Guide for contributors to the Australian Journal of Education in Chemistry

Introduction

The Australian Journal of Education in Chemistry publishes refereed articles contributing to education in Chemistry. Suitable topics for publication in the Journal will include aspects of chemistry content, technology in teaching chemistry, innovations in teaching and learning chemistry, research in chemistry education, laboratory experiments, chemistry in everyday life, news and other relevant submissions.

Manuscripts are peer reviewed anonymously by at least two reviewers in addition to the Editors. These notes are a brief guide to contributors. Contributors should also refer to recent issues of the Journal and follow the presentation therein.

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Articles should not exceed six pages in the printed form including tables illustrations and references - ca. 5000 words for a text only document. Short, concisely written articles are very welcome. Please use headings and subheadings to give your article structure.

1. We prefer to handle all submissions electronically. Our preference is for Microsoft Word files in Mac format. However, you can send files from any common Windows, DOS or Macintosh word processor.

2. On another separate page provide an abstract of 50 to 100 words;

3. All photographs should be scanned and saved in JPEG format.

4. All chemistry structures, and schemes should follow the guidelines set for ACS publications. It is preferred that Schemes, Tables; etc. be arranged to fit in a column 7 cm wide, although full page width will be accepted.

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Editors

Robert Bucat,
Chemistry,
School of Biomedical and Chemical Sciences,
University of Western Australia,
35 Stirling Highway, Crawley WA 6009, Australia.
bucat@chem.uwa.edu.au
Phone: (+61)(8) 9380 3158 • Fax: (+61)(8) 9380 3432

Mauro Mocerino
Department of Chemistry,
Curtin University of Technology,
GPO Box U1987, Perth WA 6845, Australia.
m.mocerino@curtin.edu.au
Phone: (+61)(8) 9266 3125 • Fax: (+61)(8) 9266 2300

Leslie Glasser
Department of Chemistry,
Curtin University of Technology,
GPO Box U1987, Perth WA 6845, Australia.
L.Glasser@curtin.edu.au
Phone: (+61)(8) 9266 3126 • Fax: (+61)(8) 9266 2300

David Treagust
Science and Mathematics Education Centre,
Curtin University of Technology,
GPO Box U1987, Perth WA 6845, Australia.
D.Treagust@smec.curtin.edu.au
Phone: (+61)(8) 9266 7924 • Fax: (+61)(8) 9266 2503

All manuscripts should be sent to Mauro Mocerino

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In this issue ……….

In a paper that illustrates that chemistry is a human activity, Lagi and Chase, outline how knowledge about the technique of distillation can be presented to students in a way that integrates its historical evolution with the thermodynamics of the technique. They indicate how this can be applied to simple, fractional, steam and vacuum distillation, performed in either continuous or batch modes. They throw down the challenge of devising similar approaches to other content areas.

Kieran Lim recognizes the challenge of helping students develop their skills of writing laboratory and other scientific reports – a curriculum responsibility which is not explicitly carried out in many university chemistry courses. Recognizing the importance of practice and feedback, Lim describes a system in which students can submit draft reports and, after feedback, can ‘do it again thoughtfully’ before submission. Student evaluations are reported.

Details of the ‘science as inquiry’ curriculum of Singapore at the primary and lower secondary level (general science) and upper secondary level (chemistry) are described by Tan – particularly for content related to matter. The sequencing of the learning outcomes is based on a spiral approach that tries to take into account readiness for learning at the macroscopic and particulate levels. Tan critiques the tension in any sequence decisions between satisfying a logical order and a psychological order.

With a nice link to the previous paper by Tan, de Berg reviews the meaning implied by ‘science as inquiry’. He refers to the evidence that many school teachers have not experienced inquiry-based learning in their own undergraduate education, and the challenges that this presents. He goes on to describe the transformation of a ‘recipe’ preparation of tin (IV) oxide to an inquiry-based experience.

In another coincidence – with the paper by Lagi and Chase – he melts the historical evolution of chemistry knowledge into this exercise.

Cakmakci describes an empirical study in domain-centred research, which shifts the balance of research from generalised knowledge about pedagogy to pedagogical content knowledge about a specific content area – in this case, chemical kinetics. Surely we need more of this form of ‘applied research’ about teaching and learning in particular fields. Cakmakci identifies inadequate conceptions that inhibit the development of desirable understanding, and discusses some of these in relation to imprecise, inaccurate and insufficient material commonly presented in textbooks. He draws implications for teaching from his analysis.

Construction of an inexpensive mini-colorimeter is described in some detail by Kennepohl and Connors. They describe, with presentation of quantitative data, how the colorimeter can be used to illustrate Beer’s Law, and how it can be used to analyse the kinetics of reactions involving coloured reactants or products. Some evaluative evidence is given.

In an attempt to acquaint students with economical and bio-friendly methods of degradation of dye contaminants in waste waters, Rauf and Ashraf describe an experiment that compares the efficiency of degradation of Neutral Red dye by photolysis and by Fenton’s reagent. The experiment is integrated with aspects of UV-Vis spectroscopy and theory of chemical kinetics – giving us, in turn, a useful integration with other papers in this issue.

By asking students to (inappropriately) perform calculations, at various levels of sophistication, of the solubility product of moderately soluble sodium chloride, Novak shows how ideas related to chemical equilibrium, thermodynamics of ion solvation, and ideal and non-ideal solutions can be developed.

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<tr>
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<th>Email</th>
</tr>
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<tbody>
<tr>
<td>Siegbert Schmid</td>
<td>Chair</td>
<td><a href="mailto:s.schmid@chem.usyd.edu.au">s.schmid@chem.usyd.edu.au</a></td>
</tr>
<tr>
<td>Ian Mc Mahon</td>
<td>Secretary &amp; SA Chem Ed Group Chair</td>
<td><a href="mailto:ian.mcmahon@thebartonsc.sa.edu.au">ian.mcmahon@thebartonsc.sa.edu.au</a></td>
</tr>
<tr>
<td>Dan Bedgood</td>
<td>Deputy Chair</td>
<td><a href="mailto:dbedgood@csu.edu.au">dbedgood@csu.edu.au</a></td>
</tr>
<tr>
<td>Maree Baddock</td>
<td>Treasurer</td>
<td><a href="mailto:baddockm@bigpond.net.au">baddockm@bigpond.net.au</a></td>
</tr>
<tr>
<td>Kieran Lim</td>
<td>Immediate Past Chair</td>
<td><a href="mailto:lim@deakin.edu.au">lim@deakin.edu.au</a></td>
</tr>
<tr>
<td>Mark Ellison</td>
<td>ACT Representative</td>
<td><a href="mailto:mark.ellison@anu.edu.au">mark.ellison@anu.edu.au</a></td>
</tr>
<tr>
<td>Alasdair Hey</td>
<td>NSW Chemical Education Group Chair</td>
<td><a href="mailto:ahey@ozonline.com.au">ahey@ozonline.com.au</a></td>
</tr>
<tr>
<td>Todd Houston</td>
<td>Qld Chemical Education Group Chair</td>
<td><a href="mailto:t.houston@griffith.edu.au">t.houston@griffith.edu.au</a></td>
</tr>
<tr>
<td>Brian Yates</td>
<td>Tas Representative</td>
<td><a href="mailto:brian.yates@utas.edu.au">brian.yates@utas.edu.au</a></td>
</tr>
<tr>
<td>Vinuthaa Murthy</td>
<td>NT Representative</td>
<td><a href="mailto:vinuthaa.murthy@cdu.edu.au">vinuthaa.murthy@cdu.edu.au</a></td>
</tr>
<tr>
<td>Judy Gordon</td>
<td>Vic Chemical Education Group Chair,</td>
<td><a href="mailto:judy.gordon@deakin.edu.au">judy.gordon@deakin.edu.au</a></td>
</tr>
<tr>
<td>Mauro Mocerino</td>
<td>WA Chemical Education Group Chair,</td>
<td><a href="mailto:m.mocerino@curtin.edu.au">m.mocerino@curtin.edu.au</a></td>
</tr>
</tbody>
</table>
Editorial

Learning chemistry by reading popular science books

One of my interests, when I can find the time, is to read popular science books, some being biographical books of scientists, some written as historical novels. These books provide me with an enhanced understanding of how science and scientific ideas have developed and the part played by leading, and sometimes forgotten, scientists.

From this personal interest, I have developed a course - Contemporary Issues in Science - for students in our Master of Science (Science Education) degree that can be taken as an optional unit. This unit involves readings built around the books I read or on my ‘to read’ list or suggested by the students; the unit can be taken for individual study or in a group/class setting. For assessment, students are asked to read and review three popular science books and critically review each book’s content and explore ways in which some of the ideas can be used to augment their day-to-day teaching.

It is through this readings course that I learned of the work of Oliver Sacks, initially reading *The man who mistook his wife for a hat* (1985, Picador. London). In this book, Sacks presents his narratives as case studies in order to humanise the often too clinical approach to neurological affliction. While he is successful in achieving this goal through his discussion of these cases, at times, he retains language that is too technical for the layperson, his intended audience. Sacks predominant purpose in writing this book was to bring out the personalities behind his patients. In the realm of neuropsychology, patients are generally defined by their physical and psychological state, their list of symptoms used to identify them. Overall the book is very interesting and certainly presents stories far from people’s everyday experiences.

This engaging style of writing led me to other books written by Oliver Sacks, most notably *Uncle Tungsten* (2001, Picador. London). The book has a subtitle *Memories of a chemical boyhood*. If you have not read this book, I encourage you to do so. I quote from the back sleeve:

“In this wonderful memoir, Sacks evokes, with warmth and wit, his childhood in wartime England. He tells of the large, scientifically minded family who fostered his early fascination with metals. Then there were his four years at a boarding school where, though unhappy, he developed the intellectual curiosity that would shape his life. We hear of his return to London, an emotionally bereft ten-year-old who found solace in the secret garden of his passion for learning about nature of metals, gases and chemicals, about the hidden order of things outside himself”.

Yes, it is truly an engaging book and one learns a lot of interesting chemistry in the process of learning about a boy and his childhood. This is the kind of book I encourage students to read, write a critique and then offer suggestions for how to use aspects of the book in their lessons.

Sometimes the outcomes from the students are surprising. Perhaps none more surprising than primary school teachers reading and critiquing *Chemistry in the market place* by Ben Selinger (1988, Harcourt Brace & Co, Marrickville, NSW). This book, as do many others, provides easy access to chemistry for non-chemists. Many primary school teachers marvel at the usefulness of chosen chapters in the book to develop their science lessons for primary students – and this interest from primary school teachers in a chemistry book of more than 600 pages!

David Treagust
Distillation: integration of a historical perspective

Marco Lagi and Rebecca S. Chase

1 Dept. Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA 02139 E-mail: marcol@mit.edu
2 Lesley University, Cambridge, Massachusetts, USA 02138

Abstract
We present here a possible introductory lecture of the distillation technique, different from what is commonly seen in classrooms. A rigorous thermodynamical approach to distillation could be put side by side with a historical one, where the student can see the unfolding of the primal worldview into the modern perspective. We believe that this method, where the old is redeemed to complement the new, can provide a deeper understanding of, and more interest in, this fundamental separation process.

Introduction:
Distillation is the first separation technique ever developed and still one of the most popular in a wide variety of contexts, from state-of-the-art organic chemistry labs to processing plants, from farms to abbeys. It was estimated in 1994 that 4·10^4 distillation columns were scattered throughout the USA, consuming about 7% of the entire energy demand of the country [1]. Although distillation has a low thermodynamic efficiency (around 10%), it is widely used because of the simplicity of its principle: when a liquid mixture is heated, its vapor has usually a different composition from the liquid that remains. Mankind has long made use of this knowledge - moralists would say often for its own damage.

Every undergraduate student in chemistry or chemical engineering knows the definition of distillation: a method of separation based on relative vapor pressures. They learn the distillation theory through the Clausius-Clapeyron equation, the Raoult's law and the Trouton's rule. They are taught how to determine the number of plates required to separate a 1:1 mixture of n-hexane and n-heptane, and how to set up a vacuum distillation apparatus.

But only a very few of them are also given a historical perspective of this method. The lack of this perspective is characteristic of the majority of chemistry classes, in contrast to other scientific subjects where more time is devoted to the evolution of the discussed topic. The reason can probably be found in the roots of this ancient technique, developed and brought to perfection over hundreds of years by the ancestors of the chemists, alchemists. The modern conception of this proto-science is often negative, and chemistry teachers prefer not to include references to it in their courses. But alchemy is actually the first approach to the study of matter undertaken by man, the primal genuine attempt to look at the chemical and physical transformations occurring in Nature. Students are usually interested in the naïve alchemic approach since, like the early alchemists, they are dazed by the novelty of the physical and chemical transformations of substances.

It is easy to find exhaustive monographs about the history of distillation [2,3], and about the distillation theory as well [4,5]. But in this paper, we shall try to sketch a short introductory lesson that both provides the basis of distillation and follows its evolution. We believe, as previously noted [6], that such an approach is more interesting to students and that it can provide them with a deeper understanding of 1) how the first chemists looked at matter, and 2) the distillation technique itself. The lesson has four sections: A) Principle, B) Theory, C) Practice and D) Application of distillation.

A The Principle of Distillation
Vapor pressure (also known as vapor tension), is the pressure of a vapor in equilibrium with its liquid. All liquids have a tendency to evaporate (volatility), and all gases have a tendency to condense back into their liquid form. For a liquid i at any given temperature T, there is a pressure P_i at which the gas of that substance is in dynamic equilibrium with its liquid.

Figure 1. Conceptual evolution of the distillation technique.

a) Aristotelian (simple boiler).
b) Alexandrian (boiler + alembic).
c) Medieval (boiler + alembic + condenser).
d) Modern (boiler + alembic + condenser + column).
This equilibrium can be represented as [7]

\[
\text{Molecules}_{\text{liquid}} \rightleftharpoons \text{Molecules}_{\text{vapor}}
\]

As \( T \) increases, the equilibrium is shifted to the right and the vapor pressure \( P_i \) increases exponentially. The dependence of \( P_i \) from \( T \) is given by the Clausius-Clapeyron equation,

\[
P_i = P_i^0 \exp \left( \frac{-\Delta H}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right)
\]

where \( P_i^0 \) is a known pressure at a known temperature \( T_0 \), \( \Delta H \) is the heat (enthalpy) of vaporization of the liquid and \( R \) is the gas constant.

The boiling point \( T_i \) is defined as the temperature when \( P_i = P_{\text{sat}} \). Usually, \( P_i^0 \) and \( T_i \) are taken from the normal boiling point, so that \( P_i^0 = 1 \text{ atm} \) and \( T_i = T \). \( P_i \) is therefore an indication of a liquid’s evaporation tendency: a substance with a high vapor pressure at room temperature is often referred to as volatile.

The goal of a distillation is to separate a volatile liquid from a non-volatile substance or, more frequently, the separation of two or more liquids with different vapor tensions [8]. For the sake of simplicity, throughout the paper we will refer to the distillation as the separation by means of heat of a mixture of two liquids \( A \) and \( B \), where \( B \) is more volatile than \( A \) (i.e. \( P_B > P_A \)).

Two requirements for distillation can be derived from the previous definition: 1) the process needs a heat source to force the liquid mixture into the gas phase, 2) the gas phase (enriched in \( B \)) has to be condensed back to the liquid phase in order to obtain a separation of the two components.

The first requirement (evaporation) was already known by ancient Greeks. Aristotle mentions in his Meteorologica that pure water may be obtained from seawater through evaporation. However, he does not write of any practical method to condense the vapor and take advantage of this phenomenon. Nowadays we call this process open evaporation of the mixture [9] (Fig. 1a).

The second requirement (condensation) was fulfilled around the 1 st century A.D. by the Alexandrian chemists, who added to the boiler (main vessel) an alembic (secondary vessel) connected by a side tube (see Fig. 1b).

The effect was the trickling down (destillatio in Latin) of the purified liquid in the alembic. Distillation was officially born.

When the gas in equilibrium with the liquid mixture reaches the vapor pressure, further evaporation is precluded. This limitation was overcome by the introduction of a water jacket surrounding the side tube. This device condenses the \( B \)-rich gas phase, subtracting it from equilibrium and increasing the efficiency of the process (Fig. 1c). The condenser, introduced by medieval alchemists around the 13 th century, was necessary to obtain reasonable yields of products containing high alcohol contents. This is a great advantage of distillation over the other separation methods: the only required energy is in the form of heat, which can be easily removed with the condenser. The separation process can be controlled solely by the heat supply.

Although chemical engineers have made distillation more efficient during the last century, the essence of the still apparatus has survived mostly unchanged.

In this section we learned that, in principle, a liquid mixture can be separated into its components. What to do to accomplish this is the subject of the next section.

**B The Theory of Distillation**

Alchemists had a very clear idea of what distillation was: “distilling is nothing other than purifying the gross from the subtle” [10]. The purification would make incorruptible the corruptible [11]. As with all alchemic processes, a correspondence to the inner self can be drawn; today we still use the verb to distill to mean “to extract the essential meaning of something”. Distillation was subdivided into ascension (evaporation) and descension (condensation). These processes were powerfully symbolized by a bird flying upwards or downwards (Fig 2, left panel), or by two dragons, one winged, seizing each other’s tails (Fig. 2, right panel).

Therefore, distillation was an art at its very beginning, with deep correspondence to man’s unconscious: fire somehow could remove unnecessary and leave essence.

But around two centuries ago, a radical shift took place in how man looked at matter. The works of Boyle and Lavoisier were shaping the birth of a new science, chemistry. In the following years, a parallel revolution occurred in the development of distillation, when quantitative rationalizations of the process in mathematical models improved dramatically the efficiency of this separation technique [12,13]. Boyle himself is considered to be the first to have performed analytical distillation [14].

We can trace the origins of the theory of distillation back to the question François-Marie Raoult was trying to answer at the end of the 19 th century [15]: what happens to the vapor pressures of \( A \) and \( B \) when they are mixed?
Raoult realized that for an ideal solution at a given temperature,

\[ P_M = P_A x_A + P_B x_B \]  

(2)

where \( P_i \) is the vapor pressure of the mixture and \( x_i \) the molar fraction of the component \( i \) (\( x_A + x_B = 1 \)). Again, the mixture boils at the temperature \( T_M \) when \( P_M = P_{ext} \).

Raoult's law implies that the total pressure decreases linearly from \( P_A \) to \( P_B \) as the concentration of \( B \) in \( A \) decreases (Fig. 2). This is intuitive: the more \( B \) in the mixture, the more the mixture will behave like pure \( B \).

One of the non-trivial consequences of this law is that even if \( P_A = 0 \), the total pressure is smaller than the vapor pressure of pure \( B \) (\( P_M < P_B \)), as one can see comparing Fig. 4a with Fig. 4c. If we define the relative volatility \( \alpha \) of the solution as

\[ \alpha = \frac{P_B}{P_A} \]  

(3)

and the molar fraction of \( B \) in the vapor phase \( Y_B \) as

\[ Y_B = x_B P_B \]  

(4)

then, combining Eq. 2, 3 and 4 we have

\[ \frac{Y_B}{P_M - Y_B} = \alpha \frac{x_B}{1 - x_B} \]  

(5)

Now we can plot \( Y_B \) vs \( x_B \) for different values of \( \alpha \) (Fig. 5 upper panel). As one can see, when we heat a liquid mixture 1) the gas phase is enriched in the most volatile component, 2) the enrichment increases with \( \alpha \). These conclusions may seem obvious at first sight, but they actually imply that Raoult’s law was the first theoretical justification of distillation since its birth, 2000 years before.

We notice here that even though distillation had been practiced for centuries before its theoretical formulation, only after this step could the performances of the experimental apparatus have been dramatically improved. Indeed, looking at Fig. 5 it is clear that there is no hope to separate \( A \) and \( B \) with a distillation if they have the same volatility (\( \alpha = 1 \)), because the gas phase has the same composition as the liquid phase (azeotrope). But if \( \alpha \) is larger than 1, and we condense the B-rich gas phase, we obtain a new mixture of \( A \) and \( B \) with a higher concentration of \( B \). Therefore, the larger \( \alpha \) is the easier the separation.

What if we want to distill a mixture with \( \alpha \sim 1 \)? Sometimes revolutions are born from relatively small issues. In 1807, when England organized a blockade against Europe, Napoleon was forced to open a competition to produce white sugar from beets, since his noblemen were not particularly fond of brown sugar! Extracting sugar with alcohol instead of water looked promising, but the solvent had to be purified afterwards [4]. The Frenchman Cellier-Blumenthal had an idea: continuously repeat the procedure after the first evaporation-condensation cycle to further increase \( x_B \) in the mixture. The alchemist Libavius, who had lived 200 years before Cellier-Blumenthal, had known that the alcohol content could be increased with a second distillation step [16], but he didn’t extrapolate the concept to \( n \) distillation steps. Thanks to this improvement, nowadays large-scale industrial distillations can be undertaken even if \( \alpha \sim 1.05 \) [9]. In conclusion, the effect of the noblemen’s pickiness was the development of the first distillation column (Fig 1d).
When the distillation is such a multi-stage process, it is called fractional distillation or rectification (from the Latin expression “recte facere” = improve). Each of these repetitions in a rectification process is called a theoretical plate (equilibrium stage between gas and liquid), and a path composed of several plates is shown in Fig. 6 as an example.

