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An assessment-based model for exploring the solving of mathematical problems: Utilizing revised bloom's taxonomy and facets of metacognition

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A R T I C L E I N F O

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A B S T R A C T

This paper provides a method that can be used to review the teaching, learning, and/or assessment of mathematics at either (or both of) the senior secondary and undergraduate levels. In this paper, how this method could be enacted is exemplified by considering the case of integral calculus. The method uses Revised Bloom's Taxonomy (RBT) (Anderson et al., 2001) in conjunction with Efklides's metacognition framework (Efklides, 2006, 2008) to design questions to address the different RBT cognitive processes and knowledge types. Using these two frameworks can help develop questions that target broader student thinking and a range of cognitive processes, including constructive ones, than traditional questions reach. In doing so, this method can be a starting point for Faculties seeking to reform their delivery and assessment of mathematics.

The early 21st Century has been a time of rapid social and economic change that has largely been driven by scientific and technological innovation. This has had a major impact on many Western countries with almost every sector of society being affected. There have also been significant changes to the way many everyday tasks are undertaken (Asunda, 2011). One consequence of these changes is that in many countries more graduates in Science, Technology, Engineering, and Mathematics are required (President's Council of Advisors on Science and Technology, 2012; Saxton et al., 2014) (the STEM subjects). However, there has been decreasing interest in studying these subjects (Fairweather, 2008; Jolly, 2009), for which poor teaching practices in college STEM courses has been cited as a major cause (Fairweather, 2008; Shakerdge, 2016). It has been observed that less than 40% of US students who enter university with an interest in STEM subjects, and only 20% of STEM-interested students from under-represented groups, finish with a STEM degree (PCAST STEM Undergraduate Working Group, 2012, cited in Freeman et al., 2014). This has led to concerns about possible declining international competitiveness in places like the US and the UK, with the response being efforts to reform the teaching of the STEM subjects, both in schools and at universities (e.g., Saxe & Braddy, 2015).

Efforts to reform the teaching of mathematics are not new, at both senior secondary school and undergraduate level (Fairweather, 2008; Gerritsen-van Leeuwenkamp, Joosten-ten Brinke, & Kester, 2017; Lambdin & Walcott, 2007). For example, in schools it seems that every generation has been exposed to revolutionary changes to mathematics teaching, from new maths, the back to basics movement, the problem solving approach, and numeracy-based curricula (Lambdin & Walcott, 2007). Many of these efforts have had theoretical and/or research bases. For example, over the last 25 years reform efforts have had a focus on putting into practice the constructivist learning theories of Piaget (Piaget, 1953) and Vygotsky (Vygotsky, 1978) and helping students to develop an understanding of mathematics through active participation in their learning. However, evidence suggests that at the senior secondary school and undergraduate levels there has been little change to teaching practice; mathematics teaching at both levels still tends to be dominated by the transmission of knowledge approach (e.g., Alsina, 2001; Radmehr, 2016; Fairweather, 2008). In schools, this takes the form of the teacher detailing a procedure for solving a type of problem which students then practice (Timperley, 2013). At undergraduate level this follows the deductive organisation of knowledge based on definitions, theorems, and proofs (Alsina, 2001). Both formats promote passive learning and present mathematics as a known field of knowledge that students need to assimilate, rather than a dynamic subject with errors and false trails that plays a crucial role in our development of new knowledge (Alsina, 2001). Such passive teaching methods also produce lower pass rates than those that engage students in active learning (Freeman et al., 2014).

A number of reasons have been given for the general lack of impact of reform efforts. At school level one is the lack of change to school texts – despite publishers' claims to the contrary (Green, 2014). Another is the absence of a vision of and resources to support alternative practices,

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Table 1
RBT Table with subtypes. RBT Table showing how the knowledge and cognitive process dimensions are broken down.

The Knowledge Dimension	The Cognitive Process Dimension					
	Remembering	Understanding	Applying	Analysing	Evaluating	Creating
	– Recognising – Recalling	– Interpreting – Exemplifying – Classifying – Summarising – Inferring – Comparing – Explaining	– Executing – Implementing	– Differentiating – Organising – Attributing	– Checking – Critiquing	– Generating – Planning – Producing
Factual knowledge – Knowledge of terminology – Knowledge of specific details and elements						
Conceptual knowledge – Knowledge of classifications and categories – Knowledge of principles and generalisations – Knowledge of theories, models, and structures						
Procedural knowledge – Knowledge of subject-specific skills and algorithms – Knowledge of subject-specific techniques and methods – Knowledge of criteria for determining when to use appropriate procedures						
Metacognitive knowledge – Strategic knowledge – Knowledge about cognitive tasks, including appropriate contextual and conditional knowledge – Self-knowledge						

leaving many new teachers to fall back on the models they experienced during their own education – their apprenticeship of learning (Alsina, 2001; Green, 2014; Lampert & Ball, 1999). At college level, Fairweather (2008) identifies that most reform attempts are individual rather than Faculty wide so do not lead to systemic change. In addition, the emphasis on research at universities can lead to a decline in interest in lecturing (Alsina, 2001; Fairweather, 2008).

