Multidisciplinary teaching: The emergence of an holistic STEM teacher

Niall Seery*, Lena Gumaelius†, Arnold Pears†

*Athlone Institute of Technology
Dublin Road, Athlone, Co. Westmeath, Ireland

†Department of Learning in Engineering Sciences
School of Industrial Technology and Management
KTH Royal Institute of Technology, Sweden
lenag@kth.se, pears@kth.se

***Abstract*—This full research paper approaches the teaching of STEM from a new multi-disciplinary perspective. While the importance of the STEM agenda is not in dispute, the plurality in treatment of STEM as individual subjects or disciplinary areas of study potentially limits the evolution of a new conception of STEM education. In this paper, determinist disciplined learning is challenged through the advocacy of a learning science agenda, which we argue from the perspective of modern teacher education.**

Unintentionally, our educational systems and structures can create a silo-effect, sometimes impeding the development of multi and trans-disciplinary competencies. This paper advances an argument for a conception of teacher education that supports the development of the holistic STEM teacher. Our conception of the holistic STEM educator revolves around central themes focused on building, manipulating and synthesising STEM specific attitudes, skills and knowledge. The proximal and distal effects are also considered in subsequent discussion.

This paper does not propose a generalist teacher, as the significance of content knowledge as a critical component of teacher efficacy is not contested. On the contrary, it considers an unbounded and applied perspective to the treatment of STEM with implications for an enhanced comprehension of abstracted knowledge and support for a more robust construction of meaning. The vision of a STEM teacher is articulated with respect to position, treatment and competencies intending to qualify and sustain the STEM agenda through pragmatic action.

***Keywords*—STEM, teacher education, professional competencies; intellectual alignment; student learning**

I. INTRODUCTION

Our philosophy of teacher education adopts three perspectives: Science, Technology and Computer Science education are used to illustrate the complementarity of STEM elements when considered from a cognition and learning science perspective. This paper approaches these three areas of study by exploring the nature of each subject with respect to epistemology and pedagogy. The relationship between theoretical and applied understanding is critically reviewed, with emphasis on the contrast between the approaches to scientific enquiry as opposed to the iterative dialectic that governs much of technology education. Computer science is positioned in the paper as a vital mediated position, which negotiates the relationship between abstraction and realisation.

Foregoing a single discipline perspective, this paper develops a broader perspective rejecting the single discipline ethos, proposing a framework in which we consider subject complementarity as the underpinning for further evolution of STEM education, and by association STEM pedagogy. Balancing the critical with the speculative with a focus on non-determinism supports a learning science approach and advocates for a design epistemology to emerge as an integral function of future STE(A)M discourse.

The idea of STEM education has a well-established evolution and the agenda for developing the overlap in subject areas is well articulated. Wang et al. [1, pp. 1] , demonstrates the holistic benefits of an integrated approach to STEM students and their studies, and the agenda is well supported from an economic perspective. However, there remains significant variance across stakeholders [2, pp. 9] that limits the concept and agenda with respect to practice. Pitt [3] highlights the lack of a definition as being problematic as it has a direct impact on the interpretation of curricula and as a result the definition of capability. With no common operational definition, the fluid nature of STEM interpretation creates a challenge for "changing the paradigm from compartmentalising academic disciplines to the integration of these disciplines as advocated by many through the STEM movement" [2, pp.9] Breiner et al. (2012, P.9). STEM education has highlighted the potential relationship between traditional disciplines and the idea that the interdisciplinary approach potentially offers the opportunity to develop a more comprehensive understanding of areas through the application of knowledge and skills. Considering STEM education in the context of the Post-Primary curricula, Banks and Barlex [4] challenge the assumption that STEM may not be a relationship among equals. As a result the plurality in treatment of the individual subjects potentially limits the evolution of a new conception of STEM education. Traditional approaches to subject specific education are predicated on the adoption of the dominant ontology and epistemology of the subject area. Well-articulated areas like Science and Mathematics in particular derive a clear determinist educational agenda. As a result this gives them a legitimism and as such a ‘power’. McGarr and Lynch [5] argue from a sociological lens the classification of the STEM subjects using Bernstein’s curriculum codes framework, they demonstrate the variance between the STEM components, and reinforce the underlying impediment to a fully integrated approach. By comparison to Science and Mathematics, Technology is weakly framed and weakly classified, resulting in unclear discipline boundaries. The variance in a subject’s perceived status, coupled with the nature of the treatment and associated knowledge base, begins to erode the capacity to deliver an integrated provision. However, it may be this lack of agreed definition that creates the opportunity to develop a new conception of post-primary provision, framing a new multi-disciplinary perspective. Therefore, there is an opportunity to frame the relationships and the associated position focusing on enacted practice.