The larger $\alpha$ is, the smaller the number of plates $n$ necessary to achieve the desired concentration of B.

After a little algebra, one can demonstrate that the two quantities at $P_M = P_{atm} = 1$ are in fact inversely related according to

$$n = \frac{1}{\log \alpha} \frac{x_f^B (1-x_f^A)}{x_i^B (1-x_i^A)}$$  \hspace{1cm} (6)

where $x_i^B$ and $x_f^B$ are the initial and final concentrations of B, respectively. If $n \notin N$, it should be rounded to the next higher integer.

In this section we learned what to do to separate an ideal bicomponent liquid mixture. How to do it is the subject of the next section.

C The Practice of Distillation

As we saw schematically in Section A, the still apparatus for a simple distillation is composed of a heat source, a boiler, a condenser and a receiving flask (the alchemic alembic). The thermodynamic conditions are chosen so that the constituent to be separated (B in our case) enters the second phase in the receiving flask. The rule of thumb is to use this method when the boiling temperatures of A and B differ by at least 60 K ($T_A > T_B + 60$ K). An important addition to the alchemic setup is therefore a thermometer, to check the temperature of the boiling mixture: $T$ will stay constant while the mixture is boiling at $T_M$ and B evaporates, then it will rise towards $T_B$. At this point, the distillation can be considered over.

One could ask a similar question to the one seen in Section B: what happens to the boiling points of A and B when they are mixed? To answer this, we can consider that the mole fraction of liquid A is given by rearranging Raoult’s law (Eq. 2),

$$x_B = \frac{P_M - P_A}{P_B - P_A}$$  \hspace{1cm} (7)

Substituting the Clausius-Clapeyron equation (Eq. 1) in Eq. 7 for both A and B at their normal boiling point, we get

$$x_B = \frac{P_M - \exp\left(-\frac{\Delta H_A}{R} \frac{1}{T - T_A}\right)}{P_B - \exp\left(-\frac{\Delta H_B}{R} \frac{1}{T - T_B}\right)}$$  \hspace{1cm} (8)

This equation is valid in general for every temperature, and in particular for the boiling point of the mixture. We can get a similar equation for the mole fraction of vapor B, $Y_B$, substituting Eq. 8 in Eq. 4.

When the mixture boils, $P_M = 1$ atm and the only variables in Eq. 8 and 9 are the boiling temperature and the fraction of B. Therefore while Eq. 8 is the bottom line of the temperature-mole fraction diagram in Fig. 6, Eq. 9 is the upper line.

$$Y_B = \frac{P_M - \exp\left(-\frac{\Delta H_A}{R} \frac{1}{T - T_A}\right)}{\exp\left(-\frac{\Delta H_B}{R} \frac{1}{T - T_B}\right) - \exp\left(-\frac{\Delta H_A}{R} \frac{1}{T - T_A}\right)}$$  \hspace{1cm} (9)

Figure 6. Temperature-molar fraction diagram. The cycle 1-2-3-4 represents one distillation (theoretical plate). The horizontal dashed arrows are sometimes called liquid-vapor tie-lines.

One distillation cycle is represented by the path 1-2-3-4 in Fig. 6. Starting from a mixture of B = 20% and A = 80% at room temperature (1), if we heat the mixture it will reach its boiling point $T_M (2)$ with the same composition. Its vapor has composition (3), and when we lower the temperature it condenses reaching (4). As expected, the new liquid in (4) is richer in the lower-boiling component B. This is the result of a simple distillation, $n = 1$.

As we learned in Section B though, the required $n$ is usually bigger than 1. So at least one more thing is necessary for a high-efficiency distillation: an appropriate column, that includes as many theoretical plates as are necessary for the separation. To be more specific, the column must realize $n - 1$ plates, since the last plate is the head of the apparatus. The whole setup is shown in Fig. 7.

When the vapor travels up the column, it cools, condenses into liquid, and then it vaporizes again after it comes into contact with hotter vapor rising from below. We want to stress here that there are two reasons why they are called theoretical plates: 1) in practice one needs more plates than the calculated $n$, since the efficiency of each plate is less than 1 [17]; 2) distillations can be carried out on bubble-plate columns, composed of several horizontal glass plates. A discrete distillation occurs at each plate, but the concept can be extended to columns without physical plates. A plate is in fact realized by any physical device that provides good contact between the vapor and the liquid phases: the simplest column that one can think of is therefore just a glass tube. Each plate will occur at the interface between vapor and the liquid droplets that condense on the column. This is the open tube column, and it is displayed in Fig. 8a.
Henri Vigreux, a French chef and glassblower, realized around 1920 that the separation can be enhanced by increasing the surface area of the glass of the column [18]. A Vigreux column has, therefore, a series of downward pointing indentations (Fig. 8b): in this way, the number of plates can be increased roughly up to a factor 5. The next step to increase the surface area was taken by Clement by adding a filler (glass balls) to the column of an alcohol still: a packed column is therefore packed with small inert objects (Fig. 8c). Now n can be up to 20 times larger than an open tube column of the same length. When a column is added to the apparatus, simple distillation becomes fractional distillation. If the fractionating column is ideally efficient, the vapor that reaches the distilling head at the top of the column will be composed entirely of B: Vigreux columns can be used if $T_A > T_B + 25 \text{ K}$, packed columns even if $T_A > T_B + 1 \text{ K}$.

The heating bath allows for the uniform distribution of heat to the liquid: usually oil or water is used, implying that the boiling point of the mixture must be $T_M < 420 \text{ K}$. If this condition is not satisfied, A or B may decompose before reaching the boiling point, so $T_M$ must somehow be decreased. Lavoisier had shown the spontaneous evaporation of ether in vacuum and Philippe Lebon worked on this idea in 1796 to conceive vacuum distillation [19]. Applying a partial vacuum to the apparatus decreases the temperature at which $T_M = P_{ext}$, and therefore the boiling point of the mixture. In other words, in these conditions molecules require less energy to leave the surface of the liquid.

In 1800, the great scientist and inventor Sir Benjamin Thomson, Count Rumford used open steam as a heating agent [20], creating steam distillation. This process is still very useful if one wants to separate essences or flavor oils from plant material (leaves or seeds). In this case, B can be distilled from the mixture at a temperature well below $T_B$ if it is not soluble in A (water), and can exert its own full vapor pressure $T_B$ (Raoult’s law cannot apply). B does not have to be a liquid at room temperature: caffeine (a solid) can be steam distilled from green tea, for example [21].

Furthermore, all the various distillation methods discussed can be performed in continuous (ongoing separation in which a mixture is continuously fed into the process without interruption) or batch mode (where the mixture is added at the beginning, distillate fractions are taken out sequentially and the remaining bottom fraction is removed at the end).

In this section we learned that there are 4 main classes of distillations (simple, fractional, vacuum and steam) that can be performed in two modes (continuous and batch). Distillation comes in many forms. Why to do it is the subject of the next section.

Figure 7. Schematic illustration of a modern organic chemistry lab setup for a fractional distillation.

Figure 8. Representation of 3 different columns for distillation in order of efficiency: a) Open tube, surrounded by a vacuum chamber b) Vigreux column, c) Packed column.

D The Application of Distillation

As we will see in this section, distillation has a fundamental role in our society. Without it, we could not move cars or planes, separate nitrogen from oxygen on a large scale or even enjoy a cognac. This is a short list of the most important uses of distillation: many more applications of this technique could be named, in a wide variety of fields.

The first uses of distillation were alchemic: mercury, nitric acid, sal-ammoniac (ammonium chloride), acetic acid and sulfur, together with many other substances (including urine!), were purified through distillation. Today, the “purification” concept is still applied to solvents, after they have been used in laboratory or industrial extractions.

Dioscorides [3] writes around the 1" century that sailors used to evaporate seawater and condense it into sponges to get fresh water. Strangely enough, evaporation is still, at present, the most valid alternative to get desalination of seawater [22].

It was probably around the 11" century that it was first used in Italy to increase the alcohol percentage of aqueous mixtures, derived from the fermentation of plant extracts rich in carbohydrates. Fermentation usually stops when the yeast dies in its own 15% ethanol solution, so the concentration had to be increased by distillation. The results were the spirits, or waters of life. Depending on where and from what they were produced, they had different names: brandy from fruit, grappa from pomace, vodka from grain or potatoes, rum from molasses,
whiskey from grain mash, shochu from rice, tequila from the cactus blue agave and so forth [23]. This field of application (which was initially practiced by monks, and later became the first industrial application of the distillation) has greatly influenced the development of the still apparatus. As a side note, due to the formation of an azeotrope, ethanol-water mixture cannot be distilled to get pure ethanol (the azeotrope is at $x_{\text{ethanol}} = 0.95$, $x_{\text{water}} = 0.05$), but this obstacle can be removed by adding small amounts of benzene.

Pure nitrogen, oxygen and argon are obtained by rectification of air. To separate air by rectification, part of it must be liquefied and this can only be achieved below its critical point ($T_c = 132.5 \text{K}$, $P_c = 37.7 \text{ bar}$) [24]. $N_2$ is then used for ammonia synthesis, as an inert gas and as a cryogenic liquid, while $O_2$ is used in medicine, as a reactant or in oxyacetylene flames instead of air [25].

![Figure 9](image)

**Figure 9.** Schematic representation of a fractional distillation of crude oil. The various fractions are collected at different heights of the column. From top to bottom, the average boiling point of the fraction increases (number in parentheses), like the average density. Fractions are usually identified with the number of carbon atoms of their constituents, since this parameter roughly determines their volatility.

Nowadays, the most common (and one of the most recently developed) application of distillation is by far the separation of petroleum into its components [26]. Crude oils are complex mixtures of hydrocarbons with a wide variety of properties, hence they have to be separated for industrial or commercial applications. Different fractions are collected at different heights of the distillation tower (see Fig. 9): gas fuels on top (collectively known as liquefied petroleum gas, LPG), then naphtha, motor gasolines, kerosene, diesel oils, lubricating oils, fuel oils and residues at the bottom (asphaltene).

Finally, the concept of distillation can also be applied to dry materials: wood can be “distilled”, for example. In this destructive process that now involves chemical reactions, wood decomposes to leave charcoal as a residue and methanol and terpenes as distillate. Methanol is in fact also known as wood alcohol.

**Conclusions**

In this paper, we presented a possible introductory lecture on distillation that includes on the one hand its thermodynamical basis, and on the other continuous links to the conceptual evolution of this method over the centuries. We would like to stress that a similar approach can be used for many other topics: from the symbols of chemical elements to the familiarization of glassware in a chemical laboratory, from the concept of acid to the transmutation of elements in high-energy colliders. According to our experience, such an integration seems to be an important step if one wants to give the students a complete understanding of the concepts and the techniques they will use for the rest of their professional lives.

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Doing it again, thoughtfully: Using feedback on draft reports to improve learning outcomes

Kieran F. Lim

School of Life and Environmental Sciences, Deakin University, 221 Burwood Highway, Burwood, Victoria 3125, Australia, kieran.lim@deakin.edu.au

Abstract
A lack of communication skills is one of the graduate skill deficiencies most commonly cited by employers. Although the writing of laboratory and other scientific reports is a common teaching-and-learning task in university chemistry curricula, this skill is not fully developed in most Australian undergraduate science degrees. Usually, there is no opportunity for practice and feedback before the reports are used for summative assessment. This paper describes a system whereby students are given the opportunity to submit draft reports. After feedback, they can “do it again, thoughtfully”: only the final report is assessed. Student evaluations of the effectiveness of this approach are reported.

Introduction
The writing of laboratory and other scientific reports is a common teaching-and-learning task in university chemistry curricula, because it is an essential skill in the scientific and technical professions. Larry Woolf, a physicist at General Atomics, summarises the common view of the profession (1):

“As an industrial scientist, I write extensively: monthly reports, proposals, memos, etc. I also often prepare PowerPoint presentations for internal as well as external customers. Clear scientific writing to propose, document, and communicate results is a critical aspect of my job.”

As a teaching-and-learning activity, report writing encourages students to organise their data and knowledge. Furthermore, guided instruction about writing can enhance learning (2,3).

It is not the place of the chemistry educator to provide remedial writing instruction on the use of sentences, paragraphs and punctuation — that is the role of a school or university remedial instruction office. However, since scientific writing is a separate genre, with specialised use of references, tables, tense of verbs and equations (3-7): instruction on such writing is within the remit of the chemistry educator.

Despite the importance of technical writing skills, both as a learning tool and for future employment, they have generally been under-developed in Australian universities. A lack of communication skills is one of the graduate skill deficiencies most commonly cited by employers (8). In 2001, a survey of science graduates found that 82% thought writing skills were important in their employment, but that only 57% had gained those skills in their undergraduate degrees (9). This is probably due to the lack of opportunity for practice of report writing, with feedback, before the reports are used for summative assessment in most courses.

This paper describes a system whereby students are given the opportunity to submit draft reports (10). After feedback, they can “do it again, thoughtfully (DIAT)”: only the final report is assessed.

Implementation of doing it again, thoughtfully (DIAT-ing)
In his 1995 article, Ehrmann (10) describes a visit to Reed College1 in Portland, Oregon, where members of teaching staff had:

“…unintentionally implemented a strategy of Doing It Again, Thoughtfully (DIAT-ing). Students had easy access to computers, and asked faculty for opportunities to revise their drafts. Gradually the texture of the curriculum in each course was changing: toward projects developed in stages -- plan, draft, conversation, another draft, final version.” (10)

This has been the inspiration for the system that has been implemented in the author’s units at Deakin University. Students may submit reports for comment on the writing style of their reports, and then revise and resubmit reports. The earlier version of the report undergoes formative assessment only: it is the final resubmitted report that is assessed for marks (and further feedback).

Table 1 Marking schemes used by the author. Scheme 1 is typical of an assessment scheme used prior to the induction of the DIAT-ing approach. Scheme 2 is used to encourage the development of generic skills, such as technical writing and teamwork.

<table>
<thead>
<tr>
<th>Task</th>
<th>Scheme 1</th>
<th>Scheme 2</th>
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</thead>
<tbody>
<tr>
<td>Laboratory report (content)</td>
<td>Major mark</td>
<td>10</td>
</tr>
<tr>
<td>Laboratory report (style)</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Completion of laboratory work, etc</td>
<td>Minor mark</td>
<td>3</td>
</tr>
<tr>
<td>Teamwork, etc</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>More than one draft submitted for DIAT-ing</td>
<td>Not applicable</td>
<td>Deduct 1 mark per additional draft</td>
</tr>
</tbody>
</table>

The development of technical writing skills must be matched by other changes in teaching and learning practice. Ehrmann (10) and other authors have noted that the method of assessment is a major motivator in student learning. Changes in assessment will cause students to change how they learn. In the present situation, the author
has allocated a small, but not insignificant, component of the laboratory-assessment marking scheme (see Table 1) for a good scientific writing style. All students are offered feedback for one optional “free” draft report. In order to prevent students submitting multiple drafts or drafts with minor, incremental revisions, subsequent drafts “cost” 1 mark, as shown in Table 1. Detailed advice and exemplars are given in The Chemistry Style Manual (6), which is available from the bookshop, the university website or from the website of the Physical Sciences Centre of the Higher Education Academy (UK).

**Evaluation**

Units taught by the author have been evaluated by anonymous questionnaires distributed by and analysed by administrative staff. Some students specifically mentioned the DIAT-ing approach in their free-text responses to a generic question asking students what they liked about the unit: their responses are given in Table 2.

Table 2 Free-text comments from students in response to the prompt “… things I liked … [about the author’s unit]. The words and spelling errors have been transcribed directly from the students’ responses. (Note that the questionnaire does not make reference to any particular aspect of the unit or to any particular teaching and learning activity.)

| S1 | “… to give drafts of assignments/prac reports” |
| S2 | “Emphasis on computing skills” |
| S3 | “DIAT was particularly useful” |
| S4 | “… the writeup” |

Secondly, graduates who had used DIAT-ing in a number of the author’s units were asked to provide anonymous feedback about their experiences of DIAT-ing. Three responses were received and are reproduced in Table 3. A third measure of the efficacy of the DIAT-ing approach is given by the proportion of students who used DIAT-ing and the frequency of use. By this measure, the DIAT-ing approach at Deakin University has had mixed success, because most (roughly three-quarters) students have not accepted the offer for DIAT-ing. On the other hand, those students who do use DIAT-ing, do so for most of their reports. Furthermore, these students are the best-performing students as ranked by their performance in classes taught by the author’s colleagues.

**Discussion**

A great deal of practice is required to achieve expertise, even in the case of “talented” individuals. Furthermore, “deliberate practice” involves learners actively seeking and using feedback about their progress (11,12). In the DIAT-ing approach, feedback is given in the form of detailed checklists, some of which are in the Appendix. (The page citations in the checklists refer to sections in The Chemistry Style Manual (6).)

As Ehrmann has noted, such revision and resubmission of reports depends on the use of technology: multiple revisions by hand is too tedious to be practical (10). The use of technology enables learners to concentrate on learning aspects of organising and communicating ideas in a report, without the tedium of the mechanical writing process. The value of writing as a vehicle for thinking about chemistry and organising information (2,13) is clearly appreciated by student S7: see Table 3. A comparative study of the effects of pens and word processors found that use of the latter was more effective in developing the conceptualisation and synthesis of abstract ideas, and led to greater student independence and initiative (i.e., less teacher-centred), while fostering more interactive cooperation and collaboration (14).

Table 3 Free-text comments from students in response to the prompt “What I think about DIAT-ing”. The words and spelling errors have been transcribed directly from the students’ responses.

| S5 | “I think having the option of submitting a draft report in Kieran’s classes is very useful, particularly with second and third years. As these years are very important and the prac reports account for a fairly large percentage of the final mark, it is more than helpful to have feedback before you have to submit the final report.” |
| S6 | “I found the drafts useful in Kierans classes as we were able to gain feedback on our writing styles and calculations before handing them in for the final correction. Because of this I feel that my final score was higher than if I had just handed in the report unchecked. The calculations in Kierans classes were often quite difficult and the drafting helped get me through the calculations that I had trouble with.” |
| S7 | “I think that drafting lab reports is important and give students an advantage over their peers who do not draft lab reports. This is because: The correct scientific style of writing reports is not fully introduced until second year, and there are not many opportunities in second and third year to practice report writing, so it is important to get it right early on. It is important to be able to communicate knowledge briefly and accurately. Most students have bad habits from secondary school, in that they believe more words equals more information, but this is not true. Drafting can aid them in removing extraneous information, important for reports to non scientific colleagues and for journal reports. Drafting allows students to improve the presentation of the report. Most of the knowledge and teaching points are present in the first draft. The subsequent drafts are more focused on improving layout and condensing knowledge. Condensing knowledge also has the benefit that students look at the problem again, thinking more in-depth about the problem and helping to retain the knowledge for longer. I also feel that I am better prepared for writing reports and that is easier to write reports than my fellow students who did not undertake the subjects that allowed report drafting.” |
The educational value of practice and of purely formative assessment is well established. In the absence of writing practice and feedback, students have expressed that they have anxiety over report writing; often reports are used for summative assessment, with little opportunity for “practice”. This is especially problematic in physical chemistry laboratory practical classes, where there are so many experimental methods that almost no two practical exercises have similar equipment or set-up (15,16). Naveh-Benjamin (17) has concluded that allowing students to practise “dummy” or trial assessments, desensitised students to the stress of the assessment situation and increased mastery of the assessment task. DIAT-ing allows the student to focus on the writing task without the stress of wondering, “am I doing it correctly?”

In some other universities, feedback to students is done through peer critique (7,18,19). Tilstra asks students to focus on only one part of laboratory report (20). Other approaches are also possible (21-26). With the exception of the Calibrated Peer Review™ (18), these are mostly a series of activities which over a semester-long unit culminate in full review (7,19-26). The approach described in this paper offers students the opportunity to have the first draft of up to four entire reports or papers per semester, over a three-semester sequence reviewed by the instructor. (To date, no student has asked for review of the first draft of all reports or papers over the three semesters.)

The use of (draft) writing is not effective when done in isolation. Students who perceive DIAT-ing as separate from other learning tasks obviously place no value on it and do not participate. Informal comments by these students indicate that they believe they already have a good writing style, or that they perceive that the additional time commitment is not worth the benefit. Indeed, improvements in writing, like any other activity, occur with sustained practice: submitting only one report for DAiT-ing over the course of an undergraduate career will have limited benefit.

