Contents

* APCELL: The Australian Physical Chemistry Enhanced Laboratory Learning Project 6
  Simon C. Barrie, Mark A. Buntine, Ian M. Jamie and Scott H. Kable

* The Determination of the Dissociation Constant of a Weak Acid by Titration 13
  Barry O'Grady

* Effectiveness of Flow Diagrams as a Strategy for Learning in Laboratories 18
  Bette Davidowitz and Marissa Rollnick

* Capturing the Imagination with Green Chemistry and Explosions, Froth, Color, Phase Changes and Lollies. 25
  Michael Clarke, Nicholas Barlow, Antonio Patti and Janet L. Scott

* Chemistry Through the Looking Glass 32
  Igor Novak

* Refereed papers
Inaugural Guest Editorial

The Editors have kindly invited me to write a guest editorial for the first issue of this Journal under its new masthead, or, as one of them wrote, “to smash a bottle of champers across its bow, so to speak”. Such nautical analogies seem to be worth pursuing here for a while...

It is a great pleasure to christen this time-honoured craft, the flagship of The Chemical Education Division of the RACI. It was initially registered and launched by the inaugural Master Mariners, Charles Fogliani and John Mackellar, at Mitchell CAE, Bathurst, in October 1978, under the name Chemeda (which was derived from “Chemical Education Australia”). Chemeda has been published as The Newsletter of the Chemical Education Division of the RACI (Numbers 1 - 25) and as The Australian Journal of Chemical Education (Numbers 26 - 56). This present issue constitutes The Journal’s relaunching under a new name, The Australian Journal of Education in Chemistry, no doubt soon to be referred to as AusJEC. As a former editor of Chemeda (Numbers 21 - 31), I find it very gratifying to know that, following an extensive refit and the installation of new officers on the bridge, this once weather-beaten vessel is again free to sail the High Seas of Science Education.

Earlier this year, three superb Master Mariners from Western Australia – Bucat, Mocerino and Treagust – were given a joint commission to plan AusJEC’s voyages. The Owners (The Standing Committee of The Division) have issued a worthy charter and apposite sailing orders accompanied by mercantile protection sufficient to last until December 2002 at least. Our new Master Mariners have, in turn, wisely appointed their competent colleague Kristy Blyth as Bo’s’n, and have compiled an interesting register of Australian and international maritime pilots. The pilots’ duties are to keep a weather eye open, to study the almanac and to recommend an appropriate selection of charts for navigating the shoals near less well-known ports.

And now, as AusJEC is about to leave the slipway, who knows what exciting and exotic ports of call she may visit? What interesting Able Sailors will she enlist, and how much valuable cargo will she take on board? How will she respond to the unpredictable Winds of Change, the piratical Ravages of Copyright and Plagiarism, the treacherous Under-Currents of Political Expediency and the menacing Low Tides of Dwindling Resources? We cannot know the answers to all these questions, but I have every faith in the determination, skill and expertise of our Master Mariners and I look forward to many fascinating voyages with AusJEC.

And so it is with excitement and high expectations that I prepare to send AusJEC to sea in the traditional manner – by smashing “a bottle of champers across its bow”.

Before doing so, I propose to expand a little upon two comments I made in earlier issues of Chemeda. My purpose is to consider some possibilities for the future.

While preparing to write this particular editorial, I began to peruse some of the editorials which I wrote for Chemeda ten or more years ago. It was interesting to note that some of the assertions which I made then, seem relevant now, at the relaunching of The Journal. I therefore ask The Reader’s indulgence to allow me to quote from Number 31 (July, 1991), prepared for the Chemical Education Division’s Conference in Perth, which I attended. In Number 31 the editorial offered the conferees an opportunity for evaluation of the Journal, of its Editor...

and indeed, of those who would claim to be its readers and supporters, for the worth and strength of any such journal lies, ultimately, in the quality of the response of the journal’s readers to its contents. [Italics added].

What I was trying to suggest was that, no matter how high the quality and quantity of content might have appeared to The Editor’s eyes, The Journal was not worthwhile unless a significant proportion of readers found, over time, that Chemeda contributed importantly to their thinking about, and practice of, the art of teaching chemical science. Implied here, for The Editors and for The Readership, was the reciprocal responsibility of communicating about meeting professional needs – both real and perceived. And this was no simple task for either party.

The same difficulty is with us today, at this stage simply because AusJEC is at the very beginning of its part in making history – The Editors lack information about their readers. The Readership (certainly the sought Readership) is likely to be quite
diverse – in professional employment, interests and outlook, as well as in experience and teaching skills. The Editorial Staff, currently faced with the important task of building up The Journal’s circulation, can but try to estimate what the range of The Readership’s current professional needs might be, and act accordingly. Hopefully, this problem will diminish over time, as The Readership is stimulated to respond to editorial efforts to understand and identify with it.

But, there is more – I believe that a professional journal needs to demonstrate a degree of intellectual leadership by exhibiting, in a relatively small but important way, some of the desirable characteristics of a university. An idea of what I mean can be found in Looking for Leadership, in which Donald Horne describes universities as “...curators, refashioners and presenters of bodies of learning, and ... also centres for the spirit of inquiry, curiosity and speculation” (p. 140). In the context of education in chemistry, this kind of leadership is, I suggest, an apt and feasible long-term objective for AusJEC. I have great confidence that The Readership would respond approvingly to such a goal.

In the meantime, I hope that two-way communication between The Editors and their readers develops constructively and fruitfully. I would like to encourage readers to outline their perceived professional expectations and needs to The Editorial Staff. There is no doubt that The Editors will respond, because, in the words of one of them, The Journal aims at “striking up a conversation across the total chemistry community”. With the possible introduction of an electronic version of The Journal, this conversation may become more readily achievable. Likewise, the development of The Division’s web-page may give additional opportunities.

What more can one say at a launch of this Journal? Perhaps this. Examining recent issues of other journals devoted to chemistry education or science education, I found very few papers on that very important topic, assessment. Perhaps the sample was atypical. Perhaps not. Perhaps editors and readers assume that we already know enough about assessment to satisfy our needs and thus view the topic as uninteresting or unimportant. Or are there too few authors willing to write about it? Whatever the answer, my own view is that, if we are truly interested in quality learning (stimulated by quality teaching) then we should submit our own assessment practices to frequent scrutiny. And so I would claim that there is a need for more to be written, read and thought about assessment practices and philosophies. If I may quote from my editorial of Number 26 (December 1989) –

... fundamentally, what we really feel about quality learning is embodied in the nature and extent of the assessments we develop and administer. Our assessment practices display to both teacher and taught (particularly the taught), explicitly or implicitly, a taxonomy, simple or profound, of our assumptions, values and beliefs about education in (and through) chemistry.

Quality assessment sustains quality teaching.

In this the twenty-first century, there should be no doubt about the need for quality teaching and learning. May AusJEC lead the way!

With great pleasure and anticipation, I now declare The Australian Journal of Education in Chemistry well and truly launched!

Glen Chittleborough

October 2001

Reference

**APCELL: The Australian Physical Chemistry Enhanced Laboratory Learning Project**

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**Abstract**

The Australian Physical Chemistry Enhanced Laboratory Learning project was established to address the problem of falling student enrolments and continuations in Australian physical chemistry courses. The Project has pooled the resources of over 30 Australian universities (and several New Zealand affiliates) to establish a protocol for developing and assuring the quality of laboratory teaching experiments. Using a ‘research-led teaching’ approach an “Educational Template” was developed which ensures that contributions to the project are strongly learner focussed. In this paper we introduce the APCCELL project, describe some of the approaches that have been employed in developing the project, outline important progress achieved to date, and discuss the interaction between APCCELL and *This Journal*.

**I. Introduction and Motivation**

In late 1999, the Committee for University Teaching and Staff Development (CUTSD)* funded the Australian Physical Chemistry Enhanced Laboratory Learning (APCELL) project. The APCCELL project was established to use the context of laboratory learning to address the problem of low intake and poor retention of students in Australian physical chemistry courses. One of the primary objectives of the APCCELL project is to disseminate widely the results, outcomes and practical developments in physical chemistry laboratory exercises that are based upon student-focused pedagogical tenets. The rejuvenation of the Australian Journal of Education in Chemistry (*This Journal*) offers an ideal opportunity for APCCELL to disseminate key aspects of its work, and for *This Journal* to present innovations in university chemistry laboratory teaching and learning, including rigorously tested chemistry experiments, to a wide audience.

APCELL officially started in January 2000. The project’s genesis, however, can be traced back several years earlier to discussions between academics attending research conferences around Australia, concerning anecdotal evidence that an increasing number of students were finding their physical chemistry laboratory courses to be uninteresting and unmotivating. These informal discussions highlighted a widespread recognition amongst academics that students studying physical chemistry were not learning in the laboratory as well as they should, or could. While academics at individual institutions routinely attempted to improve learning in the laboratory, it was apparent that no single institution had been successful at overcoming the multiple barriers to learning. These barriers are those imposed by limited physical resources, limited specialist expertise, limited pedagogical expertise and limited active student involvement in the learning process. It was agreed that a collective effort involving the resources of multiple institutions was required to overcome the problems and the idea of APCCELL was born.

Such anecdotal evidence suggesting the existence of poor student perceptions of physical chemistry is born out by recent statistics published by the Australian Commonwealth Department of Education, Training and Youth Affairs (DETYA) [1] and the Australian Council of Deans of Science. [2, 3] The histogram in the upper panel of Figure 1 shows the total number of students enrolled in university degrees for the period 1983-2000 as reported by DETYA [1]. In this 18-year period total university student numbers have almost doubled from roughly 350,000 to approximately 650,000. The solid circles in the upper panel of Figure 1 report the total number of students enrolled in science-based subjects over the same 18-year period. The latter figures have been normalised to the total student enrolment numbers for 1983 in order to illustrate the relative increase in the proportion of students studying science, particularly since the mid-1990s. Over the 1983-2000 period the number of students studying science subjects has more than doubled, a rate of increase greater than that observed for overall student enrolments.

The lower panel of Figure 1 shows the percentage of students enrolled in four broad science disciplines,
Aust. J. Ed. Chem., 2001, 57, viz., the chemical, biological, mathematical and physical sciences for the years 1989, 1993 and 1997 (the years for which figures are available). [1, 2] For clarity, the percentage of students enrolled in the computing sciences (included in the upper panel of Figure 1) has been omitted. Over the 8-year period for which data are available, student enrolments in the biological sciences have increased from 30% to 40% of all students enrolled in science subjects. Conversely, enrolments in the mathematical sciences have decreased from 26% to 18% and enrolments in the physical sciences have decreased from 11% to 8% of all students enrolled in science subjects. The trend in the chemical sciences is less dramatic, with a decrease in fractional science enrolment from 17% to 15% over the 1989-1997 period. Chemistry is the “central science” and as such, it is not surprising that the chemistry trend is intermediate between the physical and biological data. In fact, “chemical science” not only falls between these two other categories, it includes them in sub-disciplines such as biological chemistry and physical chemistry. While data are not available at this level of detail, anecdotal evidence certainly supports the view that physical chemistry is under a greater threat from falling student numbers than is biological chemistry.

