HERDSA

Higher Education Research and Development Society of Australasia Inc

Research and Development in Higher Education: Curriculum Transformation

Volume 40

Verkade, H., Lodge, J.M., Elliot, K., Mulhern, T.D., Espinosa, A.A., Cropper, S.J. & Rubinstein, B.I.P. (2017). Exploring misconceptions as a trigger for enhancing student learning. In R.G. Walker & S.B. Bedford (Eds.), Research and Development in Higher Education: Curriculum Transformation, 40 (pp 392-401). Sydney, Australia, 27–30 June 2017.

This research paper was reviewed using a double blind peer review process that meets DIISR requirements. Two reviewers were appointed on the basis of their independence and they reviewed the full paper devoid of the authors' names and institutions in order to ensure objectivity and anonymity. Papers were reviewed according to specified criteria, including relevance to the conference theme and audience, soundness of the research methods and critical analysis, originality and contribution to scholarship, and clear and coherent presentation of the argument.Following review and acceptance, this full paper was presented at the international conference.

Exploring misconceptions as a trigger for enhancing student learning

Heather Verkade
University of Melbourne, Parkville, Australia
heather.verkade@unimelb.edu.au

Jason M. Lodge
University of Melbourne, Parkville, Australia
jason.lodge@unimelb.edu.au

Kristine Elliott
University of Melbourne, Parkville, Australia
kaelli@unimelb.edu.au

Terrence D. Mulhern
University of Melbourne, Parkville, Australia
tmulhern@unimelb.edu.au

Allen A. Espinosa
University of Melbourne, Parkville, Australia
espinosaa@student.unimelb.edu.au

Simon J. Cropper
University of Melbourne, Parkville, Australia
scropper@unimelb.edu.au

Benjamin I. P. Rubinstein
University of Melbourne, Parkville, Australia
benjamin.rubinstein@unimelb.edu.au

This article addresses the importance of confronting misconceptions in the teaching of the STEM disciplines. First, we review the central place for threshold concepts in many disciplines and the threat misconceptions pose to quality education. Second, approaches will be offered for confronting misconceptions in the classroom in different contexts. Finally, we discuss what we can learn about these approaches and the common threads that reveal successful approaches. These steps have been explored in relation to four case studies across diverse disciplines. From these case studies, a set of principles about how best to address misconceptions in STEM disciplines has been distilled. As conceptual knowledge increases in importance in higher education, effective strategies for helping students develop accurate conceptual understanding will also be increasingly critical.

Introduction

The problem with misconceptions

Facts and declarative knowledge have lost their lustre. In the global era of 'post truth' that our graduates now face, inert pieces of declarative knowledge are declining in importance. This decline has been brought about and hastened by the increasingly ubiquitous nature of technologies allowing access to declarative knowledge any time and almost anywhere via the Internet. Consequently, there is an increasing need for graduates to develop high-level conceptual knowledge. The complex issues and problems that young people face in the 21st Century will not be solved through rote memorisation of facts or processes, but through the development of epistemic fluency in complex and interconnected ideas (Markauskaite & Goodyear, 2016). The development of complex knowledge of this kind, however, is not straightforward. Factors such as students' prior knowledge, confidence, and capacity to self-regulate and monitor their learning all have an impact on how effectively they are able to acquire conceptual knowledge (Kennedy & Lodge, 2016). This difficulty has long been evident in higher education research concerning threshold concepts and troublesome knowledge (Meyer & Land, 2003).

The conceptual nature of STEM (Science, Technology, Engineering and Mathematics) disciplines and their extensive experience in the physical world can lead to students entering university with well-established but incorrect assumptions about phenomena (Cordova et al., 2014). Naïve understandings such as these assumptions that are held prior to advanced, discipline-specific instruction are known as preconceptions. Preconceptions that conflict with currently accepted core concepts and empirical findings of a discipline, and which result in systematic patterns of error can be defined as misconceptions (Bensley & Lilienfeld, 2015; Vosniadou, 2009).

Misconceptions are thought to have two major origins. Factual misconceptions are beliefs that arise from inaccurate or incomplete information that an individual is exposed to via the media, books, the classroom, or through interaction with other people (Hughes et al., 2013). The Internet is another increasingly significant source of inaccurate and incomplete information (Keen, 2015). Ontological misconceptions, on the other hand, derive from intuitive theory-like beliefs that are based on an individual's subjective experience and anecdotal evidence (Hughes et al., 2013). These seemingly 'commonsense' or 'folk' beliefs arise because people seek to understand and explain the world around them, often without the foundational knowledge of a formal science education. These misconceptions take hold because intuitive conceptions are easier to comprehend than the more complicated, counterintuitive truth.

