TOWARDS A NEW PEDAGOGY FOR ENGINEERING EDUCATION IN THE 21ST CENTURY

D. Ó Sioradáin [1]
TU DUBLIN
Dublin, Ireland

M. Carr
TU DUBLIN
Dublin, Ireland

Conference Key Areas: *Problem-based learning, learning theories*
Keywords: *PBL, Minimal Guidance, long-term memory*

ABSTRACT

There have been many advances over the past four or five decades in understanding brain architecture, and how the process of learning aligns with this architecture. One of the more interesting results has been that of John Sweller [1] and his theory of cognitive load. Sweller identifies the task of learning as effecting change in long-term memory. This long-term memory is, in his view, almost limitless. The problem lies in working, or short-term memory, which has a bottleneck of around five items. Any instructional mode which places too many items into working memory will be, at best, inefficient, and at worse, pointless.

It is interesting to note that over the same decades new instructional modes, such as Problem-Based Learning (PBL) have become popular [2]. Sweller, and others such as Paul Kirschner [3], argue that PBL cannot work as advertised, as the student is faced with too high a cognitive load; they can either learn how to solve the problem, or learn the underlying concepts, but not both.

This paper outlines the theoretical background to this issue, and presents an intervention undertaken over the last decade in TU DUBLIN to devise new instructional modes which take account of cognitive load problems, whilst maintaining some of the advantages and benefits of PBL. This intervention initially followed the ideas of Louis Bucciarelli [4] of MIT on open design in Engineering education but was later adjusted to take into account the ideas of Kirschner on minimizing cognitive load in developing problem-solving skills.

---

[1] *D. Ó Sioradain, domhnallcos@gmail.com*

doi:10.5821/conference-9788412322262.1380

1 INTRODUCTION

In March 2017, the president of MIT, L. Rafael Reif, launched a new research initiative into learning, asking the question, ‘If we don’t know how we learn, how on earth do we know how to teach?’ [5] Whilst this is undoubtedly a very noble and worthwhile enterprise, it is, at one level, surprising. Surprising because, for the last five decades, great progress has been made by neuroscientists, educational psychologists and others in understanding the architecture of the human brain, and how that architecture affects human learning.

New innovations over the past few decades, such as Problem Based Learning and other minimally guided instruction methods is perplexing when one considers the weight of psychological evidence against it, particularly the 2006 paper by Kirschner et al arguing against all forms of PBL as they conflict with how the human brain learns [6].

A related goal of much modern teaching is the acquisition of critical thinking and problem-solving skills, much in demand by companies, and hence by governments. Unfortunately, as the American psychologist Daniel Willingham points out, no such skill exists. [7]

Finally, there is the work of Nobel Prize winner, Daniel Kahneman, an Israeli psychologist who studies how decisions are taken. His results suggest, somewhat surprisingly that 95% of decisions are taken automatically, based on experience, and only in a very small number of cases do humans sit down and work it out. [8] This he calls Type I thinking, fast, but not necessarily accurate. The quality of most decision making therefore depends on the domain specific knowledge base of the person, not on their problem-solving abilities, which Kahneman calls Type II, slow, deliberate, but costly for humans in terms of time and energy.

What all this diverse work points to is that both expertise, critical thinking and problem-solving skills all depend on a large domain specific knowledge base. Given those facts, it seems reasonable that teaching should concentrate on building a student’s knowledge base and helping them use it in problem solving.

As Frederick Reif points out [9], science has acquired a large body of knowledge over many centuries. Is it reasonable to expect the average student to have the same keen analytical mind as Newton, or Einstein, in discovering that knowledge themselves?

This paper outlines the current knowledge about human memory, and how it actively supports learning. It then gives a brief overview of PBL and outlines the problems identified by a number of educational psychologists in this approach. Finally, it presents an intervention in TU DUBLIN, which has been developed over the past 13 years, that attempts to build an instructional design that reflects what psychologists know about learning.

2 THE PSYCHOLOGY OF MEMORY

If there is one major research finding in the psychology of learning in the past twenty years, it is the role of memory. Long regarded as merely a passive store of information, psychologists now see long-term memory as an active and critical component of problem solving.

The modern theory of human memory derives from the work of Atkinson and Shiffrin in the 1960s [10]. They distinguish between sensory memory, a passive recording of incoming sensory data that runs on a continual loop lasting around 3 seconds. That data is lost unless conscious attention transfers it to the working memory. That data too is lost after 30 s unless the brain rehearses it, a process that transfers it to long-term memory. This is shown in Figure 1 below.

