Determining a Student's Optimal Learning Zone in Light of the Swiss Cheese Model

Patricia Morley
Luckmor
<trishmorley@luckmor.com>

Simone Zmood
Monash University
<simone.zmood@monash.edu>

Participation in society is increasingly dependent on educational achievement. Accordingly, society as a whole is committing more resources to education to prevent the adverse outcome of students moving through the school system only to emerge without the knowledge and skills that they might be expected to attain. In this paper, we explore the application of two models developed to prevent adverse outcomes in industrial and medical settings to the issues involved in providing an optimal mathematics education for all children.

Introduction

Teachers and parents may dream of optimal learning for their students and children, respectively, but defining what this means and putting it into practice is complex. Vygotsky's (1978) Zone of Proximal Development (ZPD) suggests that a student learns optimally in the zone requiring guided learning which is beyond what can be accomplished solely by independent learning. It can be thought of as the *stretch* zone where students are being challenged but able to learn through the guidance of a more knowledgeable teacher or peer. When there is insufficient challenge, students will *coast* and if the learning expectations are too great then the student may *crash*, having been overwhelmed by the cognitive or affective load.

This paper provides a theoretical discussion on the practical implications of determining a student's ZPD in light of the diversity of learning and understanding even within one individual. Both the Swiss Cheese Model and the enhanced Hot Cheese Model are used to explore 'holes' which impact on mathematics learning from a system, classroom, curriculum, and student perspective. We suggest that both models have the potential to clarify issues involved in the assumptions made about student knowledge, and the role and interpretation of assessments. In particular, this paper focuses on determining what the base level is that a student can move forward from in his or her learning – an important starting point for ensuring students are learning within their ZPD.

Models of Student Learning and Mathematical Errors

The implication of the ZPD is that teaching and learning are effective when instruction is tailored to current level of understanding of the child. Care, Griffin, Zhang, and Hutchinson (2014) describe a project which uses assessment to identify where children are in their learning development in order to enable differentiated instruction.

The Swiss Cheese Model (SCM) was introduced as a metaphor to explain how the combination of several factors can lead to industrial accidents in complex systems and as a framework for the investigation of those accidents systems (Reason, 1997). It allows for consideration of multiple factors that lead to adverse outcomes, rather than placing emphasis on the final straw. *Hazards* are known potential causes of problems. *Defences* are the actions taken to prevent hazards contributing to *adverse outcomes*. Figure 1 shows a

2015. In M. Marshman, V. Geiger, & A. Bennison (Eds.). *Mathematics education in the margins* (Proceedings of the 38th annual conference of the Mathematics Education Research Group of Australasia), pp. 437–444. Sunshine Coast: MERGA.

generic Swiss cheese model. Each slice of cheese represents a *defence layer* within the system, the holes in each slice of cheese represent gaps or imperfections in the defence, and when the holes in several slices of cheese align creating a *hazard trajectory* then this accumulation of multiple failures can result in harm. The SCM is a useful focus of attention for investigating unwanted outcomes in order to put in place layers of defence against future harm. A key feature of this model is its flexibility. The number of layers of defences can be adjusted to suit the situation. The SCM, despite its simplicity, has been widely used to draw attention to the multi-faceted nature of adverse events. In particular, it encourages a more holistic view through recognition of contributing factors in addition to the most proximate cause.

The Hot Cheese Model (HCM) refines the SCM by including interactions between the defence layers of the system which are referred to as *feature interactions* (Li & Thimbleby, 2014). The HCM explicitly recognises that a system of defences – the slices of cheese – is active and not passive nor unchanging. It is not enough to put multiple layers of defence in place with non-aligning holes as any new defence layer introduced may end up causing new errors and thus harm. Li and Thimbleby (2014) provide an interesting example of feature interactions. In Detroit, a monitoring camera was installed as safety device in a nuclear reactor. However, it fell and blocked a coolant drainage hole. The blockage resulted in temperatures that destroyed sensors, leaving a nuclear meltdown to go undetected by the reactor operators.

From its origin in industrial accidents, the SCM has been transferred and adapted to other fields such as medicine, demonstrating that transfer of these ideas from one field to another field was not only possible but useful. Both the SCM and the HCM allow clearer thinking about complex situations. We will now discuss how the SCM, and also the HCM, can be used in the educational context.