The motivations for students to move away from the mathematical and physical sciences towards the biological are complex and difficult to fully understand. There might be a perception by students at secondary school and university that jobs are more readily available and/or better remunerated in the life sciences. A recent analysis, however, does not bear this out. Employment rates are similar across all of these four science disciplines (mathematical sciences actually performing better), and salaries correlate in the other direction, favouring the more mathematical and physical sciences (Table 1).[3] These two trends, lower student numbers and higher salaries in physical science, might be related by supply-and-demand economic factors. Regardless, it seems clear that incoming students do not perceive curricula in the physical sciences as being relevant to them, nor is the wider relevance of such studies explained. It is therefore reasonable to contend that improved enrolment and retention numbers in physical chemistry can result from providing a better learning environment for students. The APCELL project has focused upon addressing one important aspect in improving student motivation and learning in physical chemistry – the student laboratory experience. Laboratory work is considered to be of great importance in the chemistry curriculum, yet research suggests that it may not achieve the desired learning objectives ([4, 5] and references therein). Students can often see the laboratory exercise as simply a task to be completed as quickly as possible, with the minimum possible effort [6], and this attitude can defeat any attempts to use the experience as a teaching and learning tool. Students may not see the relevance of the laboratory exercise to either the study they are undertaking or their experiences outside of the teaching institution. On the other hand, perhaps because the importance of laboratory work is taken for granted by academics, there are rarely any mechanisms in place to monitor the effectiveness of these courses. This is not to say that physical chemistry academics (including the authors) have been idle in rejuvenating and modernising physical chemistry laboratories. Such efforts, however, have met with limited success due to the constraints of limited time, and limited expertise or experience in pedagogy. The APCELL project is overcoming the resource constraints of individual chemistry departments by treating participating institutions as if they belong to one large department. The project has brought together, for the first time, diverse physical chemistry educational expertise and resources from across almost all Australian universities.

Figure 1. Total Australian university student numbers covering the period 1983 – 2001. The upper panel shows total student numbers and total students studying science (normalised to 1983 by multiplying by 7.2). Science numbers are increasing at a slightly faster rate than general numbers. The lower panel shows the breakdown of science students in four broad scientific areas. The data show the more “physical” and “mathematical” the science the greater the decrease in relative student numbers.
During the course of the project to date the APCELL team (i.e. members from all participating universities, Appendix 1) has developed an “Educational Template”, established a novel review process for submitted experiments and set-up an extensive database of experiments with full documentation. The purpose of this article is threefold:

i) to explain how and why these processes have evolved,

ii) to disseminate information about APCELL, and

iii) to explain the interaction between APCELL and this rejuvenated journal.

II. Research-Led Teaching and the Educational Template

‘Research-led teaching’ (RLT) and ‘scholarship of teaching’ are phrases that are being heard in discussions about teaching in Australian universities. [7, 8] The current focus on RLT exemplifies various trends and changes in Australian and international higher education. [9] The use of the term is, in part, a reflection of the increasing recognition of the scholarly and professional nature of university teaching as an added dimension to the disciplinary expertise of academics. The focus on RLT supports, and is supported by, a growing body of research literature on teaching and student learning. At a more pragmatic level the interest in RLT reflects a university strategy of building upon established research expertise and performance in the increasingly competitive teaching quality market. [10]

The term ‘research-led teaching’ has various meanings in different contexts. [11] Amongst other things RLT can refer to:

- The use of disciplinary research in teaching - for example, designing a learning task on the basis of published education research or one’s own inquiries into how students approach particular assessment tasks;

- Research into teaching and learning - for example, a research investigation into how students approach different learning tasks.

While the APCELL project can be described in terms of each of these aspects, it is primarily an example of the second category of RLT – a teaching and curriculum development initiative that is based on research. The methods employed in the APCELL project were selected on the basis of the research literature in the field of change management and academic development. [12] While there were numerous publications that espouse excellent practice in designing and teaching in laboratories, these do not appear to have had much influence on laboratory teaching practices. [13] The problem faced by physical chemists at the teaching coalface is that, in the main, they are discipline experts but not well read in educational research. Educational research, like any other field of inquiry, has its own language and methodologies that are not always transparent to those outside the field.

The project therefore planned to engage academics in reflecting on their own curriculum decisions about teaching and design of laboratory practice. [14] The project methodology identified the need to engage participating academics from the participating universities (see Appendix 1) at the level of their underlying ideas about teaching and learning, rather than at the level of teaching behaviours. The project aimed to use processes that would encourage academics to design their laboratory teaching from a learner-focused perspective rather than a teacher-focused perspective. This strategy required that the project start with the participants’ own ideas and conceptions of teaching, even if these were teacher-focused, then reflect on, and challenge these ideas in developing the parameters for the laboratory curriculum design. The result is an “Educational Template” that bridges the gap between relevant educational research and practising teachers. The educational research that underpins the template and laboratory-based learning in particular has been described previously. [11]

Text box 1 shows the concise explanatory notes that now form the first part of the template. These explanatory notes (and indeed the whole template) are studded with concepts from the education research literature, but cast in a language and in a context that is more readily accessible for discipline-
based teachers (physical chemists in particular). The full template is freely available at the APCELL web site. [15] It is not intended that the objectives or methods described in the template and accompanying documentation be prescriptive. In fact, users of the database are encouraged to adapt the APCELL experiments to suit particular teaching contexts and resources. Users should also be able to adopt the teaching approaches and strategies described in these templates to other experiments and other undergraduate laboratory teaching activities. Submitters of experiments are encouraged to take this into account and present options, alternatives and extensions wherever possible and appropriate.

The five sections of the Template, as summarised in the Text Box, present

(1) a general summary;
(2) an analysis of the educational objectives;
(3) student experiences;
(4) documentation and
(5) peer review criteria for acceptance to the database.

Section (1) provides a context for the experiment in terms of course objectives, student abilities, relevance to students’ aims and interests, etc.

Sections (2) and (3) ensure that the experiments are focused on achieving high quality learning by students, by examining the experiments from the students’ perspective. An important aspect of this process is documenting ways in which the outcomes of the students’ learning experiences will be evaluated.

The intention of Section (4) is to make the implementation of the experiment as straightforward as possible by new users.

Section (5) encourages critical self-review prior to submission to the APCELL database.

**Text Box 1:**

Descriptive page from the APCELL “Educational Template”. This page explains to the academic the rationale of the template to form a bridge between educational research and academic practice. See the APCELL web site for the full template. [15]

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**Structure of the Template**

There are five sections to the template.
Sections (1) to (4) must be completed and peer reviewed prior to an experiment being included in the APCELL database.

Section (5) gives the criteria against which the assessment will be made.

**Section 1: Summary:**

This section provides general information that can be used as an overview of the experiment and to quickly determine how the experiment is relevant to a particular course.

**Section 2: Educational Analysis:**

The second section is a table that provides a clear description of the intended learning outcomes (i.e., what you anticipate that a student will learn by undertaking this experiment), a description of how this learning will be achieved and a description of how this learning can be monitored.

The learning outcomes might cover theoretical understanding, technical skills or generic skills and provide the basis for the learning outcomes that should be included in the student notes. The description of how this learning will be achieved and a description of how this learning can be monitored provides the basis for assessment criteria that could be used by demonstrators and students to monitor learning.

Intended learning outcomes and assessment criteria should be clearly given in both the student and demonstrator notes.

**Section 3: The Student Learning Experience:**

The third section presents evidence from students regarding the quality of their learning experiences in this laboratory. A summary should be given of the key issues identified through the student feedback questionnaires. As well as quality assurance evidence, the questionnaire used in this section provides a valuable tool for ongoing evaluation of teaching experiments in general.

**Section 4: Documentation:**

The fourth section contains the student, demonstrator and technical notes for the experiment.

**Section 5: Peer Assessment:**

The final section shows the criteria against which the submission will be peer assessed and should be used to self-assess your submission.
III. The Review Process

The review process for an experiment submitted to APCELL has also evolved with the project. This process is based rather heavily on the experience of the first Experiment Workshop held in Sydney in Feb, 2001. At this workshop 60 staff and students from participating institutions came together to engage in an inquiry into the student learning experience of the 30 submitted experiments. During the workshop both teachers and students participated as learners and both contributed ‘learner’ evaluation data to the inquiry into the experiments submitted. At all stages the methods of review were focused on overcoming the identified barriers to effective student learning in the laboratory. [16]

The experience from the workshop showed clearly to all participants the value and necessity of evaluating experiments in a hands-on, interactive environment. The workshop also reminded academics of what it is like to carry out an unfamiliar experiment, i.e. to adopt the role of a student. (Academics took their role as student very seriously and realistically duplicating the student learning experience - many did not read the practical notes beforehand!)

As a result of the experience of the first workshop, it was decided that experiments submitted to APCELL should be submitted to an extensive and rigorous review process. The first stage of this review involves the anonymous critical feedback of the submitted documentation from both an academic and student member of the APCELL team. The second stage involves the experiment being set-up (preferably in a different laboratory) and evaluated in the same hands-on, interactive, student-focused way as the experiments evaluated at the first workshop. This two-stage review process provides experiments that are a strong, student-focused, relevant learning experience, and that have been proven to be flexible enough to set up in more than one laboratory environment. It is an important part of the process that students are involved in the evaluation of the experiment. It is not always possible for academics, even with the best of intentions, to see an experiment from the perspective of a student, who does not bring with him or her the experience and preconceptions of an academic.

The experience of the first workshop has led us to investigate the possibility of holding more workshops, linked to existing conferences. This will allow submitters to have their experiments reviewed in bulk, and would reinforce the student-centred learning experience that was such a valuable outcome from the first workshop. To this end, a second experiment workshop will be held at the RACI Chemical Education Division Conference to be held in Melbourne in Dec, 2002.

A secondary, pragmatic, benefit of incorporating peer-review into the submission process is that it adds a degree of credibility to the process. This allows the submission of an experiment to the APCELL database to be recognised as valuable scholarly activity, thus providing a mechanism for acknowledging the important practice of reflecting on and contributing to teaching activities. This is further reinforced by the collaboration between APCELL and This Journal, discussed in section V.

IV. The APCELL Database

The most practical outcome of APCELL will be the database of reviewed and tested experiments. This database already exists and there are over 30 experiments somewhere in the process between submission and full review. Once an experiment is fully reviewed it is completely and freely available on the APCELL web site. [15] In addition to the Educational Template, supporting documentation for each fully reviewed experiment includes a set of student notes, demonstrator notes and technical notes to allow ready implementation into a new laboratory. Experiments that have not been completely reviewed are not freely available but the web site contains a complete list of all submitted experiments under review, including a brief description of each experiment, and the contact details of the submitter.

