REVIEW

The implementation and effects of contemporary Problem-Based Learning in chemistry.

Joshua Hoyland and Julie Hyde*

Department of Chemistry, University of Sheffield, Sheffield, S3 7HF, UK.

*Corresponding Author: julie.hyde@sheffield.ac.uk

Keywords: *Problem Based Learning (PBL)*; *Context Based Learning (CBL)*; *Skill Development*; *Employability Skills*; *Undergraduate courses*

Abstract

Chemistry courses are seeing an increasing inclusion of the relatively novel methods of Problem Based Learning (PBL). With roots dating back to 18th Century philosophers, it aims to develop the Higher Order Cognitive Skills (HOCS) of prospective graduates, alongside other transferrable skills and social benefits that traditional teaching has failed to build upon. The utilisation of real-world problem-solving projects in chemistry modules has a wide array of seemingly verifiable benefits but a lack of trained facilitators and minimal exposure of students to PBL at lower levels provides significant drawbacks to the methodology. This review looks at the pros and cons of PBL in detail to estimate its viability in future chemistry courses around the world.

Introduction

PBL is a learning method that seeks to assist a student's learning by encouraging intellectual exploration and teamworking to develop higher level skills like critical thinking and problem solving. This will also provide a context centred mechanism of learning new material by which students may be able to use life experience to grasp a better understanding (Ceker & Ozdamli, 2016). This *cognitive constructivism* is a model that suggests new information can only be truly retained if it agrees with the student's prior knowledge and experiences (Bodner, 1986). These make up the mental structures (*schemata*) through which learning is filtered (Prince & Felder, 2006). It can be traced back to the 18th century philosophers such as Immanuel Kant and Giambattista Vico and even as far as the 4th Century BC with connections to the studies of Lao Tzu, Buddha, and Heraclitus (Prince & Felder, 2006).

PBL is a relatively recent technique within the field of higher education STEM subjects (Science, Technology, Engineering and Mathematics) and, in particular, chemistry. Traditional teaching methods have been teacher-centred, focusing on standard dissemination of information in lectures supported by supplementary mathematical formulae and evidence. These traditional teaching methods are an effective means of providing essential information but fall short of preparing students for further study and real-life situations by failing to ensure that students understand important concepts. This will not develop HOCS like problem solving and decision making that are essential to both scientific progression and employability of future graduates (Zoller, 1993).

Laboratory practical work is a teaching area unique to STEM subjects and is a key area where development of critical thinking skills should take place with a focus on self-led experimental work. Instead, new students are typically 'stuck' in the practice of traditional recipe-style laboratory work, causing a lack of motivation for self-managed experiments with no 'correct' result which may seem both confusing and challenging without prior exposure. Furthermore, undergraduates are typically still largely taught through by-the-book experiments with self-led skills being slowly introduced throughout the course leading to only 40 per cent of year 4 students preferring those experiments whose outcome is unknown (Kelly & Finlayson, 2010).

It is clear then that the development of new teaching schemes that encompass these HOCS and critical thinking skills is necessary for the improvement of student education within all faculties of a chemistry degree. Although PBL represents a significant improvement in teaching methodology, exemplified by the studies discussed in this review, there are notable hurdles in its implementation. These include a lack of engagement from new students, who are largely accustomed to traditional passive teaching methods from lower-level education, and an absence of lecturers with the required skills to teach in a PBL format (Doyle, 2011).

PBL has a succinct process that acts as a cycle with clearly defined goals for student development such as developed by Hmelo-Silver and Cindy (Hmelo-Silver, 2004), *Figure 1*.

1. Create a full and variable knowledge base.
2. Further problem-solving skills.
3. Expand self-directed learning skills.
4. Develop into efficient team-workers.
5. Be internally motivated to learn.

