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KNOWLEDGES FOR EFFECTIVE INTEGRATION OF MATHEMATICS AND SCIENCE

Páraic Treacy
NCE-MSTL, University of Limerick

John O'Donoghue
NCE-MSTL, University of Limerick

Abstract: The level and complexity of knowledge held by a teacher affects what is done in classrooms and, as a consequence, also influences what students learn (Fennema and Franke 1992). Integrating mathematics and science requires the teacher in question to have a certain level of both content knowledge and pedagogical knowledge to educate students in both disciplines successfully (Frykholm and Glasson 2005). Consequently, the knowledges required to effectively instruct students in an integrated setting is a vital element of the successful implementation of such lessons. Research indicates that a teacher's content knowledge in the subjects he/she teaches is of utmost importance, this translates to an integrative setting – content knowledge and pedagogical content knowledge within both mathematics and science must be of a high standard to implement these lessons successfully. This can be achieved through provision of the relevant resources, a working support structure, and teacher training.

Keywords: Integration, mathematics, science, knowledges, pedagogy.

INTRODUCTION

The level and complexity of knowledge held by a teacher affects what is done in classrooms and, as a consequence, also influences what students learn (Fennema & Franke, 1992). Integrating mathematics and science requires the teacher in question to have a certain level of both content knowledge and pedagogical knowledge to educate students in both disciplines successfully (Frykholm & Glasson, 2005). Consequently, the knowledges required to effectively instruct students in an integrated setting is a vital element of the successful implementation of such lessons. This piece of writing will investigate the knowledges required to teach effectively during lessons which integrate mathematics and science by considering research conducted in this field and applying it to the preparation required of teachers prior to implementing lessons which integrate mathematics and science in classroom.

Such an understanding of the knowledges required to integrate mathematics and science was developed by the author in order to successfully implement a new teaching model for integrating mathematics and science in second level classrooms. This new model, entitled 'Authentic Integration', caters for the specific needs of integration of mathematics and science as it requires that each lesson be based around a rich task which relates to the real world, explores concepts from both subjects, and ensures that hands-on group work, inquiry and discussion are central to the lesson (Treacy, 2012). This model was applied in four post-primary schools in Ireland. Understanding the knowledges required to effectively integrate mathematics and science in the classroom proved to be vital in the overall success of the intervention. The development and implementation of this understanding is discussed in this article as well as its contribution to the efficient execution of the lessons.

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*Corresponding author: Páraic Treacy - e-mail: paraic.treacy@ul.ie

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KNOWLEDGES FOR EFFECTIVE TEACHING

Shulman's (1986) work was the first foray into the area of knowledges for effective teaching and provided a base for the work which was to follow from the likes of Ernest (1989), Fennema and Franke (1992), and Rowland et al. (2005). Shulman (1986) identified three domains when constructing his model:

- Subject Matter Content Knowledge
- Pedagogical Content Knowledge
- Curricular Knowledge.

He believed that 'Subject Matter Content Knowledge' was the most important of the three, claiming that teachers must have a deep understanding of the content in order to teach it effectively (Shulman 1986). This is an important issue when considering integration of mathematics and science as, depending on the approach taken, it may require one teacher to educate pupils in mathematics and science simultaneously (Jacobs, 1989). If this occurs then the teacher must, according to Shulman (1986), possess a decent depth of knowledge within both subjects.

'Pedagogical Content Knowledge' refers to the repertoire of representations of the content that a teacher draws on to aid pupils in comprehending the subject matter. These could be demonstrations, examples, analogies or illustrations which help pupils form a greater understanding of what is being examined (Shulman 1986). In other words, it is the ability of a teacher to draw on various exemplifications of the given content to enhance the quality of their instruction so as to ensure a greater depth of understanding amongst the pupils. An example of this could be the use of a balance scales to explain procedures adopted when solving mathematical equations. With a balance scales, if a weight is added to one side then a weight of the same magnitude must be added to the other side to maintain balance. It is the same with equations: if a number is added to one side of the equation then the same number must be added to the other side of the equation to 'maintain balance'. This offers a concrete example which pupils can recognise and refer to, thus improving understanding of the concept.

