Teaching Chemistry in Higher Education

A *Festschrift* in Honour of Professor Tina Overton

Edited by

Michael K. Seery and Claire Mc Donnell

Published by Creathach Press

Cover image by Christopher Armstrong

Back cover image (Courtesy of Tina Overton/University of Leeds)

ISBN: 978-0-9928233-1-3

overtonfestschrift.wordpress.com

To access Supplementary Information, use the code: **overtonfs3**
when prompted on the website

5 Developing problem-solving skills in physical chemistry

Elizabeth Yuriev, Sabrina Basal and Kimberly Vo
Faculty of Pharmacy and Pharmaceutical Sciences, Monash University
elizabeth.yuriev@monash.edu

Developing problem-solving skills by chemistry students and teaching of these skills by instructors are two of the recognised challenges of chemistry education (Herron, 1996b). There is extensive chemical education literature dealing with the nature of associated difficulties and instructional approaches to address these difficulties. One of the main difficulties experienced by students when solving chemistry problems stems from the lack of process skills. To tackle this challenge, we have developed and evaluated the problem-solving workflow called *Goldilocks Help*. It provides specific scaffolding for students faced with procedural difficulties when solving chemistry problems. We have implemented it into the teaching of physical chemistry in a holistic manner where teaching, practice, and assessment are constructively aligned. The evaluation of the workflow showed that it was associated with the shift in students' beliefs in their abilities to use productive self-regulation strategies in problem solving: planning, information management, monitoring, debugging, and evaluation. In fact, many students could effectively regulate their problem solving though planning and analysis. Analysis of student work showed that students who demonstrated more expertise by engaging in structured problem solving and explicit reasoning were more successful in their problem-solving attempts. However, contrary to their stated values, they were not as effective in employing monitoring, debugging, and evaluation. We propose that it is important to constructively align teaching and learning activities with assessment that explicitly encourages students to engage in demonstrating their reasoning during problem-solving, as well as other reflective and evaluative practices.

Influence of Professor Tina Overton

Our education research and teaching practice are influenced by Tina Overton's research into problem solving and numerous insightful discussions with Tina over the term of her tenure in Monash University, Australia. Specifically, the work on expert vs. novice problem solving (Overton et al., 2013; Randles and Overton, 2015) provided theoretical foundation for the student-tailored implementation of the Goldilocks Help problem-solving workflow, and the work on open-ended problems (Overton et al., 2013; Overton and Potter, 2008; Overton and Potter, 2011; Randles and Overton, 2015; St Clair-Thompson et al., 2012) inspired the development of several learning and teaching activities described below.

To cite: Yuriev, E., Basal, S. and Vo, K. (2019), "Developing problem-solving skills in physical chemistry", in Seery, M. K. and Mc Donnell, C. (Eds.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*, Creathach Press, Dublin, pp. 55-76.

Introduction

Student difficulties in solving chemistry problems

We have previously reviewed student difficulties manifested when solving chemistry problems (Yuriev *et al*., 2017). Poor problem-solving approaches and strategies, together with the lack of knowledge of subject matter (Gulacar *et al*., 2013; Herron and Greenbowe, 1986) and misconceptions or alternative conceptions (Taber, 2002), are among the main causes of such difficulties. Also, when students fail to operationalise appropriate problem-solving processes, they resort to memorising algorithms. This usually occurs when students are not motivated to tackle problems conceptually or when they are cognitively overloaded and thus cannot afford the mental capacity required for conceptual problem solving (Gulacar *et al*., 2014; Overton and Potter, 2008).

The following issues may further confound problem-solving attempts: an inability to extract relevant information from a problem (Bodner and McMillen, 1986; Cohen *et al*., 2000; Gulacar *et al*., 2014) or recognise a need for additional information that may be required (Van Ausdal, 1988), being unable to handle conceptual complexity (Gulacar *et al*., 2014), and poor reasoning skills (Cohen *et al*., 2000). When one or more of these issues arise, students tend to dash into the solution without first clarifying the problem (Drummond and Selvaratnam, 2008; Harper, 2005; Selvaratnam, 2011), guess (Gulacar *et al*., 2014), not know where to start (Gulacar *et al*., 2014; Van Ausdal, 1988), or give up (Drummond and Selvaratnam, 2008; Harper, 2005). Finally, students may arrive at an incorrect, or incomplete, answer and not recognise it because they are not used to habitually reflecting on or evaluating the outcome (Herron and Greenbowe, 1986; Van Ausdal, 1988).

Academic value conflicts in teaching problem solving

Students are not the only contributors to the difficulties summarised above. Several teaching and assessment practices contribute to students developing flawed approaches to problem solving. Teachers often claim that they value reasoning in problem solving. However they frequently assess in a manner that discourages, or at least does not reward, explicit reasoning demonstrated in students' work, instead assigning all or most marks for the correctness of the answer (Petcovic *et al*., 2013). A similar value conflict arises when teaching is focused on conceptual learning, while assessment deals primarily with algorithmic problems (Overton and Potter, 2011).

Other instructor-driven causes of poor problem-solving skills include instruction which focuses on application of procedures at the expense of reasoning (Bodner and McMillen, 1986; Cohen *et al*., 2000; Harper, 2005; Nyachwaya *et al*., 2014; Pushkin, 1998; Zoller, 2000), and insufficient training of metacognitive strategies (Cohen *et al*., 2000; Drummond and Selvaratnam, 2008; Selvaratnam, 2011; Yu *et al*., 2015).

Analysing problem-solving processes

There are several classifications of students based on their approaches to chemical problem solving (Table 1). While the novice *vs*. expert paradigm is widely known, the additional classifications go beyond such simple distinction. They further empower the instructors by demonstrating the features of higher-order problem solving and providing guidance in terms of type of practice required.

Think-aloud protocol is the most common data collection method for analysing problem-solving practices. Using think-aloud interviews, Overton and co-workers (Gulacar *et al*., 2013) developed a coding scheme to categorise problem solving of stoichiometry problems as successful, neutral, and unsuccessful, with additional detailed codes for the neutral and unsuccessful categories. When they investigated open-ended problems, a marking scheme was used to assess student work based on how they dealt with the data, method, and goals (Overton and Potter, 2011). In consequent studies, this scheme was elaborated based on the themes emerging from the interviews and included codes for problem framing, strategising, logic and scientific approach, information management, approximations and estimations, algorithms, evaluation, ability to focus, and confidence (Overton *et al*., 2013; Randles *et al*., 2018; Randles and Overton, 2015). Rodriguez *et al*. (2018) focused on characterising the productive and unproductive features of problem-solving pathways used by students when solving chemical kinetics problems. Mason *et al*. (1997) used a graphical method (incident identification graphs) to measure time spent by students during specific "episodes" of problem solving: read, define, setup, solve, and check.

Think-aloud interviews have the advantage that students can verbalise their thought processes, may be more comprehensive than if they just had to write down their solution, and could be probed with clarifying questions. On the other hand, having to talk while solving a problem may influence the student's problem-solving process and behaviour. Also, this data collection method is inevitably limited to a relatively small number of participants. Conversely, students' written work, which is admittedly usually limited to what is produced on the page, is free from the stress of talking while thinking and could be generated in large numbers, for example through collecting exam solutions. A scheme to analyse written solutions was developed to code for reasoning: fully shown and correct, partially shown and incorrect, partially shown and ambiguous, and fully shown and incorrect (Henderson *et al*., 2004; Petcovic *et al*., 2013). Stoichiometry problems were used in this analysis, albeit the solutions were not the real student work, instead they were simulated to include common mistakes and approaches. In another study, a computer-based assessment was developed where students' work (for example answers to MCQ questions, concept maps, log files) was used to map their problem solving to four dimensions: understanding and characterising the problem, representing the problem, solving the problem, and reflecting and communicating the solution (Scherer *et al*., 2014).

Problem-solving rubrics developed as part of the ELIPSS project (Cole *et al*., 2017; Cole *et al*., 2018) are available for analysing both students' written work (product) or observed problem-solving behaviours (interaction). The rubrics categorise problem solving in terms of: evidence of thought process (work), ability to identify necessary information and use information correctly, choosing problem-solving strategy, completeness, logic of the solution, and judgement of reasonableness of the solution.

