e. n(NaOH), is a verbal marathon that does not flow easily and is difficult for students to use correctly. The Green Book[3] acknowledges the problem in suggesting that the name may often usefully be abbreviated to the single word 'amount'. Unfortunately, in the hands of inexperienced students, this easily becomes synonymous with mass or less frequently volume.[4] The alternative name 'chemical amount', given by Lee without comment, is a more descriptive name that acts as a pointer for beginning students since it can be introduced as the 'chemist's amount'. First suggested by Gorin[5], it was given as an alternative to 'amount of substance' in the second edition of the Green Book[3] (it did not appear in the first edition in 1988), similarly with the suggestion that it may usefully be abbreviated to 'amount'. It is a two-word name, comparable to the base physical quantity, 'electric current' but whereas the common practice of abbreviating the latter to 'current' seldom leads to confusion this is not the case when 'chemical amount' is abbreviated to 'amount'.

I believe strongly that many of the difficulties that arise with calculations involving n would be not arise if it is called 'chemical amount' rather than 'amount of substance': students are very much more at ease with 'the chemical amount of sodium hydroxide' in both the written and spoken word. However I do not believe it is beneficial in the majority of cases, particularly for beginning students, to abbreviate this to 'amount' and recommend for example, that we refer to 'the chemical amount of Cl_2' rather than 'the amount of Cl_2' and 'chemical amount concentration' rather than 'amount concentration'. After all these are still less cumbersome and confusing than 'amount of substance of Cl_2' and 'amount of substance concentration' and lead to fewer mistakes.

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Conceptual understanding of electricity: galvanic and electrolytic cells.

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I was very interested in reading the recent paper on this topic.[1] While commending the authors on their attempt to unravel the complex understandings of prospective teachers on this matter I would like to take the opportunity to comment on their own explicit understandings and some of their pedagogic implications.

For me this area of study has been of interest for many years, particularly the problematic issue of the conduction of electricity *within* a Galvanic cell.[2] I was still unable to explain to myself – in terms of electrical charges – how it is that in, say a Daniell cell (Figure 1), positively charged copper ions are deposited on the copper electrode *labelled positive* when current is drawn from the cell. (As is discussed below the a major part of the problem is linked with the labelling of the electrodes. Indeed, a moment's thought demonstrates a fundamental

Figure 1
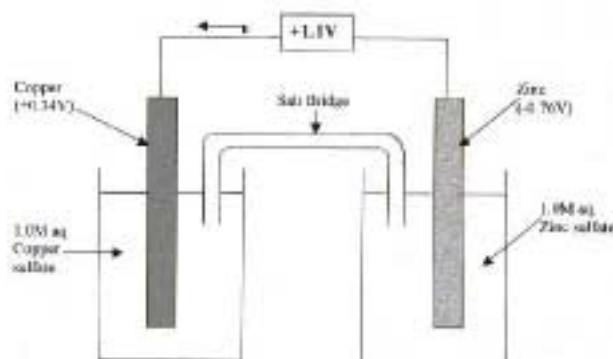
issue – although I did not notice this in forty years – that if the current flows in a complete circuit and the cell electrodes are labelled '+'and '–'then it is *logically not possible* for the conventional current to flow from '+' to '–' in both the external circuit and within the cell.) I was unable to find a convincing explanation in texts and essentially I was left with the idea, consistent with the Ogude and Bradley's[3] statement:

> *"It must be emphasised that the motion of ions in the two half cells is not caused by the charge at either electrode."*

Essentially the idea is that electrons entering the copper electrode from the zinc via the external circuit disturb the pre-existing equilibrium at the interface between the copper and the copper ions in the solution (the equilibrium gives rise to the electrode potential). Since the positive charge is reduced, more copper ions are now deposited at the surface in the attempt to restore the equilibrium. However I was not able to articulate the idea in a way that provided an explanation in terms of 'opposite charges attracting'. I have a deeply held belief (is that scientific?) that that unless there is an *electrical potential difference* it is not reasonable to expect a current to flow! Certainly the research of Ogude and Bradley[3] and others shows that the one relationship that dominates learners' understandings of science is that positive charges attract negative charges and that like charges repel. This relationship invariably *determines* the direction of electron/ion/charge carrier flow in any part of any electrical circuit.