'Curricular Knowledge' refers to knowledge and competency in relation to the range of programmes and materials available to the teacher with regards to a particular subject or topic. It refers to the knowledge of the various ways an educator can teach elements of the curriculum to their pupils and the educator's recognition of which way is best in given situations (Shulman 1986). In other words, this element refers to the notion that there is more than one way to teach a topic or subject and a teacher should have a certain level of expertise in the various approaches which could be deployed as well as knowing when best to deploy them.

Schulman's (1986) work was not subject specific hence it was aimed at encompassing all teaching. It formed the key reference for subsequent attempts at modelling subject specific and non-subject specific knowledges for effective teaching. As the issue of knowledges for effective teaching began to develop, more authors offered theories in relation to its make-up. Two of these authors, Ernest (1989) and Fennema & Franke (1992) lead the way in defining the knowledge make-up of effective mathematics teachers, leading onto Rowland et al. (2005) and their work on the 'Knowledge Quartet'.

KNOWLEDGES FOR EFFECTIVE MATHEMATICS TEACHING

Following Shulman's (1986) ground-breaking work, academics began to apply his theory to specific subjects with Ernest (1989) developing one of the first models of teacher knowledges for effective mathematics teaching. This model was quite detailed, outlining the knowledges, beliefs and attitudes vital for effective mathematics teaching. Similar to Shulman (1986), Ernest (1989) highlighted subject content knowledge, i.e. knowledge of mathematics, as the most important element. When Fennema and Franke (1992) published their model of knowledges for effective mathematics teaching, content knowledge was also identified as the most vital characteristic. This aspect continues to be regarded as being of the utmost importance in present day models of this nature.

Surprisingly, content knowledge has been shown to be negatively related to the use of inquiry-based classroom instruction and to beliefs in the effectiveness of such instruction (Wilkins, 2008). Many teachers with strong content knowledge tend to rely on 'traditional' methods i.e. focus on rules and procedures (Mewborn, 2001). It is, rather, positive attitudes towards the subject that facilitate the adoption of inquiry-based instruction in the classroom (Karp, 1991; Wilkins, 2008). These findings show that content knowledge is of great importance for effective mathematics instruction but must be supplemented with positive beliefs in relation to inquiry-based instruction if such an approach is to be adopted.

Returning to the aforementioned models: interestingly, the knowledge characteristic which Ernest (1989) terms as the next most important, 'Knowledge of Other Subject Matter', is an endorsement of the assimilation of mathematics with other subjects. Ernest (1989, p.17) claims that knowledge of other subject matter "provides a stock of knowledge of uses and applications of mathematics" which he believes forms an important contribution to the teaching of mathematics. Similarly, Rowland et al. (2005) cited such a characteristic in his 'Knowledge Quartet' model – 'Connection Knowledge'. This aspect deals with the knowledge required to make connections within mathematics i.e. between concepts and/or procedures; and between mathematics and other subjects or disciplines (Rowland et al., 2005). As such, the 'Knowledge Quartet' may lend itself to underpinning the knowleges required to effectively integrate mathematics and science in the classroom.

The Knowledge Quartet

The 'Knowledge Quartet' provides the most recent widely endorsed version of what knowledges it takes to be an effective mathematics teacher. Again, Mathematical knowledge tops the list of most important characteristics; within the quartet it is referred to as 'Foundation Knowledge'. But there is one important difference in the definition of this aspect compared to previously mentioned models – it not only includes knowledge of mathematics itself but also the beliefs which the teacher holds in relation to mathematics, and it is upon this foundation that the other characteristics of the model are built (Rowland et al. 2005). This is significant due to the observation, discussed earlier, that although content knowledge is vital for effective teaching, beliefs determine whether innovative practices such as active and experiential learning are adopted (Wilkins 2008, Karp 1991). Thus, if an innovation like the integration of mathematics and science is to be adopted, 'Foundation Knowledge' within teachers, which encompasses the desirable beliefs and levels of mathematical knowledge, would be a cornerstone of its implementation. The significance of this to the author is the realisation that an effective implementation of an integrative framework would require training for teachers to ensure they have the required content knowledge but also, possibly more importantly, it would require teachers to 'buy into' the approach being used i.e. hold the belief that experiential and active learning is a worthwhile endeavour.