Theoretical framework

Our teaching standpoint is underpinned by the concepts of scaffolding and prompting. Scaffolding enables learners to accomplish a task that could not be completed without assistance (Belland, 2011; Pea, 2004; Vygotsky, 1978; Wood *et al*., 1976). With respect to problem solving, scaffolding comprises the structuring of the process and metacognitive and procedural prompting (Reiser, 2004). It emphasises problem-solving processes (Wood *et al*., 1976), focuses students' attention on important process elements (Reiser, 2004), and promotes reflection (Davis, 2000). Prompts point students to important, possibly overlooked, information and potential knowledge gaps, help in organising thought processes, make their thinking visible, and emphasise the need to evaluate the validity of their solutions (Ge and Land, 2003). Guiding-through-questions, or Socratic questioning, essentially promotes logical reasoning, structured problem-solving processes, and reflection (Ge and Land, 2003; Rhee, 2007). Question prompts convey transcendent messages about what is important in problem solving.

Our perspective on learning is based on the theory of metacognitive self-regulation. Metacognition is the ability to monitor and critically evaluate one's understanding and problem-solving processes (Flavell, 1979). Self-regulated learning comprises proactive processes, which learners use to set goals, choose and implement strategies, and monitor their effectiveness (Pintrich *et al*., 1991; Zimmerman, 2008). Thus, metacognitive self-regulation involves planning, monitoring, and regulating (Pintrich *et al*., 1991).

Table 1: Problem-solving approaches and associated literature references

Problem-solver classification	Description	Reference
Novices and experts	Novices take an unstructured approach to problem solving; experts use a structured, or scientific, approach	Bodner and Domin, 1991
Novices, experts, and transitional	As above, with the recognition of a developmental stage	Overton *et al*., 2013
Instrumental and relational	Instrumental problem solvers recognise algorithms; relational problem solvers use conceptual schema	Skemp, 1979
Successful and unsuccessful	Successful problem solver is able to extract relevant information from the problem statement, often uses drawing to represent a problem, is willing to try something when stuck, keeps track of the problem-solving process, and checks answer to see if it makes sense	Bodner, 2003; 2015
Productive and unproductive	Based on specific strategies used by problem solvers	Rodriguez *et al*., 2018

Design of the Problem-Solving Workflow

While there is an extensive range of problem-solving processes (reviewed by us in (Yuriev *et al*., 2017)), they usually involve several common steps: understanding and representing the problem, planning a solution, implementing it, and evaluating an outcome (Polya, 1945). We have designed the Goldilocks Help workflow (Table 2) to achieve the following:

1. scaffolding of a systematic problem-solving process with an explicit designation of phases;
2. introducing students to the types of prompts that could guide them through the process;
3. encouraging explicit reasoning necessary for successful conceptual problem solving; and
4. fostering the development of metacognitive self-regulation by the inclusion of monitoring, evaluation, and reflection prompts.

The workflow is designed for quantitative problems, mostly with a specific correct answer. Whereas it is presented in a sequential fashion, it contains multiple feedback loops to expose a non-linear nature of problem solving (Figure 1).

The design of the workflow was informed by common student difficulties in solving chemistry problems and prior research on problem-solving processes (Yuriev *et al*., 2017). Specific strategies were included to help students avoid, or be able to deal with, points where they commonly get stuck while solving problems: dead ends and false starts. Dead ends are points on unproductive problem-solving pathways that prevent reaching a correct solution. False starts are a consequence of lacking required knowledge, but being unaware of it.

At the extremes of problem-solving instruction, students are either given a generic advice, for example to analyse or to plan, or are provided with an algorithm. When designing the workflow, we aimed for the

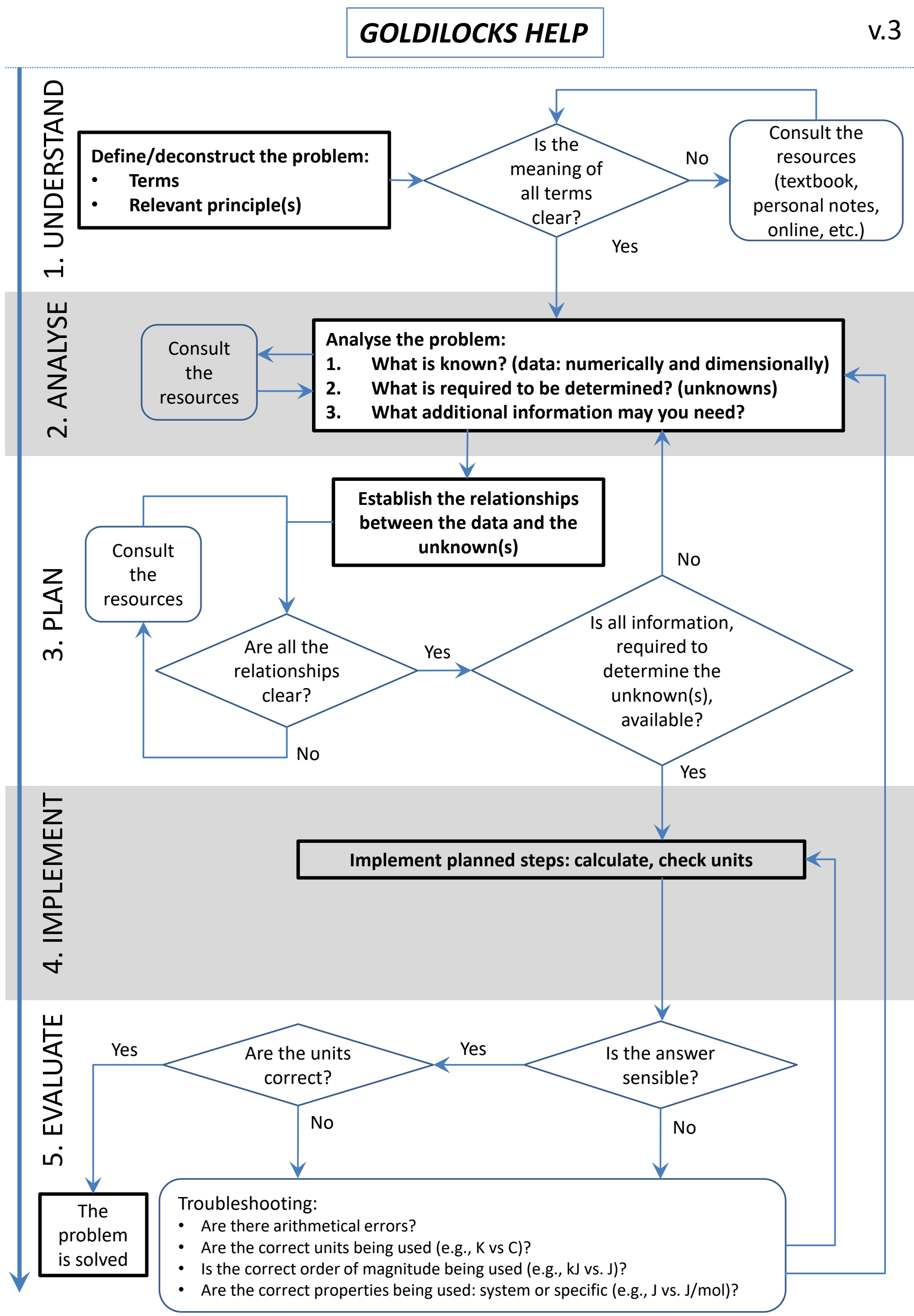

Figure 1: Problem-solving workflow

Table 2: Problem-solving workflow

Problem-solving phase	Main action(s)	Prompts/questions	Additional actions (if stuck, or negative answers to prompts)
Understand	Define/ deconstruct the problem	Is the meaning of all terms clear?	Consult the resources (textbook, personal notes, online, etc.)
Analyse	Analyse the problem	What is known? (data: numerically and dimensionally) What is required to be determined? (unknowns) What additional information may you need?	Consult the resources
Plan	Establish the relationships between data and unknown(s)	Are all the relationships clear? Is all information, required to determine the unknown(s), available?	Consult the resources Return to the *Analysis* phase
Implement	Implement planned steps: calculate, check units		
Evaluate	Troubleshoot, if necessary	Is the answer sensible? Are the units correct?	Troubleshoot: Are there arithmetical errors? Are the correct units being used? Is the correct order of magnitude being used? Are the correct properties being used: system or specific? Return to the *Analysis* phase Return to the *Implement* phase

balance between these two approaches. In Socratic questioning fashion, the prompts mean to increase students' awareness of what they do not understand and to trigger the use of additional information where necessary.

Understanding

Problem representation, or cognitive restructuring, is the critical step of problem solving (Bodner and McMillen, 1986). Following the review of known student difficulties in solving chemistry problems, we decided to split the representation step into two separate processes: *understanding* the problem statement (comprehending) and *analysing* the problem (exploring it).