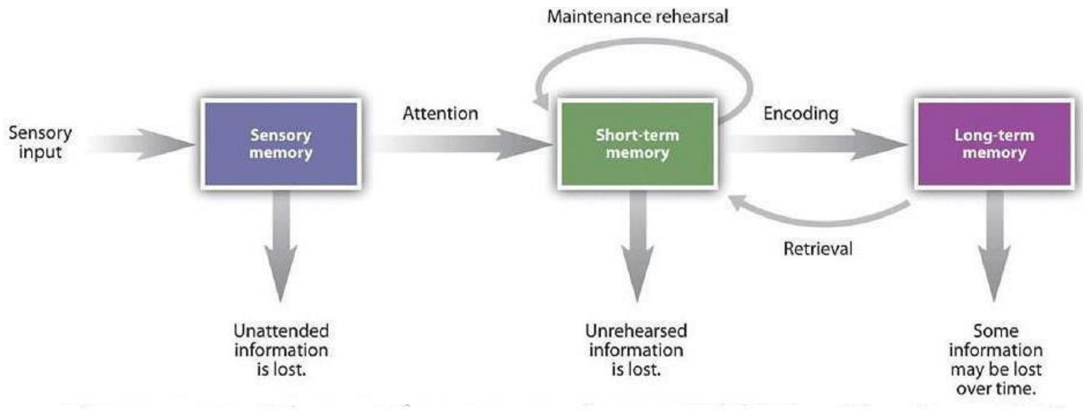

Fig. 1. Atkinson and Shiffer's 1968 Model of Memory [10]

It is clearly crucial that a student pays attention, or else they cannot learn: no transfer occurs from sensory to working memory. This is an area where some misunderstandings can arise. All psychologists studying memory agree that a passive student cannot learn, because attention is an active task. That does not mean that a student cannot learn by listening to a teacher; attentive listening is an active task. It is not necessary for the student to be physically doing something, in order to learn.

The desire to learn comes from humans' innate curiosity about their world. Curiosity is founded upon metacognition, thinking about thinking. The French scientist Stanislaus Dehaene writes: "in order for children to be curious, they must be aware of what they do not yet know. In other words, they must possess metacognitive faculties at an early age. "Metacognition" is cognition over cognition: the set of higher-order cognitive systems that monitor our mental processes." [11]

Sweller develops the theory of how long-term memory acts, by focusing on the work of the Dutch psychologist, de Groot [12] who studied chess grandmasters. "He showed masters and weekend players a board configuration from a real game, removed it after five seconds, and asked them to reproduce the board. Masters could do so with an accuracy rate of about 70% compared with 30% for weekend players."

It is not that chess grandmasters have superior problem-solving skills; rather that they have acquired, over many years (at least ten), a database of chess games, and can recognise the strategic value of a game, whereas the novice cannot. It is the strategic value that they are using to remember the positions of the pieces on the board, not the actual pieces, which are too numerous for short-term memory.

Sweller et al continue: “They tell us that long-term memory, a critical component of human cognitive architecture, is not used to store random, isolated facts but rather to store huge complexes of closely integrated information that results in problem-solving skill. That skill is knowledge domain-specific, not domain-general. An experienced problem solver in any domain has constructed and stored huge numbers of schemas in long-term memory that allow problems in that domain to be categorized according to their solution moves.”

Kirschner, Sweller, Clark in their 2006 paper, ‘Why Minimal Guidance During Instruction Does Not Work’ [13] emphasise the key importance of long-term memory in learning: “It is no longer seen as a passive repository of discrete, isolated fragments of information that permit us to repeat what we have learned. Nor is it seen only as a component of human cognitive architecture that has merely peripheral influence on complex cognitive processes such as thinking and problem solving. Rather, long-term memory is now viewed as the central, dominant structure of human cognition. Everything we see, hear, and think about is critically dependent on and influenced by our long-term memory.

Lord Kelvin famously remarked: “When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.” [14]

Kirschner et al define learning as: “The aim of all instruction is to alter long-term memory. If nothing has changed in long-term memory, nothing has been learned.” [15]

This is a critical problem for PBL, which assumes that learning occurs when problems are solved. There is no direct way to measure this, and so by Kelvin’s definition, it is not science.