A particular insight can be gained when considering a Galvanic (Daniell) cell on open circuit. With an appropriate salt bridge linking the electrolyte solutions in the electrode compartments the electrodes (Fig 2A) must be at the same potential from the perspective of the electrolyte solution. Thus, within the copper electrode compartment, the excess anions (the solution must carry a net negative charge, although I am now persuaded that this is effectively contained within an 'electrical double-layer' of ions that effectively prevents an electric potential gradient from being 'felt' by ions more than a few ionic diameters away from the electrode surface; See Note 1 at the end of the letter) will shield the electrode such that *from the perspective **within** the solution* the electrode appears uncharged.

Figures 2B and 2C indicate *qualitatively* and as a 'thought experiment' how the electrical potential differences change across the external circuit and within the cell when electricity flows around the circuit. 2B shows a small current when the internal resistance of the cell is equivalent to the resistance of the external circuit (small because the internal resistance of a Daniell cell is quite high.) 2C would be the situation if the cell were completely shorted out (external circuit has zero resistance). The numbers given are not exact (except in 2A for a standard cell) since the cell does not operate under conditions of thermodynamic reversibility. Also it is not being suggested that these could sensibly model the situation in cells actually used to produce electricity since the internal resistance of a cell as shown in Figure 1 would be huge. However, the important factor is that *from the perspective of the solution, when current flows* the sign on the copper electrode is **negative** whereas *from the perspective of the external circuit* the copper electrode is still **positive.** (It now begins to seem obvious that charges on the electrode must be +/- and -/+ from the two different perspectives otherwise it would not be logically possible for a flow of negative charge to complete the circuit (Figure 3). Again it is *not* being suggested that this is how electrodes should be labelled, only that the perspective of the 'user' must be carefully considered before any sign is ascribed. It may well be better if no sign is automatically ascribed to an electrode and any explanations first justify the sign given by reference to the reaction that is taking place *and* make clear the perspective.

The recommendations given in the paper[3] (for teaching require a very careful appraisal before being implemented since, it seems to me, the idea that we should try to persuade students that 'the net charge' on the electrode is 'exceedingly small' and 'simple electrostatic arguments do not correctly explain the direction of ion and electron flow and may be pedagogically and scientifically unsound. Suggesting that the *small amount of charge* on the electrode inhibits confident prediction of the direction of current flow seems equivalent to suggesting that a *small amount of heat in an object* inhibits prediction of the direction of heat transfer. Surely it is the potential difference (or the temperature difference) that is the determining factor and the EMF of a Daniell cell applied to an external circuit is considerable (1.1V) and well known. (The actual *amount* of charge on an electrode is irrelevant and depends only on the
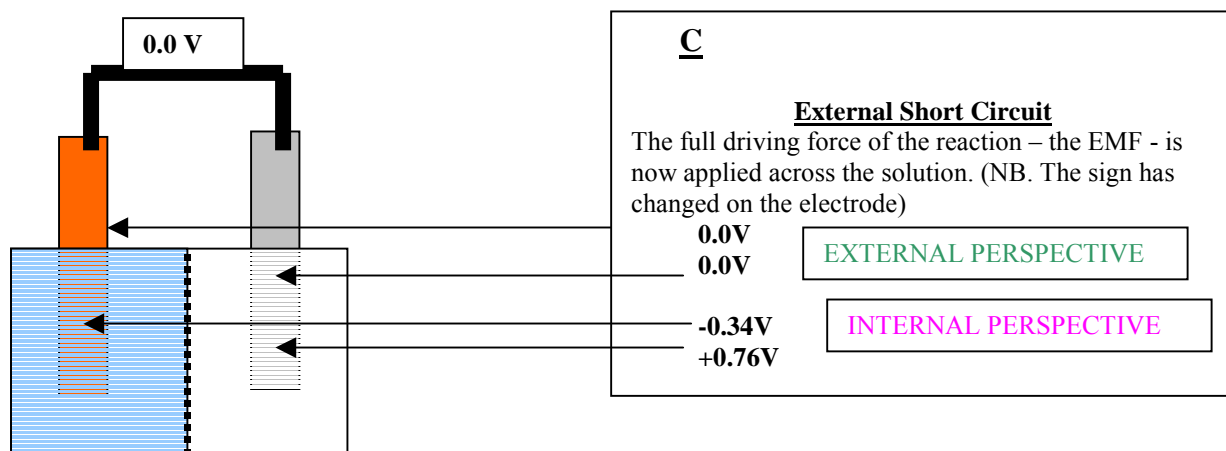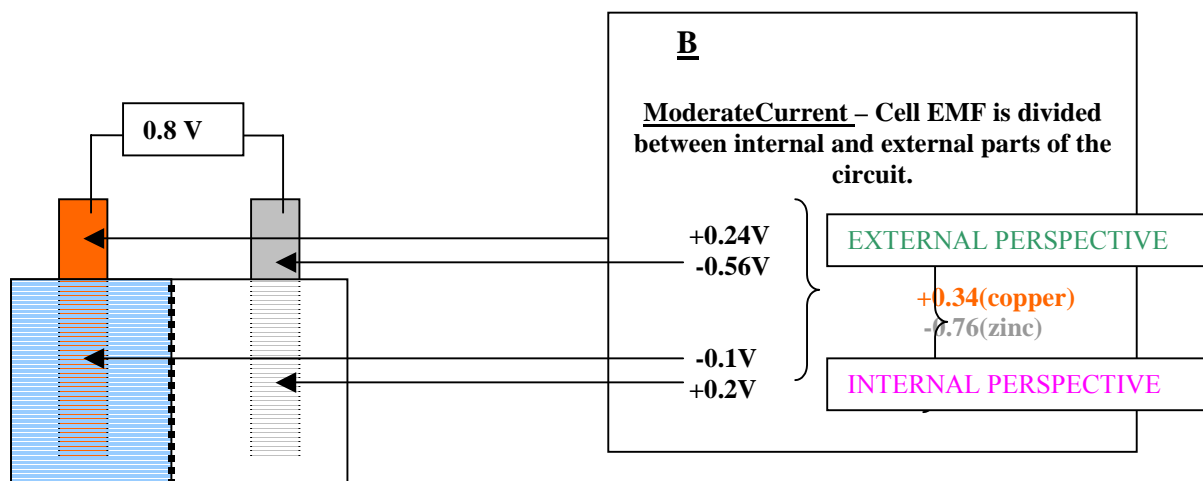
Figure 2