On the other hand, students who use DIAT-ing, often see it as part of a larger computer literacy objective, as evidenced by the comments of students S2 and S6 (see Tables 2 and 3) (27-29). As students progress through the DIAT-ing process, they receive advice on the use of fonts, superscripts and subscripts, tables, importing graphics and the use of chemical and mathematical equations within the word-processing environment. Students are also introduced to the use of bibliographic software (EndNote), on-line literature searches, the use of chemical-structure drawing software (ChemDraw, ISIS/Draw) and the use of spreadsheets for plotting and analysing data. By focussing on the (draft) writing task, the technology has become part of the assumed background. The essence of bringing technology “into the mainstream” is to make it so “taken for granted” that it is not noticed, in the same way that we no longer remark on the use of electronic calculators in educational institutions: it is part of the norm.

Summary
The author has used provision of feedback on draft reports (“Doing It Again, Thoughtfully”: DIAT-ing) (10) as part of a holistic approach to using technology in learning. Students who take the opportunity to submit and receive feedback on draft reports are assessed not on their first submission, but after they have had the opportunity to revise and improve their report. While most students chose not to use DIAT-ing, those who did, did so repeatedly. The value of DIAT-ing to these students is evidenced by feedback in anonymous surveys. Finally, by focussing on the writing task, students accept the use of technology (word processors, bibliographic software, online literature searches, the chemical-structure drawing software and spreadsheets) as part of the norm.

Acknowledgments
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Note
1 In the USA, many tertiary education institutions are called “Colleges”.

References
1. Woolf, L., General Atomics, Reading a contribution to the Chemistry Education Discussion List (Item #28909 (19 Nov 2003 19:42). Registered subscribers can access the list archives) <http://mailer.uwf.edu/listserv/wa.exe>.
Appendix

This appendix presents part of a detailed checklist template, used to provide feedback to students on the technical writing aspects of their reports. The page numbers refer to The Chemistry Style Manual (6).

<table>
<thead>
<tr>
<th>Your report should satisfy the following general guidelines.</th>
<th>Yes</th>
<th>No</th>
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<tbody>
<tr>
<td>Does your report satisfy with the statements in this column?</td>
<td></td>
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<tr>
<td>There must be sufficient data, details and discussion in the main body of the report, so that a classmate, who has done everything you have done except this exercise (or this unit), can understand the report (see page 3).</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>All pertinent data, details and discussion, which are essential to the report, must be placed in the main body of the report (see pages 3, ff).</td>
<td>✗</td>
<td>✔️</td>
</tr>
<tr>
<td>All (extra) data, details and discussion, which are not essential to the report, but which aid the reader, must be placed in an appendix (see page 3, ff).</td>
<td>✗</td>
<td>✔️</td>
</tr>
<tr>
<td>Trivial arithmetic and other trivial details can be omitted altogether (see page 3).</td>
<td>✗</td>
<td>✔️</td>
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<table>
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<tr>
<th>Your report should satisfy the following guidelines for writing the introduction.</th>
<th>Yes</th>
<th>No</th>
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<tbody>
<tr>
<td>Does your report satisfy with the statements in this column?</td>
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<tr>
<td>The Introduction should begin broadly, indicating the area under study and why it is being studied (see pages 3 and 6).</td>
<td>✗</td>
<td>✔️</td>
</tr>
<tr>
<td>The Introduction should describe the work of previous researchers (ie “background”) whose results have led to your study (see pages 3 and 6).</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>The Introduction should state the aims, and the specific question(s), issues or problems being addressed in your study (see pages 3 and 6).</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>The Introduction should describe the work of previous researchers (ie background) whose results have led to the present study. At the end of the Introduction you should state the aims of your study and the specific hypotheses, which are predictions of what results you expected in your study (see pages 3 and 6).</td>
<td>✔️</td>
<td>✗</td>
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<tr>
<th>Your report should satisfy the following guidelines for writing the method section.</th>
<th>Yes</th>
<th>No</th>
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<tr>
<td>Does your report satisfy with the statements in this column?</td>
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<tr>
<td>The method section should tell the “story” of what you have done, in your own words. It should not be a set of instructions for what someone else should do (see pages 3 and 7).</td>
<td>✗</td>
<td>✔️</td>
</tr>
<tr>
<td>The method section should include all relevant details eg (where appropriate), solvent, source of reagents, wavelength range, computer program, instrument brands and names, etc (see pages 3 and 7).</td>
<td>✗</td>
<td>✔️</td>
</tr>
<tr>
<td>The method section should mention any calibrations to check that the observed values actually match the true values. ie that there is no systematic error in the instrument.</td>
<td>✔️</td>
<td>✗</td>
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<tr>
<th>Your report should satisfy the following guidelines for writing the results section.</th>
<th>Yes</th>
<th>No</th>
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<tr>
<td>Does your report satisfy with the statements in this column?</td>
<td></td>
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<tr>
<td>All graphs and mathematical equations, which are used in the interpretation of data and/or spectra (to get the results), are part of the experimental method and results, and should be included in the main body of the report.</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>Your report should normally use x-y scatter plots, which are the most common type of graph in chemistry (see page 67).</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>Your report should normally not use a “line” graph in MS Excel (see pages 67 and 68).</td>
<td>✗</td>
<td>✔️</td>
</tr>
<tr>
<td>Linear plots may (should) be omitted from the report, especially if the data is reported in another diagram or table elsewhere in the report.</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>Useful methods of presenting numerical results are to use tables or diagrams. Numerical results can include both experimental measurements and quantities derived from measurements by the use of mathematics. All numerical results should be included in the main body of the report.</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>The purpose of any table or diagram is to present data in a useful format. Where there are too many numbers, you should try to plot the data in a diagram (ie graph).</td>
<td>✔️</td>
<td>✗</td>
</tr>
<tr>
<td>Use terminology correctly. “Calculated” results are computed or calculated from a theory or mathematical model (without experimental input). Numerical experimental results are determined from experiment.</td>
<td>✔️</td>
<td>✗</td>
</tr>
</tbody>
</table>
Your report should satisfy the following guidelines for writing the **discussion** section.

<table>
<thead>
<tr>
<th>Does your report satisfy with the statements in this column?</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>The discussion section should evaluate your results. Are they reliable? Do they agree with literature values? (If not, why not?)</td>
<td></td>
<td></td>
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<tr>
<td>The discussion section should be devoted to a discussion of the scientific meaning or significance of your results. How or why is it so? (see pages 3 and 7).</td>
<td></td>
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</tr>
<tr>
<td>The discussion should be concise (compact and “to the point”).</td>
<td></td>
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<tr>
<td>Where appropriate, chemical structures, reactions or mechanisms should be used to illustrate the textual discussion.</td>
<td></td>
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<tr>
<td>The discussion section should be a single coherent “story”, not a collection of separate and disjointed points.</td>
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</tr>
<tr>
<td>The purpose of any table or diagram is to present data in a useful format. Where there are too many numbers, you should try to plot the data in a diagram (ie graph).</td>
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<tr>
<td>Use terminology correctly. “Calculated” results are computed or calculated from a theory or mathematical model (without experimental input). Numerical experimental results are determined from experiment.</td>
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</tbody>
</table>

Your report should satisfy the following guidelines for writing the **references** section.

<table>
<thead>
<tr>
<th>Does your report satisfy with the statements in this column?</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>The references or bibliography should be in a consistent style with all details recorded. See any research journal for examples. (See Chapter 4: Use of References in Chemistry).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The references or bibliography should be at the end of the report (“end notes”), not as footnotes (See pages 54, ff).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facts, which are not “common knowledge”, must be supported either by your experimental or computational data (or mathematical modelling) or by a reference to the scientific literature (See pages 54, ff).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numbers in the body of the report should cite references, with the references numbered in the order of first citation in the report. Multiple citations to the same reference are given the same number (See page 56).</td>
<td></td>
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<tr>
<td>The original source of information (eg journal or book) should be cited, not the secondary reference (eg lecture notes).</td>
<td></td>
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<tr>
<td>The original source of all diagrams should be cited.</td>
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<td>Computer programs, files (eg spreadsheets), internet documents, etc., should be referenced in the same manner as books ie, with details of author(s), title, publisher, city-of-publication, edition or revision, year (see pages 61, ff).</td>
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</table>

Your report should satisfy the following guidelines for the use of Figures, Tables, etc.

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<th>Does your report satisfy with the statements in this column?</th>
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<tr>
<td>Figures can include graphs, structures and other types of diagrams. Each figure should have a caption (or title). All figures should be numbered (Figure 1, Figure 2, etc) in consecutive order, starting from one. (See pages 11 and 72).</td>
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<td>Each table should have a caption (or title). All tables should be numbered (Table I, Table II, etc) in consecutive order, starting from one.</td>
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<td>Important equations should be numbered (Equation 1, Equation 2, etc), in consecutive order, starting from one. Less important equations do not need to be numbered.</td>
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<td>Figures, tables, equations and references should each have their own separate numbering, so that you can refer to (for example) “Equation 3”, “Table I”, or “Figure 6” in the report.</td>
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<td>Equations should be prepared using an equation editor.</td>
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<td>Colour should only be used where it is essential to convey information.</td>
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<td>All figures, etc which are prepared using a computer should be “cut-and-pasted” into the report using computer editing, not physically cut and glue-pasted using scissors and glue (see page 75).</td>
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<tr>
<td>The figures and equations should use the correct “arrows”. Resonance (↔) involves only the rearrangement of electrons in a Lewis structure: no atoms or connectivities are altered. If atoms or connectivities (σ bonds) are rearranged, then isomerisation (→) or equilibrium (↔) is involved (see pages 44, ff and Appendix B: Non-Roman Alphabets).</td>
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Your report should satisfy the following guidelines for miscellaneous matters.

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<th>Does your report satisfy with the statements in this column?</th>
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<tr>
<td>The report should be written or typed in blue (or black) pen (or ink or printer). You should not use red or green. You must not use pencil.</td>
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<td>Non-standard abbreviations and colloquialisms (eg “mass spec”) should be either spelt in full, or replaced by the correct, standard abbreviations (see pages 8, ff).</td>
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<td>The IUPAC convention of using superscripts for units (eg kJ mol(^{-1})) should be followed, instead of using a solidus (eg kJ/mol) (see page 8 and Appendix A: The SI System of Units).</td>
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<td>The correct mathematical and scientific symbols and fonts should be used: eg, arrows ((\rightarrow)) not (--&gt;), multiplication ((\times)) not “ex” (x), Greek letters (eg (\nu) or (\omega) in symbol font) not an English/Roman look-alike (v or w), etc. and equations should use the correct “arrows” (see pages 44, ff and Appendix B: Non-Roman Alphabets).</td>
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<td>Superscripts and subscripts should be used where appropriate (see pages 49, ff).</td>
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<td>All pages in the report should be numbered. Reports should be securely stapled.</td>
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<td>The report should be carefully proofread to correct any spelling mistakes. You should not rely on the “spell checker”! A small number of spelling mistakes may be corrected by crossing out the misspelt mistakes and neatly writing the corrections. If there are too many spelling mistakes, you should redo the relevant page(s) (see pages 27, ff).</td>
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General matters.

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<th>Does your report satisfy with the statements in this column?</th>
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<td>Standard A4 size (297 mm (\times) 210 mm) paper should be used.</td>
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<td>There should only be text and diagrams on one side of the paper (single-sided).</td>
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<td>Standard fonts (Times, Times New Roman, Arial, Helvetica, Symbol) should be used (see pages 20, ff).</td>
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<td>More than the basic minimum (pass) grade requires more-than-minimal work, eg understanding, insight, extra reading, etc.</td>
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<td>In most spectroscopy experiments, the spectrum is the main experimental result and must be placed in the main body of the report, not the appendix.</td>
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An invitation

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ICCE 2010

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Chemistry in the Singapore school curriculum

Kim Chwee Daniel Tan

National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, daniel.tan@nie.edu.sg Singapore

Abstract
Singapore adopts a spiral curriculum to help students gain better understanding of the concepts in matter as they progress from primary to upper secondary education. The syllabuses for each year of primary (ages 9 to 12) and lower secondary science (ages 13-14) are spelt out in detail and are closely followed by teachers. Upper secondary teachers are given the liberty to sequence the learning outcomes but they need to complete the syllabus within two years to prepare students for the national examination at the end of upper secondary education (age 16). This paper argues that the sequencing of learning objectives in a ‘logical’ order by teachers, especially in upper secondary, poses problems for students as they may have difficulty understanding the abstract concepts taught as well as the representational systems used to explain the characteristics and interaction of matter.

Introduction
Singapore was a British colony and, prior to 1960, the school curriculum offered was that of a typical English grammar school of the time (Mackie, 1971). Even till today, the University of Cambridge Local Examination Syndicate (UCLES), first introduced in 1891, still has close links with the Ministry of Education, Singapore. The syndicate collaborates with the Ministry of Education to develop the school curricula and national examinations at the end of secondary and pre-university education. The educational system in Singapore is constantly evolving to meet the changing demands of society, and is becoming more diverse and flexible, with greater choices and pathways for students. Broad-based education is now emphasized to facilitate the development of life skills, independent learning, critical and creative thinking.

The syllabuses for each year of primary and lower secondary science are spelt out in detail in documents produced by the Curriculum Planning and Development Division (CPDD), Ministry of Education, and are closely followed by teachers. The learning objectives were developed in consultation with experts and practitioners, and took into account any educational initiatives from the Ministry of Education, such as the implementation of school-based practical assessments to replace the one-off end of year practical examinations from 2006 which expanded the scope of practical work that was done in schools. In general, teachers in the upper secondary and pre-university levels have two years to complete the respective syllabuses which are co-developed by the CPDD, the School Examination and Assessment Board (SEAB), which is a statutory board in charge of national examinations, and the UCLES, but have the flexibility to structure the instructional sequence over the two years. The SEAB and the UCLES also collaborate in administering two national examinations in Singapore, the General Certificate of Education Ordinary Level examinations at the end of Secondary Four (age 16) and the General Certificate of Education Advanced Level examinations at the end of Pre-University Two (age 18).

In addition, the SEAB is responsible for administering the national examinations for primary education, the Primary School Leaving Examinations, at the end of Primary Six (age 12).

The primary science (ages 9-12) and lower secondary science (ages 13-14) curricula (Curriculum Planning & Development Division, 2004a,b) are based on a ‘science as inquiry’ framework, and comprise five themes in primary science (Diversity, Cycles, Systems, Energy, and Interactions) and six themes in lower secondary science (Diversity, Cycles, Energy, Interactions, Models and Systems, and Measurement). The syllabuses encompass a core body of concepts in both the life and physical sciences to provide a broad understanding of the environment, and the interaction between science, technology and the environment. The ‘science as inquiry’ framework in primary and lower secondary science continues in the upper secondary (ages 15-16) curriculum (CPDD, 2000) and the pre-university (ages 17-18) curriculum (CPDD, 2003a,b,c). However, students learn science as separate subjects, physics, chemistry and biology, in upper secondary and pre-university. This is different from the general science focus in primary and lower secondary science. The end goal of the upper secondary and pre-university science curricula is to produce confident citizens in a technological world, able to take or develop an informed interest in matters of scientific import, and to recognise the usefulness, and limitations, of the scientific method and to appreciate its applicability in other disciplines and in everyday life. Pupils sit for high stakes national examinations at the end of primary, secondary and pre-university schooling.

Sequencing of the Learning Outcomes Related to Matter
The sequencing of the learning outcomes related to matter is based on a spiral approach to match pupils’ cognitive development, build upon their existing understanding and facilitate the gradual mastery of concepts and process skills (CPDD 2004b). This paper will focus on the learning of matter (non-living things) at the primary and secondary levels. The learning outcomes for matter at different levels in primary and secondary education can be found at the CPDD website1 and the SEAB website².
Primary Science

The percentages of learning outcomes in the primary science syllabus (CPDD, 2004a) associated with matter, living things, and energy and forces are given in Table 1. The percentages are calculated based on the ratio of the number of learning outcomes associated with matter, living things and energy and forces to the total number of learning outcomes. This gives a rough overview of the balance of the learning outcomes assuming the learning outcome statements are of equal ‘content value’. Students do not learn science in the first two years of primary education; they concentrate mainly on the English language, a second language and mathematics. The students start their formal science education at Primary Three (age 9). In their first lesson on matter, they learn about different materials (solids only) with different physical properties, and relate the uses of these materials with their properties. Students would have encountered the materials in their everyday life, so they should be able to link their experiences of materials with what is taught in class. In Primary Four (age 10), students learn about the properties and states of matter under the theme of Cycles, and that air is a mixture of gases under the theme of Systems. These concepts on matter are more difficult and abstract than those encountered in Primary Three. There is no learning outcome related to matter in Primary Five (age 11) but in Primary Six (age 12), students revisit the topic of materials and their uses under the theme of Diversity.

<table>
<thead>
<tr>
<th>Learning outcomes associated with</th>
<th>Number of learning outcomes (n=106)</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Matter</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Living things</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Energy and forces</td>
<td>40</td>
<td>38</td>
</tr>
<tr>
<td>Others</td>
<td>5</td>
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It can be seen from Table 1 that the percentage of learning outcomes associated with matter (19%) is lower than those of living things (40%), and energy and forces (38%). The concepts in the learning of matter, especially the particulate nature of matter, are generally more abstract and less readily related to the everyday experiences of the primary school students as compared to those in living things, and energy and forces. Hence, only the simpler concepts of matter are taught in primary science, leading to the lower percentage. Indeed, Nakhleh and Samarapungavan (1999), and Stavy (1994) found that students had difficulties learning concepts related to matter, for example, the macroscopic physical attributes of solids and liquids, and the particulate nature of matter. As for gases, Snir, Smith and Raz (2003) state that students may have difficulties thinking of them as matter because they “think that matter is something that they can see, touch, and feel” (p. 799).

Lower Secondary Science

The percentages of learning outcomes in the lower secondary science syllabus (CPDD, 2004b) associated with science as an inquiry, measurement, matter, living things, and energy and forces are given in Table 2. The percentage of learning outcomes associated with matter (25%) is still lower than those of living things (34%), and energy and forces (31%) but more comparable than in primary science.

<table>
<thead>
<tr>
<th>Learning outcomes associated with</th>
<th>Number of learning outcomes (n=106)</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Science as an inquiry</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Measurement</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Matter</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Living things</td>
<td>54</td>
<td>34</td>
</tr>
<tr>
<td>Energy and forces</td>
<td>49</td>
<td>31</td>
</tr>
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</table>

In the lower secondary science syllabus, the sequence of learning objectives starts with the classification and uses of materials in Secondary One (age 13), something which is very similar to what students learn in primary science. This is followed by the topics of ‘elements, compounds and mixtures’, separation techniques, ‘solutions and suspensions’, and ‘acids and bases’. In Secondary Two (age 14), students will learn the particulate model of matter, simple concepts of atoms and molecules, and chemical changes and reactions.

Learning about elements, compounds and mixtures at Secondary One without knowing the particulate model of matter (which is taught in Secondary Two) may be problematic because it can be difficult for students to differentiate elements, compounds and homogeneous mixtures at the macroscopic level. For example, a shiny, metallic substance can be an element or an alloy, and a colourless liquid can be a compound or a solution, so students need to know the representations of elements, compounds and mixtures at the microscopic level to make sense of the differences. In addition, the lower secondary science syllabus has no explicit learning outcome on the microscopic level representations of elements, compounds and mixtures; the students are only required to know the simple model of solids, liquids and gases in terms of the arrangement and movement of particles, and the distinction between an atom and a molecule. Nonetheless, students need to be taught the particulate representations of elements, compounds and mixtures to have a better understanding of these substances. However, this is not an easy task as “students have to take their existence on faith and build up knowledge structures of molecules and molecular behaviour without having direct experience with molecules” (Fellows, 1994, p. 988). Even college students had difficulty differentiating microscopic level representation of pure compounds, homogeneous and heterogeneous mixtures (Sanger, 2000); many classified microscopic representations of pure compounds as homogeneous mixtures, and several of them classified all mixtures as heterogeneous. Snir et al. (2003) also maintain that the particulate model of matter is difficult for students to understand because “it requires that students develop an understanding of two profoundly important, but counterintuitive, ideas” (p. 795) - the
discontinuity of matter and the use of “an explanatory model as a metaconcept in science.” (p. 795). In the lower secondary science syllabus, models are described as simplified representations of phenomena constructed to facilitate understanding of phenomena. However, the use of models in science is seldom discussed in class, so students may not have clear ideas of a scientific model, its usefulness and limitations.