They then tackle the nub of the problem, which is the limitations of working memory when dealing with new information. Those limitations are temporal and physical. Unless new information is rehearsed, and transferred to long-term memory within 30 s, it is lost. Physically, working memory can handle between 4 and 7 new items, and for items that require intensive processing, this may be as low as 2 or 3. Sweller has published [16] on the extreme load that problem solving places on working memory. Kirschner et al point out that: “The consequences of requiring novice learners to search for problem solutions using a limited working memory or the mechanisms by which unguided or minimally guided instruction might facilitate change in long-term memory appear to be routinely ignored." [17]

There have been many responses to the 2006 paper, but none have really answered the Kelvin question: how is successful learning via the minimally guided problem solving being measured?

3 PROBLEM-BASED LEARNING

Many types of student driven, minimally guided learning developed from the 1960s onwards. Perhaps the best known is Problem Based Learning (PBL), in which students work in small groups (8 to 10) to solve unstructured problems. PBL was first developed in medical schools in the 1970s, to provide medical students with more realistic situations that they would encounter in practising medicine. From an early beginning in McMaster's University in Canada, it spread to other medical schools, such as the new University of Maastricht, which became the first university in the world to apply PBL methods across all faculties [18]. It is interesting to note that the development and adoption of PBL in medical programmes grew out of dissatisfaction with the clinical skills of new graduates.

The 1990s saw PBL being applied to other university disciplines, and even to second-level education (K-12). In his chapter on PBL in the 2007 *Handbook of Research on Educational Communications and Technology*, Woei Hung, stated that a key assumption of PBL is that when we "solve the many problems we face everyday, learning occurs". Educational psychologists such as John Sweller would profoundly disagree. For them, learning occurs only when there is a change in a person's long-term memory. When a problem is solved during PBL, there may be no change in a person's long-term memory, because the students may have hit upon the solution by random chance, as they poured over search engines. [19] Hung goes on to say that, "PBL proponents assume the primacy of problems in learning; that is, learning is initiated by an authentic, ill-structured problem". Notice the crucial word in that sentence: 'assume'. There is no evidence produced for it.

He then goes on to say: "Problem-based learning is based on constructivist assumptions about learning, such as:

- Knowledge is individually constructed and socially co-constructed from interactions with the environment; knowledge cannot be transmitted.
- There are necessarily multiple perspectives related to every phenomenon.
- Meaning and thinking are distributed among the culture and community in which we exist and the tools that we use.
- Knowledge is anchored in and indexed by relevant contexts."

The constructivist perspective, as outlined by Chan et al [20] is that: "Constructivism is a view of learning that knowledge is not a thing that can be simply given by a teacher at the front of the classroom to students at their desks. Rather, knowledge is constructed by learners through an active, mental process of development and learners are the builders and creators of meaning and knowledge. The constructivist conception uses student-centred teaching strategies because this type of learning will help students develop critical thinking and collaboration skills and learning takes place in environments where students are able to participate actively”.

The constructivist position that knowledge must be actively constructed by students, or else it doesn’t exist, is problematical for scientists and engineers. It may be of limited validity in the social sciences but is simply not appropriate in science and engineering. To return to Reif, science is a highly complex enterprise, created by the best minds of the time; it is not possible for the average student to construct such knowledge ab initio. However, it is easy to see from this definition the appeal of PBL based on constructivist principles in medical education. Knowledge per se is useless for doctors if they cannot apply it in a clinical context.

4 TU DUBLIN INTERVENTION

In 2009, Larry Bucciarelli of MIT [21] spent a semester in TU DUBLIN (or DIT as it then was).
This was the beginning of the attempt to introduce open design problems in the Mechanical Engineering programme. The initial results of this intervention were presented at REES 2015, held in DIT, Dublin. [22] During REES 2015, Professor Ference Marton, of the University of Gothenburg, Sweden, gave valuable feedback, making the suggestion that pre and post tests used to evaluate student learning, should be conceptual, rather than the standard numerical problems then in use. This was done in subsequent years, and the initial results presented at the Portuguese Society for Engineering Education (CISPEE) conference in 2018 [23].

The results from that paper were encouraging:

Over the two sessions, pre and post the open design exercise, the mean scores for the concept questions were 20.61 and 23.98.

There is a significant difference ($p = 0.0402$) between the students’ conceptual understanding at the end of the exercise than at the beginning; in other words, the null hypothesis, that the two means are similar, is rejected at the 95% Confidence Interval.