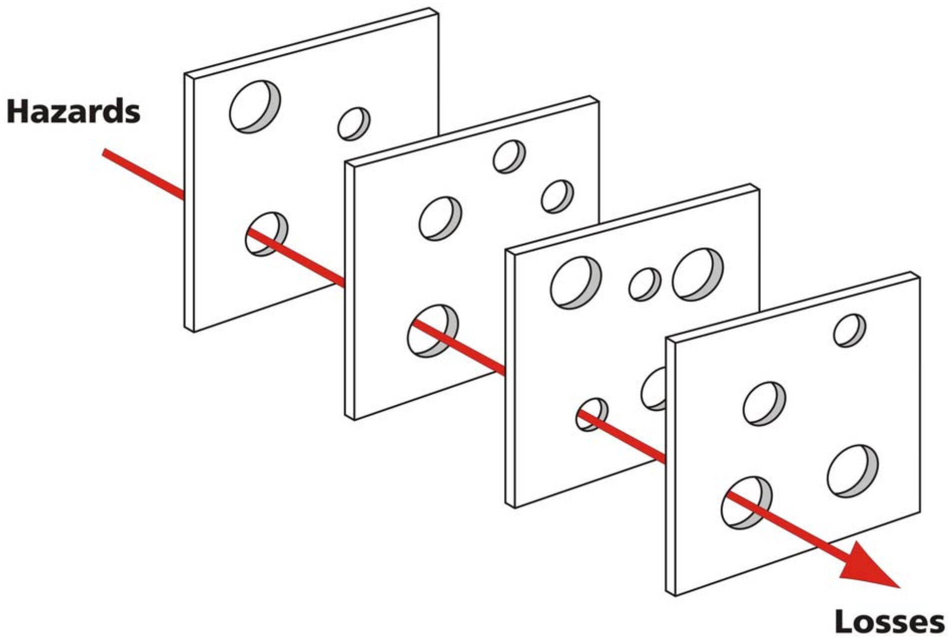

Figure 1. Generic Swiss Cheese Model (SCM) (Mack, 2014)

In Education, we might think of the process of education as one of obtaining knowledge and skills. A situation, condition, or event that might impede learning is, in this context, a hazard. The layers of Swiss cheese in this model are defensive layers that are put in place to prevent the impediments from affecting the desired outcome of learning. The arrow moving through the Swiss cheese represents a student's failure to learn despite the defences in place. Education of a population is a large endeavour in terms of resources and time required from a wide range of people. Despite this, too many children leave school without having attained some of the basic knowledge and skills that they might reasonably be expected to have. In Education, this is the adverse outcome, or losses, that we consider below.

It is acknowledged that measurement of outcomes is a necessary precondition to understanding the success and adverse effects of any process. Whether the measurement of outcomes is modelled as a defence layer in the SCM, or not, is dependent on the situation, as discussed here. Even where the measurement of outcomes is neutral, the feedback of information into the system is not necessarily neutral. To illustrate this, we draw on research on the effective use of measurement to reduce workplace injuries. The measure of work time that was lost due to injury was adopted as an Occupational Health and Safety (OHS) measure, but was found to be problematic (Blewett, 1994). Lost Time Injuries (LTI's) were used as a measure of workplace safety. However, this measure was unsatisfactory for a number of reasons, including that it was "far more sensitive to claims and injury management processes than to real changes in safety performance" (Blewett, 1994, p. 29).

In Education, much has been written about potential and actual adverse effects of assessment that interfere with the main goal of education. Many of these concerns are related to how the information is used, rather than about the measurement itself. Unlike other contexts, where measurement is neutral until it is fed back into the system, testing provides an opportunity for a learner to organise information and increase learning.

It is widely recognised that educational assessment performs a variety of functions, ranging from the use of large-scale assessments to inform policy to in-class assessments to inform teaching practices (Care et al., 2014). Educational outcomes are to some extent measured by the outcomes of assessments, and we consider them to be intrinsic to educational processes, rather than a neutral measurement. Accordingly, in this paper assessments are treated as defence layers within the model, rather than neutral measurements external to the model.

Following is a discussion on how the SCM and HCM can be used to analyse mathematics learning in school at four levels: the education system as a whole, the mathematics classroom, the mathematics curriculum, and the individual student.

Education System

At the education system level, it is recognised that good educational outcomes depend on a suitable physical environment, a well-structured curriculum, competent teachers, and student attendance. Accordingly, employing the terminology of the SCM, a poor physical environment, an inadequate curriculum, incompetent teachers, and poor student attendance each may be considered as a hazard*,* that is something which might contribute to the adverse event of students not learning at the appropriate level.

The defence layers that are in place to prevent the adverse outcomes described above are: a suitable budget for school building and maintenance; a structured curriculum;

minimum teacher qualifications and professional development; system-wide students assessments such as NAPLAN and Year 12 examinations; and student mandatory attendance. These protective layers are put in place via legislation and Education Department policy.