Upper Secondary Chemistry
Matter is mainly taught in chemistry in upper secondary science. Upper secondary students (ages 15 to 16) study chemistry as a subject by itself, or as part as a combined science subject, for example, Biology/Chemistry or Chemistry/Physics. The sequencing of the topics of the Chemistry 5068 syllabus (available at the SEAB website), which is chemistry as a single subject, by ten schools (S1 to S10) and two textbooks (T1 and T2) will be the focus of discussion in this section.

In November 2005, the author approached teachers attending a chemistry education workshop in his institution, and teachers with whom he had worked in previous research studies to request if he could study their Chemistry 5068 schemes of work and interview teachers on the schemes of work. Ten secondary schools (S1 to S10) consented to make available their schemes of work for analysis, and six senior chemistry teachers (ST1 to ST6) from three schools agreed to be interviewed on the rationale behind their schemes of work. The rankings of the topics and sub-topics in the ten schemes of work are presented in Table 3, together with that from two textbooks (T1 and T2) which are approved by the Ministry of Education for use in secondary schools. It can be seen from Table 3 that the order given in the Chemistry 5068 syllabus is generally not closely followed except by textbook T2. It has to be noted that the syllabuses for upper secondary science are not curricular documents but examination documents in that the content to be assessed in the national examination is given in detail in the documents. There is no official curricular guidance given in upper secondary science, so the schools are at liberty to sequence the learning outcomes and select the instructional material and strategies as they deem appropriate; they only need to teach all the topics stated in the syllabus within two years to prepare students for the national examination at the end of Secondary Four (age 16). This is fortunate as there does not seem to be any discernible rationale for the order of the topics in the syllabus. For example, the identification of ions and gases is the third sub-topic of the first topic in the syllabus; however, the theory involved is discussed only in ‘Redox’, the sixth topic, and in the seventh topic, ‘The Chemistry and Uses of Acids, Bases and Salts’. If the above order is followed, students could be taught to carry out tests for cations, anions, gases, oxidising and reducing agents without knowing the reactions involved, that is, why the test works (Tan, Goh, Chia, & Treagust, 2001, 2002).

Data from Table 3 show that three schools (S5, S6 and S10) and the two textbooks presented the characteristic properties of acids and bases, the preparation of salts, and redox reactions before the identification of ions and gases, which was the recommended order. However, schools S5 and S6 taught the identification of ions and gases as the last sub-topic, which could be several months after the other sub-topics; students might forget what they had learnt earlier, so teachers in schools S5 and S6 need to make explicit links with the earlier material. Six schools (S1, 2, 3, 4, 7 and 9) taught the characteristic properties of acids and bases, and the preparation of salts before the identification of ions and gases, but redox reactions after it so students might have difficulty understanding the tests for sulfur dioxide and the nitrate (V) ion which involve redox reactions. School S8 was unusual in that its sequence was redox reactions, the identification of ions and gases, and then characteristic properties of acids and bases, and the preparation of salts.

Textbook T2, which followed the sequence of topics in the Chemistry 5068 syllabus closely, might create difficulty for students using it especially if they follow the order of topics in the textbook. For example, the sequencing of ‘Electrolysis’, before ‘Redox’, might create difficulty as electrolysis essentially involves reduction and oxidation reactions. Students from school S3 might also face the same difficulty as they were taught electrochemistry before redox reactions. Another example is chemical calculations in the topic, ‘Formulae, Stoichiometry and the Mole Concept’. A student must be able to write chemical equations to do stoichiometric calculations, but they learn the chemistry of the various elements and compounds only at a later stage (schools S1, S2, S3, S7, S8, S9, T1 and T2); if they do not know the reaction that occurs in a given situation, it is nearly impossible to write down an equation describing the reaction, and hence, to do any calculation. The students should have learnt some reactions (e.g. acid-base reactions) in lower secondary science but these are insufficient for upper secondary chemistry. Thus, to overcome this, teachers will generally give the equations involved. This can result in chemical calculations becoming algorithmic with little reference to the chemistry involved. Three teachers from school S6 which sequenced ‘acids, bases and salts’ before chemical calculations realized the consequence of the reverse order as indicated in the following transcript:

ST3:...I think to do the mole concept so early in Secondary 3...they are not ready...it is too overwhelming for them...it is too overwhelming...I think reactions are easier for them to grasp than to do the calculations...so I think they are not ready...so I switch the order...one reason is that they can write the equation themselves...the other thing is their readiness for mole concept.

ST2:You don't have enough exposure to chemicals if you start so early...whereas if you have like a lot of reactions, a lot of chemicals, they are familiar with acids, they are familiar with solutions...they are familiar with salts, then at least they...their understanding will be...

ST1:It will be more meaningful.

ST2: They need concept of chemical reactions so they have something that they can link to in the calculations.

Note 1. The above transcript has been lightly edited to improve its readability.
Some of the difficulties that the curriculum writers in the CPDHD have at each syllabus revision are what to retain, add or remove as changes can create problems for the teaching and learning of particular topics in the revised syllabus. For example, in the sub-topic, ‘Identification of ions and gases’, students are required to test for the gas, sulfur dioxide. However, the reactions which liberate sulfur dioxide are not included in the syllabus. If their teachers do not discuss the reactions, the situation will arise where students have to test for sulfur dioxide but do not know when to test for it, that is, they do not know when the gas will be liberated. Another point of contention is the removal of chemical equilibrium from the present syllabus because the topic was considered difficult at this stage, and that students taking chemistry at the next (pre-university) level will study the topic in greater detail. Driel, de Vos, & Verloop, (1999) does show that chemical equilibrium is difficult for students to understand, and this might be the reason for its removal from the present syllabus.
involve concepts in chemical equilibrium. Thus, students may not be able to make sense of the conditions involved in the Haber and Contact processes and would merely memorize the conditions required unless teachers devote some time to the discussion of chemical equilibrium.

Logical versus psychological order
It can be seen from Table 3 that the schools and textbooks focus on methods of purification and analysis, the particulate nature of matter, chemical formula and equations at the start of the Chemistry 5068 course. Learning chemistry involves “operating on and interrelating three levels of thought: the macro and tangible, the sub micro atomic and molecular, and the representational use of symbols and mathematics” (Johnstone, 2000, p. 9). This is because when changes occur in chemical substances (which may or may not be visible), the underlying mechanisms that account for these changes are developed based on the theories and representations developed by scientists, so the microscopic and symbolic representations “afford certain ways of thinking and talking about underlying entities and processes” (Schank & Kozma, 2002, p. 256). Thus, it is logical to teach particulate nature of matter, bonding, and chemical formula and equation early in the course because chemical phenomena and reactions which are encountered later can then be discussed and interpreted at the microscopic and symbolic levels. For example, teachers ST1, ST2 and ST3 believed that the concept of ions, which was taught in atomic structure, was essential for the understanding of ‘acids, bases and salts’ as the following excerpt shows:

ST3: Acids, bases and salt, whether they have done in the lower secondary…so it is at least not so overwhelming
ST2: Acids, bases and salts form ions
ST3: But at least the ions they must know
ST1: They will understand what hydrogen ions are because you already teach it in the atomic structure
ST2: So it’s like if you…do the atomic structure already…then of course you go into it…they form ions, some of them…you just tie up with the bonding quite naturally rather than split up the bonding and do later on
ST3: Then when we talk about degree of ionization, we talk about…strength of acids, they are able to appreciate the ions…at that point already they don’t question so much…what is ion, because they already done that…they are quite accepting…for us to illustrate the strength of acids with the ions, the dissociation…actually they are quite ok

However, as previously mentioned, microscopic entities such as atoms, ions and molecules cannot be seen, so students have to accept that such things exist. In addition, the learning of these concepts requires “formal operational reasoning in the Piagetian sense, and at the same time pose a heavy burden on students’ working memory” (Zarotiadou & Tsaparlis, 2000, p. 38). Though the students have encountered the particulate model of matter and basic concepts of atoms and molecules in the lower secondary science programme, it is uncertain if they have understood these concepts sufficiently to make sense of the more advanced concepts discussed in upper secondary chemistry. There is also a possibility that the difficult and abstract topics may turn students off chemistry early in the course (within the first six months!) and it may be difficult to motivate students to persevere in their learning of chemistry, especially those who do not intend to pursue further chemical education (Harrison & Treagust, 2002). To help students understand the microscopic and symbolic representations of chemical phenomena, schools tend to use physical models and technology such as multi-media resources and dataloggers as reflected in their schemes of work. Multimedia CD-ROMs and internet websites are commonly used to show animations, for example, of the structure of atoms, bonding and electrolytic processes, and research has indicated that these resources have a positive impact on students’ understanding (e.g. Schank & Kozma, 2002; Wu, Krajcik, & Soloway, 2001). Teachers also use dataloggers in demonstrations and experiments to help students ‘visualize’ certain processes in topics such as energetics and kinetics. For example, research on the use of dataloggers in Singapore (Tan, Hedberg, Koh, & Seah, 2006) shows that dataloggers are commonly used to generate heating, cooling and titration curves, illustrate changes in temperature in exothermic and endothermic reactions, monitor rates of reactions and determine the potential of galvanic cells. The real-time graphical display allows students a glimpse of underlying processes especially where there are no visible changes at the macroscopic level, for example, in neutralization reactions.

The sequence of instruction generally continues with ‘acids, bases and salts’, chemical calculations, periodic table, qualitative analysis, redox, metals, environmental and industrial chemistry, electrochemistry, kinetics, energetics and organic chemistry. ‘Acids, bases and salts’ is the first ‘descriptive’ chemistry topic where students encounter many chemical reactions which they can see in demonstrations or do in experiments; this topic gives students first hand knowledge of the materials and “a feel for the phenomena” (Woolnough & Allsop, 1985, p. 34). Apart from chemical calculations, the other topics also provide macroscopic experience, albeit to varying degrees. Johnstone (2000) and Nelson (2002) argue that the teaching of chemistry should start with the macroscopic level, to make concepts “as concrete and visualisable as possible” (Johnstone, 2000, p. 13). Explanations at the microscopic and symbolic levels could make more sense to students if they are able draw upon and to link these explanations with their experience of chemical phenomena. With appropriate instruction, students can be helped to “develop the link between the macroscopic observations in the laboratory and the microscopic models that chemist used to explain them” (Haidar & Abraham, 1991, p. 932).
Except for School S7, all schools and textbooks discuss organic chemistry towards the end of the chemistry programme, and a possible reason is that organic chemistry is generally considered difficult for beginning students. However, Johnstone (2000) argues the syllabus should begin with organic chemistry as students are familiar with “petrol, camping gas, plastics and foods” (p. 12) and the organic chemistry at secondary level involves only simple bonding concepts, structures and formulae.

**Research on the sequencing of chemistry topics**

The author has been engaging teachers since August 2006 to explore different ways of sequencing the topics in the Chemistry 5068 syllabus. A few teachers are exploring teaching descriptive chemistry topics first before proceeding to the more abstract topics. This is to enable students to be familiar with reagents and reactions so that they can link abstract concepts which they learn later to these reagents and reactions. However, the teachers are concerned with students’ ability to cope with all the abstract and difficult topics or sub-topics if they are ‘bunched up’ together in the latter part of the course.

Other teachers are trying not to teach abstract topics such as chemical bonding as a topic but to ‘drip-feed’ the relevant abstract concepts where applicable when they teach the more descriptive chemistry topics. Instead of teaching atomic and molecular structures as a topic, molecules, ions and dissociation may make more sense to students if they investigate the properties of hydrogen chloride when dissolved in water and when dissolved in toluene in the topic of acids, bases and salts; hydrogen chloride remains as a molecule in toluene but dissociates to form hydrogen and chloride ions in water, and it is the hydrogen ions that give acids their characteristic reactions. Research is ongoing to determine if alternative ways of sequencing the topics help students to understanding chemistry better; teachers will be reluctant to change established sequences of instruction without any evidence that alternative sequences can lead to better understanding of concepts.

**Conclusion**

Formal learning of matter begins in primary school when students are nine years old when they learn that different materials have different properties and link the use of the materials with their properties. In lower secondary science, the students also start with the classification and use of materials followed by topics such as elements, compounds and mixtures, separation techniques and the particulate nature of matter. The spiral curriculum continues in upper secondary when students revisit concepts on separation techniques, element, compounds and mixtures, particulate nature of matter, but in greater detail, before moving on to more complex concepts such as atomic structure, bonding, stoichiometry and periodic trends. This structured curriculum is planned to help students gain better understanding of the concepts in matter that they encounter at various levels. However, the sequencing of learning objectives in a ‘logical’ order by teachers, especially in upper secondary, may pose problems for students as they may not be able to cope with abstract concepts encountered early in the programme, as well as the representational systems that chemists use.

**Notes**

1 URL of the CPDD website: http://www.moe.gov.sg/cpdd/syllabuses.htm
2 URL of the SEAB website: http://www.seab.gov.sg/

**References**


Towards Enhancing Science as Inquiry: A Case Study from Inorganic Chemistry

Kevin C de Berg

Avondale College, PO Box 19, Cooranbong, NSW 2265. kdeberg@avondale.edu.au

Abstract
There has been a strong belief within the science education community since the 1950’s that science education ought to involve students in inquiry processes endemic to scientific practice as opposed to just learning the facts of science. This belief is reflected in the emphasis given to ‘science as inquiry’ in the National Science Education Standards Document (NRC, 1996) and the American Association for the Advancement of Science Benchmarks for Science Literacy (AAAS, 1993). In spite of this commitment to inquiry in our standards documents, it has been reported that students who have completed both a high school qualification and an undergraduate degree may not have experienced such inquiry-based science (Roth, 1998). That is, pre-service teachers are unlikely to have experienced either inquiry methods of teaching and learning or the discipline of science as inquiry in their own science education. In this paper the discipline of science as inquiry is the focus and an account is given of how a traditional laboratory exercise for the preparation of tin (IV) oxide was converted to an inquiry-based laboratory exercise through the use of historical material from the 19th century and through a focus on the status of the guiding principles and assumptions behind the determination of chemical composition.

Introduction
Scientific inquiry is characterized in the National Science Education Standards document (National Research Council, 1996:23) as:
A multifaceted activity that involves observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results.

It is significant that scientific inquiry was recognized as a ‘multifaceted activity’ because, as Grandy and Duschl (2007) point out, it has almost exclusively been associated with the hypothetico-deductive method to the exclusion of other key elements in the inquiry process. They identify these other key elements as theory development, conceptual change, and model construction along with the following caution (Grandy & Duschl, 2007:143): This is not to imply that scientists no longer engage in experiments. Rather, the role of experiments is situated in theory and model building, testing and revising, and the character of experiments is situated in how we choose to conduct observations and measurements; i.e., data collection. The danger is privileging one aspect of doing science to the exclusion of others.

The term ‘inquiry’ has taken on almost an ‘iconic’ status in science education documents (AAAS, 1993; NRC, 1996) to the extent that one might be tempted to think that inquiry processes belonged only to the science discipline and were somehow excluded from all other scholarly endeavours. Surely all other scholarly disciplines feature inquiry otherwise they would not be scholarly? Could not the above statement by the National Research Council defining scientific inquiry also apply, with the possible exception of the word ‘experimental’, to all scholarly disciplines? What is it, then, that sets scientific inquiry apart from historical inquiry, or economics inquiry, or philosophical inquiry? The distinguishing feature must be the subject matter and the special tools by which data is gathered and knowledge is created in the discipline that sets it apart from other forms of inquiry. This is why Joseph Schwab (1962:102) considers that one cannot understand science as inquiry apart from the content of science. Goodrum, Hackling and Rennie (2000:145-146) make this point when they say that, “Inquiry means that students combine these scientific processes with scientific knowledge as they reason and think critically about evidence...”. Rutherford (1964:84) claims that, “To separate conceptually scientific content from scientific inquiry is to make it highly probable that the student will properly understand neither”. It is well argued by Rutherford that scientific concepts such as the universal law of gravitation cannot be separated from the experimental and theoretical inquiries used to produce the law. Unfortunately the impression is often created that inquiry should always take precedence over content in reformed curricula. For example, in a well-intentioned article by Edwards (1997:20) it is stated that in promoting student inquiry, “the focus is on inquiry, not in transmitting science concepts to students”. While the intention of the author is to promote student-centred learning over teacher-centred transmission, the fact that scientific concepts are attached to transmission and not inquiry creates this impression of a divorce between inquiry and content. Rutherford (1964:80) insists that, “the choice is neither facts and laws nor inquiry and process; it is both facts and laws and inquiry and process”.

Although scientific inquiry is sometimes portrayed as a methodical procedure there is universal agreement that
there is no one scientific method or inquiry process in science. Schwab (1962:100) emphasizes the importance of different methods of inquiry within a science discipline and strongly opposes a doctrine of inquiry. “If one ends up with enquiry as involving a uniform procedure it will end up conveying, not science as enquiry, but a doctrine about knowledge and enquiry which is more questionable and less useful than our present dogmatic teaching of science”. Well-intentioned authors [Edwards, 1997:18 for example] still speak, however, about “the step of the scientific method to solve problems...” as if there was one universal procedure for problem-solving. Schwab (1962:102) warned us in his Inglis Lecture even before the great curriculum reforms of the mid to late 1960’s that scientific inquiry is “not a universal logic, it is only a generic envelope for a plurality of concrete inquiries”.

A significant number of inquiry research papers acknowledge the distinction that Schwab (1962) originally made between ‘teaching as inquiry’ and ‘science as inquiry’. Tamir (1983) identifies the latter in terms of what is taught and learned and the former as to how teaching and learning are executed. Rutherford (1964) identified with the distinction by speaking of inquiry as content or inquiry as pedagogic technique. Chiappetta (1997) deals with the two ways of thinking about inquiry in terms of general inquiry and scientific inquiry. General inquiry refers to teaching science by inquiry and scientific inquiry refers to teaching science as inquiry. Boujouade (2004) distinguishes between teaching science as inquiry and teaching science through inquiry and makes the observation that science curricula tend to encourage the latter, what he terms as the ‘doing science’ phase, and neglects the former, what he terms as the ‘minds-on’ or ‘thinking’ science component. Lederman (2004:402) acknowledges the important function of ‘doing science’ but calls for a greater stress on ‘thinking science’ because “a stress on understandings about inquiry is clearly more consistent with the goal of scientific literacy than the more perennial stress on doing inquiry”. This statement is consistent with that made by Schwab (1962:71) forty-two years earlier: “Of the two components-science as enquiry and the activity of inquiring- it is the former which should be given first priority as the objective of science teaching in the secondary school”. However, a number of recently published papers on inquiry (Crawford, 2007; Roehrig, Kruse & Kern, 2007; Zion, Cohen & Amir, 2007) focus on the activity of inquiry rather than on ‘science as inquiry’ and even, in one case, claim Schwab in support. Zion et al (2007: 423) claim that “Schwab (1962) led the way for these reforms by describing inquiry as a way of teaching classroom science”, without acknowledging that Schwab preferred the emphasis to be placed on ‘science as enquiry’, that is, on the nature of science.

To understand what Schwab (1962) meant by ‘science as inquiry’ it is worth re-reading his Inglis Lecture even though it was delivered over forty years ago. It remains, in my opinion, one of the best accounts of science as inquiry. Scientific knowledge is not self-evident (Wolpert, 1992). It depends on what Schwab calls the guiding principles of inquiry, the guiding conceptions, or the special way the scientist chooses to look at the world of nature. According to Rutherford (1964:83), for example, it was the invention of the concept of ‘light ray’ that enabled the law of reflection in a plane mirror to be articulated. “A light-ray is fictitious: its virtue is that it provides a useful way to talk about....the regularity of image reflection. It is the invention of the light-ray as the physical analogue of the Euclidean straight line, and the related acceptance of the correspondence between plane geometry and optical phenomena (rather than the discovery of the rule of equal angles), that was the key step here”. The important point to note is that this conception of light-ray then dictates the nature of what Schwab calls the other constitutive components of scientific knowledge; the experimental techniques; the data obtained; the interpretation of the data; and the conclusions. Schwab strongly emphasizes how important it is for students to understand how difficult it often is to obtain data, how to get reproducible results, and how data are usually interpreted through the conceptions used to produce them. At certain periods in the history of science the conceptions have had to be changed in order to explain anomalous data thus demonstrating the dynamic and fluid character of scientific knowledge. It is partly in this context that Rutherford (1964) and Tamir (1983) suggested that if teachers are to successfully communicate something of the nature of science or science as inquiry to their students they should have some exposure to history and philosophy of science in their professional development.