The student t-test results for the 41 pairs involved showed similar results, i.e. at a 1% Confidence Interval and a one-tailed test, the result was significant, with a p-value of 0.006457.

The intervention with a single cohort of TU Dublin Mechanical Engineering students is limited, and with a relatively small number (41), difficult to generalize. None the less, it does show that a modest intervention, not requiring major changes to the curriculum or to the module delivery, can have measurable effects in improving student learning.

In 2020, the Coronavirus pandemic forced teaching to go online in TU DUBLIN, as elsewhere. To help students engage with the material in an active manner, the idea of using Mind Maps as a Continual Assessment (CA) tool was introduced. Mind

Maps are a method to make learning active and to aid retention of knowledge in long-term memory. They were popularized in the 1970s by psychologist Tony Buzan. [24] Mind Maps draw out the relationships between concepts, making the overall structure clear, in a visual manner. They require the student to actively engage with the material, and also to apply judgement as to what things are important (metacognition).

5 SUMMARY

PBL is based on a constructivist philosophy of knowledge, which is not compatible with science. It is also based on a flawed understanding as to what is meant by active v passive in learning. PBL can be passive, if someone is not engaged, traditional lectures can be active, if students are motivated and attentive, and taking notes intelligently.

Changes in long-term memory define learning, not problem solving. Active attention is the only way in which learning can occur, and this relies heavily on a student's intrinsic motivation. Millions of years of evolution have made humans curious, and anxious to learn. This should be exploited by educators.

The clash of scientific instruction with constructivism lies in science's foundation with Aristotle's empiricism. There is another aspect of Aristotle, his ethics, which should also be borne in mind by all educators. In his Nicomachean Ethics [25], Aristotle talks of the importance of the Golden Mean, a position between extremes. Too much courage is recklessness, too little, cowardice. Traditional instruction, where a teacher dispenses knowledge to students, who passively acquire it (or perhaps, not), is not a very effective method of teaching. Neither is its opposite extreme, active learning with no (or very little) guidance.

The Golden Mean for teaching and learning is surely to do both, provide instruction and guidance to the novice to build up expertise, and also to provide open-ended problem-solving opportunities to develop their skills. This is how doctoral programmes work, where students are guided by an expert supervisor. Only as a post-doc, does the successful student can engage in their own unsupervised research. At that point, they have completed the transition from novice to expert.

Constructivism began with the work of the Swiss psychologist, Jean Piaget, whose theories of how children develop centered around the idea of the child construction and testing ideas, mainly through the medium of play in the early years. A century later, the French neuroscientist, Stanislas Dehaene [26] suggests that the child acts much like a scientist, being genetically hard-wired to create and test hypotheses, and having an innate understanding from birth of both numbers and probability. Dehaene prefers to define humans as *homo docens*, as the key difference between humans and the rest of the animal kingdom is the ability to learn. It is an educational tragedy, according to Dehaene, that in the last thirty years research has “elucidated the algorithms that our brain uses; the circuits involved, the factors that modulate their efficacy, and the reasons why they are uniquely efficient in humans", but educators are unaware of this work, and so are not applying it. Dehaene identifies four key components to learning: "focused attention, active engagement, error feedback, and a cycle of daily rehearsal and nightly consolidation" [27]

Memory is critical here: nothing will move from sensory to working memory, or from working to long-term memory unless the learner is paying attention and is actively engaged in the task. It doesn't really matter what kind of instructional design is being used, as students can be using their smartphones to check social media in a traditional lecture or in a PBL group session. 'Active' is in the mind of the student, not in the structure of the lesson.

There is no need for a complete revolution from traditional teaching to PBL or any other radical implementation of active learning. It is possible, as has been done in TU Dublin, of building gradually, reflecting the latest research into learning. This suggests seven steps:

1. Teach students the basic facts, e.g., the gas laws.
2. Take them through worked examples.
3. Get them to tackle traditional closed problems.
4. Get them to create Mind Maps for the topic (metacognition)
5. Give them an open-ended problem to tackle on their own or in groups.
6. Give them conceptual tests on the topic before and after the open exercise to test its effectiveness.
7. Give them good feedback, so they can improve.