Misconceptions pose a significant challenge for university teachers because they are often strongly-held and highly resistant to correction through standard instructional methods (Hughes et al., 2013). This is especially relevant to large class teaching where it can be difficult to help individual students achieve conceptual change by fostering higher order thinking (Hornsby & Osman, 2014), and because misconceptions are more likely to be missed than in small classes (Finn & Achilles, 1999). Misconceptions are also likely to have a negative impact on the learning of new knowledge, if inaccurate knowledge or beliefs contradict newly acquired information (Chinn & Malhotra, 2002; Hughes et al., 2013). Furthermore, students appear to be unable to generalise their learning about one misconception to others that are based on similar assumptions and beliefs (Kowalski & Taylor, 2009).

STEM disciplines typically rely on an accurate understanding of core concepts before more difficult concepts can be learnt. Misconceptions not only block further learning, but they also prevent students from solving scientific problems, which is a key application of STEM knowledge. Many of the misconceptions in STEM arise from naïve preconceptions students hold when they enter a course (Coley & Tanner, 2012). Several common epistemological approaches are thought to lead to misconceptions: Teleological thinking causes people to consider events to have happened for a purpose, such as evolution having a goal; Essentialist thinking leads to an expectation of stability, that nothing can change, and since many physical, chemical and biological phenomena are explained by random events an expectation of stability can cause difficult blocks in conceptual learning (Garvin-Doxas & Klymkowsky, 2008); and finally, anthropocentric thinking, especially in biology, projects an expectation that all organisms share the familiar traits of humans.

Correcting misconceptions

Detection is the first step towards repairing students' misconceptions. Concept inventories have been developed in many science disciplines to measure the extent to which students understand core concepts (Hestenes et al., 1992), for example, in astronomy, chemistry, computer science, engineering, genetics, geoscience, mathematics, physics, life science, and psychology. Concept inventories typically use forced-choice questions in which one response is correct and the remainder are incorrect (the distractors). Distractors are grounded in common misconceptions so that students' choices reveal their misconceptions. Concept inventories have been found to be more accurate at identifying student misconceptions than misconception tests with simple true/false response (Kowalski & Taylor, 2009), although deeper knowledge about the cause and structure of misconceptions requires talking to students (Adams & Wieman, 2011).

'Conceptual change' is the most prominent theory to describe how misconceptions can be corrected (Clement, 1993). It posits that learning will only be successful when previously held beliefs are critically evaluated, revised and replaced with new discipline-consistent information. Conceptual change often involves restructuring, adjusting and/or reworking the interconnected assumptions, concepts and beliefs that comprise a misconception (Amsel et al., 2011). However, it can sometimes be easier for students to reject, ignore or reinterpret new information, than it is to revise their inaccurate beliefs. There is a serious risk that this failure to revise a conception will lead to a 'backfire effect' where the initial conception is instead reinforced and becomes even more persistent as a result (Trevors et al., 2016). Additionally, the more confident an individual is in the accuracy of their belief, the more it can reduce comprehension of new material that conflicts with the prior belief (Dole, 2000). Students may even integrate the new knowledge with their existing misconception, generating a 'synthetic model' (Vosniadou, 2009). In general, strong critical thinking skills help to correct misconceptions (Bensley et al., 2014; Taylor & Kowalski, 2004).

Confronting misconceptions in the classroom

A number of teaching strategies have been reported to effectively correct misconceptions. Refutational approaches, including refutational lectures, text and posters, aim to highlight a misconception and then directly refute it using empirical evidence (Kowalski & Taylor, 2009; Taylor & Kowalski, 2004). Research suggests that refuting students' misconceptions is more successful if refutational text is combined with refutational lectures/tutorials (Kowalski &

Taylor, 2009). *ConcepTest* is another effective refutational strategy that involves administering in class a multiple-choice question that contains a common misconception (Chew, 2004). Students are asked to select a response and publicly indicate their selection. Students then discuss and defend their choice with their peers and are again asked to publicly indicate their correct answer. Finally, the lecturer reveals the correct answer and discusses why it is correct and why the misconception is incorrect. Through this process the misconception is activated and then the correct answer is learned with the reasoning behind it.

Analogy is another strategy used to correct misconceptions. This approach is a form of guided constructivism that uses students' correct prior knowledge (anchoring conceptions) and their incorrect prior knowledge (misconceptions) to bring the conflict to their attention. It encourages them to discuss this conflict with other students and the teacher and allows them to evaluate their ideas in light of the empirical evidence. No single analogy will be effective for all individuals and therefore it is important for teachers to use a variety of analogies. For example, several studies have found the use of analogy to be an effective strategy to overcome students' misconceptions in chemistry (Tsai, 1999).