Students often do not recognise that they do not know something. This lack of knowledge, combined with a lack of awareness, leads to false starts in problem solving. Furthermore, misconceptions and alternative conceptions (Taber, 2002) can lead to dead ends of wrong answers. An example solution pathway is shown in Figure 2 (common error (i)). In the workflow, students are prompted to first examine all the terms and concepts they encounter in the problem with the question: "*is the meaning of all terms clear?*"

Problem and solution	**Common errors**
A sample containing two moles of oxygen gas is heated from 25.0°C to 45.0°C at atmospheric pressure. Predict enthalpy for this process given that $C_v (O_2) = 20.8\ J\ K^{-1}\ mol^{-1}$.	
Understanding: Enthalpy is a heat absorbed or released by a system for a process at constant pressure. Heat is proportional to the change in temperature and the heat capacity.	(i) Not fully *understanding* the concept of enthalpy: $\Delta H = \mathbf{C} \times n \times \Delta t$ $= \mathbf{20.8}\ J\ K^{-1}\ mol^{-1} \times 2\ mol \times (45-25)\ K$ $= 838\ J$
Analysis. Relationships: $\Delta H = q_P$ $q_P = C_P \times n \times \Delta t$ $C_P = C_V + nR$	
Planning: The heat capacity data available is for molar heat capacity ($n = 1$) at a constant volume. $C_{P,m} = C_{V,m} + R$ $\Delta H(system) = C_{P,m} \times n \times \Delta t$ $\Delta t = t_{final} - t_{initial}$	(ii) Ignoring units during *planning* and *implementation*: $C_P = C_V + nR = \mathbf{20.8 + 2 \times 8.314} = 37.428$ $\Delta H = C_P \times \Delta t = 37.428 \times (45-25) = 10966$
Implementation: $C_{P,m} = 20.8\ J\ K^{-1}\ mol^{-1} + 8.314\ J\ K^{-1}\ mol^{-1}$ $= 29.114\ J\ K^{-1}\ mol^{-1}$ $\Delta H(system) = 29.114\ J\ K^{-1}\ mol^{-1} \times 2\ mol \times (45-25)\ K$ $= 1164.56\ J = 1.16\ kJ$	
Evaluation Value: positive value – correct for an endothormic process (heating) Units: *J* or *kJ* – correct for a system (not 1 mole) Is there an alternative strategy? Yes: to determine the heat capacity at constant pressure for the system ($n = 2$) first: $C_P = C_V + nR$ $\Delta H(system) = C_P \times \Delta t$	(iii) Not *evaluating* the final answer for making sense: $\Delta H = C_{P,m} \times n \times \Delta t$ $= 29.114\ J\ K^{-1}\ mol^{-1} \times 2\ mol \times (\mathbf{25-45})\ K$ $= -1.16\ kJ$

Figure 2: Heat capacity problem – illustration of student difficulties (specific errors are shown in bold). This problem is presented to students in the context of reversible processes with no non-expansion work occurring

Previously, we have shown that deep understanding of terminology promotes successful problem solving (Yuriev *et al*., 2016).

Analysis

A commonly known pitfall of student problem solving is to look for an equation as a strategy (Harper, 2005). In such an algorithmic approach, if students cannot locate a correct equation, they are stuck, another false start. If however, they pick an inappropriate equation and fail to realise its unsuitability, they embark on an unproductive pathway leading to another dead end (Nyachwaya *et al*., 2014). A productive alternative is to prompt:

> *What is known (data)? What is required to be determined (unknowns)? What additional information may be needed?*

At this stage, it is also important to state explicitly any relevant assumptions, particularly to avoid incorporating non-normative ideas in reasoning. An example of such incorporation in chemical kinetics problems is applying first-order rate laws to zero-order processes, without accounting for differences between these processes (Rodriguez *et al*., 2018).

Planning

Skipping the planning step is frequently recognised as the feature of student problem solving (Herron, 1996a). While this skipping may be another instance of not knowing what one does not know, it is commonly manifested in the superficial manipulation of mathematical formulas (Cohen *et al*., 2000; Drummond and Selvaratnam, 2008; Gulacar *et al*., 2014; Selvaratnam, 2011; Van Ausdal, 1988) and/or in the failure to account for the dimensional nature (units) of physicochemical properties. (Gulacar *et al*., 2014; Van Ausdal, 1988). As a result, students may arrive at the dead end of a wrong answer, exemplified by Figure 2 (common error (ii)).

The workflow encourages students to set up relevant equations meticulously and to use symbols and units ahead of numbers when substituting properties into equations:

> *Establish the relationships between the data and the unknown(s). Are all the relationships clear? Is all information, required to determine the unknown(s), available?*

Implementation

For quantitative problems, implementation is simply doing maths. Given good mathematical background, this phase of problem solving is not challenging to most students. What is challenging though is not to jump into implementation, without first doing analysis and planning. As stated above, many students skip these important steps, and thus jeopardise the success of implementation.

The workflow makes it explicitly clear that implementation cannot come before these crucial steps. This order should emphasise to students the importance of analysis and planning. Furthermore, this step is presented as a prompt to calculate and check units. This description is intended as a reminder that physicochemical properties are not dimensionless and the execution of implementation involves unit checking as well as mathematical calculation.

Evaluation

Our review of literature on chemical problem solving revealed a general frustration with students' resistance to engage in reflective practice while solving problems. "*Teachers know that admonitions to do so fall on deaf ears*" (p. 73) (Herron, 1996a). It has been suggested that students recognise answer checking as valuable, but still do not engage in it simply because they do not know how (Frank, 1986).

An example of a non-sensible answer is a numerically correct answer with a wrong sign — shown in Figure 2 (common error (iii)) — a solution dead end. To scaffold evaluation, the workflow prompts students to consider the question: *Is the answer sensible? Are the units correct?*

If a student realises that one or both answers are *No*, they need strategies to go back through the solution process to identify where they went wrong. The workflow contains a (non-comprehensive) list of troubleshooting prompts as well as feedback loops to earlier solution stages.

Implementation of the Problem-Solving Workflow

Many students demonstrate a value conflict between what they know are successful learning and problem-solving strategies and actual strategies they use to do well in the course (Elby, 1999; White *et*

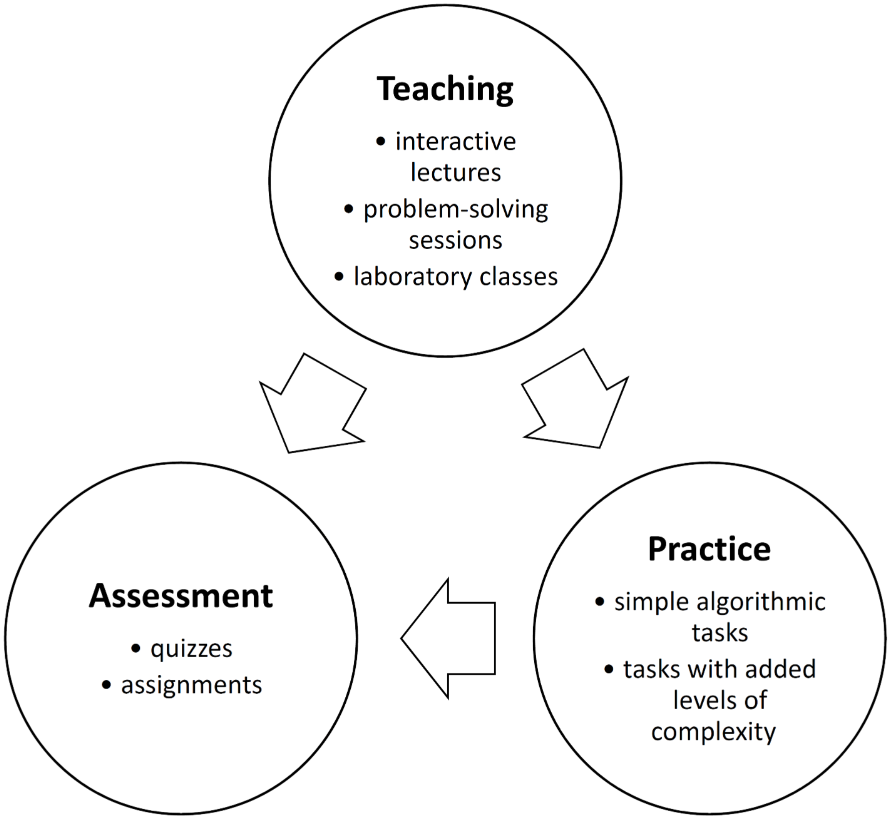

Figure 3: The workflow is used in *teaching* when problem solving is modeled by instructors. Students are encouraged to use the workflow when *practicing* problem solving. During *assessment*, students' solutions are marked both for correctness and explicit demonstration of the problem-solving process

al., 2015). Therefore, it is critical that assessment is constructively aligned with desired learning outcomes and, in the case of problem solving, rewards explicit reasoning and reflection. Providing students with explicit cues that they are expected to evaluate, check, reflect, and/or comment on the outcome should be standard practice in chemistry teaching, at least for novice problem solvers.