As post-primary education is considered general education, the idea of an integrated STEM subject aligns with the aims and scope of this level of education. But there is contention between the treatment of an explicit subject and a new perspective governed by the integration of sub-disciplines. The remaining sections of this paper discuss the key considerations with impact on the conceptualisation of a general STEM education. Knowledge is considered with respect to acquisition and application in the context of a number of STEM sub-disciplines. Although, it is proposed that the content is broad, it is also bounded and aligned with the evidence based on how to develop general STEM competencies. This approach frames a learning science agenda that is based on evidence for how people learn. The potential variance when you transition from a single subject where the end goal is knowledge acquisition to an integrative subject where the goal is knowledge acquisition in addition to search, evaluation, and application are of considerable significance.

II. The Integrative STEM Approach

Considering an amalgam of STEM disciplines requires the careful alignment of a STEM agenda with practice, this involves shifting from a subject paradigm to an agenda of cross-cutting capability. How to positively influence this requires consideration from the learning science practices that frame the secondary knowledge assumptions, expectations, qualities, and standards. Considering the dichotomy of knowledge types based on the work of Geary [6], [7], the differentiation between biological primary and secondary knowledge frames the argument effectively. Biological primary knowledge is knowledge humans have evolved to be able to acquire through osmosis. Examples include general problem solving skills and learning a first language. Kirschner et al. [8] highlights “in most cultures, there are many concepts and procedures that we have not specifically evolved to acquire such as reading, doing mathematics, working with a computer or searching the internet” that are biological secondary knowledge, as this must be taught. Biological secondary knowledge is teachable. It is the knowledge within our curricula and is culturally determined in terms of its importance. When considering a single subject like science, we teach biological secondary knowledge. If we are to consider an integrative subject like a single STEM subject, we may use biological secondary knowledge fluidly, and we may use biological primary knowledge (not teachable) such as general problem solving skills like means end analysis, together to solve problems. We can hypothesise that our end goal is to develop a critically reflexive thinker who can search, evaluate, acquire and apply knowledge.

When we now consider the evidence for how we teach and how people learn, currently the scientific study of how people learn (learning science agenda) is contextualised within a system of single subjects where the end goal is knowledge acquisition. This evidence puts direct instruction as the favourable approach over problem based learning and inquiry-based learning. When we change the context to an integrative subject, we may see a difference in how we should teach. However, there is much evidence supporting a series of specific approaches to teaching biological secondary knowledge, these are still important as we would still need to teach knowledge as a medium to achieving the aim of an integrative subject. These include spaced practice, retrieval practice, dual coding etc. [9].

Understanding knowledge has implications for how we consider post primary education. While cognitive architecture supports direct instruction, educationalists often advocate for constructivist, discovery approaches, predicated on the withholding of information during a problem solving learning transaction. Interestingly in Design and Technology the information is often unknown and not withheld. This is a critical aspect of technology education and is potentially the unique contribution of this paper. The blurred discipline boundaries [5] frame an approach that perfectly marries the speculatively with the critical. It is this balance that builds on the confirmatory and exploratory dispositions essential for effective learning.

Integrative STEM, should not bound knowledge as with traditional subjects. The aim of the new frontier is to develop general skills through the medium of integrated STEM knowledge. With a refocused emphasis on the treatment of knowledge to include search, critique, and application, the acquisition of knowledge is considered important, both as a means of developing a new treatment and disposition. Critically the evidence for how people learn is important, as knowledge acquisition is important, but the weight of its importance is different due to the new conceptual context.

III. A Learning Sciences Perspective

This paper considers the development and creation of disciplined knowledge by virtue of a central theme defined by learning science. This approach has two significant advantages, it places the learner and evidence based practice at the centre of the discourse when developing a learner and secondly as a result it provides a framework to consider multidisciplinary and trans-disciplinary teaching and learning.