Next in the Knowledge Quartet is 'Transformation Knowledge' which is very similar to Shulman's (1986) 'Pedagogical Content Knowledge' described earlier. In essence this characteristic separates those who know mathematics from those who know how to teach mathematics. This leads into the third element of the 'Knowledge Quartet' – 'Connection Knowledge' which, as discussed earlier, is the knowledge required to make connections within mathematics i.e. between concepts and/or procedures; and between mathematics and other subjects or disciplines (Rowland et al. 2005). The ability to make connections to areas within and outside mathematics is of course an essential element of integration of mathematics with other subjects thus it is imperative that teachers pursuing an integrative approach have this characteristic.

Finally, within Rowland et al.'s (2005) 'Knowledge Quartet', 'Contingency Knowledge' which describes a teachers ability to adjust to unexpected situations such as an unforeseen circumstance, or a question which had not been anticipated. It also alludes to a teacher's recognition of when and how a lesson needs to be adjusted from the original lesson plan if required (Rowland et al., 2005). Once again, this is quite relevant to issues relating to integration of mathematics and science, as a teacher's ability to think on their feet is essential in an active or experiential lesson as there is a great element of discovery learning involved which can go down various paths thus calling on the teacher to be able to adjust and react to various scenarios and questions, some of which could (and probably will) be unanticipated.

KNOWLEDGES FOR EFFECTIVE SCIENCE TEACHING

Research into the knowledges required to effectively teach science produced similar findings to those outlined previously i.e. a teacher's content knowledge plays a pivotal role in the depth of learning achieved by their students as well as the manner in which they learn in the classroom. Science teachers with well-developed levels of content knowledge ask more questions while there is a greater probability that their students will consider alternative explanations, propose more investigations, and embark on unanticipated inquiries compared to teachers with weaker content knowledge (Alonzo, 2002; Sanders, Borko, & Lockard, 1993). Teachers with poor content knowledge tend to teach in a more direct manner, telling the students the content rather than allowing them to develop their own understanding through inquiry (Alonzo, 2002; Sanders et al., 1993). Consequently, it is clear that the greater content knowledge a teacher has, the more they are open to holistic approaches to tuition in which students explore topics and concepts, by which they develop their own meaning and understanding.

Pedagogical content knowledge (PCK) has previously been flagged as an important part of the range of knowledges a teacher possesses in both typical tuition (Shulman, 1986) and in a setting which integrates mathematics and science (Frykholm & Glasson, 2005). Greater focus has been placed on PCK recently by those researching knowledges for effective science teaching with Loughran et al. (2012) exploring the PCK of science teachers held in high-regard to gain a greater insight into how this translates into their teaching. This research clearly indicated the importance of in-depth understanding of PCK as Loughran et al. (2012) regularly observed that the knowledge of practice which science teachers relied upon and the manner in which they conceptualised science content in the classroom was a clear indicator of whether or not a teacher could be termed as being expert in their field.

BUILDING TEACHERS' KNOWLEDGES FOR EFFECTIVE INTEGRATION OF MATHEMATICS and SCIENCE

Analysis of the knowledges required for effective instruction indicates that content knowledge is a vital characteristic of successful educators. Content knowledge, characterised in one way or another, was labelled the most important aspect of all the models outlined (Ernest, 1989; Fennema & Franke, 1992; Rowland et al., 2005). It is of great importance to find ways to counteract any gaps in knowledge within mathematics and/or science amongst teachers prior to attempting an integrative approach. One solution to this would be for teachers of each subject to work in tandem i.e. team teach a lesson. This would probably be an unrealistic aim for schools that typically follow a set timetable as both teachers would need to be free to work at the same time with one class.

Another solution would be to conduct the mathematics aspect of the intended problem or project during the mathematics lesson and the science aspect during the science lesson. Such an approach may be possible for certain problems or projects but for most lessons it would most likely negatively affect the learning that takes place in the lesson and could greatly reduce the integrative element of the lesson and any positives that come with that.

A third solution, and probably the most practical one, would be to up-skill the teachers in relation to the knowledge gaps they have i.e. improve the mathematics teachers' science content knowledge and pedagogical content knowledge in relation to the material which would come up in each lesson they are to teach, and vice versa. In other words, give them the knowledges they require to deal with any questions from the pupils and to successfully use various representations and exemplifications of concepts in both disciplines to effectively aid student understanding.