The process provides a rigorous framework for lecturers to develop classes based on a PBL format. The goals of the learning technique are important for all students' future endeavours. This literature review aims to discuss the implementation of PBL principles in higher education courses. The focus of the text will be chemistry courses, with an analysis of PBL in both laboratories and lectures in order to assess the effectiveness of current PBL techniques with regards to skill development. The value and challenges of this teaching approach will also be examined and compared to past techniques.

Results and Discussion

PBL is an example of context-based learning (CBL) which is about putting academic learning into the context of modern social and cultural

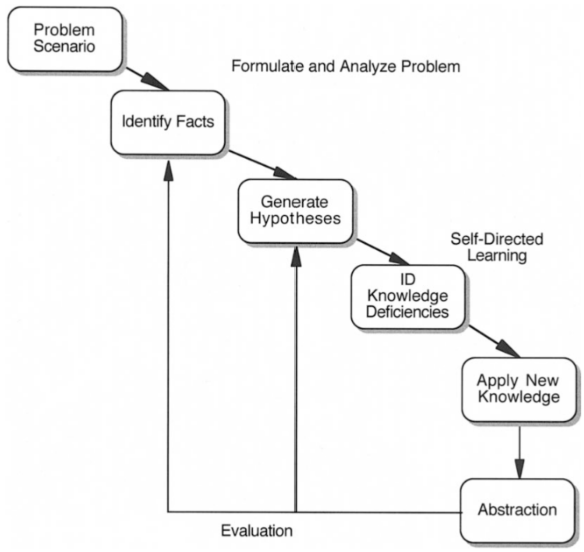

Figure 1. The PBL cycle, and related outcomes. (Hmelo-Silver, 2004),

environments and using real-world situations to test taught theories. CBL aims to motivate students and bring additional enthusiasm to a subject whilst maintaining full understanding of academic material. This means that CBL has been increasingly adopted in lower education like A-level and BTEC qualifications. The steady implementation of PBL into STEM courses over the past 30 years helps to continue the development of students that CBL techniques previously fostered (Overton, 2007).

Earlier education, such as BTEC courses, may seek to fully utilise CBL or PBL techniques throughout their courses. This permits students to apply the fundamental theories in many practical situations and therefore obtain greater understanding of the academic material (Overton, 2007). In comparison, higher education STEM courses tend to apply PBL into a few modules early in the course, with small groups, to focus on developing key higher order cognitive skills as well as interpersonal/communication skills along with a greater enthusiasm for the content, (Williams et.al. 2010). These courses often place a much greater degree of responsibility on the students, often involving planning, research and formation of solutions to novel real-world problems with teachers taking the more managerial role as facilitators. These PBL mini projects also allow for greater creativity from students which in turn heightens the students' morale and even increases attendance (Williams et.al., 2010, McDonnell et al., 2007). As an additional side benefit, small scale projects in lower levels will better prepare students for the process of larger scale research projects in levels 3 and 4 (Mc Donnell et al., 2007). These smaller scale adoptions of PBL may be appropriate for chemistry courses due to a relative necessity for a lot of traditional content dissemination in order to cover a broad range of topics as well as the large number of contact hours required for consistent practical work throughout a course.

To provide an example of how PBL might be implemented into practical work to aid teaching, The University of Sheffield's relatively recent 'Skills for Success' projects provided to level 3 students creates a wide array of opportunities including a project which tackles the problem of producing high quality scientific data without the access to high accuracy scientific apparatus. Instead, students are tasked with utilising familiar household items to test a novel scientific hypothesis (Burnham et, al., 2019). This gives students the chance to internalise the scientific process and techniques whilst facing a problem based in a setting students will be familiar with. Additional projects like these in lower levels could help to teach basic laboratory techniques such as error propagation which will at first be difficult to new students.

Developing a course that incorporates PBL requires careful consideration of resources, staff and students in order to maximise the desired results and navigate any potential challenges. For example, adapting pre-made resources to the course will make for a gradual introduction to the new teaching methods alongside traditional lecture-style courses. Additionally, ensuring that developed skills are highlighted to students is vital to procuring good student feedback and even allows students to develop novel PBL resources themselves. It is also important that, when a new problem is produced, it mirrors real world issues that have various possible answers, places emphasis on the interdisciplinary aspects of modern research and ensures good utilisation of higher order cognitive skills (Williams, 2015).