Mathematics Classes

At the classroom level, children need good rapport with the teacher, a teacher who has the requisite knowledge to teach mathematics, and learning resources such as manipulatives, textbooks and ICT. Associated hazards are impediments to learning such as: when the children are absent; when children are disengaged from the subject material; and when connections are not made with previous knowledge. The protective layers are accordingly: roll calls or attendance lists; lesson plans; monitoring of students' learning via quizzes, exams; review of homework books; and projects. Roediger III, Putnam, and Smith (2011) identify ten benefits of testing, ranging from identifying gaps in knowledge and providing feedback to teachers, to encouraging active learning by encouraging "students to study", producing "better organisation of knowledge", improving "transfer of knowledge to new contexts", and improving "metacognitive monitoring". An accurate understanding of the source of a *gap* is essential in order to match the teaching intervention to the type of error, and at the appropriate level of the individual student or the whole class (Holmes, Miedema, Nieuwkoop, & Haugen, 2013). The responsibility for these layers derives from the individual teacher, who operates within the larger framework of the school and wider educational policies.

Mathematics Curriculum

The mathematics curriculum is both a defence layer in the complex system of education – across the educational system and within the mathematics classroom – and a system in its own right. It provides a framework for teaching the desired mathematical knowledge in a structured way so that concepts and procedures are built up on previous knowledge. If one applies the traditional SCM at the curriculum level, hazards could be that the curriculum expects too much (or too little) of students, and presuming that students have actually mastered previous teachings and are ready to learn new material. Thus, in a somewhat recursive situation, the curriculum and its periodic revision act as defence layers.

However, transforming the SCM, one can look at each slice of cheese as a study area of the mathematics curriculum. To illustrate this, the Australian curriculum outlines the scope and sequence for three interlinked branches of mathematics: number and algebra; measurement and geometry; and statistics and probability. Each of these branches of mathematics is broken down into more detailed study areas. For example, the number and algebra branch comprises six strands: number and place value; fractions and decimals; real numbers; money and financial mathematics; patterns and algebra; and linear and non-linear relationships.

If each of these study areas represents a slice of cheese, then some holes in conceptual understanding will impact mastery of learning in another slice. Roman numerals are often introduced in primary school maths to explore alternative number systems and emphasise place value. However, provided a student has conceptual understanding of place value, a hole in knowledge of Roman numerals is unlikely to be detrimental in the long-term, other than on an assessment with test items for Roman numerals. In contrast, an understanding of fractions is critical for developing working knowledge of algebra which, in turn, is important in developing an understanding of calculus. Following this line of reasoning, some study areas of mathematics are pre-requisites for mastery of other study areas and any gaps may have escalating consequences and long term implications. For example, misguided early number concepts (Mazzocco, Murphy, Brown, Rinne, & Herold, 2013), fractions and algebra (Gray & Tall, 1992a, 1992b).

Individual Student

Another transformation of the SCM is useful to consider the implications for an individual student. Picture a vertical stack of sliced cheese, with lower slices representing previous years of mathematics education and each slice of cheese consisting of the mathematics curriculum taught at that specific year level. Holes in understanding in earlier slices may mean that the student does not have the foundation to develop robust understanding in some areas of the current intended curriculum. There are many factors which might contribute to an individual not having the knowledge and skills in place to accommodate learning the current topic in the classroom, ranging from difficult personal circumstances, previous poor teaching, or learning difficulties. It is important for a teacher to be aware of whether the difficulties experienced by students are due to learning disabilities, and to be able to act accordingly (Butterworth, Varma, & Laurillard, 2011). Defences against such hazards include factors such as having a supportive family who values mathematics learning and having a teacher who knows how to identify the sources of gaps in knowledge and what interventions are most appropriate to fill the gaps.

Implications for Teaching

Ultimately, the SCM and HCM were developed to both pro-actively mitigate the risks of gaps aligning resulting in an adverse outcome and also to analyse what the root causes of any failures were. In this section, we discuss what the potential sources of error may be, implications for assessments and interventions, and link this back to the important task of determining a individual student's ZPD.

Sources of Error

There has been considerable research on the causes of errors in mathematics. Skemp (1976) differentiates between instrumental understanding which is understanding what to do, and relational understanding which is "knowing both what to do and why" (p. 2). Others use the terms procedural and conceptual understanding to differentiate between learning a collection of procedures or algorithms and developing a deeper understanding of what is happening mathematically. Both have their place. Procedural knowledge that is not underpinned by conceptual understanding can lead to learning lots of *rules* which only apply in certain situations. Strong conceptual understanding without the fluency of procedural knowledge can drive a student to derive formulas and rules from first principles. Whilst this is a valuable skill, there is not always sufficient time during testing situations to *derive knowledge* and a measure of fluency is useful. The ideal is strong conceptual foundations which underpin procedural fluency and flexibility.