A number of research studies of teachers participating in the teaching of science through inquiry methods projects (Aschbacher & Roth, 2002; Brown & Melear, 2006; Century & Levy, 2003; Crawford, 1999, 2007; Pine et al., 2006; Roehrig et al., 2007; Windschitl, 2002; Zion et al., 2007) demonstrate how difficult it is to engage school students in inquiry methods. Many of the teachers in these studies commented that they themselves had never experienced either the teaching of science through inquiry or the teaching of science as inquiry in either their undergraduate science studies or science methods courses, in spite of the earlier recommendations of researchers like Tamir (1983). Grandy and Duschl (2007) have recently renewed the call for the inclusion of science as inquiry in college and university science courses. In this paper an attempt is made to illustrate how a traditional college or university inorganic chemistry laboratory exercise might be recast into a format that draws upon some of the important elements of science as inquiry discussed in this introduction. In particular the experimental format for the preparation of tin(IV) oxide will be recast in a way which draws upon relevant history and philosophy of science; focuses on the relevant guiding conceptual principles and assumptions; gives significant attention to the acquisition of data and its interpretation; and illustrates how the ‘rhetoric of conclusions’ (Schwab, 1962) characteristic of much science education portrays a significant falsehood in the way scientific knowledge develops. While the teaching and learning of science as inquiry will be emphasized in this paper, some opportunities for teaching
science through inquiry will also become evident.
This paper describes the first stage of a research project examining how ‘nature of science’ or ‘science as inquiry’ elements might be incorporated into the laboratory experiences of college and university students. The first stage of the project has involved choosing historical material likely to challenge student thinking about chemistry concepts and their underlying principles and choosing an experimental design likely to lead to issues in the interpretation of data. The tin/nitric acid reaction is chosen because it is one of the few metal/nitric acid reactions leading to the production of a solid oxide rather than the metal nitrate. The second stage of the project will examine in detail how students produce and interact with the experimental data and the associated historical material and the results of this stage will be reported at a later date. In this paper we set the framework and rationale for the study.

A Rationale for Choosing Historical Material for this Study
Ian Winchester (1989, p(i)) has observed two distinct tendencies in science teaching in the Western tradition. “The first is to treat science as something with results but without a history…..And the second is to treat science as something which can be nearly completely captured by working examples from a textbook (or by doing recipe-based laboratory exercises—my addition). Both of these activities, namely, dwelling on agreed upon scientific results and standard examples, are important and part of the initiation into the complex of activities involved in a scientific discipline. But they fail to convey to the student……anything of the excitement of scientific discovery, of the conceptual problems involved in forging a new realm of scientific inquiry or of advancing in an old one, of the myriad difficulties of interpretation, theory construction, and abandonment or the moral and aesthetic problems faced in the process”. So if one is interested in providing students with an opportunity to experience ‘science as inquiry’ or ‘the nature of science’, some exposure to its history will highlight how important theory and experiment are, for example, in the formation of scientific knowledge.

For the current project I have chosen to include an excerpt from Jane Marcet’s ‘Conversations in Chemistry’ (1832) which deals particularly with a 19th century view of what happens when a metal reacts with an acid. The excerpt uses the caloric theory of heat to explain the strong emission of thermal energy in the metal/acid reaction and the oxygen theory of an acid to explain that the reaction always leads first to the formation of the metal oxide and then finally to the salt if enough acid is left to dissolve the oxide. This excerpt should, therefore, be most pertinent to the reaction at hand and give students an opportunity to observe how different theories of the past had an important role in explanation. Students are also presented with John Davy’s (1812) preparation of Tin(IV) Oxide so comparisons can be made with their own experimental results.

The Traditional Laboratory Exercise for the preparation of Tin(IV) Oxide used by students in the past
The nature of the traditional laboratory exercise is shown in Figure 1 and forms part of the p-block chemistry course studied by our undergraduate chemistry students in their second year as part of their BSc or BSc/BTech degree course. The students will have completed first-year degree level chemistry.

The Preparation of tin(IV) oxide
1. Weigh accurately, to four decimal places, a crucible and lid. Place about 0.5 gram of finely divided tin in the crucible and weigh accurately the crucible, lid, and contents and determine the mass of the tin to four decimal places.
2. Place the crucible, containing the tin, on a pipe-clay triangle set up in the fumehood. Add dropwise 70% nitric acid until no more brown fumes are emitted. Heat gently until the brown fumes are expelled. Safety Note: Wear safety glasses and gloves.
3. When all the tin has apparently reacted, place the lid on the crucible and heat strongly for five minutes.
4. Allow to cool to room temperature and then weigh the crucible, lid, and contents to four decimal places.
5. Repeat the strong heating for another five minutes, followed by cooling to room temperature and weighing. Repeat until a constant weight is achieved.
6. From your measurements confirm that the buff-coloured product is indeed SnO₂ by determining the mole ratio of tin to oxygen in the compound.

Figure 1.
Traditional instructions for the preparation of tin(IV) oxide.

This exercise is a confirmatory exercise with no inquiry-based features or nature of chemistry features. A set of five results obtained by the author is given in Table 1 for the exercise as written in Figure 1 and is representative of that typically obtained by students for this exercise. Students normally conclude that the product of the reaction is consistent with the formula SnO₂ given some allowance for experimental error. Two important questions that need to be addressed are as follows. Could this laboratory exercise be rewritten in a way that did not assume that one was preparing tin(IV) oxide but where students were required to think about the nature of the possible products of the reaction given their current chemical experience and that drawn from the history of science? Could the typical student data obtained for this exercise (Table 1) be used to challenge the conclusions typically drawn, highlight potential problems in the technique used, and/or challenge the guiding principles and assumptions used by the chemist in an exercise like this? The following is an attempt to answer these questions.
Towards a ‘science as inquiry’ approach to the preparation of Tin(IV) Oxide

One could use an open inquiry approach to answer the question, What happens when concentrated nitric acid is added to tin and, if a reaction occurs, determine what the products of the reaction are? The problem with this approach here is that one is asking students to complete, over a period most likely no longer than a laboratory session of three hours or at most a semester, a task which took chemists hundreds of years to complete. I have therefore chosen to structure the inquiry in such a way that important background knowledge is made available to the student as a preliminary step in the whole process. This background knowledge highlights the guiding principles used by a chemist when studying matter and its chemical composition and deals with some practical laboratory matters pertinent to the investigation. As mentioned in the introduction, this is a critical part of the nature of science and the teaching and learning of science as inquiry. The guiding principles and assumptions need to be highlighted if they are to be later questioned or confirmed. Specifically, the background knowledge made available to students contains practical advice on how to perform a metal-acid reaction; the problems associated with using concentrated nitric acid on metals and the related reason as to why 70 percent nitric acid is used; thinking of composition in terms of mass percentage of metal and non-metal parts; thinking of composition in terms of atoms and the related mol percentage of atoms of the elements; the law of constant composition; and the existence of two oxidation states of tin (tin(II) and tin(IV)) with the possibility of compounds possessing both oxidation states. A ‘science as inquiry’ approach to the preparation of tin(IV) oxide, developed from a study of the science education and history of science literature and the author’s experience with this reaction over a number of years, is now outlined as follows.

This ‘science as inquiry’ approach does not identify the solid product of the reaction but challenges the student to think through the process to the likely nature of the product after having read the background information and an historical account of the reaction of metals in the presence of acids. The investigation is therefore inquiry-based but is structured to the extent that quantities of materials are stipulated in the procedure which is reproduced in Figure 2. This is the scenario currently used with my science students and relies on the background information specified previously.

### Table 1. Five results (R1-R5) obtained by the author for the exercise in Figure 1.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass of tin/g</td>
<td>0.4891</td>
<td>0.5085</td>
<td>0.5023</td>
<td>0.5319</td>
<td>0.5198</td>
</tr>
<tr>
<td>mass of product/g</td>
<td>0.6061</td>
<td>0.6384</td>
<td>0.6265</td>
<td>0.6554</td>
<td>0.6479</td>
</tr>
<tr>
<td>mass of oxygen (non-metal)/g</td>
<td>0.1170</td>
<td>0.1299</td>
<td>0.1242</td>
<td>0.1235</td>
<td>0.1281</td>
</tr>
<tr>
<td>mol Sn: mol O</td>
<td>1: 1.77</td>
<td>1: 1.90</td>
<td>1: 1.83</td>
<td>1: 1.72</td>
<td>1: 1.83</td>
</tr>
<tr>
<td>mass% oxygen (non-metal)</td>
<td>19.3</td>
<td>20.3</td>
<td>19.8</td>
<td>18.8</td>
<td>19.8</td>
</tr>
</tbody>
</table>

An investigation of the product of the reaction between tin and concentrated nitric acid

1. Weigh accurately, to four decimal places, a crucible and lid. Place about 0.5 gram of finely divided tin in the crucible and weigh accurately the crucible, lid, and contents and determine the mass of the tin to four decimal places.
2. Place the crucible, containing the tin, on a pipe-clay triangle set up in the fumehood. Add dropwise 70% nitric acid until no more brown fumes are emitted. Heat gently until the brown fumes are expelled.
3. When all the tin has apparently reacted, place the lid on the crucible and heat strongly for five minutes.
4. Allow to cool to room temperature and then weigh the crucible, lid, and contents to four decimal places.
5. Repeat the strong heating for another five minutes, followed by cooling to room temperature and weighing. Repeat until a constant weight is achieved.
6. From your measurements you need to ascertain the formula of the solid product of this reaction by determining the simplest whole number mole ratio of the elements in the product and/or by determining the mass percentage of metal and non-metal and comparing with values determined for possible formulae.

As a start, to help you with this determination, you need to think about what happens in a metal-acid reaction. Study the following account of a metal-acid reaction given by Jane Marcet in 1832 and answer the accompanying questions. When you have done this determine the nature and formula of your product from your results.

Jane Marcet was a frequent attendee of the public chemistry lectures given by Humphry Davy and Michael Faraday at the Royal Institution in London and developed a love and skill for writing chemistry dialogues. Her account (Marcet, 1832) of what happens when an acid is added to a metal is most entertaining and is reproduced in Figure 3. She reflects Lavoisier’s view of acids as oxygen carriers and also the caloric model of heat which regarded heat as a material substance without weight. The conversation is between Emily, Caroline, and Mrs B. As students read this account, they are asked to consider the following questions.

1. According to Marcet all acids contain which element in common?
2. What substance corresponds to the thick yellow vapor observed when nitric acid was added to copper? Did you also get this colored vapor on mixing tin with nitric acid?

3. How does Marcet use the material theory of heat (heat is caloric) to explain the evolution of heat in the metal-acid reaction? Before you answer this question you may want to read the summary of the caloric theory of heat provided. The summary given to students refers to caloric as a massless fluid possessed by all elements and compounds with gases possessing more caloric than liquids which possess more caloric than solids. Converting solids to liquids to gases involves gaining caloric and converting gases to liquids to solids involves releasing caloric. The more caloric possessed by a substance per unit volume the higher its temperature will be.

### Emily:
Metals have, then, three ways of obtaining oxygen; from the atmosphere, from water, and from acids.

**Mrs B:**
The two first you have already witnessed, and I shall now show you how metals take the oxygen from an acid. This bottle contains nitric acid; I shall pour some of it over this piece of copper leaf....

**Caroline:**
Oh, what a disagreeable smell!

**Emily:**
And what is it that produces the effervescence and that thick yellow vapor?

**Mrs B:**
It is the acid, which, being abandoned by the greatest part of its oxygen, is converted into a weaker acid, which escapes in the form of a gas.

**Caroline:**
And whence proceeds this heat?

**Mrs B:**
Indeed, Caroline, I think you might now be able to answer that question yourself.

**Caroline:**
Perhaps it is that the oxygen enters into the metal in a more solid state than it existed in the acid, in consequence of which caloric is disengaged. The effervescence is now over; therefore I suppose that the metal is already oxidated.

**Mrs B:**
Yes. There is another important connection between metals and acids, with which I must make you acquainted. Metals, when in the state of oxides, are capable of being dissolved by acids. In this operation they enter into a chemical combination with the acid, and form an entirely new compound.

**Caroline:**
But what difference is there between the oxidation and the dissolution of the metal by the acid?

**Mrs B:**
In the first case, the metal merely combines with a portion of oxygen taken from the acid, which is thus partly deoxygenated, as in the instance you have just seen; in the second case, the metal, after being previously oxidated, is actually dissolved in the acid, and enters into a chemical combination with it, without producing any further decomposition or effervescence. This complete combination of an oxide and an acid forms a peculiar and important class of compound salts.

**Emily:**
The difference between an oxide and a compound salt, therefore, is very obvious; the one consists of a metal and oxygen; the other of an oxide and an acid.

**Mrs B:**
Very well: and you will be careful to remember that the metals are incapable of entering into this combination with acids, unless they are previously oxidated; therefore, whenever you bring a metal in contact with an acid, it will be first oxidated and afterwards dissolved, provided that there be a sufficient quantity of acid for both operations.

### Figure 3. Jane Marcet's dialogue on the metal-acid reaction

4. What is Marcet’s understanding of the structure of a salt?

5. Marcet identifies two stages in the reaction between a metal and an acid. What are the two stages? Were these two stages observed in the reaction between tin and nitric acid? Explain.

Having read the Marcet dialogue and answered the questions students are then requested to use this knowledge and their experimental results to determine the formula of the solid product.

From the background information given to students, prior experience of chemical reactions, and Marcet’s dialogue, students, on reflection, are expected to suggest the possibility of nitrate or oxide as the product of the tin-nitric acid reaction. If students have difficulty arriving at this conclusion, and some students do have difficulty, they are asked to read the Marcet dialogue again and to review their answers to the questions associated with the dialogue. The way students respond to this challenge will be studied in more detail in the second phase of this research project. Only preliminary details of student responses are available at this stage but the responses are detailed enough to suggest that not all students will find this challenge easy. Given that tin can form tin(II) and tin(IV) compounds, one might expect the possibility of nitrate or oxide each in two possible oxidation states. Also, there is the possibility of mixed oxides, that is, oxides containing both oxidation states of tin in oxides like Sn$_3$O$_6$[Sn(II)O:Sn(IV)O$_2$] and Sn$_3$O$_7$[2Sn(II)O:Sn(IV)O$_3$]. At this point students are encouraged to write down the formulae for the possible products of the reaction. Having thought of up to about six possible formulae students are asked to determine if any of these formulae are consistent with the mass percentage of metal and non-metal determined experimentally. Six examples and their metal and non-metal mass percentages are shown in Table 2. Unlike copper, iron, zinc, and lead, it is clear from the typical results for mass percentage of non-metal in Table 1 that tin does not produce the nitrate salt but forms a composition closest to the dioxide (SnO$_2$).
While this analysis should lead students to the result that SnO$_2$ is the most likely product of the reaction, one has to ask whether considerable doubt could accompany this conclusion given the range of student data typically obtained and shown in Table 1. What might cause the molar ratio of tin to oxygen to be not quite equal to 1:2 or the mass percentage of oxygen to be not quite equal to 21.3%? Could the experimental average molar ratio of 1:1.81 be explained by the presence of unreacted tin, or the presence of a small amount of SnO in addition to SnO$_2$? These ideas can be checked by asking students to assume that 10 percent of the product by mass was either unreacted Sn or incompletely oxidized SnO, for example, and see if this reduces the molar ratio of tin to oxygen from 1:2 to 1:x where x is less than 2. These are ideas that students will not necessarily think of but they can be challenged to check the possibilities through calculation. As it turns out the calculation yields a tin to oxygen molar ratio of 1:1.77 for unreacted tin in the product and a ratio of 1:1.86 for the presence of SnO in the product. Both possibilities therefore lead to a tin to oxygen molar ratio in the direction of the experimental results. There is often more than one possibility that might fit a scenario and students need to confront this aspect of the nature of science and think about how one might decide between the possibilities. The possibilities listed here are actually in the form of hypotheses that are accessible to students and can be tested. Other possibilities exist, of course, but it is essential that not too many alternatives are presented as this can confuse students. One other possibility will almost certainly present itself to students and that is the question of the accuracy of the experimental technique. This is usually the first possibility that students consider when questioned about the experimental results. In what sense could the experimental technique be improved and do suggested changes lead to more congruent results? This exercise illustrates how difficult the acquisition and interpretation of data can be in chemistry.

### Table 2. Formulæ and mass percentage for six different proposed products of the tin-nitric acid reaction.

<table>
<thead>
<tr>
<th>Compound (Molar mass)</th>
<th>Mass% Sn</th>
<th>Mass% O or NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO (134 g mol$^{-1}$)</td>
<td>88.1</td>
<td>11.9</td>
</tr>
<tr>
<td>SnO$_2$ (150 g mol$^{-1}$)</td>
<td>78.7</td>
<td>21.3</td>
</tr>
<tr>
<td>Sn$_2$O$_3$ (285.4 g mol$^{-1}$)</td>
<td>83.2</td>
<td>16.8</td>
</tr>
<tr>
<td>Sn$_3$O$_4$ (420.1 g mol$^{-1}$)</td>
<td>84.8</td>
<td>15.2</td>
</tr>
<tr>
<td>Sn(NO$_3$)$_2$ (242 g mol$^{-1}$)</td>
<td>48.8</td>
<td>51.2</td>
</tr>
<tr>
<td>Sn(NO$_3$)$_3$ (366 g mol$^{-1}$)</td>
<td>32.2</td>
<td>67.8</td>
</tr>
</tbody>
</table>

Another important consideration here is whether the law of constant composition could be rightly challenged given the spread of compositions shown in Table 1. Could the atomic hypothesis used to produce the molar ratios in Table 1 and the mass percentage compositions in Table 2 also be challenged? Are the experimentally determined compositions close enough to those expected to warrant the retention of these well-known guiding principles? Many students initially have difficulty with such questions because they are accustomed to a science education where answers are either correct or incorrect. What about situations like that presented here where it might be difficult to judge whether there is a legitimate basis to challenge a law? This does give students an opportunity to express an opinion related to some experimentally determined data, and to learn that the interpretation of data is not always a straightforward matter. A number of chemists of the 19th century, including the great French chemist Berthollet, were not convinced of the law of constant composition, for example, and believed composition could change continuously within certain limits. Dalton, on the other hand, believed that composition was invariant unless there was a different atomic combination. That is, Dalton viewed changing composition as a discontinuous phenomenon based on atomic theory, while Berthollet viewed changing composition as a continuous phenomenon (Leicester, 1971:155). What is important here is that, based on the data in Table 1, students can be led to sympathise with the struggles early chemists had in coming to terms with the notion of compound composition and the notion of matter as atomic in nature. An important lesson in interpreting data is the observation that the scientific profession would be in utter chaos if long-standing laws were overthrown as soon as someone produced results which seemed to challenge the laws. It is not until a large number of studies point in the direction of an anomaly that laws are seriously challenged.

Early 19th century chemists did explore the reaction between tin and nitric acid with varying degrees of success (de Berg, 2008). John Davy, brother to Sir Humphry Davy, describes the reaction as follows (Davy,1812:194).

42.5 grains of tin, which had been precipitated from the muriat (chloride) of this metal by zinc, were heated with nitric acid in a platina crucible, and slowly converted into peroxide; the acid and water were driven off by gentle evaporation at first, and afterwards by a strong red heat continued for a quarter of an hour. The peroxide thus produced was of a light yellow colour, and being very gradually dried, it was semi-transparent, and hard enough to scratch glass; it weighed 54.25 grains. Hence, as 42.5 grains of tin acquire, on conversion into peroxide, 11.75 grains of oxygen, this oxide appears to contain 21.66 per cent of oxygen,…. His mass percentage of oxygen (21.66%) is a little closer to the theoretical SnO$_2$ value (21.3%) than the results in Table 1 (18.8-20.3%) but it is difficult to compare the results adequately given the level of accuracy of weight measurements in 1812. Nevertheless the description is very interesting from three points of view; firstly, that of the mass units used (grains) in the early 19th century in England. The grain measure of mass has its origins in agricultural antiquity when a single seed of a typical wheat or barley cereal was used as a unit (grain) for mass. Given the variability of such a mass, the grain was eventually standardized to represent precisely 64.79891 milligrams. This is equivalent to 0.015.43 grains per gram. So students can now calculate the gram mass of tin that John Davy used in his experiment. Some medications in the USA still quote their active ingredients in grain units. For example, aspirin is labelled as 325 mg (5 gr) per tablet.
A second interesting feature of Davy’s description is his preparation of tin for the reaction with nitric acid. Why did he not use already available samples of tin, a metal which had been known from antiquity? And what is the chemical equation for his preparation of tin? Finally, the colour of the SnO₂ prepared corresponds to that found in the five experiments leading to the data in Table 1. But the colour quoted in the SI Chemical Data book (Aylward & Findlay, 2008:86) is white. Now it is true that when the nitric acid is first added to the tin a white solid product forms but this changes to a light yellow or buff colour when strongly heated. It is interesting that Davy also observed this.