Sweller et al. [10] describes Cognitive Load Theory as a framework for supporting research into how people learn. It is premised on the information processing theory of human cognition and importantly, it is founded upon five principles of an information processing system. Although the breadth and depth of knowledge is determined relative to the agenda and stage of education, successful learning will always require a comprehensive knowledge base. The Information store principle, describes the importance of the long-term memory for storing information. Both primary and secondary knowledge are stored in long-term memory and as a biological primary skill it does not need to be taught [8]. Recognising that knowledge is a constant, an integrative subject still relies on storing information, however the epistemological difference of a single subject over that of an integrative subject shifts the explicit nature and treatment of knowledge. This has significant implications for how we teach and to what end.

How we access information is framed in the borrowing and reorganising principle. This principle suggests that learners 'borrow' information that is stored in the long-term memory of others. Through teaching or collaboration, learners access information that they then reorganise either by assimilation or accommodation (Piagetian theory [11]) into schema. This principle applies to all learning transactions in principle, however the purpose of the learning activity in a STEM subject is changed as the explicit nature of knowledge is now fluid and can be selected more freely by the teacher. The associated pedagogical orientation becomes more critical as the scope and intent from an explicit knowledge acquisition perspective is less important. The organisation and reorganisation is more dependent on the collaborative nature of the learning and the access to a multitude of 'long-term' stores, usually provided for by peer and group learning activity.

Where access to information is limited or insufficient the third principle explains how information is generated. The randomness as genesis principle explains how we use primary biological skills to generate information through problem solving. If knowledge does not exist, a heuristic like the 'generate and test' heuristic [12] is implemented to generate new knowledge relative to the learners' schema. This can be quite inefficient and considering the traditional aim of knowledge acquisition, this may not be an efficient pedagogical strategy. Kirschner et al. [8] note, "Problem solving is only useful when we do not have alternative access to problem solutions. However, considering an integrative subject, problem solving is an important process to understand and align with the broad educational objectives. Focusing on the information processing theory it is apparent that an integrative STEM subject will not change the principles of how people learn, but clarify the concept of capability based on the weighting and treatment of knowledge. Kirschner et al. (2018) highlight that in order to avoid combinational overload during the generation of information, limits are imposed by the capacity and duration of our working memory. The 'Narrow limits of change' principle only applies to novel information. It is now more apparent that the importance of pedagogical practice is amplified when considering learning practices from the perspective of human cognitive architecture. Where too many new elements in new knowledge generation causes a high degree of cognitive load, pedagogical approaches become critical. Kirschner [13], highlight that collaborative learning may address some of the limitations of working memory, as learners can benefit from the 'collective working memory effect'. This is a problem for the integrative subject conception. By having too much scope and working within novel problems, there can be too much information and this can result in no learning. This means how we teach will have to be considered. Perhaps some direct instruction is needed initially to provide a remit and context for novices, then the constructivist agenda can be introduced later but the goal is not to acquire knowledge, but to become better at being a constructivist learner. This will require more evidence through a learning science approach to research and a need to direct teacher education attention.

"While working memory is limited when dealing with novel information it has no know limits when dealing with organised information from the information store of long-term memory" [8]. Essentially, information is stored in our long-term memory, which is there in storage and not being consciously thought about. The 'environmental organising and linking' principle trigger can bring this into our working memory. Although, there is no real effect on individual learning when considered from the argument of the paradigm shift, it is useful from a pedagogical perspective. It is recognised that some skills associated with knowledge generation, appraisal, and confirmation can be developed by learners through mediated collaborative educational transactions, where the apparent benefit of an integrative problem-solving subject begins to emerge.

IV. The Relationship with Practice

Since the emergence of a scientific approach to research on learning, we have established some methodologies or pedagogical approaches which are effective. This is critical, however this research was contextualised in an education system where the end result is the assessment of knowledge acquisition. An integrative STEM subject should not have the same emphasis on knowledge. Therefore it is essential to frame what an integrative STEM subject would look like relative to knowledge. The following section is not intended to be a comprehensive review of science, technology or computer science education, but rather a means of framing the variance in epistemology and pedagogy and the similarities that could support the development of a general STEM subject at post primary level.

Knowledge structures in science education are well defined and as a result pedagogical activities are focused on an explicit agenda. For the most part education systems are knowledge focused, leading to quantifiable performance measures and a very clear definition of capability. This is well established in science education, with a clear focus on knowledge and the scientific method. To some degree, it can be argued that the determinist agenda frames a deliberate pedagogy, where knowledge is generated and referenced to a confirming knowledge base. Capability in Science is predominantly determined by knowledge and as such, Science is primarily about describing and explaining phenomena in the world (see Norström [14]).