A

No Current flowing – Cell EMF is applied at external terminals.

+0.34V
-0.76V

EXTERNAL PERSPECTIVE

0.0V
0.0V

INTERNAL PERSPECTIVE

No internal current, thus no potential difference **across** the solution gap.

1.1V

B

ModerateCurrent – Cell EMF is divided between internal and external parts of the circuit.

+0.24V
-0.56V

EXTERNAL PERSPECTIVE

+0.34(copper)
-0.76(zinc)

-0.1V
+0.2V

INTERNAL PERSPECTIVE

0.8 V

C

External Short Circuit

The full driving force of the reaction – the EMF - is now applied across the solution. (NB. The sign has changed on the electrode)

0.0V
0.0V

EXTERNAL PERSPECTIVE

-0.34V
+0.76V
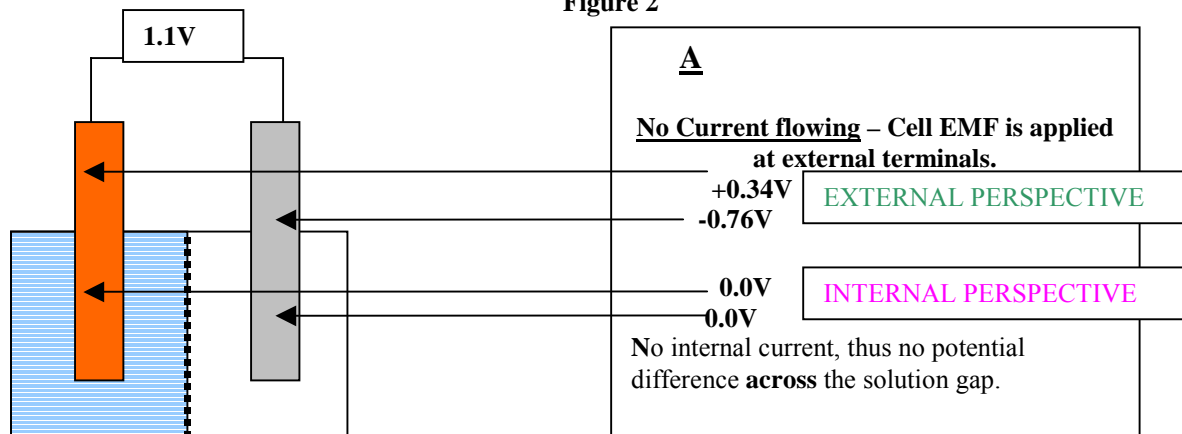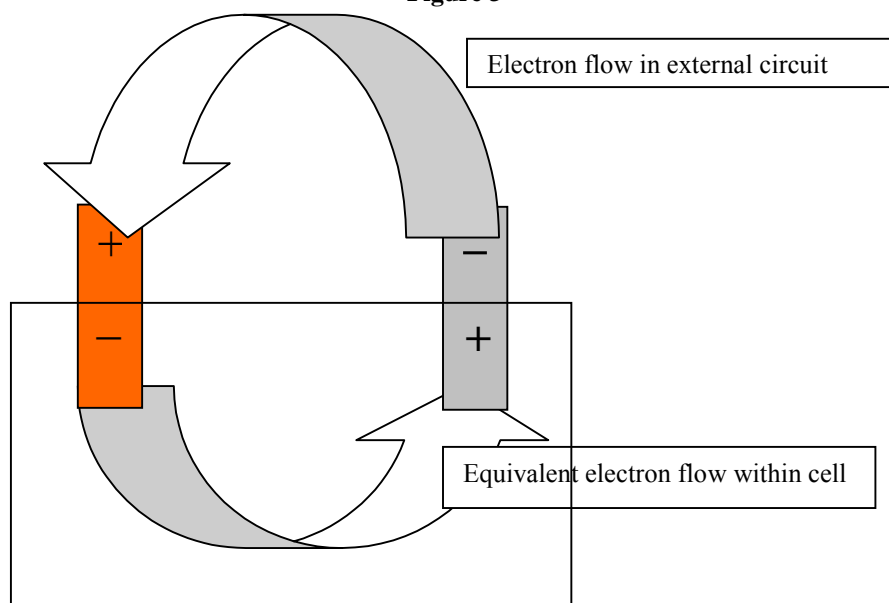
INTERNAL PERSPECTIVE