A slight variation on typical PBL techniques known as dynamic problem-based learning involves the independent research and solving of self-chosen real-world problems with the addition of changing external factors, such as economics and laws, that force students to make quick adaptive adjustments to formulated solutions. This has been shown to further develop key life skills with the best possible representations of real-life issues with little extra resources required to implement the necessary changes to a standard PBL course (Overton & Randles, 2015).

It has been shown that active learning techniques in higher education STEM courses increase typical examination grades by around 6% as well as indicating that students that do not experience any CBL techniques are 1.5 times more likely to fail (Freeman et. al., 2014). When PBL techniques were used in an introductory organic chemistry course, the performance of students increased by an average of 110% for essay questions, 53% in mechanism questions and 10% for short answer questions showing an increasing trend in analytical thinking skills for students experiencing PBL methodologies (De Jesus,1995). When CBL was implemented into an analytical electrochemistry course the feedback shows that 81% of students in a PBL group had a clear understanding of the course whereas only 48% of traditionally lectured students did (Alpat & Gunter, 2017). All this data, along with many case studies, shows a strong relationship between comprehension of material and degree of context in the teaching methods (Belt, 2009).

Although the effectiveness of PBL techniques on student performance in STEM seems strong, case studies show significant challenges in implementing the relatively novel method. For example, students can have difficulty with recognising where group work may require divided workloads or stringent time organisation to meet with group members. This would require significant guidance from a facilitator. Also, some students and teachers may not be familiar with any kind of problem-based learning and would therefore need time and teaching in the methodology to be effective. Stemming from this, teachers may not know how to give adequate feedback for PBL problems and would not be meeting the needs of students to be able to address weaknesses. Additionally, it is possible for parents and educators to be uncomfortable with the new learning techniques, remaining firm in the belief that students should memorise and learn content without seeing the benefit of a focus on skill development (Shariff, 2009).

It also seems that PBL could be less effective for larger groups due to the intensive time commitments required of the instructors in order to be able to provide the most effective feedback to students (De Jesus, 1995). In addition, the expectations of students with regards to assessment may change to reflect the PBL teaching format. They may believe that an assessment of reports, presentations or home assignments would reflect their individual abilities better (Jansson *et.al.*, 2015). Student feedback has shown difficulties with problems without a defined answer due to a lack of PBL teaching in lower-level education, as well as a dislike of problems based on previously covered material and the heavy reliance on group members to complete portions of their work; they would prefer to remain independently assessed (Williams, 2017).

Further to the positive effect PBL has on academic performance, there are a great number of additional benefits, such as large boosts to motivation and significant social benefits, especially when implemented early for new students, (Williams et al., 2010, Williams, 2015). It is also able to increase the memory capabilities of students as the course content is now connected by interactive problems that support reflection, explanation and creativity (Dods, 1996). As a side benefit, the problems can be posed as specifically as desired to encourage students to tackle particular areas of a broader issue as exemplified by Fischbach and Sell:

"*Less specific* acid rain may be enhanced by SO_2 emissions, acid rain can be a severe environmental problem. *Original statement*- acid rain can decrease the pH of certain lakes; acid rain can lead to a decrease in certain desirable fish species. *More specific*- acid rain can lower the survival rate of young fish; methods should be developed to decrease the effect of acid rain on the survival rate of young fish." (Fischbach and Sell, 1986).

The small-knit groups ideal for PBL also allow students to benefit from socialisation such as respecting group members, hearing the contributions of others and providing praise as well as learning skills for conflict resolution (Shariff, 2009). The ability for students to be creative during learning has been shown to increase attendance and heighten camaraderie in the groups (Mc Donnell et.al., 2007). The student-focused learning gives students greater self-confidence and promotes inductive learning where students are motivated to ask questions and solve problems to meet expectations of knowledge (Jansson et.al., 2015).