The APCELL project does not claim the copyright or intellectual property ownership rights to any experiment submitted for review and dissemination via the publicly accessible database. These rights remain with the experiment’s originators and/or the submitters of the experiment to the database, as appropriate. The project requires that submissions for review and subsequent dissemination acknowledge the original sources of the experiment and any contributions that have been made in the experiment’s development. If the origin of the experiment is, to the best of the submitter’s knowledge, unknown, this should be clearly stated. The project requires that the submitter’s Head of Department certify all submitted material has been released to unrestricted public access.
V. Australian Journal of Education in Chemistry and APCELL

APCELL not only draws upon the results of previous teaching and learning research in terms of teaching and curriculum design, but the project methodology also uses the processes of scholarly inquiry into teaching and student learning. Moreover, the products of the APCELL project have the potential to generate and support further pedagogical research, which is the third category of research-led teaching described earlier. This third area of RLT falls outside the purview of the core business of the APCELL project as CUTSD funding specifically prohibits the use of funds to support educational research – the funds are intended to produce tangible products to assist better teaching and learning in universities. Because APCELL is naturally spawning educational research we have sought the proper vehicle for its dissemination and the cooperation between This Journal and APCELL was established to do this.

APCELL provides a very practical resource for physical chemists – the database of student-centred, validated experiments. These experiments are themselves not necessarily innovative or new. In many cases their heritage is completely unknown, and in others the experiment itself has been previously published. The innovation of APCELL is the RLT approach, as exemplified by the Education Template. Utilising RLT and student-centred approaches to an existing experiment can turn it from one where students are not motivated to learn (for a variety of reasons, e.g. lack of clear objectives, or lack of context), into one that provides a good learning experience. Publication is a peer-reviewed journal, such as This Journal, provides a mechanism for acknowledgment of such pedagogical activity.

This Journal will not therefore publish the experiments themselves (unless they have been created anew). However, the pedagogy of an experiment, as summarised by the Template, and aspects of the appraisal and review by academics and students, may be of significant interest to the chemical education community. In those cases, This Journal will consider publication of the educational research aspects of the experiment. Following this article is the first such publication. We hope it will be the first of many over the years.

VI. Other Areas of Chemistry

While this paper has been written in terms of the utility of the APCELL concept to physical chemistry, we believe that it is equally useful in all areas of chemistry, and perhaps more generally in any experimental science. It is the intention of the Directors of the APCELL project to, in the near future, widen its scope and accept submissions from across the full range of chemistry laboratory teaching programs. Further details of such expansions will be reported in This Journal as they occur.

VII. Conclusions

The APCELL project is bringing together academics from most Australian Universities to enhance the quality of laboratory teaching in physical chemistry. The project is built on sound educational research. Participants are asked to reflect upon the pedagogy of an experiment by being guided through an Educational Template. The practical outcome of APCELL will be a database of educationally sound and tested experiments available to all via the Web. New educational research spawned by the project will be published in This Journal and elsewhere.

VIII. Acknowledgements

The APCELL project is supported by a CUTSD grant and the contributions of the Chemistry Departments of the participating universities, in particular the Chemistry Department of Adelaide University and the School of Chemistry, and Institute for Teaching and Learning, of the University of Sydney.

IX. References


Appendix 1: APECELL Participants.

Staff and student participants in the APECELL project, together with institutional affiliations.

Directors
Simon Barrie, University of Sydney
Mark Buntine, Adelaide University
Scott Kable, University of Sydney

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Olivia Oldfield, Edith Cowan University
Alison Radford, University of Tasmania
Michael Rossbach, University of New South Wales
Joanna Turner, University of Southern Queensland
Alistair Usher, University of Western Australia
Linda Walpole, University of Newcastle
Nial Wheate, Australian Defence Force Academy

New Zealand Affiliates
Gordon Heely, Victoria University of Wellington
Jim Johnston, Victoria University of Wellington
Michael Mucalo, Waikato University
Bryce Williamson, University of Canterbury
Acid/base systems are of fundamental importance in many areas of chemistry, biochemistry, environmental science and biology but receive little attention after the traditional general chemistry course in first year. In recent years there has been a questioning of the validity of the equilibrium calculations usually carried out in these courses but few of the standard texts used in such courses make any attempt to point this out. In the absence of a rigorous thermodynamic treatment of aqueous systems, students are unaware that in real systems equilibrium constants have a strong dependence on the ionic strength of the solution. As most tables of equilibrium constants in aqueous systems refer to the thermodynamic equilibrium constant at infinite dilution the use of these values in dilute ionic solution can lead to considerable error.

This experiment was designed to reinforce the basics of acid/base chemistry through the determination of the dissociation constant of a weak acid in the presence of an inert electrolyte. Experimentally the experiment is straight forward but allows the student to carry out optional extensions including the potential for observing the effect of varying values of $K_a$ and $K_w$ on the shape of the titration curve.

Even though the data collection process is a bit tedious it does give the student a good set of data on which to base their calculations. I believe the challenge in physical chemistry is always to develop an experimental method that will give the experimenter reliable and reproducible data, then the subsequent collection of that data will become somewhat less challenging.

The experiment exposes the student to the possibility of manipulating the data in several ways, arriving at a conclusion about which method may be the most appropriate and to think about the assumptions involved in each of the treatments. A comparison between the determined value of $K_a$ and the literature value will show a significant difference.

The student is able to explore the power of a spreadsheet package such as Excel for the handling of large data sets. The extension introduced allows students to do some simple mathematical modelling of the titration curve and to use $K_a$ and $K_w$ as adjustable parameters to obtain the best fit between calculated and experimental data. Although the goodness of fit is obtained visually, it does introduce the student to the concepts involved in more rigorous calculations.

**Educational Template**

**Section 1 – Summary of the Experiment**

1.1 Experiment Title:

The Determination of the Dissociation Constant of a Weak Acid by Titration

1.2 Description of the Experiment

The acid strength of a weak acid as measured by the dissociation constant, $K_a$, is of relevance in many areas of chemistry and in biological systems. Weak acids are an integral component of buffer systems and the range of a buffer is controlled by its $pK_a$. In this experiment students can build on these basic skills by

- following the progress of a titration potentiometrically
- see how the pH changes during the titration use the pH-volume data to estimate the equivalence point by different methods
- determining the dissociation constant of the acid by several techniques including the Gran technique which is not normally covered in a physical chemistry course.

By carrying out the titration at constant ionic strength, students can also see that the value of $K_a$ is significantly different from the thermodynamic $K_a$ usually reported in the literature.

The calculations involved are not complex and can readily be carried out using a spreadsheet. Depending on the time available the titration can be modelled using a spreadsheet to carry out the calculations either as an integral part of the experiment or as an

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*The complete documentation for this experiment is freely available on the APCELL web site [www.apcell.org]. This includes the educational template, a set of student notes, demonstrator notes and technical notes to allow ready implementation into a new laboratory.*
extension. This enables the student to explore the effect of changing the value of $K_a$, on the fit of the calculated results to the experimental pH/Volume curve.

### 1.3 Course Context and Students’ Required Knowledge and Skills

The basic theoretical skills (weak acids and bases, $pK_a$, $pK_b$, $pK_w$, buffers, etc) are covered in the typical textbook of General Chemistry used in first year courses. First year chemistry courses cover the basic skills of titration and in some cases students would use a pH meter to measure pH and so be familiar with its operation. The mathematical skills required are algebric and should not be beyond the average student.

Acid strength is an important concept in most areas of chemistry but its formal study after first year would normally be limited to analytical chemistry courses. This experiment provides a reinforcement and extension of first year concepts in this area.

### 1.4 Time Required to Complete:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to Lab</td>
<td>1 hr</td>
</tr>
<tr>
<td>In Laboratory</td>
<td>3 - 6 hrs</td>
</tr>
<tr>
<td>After Laboratory</td>
<td>1 - 3 hrs</td>
</tr>
</tbody>
</table>

### 1.5 Acknowledgments

The original experiment was based on a description of the determination of stability constants. The theoretical treatment for the simulation of the titration was initially taken from Harris. A more recent treatment with relevance to the spreadsheet approach is in the Fifth Edition of the same text, p294.

### 1.6 Any Other Comments:

The experiment is open-ended. Students can repeat the experiment at different ionic strengths, use the same approach on a diprotic acid or look at the effect of substitution on acid strength.

## Section 2 – Educational Analysis

### Learning Outcome

**What will students learn?**

**Process**

**How will students learn it?**

**Assessment**

**How will staff know students have learnt it?**

**How will students know they have learnt it?**

### Theoretical and Conceptual Knowledge

<table>
<thead>
<tr>
<th>K$_a$ is a function of ionic strength.</th>
<th>By comparing the experimental value at a known ionic strength with the literature value at zero ionic strength.</th>
<th>By the student commenting on the difference between the two values in their laboratory report.</th>
<th>By realising the difference between the experimental and the literature values are significant.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical application of weak acid/base theory.</td>
<td>By calculating the value of K$_a$ by several methods from different applications of the same basic equation to their experimental data.</td>
<td>By the students demonstrating that they can carry out the relevant calculations and being able to critically compare the values of K$_a$ by the different methods.</td>
<td>By being able to understand the derivation of the relevant equations.</td>
</tr>
<tr>
<td>The application of computer modelling to simulate experimental results.</td>
<td>By rearranging the master equation for the titration into a suitable form for spreadsheet analysis and carrying out the analysis.</td>
<td>By the presentation of the calculated and experimental titration curve in the laboratory report.</td>
<td>By being able to produce a titration curve that approximately matches the one obtained experimentally.</td>
</tr>
<tr>
<td>Be able to solve acid base problems.</td>
<td>By being able to understand the derivations being presented and to derive an equivalent equation for the titration of a weak base with a strong acid.</td>
<td>By deriving the relevant equations.</td>
<td></td>
</tr>
</tbody>
</table>
### Scientific and Practical Skills

<table>
<thead>
<tr>
<th>To be able to critically evaluate the ‘best’ method for determining the equivalence point of a potentiometric titration.</th>
<th>By recognising the error involved with determining the volume at the point of inflexion on the titration curve.</th>
<th>From the discussion by the student in the laboratory report. By determining the equivalence points by the methods described in the experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>To be able to critically evaluate the ‘best’ method for determining the value of $K_s$.</td>
<td>By evaluating the uncertainty in the determined values.</td>
<td>From the error analysis undertaken by the student. By being able to carry out an error analysis on the results.</td>
</tr>
<tr>
<td>To be able to calibrate a pH meter using appropriate buffers.</td>
<td>By carrying out the calibration after being instructed by a demonstrator.</td>
<td>The pH values recorded during the titration are what would be expected. By obtaining a $K_s$ value in reasonable accord with the literature.</td>
</tr>
<tr>
<td>To be able to use a spreadsheet to present a large amount of data in an appropriate graphical form.</td>
<td>By being instructed in the basic principles of using spreadsheet (if required) and how to apply it to the data from this experiment.</td>
<td>From the presentation of the appropriate plots in the laboratory report. By being able to produce suitable plots for the laboratory report and to obtain the required $K_s$ and equivalence point from the plots.</td>
</tr>
</tbody>
</table>

### Generic Skills

<table>
<thead>
<tr>
<th>Manipulation of complex algebraic equations into a suitable form for analysis.</th>
<th>By rearranging the equations given into a suitable form for plotting.</th>
<th>By producing appropriate plots of the measured data. By determining the equivalence points by the methods described in the experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying out appropriate error analysis on the experimental results.</td>
<td>By estimating the uncertainties in the various experimental values obtained. Carrying out a least squares analysis on the Gran plot to estimate the standard deviation in the value of $K_s$ and the equivalence point.</td>
<td>From the error analysis undertaken by the student. By being able to carry out an error analysis on the results.</td>
</tr>
</tbody>
</table>

### Section 3 – Student Learning Experience

**3.1 Did this experiment help you to understand the theory and concepts of the topic? If so, how, or if not, why not?**

**S1:** Yes it helped me consolidate theory.

**S2:** The experiment allowed me to understand the importance of using several methods in interpreting experimental data. It also reinforced the ideas of accuracy in standardisation and titration.