The approaches that university teachers take to confront misconceptions in the classroom is the focus of a study across a range of science disciplines in a large Australian university. The study is using student questionnaires, interviews, scores and classroom observations to investigate the effectiveness of university teachers' classroom practice to correct common misconceptions in computing science (Machine learning), biomedical science (Biochemistry and Molecular biology) and behavioural science (Psychology). In this paper, we provide an overview of the effectiveness of the examined approaches. We describe four case studies and, through critical analysis of the key features of each, identify commonalities and differences that form the basis of a framework for effective pedagogy to overcome students' misconceptions in science disciplines in higher education.

Findings

Case 1: Computing science - Trial and error tutorial
Machine learning is a Masters level subject that requires a solid understanding of statistical modelling. Students come to this subject with a wide variety of undergraduate backgrounds and experiences and importantly, with different strengths in statistics. A common misunderstanding held by students entering this subject is that a complex statistical model would more accurately describe the patterns in a data set than a simple one. This can lead to over-fitting, in which the model describes random error or noise rather than an underlying relationship, thereby reducing the predictive performance of the model. This is due to a misconception that complex data can only be explained by complex statistical models.

In this case, students were asked to apply their statistical knowledge to a problem of data modelling. Students (n=100) worked with data sets in tutorial settings of 30 – 35 students per tutorial. The task was designed in such a way that if students held the key misconception detailed above, then their first attempt at modelling the data would not be successful. Peer discussion and assistance from the tutor followed, so that students could then successfully re-try the task using a simpler statistical model that ignores noise. This trial-and-error learning approach used students' attempts to model the data as a trigger for conceptual change. In this case, the coordinator observed that the failure point created surprise, and the cognitive

dissonance caused the students to rethink their approach. As one student reported on changing their mind, it was "…like things in the subject made more sense".

Case 2: Biomedical science - Tutorial structured around a concept inventory
Concept inventories are validated instruments useful for assessing students' concepts (Klymkowsky & Garvin-Doxas, 2008). They contain multiple choice questions with distractors written from students' own writing, so that they reveal the key misconceptions that can not necessarily be seen from standard assessment tasks. These instruments are highly valuable for evaluation of the level of student understanding, but they are not designed for the important next stage of confronting the misconception. In this case, a concept inventory was used as the launch point for tutorial work that required students to question their understanding.

The setting was three large class tutorials of 150 – 250 students in a second year Biochemistry class (n=651). The lecturer administered a concept inventory to evaluate the students' understanding of crucial first year chemical concepts that are required for an understanding of biochemistry, such as: pH, acids, bases and interactions between molecules (Villafane et al., 2011). As an interesting addition to this tool, students reported their confidence for each answer. The concepts that were prioritised for follow up were those that the students got wrong, and yet they had a high degree of confidence in their incorrect answer. In the follow up tutorial, the students were informed, for example, that actually, 70% of them got a question wrong despite being confident in their answer, thus generating surprise and doubt. These cognitive states define the ideal conditions for conceptual change (Ranney et al., 2016). During the tutorial, the students engaged in peer discussion and re-questioning of the concept with similar questions, while the lecturer gradually revealed more information. The change in student understanding was monitored using an online in-class polling tool. The accuracy of the students' answers increased during the process, and their answers to similar questions on the exam were higher than in previous years. Interviews revealed that students were surprised that they had been wrong on the initial question, and were embarrassed if a neighbouring student had the correct answer. For example, one student reported that they "…felt kind of stupid but happy that I've learned something", and that "I was a bit embarrassed that, you know, I missed something so simple". This approach applied itself well to large class settings, as students also said that "because when I kind of worked it out, I think it was good that I felt like I've worked it out and I didn't actually need help of the tutor".

Case 3: Biomedical science - The big reveal
This case from Molecular Biology addressed threshold concepts concerning the structure of DNA. It shares similar techniques to those used in case 2, although it did not start with a concept inventory. Tutorials were conducted in large classes of 150-250 students, in second year Molecular Biology (n=372).