Conclusion
Grandy and Duschl (2007:158) summarize current research findings in science teaching as follows. “Research shows that prevailing models of science teaching are lesson based rather than unit based, emphasize concept learning rather than knowledge system learning, and focus inquiry lessons on completing experiments rather than on testing and revising explanatory models”. One can see just from the illustrations given in this paper that inquiry processes take time and will mean choosing to reduce content coverage to accommodate inquiry processes. This may be another reason why teachers are reluctant to engage in deep inquiry processes in the classroom. As Grandy and Duschl (2007:158) continue to say, “The unfolding of data and evidence takes time and is another reason why effective inquiry units are longer in length. By pausing instruction to allow students to discuss and debate what they know, what they believe and what evidence they have to support their ideas, their thinking is made visible thus enabling the monitoring and assessment of the communication of information and of the thinking”. This orientation to teaching and learning does produce a dilemma for the tertiary chemistry educator. There is a perceived need to give students access to the breadth of knowledge and skills in the discipline so that they emerge from their formal education with a comprehensive understanding of chemistry concepts and, in addition, be equipped for a range of roles in the chemistry profession. On the other hand new demands are being placed on chemistry educators to reduce breadth in order to increase the depth of knowledge and intellectual skills along the lines described by Grandy and Duschl. One cannot really argue against such demands for intellectual skills which address the epistemological issues of big-picture chemistry, particularly if we are in the business of education as opposed to training, but like many other recommendations in education the challenge is to try to achieve some balance between both approaches.

This paper has attempted to show how some of the concerns voiced by Schwab over 40 years ago, and more recently described by Grandy and Duschl (2007), might be addressed in an inorganic chemistry laboratory and class session. The scenario introduced here potentially gives an opportunity for students to sympathise with some of the challenges chemists faced in the 19th century in coming to terms with the atomic view of matter and the nature of chemical composition. There is much labour and research required in the advancement of chemical knowledge and students should experience some of this dynamic character of knowledge production if they are not to view chemical knowledge as a ‘rhetoric of conclusions’. The second phase of this project will entail an in-depth study of the way students engage in this kind of experience. What specific difficulties do students relate when they are challenged to think about the security, origin, and nature of their knowledge and the discipline’s knowledge base? How do students engage with historical material? Is their picture of chemistry more enlightened by such an approach? It is hoped that the analysis offered in this paper will encourage chemistry educators to persevere with attempting to introduce students to chemistry as inquiry because, if philosophers like Schwab are correct, the benefits should outweigh potential difficulties for both teacher, student, and the discipline of chemistry. The second phase of the project should shed some light on this prospect.

Notes
Moles of tin can be calculated from the mass of tin used. If one assumes that the increase in mass of the crucible contents is due only to the addition of oxygen, then moles of oxygen atoms can be calculated from the mass increase.

The use of very concentrated nitric acid with metals tends to place an impervious oxide layer on the surface of the metal thus preventing reaction of all the metal present. Seventy percent nitric acid is strong enough to react all the metal vigorously but not so strong to cause the reaction to cease.

Marcet’s mechanism described here reflects Lavoisier’s understanding of acid action on a metal. Other alternatives are possible of course. For example, the nitrate of tin could be formed initially and when heated strongly could form the oxide. Lead nitrate, for example, forms PbO₂ when heated.

Kane (1851:370-371) also reports a pale yellow colour for the peroxide of tin. “It is most readily prepared by pouring the liquid nitric acid, sp.gr. 1.42 on metallic tin, in foil or powder; the action is very violent, and the metal is totally converted into a white powder, which is the hydrated peroxide. By ignition the water is given off; and the anhydrous oxide remains of a pale yellow colour”.

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includes ion pairs. This form is known as Onsager’s “triangle reaction” network (8). The relationships between equilibrium constants then are: \( K_{sp} = [Na^{+}][Cl^-] = K_1 K_2 K_3 = 1 \), where \( K_1 \) and \( K_2 \) involve (NaCl) \( _{(aq)} \) contact ion pairs which are not the most abundant species present; hence \( K_1 \) and \( K_2 \) values would be <1 which in turn will make the \( K_{sp} \) value >1. However, the important point to note is that the product of \( [Na^+][Cl^-] \) is still constant and our original definition of solubility product remains valid. However, since the [Na+] and [Cl-] concentrations are smaller than in V1 due to the presence of ion pairs the solubility product should be smaller than V1 prediction.

The best value for \( K_{sp} \) is then obtained from V2 because the activity coefficients account for non-ideality of solutions caused by various secondary processes.

There are several messages and pedagogically important issues arising from this work. First, how can the concept of chemical equilibrium learnt in Year I and applied to ideal solutions be applied outside this narrow textbook context (i.e. sparsely soluble salts). Second, the work highlights the effects of extreme conditions (e.g. high ion concentrations of saturated solutions) on the behavior of species involved in the equilibrium, i.e. the difference between ideal and non-ideal solutions. Third, it demonstrates to students how a seemingly simple question whose answer can be obtained by plugging numbers into the known equation subsumes a wealth of important chemical concepts.

The subject of this article also involves lateral thinking by encouraging students to link and relate concepts like equilibrium, activity coefficient, molar concentration, ion hydration and ion-pair formation. This lateral thinking is brought about by the expansion of understanding of a known concept as new material is being learnt.

References


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Emerging issues from textbook analysis in the area of chemical kinetics

Gultekin Cakmakci

Faculty of Education, Department of Science Education, Hacettepe University, Ankara, Turkey
cakmakci@hacettepe.edu.tr

Abstract
This paper discusses how an empirical study on students’ ideas about chemical kinetics and on the analysis of documentary evidence can contribute to teaching and learning chemical kinetics in schools and universities. A number of issues were identified that appeared to serve as barriers to students in developing more appropriate ideas about the notion of chemical kinetics. Specifically, some of the conceptual difficulties encountered by students appear to be associated with imprecise, inconsistent, or insufficient information in the textbooks. Some possible implications for teaching are proposed in the light of the results.

Key words: Chemical kinetics, multiple representations, critical details of science contents.

1 Introduction:
In recent years, significant research has been conducted on students’ ideas on a range of science concepts, and thus science educators have become increasingly aware of the importance of this domain-specific research (Palmer, 2006; Duit, 2007; Cakmakci, 2008). Accordingly, they have started making use of such information in order to improve science teaching and learning (Leach & Scott, 2002; Viennot, 2003; Leach et al, 2006). Nevertheless, transforming findings from research into classroom practice and bridging the gap between outcomes of the research on students’ domain-specific knowledge and the practice of science education, has presented a challenge (Duit & Treagust, 1998; Viennot et al, 2005). Several reasons have been identified for this situation (Gilbert et al, 2004; Viennot et al, 2005). For instance, in some cases teaching materials (e.g. textbooks) do not consider students’ difficulties. In other cases, teachers are not given sufficient guidance to transform findings from research into classroom practice or the linkage between certain “critical details” of practice (Viennot et al, 2005; Viennot & Kamiński, 2006) and the fundamental rationale of a teaching sequence are not easily understood by teachers. We agree with the view that developing effective teaching activities and curriculum development are essentially a research activity (Duit et al, 1997) and that “critical details” (Viennot, 2003) of a particular science content (i.e. an analysis of a particular content to be taught) is a key issue in the development of teaching activities. Bearing these points in mind, this paper discusses how an empirical study on students’ ideas about chemical kinetics and on the analysis of documentary evidence can contribute to teaching and learning chemical kinetics in schools and universities. A number of issues were identified that appeared to serve as barriers to students in developing more appropriate ideas about the notion of chemical kinetics. Specifically, some of the conceptual difficulties encountered by students appear to be associated with imprecise, inconsistent, or insufficient information in the textbooks. An analysis of some popular chemistry textbooks used in some other countries also suggested similar findings. Therefore, the findings of the study contribute to Turkish chemistry education, as well as being of broad interest internationally. As a result, the information produced from the present study can be drawn upon by teachers, textbook writers, and curriculum designers in other countries when planning more effective teaching activities in the area of chemical kinetics and in other areas of chemistry.

2 Methodology
This paper extends the author’s previous studies (Cakmakci, 2005; in press; Cakmakci et al, 2005; Cakmakci et al, 2006) on the evaluation of secondary and undergraduate students’ conceptual understanding of chemical kinetics in the light of the aims of the Turkish chemistry curriculum.

One component of the research contains a detailed analysis of the curriculum for chemical kinetics so as (1) to identify the key scientific ideas in chemical kinetics, (2) to explore the types of explanations (or representations) that have been provided in the textbooks, (3) to explore the ways in which the explanations are related to the scientific explanations, (4) to specify their limitations (Duit et al, 1997), and (5) to identify the intended development of the subject within the school and university courses in Turkey.

A further component includes the empirical investigation of students’ conceptual understanding of chemical kinetics. The sample included 108 upper secondary school students (ages 15-16) in three classes from two schools, 48 university first-year students, and 35 university third-year students. Open-ended diagnostic questions were used as a main data collection instrument in conjunction with individual interviews with a number of students. Our investigation of students’ understanding of chemical kinetics suggests that a part of the students’ difficulties rests with the nature of chemistry itself (i.e., the abstract and complex structure of explanations of chemical change), but more seems to stem from the ways by which
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the concepts are customarily taught without regard to what is known about students’ learning and about the content structure of the domain (Cakmakci, 2005: in press; Cakmakci et al. 2005; Cakmakci et al. 2006). Some of the knowledge and representations in the textbooks is found to be compatible with common students’ misconceptions in kinetics. Hence, “critical details” (Viennot, 2003) of chemical kinetics become crucial for teaching and learning kinetics. Bearing these points in mind, this paper aims to analyse chemistry textbooks by considering the content structure of chemical kinetics and students’ difficulties in this field.

2.1 Analysis of the curriculum

Within the educational literature, there are different curriculum representations. For instance, Goodlad (1994) classified curriculum as societal or system level (macro); institutional or school level (meso); and classroom level (micro) (quoted by van der Akker, 1998, p. 421). In a similar view, three models of the curriculum have been propounded: the intended curriculum, the implemented curriculum and the attained curriculum (Third International Mathematics and Science Study [TIMSS], 1999). The intended curriculum is that laid down in official documents such as the National Curriculum of Turkey. Evidence of the intended curriculum can be obtained from analysis of official documents or textbooks. The implemented curriculum is the actual instructional process in the classroom. Evidence of the implemented curriculum can be obtained from systematic observation of lessons, analysis of students’ notes or interviews with teachers. The attained curriculum (i.e., outcomes of the curriculum) is concerned with the knowledge, skills and understanding exhibited by students, whether acquired in the classroom or outside it.

Turkish school students follow a common science curriculum, which is developed and approved by the Ministry of National Education. However, there is no national or centralized curriculum for universities in Turkey. Thus, with respect to the curriculum, although there is no written national curriculum available for universities, textbooks can be seen as the intended curriculum for universities. Therefore, for this study, data for the intended curriculum were obtained from analysis of the school science curriculum and school and university chemistry textbooks. In addition, teachers and lecturers’ written lesson plans were collected and analyzed. Data for the implemented curriculum were obtained through an analysis of students’ notes and interviews with teachers and lecturers. Data for the outcomes of that curriculum in terms of students’ learning were obtained from the analysis of diagnostic tests and existing data (e.g. examination papers) as well as interviews with students and teachers/lecturers. The outcomes of that curriculum are reported in Cakmakci (2005; in press) and Cakmakci et al. (2006).

Textbooks define much of the content, sequence and aims of the curriculum (Behar, 1994). Textbooks have a role in both the intended and the implemented curricula. In Turkey, school textbooks follow the intended curriculum very closely. Chemical kinetics is first introduced in the curriculum in secondary school; therefore, these chemistry textbooks (Kizildag & Dursun, 2000; Kizildag et al, 2007) were analyzed. Chemical kinetics is taught again in detail in the first-year in a general chemistry course and in a general chemistry laboratory course in a five-year pre-service chemistry teacher-training program. Furthermore, the concept is introduced in a physical chemistry course and in a physical chemistry laboratory course in the third year of the teacher-training program. Therefore, a content analysis of these undergraduate textbooks ( Mortimer, 1989; Sarikaya, 1997; Atkins, 2001; Chang, 2000) and the laboratory books (Alkan et al, 1996; Gurses & Bayrakceken, 1996) was also undertaken.

3 Results and discussion

3.1 Conceptual analysis of chemical kinetics

Conceptual analysis of the domain suggested that it is premised on the idea that the rates of chemical reactions can be explained by a qualitative approach (particulate modelling) and may also be understood in terms of a quantitative approach (mathematical modelling) (Cakmakci et al., 2006). These two approaches are interconnected in some levels. The relationship between chemical phenomena and theories/models is shown in Figure 1. The framework depicted in Figure 1 reflects others used in the literature such as Logan’s (1984) distinction between the empirical and theoretical level of chemistry, Johnstone’s (1991) distinction between macroscopic, sub-microscopic and symbolic levels in chemistry, and Tiberghien’s (2000) distinction between the world of objects/events and the world of theories/models. The aspects of Figure 1 were taken into consideration during content analysis of chemistry textbooks. For instance, as reported later in this paper, in some areas of the domain there were such large gaps in the presentation that the students appear to have little possibility of understanding the relationships between different modes of representations (i.e. macroscopic, particulate and mathematical modelling) without additional input from teachers.

![Figure 1](image.png)

**Figure 1.** The relationship between chemical phenomena/events and theories/models

3.2 Emerging issues from textbook analysis

A number of issues have been identified that appeared to serve as barriers to students in developing more appropriate ideas about the notion of reaction rate. Evidence is presented to support the following claims. First, an imprecise usage of the terms such as “reaction
rate” is found in the school textbook. Second, there is a mismatch between different forms of representations in the area of kinetics. Finally, relationships between different forms of representations are not explicitly addressed in the curriculum.

3.2.1 An imprecise usage of the terms
The term “rate” is often used to describe the change in a quantity that occurs per unit of time. Students have experience of the term “rate” in their everyday lives (e.g. the rate of inflation) or in their schooling (e.g. the rate of a reaction, the rate of dissolving). The rate of a reaction is commonly expressed in three different forms: the initial rate of a reaction, the instantaneous rate of a reaction, and the average rate of a reaction over a time interval. Nevertheless, an analysis of school textbooks and undergraduate laboratory books indicated that the differences between these terms are overlooked. In most cases, only one term is used for the others, such as the “initial rate” being termed as the “average rate” or termed as the “rate”. For instance, as presented in Table 1, “initial rate” (in Turkish “Baslangic Hizi”) is termed as “rate” (in Turkish “Hiz”) in a question (Kizildag & Dursun 2000, p.105; Kizildag et al, 2007, p.19; Gurses & Bayrakceken, 1996, p.73). The question requires students to determine the rate law from (initial) concentrations and (initial) rates.

The results of our empirical research suggested that many school students could not differentiate “the instantaneous rate” and “average rate” (Cakmakci, 2005; Cakmakci et al, 2006). Many school and undergraduate students did not anticipate that a reaction may have different rates during a reaction. In fact they tended to use the term reaction rate instead of using average reaction rate, but actually what was meant was the instantaneous rate. In addition, the term “reaction rate” was used differently in different contexts by the students. In fact, when we, as science educators, use terminology in kinetics, we make some assumptions (i.e. we also use the word with different meanings in different contexts). For example, when we ask students “how would a rise in temperature affect the reaction rate?”, we assume that students understand what we are talking about (actually we are asking “how would a rise in temperature affect the average reaction rate?”). However, we cannot be sure they really understand what we meant. Another example is that when we ask students “how would the reaction rate change during the reaction?” we actually mean “how would the instantaneous rate change during the reaction?” As science educators, we use the same term with different meanings in different contexts (i.e. in the examples given above, the reaction rate is used referring to the average reaction rate in one question and referring to the instantaneous rate in the other). The main claim here is that students’ understanding of the notion of reaction rate and an appreciation of differences between these terms are essential for understanding the dynamic nature of the reaction system and other related concepts in kinetics. During teaching and in the textbooks the differences between these terms needs to be acknowledged and the teacher should monitor whether students understand the differences between these terms/ concepts. This is one of the fundamental issues for teaching the notion of reaction rate.

Table 1. An imprecise usage of a term in the school textbook: “initial rate” (baslangic hizi) is termed as “rate” (Hiz) (Source: Kizildag & Dursun 2000, p.105)

Another issue emerge from textbook analysis was related to an imprecise definition of the term catalyst. Students’ responses to the written questions revealed that many students believed that a catalyst did not react with any of the reactants or products (Cakmakci, 2005). One of the reasons for this would be scientifically imprecise definition of the catalyst used in the school textbooks, which defines catalysts as “…a substance that changes reaction rate without entering into the reaction” (in Turkish: “Kendisi tepkimeye girmediği halde, tepkime hızını değiştiren maddeleva, katalizor denir.”) (Kizildag & Dursun 2000, p.108; Kizildag et al, 2007, p.13). This kind of scientifically imprecise statement can promote misconceptions about the mechanism of catalysis. Therefore, a more comprehensible definition for a catalyst would be that a catalyst is a substance that works by changing the mechanism of a reaction in that it actually reacts with the one or more of the reactants present or adsorbs reactant molecules (cf. van Driel & de Vos 1989, in Justi 2002). It should be emphasized that a catalyst affects the rate constant and the activation energy of a reaction.

3.2.2 There is a mismatch between different forms of representations
Chemical kinetics is one of the areas in chemistry where several different pictorial representations are used. Our results, however, indicate that students often did not interpret the pictorial representations used in the textbooks appropriately and failed to grasp the underlying scientific knowledge expressed through pictorial representations (Cakmakci et al., 2006). Some forms of representation containing characteristics that may lead students to misconceptions were also identified. For instance, school textbooks do not explicitly or implicitly present how a catalyst affects the mechanism of a reaction, nor do they explain the nature of the catalytic process. The effect of a catalyst on reaction rates is usually mentioned as on the diagram shown in Figure 2 (Sarikaya, 1997, p.728; Chang, 2000, p.539; Kizildag & Dursun 2000, p.109; Kizildag et al, 2007, p.14). Such diagrams do not depict the most important feature of catalysed reactions, that catalysed reactions involve sequences of several activated complexes and intermediates (Haim, 1989). Such diagrams, which do not provide sufficient evidence for the mechanism of a reaction, can give students the
impression that the catalysed and uncatalysed reactions proceed via the same mechanism (a one-step mechanism). Indeed, these diagrams and representations might be one of the reasons for students’ lack of knowledge and for their commitment to scientifically incorrect arguments about the notion of catalysis (Cakmakci, 2005).

Some popular chemistry textbooks used in other countries (Hill & Holman, 1995, p.415; Atkinson & Hibbert, 2000, p.109; Zumdahl & Zumdahl, 2003, p.589; Malone, 2004, p.428; Timberlake, 2004, p.206; Chang, 2005, p.567) also introduce the effect of a catalyst on reaction rates based on the diagram shown in Figure 2.

It is proposed that there should be greater consistency between different forms of representation and that the limitation of each representation needs to be acknowledged. For example, the nature of the catalytic process would be explained at the sub-microscopic and also at the symbolic level (Johnstone, 1991). At present, there is often a mismatch between different forms of representations. For instance, equations for the catalysed and uncatalysed reactions would be as follows:

The equation for without a catalyst:

\[ \text{O}_2(g) + \text{O}^*(g) \rightarrow 2 \text{O}_2(g) \]

The equations for a catalysed reaction are given below

(Cl\textsuperscript{•} (atomic chlorine radical) is the catalyst for this reaction). The mechanism can be divided into two steps:

Step 1: Cl\textsuperscript{•} reacts with ozone to form ClO\textsuperscript{•} and O\textsubscript{2}

\[ \text{Cl}^*_{(g)} + \text{O}_3(g) \rightarrow \text{ClO}^*_{(g)} + \text{O}_2(g) \]

Step 2: ClO\textsuperscript{•} reacts with O\textsubscript{2} to produce Cl\textsuperscript{•} and O\textsubscript{2}

\[ \text{ClO}^*_{(g)} + \text{O}^*_{(g)} \rightarrow \text{Cl}^*_{(g)} + \text{O}_2(g) \]

Overall: \[ \text{O}_3(g) + \text{O}^*_{(g)} \rightarrow \text{Cl}^* \rightarrow 2 \text{O}_2(g) \]

The catalyst, Cl\textsuperscript{•} (atomic chlorine radical), gets involved, initiating a sequence of reactions and yet is regenerated. From those equations the catalysed reaction occurs in “two steps”, however in terms of the energy profile graph (see Figure 2) both the catalysed and uncatalysed reactions occur in “one step”. Therefore, these two forms of representations are not consistent with each other (e.g. see Malone, 2004, p.428).

Drawing upon a content analysis of the domain and an empirical investigation of students’ conceptions, an alternative approach for teaching the concept of catalysis is proposed with the aim of overcoming the learning difficulties identified in our study (Cakmakci, 2005). By attempting to provide a more comprehensible approach for teaching the concept of (homogeneous) catalysis, it might be more fruitful to teach the role of a catalyst in reaction mechanisms as on the diagram shown in Table 2.