**S3:** Yes, the difference between the true thermodynamic equilibrium constant and the concentration equilibrium constant. However for general theory on $K_s$, it wasn’t very helpful at all, as what we were doing was determining one dissociation constant.

**3.2 How is this experiment relevant to you in terms of your interests and goals?**

**S1:** This experiment was relevant to consolidate theory from lectures.

**S2:** I enjoy titrations and standardising acids and bases. It was relevant in that it helped me to gain a better understanding of these methods and it also introduced me to the use of the glass electrode - which I hadn’t used before.

**S3:** In so far as “interests” and “goals” referring to my personal understanding of the material, the experiment wasn’t all that relevant.
3.3 Did you find this experiment interesting? If so, what aspects of this experiment did you find of interesting? If not, why not?
S1: I found the results interesting.
S2: Although the actual method was repetitive, I found the analysis of the experimental data quite interesting. This was largely due to the fact that I had a reasonable understanding of what I was doing and why.
S3: No. Nothing was demonstrated about how $K_a$ varies with strength of acid. We only found $K_a$ for a weak acid.

3.4 Can the experiment be completed comfortably in the allocated time? Is there time to reflect on the tasks while performing them?
S1: The experiment can be completed comfortably in the allocated time. There is some time to reflect on the tasks.
S2: I easily completed the experiment in the allocated time. Although I had to restandardise the CH$_3$COOH, I still finished completely in one week (4 hr). I found this very beneficial as it allowed adequate time to reflect on and interpret results.
S3: Yes to both questions.

3.5 Does this experiment require teamwork and if so, in what way? Was this aspect of the experiment beneficial?
S1: The computer work required some assistance which was beneficial.
S2: The experiment can be successfully completed individually. Standardised solutions could be shared but for accurate results etc I wouldn’t advise it. Plus the experiment can be easily completed individually within the allocated time.
S3: No.

3.6 Did you have the opportunity to take responsibility for your own learning, and to be active as learners?
S1: Yes.
S2: Opportunity to take responsibility for my own learning during this prac really only came into play in looking up the literature values and looking in other texts for explanations about the Gran method and pH-volume curves etc. However this kind of responsibility was applicable in all experiments.
S3: Yes. These pracs are good for you to take responsibility for your own learning. If you don’t understand, you have to ask and if you don’t ask you went anywhere.

3.7 Does this experiment provide for the possibility of a range of student abilities and interests? If so, how?
S1: Yes. It involved using Excel, making graphs and using different equipment
S2: I believe that this experiment adequately provides for a range of abilities. This is largely due to the fact that the ‘hard parts’, such as the standardisation and titration, are really the basis of the majority of chemistry experiments. Also there was a variety of ways to analyse the data hopefully allowing students to at least understand a couple of ways.
S3: No not really.

3.8 Did the laboratory notes, demonstrators’ guidance and any other resources help you in learning from this experiment? If so, how?
S1: Yes. It provided clear instructions on the experiment and theory.
S2: I found the demonstrators to always be very helpful in aiding my understanding of the various components of the different experiments. I also found the different approaches to some topics in various texts to be helpful, as there usually was at least one way that I understood!!
S3: A little, in the introduction but not much.

3.9 Are there any other features of this experiment that made it a particularly good or bad learning experience for you?
S1: Good because I learnt how to make different graphs and it linked experiment to theory.
S2: I found the experiment both enjoyable and reasonably easy to understand and conduct. I found the procedure to be clearly written and easily followed. (It was definitely one of my easier experiments - both in procedures and in the write up).
S3: Computer work OK. Could draw clear graphs
3.10 What improvements could be made to this experiment?

S2: I don’t have any suggestions of improvements as such. The only thing I would suggest would be that an alternative measure of the pKₐ could be included (if one exists) that uses a different procedure so that new skills could be acquired.

S3: Explanation in introduction of how Kₐ changes with acid strength (even though I know this is first year material) and maybe compare Kₐ of different acids or find Kₐ of a range of acids.

3.11 Any Other Comments

S2: I found the experiment both enjoyable and fairly easy to understand, perform and write up. It helped me confirm my ideas about standardisation and titration. Although it was a good prac (because it was short - no just kidding) I thought that the actual procedure taught me nothing new. I mean no new methods were introduced and used during the actual experiment itself. The write up used various different techniques of analysis which I found very useful and beneficial to my overall understanding of the prac. Overall I would say that the prac was well written, easy to follow, good to perform and relatively easy to write up.

S3: Also explanation of theory for point of inflexion, pH-volume curve, Gran plot etc.

References


Effectiveness of Flow Diagrams as a Strategy for Learning in Laboratories

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Abstract

Chemistry practicals are very resource-intensive. Although we design practicals with several objectives in mind, most students view them simply as an exercise in task completion. If students are merely going through the motions then they are not getting “value for money” and neither is the institution. We tried an alternative approach with our first- and second-year university students. They were required to construct flow diagrams in advance for each experiment. At the end of the course we administered a questionnaire to investigate the success of the flow diagrams. Student responses were very enthusiastic and many said that flow diagrams had helped them to “see the bigger picture”. They also said that flow diagrams allowed them to link the experiment to the theory covered in lectures. More than half the students stated that they were useful for time management, while 40% said that they were useful for advance preparation for the experiments. About 20% of first-year students used them spontaneously for other courses. We consider that flow diagrams are a very useful strategy for learning. Samples of the flow diagrams as well as the students’ views are presented.

Introduction

Chemistry practicals are very costly in terms of staff requirements, laboratory equipment and chemicals. We design practicals with several objectives in mind, yet studies have shown that for most students the main concern is task completion (Berry \textit{et al.} 1999). Our experience has been that depending on the method of assessment, they are also seen as a way to improve grades. Nakhleh (1994) suggests that a barrier may exist because laboratories are complex, information-rich environments which prevent students from processing information effectively. Johnstone (1997) asserts that laboratories are places where students can experience information overload. If learners are unprepared, they may not be able to understand laboratory procedures. He found that students who had completed a pre-laboratory exercise asked fewer “thoughtless questions”. Some form of advance preparation is needed to guide students to what they will experience while engaging with the laboratory task.

As the person responsible for running the second-year chemistry practicals for science and engineering students, the first author (BD) became concerned because most students were unprepared for their laboratory sessions. She would find students consulting the schedule of experiments just prior to the start of the laboratories. They would carry out the instructions in order to complete the experiment as quickly as possible. At about this time BD came across the book, \textit{Thinking Tasks in Chemistry} (Bucat and Shand, 1996) in which they described flowcharts to illustrate experimental procedures. She thought that this might be a way to force students to prepare for their practical classes in advance. This struck a chord with the second author as one of her undergraduate students had developed for himself the technique of drawing flow diagrams as a way to assist him to carry out his experiments (Mngomezulu, 1993). This paper reports on the effect of the use of flow diagrams on students’ approach to preparation for laboratory sessions.

Background

Rollnick \textit{et al.} (2001) have identified three aspects of pre-laboratory preparation which they believe are helpful for successful completion of a practical. These were:

- A “bird’s eye” view of the practical. This implies an appreciation of the theory underlying the experiment and a general idea of the procedure to be used.
- Prerequisite skill and knowledge required to carry out the experiment. This means that the necessary cognitive and procedural structures would be in place.
- A detailed understanding of the both the underlying chemistry and the experimental steps to be carried out during the experiment.
They suggest that flow diagrams might be useful to satisfy the third requirement for a successful laboratory session.

Meester and Maskill (1995) recommended some form of enforced preparation before the laboratory session. They assert that:

"Preparation problems with respect to students entering the laboratories are only solved via extrinsic motivational factors (Do it or you can't begin; do it or you won't be allowed to begin) instead of intrinsic factors (it will cost you less time; you will get quicker more reliable results, etc). "page 718.

This study addresses the following questions:

1. What is the effect of the use of flow diagrams on students' level of preparation for Chemistry laboratories?
2. What are the students' perceptions on the use of flow diagrams as preparation for laboratory sessions?
3. How do first- and second-year students differ in their approach to the use of flow diagrams?

Context of the Study

In 1999 BD decided to introduce flow diagrams into the second-year practical course to enforce some preparation in advance. In previous years, students had been given the practical manual and the schedule of experiments at the beginning of the course. Students were expected to prepare in advance but there were no formal mechanisms to enforce this preparation.

At the first meeting of the second-year class in 1999, BD distributed the practical manual as usual and explained what was required in terms of the flow diagram. An example of an experiment with the accompanying flow diagram was presented to the students and included in the practical manual. Students were told to show flow diagrams to the teaching assistants at the start of the practical session and they were not allowed to carry out the practical unless they had produced a flow diagram.

At the beginning of 2000, BD took up an academic post in the Chemistry Department and is in the process of designing a new course for the Academic Development Programme. Students who enter this programme are from disadvantaged backgrounds and are given two years to complete the equivalent of the first-year chemistry course. Most of these students have never been in a laboratory, and a special course was designed to cater for their needs. Encouraged by the positive results obtained from the second-year students, BD decided to introduce flow diagrams to these students as well. Since the majority of these students had no previous laboratory experience they were presented with a flow diagram depicting the making of a cup of tea as an example. As with the second-year students those in first year were expected to produce their flow diagrams before being allowed to start the laboratory session.

Method

During the course of 1999, data was collected for a third of the class through journal notes compiled by a participant coresearcher who was a teaching assistant in one of the laboratories. Copies were made of the students’ reports, which included the flow diagrams. At the end of the course a questionnaire was administered to the entire class to investigate students’ perceptions about the flow diagrams. Based on the data collected, 12 students from the group that had been most closely observed were selected for in-depth interviews at the end of the course. These multiple data sources allowed for triangulation to increase the validity of the results.