This paper has been conceived within this context. It aims to provide a method that can be used by Faculty to begin the process of reforming the teaching, learning, and assessment of mathematics at either (or both of) the senior secondary and undergraduate levels, a critical transition point in mathematics education (Saxe & Braddy, 2015). The method is being put forward as in our experience it is not uncommon for reform to promote changes to teaching and learning practices, yet expect students to still answer the same old questions both in class and in assessments. We suggest changing the questions we ask is a critical part of effective reform, one that gives teachers and learners something different to focus on which, if also included in assessment, requires changes in practice. The method being suggested in this paper was mainly developed as part of doctoral study by the first author (Radmehr, 2016). That study focused on the learning of integral calculus around the transition from senior secondary to undergraduate mathematics. Findings suggested that in terms of RBT, many students were more proficient at tasks that required low-level knowledge and cognitive processes than higher level, and that the addition of certain types of question could lead to improved student understanding of the topic. As a consequence of that study, many of the sample questions suggested in this paper have undergone a rigorous design process to ensure they were appropriate for both the specific RBT cells (e.g., see Radmehr, 2016; Author, 2017a) and the study of integral calculus (e.g., see Radmehr, 2016; Author, 2017b). Furthermore, they have been trialled with students. However, details of that process are beyond the scope of this paper.

Various frameworks have been proposed in the literature for investigating and explaining how learning takes place, and for assessing mathematical concepts (see Pegg & Tall, 2005). This paper proposes another set of frameworks for exploring students' learning of mathematical topics – the use of Bloom's Revised Taxonomy (RBT) (Anderson et al., 2001) in conjunction with Efklides's metacognition framework (Efklides, 2006, 2008). In the past, conceptual and procedural knowledge (e.g., Mahir (2009)), factual, conceptual, and procedural knowledge (e.g., Gray and Tall's (1994) introduction of the notion of procept), and metacognitive knowledge, experiences, and skills (e.g., Jacobse & Harskamp, 2012), have all been the focus of research into how students learn mathematics and solve mathematical problems. However, we found no studies that use RBT (Anderson et al., 2001) and Efklides's metacognition framework (Efklides, 2008) in conjunction to explore student learning. We argue that using these two frameworks can provide a better understanding of how students learn mathematics and solve mathematical problems. Furthermore, joint use of these frameworks can help researchers, lecturers, and teachers investigate student learning in relation to their 1) factual, 2) conceptual, 3) procedural, and 4) metacognitive knowledge, as well as their 5) metacognitive experiences and 6) skills, and in so doing explore how a variety of cognitive processes can be activated in students' minds. In this paper, we also address how questions can be designed to target these six aspects of mathematical learning and how to activate different cognitive processes in a student's mind. Examples for each aspect are provided from integral calculus, a topic which is taught internationally at upper secondary and tertiary levels. In order to frame the study, RBT (Anderson et al., 2001) and facets of metacognition (Efklides, 2006, 2008) are described in the following sections; where terms from RBT and the facets of metacognition are used, these have been italicized for ease of reading.

1. Revised Bloom's taxonomy

Bloom's Taxonomy (BT) (Bloom, Engelhart, Furst, Hill, & Krathwohl, 1956) was redesigned to address potentially useful new approaches and theories of learning from the late 20th century, such as metacognition (Flavell, 1979) and constructivism (Piaget, Elkind, & Tenzer, 1967). The end result, RBT (Anderson et al., 2001) is a two-dimensional framework which separates knowledge and cognitive processes (Table 1).

In RBT each cell is defined as an intersection between the *knowledge* and the *cognitive process* dimensions. The *knowledge* dimension addresses four types of knowledge; *factual*, *conceptual*, *procedural*, and *metacognitive* knowledge. The *cognitive process* dimension has six categories; *remembering*, *understanding*, *applying*, *analysing*, *evaluating*, and *creating*. Each of the *knowledge* types and *cognitive processes* are further

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