This involves making it clear that a catalyst is a substance that works by changing the mechanism of the reaction in that it actually reacts with the one or more of the reactants/products. The figure with the reaction mechanisms given in Table 2\textsuperscript{1} may help students to understand the role of catalysts in chemical reactions. Writing a catalyst in the chemical equation may help students to understand that a catalyst enters into the reaction; however, at the end of the reaction it undergoes no permanent change. For example, the depletion of ozone in the stratosphere by chlorine atoms can illustrate the action of a homogeneous catalyst. This example is chosen since the depletion of ozone layer is a current issue in chemistry/the environment (Kotz & Treichel, 1996; Ebbing & Gammon, 1999) and it includes social and economic issues. It, thus, presents opportunities to weave content and context together and to demonstrate the importance and relevance of content for the life of individual and society. This would help students to understand the relationships between the content and context (Mahaffy, 2004). It is important to note that the proposed multiple representation of the action of a homogeneous catalyst is conceptually demanding. It requires students to make connections within and across different representational forms (Mayer, 2003), and to do so in a much more deliberate, explicit and consistent way than appears currently to be the case. During teaching, the role of the teacher is crucial. Critically, this role involves helping students to move between different forms of representations. Critically, this role involves helping students to move between different forms of representation.

\textsuperscript{1}It should be noted that this is not a new idea. There are good examples in some chemistry textbooks. For example, Kotz and Treichel (1996, p.733-739), Ebbing and Gammon (1999, p.590-591) and Hill et al. (2005, p.558) also introduce the effect of a catalyst on reaction rates based on the diagram shown in Table 2. What is novel in our approach is that links between different forms of representations are made more explicit during teaching and representations containing characteristics that can be problematic for proper understanding of the concept of catalysis are taken into account (Kim & Van Dusen, 1998).
Depletion of the Ozone Layer

Ozone (O$_3$) presents in the ozone layer in the stratosphere and provides protection against biological destructive, short-wave-length ultraviolet radiation from the sun. Higher levels of radiation resulting from the depletion of the ozone layer have been linked with increases in skin cancers and cataracts. Mario J. Molina and F. Sherwood Rowland (1974) discovered that the depletion of ozone in the stratosphere partly results from the Cl-catalysed decomposition of O$_3$ and it is for this work that they later in 1995 shared the Nobel Prize in Chemistry. Chlorine atoms in the stratosphere originate from the decomposition of chlorofluorocarbons (CFCs), such as CCIF$_3$ and CClF$_2$.

At one time, CFCs were used widely as refrigerants, solvents for degreasing, spray-can propellants, and blowing agents for making plastic foams. Usage of CFCs is banned in many nations, in fact its use is spreading to Third World countries, such as the nations of Africa and many in South America, and its availability has a profound effect on their economies.

The equation for **without a catalyst:**

\[
O_3 (g) + O^* (g) \rightarrow 2 O_2 (g) \quad E_a = 17.1 \text{ kJ/mol}
\]

The equations for a **catalysed reaction are given below** (Cl• (atomic chlorine radical) is the catalyst for this reaction). The mechanism can be divided into two steps:

**Step 1:** Cl• reacts with ozone to form ClO• and O,

\[
Cl^* (g) + O_3 (g) \rightarrow ClO^* (g) + O_2 (g) \quad E_a = 2.1 \text{ kJ/mol}
\]

**Step 2:** ClO• reacts with O• to produce Cl• and O,

\[
ClO^* (g) + O^* (g) \rightarrow Cl^* (g) + O_2 (g) \quad E_a = 0.4 \text{ kJ/mol}
\]

**Overall:**

\[
O_3 (g) + O^* (g) \xrightarrow{Cl^*} 2 O_2 (g) \quad E_a = 2.1 \text{ kJ/mol}
\]

### 3.2.3 Relationships between different forms of representations are not explicitly addressed in the curriculum

Analysis of textbooks indicate that the effect of temperature or the effect of a catalyst on reaction rates is usually introduced on an energy vs. reaction coordinate graph (an energy profile diagram) (see Figure 3) and on the Maxwell-Boltzmann energy distribution graph (see Figures 4-5). The way in which each of these representations needs to be thought about is different: while the energy profile graph is a portrayal of "a single reaction" event, the Maxwell-Boltzmann energy distribution graph represents the distributions of the average energies of "many particles". Specifically, making links between these two pictorial representations or making transformations between them is a demanding process which students may find it difficult to perform (Bucat, 2004). Indeed, the school textbooks (Kizildag & Dursun 2000; Kizildag et al, 2007) neglected to make links between or to specify the differences between these two pictorial representations.

A popular chemistry textbook used in the United Kingdom (AS Chemistry for AQA, Atkinson & Hibbert (2000, p.108-109)) also neglected to specify the differences between these two pictorial representations.
Although the Maxwell-Boltzmann energy distribution graph is conceptually demanding, the characteristics of the graph (i.e. explicit interpretations of the graph) and the reasons for its use are overlooked in the textbooks (e.g. see Kizildag & Dursun 2000; p.107; Kizildag et al., 2007; p. 12-13). In fact, it is questionable whether the Maxwell-Boltzmann energy distribution graph is at all necessary in elementary courses so as to introduce the effect of temperature on reaction rates. Instead, it might be more appropriate to introduce school students to the effect of a change in temperature on reaction rates by using principles of the kinetic molecular theory, collision theory and of the transition state theory. That would be easier to be understood by school students and would be more efficient in use of teaching time.

Another point related to representations is that the relationships between different forms of representations (i.e. macroscopic, particulate and mathematical modelling) are not explicitly specified in the curriculum. Very limited contextualised situations or problems (i.e. phenomenologically framed problems) (Driver & Erickson, 1983) are constructed in the textbooks and in the examinations papers. The school curriculum rarely includes an approach that presents students opportunities to weave content and context together. Nevertheless, providing more opportunity to practice using context-based problems/activities (as suggested earlier in table 2) would help students to relate chemical principles to everyday life and the natural phenomena (as suggested by Holman & Pilling (2004), in thermodynamics). One of the claims for context-based approaches is that using everyday context as starting points and employing a wide range of activities in lessons can stimulate students’ motivation in chemistry (Ramsden, 1997).

4 Conclusions

It has been said that “a picture is worth a thousand words” and in some cases that is true. In the teaching and learning process, however, the role of pictorial representations is far from being so clearly positive (Viennot & Kaminski, 2006; Potgieter et al., 2008). Research on students’ difficulties concerning the reading of images suggest that some misleading textbook images are likely to infect students with misconceptions (Pinto & Ametler, 2002; Viennot, 2003). As discussed in this paper, some of the pictorial representations which are a priori criticisable as regards a proper understanding of kinetics are likely to lead students to misconceptions (see Figure 2). The scientific knowledge which is shared by the scientific community and by the educational system community would be different from each other in some levels (Tiberghien, 2000). The types of explanations or representations that have been introduced in the curriculum may include simplifications of scientific explanations shared by scientific community. For instance, the “one-step” energy profile diagram for catalysis (see Figure 2) is extensively used around the world at upper secondary level. At university level the more-than-one-step representation of transition states (see Table 2) is introduced, usually without being explicit that it is different from the other representation, which is in fact an (incorrect) simplification and likely to infect students with misconceptions. A possible recommendation for restructuring teaching, then, is to make the relationships between different forms of representation explicit (Bucat, 2004) and to support students’ use of diverse representations interchangeably. Teachers need some explicit knowledge of the significance of different modes of representation (Erduran & Duschl 2004) (what might be called “meta-knowledge” of the domain and representation) and require a range of pedagogical strategies in order to make these links explicit in teaching. Teachers should be aware that a pictorial representation is worth a thousand words only if the learner appropriately interprets and grasps the underlying scientific knowledge expressed through the pictorial representation.

The results of the study suggest that many students’ conceptual difficulties in chemical kinetics stem from inadequate or inaccurate models of the molecular world (Cakmakci, 2005; Cakmakci et al., 2006). This might be supported by experimental work, but with respect to representational models, computers can be used to assist students’ understanding of the process of chemical reactions at the sub-microscopic level more directly (Russell et al., 1997; Reid et al., 2000; Tasker et al., 2002; Tasker & Dalton, 2006). For instance, simulations of the behaviour of specific models (e.g. pathways taken by atoms and molecules as a reaction proceeds in the presence and absence of a catalyst) or animations that portray reaction mechanisms at the sub-microscopic level could all be used. There is considerable evidence to show that using multimedia and multiple external representations can improve students’ conceptual understanding in chemistry.
(Wu, 2003) and can stimulate students’ motivation and interest in chemistry (Tasker & Dalton, 2006).

Based on theoretical and empirical insights about learning, we have proposed some suggestions for teaching the concept of chemical kinetics. Of course, the most important requirement for this or any other research-based approach to teaching (Duit et al, 1997; Leach et al, 2006) is to develop and implement the teaching activity proposed, and to assess learning outcomes. As a result, the components of the teaching activity can be modified and reconstructed.

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An inexpensive mini-colorimeter for undergraduate science laboratories

Dietmar Kennepohl and Martin Connors

Centre for Science, Athabasca University, 1 University Drive, Athabasca, Alberta, Canada, T9S 3A3, dietmark@athabascau.ca

Abstract
Construction of a portable and inexpensive mini-colorimeter using a light emitting diode (LED) source is described. Two examples of its use in a teaching laboratory are given. The apparatus can be used in a simple kinetics experiment suitable for first-year general chemistry or can also be used to illustrate Beer’s law which is suitable for both senior high school and first-year university.

Key Words
Laboratories and demonstrations, general chemistry, colorimetry, electronics, distance education, Beer’s law, kinetics

Introduction:
Access to quantitative instrumental experiments for introductory chemistry, physics or biology that does not involve substantial fiscal commitment is an ongoing challenge for science educators. It would be advantageous to have a small portable instrument that can readily be introduced and used by new students at both the senior high school and undergraduate level. Ultraviolet and visible absorption spectroscopy is a powerful technique for characterizing and determining the concentration of molecules and ions in colored solutions. In the past, bench top spectrophotometers used in teaching laboratories, such as the Spectronic 20, have an incandescent source (continuous wavelengths) and use a prism or grating system to define more specific wavelengths for the absorption experiment. For the purpose of our home-study laboratories in our Athabasca University distance education chemistry course such an instrument would not be practical to send to remote students [1]. To meet this need, we have developed our own inexpensive mini-colorimeter that can be used effectively to demonstrate Beer’s Law and carry out a simple kinetics experiment.

A portable and inexpensive mini-colorimeter can be built using a light emitting diode (LED) source and a small light-to-voltage optical sensor that gives direct readout in volts.

There are currently basic commercial spectrometers available that are more compact than the Spectronic 20. They use combinations of tungsten bulb and/or LEDs as a light source ($1200-4000 US). There are also commercial colorimeters available that are based on various colored LED light sources ($120-200 US). Simple LED colorimeters have also been previously constructed for other types of teaching laboratories. For example, they have been used to perform automated photometric titrations [2] or to detect aqueous metal ions of Ni, Cu, and Co [3]. In both cases, the students were in an undergraduate electronics laboratory course where they were first expected to build their instrument before using it to analyze solutions. Performance differences in using LEDs versus spectrophotometers do exist [4] and some of the advantages and limitations of using LEDs for use in simple colorimeters have also been previously reported for an undergraduate instrumental analysis laboratory [5]. Still, for the purpose of the teaching experiments described herein the use of LED colorimeters is quite acceptable.

We describe the design and construction of a simple mini-colorimeter, which exploits recent advances in electronic technology and only costs about $10 US (Figure 1). We also provide two examples of the application of this instrument in a first-year university general chemistry course; namely (1) illustrating Beer’s law and (2) carrying out a simple kinetics experiment.

Figure 1: Simple mini-colorimeter in use.

The Apparatus
The basic requirement for the experiments described is to supply light in an appropriate wavelength range whose interaction with the sample may be accurately measured. To make a very simple and inexpensive piece of equipment, a single wavelength is used, and light with a narrow range of wavelengths is easily obtained from a light-emitting diode (LED). Detection of the light after passing through the sample is best done with an integrated light-to-voltage optical sensor that gives direct readout in volts.

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The Apparatus
The basic requirement for the experiments described is to supply light in an appropriate wavelength range whose interaction with the sample may be accurately measured. To make a very simple and inexpensive piece of equipment, a single wavelength is used, and light with a narrow range of wavelengths is easily obtained from a light-emitting diode (LED). Detection of the light after passing through the sample is best done with an integrated light-to-voltage optical sensor that gives direct readout in volts.
A device with good properties was the Texas Instruments TSL250. This device is now obsolete but readily available on the surplus market [6]. It has been replaced by the Texas Advanced Optical Systems TSL250R, which has similar characteristics, but which cannot operate from a supply beyond 6 V. We use TSL250 from old stock, since a 9 V battery is used as a power supply suited to shipping to distance education home laboratory students, and the TSL250 can take a supply voltage up to 10 V. However, it would be a simple matter to use a 6 V lantern battery, or several AAA cells in a readily available holder if a battery powered system based on the TSL250R is made, or power from a regulated power supply in a lab setting. The advantages of these devices are stability, simplicity, broad spectral range allowing use with various LEDs appropriate to different reactions, sensitivity, convenient packaging, and, despite all of these advantages, a price that is usually below one dollar. At Athabasca University, we have used these sensors in both Physics and Chemistry home lab kits for many years. A 9 V battery is preferred to a power supply for safety reasons, and it is of course very light and easy to send to students. LEDs are available in a number of colors, and their emission spectra may be found on the web [7] and compared to that appropriate to the chemical complex under study. For example, the tetraaquasalicylatoiron(III) reaction described below is well studied using a generic green LED (Figure 2).

Figure 2: The absorption spectrum of the of tetraaquasalicylatoiron(III) complex with the emission spectrum of the green LED superimposed.

An LED is run forward-biased and must have a current-limiting resistor placed in series with it. By using a variable resistor, the intensity may be varied so as not to saturate the output of the TSL250 when there is no absorption. The LED must be housed so as to shine directly through a small test tube onto the detection surface of the TSL250. We arranged this by using a small block of wood drilled to hold a small test tube, and drilled with a small hole at right angles to that, right through the block of wood to provide a light path from the LED on the one side of the block of wood to the TSL250 on the other side (see Figure 3). The final circuit component is a switch for activation of the LED and TSL250. When short measurements are needed, such as for Beer’s law where the concentration of a solution is changed several times, followed by a rapid measurement of absorbance, a pushbutton switch is appropriate; when a series of measurements are taken continuously during a reaction, a throw switch may be more appropriate. In order to use the apparatus under normal lighting conditions, yet provide access to change solutions, everything was housed in a black plastic file box. The equipment is all readily available and comes to a total cost of under $10 US, with the battery being the most costly component.

Figure 3: Line drawing of the colorimeter.

Figure 4 shows the simple circuit which allows the implementation of a low-cost system for light absorption measurements. As noted above, we used a 9 V ‘transistor radio’ battery with a TSL250, but if a newer TSL250R is used, the voltage should not be greater than 6 V. In this diagram the negative terminal is shown at the bottom and it is important to respect the polarity. The LED portion of the circuit will simply not work if connected backwards, but the TSL250 could be damaged. The values of other components are also rather arbitrary. Use of a variable resistor (VR) is suggested; we used a trimpot of value 100 kilohms, but this was likely set very near 0 and a smaller value can be used. Resistor R1 limits the current flow through the forward-biased LED and should not be smaller than 330 ohms and likely not larger than about 1000 ohms. The LED, as mentioned, is selected to be appropriate to the reaction under study. In our case a generic green LED was used. The arrow near the LED represents light emitted by it. The LED should be placed with the sample holder between it and the TSL250. The switch may be placed at any point in the circuit. If placed as shown, it controls only the LED and the battery should be removed when the circuit is stored. The TSL250 draws little current and apart from storage may be left connected as shown here. The TSL250 has a small lens on its top. It should be connected as shown when seen from above. The output is measured between the negative (“ground”) leftmost pin of the TSL250 and its rightmost pin.

Figure 4: The circuit is made from few parts and takes advantage of the sophisticated yet low-cost circuitry in the TSL250 light-to-voltage converter chip. VR indicates a variable resistor, R1 is about 330 ohms, and the LED is selected for appropriate color for the reaction under study. The circuit is described in more detail in the text.
The Experiments

**Beer’s Law to Determine Acetylsalicylic Acid**

A spectrometer allows you to shine light of known wavelength through a solution, and to measure how much light of that wavelength is absorbed by the solution. This measurement is dependent upon concentration (c) of the species in solution, the path length of light (b), and the molecular absorptivity of the compound (ε). These factors are related to absorbance (A) by the Beer-Lambert law (Beer’s Law).

\[ A = εbc \]

This relationship has formed the basis of a classic teaching laboratory in chemistry where the student constructs a calibration curve by preparing and measuring the UV/Vis absorption, at a given wavelength, of a series of solutions of known concentrations. The concentration of an unknown sample of the same species is then determined by measuring its UV/Vis absorption, at that same wavelength, and comparing it to the calibration curve. The mini-colorimeter uses small Pyrex test tubes rather than standard 1 cm square cuvettes, which means we cannot determine ε (extinction coefficient). However, we are only interested the absorbance response to concentration (i.e. Beer’s law). The value of εb should be approximately constant throughout. We also insure this by identical positioning the same test tube for each measurement. One serendipitous advantage of using a test tube rather than a standard cuvette is that the curvature of the test tube produces a definite lensing effect that delivers more light to the sensor from the LED source. The resulting increased intensity outweighs any reduction in light through refraction or reflection processes on the curved surfaces.

We use the mini-colorimeter in our teaching laboratories to determine the actual percentage of acetylsalicylic acid (ASA) in a commercial aspirin tablet. (This determination is done again in a later experiment in the same course using a simple acid-base titration.) Since ASA itself is colorless in solution, we react it with base, acid, and then FeCl$_3$·6H$_2$O to form an intensely violet tetraaquasalicylatoiron(III) ion, which absorbs strongly at 525 nm. Students are asked to carefully make up five known concentrations of this iron complex solution (approximately 8 × 10$^{-5}$ to 2 × 10$^{-3}$ M) using a stock acetylsalicylic acid solution they prepare from pure ASA that has been weighed out. After constructing a calibration curve of absorbance as a function of tetraaquasalicylatoiron(III) ion concentration, they work up a 325 mg aspirin tablet in a similar manner to determine the percentage ASA it contains.

Graph 1 shows millivolts versus concentration of a series of tetraaquasalicylatoiron(III) ion (Fe-ASA) complexes measured using our mini-spectrophotometer. There is a strong correlation between measured voltage-concentration response and the theoretical response based on Beer’s law. Note that the transmittance (T) is proportional to the voltage readout, but there is a logarithmic relation with absorbance (A) described by A = −log(T/100). The full experiment entitled “Experiment A2: Use of a Simple Spectrophotometer” can be found in Athabasca University’s CHEM 217 laboratory manual and accessed online (http://science.pc.athabascau.ca/labinfo.nsf/testmenu4?OpenFrameSet).
we can write the rate law as a pseudo first-order rate law.

\[ \text{rate} = -d[R^-]/dt = k[R^+] \]

(2)

where \( k' = k[\text{OH}^-] \)

Since we are essentially measuring the absorbance (A) of the R\(^+\) ion, which is proportional to its concentration (Beer’s law), we can integrate and express Equation 2 as:

\[ \ln A_t = \ln A_0 - k' t \]

(3)

A single run with a plot of \( \ln A \) versus time will allow the student to ascertain that the reaction is indeed pseudo first-order (straight line observed) and obtain values for pseudo rate constant \( k' = \text{slope of the line} \). Remaining runs, using different OH\(^-\) concentrations, will allow determination of the order of reaction with respect to hydroxide concentration \( m \). A plot of the observed rate constants \( k' \) versus hydroxide concentration at 21°C gives a calculated second order rate constant of 1.4 M\(^-1\) s\(^-1\), which is comparable with the 1.33 to 2.18 M\(^-1\) s\(^-1\) range of values reported in the literature [9-11]. In all cases, we limit the discussion for first-year chemistry students to distinguish between first and second order behaviour.

Graph 2 shows a plot of \( \ln A \) versus time for a series of hydrolysis reactions of malachite green having different initial hydroxide ion concentrations (1.31 \( \times \) 10\(^{-3}\), 1.63 \( \times \) 10\(^{-3}\), 2.56 \( \times \) 10\(^{-3}\), 3.41 \( \times \) 10\(^{-3}\) M). The first 500 s of each run shows excellent linear correlation (\( R = 1.00 \)), but then deviates slightly after that as the R\(^-\) is consumed. It is recommended that data collection by students be limited to the first ten minutes of each run.