Data was collected from first-year students in the same way as for the second-year students. The questionnaire used for these students was identical to that used for the second-year students.

Participants in the Study

The sample of 113 second-year students who completed the questionnaire consisted of 56 chemical engineering and 57 science students. This group consisted of 68 males and 45 females. 51 students speak English as a first language while 62 have English as their second language. Science and chemical engineering students are combined in one chemistry course for the second year.

123 first-year students completed the questionnaire. This group consisted of 62 males and 61 females. 33 students speak English as a first language while 90 have English as their second language. The majority had no previous laboratory experience at high school.

Findings

Implementation went very smoothly and students presented flow diagrams with a wide variety of styles. This showed that they were taking the ideas on board rather than simply reproducing the examples shown in the practical manual. Examples of second-year flow diagrams are shown in Appendix 1 while those for first-year students are included in Appendix 2.
Effect of Flow Diagrams on Students’ Level of Preparation for Laboratories

The teaching assistants (TAs) and support staff found that the students were more prepared, as illustrated by the quote below.

“The students at lockers 166 and 168 worked well and followed their flow diagrams closely.” (Journal notes, 1999, experiment 1).

This shows that for some students flow diagrams were able to replace the practical manual. There was some relationship between the quality of flow diagrams and confidence in carrying out the experiment. For example at a meeting midway through the course, two of the TAs commented that most students with well-designed flow diagrams were able to tackle the experiments efficiently. On the other hand, students with a scribbled flow diagram had problems with the experiment and were constantly trying to check what was expected. Journal notes revealed that there was a definite improvement in time management and for most sessions the students left the laboratory between 16h30 and 16h45. There was no need for laboratory attendants to work overtime. It was noted at the time that most students would collect solutions or material for the next step of the experiment instead of wasting time simply watching the experimental setup. There were also fewer failed experiments. This was particularly noticeable for practicals consisting of multiple steps (Journal notes, 1999, experiment 5). For example, in previous years, at least a quarter of students failed to prepare the standard solutions of potassium permanganate required for this experiment.

Students’ Perceptions on the Introduction of the Flow Diagrams

At the end of each course the authors administered a questionnaire to probe various aspects of the implementation of the flow diagrams. Responses from 113 second-year students and 123 first-year students were clustered and are summarised in Table 1. In some cases students gave more than one response to the question: “You were required to draw flow diagrams for all experiments. What did you think of this requirement?”

The responses in Table 1 follow a similar trend for first- and second-year students, implying that flow diagrams are perceived to be an effective resource for students at all levels. There were some differences in that a larger proportion (50% against 27%) of the first-year students felt that flow diagrams helped with time management. About one in five first-year students used flow diagrams instead of the practical manual. On the other hand, very few second-year students used the diagrams in place of the practical manual.

The flow diagrams seemed to have achieved the desired effect as nearly 60% of the students mentioned that they had been useful for advance preparation of the experiment. Some typical comments are given below:

“This is a very good start before doing an experiment. The flow diagram makes me more confident when doing the practical. I am not confused and I know what I have to do step by step. Not only do I know already what is the procedure and its aim, but also save time in doing the practical.” Second-year, 201.

“Besides it being more work, it served very useful, (which I doubted at first). Having done a flow diagram encourages you to read thru (sic) and understand the practical beforehand. During the practical this serves as a quick way of following the procedure of the practical.” First-year, 104.

Almost 40% of the students found flow diagrams useful for time management:

“I think it was good requirement because during the practical it saves time having to flip through the manual for all the steps instead you have a picture of what to do which is helpful, which helps put things in perspective.” First-year, 123.

About a third of the students noted that the flow diagrams had helped them to link the experiment with aspects of theory covered in the lectures. Several

Table 1   Students’ perceptions on the requirement to draw a flow diagram

<table>
<thead>
<tr>
<th>Perception</th>
<th>Second-year students, N = 113</th>
<th>First-year students, N = 123</th>
<th>% All students, N = 236</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helpful: made me prepare in advance</td>
<td>(64%)</td>
<td>(54%)</td>
<td>(59%)</td>
</tr>
<tr>
<td>Helped with time management</td>
<td>(27%)</td>
<td>(50%)</td>
<td>(39%)</td>
</tr>
<tr>
<td>Helped with understanding key concepts seeing the big picture</td>
<td>(31%)</td>
<td>(29%)</td>
<td>(30%)</td>
</tr>
<tr>
<td>Did not have to use the manual during the laboratory session</td>
<td>(4%)</td>
<td>(22%)</td>
<td>(14%)</td>
</tr>
<tr>
<td>Not helpful</td>
<td>(5%)</td>
<td>(8%)</td>
<td>(6%)</td>
</tr>
</tbody>
</table>
students wrote that drawing the flow diagram had helped them to a better understanding of the experiment.

“It helped me to understand the whole concepts of the practical, to apply my knowledge of chemistry i.e. from lectures.” Second-year 220.

“It helped to understand the experiment and to be better prepared and ask relevant questions during the pre-practical talk. Also it was easier to follow the flow diagram than the practical manual when carrying out the practical.” Second-year, 246.

“It was a very good and essential requirement because by drawing a flow diagram you actually acquired a better understanding of what you had to do in the laboratory yourself as the flow diagram gave a pre-vision of the whole laboratory session.” First-year, 137.

One in five first-year students used the flow diagram instead of the practical manual:

“It saved time during the prac because you could refer to your diagram during the prac instead of reading through the prac manual.” First-year, 105.

A few students gave a qualified positive response:

“This (flow diagram) was irritating, but in retrospect a very good idea because it structured your thoughts and gave you a firmer grasp of the procedure.” Second-year, 204.

“For me they were just something I had to do because I hardly ever used them in the experiment. I preferred using the practical manual.” First-year, 103.

Twelve second-year students were interviewed at the end of the course and they all made very positive comments about the flow diagrams. Their responses confirmed and expanded upon the categories already identified in the questionnaire. Some of their responses to the question on the flow diagrams are given below.

“That was a most brilliant idea in that it helped you to prepare for the practical and without flow diagrams we won’t be able to understand the practical thoroughly and also do it as good as you can or you actually did.” Amina, interview.

“At first I thought it was going to be difficult but as time went on I found it very useful because you go there (to the laboratory) knowing exactly what is going to happen and if you have any enquiries so now you have got something to ask the person (TA). Meanwhile if you just came there (without a diagram) you would not have enough time to go through the practical manual.” Sipho, interview.

“I remember one other time I wrote a wrong flow diagram (she misread the practical schedule) and I was so disorganised that day cause I had to read it, (the experiment) rushing, it disturbed me that day.” Tebogo, interview.

Differences in the Use of Flow Diagrams for First-and Second-year Students

A second question in the questionnaire asked students “Did you use flow diagrams for any other subjects?” The Chemistry Department is currently the only department in the Science Faculty at the University of Cape Town which requires students to draw flow diagrams for their practicals. The responses are shown in Table 2.

Table 2. Students’ responses about the use of flow diagrams for other courses.

<table>
<thead>
<tr>
<th>Used flow diagrams for other courses</th>
<th>No of students, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-year students</td>
<td>(19%)</td>
</tr>
<tr>
<td>Second-year students</td>
<td>(0%)</td>
</tr>
</tbody>
</table>

As can be seen from Table 2, there was a major difference between the responses to the questionnaire between the first and second-year students. None of the second-year students used flow diagrams for other subjects. This is in contrast with the first-year students of whom 19% said that they spontaneously used them for other subjects. Some of their responses are given below:

“Yes, it is useful in biology where there is a great amount of text, makes the brain ‘feel’ tired. Flow diagrams makes the text seem less and more approachable. Good way of ‘storing’ important information or key concepts.” First-year, 104.

“Yes, physics, with this idea from the Chemistry department, more than 65% of PHY123 passed physics exam prac, most of these students were able to make their own flow diagrams for that exam.” First-year, 154.

First-year students have spontaneously transferred the use of flow diagrams from one course to another.
while second year students used the flow diagrams only for preparation of the their chemistry experiments.

Discussion and Conclusion

Flow diagrams, which were initially introduced as an extrinsic motivational device, were endorsed enthusiastically by most of the students. They were not initially intended to be a metacognitive device but Rickey and Stacy (2000) regard concept maps, a related technique, as a metacognitive resource. They did not, however, find them successful for enhancing conceptual learning in laboratories. This finding fits well with Domin (1999), who found that laboratories were not ideal environments for learning theory. However, flow diagrams are aimed at eliminating “noise” from practical sessions (Johnstone and Letton 1991) and hence enhance procedural understanding. Our students’ responses suggest that they also succeed as metacognitive resources by asking students to engage with the instructions in the laboratory manual. Almost a third of both first- and second-year students found that flow diagrams enabled them to relate the experiments to the theory covered in lectures or to “see the bigger picture.”

In his information processing model, Johnstone (1997) refers to “working space”. This is part of the mind that holds ideas and facts during the process of thinking about them. While this space cannot be expanded, it can be used more efficiently. At first facts occupy discrete bits of space but later they merge to one space, a process known as chunking. Flow diagrams assist students to use their working space more efficiently for their experimental work and allow them to grow concepts for themselves. This is corroborated by the finding that a number of students reported that flow diagrams helped them to link experiments with chemical concepts covered in lectures.

About 20 percent of first-year students found flow diagrams to be a useful tool and spontaneously used them for other subjects. As such, they may function to amplify the zone of proximal development, ZPD, (Vygotsky 1978) for students by simplifying tasks in this zone. The flow diagram acts as a tool to give students more space in his/her zone to carry out complex tasks more easily (Berger, 1998). Perhaps this difference in approach to the use of flow diagrams between the two cohorts of students is a reflection of the fact that in the case of first-year students academic habits have not been established and they are prepared to take new ideas on board.

The authors consider that flow diagrams are a very effective strategy for learning in laboratories. Based on the positive feedback from students, the requirement has been extended to all the undergraduate courses in the Chemistry Department at the University of Cape Town.

Acknowledgements

Financial assistance from the University of Cape Town Research Committee and the National Research Foundation is gratefully acknowledged. The authors would like to thank Mr Fred Lubben, University of York and Dr Shirley Churms, UCT, for helpful comments on this paper.

References


Appendix 1: Examples of flow diagrams drawn by second year students

**The oxidation of Benzyl Alcohol to Benzoic Acid.**

Diagram drawn by Kelly

Diagram drawn by Amīna
Appendix 2 Examples of flow diagrams drawn by first year students
Capturing the imagination with Green Chemistry ... and explosions, froth, color, phase changes and lollies.

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Introduction

In July this year, Monash University launched the Centre for Green Chemistry. Located at the Clayton campus in Victoria, this new facility is creating exciting opportunities in research and development in environmentally friendly chemical processes and products as replacements for older, more polluting technologies.