These principles underpinned the implementation of the problem-solving workflow into the teaching of physical chemistry in a holistic manner where teaching, practice, and assessment are constructively aligned (Figure 3).

Setting and scope

The workflow was used in physical chemistry units undertaken by Year 1 students enrolled in the Bachelor of Pharmaceutical Science degree in a research-intensive Australian university. The contents of the units include: thermodynamics, acids and bases, phase equilibria, and chemical kinetics in Semester 1; and solution properties (vapour pressure, conductivity, and colligative properties), solubility, and liquid-liquid systems/emulsions in Semester 2. The average enrolment is 100–140 students. The workflow was rolled out for the first time in 2015 and in its modified form — after the evaluation — in 2016. In 2017 and 2018, it has been used in both first and second semesters. It has now been used for four years, totalling six semesters of implementation.

Teaching

Teaching methods involve interactive lectures with significant flipping and active learning components (McLaughlin *et al*., 2016; White *et al*., 2016; White *et al*., 2015), problem-solving sessions, and laboratory classes. During the first week of academic year, all students participate in an induction workshop. Activity 1 involves filling out a metacognition and self-regulation inventory (Yuriev *et al*., 2017).

Activity 2 is a group discussion of a chemistry-unrelated task:

> *You are a member of a group of people organising a music festival on the outskirts of Melbourne. You are in charge of catering and your first job is to produce a budget with a restricted bottom line. How do you go about doing that?*

This task was inspired by those described by Randles and Overton (Randles and Overton, 2015). It is new to students, quite unexpected, and open-ended. It does not require any specific scientific expertise, but does prompt them to comment on their problem-solving approaches. Students brainstorm the scenario in small groups and then share their plans and decision making with the rest of the class. Their suggestions usually cover the processes involved in problem solving: identifying the challenge (understanding), finding the relationships between the variables, such as costs, and the unknown, such as the balanced budget, (analysis), assembling and organising the required information (planning), doing the calculations (implementation), and checking that the budget is indeed in the black (evaluation). Commonly, one specific term in the problem statement (bottom line) is not known to many students, who ask for clarification. Such requests present an ideal teaching moment for drawing students' attention to the importance of the understanding step, when solving problems ("*Is the meaning of all terms clear?*"). This activity is designed to make the process of problem solving visible, to urge students to monitor what they do when they solve problems (problem-solving behaviour described by Herron, 1996a), and not to disregard the early stages of problem solving: understanding, analysis, and planning.

Modelling instruction is used in lectures and problem-solving sessions, where at least one of the problems allocated to each class period is worked through interactively, using explicit workflow prompts and colour coding of the problem-solving stages (Figure 4).

Practice

During the semester, tasks of various difficulty are undertaken by students. While some are simple algorithmic tasks, others have added levels of complexity. The most common elements of complexity have to do with data: either necessary data not being provided in the problem statement or data being provided that is not required for solving the problem. These complexity elements are authentic and require students to identify what information is required to solve the problem and to source it if necessary. Further complexity is introduced when students are required to generate multiple methods for solving the same problem.

When students practice problem solving, it is important to emphasise the aspects of the process as outlined in the workflow (Table 2, Figure 1). Specifically, students are encouraged not to skip *Understanding*, *Analysis*, and *Planning* phases. It is very important to advise and support students in executing the *Evaluation* phase, particularly by instructing on effective checking strategies. Wherever possible collaborative problem solving is used to expose students to alternative ways of thinking. All these elements of practice are appreciated by students as discussed below in the Results section.

Assessment

Students are provided with regular constructive feedback on their problem-solving activities. For each topic, students undertake low-stakes assessments: a quiz and an assignment. The quizzes largely involve calculation questions with numeric answers, and are graded by the virtual learning environment. For the assignments, students submit a solution for one of the tasks allocated for a given topic. The assignments are assessed by the academic or teaching associates with focus on the problem-solving process: explicit reasoning, methodical and organised fashion in which workings are presented, including, where appropriate, formulas, unit conversions, etc. The feedback is provided to students via a simple single-row rubric comprising:

- No submission: no points
- Workings not sufficiently shown or serious flaws; missing units or steps, flawed logic: 0.5 points
- Workings are shown and in enough detail and none or almost no flaws: 1 point

After both assessments, the outcomes are reviewed by the academic, and class-level feedback is provided to students, reflecting on common errors and the process required to solve the problems. This cycle of practice and assessment sends a very important message to students: in order to succeed, they have to engage in and explicitly demonstrate their reasoning when solving problems. Even if a correct answer is obtained, students do not get full points unless their solution clearly shows their thinking.

Sodium hypochlorite, NaClO, is the active ingredient of many bleaches. Calculate the ratio of the concentrations of ClO^- and HClO in a bleach solution having a pH adjusted to 6.50 by the use of a strong acid.

Do you understand what this problem describes? Is the meaning of all terms clear?
Sodium hypochlorite is a salt of weak acid (HClO) and dissociates fully in the aqueous solution:

$$NaClO \rightarrow Na^+ + ClO^-$$

$$Na^+ + H_2O \leftarrow NaOH + H^+$$

$$ClO^- + H_2O \rightleftarrows HClO + OH^-$$

Therefore, there are both **ClO^-** (basic, ***b***) and **HClO** (acidic, ***a***) forms are present in the solution. They originate from the same source – the salt.

Let's analyse what's going on. The ratio of the concentrations of these forms (***b/a***) depends on the excess of **OH^-** or **H^+**. Adding more **OH^-** shifts the equilibrium to the left and increases ***b/a***; adding more **H^+** shifts the equilibrium to the right and decreases ***b/a***. In this case, the ***pH*** is adjusted to 6.50 by the use of strong acid. The relationship between the ***pH*** of the solution and the ***b/a*** ratio of the two forms of the weak acid is the Henderson-Hasselbach equation:

$$pH = pK_a + log\frac{b}{a}$$

What is known?	***pH* = 6.50**
What is required to be determined?	***b/a***
What additional information may you need?	**pK_a (HClO) = 7.53**

What are you planning to do next? Establish the relationships between the data and the unknown(s):

$$\frac{b}{a} = 10^{pH - pK_a}$$

Implement:

$$\frac{b}{a} = 10^{6.50-7.53} = 0.093$$

Evaluate: Should there be any units? No, the ratio is unit-less.

Figure 4: Example of problem solving with modelling instruction

Results

Evaluation of the problem-solving workflow

The study to evaluate the problem-solving workflow was approved in accordance with institutional guidelines regarding education research. The study was explained to students before they were invited to participate. Their participation in the metacognitive awareness inventory was anonymous.

The workflow was evaluated by using several types of evidence: feedback from the face-validity survey of academics, qualitative student comments from focus groups and end-of-semester reflections, and quantitative scores from the metacognitive awareness inventory. All evaluation findings have been previously described by us in detail (Yuriev *et al*., 2017) and are briefly summarised below.

Student perspectives on adopting the workflow fell into two main categories. Students either claimed that they already use a similar approach to problem solving or reported that they have fully or partially adopted the workflow. A small group of students reported that following the workflow was confusing.

Specifically, students commented on problem-solving processes and learning experiences in problem-solving sessions. They noted the importance of the *Understand* phase for the subsequent steps and the value of having strong conceptual knowledge for the success of this step. Such aspects of the *Analysis* phase as relationships between concepts, restructuring the problem, and focusing on the data and the goals were recognised as being critical. In addition, students shown an appreciation for slowing down for the *Plan* phase, noting the consequences of the lack of planning and the value of a well written-out plan for later revision. Such appreciation is a significant mature judgement. Slowing down to plan a solution is referred to in psychology as type 2, or deliberate, reasoning (Evans, 2012) and is a productive feature of chemical problem solving (Rodriguez *et al*., 2018). With respect to the *Evaluate* phase, students noted the specific checking strategies and the need to evaluate more regularly. Students observed that the workflow helped them to commence, progress, and complete the problem-solving tasks.