Students can confidently and correctly answer questions about DNA structure in the lower Bloom's taxonomy levels (e.g. remember, understand), yet still not correctly answer an application question. The lecturer began these large class tutorials with online polling of the students with a multiple choice question that required application of the concept. Without showing the answer, the lecturer gradually revealed additional information in the form of the full structure of double-stranded DNA. Interestingly, to an expert these questions would be equivalent, as the structure of the second strand of DNA can always be deduced from the first strand. Many students, however, made an incorrect assumption about the 'directionality' of

DNA structure based on the limited information. When the students saw the additional information, it revealed to them the underlying misconception. Peer discussion in the tutorial lead to many animated debates, and, when the class was polled again, the proportion of correct answers was greatly increased. The session was rounded off with a wider discussion lead by the lecturer.

Findings from student questionnaires and interviews revealed two interesting aspects to this method. Firstly, this tutorial generated surprise and doubt, as the students saw more information that was incompatible with their original answer and discussed their answer with their peers. For example, one student reported that "Originally I was actually feeling confident because like I'd worked through them and I thought I sort of have the right mindset. But then I was just talking a bit, I realised that my theory wasn't quite working". Secondly, for questions requiring detailed content knowledge, this method was able to bypass the requirement for students to remember the complex pathways and terminology, as this information was presented along with the question, allowing the students to attempt application and therefore test their grasp of the underlying concepts. For example, a student reported that "… after looking through the notes and the diagram that showed this in lectures, I found [my mind] shifting, it made more sense and it triggered memory like what it was supposed to be". It is worth noting that case 2 and 3 follow a method that is similar to that described as a *Conceptest* by Eric Mazur in 1997 (Mazur, 1997).

Case 4: Psychological science – Applying many concepts to one phenomenon
There are many different misconceptions that can arise in the understanding of vision. Many of these arise from preconceptions or naïve assumptions people make about the workings of the natural world. Understanding of the many concepts of sight is required for an accurate description of a complex visual phenomenon, such as watching a sunset.

This case was used with a very large (n=1300 students) cohort in a psychology subject taken as one of their first classes in first year. The students have diverse backgrounds; for some the subject is part of an arts degree and for others it is part of a science degree. In this case, the students were asked to spend a significant time (usually 2 hours) watching a sunset throughout all the visual changes until the sun has completely gone below the horizon, taking only handwritten notes. They would then use their notes, along with the concepts explained in their recent lectures, to describe the phenomena in detail in a piece of written work. To accommodate the range of student backgrounds the style and format of the writing assessment were not constrained, allowing students to produce their choice of practical report, descriptive reports, or even creative writing. A tutorial helped students decide how to write up the assessment.

The act of describing the sunset revealed conceptual inconsistencies to the students and challenged them to alter them using recent learnings. For example, students reported that 'the assignment helped me to actually pay attention to my environment and the changes in it', and 'the assignment made me really deeply consider why I was seeing the things I was seeing,'. Interestingly, they also said 'While watching the sunset itself did not do much, to write the sunset piece I needed more of an idea of what was happening so I did research which made everything a lot more understandable.' This case required the high-level skills of application and interpretation, but this challenge engaged the students to more clearly understand the fundamentals, rather than causing them stress. As this assessment was run outside of class time, the students had sufficient time to complete the task while referring to their notes. As one

student commented "The completion of the assignment was what really made me understand colour vision, as I had to in order to thoroughly explain myself. This was because I went back over my notes and did some external reading."

Unifying factors that make these cases work

There are several themes running through these cases that are highlighted in the literature about misconceptions and conceptual change. These themes will be examined here to identify unifying factors that may be transferable to other teaching situations.

Surprise!

A theme in common with all these cases is that they generate cognitive dissonance, such that the student re-examines the concepts that they believe that they know. There is often an element of surprise, as the student discovers an inconsistency between their understanding of a concept, and the answer to the problem. Confusion arises when students' predictions about their knowledge does not match the feedback they get. Confusion and surprise have both been found to be important elements in the conceptual change process (Lodge & Kennedy, 2015). Indeed, one student reported in case 3, that the tutorial helped because "I think the whole process going through choosing the wrong answer actually made me remember it well".

Confusion also interacts with students' confidence. Dissonanace generates engagement, which is evident from the large amount of written material generated by students in case 4, and the animated peer discussion observed in cases 2 and 3. The ease with which information can be searched for on the Internet has led to increasing confidence in what people think they know (Keen, 2015). It can be difficult to shift erroneous conceptions when they are held with high confidence, and, in case 2, the students' confidence was used to aid identification of persistent misconceptions. The findings from the cases reported here reflect similar patterns to those observed in laboratory settings, suggesting that surprise is an important element for correcting misconceptions held with high confidence (e.g. Cottrell, Berzinski & Lodge, 2015).