Holmes et al. (2013) identify three sources of mathematics error: (1) vocabulary errors which are gaps in knowledge or misinterpretations; (2) computational errors; and (3) erroneous beliefs or misconceptions. They found that it can be difficult to differentiate between computational errors and misconceptions, and yet this teacher knowledge is crucial for determining the appropriate teaching interventions. Teachers also need to "make judgement calls as to what gets addressed in the class setting and what becomes an individual student intervention" (Holmes et al., 2013, p. 32).

There are other possible sources of error. Some students may not lay out their work properly on the page and or have illegible handwriting. Some students could have issues with test taking or working under pressure. An underlying source of any error could be working memory overload, when students are trying to deal with more information than they can manage and do not have good working practices to reduce the demands on their working memory. Self-management skills can be taught to help students develop their metacognition and thus improve their learning and production.

From a teaching point of view, there is no such thing as a *silly mistake* because every error has an underlying cause. Identifying the gap, identifying its cause, and understanding the implications of the gap continuing, are all important factors in optimising a student's mathematics learning.

Implications for Assessments

In Education, one very important way of ascertaining whether successful mathematics learning has taken place is through a variety of assessments including tests, quizzes, exams, assignments and projects, problem solving journals, review of homework books, class discussions and conversations with individuals. These assessments can be designed and implemented at various levels such as large-scale national testing, school-based exams, class assessments, and individual conversations with students. The different levels of assessments match up with three of the interpretations of the SCM presented above: the education system; the mathematics class; and the individual student.

Large Scale Testing. NAPLAN is an example of a defence layer in the HCM, performing a monitoring role required for understanding the effectiveness of the education system at various points. This section discusses the role of NAPLAN under the SCM and the HCM.

The inclusion of NAPLAN in the SCM requires an understanding of the role that NAPLAN plays in the education system. If the NAPLAN assessments were considered as having a neutral role in measuring outcomes, it would not be necessary to include NAPLAN explicitly in the model. This view, however, is simplistic. NAPLAN assessments have a role in identifying areas of strengths and weaknesses in educational outcomes, and therefore NAPLAN would be included as a defence layer at the system level.

Under the HCM, it is recognised that the defence layers can interact with other defence layers in the system. As others have previously highlighted, the measurement role that NAPLAN plays is not neutral. On a positive note, NAPLAN is expected to illustrate curriculum expectations and consequently shape teacher practices in improving students' mathematics and numeracy performance. On a negative note, pressure to improve scores may have the undesired impact of encouraging shallow teaching practices.

Limits of written testing. It is important to recognise that a student's mathematical understanding is only assessed to the extent of the questions contained on a test. Some holes do not show up on typical assessments. Multiple choice tests are an example of where a student might get the answers correct on a test but actually have a hole in conceptual understanding. A teacher might pre-test the class on a given topic to help with future lesson planning. Although the test may be effective as a whole, there are likely to be some children whose capabilities are over or under-estimated. Holmes et al. (2013) emphasise that “identifying student misconceptions from their work is a matter of identifying and categorizing patterns. Thus, it is extremely important when developing assessments to have multiple questions targeting the same concept in order to better classify misconceptions” (p. 32).

Benefits of talking with students. Holmes et al. (2013) suggest that “a good way to discover what students may be thinking when examining their answer for a particular problem is simply to ask them” (p. 38). Gray and Tall (1992a) go further stating that “in general classroom activity it is essential for the teacher to talk to individual children and to listen to how those children are performing their arithmetic calculations” (p. 13) and warn that “simply allowing them to carry out idiosyncratic procedures may actually be leading them up a cul-de-sac of eventual failure at more advanced arithmetic” (p. 13).

Another method of getting inside the student’s head is to ask students to keep a journal, where they explain their thinking when solving certain problems, in order to diagnose inappropriate strategies. This can be a good way to record and capture the development of a student’s understanding. However, journals do lack the immediacy and interactivity of a conversation and thus may require some back and forth to dig deeper into the student’s reasoning.

In summary, assessments provide evidence of student's capability to understand and respond to assessment items. While it is easy to misconstrue the extent of a student's understanding, the SCM suggests two things: firstly, that sources of errors might not be the immediately obvious; and secondly, that the imperfections of any type of assessments are appropriately compensated for by using a variety of styles of assessment, including conversation, thereby exposing different strengths and weaknesses. Despite their limitations, formative, summative, and large-scale testing provide information that might suggest further lines of inquiry which might be otherwise unavailable.