This quote eloquently captures the trajectory of developing the problem-solving skills, as influenced by the workflow:

> *I have realised the importance of understanding exactly what a problem is asking and planning my solution. Instead of jumping straight into solving problems, I now more and more take the time to identify what I do and don't know and the process I need to go through to solve it. I used to just plug things into equations but I now have a greater understanding of why I am calculating something in this way and appreciating how something is derived. It not only means I am more likely to answer correctly but forces me to fully understand what I am doing and why, so this knowledge can be applied to many situations, including unfamiliar ones.*

The collaborative nature of the problem-solving sessions gave students regular opportunities to see how other students approach the same problem. They talked about others' way of thinking and strategising and, significantly, emphasised different ways of thinking rather than using different algorithms. They also indicated that the enhanced understanding of concepts, disambiguation of misconceptions, consolidation of ideas, and complementarity were the effects of collaboration on problem solving. Students acknowledged the benefits of working with more knowledgeable peers and of learning by teaching to those less proficient. Finally, some students demonstrated a mature appreciation of the fact that learning problem-solving process and improving relevant skills is a process in itself.

Not all student comments were positive. Adopting the structured approach to problem solving clearly required a change in some students' learning strategies. However, the majority of negative comments revealed their makers' grade motivation, rather than intrinsic motivation, as well as somewhat simplistic view of what problem solving is. In particular, it is not uncommon for students to see the efficiency of solving a problem fast as a goal in and of itself. For example, one student was exhorting the virtues of preparing for class, which is of course a laudable notion, but then concluded that as a result of said preparation they "*did not have to waste time rereading and trying to understand the questions*". Another commented that solving problems together with others was "*inefficient because everyone has their own way to solve the problems, so a lot of time was spent discussing rather than writing*". Such ideas indicate a need for further conversation with students to emphasise the value of re-reading questions and peer discussions as problem-solving strategies.

Quantitative results of the metacognitive awareness inventory shown consistent increases in scores for all measures: the overall scale, the knowledge of cognition and regulation of cognition sub-constructs, and their constituent categories (Yuriev *et al*., 2017). These increases are in agreement with students' qualitative comments, reported above. For example, the increased planning scores align with students appreciating the negative consequences of skipping the planning stage.

Analysis of student written work

Findings presented above resulted from collecting and analysing student self-declared anonymous responses to the inventory (quantitative) and reflections (qualitative). Conclusions that can be drawn from such evidence are limited since anonymous responses cannot be used to correlate with student performance. Furthermore, this evidence is limited to student self-reported opinions and therefore inherently is not objective. To overcome these limitations, we initiated the analysis of the relationship between student problem-solving processes (demonstrated in their written work and through think-aloud interviews) and the success of their problem-solving attempts. Specifically, we have mapped exam solutions of 74 students, against the phases of the problem-solving workflow to develop the problem-solving profiles characteristic of successful and unsuccessful problem solvers. Several problems were selected for the analysis, based on the following requirements: quantitative nature, combination of concepts and multiple solution steps, more than one possible pathway to the correct answer. The initial findings of this analysis are shown below.

A model solution was developed for each problem, containing different variants of how phases of the process could be represented. All co-authors have independently coded student work, allocating zero, half, or a full point for each phase depending on student workings. Several rounds of meetings were held to discuss and refine coding to achieve 100% agreement.

Representative results for two exam problems (thermodynamics and chemical kinetics, listed below) are shown in Figure 5.

1. *Thermodynamics problem*: Predict the boiling point of water on the top of a mountain of height 5500 m, where the atmospheric pressure is 0.5 atm. Support your answer with appropriate reasoning and calculations. Explicitly state assumptions that you have made in solving this problem.
2. *Chemical kinetics problem*: Imexon is a substance that is being studied in the treatment of some types of cancer, including pancreatic, lung, breast, prostate, melanoma, and multiple myeloma. The kinetic properties of Imexon were investigated in a pressurized metered dose inhaler (MDI), using 1,1,1,2-tetrafluoroethane (HFA-134a) as a propellant and ethanol as a co-solvent (*International Journal of Pharmaceutics* 340 (2007) 223–229). The following information was obtained for the degradation reaction of Imexon:

Sample #	HFA-134a (%)	EtOH (%)	Imexon (μg/g)	Temperature (°C)	k (h^{-1})
1	80	20	80	11	0.000009
2	80	20	80	23	0.000184
3	80	20	80	37	0.000336

- Using the data provided, carefully determine the activation energy for the degradation reaction of Imexon.
- Comment on the reliability of the result obtained above and how it could be improved.
- Using the data provided, suggest appropriate storage conditions for this formulation. Support your suggestion with relevant calculations.

The thermodynamics problem had extra complexity in that students were expected to identify what additional information was required (molar heat of vaporisation) and look it up in a textbook appendix. They were also expected to realise that they need to use the normal boiling point of water as additional data.

Students were divided into successful and unsuccessful based on whether they were able to obtain the correct answer. Successful problem solvers did indeed attend to earlier stages of problem solving with greater frequency and paid greater attention to analysis and planning. More than double the number of students in this category presented analysis and planning in full detail, compared to the unsuccessful students: 84% and 63% *vs.* 40% and 29%, respectively, for the thermodynamics problem; 68% and 63% *vs.* 32% and 12%, respectively, for the chemical kinetics problem. These findings are similar to those of Bannert *et al.*, where they observed most successful students to demonstrate greater frequency of self-regulated learning events: orientation, planning, deeper information elaboration, monitoring, and evaluation (Bannert *et al.*, 2014).

Unfortunately, both categories of students in the present study have largely failed to demonstrate the evaluation aspect of problem solving. In the thermodynamics problem, students were required to determine the boiling point of water at the pressure of 0.5 atm. The correct answer (81 °C or 354 K) would have to be compared to the normal boiling of water to conclude that the result is as predicted, that is below 100 °C. Very few students (including only 9% of the successful category) made such a comment explicitly (Figure 5 (top panel)). Exemplified in Figure 6 (top panel) are the solution workings that include clear and detailed elements of understanding, analysis, and planning, careful implementation including dimensional analysis, correct answer, but no evaluation. More disturbing are workings that do not attend to the process, result in wildly wrong answers, but still do not include any evaluative statements (Figure 6 (bottom panel)).

Notably, a greater fraction of successful students engaged in evaluation and reflection in the second problem (Figure 5 (bottom panel)), where they were explicitly asked to comment on the reliability of the obtained result and to use it to suggest appropriate storage conditions for the formulation. In this case, 35% of successful students made evaluative comments, however only 8% of unsuccessful students did so.