Overall, it has been repeatedly shown that PBL techniques appear to aptly develop a wide array of transferable skills for students making them more than prepared for the common PBL situations faced every day in the worlds of both work and post graduate research. This means that utilising context-based learning early in an undergraduate course would improve the employability, opportunities and abilities of the next generation of chemistry graduates.

In the future, issues with PBL such as the lack of trained facilitators, lack of student self-organisation and general unease with the techniques for parents and teachers will likely become diminished as PBL becomes more widespread and additional training and preparation for teaching PBL to students may further help to reduce these issues. As more positive data regarding the effectiveness of PBL techniques becomes available, opinion is likely to become more favourable.

Conclusions

To summarise, throughout history, philosophers have added to and developed the theory of *cognitive constructivism* (Bodner, 1986) that stipulates all learning must be filtered through mental structures, *schemata*

(Prince & Felder, 2006), in order to be retained. From this came the teaching methods of context-based learning which aim to correlate teaching to the context of everyday life. One of these methods, PBL, has seen increased usage in STEM subjects over the past few years and contrasts starkly with the traditional teacher-focused lecturing and 'recipe style' practicals of the past.

Traditional teaching methods were failing to provide students with HOCS that are key desirable traits for employers of chemistry graduates and important skills for any postgraduate researcher. Thus, PBL has quickly risen in popularity to fill this void due to its encompassing of so many transferrable skills along with the rigid development structure devised by Hmelo-Silver and Cindy, (Hmelo-Silver, 2004). Usage of PBL in STEM subjects varies significantly from the often complete integration, commonly seen in lower level BTEC courses, to inclusion in smaller modules of courses or 'mini projects' that have a focus on developing transferable skills and generating enthusiasm for the subject.

Many studies have shown the additional effectiveness PBL has on academic achievements as well as a plethora of additional key cognitive skills and social benefits. However, PBL is not without many drawbacks often centred around a lack of previous exposure to the methodology and the high workload placed on facilitators in order to give effective feedback to students.

To provide thoughts on the technique, PBL seems to have an undeniable effect on the development of so many important skills and social abilities without significant detriment to academic achievement. The shortcomings of the technique will likely reduce as it becomes more widely used, particularly in lower-level education, as students and teachers will become increasingly exposed to the techniques.

One concern could be that the increasing developments being made in traditional teachings to accommodate ever more common mental health issues such as anxiety and depression are just as, if not more so, important in PBL courses where many could feel alienated by the need for strong social connections and communication that would otherwise seem trivial. However, it could equally be the case that many shy or typically asocial students may rise to the opportunity to develop much needed social skills and, particularly for new undergraduates, readily form bonds with others that traditional teaching methods could be hindering by providing little opportunity for communication. This demonstrates that there are still many areas of PBL that need further research and study but there is a growing list of positive effects that PBL has on undergraduate students and therefore the world in which they will inevitably contribute.

References

Alpat, S.K. & Gunter, T. (2017). *The effects of problem-based learning (PBL) on the academic achievement of students studying 'Electrochemistry'*, Chem. Educ. Res. Pr., 78, (18), 78-98.
doi.org/10.1039/C6RP00176A

Belt, S.T. (2009). *Impacts of assignment in problem-based learning: A case study from chemistry*, New Dir. Teach. Phys. Sci., 5, 16–21.
doi.org/10.29311/ndtps.v0i5.454

Bodner, G.M. (1986). *Constructivism: A Theory of Knowledge,* J. Chem. Educ., 63, (10), 873-878.
doi.org/10.1021/ed063p873

Burnham, J.J., Ciani, B. & Grasby, J. (2019). *Skills for Success Projects at The University of Sheffield.*

Ceker, E. & Ozdamli, F. (2016). *Features and characteristics of problem-based learning*, Cypriot J. Educ. Sci., 11, (4), 195–202.
doi.org/10.18844/cjes.v11i4.1296

De Jesus, K. (1995). *A problem-based approach to organic chemistry*, J. Chem. Educ., 72, (3), 224–226.
doi.org/10.1021/ed072p224

Dods, R.F. (1996). *A Problem-Based Learning Design for Teaching Biochemistry*, J. Chem. Educ., 73, (3), 225-228. doi.org/10.1021/ed073p225.