Implications for Interventions - Dealing with ‘holes’

One of the necessary assumptions of any lesson plan is that students are able to absorb the material. Gaps, or *holes*, in students’ understanding weaken this assumption. The SCM suggests that holes are to be expected, therefore teachers need to develop approaches which accept and address the existence of holes. One possibility may be to emphasise pre-requisite knowledge over revision of procedural activities.

We interpret the SCM as suggesting that students, with a perspective differing from a teacher’s perspective, might be able to identify issues that a classroom teacher may not have seen. Empowering students to actively participate in identifying the prerequisite knowledge required for a new task may also have the desirable effect of promoting relational understanding of material prior to instrumental understanding.

Determining a student’s ZPD

Pre-testing a student’s knowledge before teaching a new unit is a well-established way to determine a student’s readiness to learn new material or whether they may already have acquired the intended knowledge. Written or online quizzes are the most common format used, and teachers should keep in mind the limitations of written testing discussed above.

Once any gaps in knowledge or understanding are identified, teachers need to decide whether the gap is of a critical nature which will impact future learning and, if so, how best to fill the gap. This process can help teachers clarify the base level of the student's ZPD, the demarcation between coasting and being stretched. The upper level of the student's ZPD – the demarcation between being stretched and crashing – is a topic for another time.

Conclusion

Reason's Swiss Cheese Model (SCM), although somewhat simplistic, has been successfully used in the engineering and medical fields to illustrate and model complex systems, in particular to highlight the multifactorial aspect of adverse events. This paper has introduces the SCM model to the field of Education, based on the consideration that children failing to learn important concepts and skills despite all efforts to the contrary is an example of an adverse event. The SCM model is flexible, and examples have been given on how the SCM can be applied at the individual student level, the mathematics classroom level, the curriculum level, and the system level.

The inherent simplicity of the SCM limits the usefulness of the model for complex situations. Li and Thimbley's (2014) Hot Cheese Model, based on the SCM, includes the potential for unintended interaction of components of measures that are intended to prevent adverse outcomes. This paper has suggested that these models might be pertinent to assessments in education, whether in the classroom or system wide.

References

Blewett, V. (1994). Beyond lost time injuries: Positive performance indicators for OHS, summary paper. *Positive Performance Indicators: Beyond Lost Time Injuries: Part 1- Issues*, 1-55.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: from brain to education. *Science*, 332(6033), 1049-1053.

Care, E., Griffin, P., Zhang, Z., & Hutchinson, D. (2014). Large-scale testing and its contribution to learning. In C. Wyatt-Smith, V. Klenowski, & P. Colbert (Eds.), Colbert, P. (2013). *Designing assessment for quality learning*. Netherlands: Springer.

Gray, E., & Tall, D. (1992a). Success and failure in mathematics: Procept and procedure, 1. a primary perspective. Retrieved from http://homepages.warwick.ac.uk/staff/David.Tall/pdfs/dot1992k-primary-procept.pdf

Gray, E., & Tall, D. (1992b). Success and failure in mathematics: Procept and procedure 2 – secondary mathematics. Retrieved from http://homepages.warwick.ac.uk/staff/David.Tall/pdfs/dot1992l-secondary-procept.pdf

Holmes, V-L., Miedema, C., Nieuwkoop, L., & Haugen, N. (2013). Data-driven intervention: Correcting mathematics students' misconceptions, not mistakes. *Mathematics Educator*, *23*(1), 24-44.

Li, Y., & Thimbleby, H. (2014). Hot cheese: A processed swiss cheese model. *The Journal of the Royal College of Physicians of Edinburgh*, *44*, 116-121.

Mack, D. (2014). Swiss cheese model of accident causation. Retrieved from https://en.wikipedia .org/wiki / Swisscheese model#mediaviewer/File:Swiss cheese model of accident causation.png

Mazzocco, M. M. M., Murphy, M. M., Brown, E. C., Rinne, L., & Herold, K. H. (2013). Persistent consequences of atypical early number concepts. *Frontiers in Psychology*, *4*, 486.

Reason, J. T. (1997). *Managing the risks of organizational accidents*. Aldershot: Ashgate Publishing.

Roediger III, H. L., Putnam, A. L., & Smith, M. A. (2011). Ten benefits of testing and their applications to educational practice. *Psychology of Learning and Motivation - Advances in Research and Theory*, *55*, 1-36.

Skemp, R. (1976). Relational understanding and instrumental understanding. *Mathematics Teaching*, *77*, 20-26.

Vygotsky, L. S. (1978). *Mind and society: The development of higher mental processes*. Cambridge, MA: Harvard University Press.