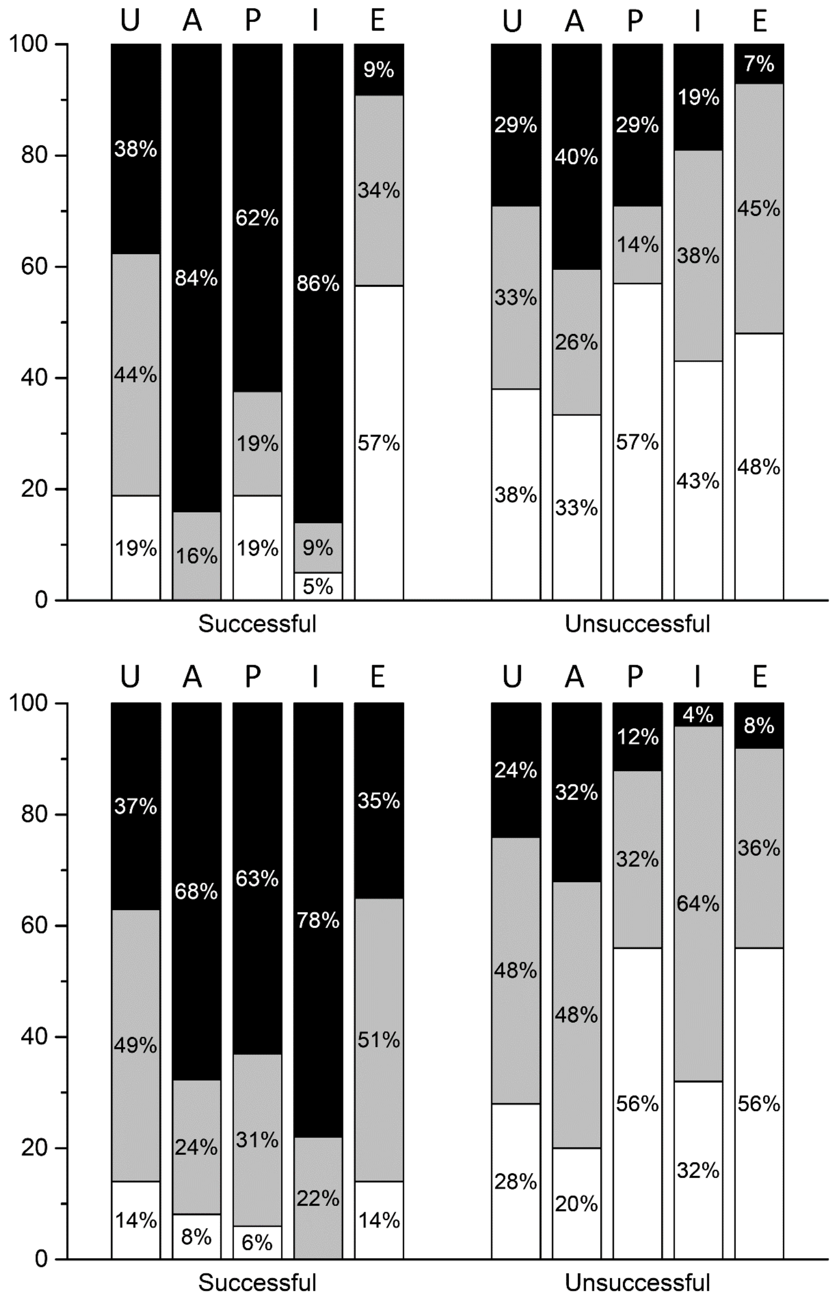

Figure 5: Mapping of student problem-solving solutions to the phases of the Goldilocks Help workflow: U (understand), A (analyse), P (plan), I (implement), E (evaluate). Colour coding represents the level of depth shown in student workings: black, full workings; grey, partial; white, none. The stacked columns show percentage of students in each of the two categories that had full, partial or no elements of each phase in their workings

Top panel: thermodynamics problem, $n_{unsuccessful}$ = 42, $n_{successful}$ = 32;
Bottom panel: chemical kinetics problem, $n_{unsuccessful}$ = 25, $n_{successful}$ = 49

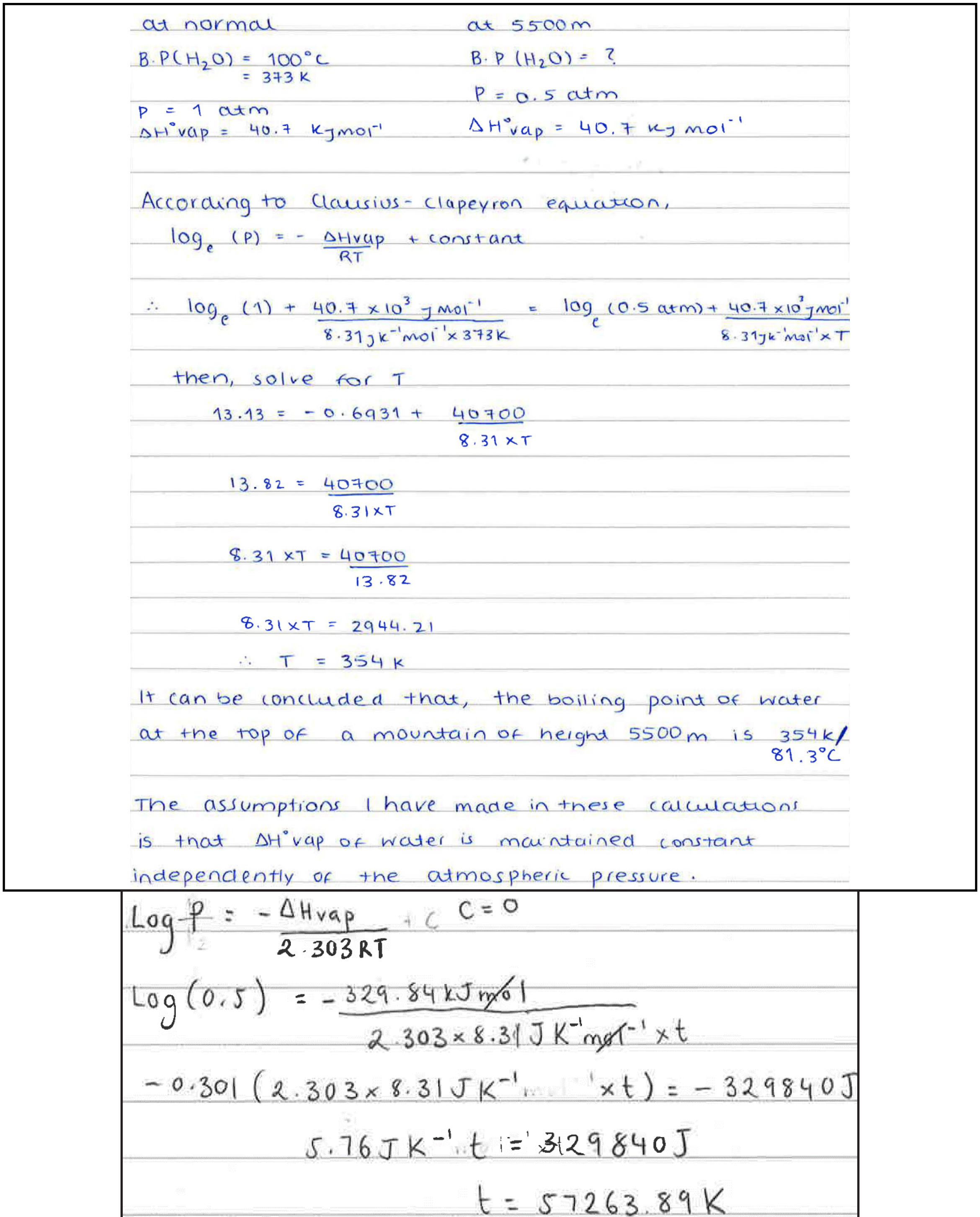

Figure 6: Examples of student workings

Discussion

Novice problem solvers are defined as those with low metacognitive self-regulation abilities (Chan and Bauer, 2014) and potentially reduced functional M-capacity, limited scientific reasoning, and lower working memory (Johnstone and Al-Naeme, 1991; Niaz, 1996; Tsaparlis, 2005). These students will manifest difficulties when starting their problem solving (false starts) or getting stuck along the way (dead ends). These students will benefit most from engaging with the Goldilocks Help problem-solving workflow.

Novice problem solvers need support in developing the metacognitive habit of self-questioning and in asking themselves appropriate questions during problem solving. With that in mind, the workflow was designed for students to incorporate the appropriate prompts into their problem-solving schema and, with sufficient practice and growth in experience, to internalise them. A novice student would not know what to ask themselves, since they don't know what they don't know. A less experienced instructor also often does not know how to prompt a student without either giving away the answer or simply throwing the question back to students, may be just by restating it. The workflow prompts mirror an experienced instructor: what would s/he ask students in class if they were to get stuck? How would s/he move them along without giving away the direction? The workflow provides these prompts to students, so they can use them when an instructor is not available, or arms a less experienced instructor with an appropriate approach to guide students.

We have identified three main categories of student engagement with the workflow: students who found it useful, students who already used a similar approach to problem solving (or at least thought so), and students who claimed the workflow to be confusing or lengthy. This third group is the most problematic. It is the type of students who give up when they find a particular way to solve problems to be too time consuming (Bunce and Heikkinen, 1986). They may also be the ones with low functional M-capacity, scientific reasoning, and working memory (Tsaparlis, 2005). Engaging and persuading these students takes time and effort. What is necessary is breaking it down and emphasising the steps of the problem-solving process: gathering information, analysis, planning, and reflective evaluation. Explicit explanation and demonstration of what the steps entail, through modelling instruction, will demonstrate to these students that it does not have to be too hard.

Our results show that while students are aware of the monitoring and reflective strategies, as indicated by the problem-solving metacognitive awareness inventory and qualitative comments (Yuriev *et al*., 2017), they do not engage in these strategies sufficiently. With respect to the written work analysed here (Figure 6), it is not unreasonable to suggest that some of the successful students may well have made an evaluative comment to themselves and simply did not write it down. However, our observations in class and during think-aloud interviews (manuscript in preparation) indicate that this lack of making an evaluative comment is representative of what students actually do (or rather do not do) when solving problems. It has long been recognised that most students lack the habit to reflect on or evaluate the outcome (Herron and Greenbowe, 1986; Van Ausdal, 1988). Even when students solve problems successfully, they could be observed not using reflection as a problem-solving route (Rodriguez *et al*., 2018). Analysis of the laboratory reports using the ELIPSS problem-solving rubric showed that almost 40% of students did not make any judgement of reasonableness of their solution, while only 3% made a judgement categorised as relevant and correct (Cole *et al*., 2018). Randles and Overton have found, in repeated extensive studies, that novice problem solvers rarely use evaluation when attempting open-ended problems, and when they do try to evaluate, they do so in a shallow fashion (Randles *et al*., 2018; Randles and Overton, 2015). Using an extended problem solver classification, the majority of successful students in the present study could be classified as transitional from novice to expert: they demonstrate some expert practices, but are deficient in their reflection. For example, we noted that when students were explicitly asked to either comment on the quality of the result or to use it for another stated purpose (as in the chemical kinetics problem) they did engage in evaluation to a greater extent.