0.0 V

Figure 3

chemistry of the materials present and the physical dimensions of the rod that determine its behaviour as a capacitor.)

I agree absolutely with the authors (p.9) that students should be expected to show (qualitative) understanding of the chemical processes involved. However it is also necessary for them to keep a critical eye on their teachers and textbooks to convince themselves that what they are learning is consistent and sensible. Teachers are human, interpretations change, words *do not have unambiguous meanings* – we all hold a variety of alternative conceptions that is neither constant nor entirely consistent .[2] Teachers need to convince their students (and themselves) honestly of the validity of the ideas being considered. I guess that some of my earlier statements still sound/are outrageous. Indeed, I have been warned against entering this debate since I am a relative novice as an electrochemist; however, it is the simple questions that often prove difficult to answer. It may be significant that there seems to be a lack of an accessible qualitative account of the process of electricity flow within galvanic cells in textbooks at any level – at least none that I can find.

One further issue with the suggested pedagogy is the use of computer simulations. This can undoubtedly be effective but the simulation is constrained neither by the facts nor by the laws of science that we are attempting to teach. Simulations will simulate the beliefs of

their authors and must be treated with due criticism.

(I am a little worried by Question 15 in Özkaya's paper.[1] This – and their offered 'correct' answer suggest that the authors believe that current between the electrode compartments will not flow along a conducting wire. This may not be true since dipping the wires in the electrolyte solutions (instead of using a salt bridge) could simply provide another pair of electrodes and thus produces a circuit with two Galvanic cells in series. I would not care to predict the overall EMF, but I am not convinced that it would be ZERO and therefore that no current would flow. I got a current of well over 100μA when I tried it using a silver wire. There was no platinum to hand.)

(Note 1. The outline of the above discussion was presented at the 'Variety in Chemistry' Conference in Dublin, September 2003 and proved to be controversial. Specialists in electrochemistry were very concerned that I was implying that ion movement within the cell when current flowed around the circuit was driven by a potential gradient between the electrodes. Apparently the electrical double-layers (multiple-layers) of ions that surround the electrodes ensure that no potential gradient is present in the solution beyond these layers. The bulk movement of material within the cell is driven by diffusion along concentration gradients (or gross physical disturbance such as convection currents or stirring.) For me this still leaves a problem as to how the charge

'flows' between the electrodes. Presumably as soon as a charge imbalance within the (from the equilibrium value required to maintain the 'electrode potential' – as measured externally between the electrodes) occurs because copper ions are deposited on the copper or zinc ions pass into solution, there is a rapid 'adjustment' in the positions of all charge carriers between the electrodes in order to retain electrical neutrality within the bulk of the solution? I have not really 'explained' this satisfactorily to myself, but it seems to me that this charge adjustment is not simply 'diffusion'.)

References:

1. A.R. Özkaya, M. Űce and M. Şahin. *U. Chem. Ed.*, 2003, **7**, 1
2. A. Goodwin, *Chemistry Education: Research and Practice in Europe*, 2002, **3,** 345.
3. N.A. Ogude and J.D. Bradley, *J. Chem. Ed.*, 1996, **73,**. 1145