As well as conducting important research, the Centre for Green Chemistry is developing a Community Outreach Programme. The aim of this programme is to inspire young people to get involved in the study of Chemistry, and to raise their awareness of the broader implications of chemicals and their potential effect on health and the environment.

In this paper we describe some developments in the Centre for Green Chemistry Community Outreach Programme. Details of an exciting demonstration lecture, designed to awaken interest in the Chemical Sciences in general and Green Chemistry in particular are provided.

Background Data - High School Enrolments

The Outreach Programme has resulted from a realisation that there is a significant decline in interest in Chemistry at secondary schools. Each year, a smaller proportion of students are electing to study Chemistry\textsuperscript{1}, while the number of students continuing to Year 12 (or the Victorian Certificate of Education - VCE) has been increasing overall, the number of students electing to study Chemistry is declining. Also, many students who begin Chemistry in Year 11 are not continuing the subject in Year 12, Figure 1.

Because Chemistry is becoming a less popular choice for VCE, even fewer students are likely to go on to study chemistry at a tertiary level.

A recent survey\textsuperscript{7} was undertaken to determine what attracts students to Chemistry and maintains their interest. The object was to investigate students’ impressions of chemistry as perceived from media exposure, their impressions of the chemical industry, and why they chose to study chemistry.

\textsuperscript{1}A survey, where responses were received from 318 students studying Chemistry at various levels in Victorian secondary schools, was conducted. Students were in the 16-18 age-bracket and included: 20 “accelerated” Year 12 students studying 1st Year University Chemistry concurrently with Year 12 Chemistry; 115 Year 12 students and 183 Year 11 students (the first year in school where chemistry is taken as a full year subject). The format was multiple choice, with multiple responses allowed for each question and some questions requiring free format responses.

\textbf{Figure 1:} Enrolment in Chemistry, Years 11 and 12 starting numbers in Victorian schools.
The two most significant factors identified as impressions of Chemistry gained from the media were: ‘an exciting development which will benefit society’ and an ‘environmental pollution incident’ as illustrated in Figure 2. These views correlated closely with the reported perception of “chemical industry”. When asked to record the first thing that came to mind when the term “chemical industry” is mentioned, many respondents listed plastics, petroleum and medicines, but also factories, smoke, pollution and environmental problems.

The target group for this survey was students who have chosen to study chemistry (for the reasons illustrated in Figure 3), who might thus be expected to have a far more positive perception of the topic than a larger, more representative, group of students in this cohort. It appears that students in Victorian secondary schools have a similar perception to that described by Kauffman and Gaskell of an industry that is dangerous, toxic and an altogether unpalatable thing to be involved with. Given this, it is not surprising that fewer students are aspiring to become chemists.

The other significant piece of information emerging from the student survey, in response to the question about how chemistry can be made more interesting and exciting, was that students want more practical work in their courses at school. However, it should be noted that their wish was for practical work that is interesting, exciting and relevant to real world chemistry. Nearly half of the students surveyed mentioned the need to improve practical work experiences. In recent years, budgetary constraints and safety restrictions have resulted in the curtailing of practical work in school and university chemistry programs. Indeed, the results of this survey suggest that one of the major attractions for studying chemistry has been removed.

Public perceptions

The attitudes of these scholars are consistent with the attitudes of the general public. Despite the many advances and contributions that chemistry has made to modern living, most people make negative associations with the words “chemistry” and “chemical company.”

The Chemical industry invests significant amounts of time and money trying to improve its image in the public eye, however; on the whole these efforts have not had the desired impact on public perception. Despite the fact that environmental standards and controls are constantly being reviewed and upgraded the public continues to see the industry as a source of pollution and environmental degradation.

The elimination of CFCs (ozone depleters) from processes and products is an example of the industry’s ability to respond to new environmental issues and conform with changing community attitudes.

While there have been advances in protections and controls, the chemical industry still deals with materials and processes which are inherently dangerous. Toxic waste materials are still produced,
and although the means of disposal have improved, the possibility of a release to the environment with disastrous effects is always present as has been very graphically illustrated in accidents such as the methyl isocyanate leak at Bhopal, India and other more recent events such as the tailings dam failure in Baie Mare, Romania which released of cyanide contaminated liquid into a major river system.

Similarly, many products of the industry create pollution and waste issues, which are yet to be truly solved. While companies are making progress with cleaner production, the nature of business dictates a reliance on established, often older, more polluting, technologies. Investment in research and development is inhibited by the need to make a return on the processes already in place and various studies have illustrated the cost of add-on, ‘end-of-pipe’ pollution prevention technologies vs. integrated process changes.

If the public perception of the chemical industry is to change, what is really needed is fundamental change in the nature of the industry and the products that it markets. As long as chemical incidents and pollution appear in the news media, public mistrust and fear are likely to remain. However, there is evidence of a change toward more sustainable practices as Companies begin to adopt the principles of Green Chemistry. This is being driven by the adoption of sustainability as a way to address all aspects of the ‘triple bottom line’ (economic, social, environment). The challenge is to ensure that sustainable practices, driven by innovation and change, are continued to be provided by the next generation of chemists.

In aiming at secondary students, the Centre for Green Chemistry Outreach programme seeks to reverse the trend in declining numbers of students who elect to study Chemistry. As more qualified students enter the workforce with knowledge of the principles of Green Chemistry, the chemical industry will benefit.

The Outreach Programme Presentation

The Royal Australian Chemical Institute (RACI) sponsored “Hartung Youth Lecture” has helped to launch the Community Outreach Program, with the theme this year being Green Chemistry. The lecture uses a combination of multimedia technology and good old-fashioned chemistry demonstrations to illustrate the key ideas behind this new and exciting area of science.

The presentation is developed as depicted in Figure 4 and detailed in Table 1. It begins with discussion of the ‘image’ of chemistry and the chemical industry. This is developed via an historical perspective and some easily understood examples.

These include the reasons behind the madness of the ‘Mad Hatter’ depicted in ‘Alice in Wonderland’; Rachel Carson’s book ‘Silent Spring’ - the first widely published expose of the deleterious effects of chemical use on the environment, and the worst chemical accident in history in Bhopal, India.

Of course, nothing is black and white. To illustrate this, an example of chemical use, which resulted in both positive and negative outcomes, is described. In the 1950s the Dayak people of Borneo were suffering severely from malaria. The World Health Organization (WHO) carried out an extensive aerial spraying campaign using DDT. This had the very positive effect of wiping out most of the mosquito hosts essential for the malarial parasites. A further consequence of the well-meaning use of a highly effective chemical was that geckoes, which ate contaminated insects, were in turn contaminated. Cats ate the poisoned geckoes and died. The subsequent decline of the cat population allowed rats to proliferate and spread typhus and sylvatic plague among the Dayak people. Faced with an epidemic of far more deadly diseases than malaria, the WHO decided to parachute live cats into Borneo in an attempt to reverse the process. In the presentation this is all illustrated by an animated cartoon.

Figure 4: Schematic of development of Green Chemistry schools presentation.
The image of chemistry and the “mad scientist” is used humorously, with time taken to have a little “mad scientist” fun with some stage props, dry ice and colored solutions (a basic aqueous solution containing universal indicator changes color as CO$_2$ dissolution towers the pH, Scheme 1).

**Scheme 1:** Universal indicator is purple in the initially basic solution becoming yellow as the pH drops as carbon dioxide dissolves forming carbonic acid.

\[
\begin{align*}
\text{Na}^+\text{OH}_\text{aq}^- & \rightarrow \text{Na}^+\text{aq} + \text{OH}_\text{aq}^- \\
\text{CO}_2\text{g} + \text{H}_2\text{O}_\text{g} & \rightarrow \text{H}_2\text{CO}_3\text{aq} \rightarrow \text{H}_2\text{O}^-\text{aq} + \text{HCO}_3^-\text{aq} \\
\text{OH}^-\text{aq} + \text{H}_2\text{O}_\text{aq}^- & \rightarrow 2\text{H}_2\text{O}_\text{aq}
\end{align*}
\]

As a counterpoint to the examples of disasters and chemical misuses, the presentation moves on to examine the benefits of a modern chemical society. Benefits, which are often taken for granted, such as items so important to the average teenagers’ existence: mobile phones, computers, high-tech sports gear, sunglasses and fashionable clothes are depicted. This is closely followed by pictures of foodstuffs, quality-of-life enhancing devices such as contact lenses and sunscreens, and, finally, medical devices and pharmaceuticals. Students are challenged to do without these things, which are a direct result of a vibrant, growing chemical industry, and have resulted in a huge increase in food production (agrochemicals) and life expectancy (drugs) during the course of the 20th century.

Some statistics relating to the increase in atmospheric CO$_2$, lead us into the ‘real chemical’ examples of emerging Green Chemistry technologies and chemical breakthroughs. A continuous thread of examples and demonstrations follow as listed in Table 1. The first is a comparison of carbon and hydrogen based fuels and the use of clean burning water producing fuel cells, Scheme 2, ‘fuelled’ by the detonation of the hydrogen bell and the explosion of some hydrogen balloons and enlivened by pictures and videos of the Hindenberg disaster (where we also point out that H$_2$ may well have been innocent of the blaze).

**Scheme 2:** Hydrogen is oxidized (burned) to produce water in a hydrogen fuel cell.

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\text{H}_2\text{g} + \frac{1}{2}\text{O}_2\text{g} \rightarrow \text{H}_2\text{O}_\text{g}
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As the presentation is about “Green” chemistry, the 12 principles of Green Chemistry are distilled to 3 important points:

- Efficient use of energy, particularly in the context of chemical reactions.
- Reduction of risk by removal of hazard, Figure 5.
- Elimination of waste

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| Table 1: Table of topics and attendant demonstrations. |
| --- | --- |
| **Topic** | **Demonstration** |
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- Efficient use of energy, particularly in the context of chemical reactions.
- Reduction of risk by removal of hazard, Figure 5.
- Elimination of waste
Risk = $f\,[\text{hazard, exposure}]$

Figure 5: Risk is a function of hazard and exposure and most risk control focuses on reduction/elimination of exposure. This allows for rapid risk escalation upon catastrophic failure of exposure controls. Elimination (or reduction) or hazard yields a concomitant elimination (or reduction) of risk and it is here that Green Chemistry is focused.

Since increases in atmospheric CO$_2$ have been used to introduce discussion of fuel cells, the use of supercritical CO$_2$ as a ‘green’ reaction solvent is introduced next and as the students remain attentive even during a simple explanation of a P/T phase diagram, Figure 6. A video, courtesy of Dr Chris Rayner of Leeds University is used to illustrate the phase changes occurring as a pressure vessel containing liquid and gaseous CO$_2$ is warmed above the critical temperature.