The limitations of this study relate to the setting. The workflow was implemented in an authentic classroom setting with the cohorts of students taught by one of the authors (E.Y.). As a result, we were not able to use an experimental control *vs*. treatment design. Beyond practical difficulties, such a design would not have been ethical. Therefore, independent variables (such as prior academic ability) were not controlled and external factors (such as teaching approaches in parallel units of study) could not be accounted for.

Implications And Adaptability

Your context

- Does your course include explicit training for generics skills, such as problem solving? If so, how can you integrate the problem-solving workflow described here with the existing approaches? Are there opportunities to incorporate the process thinking into your teaching, for example in problem-solving sessions, projects, or laboratory classes?
- Do you team-teach? Are your colleagues implementing or open to experimenting with active learning strategies, particularly with respect to problem solving?
- What is the practice for training of teaching associates in your course? Do they contribute to the development of teaching materials? Are they interested in pedagogy?
- What are your assessment practices? Do you focus on algorithmic thinking and reward only correct answers or do you encourage students to engage in demonstrating their reasoning?

The single most important aspect of implementing any teaching innovation is to align teaching and learning activities with the assessment. If assessment practice contradicts stated goals, the misalignment will quickly result in students figuring out what really matters to those assessing their work. In the case of developing problem-solving skills, holistic assessment practices should reward students for demonstrating their problem-solving process, including explicit reasoning and reflection. Instruction should be adaptive and provide scaffolding where it is needed most — less successful students need support to direct their problem solving towards productive pathways — whereas successful students should be encouraged to engage more in evaluative practices.

From a practical standpoint, implementation of the problem-solving workflow is cost-effective and does not require any additional resources nor training for the academics. However, an effort is required to train teaching associates in both the theory behind the approach and its practical application. They should be encouraged to refer to the problem-solving process in tutorials and workshops and to encourage students to monitor their problem solving, particularly planning, analysis, and evaluation.

Particular attention is needed to what happens in the interactive lectures and in collaborative problem-solving sessions. Our experience is that students, particularly those who need it most, often resist using the workflow as they consider it extra work. To overcome this resistance and get students to buy in, it is useful to expose students to problems and instruction, where they can see explicitly how the workflow can help them out of dead ends and false starts in their problem solving. In the interactive lectures, students should first be given an opportunity to tackle the problems, while the academic is walking around and discussing problems with students. Following that, modelling instruction should take place which goes beyond worked examples since it focusses on the aspects of problem solving, not just on solving a particular problem. In collaborative problem-solving sessions, students should work in small groups of 4–5 and, at the end of each class, a presenter from each group can deliver a workshopped solution to the whole class. During this short presentation (3 minutes), students can share their approaches and again are encouraged to focus on the process of solving the problem, and not just on the answer. Both types of classes present instructors with multiple opportunities to discuss the whys and hows of solving problems in a logical and scientifically appropriate manner.

Conclusions

This chapter describes the design and implementation of a scaffolding approach to support structured problem solving in physical chemistry. We have demonstrated the shift in students' beliefs in their abilities to use productive strategies to achieve success in problem solving: planning (goal setting and allocating resources), information management (organising and summarising), monitoring (assessment of own strategy use), debugging (correcting comprehension and performance errors), and evaluation (analysis of performance and of the chosen approaches). We have also shown that while many students can successfully regulate their problem solving though planning and analysis, they are not as effective in employing monitoring, debugging, and evaluation. This finding contrasts with students' qualitative comments, which suggest that they value these strategies. Therefore, we propose that it is important to constructively align teaching and learning activities with assessment that explicitly encourages students to engage in demonstrating their reasoning during problem-solving, as well as other reflective and evaluative practices.

The initially designed problem-solving workflow was intended for use in general and physical chemistry units, and has now been implemented in analytical and formulation chemistry units (without any modifications). We have also developed and implemented versions for use in spectroscopy, organic chemistry, physiology, and pharmacology units. In the future, we aim to evaluate their effectiveness in these specific areas.

We have now collected an extensive data set containing hundreds of samples of student written work, generated over a period of 5 years. This set contains rich data which will be mapped against the problem-solving process as presented in the Goldilocks Help workflow and the problem-solving metacognitive awareness inventory. In addition to established qualitative analysis methods, we are planning to employ process mining approaches (Bannert *et al*., 2014) to carry out detailed frequency analyses.

Acknowledgements

We are indebted to Prof. Tina Overton for sharing her knowledge, expertise, and passion. We would like to thank Monash University for providing Winter and Summer Academic Scholarships for SB and KV. This project was in part supported by Monash Education Academy Small Grants and a Teacher Accelerator Award to EY.

References

Bannert, M., Reimann, P. and Sonnenberg, C. (2014), "Process mining techniques for analysing patterns and strategies in students' self-regulated learning", *Metacognition and Learning*, Vol. 9 No. 2, pp.161-185.

Belland, B. R. (2011), "Distributed cognition as a lens to understand the effects of scaffolds: The role of transfer of responsibility", *Educational Psychology Review*, Vol. 23 No. 4, pp. 577-600.

Bodner, G. and Domin, D. (1991), "Towards a unifying theory of problem solving: A view from chemistry", in Smith, M. (Ed), *Towards a unified theory of problem solving: views from the content domain*, Hillesdale, NJ: Lawrence Erblaum Associates.

Bodner, G. M. (2003), "The Nyholm Lecture - Problem solving: The difference between what we do and what we tell students to do", *University Chemistry Education*, Vol. 7, pp. 37-45.

Bodner, G. M. (2015), "Research on problem solving in chemistry", in Garcia-Martinez, J. and Serrano-Torregrosa, E. (Eds), *Chemistry education: Best practices, opportunities and trends*, Weinheim, Germany: Wiley-VCH Verlag GmbH and Co. KGaA, pp. 181-201.

Bodner, G. M. and McMillen, T. L. B. (1986), "Cognitive restructuring as an early stage in problem solving", *Journal of Research in Science Teaching*, Vol. 23 No. 8, pp. 727-737.

Bunce, D. M. and Heikkinen, H. (1986), "The effects of an explicit problem-solving approach on mathematical chemistry achievement", *Journal of Research in Science Teaching*, Vol. 23, pp. 11–20.

Chan, J. Y. K. and Bauer, C. F. (2014), "Identifying at-risk students in general chemistry via cluster analysis of affective characteristics", *Journal of Chemical Education*, Vol. 91 No.9, pp.1417-1425.

Cohen, J., Kennedy-Justice, M., Pai, S., Torres, C., Toomey, R., dePierro, E. and Garafalo, F. (2000), "Encouraging meaningful quantitative problem solving", *Journal of Chemical Education*, Vol. 77, pp. 1166-1173.

Cole, R., Lantz, J. and Ruder, S. (2017), "Enhancing learning by improving process skills in STEM", available at: http://elipss.com/ (accessed 14th October 2018).

Cole, R., Lantz, J. M., Reynders, G. J. I. and Stanford, C. (2018), "Enhancing learning by assessing more than content knowledge", *ASEE Annual Conference and Exposition*, Salt Lake City, Utah, USA, Paper #22684.

Davis, E. A. (2000), "Scaffolding students' knowledge integration: prompts for reflection in KIE", *International Journal of Science Education*, Vol. 22 No. 8, pp. 819-837.

Drummond, H. P. and Selvaratnam, M. (2008), "Students' competence in intellectual strategies needed for solving chemistry problems", *South African Journal of Chemistry*, Vol. 61, pp. 56-62.

Elby, A. (1999), "Another reason that physics students learn by rote", *American Journal of Physics*, Vol. 67, S52-7.

Evans, J. S. B. T. (2012), "Dual-process theories of deductive reasoning: facts and fallacies", in Holyoak, K. and Morrison, R. (Eds), *The Oxford Handbook of Thinking and Reasoning*, New York, NY: Oxford University Press, pp. 115-133.

Flavell, J. H. (1979), "Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry", *American Psychologist*, Vol. 34, pp. 906-911.

Frank, D. V. (1986), "Implementing instruction to improve the problem-solving abilities of general chemistry students". PhD, Purdue University.

Ge, X. and Land, S. M. (2003), "Scaffolding students' problem-solving processes in an ill-structured task using questionprompts and peer interactions", *Educational Technology Research and Development*, Vol. 51, pp. 21-38.