Social constructivism at its best

A second common factor for the success of the tutorial-led approaches described here in cases 1, 2, and 3 was the used of discussion as a precursor to peer learning. There are many cases of peer discussion being used to compensate for large class situations (Armstrong et al., 2007). Discussion has also been long known to be effective for enacting conceptual change, particularly when implemented using methods such as Socratic dialogue (Chi et al., 2017; Muller et al., 2008).

Interestingly, the first year psychology assignment in case 4 was not grounded in social constructivism. Writing is essentially a solo task, although the tutorial for checking the writing approach gave ample time to explore ideas in a social context. One significant difference in this assignment was that it was aimed at an audience broad enough to span disciplines, as some students were doing a Bachelor of Science and some were doing a Bachelor of Arts. The open-ended nature of the assignment was an important way for students to satisfy the terms of the assessment using different disciplinary conventions. Although the fundamentals needed by the students to describe the sunset were neuroscience in nature, this discursive approach would suit disciplines outside of STEM, in which time needs to be taken to fully explore complex interconnected ideas.

Great expectations

It might be expected that challenging less advanced students with questions requiring higher Bloom's levels (e.g. application) could cause students to shut down rather than engage. However, a third theme in common in these cases is that they require students to apply knowledge in a way that initially seems straightforward, but the complexities of the question progressively reveal themselves. Fascinatingly, this appears to maintain strong engagement. The application of a complex model in Case 1, making quick assumptions in Case 2 and 3, and applying simplistic 'common sense' understandings in Case 4, ultimately fail to satisfy the requirements of the questions and so the students re-think their positions by: re-trying the statistical analysis, discussing the question with neighbours, or reading and researching the topic to develop a better explanation for the observations. It is gratifying to think that students are willing to accept a challenge to use the skills of application and interpretation, and it is important to set this challenge in the right context where the students are well supported and assisted.

Implications for practice

An alternative view sometimes taken in this area of learning research is that misconceptions do not necessarily need to be confronted. Sometimes, a misunderstanding is actually a pre-conception that does not pose a block to further understanding. A student will build on this pre-conception by constructing synthetic or hybrid models that account for new information in the light of their previous mental model, and this will allow the student to transition to the new way of understanding. In this approach, misconceptions are considered benign precursors rather than damaging misunderstandings (Chi, 2013; Clement, 1993). The approaches described here all allow students to examine their misconceptions in the light of new information, and whether they are altering their mind due to shock and chagrin, or they are melding the old and the new information for a more complete understanding, these are both important steps to further advancement in their learning.

Dealing with misconceptions in higher education settings needs to be handled with some care. Misconceptions can occur for several different reasons that may relate to either faulty or missing knowledge, incorrect mental models or missing schema (Chi, 2013). It is not always possible to provide personalised feedback to ensure that each student has effectively acquired and updated correct conceptions. We have attempted here to highlight possibilities for dealing with commonly misconceived notions across several disciplines. What is perhaps most important in each case is that students are given an opportunity to test out their ideas and discover for themselves that their understanding is not as complete as they thought. Ultimately, our role as higher educators is to develop students so as to allow them to monitor their own conceptual understanding and make good decisions about how to come to more accurate conceptions themselves. Future research examining effective practices for dealing with misconceptions could extend in this direction. Effective pedagogical strategies for assisting students to better self-regulate their conceptual understanding in a conscious, deliberate way is critical in the information-rich 21st Century.

Conclusions

In this paper we have introduced a misconception-driven pedagogy across STEM disciplines. We have described four case studies across the sciences that have used misconceptions as a key focus for student learning. There are similarities between each of these case studies that provide clues about the most effective practices for driving conceptual change in university settings. We hope that this paper will serve as a catalyst for more research into effective approaches for helping students overcome misconceptions. Moreover, it is vital that students develop the capacity to identify for themselves when they have a misconception and therefore make effective decisions about how to update their understanding. The information-rich world in which our graduates are finding themselves now increasingly demands this capability.

Acknowledgements

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Author/s:
Verkade, H; Lodge, JM; Elliott, K; Mulhern, TD; Espinosa, AA; Cropper, SJ; Rubinstein, BIP

Title:
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Date:
2017

Citation:
Verkade, H., Lodge, J. M., Elliott, K., Mulhern, T. D., Espinosa, A. A., Cropper, S. J. & Rubinstein, B. I. P. (2017). Exploring misconceptions as a trigger for enhancing student learning. Walker, R (Ed.) Bedford, S (Ed.) Research and Development in Higher Education Series, 40, pp.392-401. Higher Education Research and Development Society of Australasia, Inc.

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