In contrast to Science, capability in Technology is more difficult to define [15] and there is recognition that Design and Technology (D&T) Students can be successful in dramatically different ways [16]. With reference to knowledge the contrasting blurred boundaries of Technology and the focus on applied topics, presents a broader range of relevant knowledge bases, with learning activities often borrowed from other disciplines (c.f. McGarr and Lynch [5]). Spendlove [17] "highlighted that working in a space bereft of explicitly defined content knowledge as a unique advantage of D&T education, in that ownership lies with the teacher". D&T is said to be characterised by a pedagogy where there is no 'right answer' but rather different responses to the same problem are valued, some more than others (Banks et. al., 2004). Therefore the dominant pedagogical strategy is a project-based approach that connects designing and making. This combination of knowledge acquisition and application gives significant opportunity to the Technology teacher to decide on the knowledge focus from an infinite number of possible project/problems.

As a mediated position, Computer Science offers a useful example of a defined yet expansive knowledge base coupled with a structured pedagogy that supports explorations, evaluation and confirmation/affirmation as a standard pedagogical approach. Focused on computational thinking and its premise of logic and innovation creates a bounded and controlled marriage of speculation and critique. Unlike D&T education computer studies has the advantage of explicit function and as such makes the learning progress visible throughout the learning transaction. The dependence on their peer or teacher can be lessened by a 'debugging' process, which results in learning that is not socially mediated, but instead can be affirmed by the computer. The scope for a pedagogy that enables speculative enquiry is facilitated by the 'undo' culture. For the purposes of this paper, this approach, when applied to STEM learning illustrates the balance between learning of abstractions with tangible applications and discoveries (not necessarily of new knowledge, but affirming and confirming information).

The agenda to build knowledge at the same time as to foster a disposition of enquiry is a laudable educational agenda. Considering knowledge as an absolute and developing a pedagogy that is efficient in knowledge acquisition may limit the capacity of formal education to serve a more comprehensive agenda. Although any conceptual change must take the shape of a policy reorientation, this paper considers a somewhat more pragmatic approach to exploring the implications for practice. It is acknowledged that the details of a general STEM subject would need careful consideration and framing, therefore the focus of this paper is on the considerations for practice, starting with the need for an 'holistic' STEM teacher. Future teachers need to be educated on the aims of post-primary education, the distinction between a singular subject and an integrative general subject, and the science behind how people learn to ensure pedagogical approaches are contextualised within an appropriate evidence base.

The new conception of STEM as an integrative subject must relax the disciplinary epistemological boundary. Knowledge from mathematics, science, technology and engineering fields could be drawn on, selected by teachers (maybe from a broadly defined syllabus for pragmatic reasons) as appropriate. The approach to teaching would have to change to become more problem orientated so constructivist approaches would possibly align better.

V. The Holistic STEM Teacher

There are an exhaustive number of positions to take when focusing on STEM education. The position of this paper is to consider the possibility of developing an Holistic STEM teacher. The concept challenges the conventional approach to determining the discipline and the defining characteristic of the associated professional competencies and qualities. Dakers (2006) describes that one of the challenges facing Design and Technology Education is shifting from the traditional origin of the subject. Challenging the 'hegemonic behavioural cycle' is how he describes the significant issue. STEM as a singular is a complex concept that challenges established definitions and perspectives on the idea of a subject. By comparison to Higher Education, the multi-disciplinary STEM agenda when considered from a second level education perspective can be simplified based on the agreed agenda of second level education. At either end of a spectrum of agendas, knowledge can be qualified differently, the agenda of developing domain and topic specific expertise (at the associated level) verses developing active citizens, refines the position so as to question 'what students need to know' verses 'why they need to know it'.

Keirl [18] highlights the origin of disciplines as 'historical baggage' of Western Cultures and frames how disciplines were determined by an identifiable 'body of knowledge', where the tighter the knowledge base the more 'academic' the subject. This is the foundation of our school subjects. Keirl further denounces the idea that knowledge is something 'detached, objective, out-there, and identifiable' (pg. 22) and structured to dictate what we must learn. The proposed repositioning of knowledge and redirection of curriculum design challenges the orthodoxies of school subjects. STEM as a grouping of sub-disciplines challenges the individual conventions as evolved over time and as such forces a re-conception of the relationship between domain specific knowledge and the development of the learner.