In summation, with this close look at knowledges for effective teaching, it is clear that work must be done with teachers prior to an implementation of an integrative framework. Work must be carried out on the level of content knowledge they possess in both mathematics and science, while also developing their pedagogic content knowledge within both subjects to enhance the manner in which they guide the pupils' learning. Such an approach was taken to provide a basis for integration of mathematics and science during the author's intervention.

APPLYING IMPROVED TEACHER KNOWLEDGES FOR INTEGRATION OF MATHEMATICS and SCIENCE

The requirement for teachers to have a working knowledge of both mathematics and science can obstruct the implementation of integrative lessons as teachers may be aware of how the subjects connect but may not have the expertise or the confidence to carry through these connections into their teaching:

"[O]bviously I'd be aware of the link [between the subjects], but it took someone to point it out for me to actually explain it perfectly to the students."

Jennifer Collins (mathematics teacher)

(Treacy, 2012)

Later in the interview she confirmed this anxiety:

"At the start I was a bit apprehensive about how I'd incorporate it into my teaching, how I'd put the whole lesson across and would I be able achieve what I was hoping to. But as I got into it, and the resources were brilliant that I was provided with, and it was laid out so well that it was easy to follow and deliver the lesson to the students. I really enjoyed it. It also gave me an awakening; it showed me how you can teach a topic in different ways and integrate it with something else."

Jennifer Collins (mathematics teacher)
(Treacy, 2012)

The author, due to the careful consideration of the nature of knowledges for effective teaching outlined previously, anticipated that this would be an important element within this research and thus ensured that each teacher would have the requisite level of knowledge within both mathematics and science prior to implementing the lessons by providing plenty of resources as well as teacher training. Focus was placed on content knowledge and pedagogical content knowledge in both mathematics and science.

This support system – which included electronic presentations on all the topics, teacher training, availability of the lead researcher for assistance – evidently proved to be quite important in ensuring that teachers were comfortable in implementing the lessons. Collins (mathematics teacher) had some anxiety in relation to her ability to teach lessons which incorporated both mathematics and science, as stated above, but made use of the resources and training available which gave her the confidence to conduct the integrative lessons.

It proved not to be a stumbling block for the other teachers involved in this project as each of them found the content to be very manageable and none voiced any problems grasping elements that they weren't previously overly familiar with. In fact, the participants gained great benefit from combining the subjects:

"I think it worked very, very well. From my own point of view, there's a lot I didn't know – some of the definitions in science… there's a lot I didn't know myself and they're very maths related. So I think there's so many areas in science that are related to maths and I think it'll come through with the project maths type of questions that are coming in".

Martina O'Reilly (mathematics teacher)
(Treacy, 2012)

O'Reilly gained a greater insight into elements of science that mathematics could be related to and envisions the benefits that this will provide for her when adapting to the new 'Project Maths' syllabus which was being introduced in Ireland at the time of the intervention.

CONCLUSION

Students learn more from teachers who are skilled, experienced, and know what and how to teach (Darling-Hammond, 2000; Goldhaber, 2002; Rice, 2003). A teacher may tick all these boxes when it comes to his/her specialised subject but the adoption of an additional subject within their classroom setting provides a further challenge. This is because their content knowledge, which is the best indicator of an effective teacher (Shulman 1986), and/or pedagogical content knowledge within that auxiliary subject might not be of the required standard.

At the commencement of the aforementioned intervention, some of the teachers, i.e. those not specialised in both mathematics and science, displayed some anxiety and indicated their trepidation regarding their lack of content knowledge within their non-specialist subject. The allocation of teacher training and the support structure put in place for this investigation allowed them to develop their content knowledge and pedagogical content knowledge within the topics they studied with the pupils through the lessons. It became clear as the study progressed, and through interviews with the teachers, that such development of knowledges was a vital element in the success of the lessons.

As such, research indicates that a teacher's content knowledge and pedagogical content knowledge in the subjects he/she teaches is of upmost importance. This also translates to an integrative setting – content knowledge and pedagogical content knowledge within both mathematics and science must be of a high standard to implement these lessons successfully. As shown in this study, this can be achieved through provision of the relevant resources, a working support structure, and teacher training.

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