Graph 2: \( \ln A \) versus time for the hydrolysis of malachite green. Each run contains a different initial hydroxide ion concentration. Maximum absorption set to \( t = 0 \) s and straight lines are best fit for first 500 s of data.

Schneider has developed an elegant version of this kinetic experiment using both crystal violet and malachite green [12,13]. Measurements are carried out using Spectronic 20 and 21 spectrophotometers. With these instruments, it is important that students take a fresh sample of the reaction mixture for each individual measurement. Leaving a sample for too long in the warm environment of the spectrophotometer varies the temperature of the sample enough to make the resulting kinetic data unreliable. In contrast, the amount of heat generated by the LED light source in the mini-colorimeter is negligible. Whether the LED light source is used continuously or intermittently there is little difference in the measurements.

Student Response

The kinetics experiment using the mini-colorimeter is newly developed and has not been fully evaluated. However, the Beer’s law experiment has been incorporated into the regular part of our first-year chemistry course for a number of years. The mini-colorimeter is sent out as part of the home-study laboratory kit for students. One vital feature of the home-study kit that should be noted is the accompanying instructional CD containing indexed video clips. Although all the safety instructions and information to carry out each experiment are available in the printed laboratory manual, the CD is an effective medium to emphasize safety and demonstrate experimental techniques. It provides a closer connection between the student and the content by reinforcing the text in the laboratory manual, making the experiments less daunting, and giving the students more confidence in carrying out the experiments.

In previous years we did the same Beer’s Law experiment in this course in supervised on-campus laboratories using a Spectronic 20. The students working entirely at home were surveyed and asked about their laboratory experience at the end of their course. Their perception was quite positive (average score 4.2 out of 5) when asked if instructions were easy to follow, if it was easy to obtain all equipment, if the experiment was interesting, and if course material was reinforced. Many also freely commented on the flexibility and stress-free environment the home-study experiment offered. The performance of students carrying out this experiment with the mini-colorimeter at home was also tracked over several years and compared with the performance of students carry out the experiment on campus in a supervised laboratory. Even though grades slightly increase with the home-study students, both the survey and the course performance statistics indicate that the home-study laboratory mode is essentially equivalent to our earlier supervised laboratories.

Summary

The mini-colorimeter described herein is an inexpensive and easy to operate instrument that can be used both in the laboratory and off campus as a home-study laboratory. The instrument provides experimental results that correspond well with Beer’s law. It also is readily adapted to perform simple kinetics experiments. As such it provides a good alternative to using more sophisticated UV/Vis spectrophotometers in a teaching laboratory for senior high school and undergraduate science.

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Comparison of two different remediation methods for contaminated water treatment.

M. A. Rauf and S. Salman Ashraf

Department of Chemistry, P O Box 17551, UAE University, Al-Ain, UAE, email salman.ashraf@uaeu.ac.ae

Abstract

There is a pressing need to ensure that chemistry students are educated about the various environmental issues facing us. Organic pollutants, in the form of synthetic dyes, are a serious threat to the marine environment and need to be dealt with effectively. It is therefore not surprising that a host of economical and bio-friendly approaches have been developed to degrade dye-contaminated waste water resulting from extensive use of dyes in various industries. Among these approaches are various "Advanced Oxidation Processes" that can be employed for remediation of waste water, with the Fenton, Photolytic, Photo-Fenton, Photo-catalytic and Ozonolysis being the most common ones. This paper describes a relatively simple experiment (that can easily be incorporated in a general chemistry lab) comparing the efficiency of degradation of Neutral Red dye by two different advanced oxidation processes: namely, the photolytic method and the Fenton process. The degradation of the dye can be monitored using a spectrophotometer that is available in all teaching labs. Both the processes degraded the dye efficiently in course of time. However, the rate of degradation of the dye was faster with Fenton’s reagent. The underlying principle of dye degradation by reactions of OH radicals generated in solution is emphasized. This experiment not only shows the students how chemistry can actually be used to solve a very important environmental issue, but also integrates aspects of analytical chemistry (UV-Vis spectroscopy) with physical chemistry (kinetics and rate-orders).

Keywords

Dyes, Pigments, Degradation, Photolysis, Fenton’s reagent, Advanced Oxidation Processes, Kinetics, UV-Vis Spectroscopy, First-Year Undergraduate, General Chemistry Laboratory

Introduction:

Synthetic organic dyes are an integral part of many industrial processes (1-2). Many of these dyes have an adverse effect on the environment when they become a part of the industrial effluent. Small amounts of these dyes can cause damage to aquatic life and many other organisms which are exposed to these dye containing water bodies (3). It is therefore necessary to treat the effluents before they are discharged to main streams. Various approaches in this regard have been suggested to treat the effluents. These include adsorption (4), coagulation (5), ultrafiltration (6), etc. However all of them end up as sludge or with secondary waste material which in itself is an environmental hazard to deal with. Advanced oxidation processes (AOP’s) are techniques which are based on destroying the macromolecules by introducing some external reagent which can react with the targeted molecule and convert it into environmentally friendlier smaller molecules (7,8). Many suggestions in this regard have been proposed, however simple approaches include the photolytic degradation (9) and the use of Fenton’s reagent (10). The former involves dilute hydrogen peroxide and UV light to initiate the reaction, whereas the latter demands dilute sulfuric acid and ferrous sulfate solution. All the reagents required for this work are easily available and can be handled safely by students in the lab. Treatment of aqueous solutions containing dyes has been reported as an undergraduate laboratory experiment (11-13). However there is no literature citation on the comparative efficiencies of two different AOP’s to help undergraduate students to understand the working nature of two different techniques. This paper demonstrates the use of two different techniques namely the Photolytic method and the Fenton method to decolorize the Neutral Red dye solution (C.I name is Basic Red 5) (Figure 1). Both the techniques can be used as a laboratory experiment to treat the dye solution and remove its color. However because of the inherent difference in the two approaches, the results are remarkably different in each case.

![Figure 1. Structure of Neutral Red dye](image)

Experimental Procedure

**Reagents required**

Neutral Red, hydrogen peroxide (10 mM and 1 M solutions) and dilute sulfuric acid (0.1 M), iron(II)sulfate solution (0.1 M)

**Instrument requirement**

Hand-held UV lamp, spectrophotometer, micropipettes

**Glassware requirement**

Volumetric flasks, cuvettes

**Method**

1) Photolytic process

In the first step, the students are asked to prepare a stock Neutral Red dye solution (2 mM), which will be further diluted to give a final working concentration between 50 -100 uM. The absorption spectrum of the dye solution is then obtained using a standard spectrophotometer. It is suggested that a quartz cuvette is used in this step so that the students can see that the dye not only has an absorption peak in the visible region, but also has
a distinct absorption peak in the UV region. All the subsequent experimentation can be carried out using a glass cuvette or even a disposable plastic cuvette and the spectral monitoring be restricted to the visible region (380-800 nm). The $\lambda_{\text{max}}$ of the dye solution will be noted by the student (in this case it should be around 540 nm). To a given amount of working solution of dye (e.g., 2.95 mL of 65 µM dye) in a 4-ml cuvette, 50 µl of 1 M hydrogen peroxide is added and the mixture is scanned again. Addition of $\text{H}_2\text{O}_2$ should not cause any significant decrease in the absorption spectrum of the dye solution. This dye/$\text{H}_2\text{O}_2$ mixture is then exposed to 254 nm UV radiation using the hand-help UV lamp. Figure 2 shows a typical set-up that can be used for this sort of study. At specific time intervals (ranging from 2 minutes to 5 minutes), the cuvette is carefully removed from under the lamp and the solution is scanned again to obtain the absorbance spectra of the solution. Exposure to both $\text{H}_2\text{O}_2$ and UV radiation should cause production of hydroxyl radicals which then react with and degrade the dye, as a result, a decrease in the absorbance of the dye will be observed as a function of time. Figure 3 shows results from a typical experiment in which Neutral Red solution is being decolorized by the photolytic method.

2) Fenton process

Remediation of dye using the Fenton process is carried out similarly as the photolytic process described above. In a 4-ml cuvette containing the dilute dye solution (e.g., 2.94 ml of 65 µM NR solution), 10 µl of 0.1 M FeSO$_4$/1 mM H$_2$SO$_4$ is added and the mixture is scanned in the spectrophotometer. Addition of the acidic Fe$^{2+}$ solution to the dye should not cause any decrease in the absorbance of the dye. With the cuvette in the spectrophotometer, 50 ul of 10 mM H$_2$O$_2$ is carefully and added and quickly mixed. Immediately the students are to start taking 5 second scans of measurements of the absorbance of the dye. Addition of H$_2$O$_2$ to the acidic Fe$^{2+}$ solution starts the Fenton process, which results in the production of hydroxyl radicals, which in turn reacts and degrades the dye, as shown in Figure 4.

3. Possible extensions/variations

The dye decoloration and degradation is basically dependent on the availability of hydroxyl radicals in solution, so there are many factors that can affect hydroxyl radical production and availability and hence dye degradation. Therefore, one can easily try “playing” with various factors such as light source, UV distance from the dye solution, affect of ions, dye concentration etc… as possible extensions of the experiment described here. (Reference 8 describes the results from a systematic study carried out to examine the effect of various parameters on Crystal Violet degradation and would be a very useful reference to use in this regard.)

If these extensions and variations are carried out, then they would also provide an excellent discussion point at the end of the experiment by comparing and discussing the results of the different groups.

Data Analysis

Both the procedures of dye degradation as outlined above will generate spectra in which the absorbance value of the solution would become less with time. The student will note the decrease in the absorbance of the dye spectra and with the help of MS EXCEL, plot the change in dye absorption value with time (Figure 5). This change in absorbance value which corresponds to the amount of dye degradation would then be calculated with the MS EXCEL program by the following formula:

\[
\% \text{ degradation} = \frac{[A(\text{initial})-A(\text{final})]}{A(\text{initial})} \times 100
\]

(1)

where $A(\text{initial})$ is the absorbance value of dye solution before the start of the experiment and $A(\text{final})$ is absorbance value of dye solution after a given interval of time.
Figure 5. Decoloration of Neutral red dye solution by photolytic treatment

The absorbance value in both the above experiments would also be subjected to kinetic analysis. This again would utilize the MS EXCEL program. The absorbance value of the dye solutions will be calculated as ln values and plotted against time. This is done because the decoloration fits the pseudo first order kinetics of the reaction which is mathematically given by

\[
\ln[A_{\text{final}}] - \ln[A_{\text{initial}}] = -kt
\]  

A plot of \(\ln[A_{\text{final}}]\) against time should generate a straight line with a negative slope. From the slope of the line one can calculate the apparent rate constant value \(k\) of the reaction, as shown in Figure 6. A quick comparison of the \(k\) values generated by this exercise would reveal that it has a higher value in the case of Fenton’s process as compared to the photolytic process. This can be rationalized on the basis that in the Fenton’s process, the dye is degraded faster as compared to in the photolytic process (Table 1).

Table 1. Relative efficiencies of decoloration of NR by Photolytic- and Fenton-Advanced Oxidation Processes

<table>
<thead>
<tr>
<th>AOP method (([\text{NR}] = 65 \text{ mM}))</th>
<th>Apparent rate constant (sec(^{-1}))</th>
<th>% Decoloration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photolytic (6.7 mM H(_2)O(_2) + UV)</td>
<td>(1.1 \times 10^{-3})</td>
<td>84 % (30 min)</td>
</tr>
<tr>
<td>Fenton (0.17 mM H(_2)O(_2) + 0.34 mM Fe(^{2+}))</td>
<td>(13 \times 10^{-3})</td>
<td>88% (in 5 min)</td>
</tr>
</tbody>
</table>

Although both processes involve the production of \( \cdot \text{OH} \) radicals (which are involved in dye degradation), the concentration of these radicals are presumably more in the Fenton’s process which account for a higher \(k\) value. The overall reaction scheme involved in this experiment is as follows:

\[
\text{a) Photolytic process} \quad \text{H}_2\text{O}_2 + h\nu \rightarrow 2 \cdot \text{OH} \quad (3)
\]

\[
\text{Dye + } \cdot \text{OH} \rightarrow \text{intermediates} \rightarrow \text{degraded products} \quad (4)
\]

\[
\text{b) Fenton process} \quad \text{H}_2\text{O}_2 + \text{Fe}^{2+} \rightarrow \cdot \text{OH} + \text{OH}^- + \text{Fe}^{3+} \quad (5)
\]

\[
\text{Dye + } \cdot \text{OH} \rightarrow \text{intermediates} \rightarrow \text{degraded products} \quad (6)
\]

It should be noted that the Photolytic approach is more bio-friendly and aligned with Green Chemistry principles than the Fenton approach (which uses Fe\(^{2+}\) and H\(_2\)SO\(_4\)). However, the Photolytic approach is very slow and is not practical when large amounts of waste-water need to be treated. The Fenton approach, though not as benign, is faster and more practical in such cases. In fact, this can be a class discussion point that for the sake of practicality one has to sometimes choose a less bio-friendly approach (for the greater ‘good’).

Learning Objectives

1. To raise awareness of the environmental issues with regards to pollution of water bodies by organic pollutants, such as textile dyes.
2. To highlight “Chemistry at Work” by showcasing a possible solution (AOP - Advanced Oxidation Process) that can be used to address this environmental issue.
3. To prepare solutions of known concentrations for different chemicals.
4. To measure absorbance spectra of solutions.
5. To use EXCEL program for data analysis.
6. To demonstrate the use of kinetic equations for calculation purposes.
7. To compare the efficiencies of two different AOPs towards dye degradation.

Learning Outcomes

1. The student will become aware of chemical (and possibly more bio-friendly) ways to treat waste-water.
2. The student shall learn to prepare solutions of different concentrations.
3. The student will learn the use of spectrophotometer to measure absorbance values of solutions.
4. The student will learn the use of EXCEL program for data analysis.
5. The student will learn the use of kinetic equation as applied to a particular case.

Outcomes Assessment

The learning outcomes can be assessed and judged by using assessment tools such as lab report, in-class discussion, and perhaps most importantly, a short theoretical quiz and lab practical exam towards the end of the semester. In the quiz, the students can be asked to explain/list different environmental contaminants, specifically with regards to water pollution and ways to treat such contaminated water bodies. They can also be given some data and asked to do various data manipulation operations, plot the data on a graph paper provided as well as to use MS-EXCEL (or other appropriate software) to carry out linear-regression. In the lab practical exam, the students can be assessed to
see if they can use a spectrophotometer by themselves to measure the absorbance of various solutions which they will need to make themselves from a stock solution. They can then be asked to make an “Absorbance vs. Concentration” graph to see the linearity of their measurements (Beer-Lambert Law). Of course, individual instructors can further fine-tune these additional tools or use additional assessment tools.

Safety requirements and hazards
1. The students should use gloves, safety glasses and lab coat during the course of the experiment.
2. Dyes are highly colored compounds and should only be handled by using spatulas.
3. Proper care should be taken when using sulfuric acid and other reagents.
4. Hydrogen peroxide is a strong oxidizing agent and proper care is necessary not to spill it on your clothes or hands.
5. The students will use UV lamp for radiation. The students will take every precaution not to look directly at the emitted light or expose any part of their body to UV radiation.

Summary
The experiment described here is intended to be taught in a general chemistry lab and can be used to raise the awareness of environmental issues and how chemistry can provide “real” solutions to “real” problems as opposed to just providing academic information. The experiment is simple and easy enough to be adopted easily in the laboratory courses and will give chemistry students many valuable skills. In addition, this experiment provides many opportunities for in-class discussions to highlight various environmental and practical issues with regards to waste-water treatment.

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Solubility Product of NaCl

Igor Novak

Charles Sturt University, Orange NSW 2800, Australia, inovak@csu.edu.au

Abstract
The title topic highlights several important concepts in physical chemistry: chemical equilibrium, thermodynamics of ion solvation, ideal and non-ideal solutions and solubility of salts. Furthermore, the selection of pedagogically novel example (a single, moderately soluble salt) emphasizes mutual links and relative roles of each concept.

The topic of solubility product (K\text{sp}) is introduced at Year I level in general chemistry subject and applied to sparsely soluble salts. At this level simple molar concentrations of ions are used to calculate K\text{sp}. In such cases K\text{sp} refers to the equilibrium between aqueous ions and ions bound in the solid crystal lattice. Some perceptive students have wondered whether a similar equation will hold true for saturated solutions of moderately soluble salts. In such solutions aqueous ions and the solid phase are also present in a constant, time independent ratio. Can K\text{sp} therefore also be defined for such systems? This topic is not revisited during discussions of advanced physical chemistry topics in higher years of study. However, there is an opportunity here for students to learn about additional phenomena which become significant at high ion concentrations and to link the knowledge of these phenomena to less sophisticated Year I concepts. The problem posed in this article is pedagogically useful because it stimulates lateral thinking. Students are required to apply a known concept outside the initial context in which it was defined and learnt. The calculations of K\text{sp} encountered in the chemical education literature, deal only with sparingly soluble salts and thus suggest that K\text{sp} cannot be defined for highly soluble salts. This immediately raises the question: “How insoluble must the salt be for it to have K\text{sp} value associated with it?” The author had often asked students: “What is your estimate of K\text{sp} for NaCl at 298K?” The student answers which the author received ranged from “infinitely large” (justified by the claim: “because the highly soluble salt dissolves completely and there is no solid phase!”) to “very big” (students were unable to quantify “big”). The NaCl was selected as an example of a soluble salt, because it is unlikely to participate in secondary reactions in the solution e.g. complex ion formation or ion hydrolysis, which may obscure and complicate the analysis of K\text{sp}. A lot of discussion concerning pedagogical merits (or otherwise) of teaching K\text{sp} and the caveats which must be considered when performing K\text{sp} calculations, has been published (1-4). The cited articles contain long lists of K\text{sp} values for sparsely soluble salts from which the importance of secondary reactions had been demonstrated by pointing out errors and discrepancies between K\text{sp} values calculated with and without taking these reactions into account. Our aim is to discuss several important concepts related to ionic equilibria on the example of the single soluble salt. We give three variations of the workout for K\text{sp} which are suitable for different levels of study.

**Variation 1 (1\textsuperscript{st} year level)**
Calculate K\text{sp} at 298K and 1 atm for NaCl given that the saturated aqueous solution of the salt has density ρ=1.1975 g/mL and the concentration of 26.45% (w/w).

**Variation 2 (2\textsuperscript{nd} year level)**
Repeat the calculation taking into consideration that the mean activity coefficient γ± at the concentration of saturation is 0.873.

**Variation 3 (final year level)**
Repeat the calculation given that standard Gibbs free energies (ΔG°/kJmol\textsuperscript{-1}) for the NaCl(s), Na\textsuperscript{+} (aq) and Cl\textsuperscript{-} (aq) are -384.1, -261.9 and -131.2 kJ/mol, respectively at 298K and 1 atm.

Possible Solutions:
V1. The standard equations can be used to convert % solubility to molarity which for saturated NaCl solution is s=5.42M. K\text{sp} is an equilibrium constant for the process NaCl(s) ⇄ Na\textsuperscript{+} + Cl\textsuperscript{-} and is expressed by the equation K\text{sp} = s\textsuperscript{2}. The student answers which the author received ranged from “infinite” to “very large” to “very big” (students were unable to quantify “big”).

V2. The K\text{sp} can be expressed through activity coefficients (7) as K\text{sp} = γ\textsuperscript{+} s\textsuperscript{2} (7) which gives the answer of 22.4. The answer clearly shows why the activity coefficients in saturated, moderately concentrated, non-ideal solutions cannot be neglected!

V3. A possible answer can be obtained by noting that ln K\text{sp} = -ΔG°/RT where

ΔG° = ΔG°(Na\textsuperscript{+}) + ΔG°(Cl\textsuperscript{-}) - ΔG°(NaCl(s)]. Plugging the values into the equation gives K\text{sp} = 37.7. The students should notice that this value is higher than the answer for V1 and thus unrealistic. Why are there discrepancies between V1-V3 values?

A possible explanation is the existence of secondary processes which reduce the number of free Na\textsuperscript{+} (aq) and Cl\textsuperscript{-} (aq) ions. Measurements of the saturated NaCl solution using X-ray diffraction have shown (7) that 30% of ionic species in the solution exists in the form of contact ion pairs (Na\textsuperscript{+}Cl\textsuperscript{-})(aq).

**Scheme 1**

\[
\text{NaCl(s)} \rightleftharpoons (\text{Na}\textsuperscript{+}\text{Cl}\textsuperscript{-})(aq)
\]

\[
\text{Na}\textsuperscript{+}(aq) + \text{Cl}^- (aq) \rightleftharpoons K_3
\]

\[
K_1
\]

\[
K_2
\]

We can set up an equilibrium scheme (Scheme 1) which...
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Bob Morton, Publications Coordinator:
Mail: PO Box 749, Blackwood, SA, 5051
Email: rjmorton@adelaide.on.net
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