Gulacar, O., Eilks, I. and Bowman, C. R. (2014), "Differences in general cognitive abilities and domain-specific skills of higher- and lower-achieving students in stoichiometry", *Journal of Chemical Education*, Vol. 91 No. 7, pp. 961-968.

Gulacar, O., Overton, T., Bowman, C. R. and Fynewever, H. (2013), "A novel code system for revealing sources of students' difficulties with stoichiometry", *Chemistry Education Research and Practice*, Vol. 14, pp. 507-515.

Harper, K. A. (2005), "Student problem-solving behaviors", *The Physics Teacher*, Vol. 44, pp. 250-251.

Henderson, C., Yerushalmi, E., Kuo, V. H., Heller, P. and Heller, K. (2004), “Grading student problem solutions: The challenge of sending a consistent message”, *American Journal of Physics*, Vol. 72, pp. 164-9.

Herron, J. D. (1996a), *Problem solving, The chemistry classroom*, ACS, Washington, DC, pp. 63-82.

Herron, J. D. (1996b), *Teaching problem solving, The chemistry classroom*, ACS, Washington, DC, pp. 83-104.

Herron, J. D. and Greenbowe, T. J. (1986), “What can we do about Sue: A case study of competence”, *Journal of Chemical Education*, Vol. 63, pp. 528-531.

Johnstone, A. H. and Al-Naeme, F. F. (1991), “Room for scientific thought?”, *International Journal of Science Education*, Vol. 13, pp. 187-192.

Mason, D. S., Shell, D. F. and Crawley, F. E. (1997), “Differences in problem solving by nonscience majors in introductory chemistry on paired algorithmic-conceptual problems”, *Journal of Research in Science Teaching*, Vol. 34 No. 9, pp. 905-923.

McLaughlin, J. E., White, P. J., Khanova, J. and Yuriev, E. (2016), “Flipped classroom implementation: A case report of two higher education institutions in the United States and Australia”, *Computers in the Schools*, Vol. 33, pp. 24-37.

Niaz, M. (1996), “Reasoning strategies of students in solving chemistry problems as a function of developmental level, functional M-capacity and disembedding ability”, *International Journal of Science Education*, Vol. 18, pp. 525-541.

Nyachwaya, J., Warfa, A. R. M., Roehrig, G. H. and Schneider, J. L. (2014), “College chemistry students’ use of memorized algorithms in chemical reactions”, *Chemistry Education Research and Practice*, Vol. 15, pp. 81-93.

Overton, T., Potter, N. and Leng, C. (2013), “A study of approaches to solving open-ended problems in chemistry”, *Chemistry Education Research and Practice*, Vol. 14, pp. 468-475.

Overton, T. L. and Potter, N. (2008), “Solving open-ended problems, and the influence of cognitive factors on student success”, *Chemistry Education Research and Practice* Vol. 9, pp. 65–69.

Overton, T. L. and Potter, N. M. (2011), “Investigating students' success in solving and attitudes towards context-rich open-ended problems in chemistry”, *Chemistry Education Research and Practice*, Vol. 12 No. 3, 294-302.

Pea, R. D. (2004), “The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity”, *The Journal of the Learning Sciences*, Vol. 13, pp. 423–451.

Petcovic, H. L., Fynewever, H., Henderson, C., Mutambuki, J. M. and Barney, J. A. (2013), “Faculty grading of quantitative problems: A mismatch between values and practice”, *Research in Science Education*, Vol. 43 No. 2, pp. 437-455.

Pintrich, P. R., Smith, D. A. F., García, T. and McKeachie, W. J. (1991), *A manual for the use of the motivated strategies questionnaire (MSLQ)*, National Center for Research to Improve Postsecondary Teaching and Learning, Ann Arbor, MI: University of Michigan.

Polya, G. (1945), *How to solve it; a new aspect of mathematical method*. Princeton, NJ: Prinston University.

Pushkin, D. B. (1998), “Introductory students, conceptual understanding, and algorithmic success”, *Journal of Chemical Education*, Vol. 75, pp. 809-810.

Randles, C., Overton, T., Galloway, R. and Wallace, M. (2018), “How do approaches to solving open-ended problems vary within the science disciplines?”, *International Journal of Science Education*, Vol. 40 No. 11, pp. 1367-1390.

Randles, C. A. and Overton, T. (2015), “Expert vs. novice: Approaches used by chemists when solving open-ended problems”, *Chemistry Education Research and Practice*, Vol. 16, pp. 811-823.

Reiser, B. J. (2004) “Scaffolding complex learning: The mechanisms of structuring and problematizing student work”, *The Journal of the Learning Sciences*, Vol. 13 No. 3, pp. 273-304.

Rhee, R. J. (2007), “The Socratic method and the mathematical heuristic of George Pólya”, *St. John's Law Review*, Vol. 81 No. 4, pp. 881-898.

Rodriguez, J.-M. G., Bain, K., Hux, N. P. and Towns, M. H. (2019), "Productive features of problem solving in chemical kinetics: More than just algorithmic manipulation of variables", *Chemistry Education Research and Practice*, Vol. 20, pp. 175-186.

Scherer, R., Meßinger-Koppelt, J. and Tiemann, R. (2014), "Developing a computer-based assessment of complex problem solving in Chemistry", *International Journal of STEM Education*, Vol. 1 No. 1, pp. 2-15.

Selvaratnam, M. (2011), "Chemistry students' competence throughout their BSc course in some problem-solving strategies". South African Journal of Chemistry, Vol. 64, pp. 44-48.

Skemp, R. R. (1979), *Intelligence, learning, and action: A foundation for theory and practice in education*, Chichester: Wiley.

St Clair-Thompson, H., Overton, T. L. and Bugler, M. (2012), "Mental capacity and working memory in chemistry: algorithmic versus open-ended problem solving", *Chemistry Education Research and Practice*, Vol. 13, pp. 484-489.

Taber, K. (2002), *Chemical misconceptions: Prevention, diagnosis and cure*, Cambridge: Royal Society of Chemistry.

Tsaparlis, G. (2005), "Non-algorithmic quantitative problem solving in university physical chemistry: a correlation study of the role of selective cognitive factors", *Research in Science & Technological Education*, Vol. 23, pp.125-148.

Van Ausdal, R. G. (1988), "Structured problem solving in kinematics", *The Physics Teacher*, Vol. 26 No. 8, pp. 518-522.

Vygotsky, L. S. (1978), "Interaction between learning and development", in Cole, M., John-Steiner, V., Scribner, S. and Souberman, E. (Eds), *Mind in society the development of higher psychological processes,* Cambridge, MA: Harvard University Press, pp. 79-91.

White, P. J., Larson, I., Styles, K., Yuriev, E., Evans, D. R., Rangachari, P. K., Short, J. L., Exintaris, B., Malone, D. T., Davie, B., Eise, N., Naidu, S. and McNamara, K. (2016), "Adopting an active learning approach to teaching in a research-intensive higher education context transformed staff teaching attitudes and behaviours", *Higher Education Research & Development*, Vol. 35, pp. 619-633.

White, P. J., Larson, I., Styles, K., Yuriev, E., Evans, D. R., Short, J. L., Rangachari, P. K., Malone, D. T., Davie, B., Naidu, S. and Eise, N. (2015), "Using active learning strategies to shift student attitudes and behaviours about learning and teaching in a research intensive educational context", *Pharmacy Education*, Vol. 15, pp. 116-126.

Wood, D., Bruner, J. S. and Ross, G. (1976), "The role of tutoring in problem solving", *Journal of Child Psychology and Psychiatry*, Vol. 17, pp. 89–100.

Yu, K. C., Fan, S. C. and Lin, K. Y. (2015), "Enhancing students' problem-solving skills through context-based learning", *International Journal of Science and Mathematics Education*, Vol. 13 No. 6, pp. 1377-1401.

Yuriev, E., Capuano, B. and Short, J. L. (2016), "Crossword puzzles for chemistry education: learning goals beyond vocabulary", *Chemistry Education Research and Practice*, Vol. 17 No. 3, pp. 532-554.

Yuriev, E., Naidu, S., Schembri, L. S. and Short, J. L. (2017), "Scaffolding the development of problem-solving skills in chemistry: guiding novice students out of dead ends and false starts", *Chemistry Education Research and Practice*, Vol. 18, pp. 486-504.

Zimmerman, B. J. (2008), "Investigating self-regulation and motivation: Historical background, methodological developments, and future prospects", *American Educational Research Journal*, Vol. 45 No. 1, pp. 166-183.

Zoller, U. (2000), "Teaching tomorrow's college science courses - are we getting it right? Preparing students to become informed and responsible participants in the decision-making process", *Journal of College Science Teaching*, Vol. 29, pp. 409-414.