Doyle, T. (2011). *Learner-centered teaching: putting the research on learning into practice*, 1st Edition, Stylus Pub., LLC, Virginia, USA, Ch 1.
doi.org/10.1111/teth.12122

Freeman, S., Eddy, S.L., McDonough, M., Smith, M.K., Okoroafor, N., Jordt, H. & Wenderoth, M.P. (2014). *Active learning increases student performance in science, engineering, and mathematics*, Proc. Natl. Acad. Sci. U. S. A., 111, (23), 8410–8415. doi.org/10.1073/pnas.1319030111

Fischbach, F.A. & Sell, N.J. (1986). *A structures approach to teaching applied problem solving through technology assessment*, J. Chem. Educ., 63, (6), 522-5 doi.org/10.1021/ed063p52225.

Hmelo-Silver, C. E. (2004). *Problem-based learning: What and how do students learn?* Educ. Psychol. Rev., 16 3, 235-266. doi.org/10.1023/B:EDPR.0000034022.16470.f3

Jansson, S., Soderstrom, H., Andersson, P.L., & Nording, M, L. (2015). *Implementation of Problem-Based Learning in Environmental Chemistry*, J. Chem. Educ., 92, 2080–2086. doi.org/10.1021/ed500970y

Kelly, O.C. & Finlayson, O.E. (2010). *Easing the transition from secondary school to higher education through recognition of the skills of our students*, New Dir. Teach. Phys., Sci., 6, 51–55.
doi.org/10.29311/ndtps.v0i6.385

Mc Donnell, C., O'Connor, C. & Seery, M.K. (2007). *Developing practical chemistry skills by means of student-driven problem-based learning mini-projects*, Chem. Educ. Res. Pract., 8, (2), 130–139.
doi.org/10.1039/B6RP90026G

Overton, T. (2007). *Context and problem-based learning*, New Dir. Teach. Phys. Sci., 3, 7–12.
doi.org/10.29311/ndtps.v0i3.409

Overton, T.L. & Randles, C.A. (2015). *Beyond problem-based learning: using dynamic PBL in chemistry*, Chem. Educ. Res. Pr., 16, 251-259.
doi.org/10.1039/C4RP00248B

Prince, M.J. & Felder, R.M. (2006). *Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases*, J. Eng. Ed., 95, (2), 123-138.
doi.org/10.1002/j.2168-9830.2006.tb00884.x

Shariff, A. (2009). *Reflections on a first-time experience of problem-based learning*, New Dir. Teach. Phys. Sci., 5, 48–54.
doi.org/10.29311/ndtps.v0i5.453

Williams, D.P., Woodward, J., Symons, S.L. & Davies, D.L. (2010). *A Tiny Adventure: the introduction of problem-based learning in an undergraduate chemistry course*, Chem. Educ. Res. Pract., 11, 33-42.
doi.org/10.1039/C001045F.

Williams, D.P. (2015). *Problem based learning approaches to teaching chemistry*, Innov. H. Educ. Teach. Learn., 4, 93-112.
doi.org/10.1108/S2055364120150000004007.

Williams, D.P. (2017). *Learn on the Move: A Problem-Based Induction Activity for New University Chemistry Students*, J. Chem. Educ., 94, 1925–1928.
doi.org/10.1021/acs.jchemed.7b00399

Zoller, U. (1993). *Are Lecture and learning compatible? Maybe for LOGS: Unlikely for HOCS*, J. Chem. Educ., 70, (3), 195–197.
doi.org/10.1021/ED070P195