Carbon dioxide is condensed from the atmosphere and may be released again after reaction. This ‘traceless solvent’ is finding extensive application in chemical synthesis as well as extraction processes and even dry-cleaning! The concept of the phase changes is further illustrated using solid CO$_2$ which is allowed to sublime in air and is added to a colored aqueous solution to produce vigorous bubbling while readily available props such as CO$_2$ fire extinguishers are brought to bear. An example of de-caffeination of coffee by supercritical CO$_2$ extraction of caffeine is enlivened by distribution of the newly popular caffeine enriched chocolate bars or drinks.

Still maintaining the CO$_2$ thread, brewing as a source of the gas is discussed and a yeast fermentation reaction set up using sucrose as a feedstock, Scheme 3.

Scheme 3: During brewing yeast feeds on sugars producing ethanol, carbon dioxide and water. Similar processes can be used to generate useful chemicals by biotransformations.

![Pressure/temperature phase diagram of CO$_2$ indicating solid, liquid, vapor and supercritical phases.](image)

Following this is a description of one of the Presidential Green Chemistry Challenge award winning innovations: that of DuPont’s 100% CO$_2$ blown polystyrene foam which is developed by illustration of replacement of products (polystyrene packing material) by renewable resources (Ecofoam: starch based, steam blown packaging foam). The nature of this material is illustrated by distribution of clean unused material which may be (and usually is) eaten! Hopefully the lack of ill-effects later in the day helps drive home the concept of ‘biodegradability’.

Scheme 4: Ethyl lactate is produced from lactic acid of botanical origin. The source is commonly soybeans or corn but may be a variety of plant sources.

![Scheme 4: Ethyl lactate is produced from lactic acid of botanical origin.](image)

By this stage the yeast reaction is bubbling away merrily and allows further development of this theme with examples of ethyl lactate, a biodegradable solvent produced from a renewable resource by a biocatalytic process, Scheme 4, and another PGCC award winner. Biocatalysts leads to catalysts as a method of greening of a reaction and Terry Collins’ TAML self-destructing oxidation catalysts are used as an illustrative example.

Scheme 5: Potassium sodium tartrate (Rochelle’s salt) is oxidised to (finally) carbon dioxide by hydrogen peroxide. This is a slow reaction that requires heating. The addition of the catalyst, cobalt(II) chloride, causes vigorous reaction with an explosion of green foam. After the reaction the green Co$^{3+}$ returns to the initial pink Co$^{2+}$, indicating that the catalyst is unchanged and reusable. In fact, this solution can then be added to a second unreacted solution to demonstrate basic catalytic recovery.

![Potassium sodium tartrate (Rochelle’s salt) is oxidised to (finally) carbon dioxide by hydrogen peroxide.](image)

The fizzing, colour changing CoCl$_2$ mediated oxidation of Rochelle’s salt is done during the
explanation, Scheme 5, and this leads to the luminol reaction, Scheme 6, which is linked as a lesson from nature (chemiluminescence -> bioluminescence).

Scheme 6:

Luminol (1) is oxidized (using the clean oxidant \( \text{H}_2\text{O}_2 \)) to produce the aminophthalate dianion (2), which exhibits blue fluorescence.

Lots of fun is had at this point by throwing handfuls of luminescent “light-sticks” to an enthusiastic (bordering on riotous) audience. Once order has been restored, the presentation is concluded by recapping the key principles of Green Chemistry and encouraging the students to think about how it applies to their own activities and study.

To finish up, a final bonus demonstration is conducted outside. Students leave the lecture room to find a thermit reaction demonstration set up behind a protective screen. It is explained that this is a redox reaction which produces molten iron, and not only is it spectacular, it also has practical applications such as weld-repairing railroad tracks.

This last demonstration helps leave an impression on the students and importantly, allows them to gather around and ask questions in a less formal setting than the lecture room. Of course, the most common question is usually “Have you got any more light sticks?”.

This presentation, when offered in schools, is modified to suit the available facilities, although, careful choice of demonstrations means that most can be readily transported, set up and performed with a minimum of fuss.

The goals of the programme are to familiarize the students with the basic principles of green chemistry, while at the same time indicating that chemistry is both exciting and highly relevant to our everyday lives. The point that “not all chemicals are bad” is stressed and the positive effects of many chemical discoveries emphasized while acknowledging that the chemical industry is not entirely blameless for its “dirty” image. The concept of using the science of chemistry (Green Chemistry) to overcome many of these problems is presented and it is remarkable how frequently comments such as “I didn’t know that chemists did this sort of thing...” or “this seems much more interesting than I thought chemistry could be...”. Perhaps not surprisingly, questions relating to “relevance to industry” and acceptance and implementation of Green Chemistry principles and technologies are often asked and it is heartening to be able to point to some great success stories. It would be a mistake to underestimate the awareness of economic drivers amongst the young audiences targeted and we have had to collect information relating to actual new products or processes developed by well known companies such as Eli Lilly, Roche, Dow, 3M and others. This sometimes even leads to discussion of the “triple bottom line” concept of equal weight given to economic, social and environmental drivers being adopted by so many companies aware of the need for sustainability in business.

Concluding Comments

Multinational bodies such as the United Nations, the OECD, the European Union and the Asian Pacific Economic Community are all seeking roles in promoting and implementing Green Chemistry. The new journal, Green Chemistry, published by the Royal Society of Chemistry and a number of other publications (many referenced in this paper) provide examples of Green Chemistry for use in teaching while several prestigious journals have devoted special issues to this and related topics. The ACS has received a significant EPA grant for development of Green Chemistry outreach and educational activities and more teaching materials are becoming available. This programme is a small step towards
increasing awareness amongst secondary school students of the nature of chemistry and new developments in Green Chemistry.

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8. For more information and links see: http://antenna.nl/wise/uranium/mdafbm.html


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30. For example

Chemistry Through the Looking Glass

Igor Novak

Department of Chemistry, National University of Singapore, Singapore, 117543, Singapore, chmigorn@nus.edu.sg

Abstract

This paper describes a nontraditional chemistry course (at under or postgraduate levels) whose aim is to broaden the educational background of chemistry graduates. The course discusses mechanisms by which science/chemistry functions and how it fits into the social environment. The acquired knowledge should help graduates in developing lateral and creative thinking, flexible working attitudes, communication and critical thinking skills, all of which are highly prized by employers.

Introduction

As this century unfolds, one can expect that unprecedented advances will take place in all the fields of modern science and technology, including chemistry. Ironically, however, the gap between the widespread use of scientific discoveries and the understanding of science’s capabilities and limitations, its operating principles and its social context grows ever wider. To put it in other words, the scientific literacy of a great majority of the population does not keep pace with scientific progress. This situation entails some risks for science because the essential public support may dwindle as the result of science being perceived as sinister, detached from human problems, secretive and thoroughly incomprehensible. As McClellan and Dorn (1999) have pointed out, science is a historical phenomenon; it came into being and may pass away. Improved scientific literacy can help to alleviate such stark expectations. It can also help students to overcome challenges and difficulties that they face when selecting chemistry as a career, including the reduction in the number of traditional chemistry jobs, the likelihood of employment outside chemistry, low social standing and unfavourable public perception of chemistry. The outreach of chemical education is described in Figure 1 in the broadest sense.

Figure 1: Outreach of chemical education

To produce a scientifically literate population

▼ Students becoming chemists (tiny minority)

▼ Students requiring scientific literacy (majority)

▼ Students requiring chemistry as an auxiliary subject (minority)

▲ Students becoming scientists (small minority)

Many issues discussed in the course are relevant for science in general and not just for chemistry. That is the course’s strength because it emphasizes the unity of the natural sciences and encourages interdisciplinary approaches to problem solving, and lateral thinking in general. What follows is a description of the course’s topics which are stated in response to questions.

To produce a scientifically literate population

▼ Students becoming chemists (tiny minority)

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▲ Students requiring chemistry as an auxiliary subject (minority)

▼ Students becoming scientists (small minority)
The origin of the word “chemistry” and misconceptions about chemistry

The origin of the word CHEMISTRY is shown in the scheme:

\[ \text{chemistry} \rightarrow \text{alchemy} \rightarrow \text{al-khimia (Arab.)} \]

The problem arises with the root “kim”. It is not of Arabic origin and several suggestions have been made for its possible source. Propositions for “kim” are as follows:

a) Khemia (χηµια) \(\rightarrow\) transliteration of the Egyptian word for black soil which sounds plausible because Egyptians were early alchemists

b) Khemeia (χηµεια) \(\rightarrow\) Khumeia (χυηεια) \(\rightarrow\) Khuma = “that which is poured”, ingot (bar) which again ties up with alchemical origins

c) Chinese character for gold “jin” \(\rightarrow\) Romanized as “kim” since gold was used in immortality elixirs

Proposition a) is today considered unlikely since it is mentioned in a single source only, while b) & c) are equally likely indicating the uncertainty about word origins (Butler & Reid, 1986). All this signifies the eminently empirical origins of chemistry. Chemistry for a long time remained devoid of a unifying rational framework and thus had to struggle to establish independent identity versus other sciences. Chemistry appeared in its modern form after mathematics or physics and there have been attempts to reduce chemistry to physics (Kutzelnigg, 2000).

These comments furnish a useful pedagogical starting point for the discussion of reductionism and theories of everything (TOE). TOE and reductionism are very interesting fundamental philosophical and methodological questions.

Philosophical and methodological aspects of chemistry

The primary aim of Chemistry is the accumulation of facts! (WRONG!)

A collection of facts does not constitute scientific knowledge as students need reminding when preparing for their exams!

Chemistry deals with artificial substances (chemicals) which are harmful and cause pollution (WRONG!)

Chemicals are not only produced by humans, but also in nature. Chemistry studies all substances regardless of their origin.

Chemical knowledge is Truth! (WRONG!)

Science/chemistry does not search for ultimate explanations; every scientific law is subject to modification; there are no absolute truths in science.

Such misconceptions are related to TOE, reductionism!? Chemistry is (or should be?) concerned primarily with solving practical problems! (WRONG!)

Chemistry also seeks understanding; technological advancement does not necessarily lead to a better understanding of nature.

Popular misconceptions about Chemistry

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Such misconceptions are related to TOE, reductionism!? Chemistry is (or should be?) concerned primarily with solving practical problems! (WRONG!)