Students are results focussed, and that often means a final exam. Daniel Willingham asks his students not to revise by looking over notes [28], but to create new notes from memory, and then compare them to the original notes. It would be even better to get students to draw new Mind Maps as they revise, and then compare them to the originals. This reinforces learning, and as students compare the two, they are made aware of errors. And error correction is, as Dehaene emphasises, one of the keys to successful learning [29].

In fact, he goes as far as saying: "Organisms only learn when events violate their expectations." The learner as scientist continually updates their mental model of the world when outcomes are not as expected. Dehaene believes one of the most important roles of the teacher is to provide good, non-judgemental feedback to the student as quickly as possible.

Education is not about traditional or modern; it is about both. All innovations in teaching and learning must be founded upon research findings, especially neuroscientific and psychological findings into how the brain, and especially the memory, works. New research does not mean throwing away all traditional methods. It is all about the Golden Mean.

REFERENCES

[1] Tindall-Ford , S, Agostinho , S, Sweller , J, (editors), (2019), Advances in Cognitive Load Theory, Taylor and Francis.

[2] Hung, W, Problem-based learning, Handbook of Research on Educational Communications and Technology, Chapter 38, Routledge, 2007

[3] Kirschner, P. A., Hendrick, C., How Learning Happens, Taylor and Francis, 2020

[4] Bucciarelli, L. L.,Designing and learning: a disjunction in contexts, Design Studies Vol 24 No. 3, May 2003

[5] Bothwell , E., “President turns MIT’s research might to study of how people learn”, Times Higher Education Supplement, March 23, 2017

[6] Kirschner, P. A., Sweller, J., Clark, R. E., Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching, Educational Psychologist, 41(2), 75–86, 2006.

[7] Willingham, D. T., Critical Thinking: Why Is It So Hard to Teach?, American Educator, p 8-19, Summer 2007.

[8] Kahneman, D., Thinking, Fast and Slow, Penguin, 2011.

[9] Reif, F., Applying Cognitive Science to Education: Thinking and Learning in Scientific and Other Complex Domains, The MIT Press, Cambridge, Massachusetts, 2008.

[10] Atkinson, Shiffrin, Human Memory: A Proposed System and its Control Processes, Psychology of Learning and Motivation, Volume 2, 1968, Pages 89-195.

[11] Dehaene, S., How We Learn, Viking 2020

[12] Sweller, J., Clark, R. E, Kirschner, P. A., Teaching General Problem-Solving Skills Is Not a Substitute for, or a Viable Addition to, Teaching Mathematics, AMS Notices, November 2010.

[13] Kirschner, P. A., Sweller, J., Clark, R. E., op cit [6].

[14] Oxford Essential Quotations, Online version 2016, Oxford University Press.

[15] Kirschner, P. A., Sweller, J., Clark, R. E., op cit [6].

[16] Tarmizi, R., Sweller, J., Guidance during mathematical problem solving, Journal of Educational Psychology, 80, 424–436, 1988.

[17] Kirschner, P. A., Sweller, J., Clark, R. E., op cit [6].

[18] Moust, J. H. C., van Berkel, H. J. M., Schmidt, H. G., Signs of Erosion: Reflections on Three Decades of Problem-Based Learning at Maastricht University, Higher Education, Nov., 2005, Vol. 50, No. 4 pp. 665-683, Springer.

[19] Kirschner, P. A., Sweller, J., Clark, R. E., op cit [6].

[20] Chan, K. W. & Elliott, R. G. (2004). Relational analysis of personal epistemology and conceptions about teaching and learning. Teaching and Teacher Education, 20, 817-831.

[21] Bucciarelli et al, Introducing Independent Thinking and Project Skills to First Year Engineering Students, Proc. of the SEFI 2013 Conference.

[22] Sheridan et al, Using Open-ended Problems with First Year Engineering Students in Order to Foster a Cognitive Paradigm Shift, 6th Research in Engineering Education Symposium (REES 2015).

[23] Sheridan et al, Nádúr Daonna (Natureza humana): An Intervention to Work with nature in the Intellectual Development of First Year Engineering Students, Proc. of CISPEE 2018.

[24] Buzan, T., Mind Map Handbook, Thorsons, HarperCollins, 2005.

[25] Aristotle (translated by David Ross), The Nicomachean Ethics, Oxford World Classics, 2009.

[26] Dehaene, S., op cit [11]

[27] Dehaene, S., op cit [11]

[28] Carey, B., How We Learn, Chapter 3: The Effect of Context on Learning, Random House, 2014.

[29] Dehaene, S., op cit [11]