Chemistry also seeks understanding; technological advancement does not necessarily lead to a better understanding of nature.
anachronistic thinking
the use of theories discarded long ago as inadequate

seeking of mysteries
deliberate search for anomalies in nature in the mistaken belief that the new theory which explains the anomaly can be accepted (UFO, Yeti, Bermuda Triangle)

appeal to myths
use the ancient myths and devise a hypothesis which explains it (assuming the myth to be true). Example: Velikovsky based his “Worlds in Collision” on ancient manuscripts, legends and traditions. He “explained” parting of the Red Sea, manna from Heaven, Egyptian plague etc.

casual approach to evidence
use of large amount of data irrespective of the quality of the process utilized when data were collected; refusal to weed out unsatisfactory data. In science it does not only matter what we know, but also how and why. The importance is not only in the theory itself, but also in the arguments which support it.

irrefutable hypothesis
proposal of a hypothesis which is impossible to falsify

spurious similarities
use of artificial similarities with established scientific results

explanation by scenario
explanation by scenario without regard for the known laws or principles. E.g., Velikovsky postulated that Venus’s near collision with Earth caused Earth to flip and reverse its magnetic poles. He gave no mechanism or described the process through which it could have occurred.

research by literary interpretation
use of literary analysis of scientific statements instead of focusing on facts and reasons behind scientific statements

refusal to revise
cranks & crackpots never admit to be wrong, they use rhetorical arguments and never revise their position in view of the criticism. The pseudo-scientists put the burden of proof on the scientific community and claim that if scientists can not disprove the theory, then their theory is justified. [Logical flaw: Not being able to prove the theory wrong does not make it right!]

What are the characteristics of Science vs. Religion or other alternative forms of knowledge? How do scientific theories develop and evolve (“dynamics of theories “) ? on What are the ethical principles related to Science?

The practice of science/chemistry is guided by several principles/ideals:

• originality: scientific studies should produce new results, studies which add nothing new are not part of science
• detachment: scientist should work for the advancement of knowledge without personal attachment to the particular point of view
• global and collaborative nature: scientific claims are given weight according to their intrinsic merits alone, regardless of religious, social, ethnic or personal attitudes of people who made them.
• scepticism: all scientific claims are scrutinized for invalid arguments and these should be made public
• public accessibility: scientific knowledge should be made publicly available and this free flow of ideas is essential for progress of science. (Does classified research constitute science?)

Sociological aspects of chemistry

The discussion is focused around the following specific questions:
What motivates chemists in their work and what is the role of scientific community?

Personal motives include:
• scientific curiosity
• pleasure in doing research
• desire for scientific reputation
• desire for influence within the scientific profession

External motives:
• attraction of public fame
• desire to find practical applications of scientific knowledge
• need to secure funding or make profit from research
• desire to influence public policy

This discussion of motives is very important because it shields young graduates from the false notion of Science/Chemistry as the “pure, ivory tower” where common good is the only object.
How (and why) is chemistry perceived by the general public?

Baconian and Frankensteinian visions of Science as well as “chemophobia” are discussed (Kauffman 1991; Stevenson & Byerly 1995).

Baconian vision (after philosopher Francis Bacon) states that the progress of mankind can be only achieved through the development and application of science and technology in the exploitation of natural resources. Knowledge is power! The improvement in physical environment will inevitably lead to better social environment and to the more humane society. Most scientists and governments subscribe to this belief, which originated during the Age of Enlightenment in Western Europe. This vision is an important point to consider when analysing and comparing developments of science in the west and elsewhere.

Frankensteinian vision (after the novel by Mary Shelley) expresses the concern at unrestrained development of Science and Technology (“Man playing God”) and points to the role of Science and Technology in development of weapons of mass destruction and environmental degradation. Many people in the Green and anti-globalization movements subscribe to this view of science. The view/dilemma was put forward even in ancient times (expulsion from the Biblical Garden of Eden; Greek myth of Prometheus and Pandora).

What is the relationship between science & human values?

The false notion which many scientists and members of general public have is that science discovers facts and it is “up to the society” to decide how the discoveries shall be made use of. Modern societies are very complex and the executive authority rests in the hands of various social institutions (governments, courts, business corporations, banks, universities, churches, political parties) which act as a buffer between citizens at large and the applications/directions of science. These institutions wield great economic resources, but can sometimes pursue their own, narrow interests and thus adversely influence the functioning of science (see case studies in next section). Modern experimental science requires large funds (professionalization and industrialization of science) which can only be obtained through such institutions. Furthermore, the motives that scientists have are diverse (see above) which makes them susceptible to influence from such organizations. As a result, the influence of the general public or even scientists themselves on scientific and technological developments may often be less direct than is commonly thought!

What are the cost/benefits of chemistry to society at large and who should assess them?

The immense importance of chemistry for the modern society is illustrated with a broad spectrum of interesting statistical data related to various fields of chemistry (Quadbeck-Seeger, 1999). The students are encouraged to develop an attitude of critical realism, which accepts that benefits originating from science may entail various costs and unforeseen circumstances (e.g., ecological degradation, social dislocation). The point is to assess cost/benefits in an open, democratic way so that there are no uncontrolled technological developments.

Historical aspects of chemistry

The most important questions are:

What social and economic conditions gave rise to Science and why did modern science/chemistry originate in Western Europe in the 16th century? (temporal and spatial aspect)

The analysis of the development of science is based on the causal chain:

Physical/geographical environment –> social structure –> nature of science –> scientific discoveries

This type of explanation (Diamond, 1998) differs from the conventional cultural explanations usually proffered in textbooks and reflected in public perceptions.

In the course of discussion, a survey of the history of chemistry is presented with the distinct aim of demonstrating how the social environment influenced the development of science by raising questions and suggesting interpretations. Chemistry is compared with the development of other natural sciences throughout and the direct comparisons are made with scientific achievements in other civilizations, eg., China (Brock, 1992).

What are the examples of scientific revolutions in Chemistry?

What is the “scientific revolution”

• Radical reinterpretation of the existing thought
• The resolution of a long-standing debate, the solution of which revolutionizes the kinds of problems scientists can successfully tackle on a routine basis
• The opening of a new level of theoretical understanding that subsumes older theories as special cases (Jensen, 1998)
1st chemical revolution: molar composition (1770-1790)
The introduction of the concept of chemical composition at molar level

2nd chemical revolution: molecular composition/structure (1855-1875)
The introduction of self-consistent atomic and molecular weights, concepts of valence (definite combining power) and molecular structure (arrangements of atoms)

3rd chemical revolution: electrical composition/structure (1904-1924)
This revolution was external (unlike the other two) with significant contributions from physicists as well as chemists. It started the perception that chemical properties are related to electronic properties and forces.

Case studies in the history of chemistry

Case A (Combustion theories)
Phlogiston theory: substance → residue + phlogiston
Oxygen theory: substance + oxygen → oxide
Combustion theories provide an excellent example which explains how a scientific theory may be wrong (eg., phlogiston theory) and still be scientific, because it contains all the essential characteristics of the scientific method (see methodological aspects of Science above).

Combustion theories provide an opportunity to discuss how scientific theories rise, develop and are displaced (“dynamics of theories”). The discussion may be based on the concept of paradigm shift introduced by Thomas Kuhn.

Normal science:
Pneumatic chemistry operating within the phlogiston paradigm

▲
Anomalies:
Iron gains weight on rusting?? Challenge to the ruling paradigm

▲
Paradigm shift:
Combustion is not about losing substance, but about adding substance to the substrate being combusted. Replacement of one paradigm with another

However, students are also encouraged to reflect on the modern concept of oxidation as the “loss” of electron (Brown, 1999; Brown & Dronsfield, 1991). Finally, the “explanatory coherence” is mentioned as the prime reason for the rise and fall of scientific theories.

Case B (Periodic system of elements)
The role of the periodic system as the “grand unified theory” of chemistry can be compared with the similarly far-reaching theory of evolution in biology or Newton’s laws in physics. The study of periodicity provides an excellent illustration of how the best scientific theory must have predictive and not only explanatory ability. Mendeleev is not considered as the “father” of the periodic table because of the primacy of his idea, but rather because he used the periodic system to predict the existence of unknown elements. It also illustrates the nearly simultaneous appearance of very fundamental ideas in different countries and scientific environments (the question of the priority of discovery and international nature of science). The periodic system could only have been developed on the basis of previous theories and discoveries: Dalton’s atomic theory, the concepts of atomic mass/mole, law of constant composition. This demonstrates that Chemistry is a communal effort and can only progress within the scientific community. Like every important theory, the periodic system helped to foster new developments in science: discovery of new chemical elements and support for the quantum theory. The reductionist question of whether the periodic system can be derived from quantum mechanics is a hotly debated issue and useful for students to explore in order to develop their lateral thinking ability.

Case C (Life and work of Fritz Haber)
The life and work of Haber (Heilbronner, 1995) is an excellent illustration of several important points of which young chemists should be aware.

Haber worked successfully on research projects within various branches of chemistry (organic, physical, electrochemistry) – a useful reminder of the interdisciplinary nature of chemical problems.

He worked in academic and industrial environments and won a 1918 Nobel prize for applied chemistry project: the synthesis of ammonia from the elements. His work on the project was driven by economic and military considerations (Germany required a free source of nitrates that cannot be affected by naval blockade in case of war) and not only by purely scientific interests. This is an example of the strong influence of society on chemistry. For comparison,
the 2000 Nobel prizes for chemistry also were awarded for predominantly applied research in polymer chemistry. This should encourage young chemists to consider various career paths and research subjects not necessarily related to their area of expertise, i.e., to display a flexible working attitude. Haber was “father” and director of the first chemical weapons programme in history (during WWI) and even had a military rank of captain. This is an important illustration of various ethical problems pertaining to science/chemistry, some which are illustrated below:

Can science, performed under the conditions of military or commercial secrecy be considered as true science?

Most research results can have civilian or military uses and scientists may have little control over the fruits of their research. Synthesis of ammonia was (and is) used for the manufacture of both fertilizers and explosives.

Should the primary responsibility of a scientist be directed towards universal human and scientific values or towards the needs of his own country or employer?

What influence can politics of a particular society/country have on the development of science?

An exodus of top German scientists to USA in 1930s was a major factor in the present dominance of USA in many fields of science. Natural Sciences not only employ similar scientific/logical methods for research, but also share problems concerning social institutions and values. As an illustration, one can discuss and compare ethical problems experienced by Haber with chemical weapons vs. those of nuclear physicists working on the Manhattan project.

Author’s Comment

I am aware of one of the referee’s concerns about the omission of key persons in the history of chemistry. However, this is not a course on the history/philosophy of science. Rather, this is also the reason why I have used historical references in journal articles and not from standard histories of chemistry such as Brock and Hudson that the referee has mentioned. Such articles are more concise and accessible to these students than long textbooks. An additional useful reference since submitting this paper is by Ware (2001).

References


Contents

* APCELL: The Australian Physical Chemistry Enhanced Laboratory Learning Project 6
  Simon C. Barrie, Mark A. Buntine, Ian M. Jamie and Scott H. Kable

* The Determination of the Dissociation Constant of a Weak Acid by Titration 13
  Barry O'Grady

* Effectiveness of Flow Diagrams as a Strategy for Learning in Laboratories 18
  Bette Davidowitz and Marissa Rollnick

* Capturing the Imagination with Green Chemistry and Explosions, Froth, Color, Phase Changes and Lollies. 25
  Michael Clarke, Nicholas Barlow, Antonio Patti and Janet L. Scott

* Chemistry Through the Looking Glass 32
  Igor Novak

* Refereed papers