Focusing on epistemology, we can move from orthodoxy of positivist thinking to make room for more inclusive alternatives. Habermas' theory of Commutative Action (1984, 1987) is useful in framing the treatment of knowledge that considers a critical theory perspective. Habermas [19], [20] frames three knowledge interests that are useful underpinnings for the argument for an integrated STEM subject. His work explains technical knowledge, which focuses on non-critical utility and function, practical-hermeneutic knowledge interest as knowledge utilised to make meaning, sensitive to context and situation and critical-emancipatory knowledge interests that allow for well-informed decision making. The critical capacity that results must be the ambition of formal education, albeit contextualised in 'useful' knowledge.

Teacher education is a useful lens as it can be considered as an unadulterated starting point, with the capacity to avoid confounding variables that have the potential to skew or distract the concept as a propositional argument. Our conception of the holistic STEM educator revolves around central themes focused on building, manipulating and synthesising STEM specific attitudes, skills and knowledge. The position qualifies teachers as critical agents of change (see Lynch, [21]) and as such focuses on teacher education. Conceiving a new approach to developing STEM teachers as a singular has the potential to foster inter-disciplinary and trans-disciplinary education. The impact is more significant when changing the underpinning ontological and epistemological constructs that govern teachers' practices.

Teacher education has the capacity to amplify policy planning and curriculum design decisions. The framing and translation of knowledge by value and pedagogy has a substantial impact. Darling-Hammond conclude that "Although many people believe that anyone can teach – or, at least, that knowing a subject is enough to allow one to teach it well – the evidence strongly suggests otherwise" [22]. Yet, it is difficult to define the knowledge base that higher education offers Initial Teacher Education Students (Edwards, 2002). Medicine presents a useful analogy for considering a STEM teacher. The position of a General Practitioner is interesting as their specialism is not in a specific area of medicine, but instead their specialism is in general practice. This paper is not proposing a generalist teacher, as the significance of content knowledge as a critical component of teacher efficacy is not contested. On the contrary, instead it considers an unbounded and applied perspective to the treatment of STEM with implications for an enhanced comprehension of abstracted knowledge and support for a more robust construction of meaning. Therefore the specialism of the STEM teacher is in the integrative general STEM agenda and as such will focus on developing a critically aware student with developed STEM competencies such as problem solving through knowledge search, appraisal, acquisition and application.

VI. Supporting Teacher Education through a design Epistemology

Teacher Education Programmes are generally categorized as either concurrent or consecutive. Concurrent degrees develop the discipline understanding simultaneous to the educational credentials, while the translational focus of the consecutive model provides for a philosophical shift from an applied disciplined qualification (usually at degree level) to that of an educator. Both have a distinct and lasting relationship with the dominant ontological and epistemological orthodoxies. Shifting to an integrative STEM agenda will challenge teachers to select knowledge and align it with the governing agenda of developing STEM capable learners. The selection of appropriate knowledge will require a determination of 'appropriate' together with a definition of what it means to be capable. This is standard practice in design education, where the rational-analytic is shadowed by the innovative creative endeavours of the learner. The significant challenge when leaning on design education practice is that there lacks an agreed design epistemology [23] (Norman and Baynes, 2017) and as such it is impractical to try and articulate the development of design capability. Although aligned with the STEM agenda, it may be useful to propose some examples of a knowledge base that would support holistic STEM teachers develop their practice, while focusing on an integrative agenda and building on design education through the lens of cognitive architecture.

Cognitive Load Theory [10] is a useful theory for an integrated STEM education as it considers how we utilise cognitive resources and the impact instructional design has on cognition. Cognitive load can be categorised as either intrinsic or extraneous load. Intrinsic load captures the effort associated with the complexity to process information. Complexity is defined as element interactivity [10]. For example, learning the colour codes for a resistor has low element interactivity, where the colour code is linked to a resistance value; the low interactivity is described by the colour representing a numeric value. Although the knowledge in isolation is important, in isolation it is not often useful. Element interactivity increases when you consider the combinations of colours as a representation of resistance value and tolerance, this knowledge increases utility. High element interactivity occurs when the selection of a resistor is required for the design of a circuit with specific utility and function. The increased element interactivity increases the degree of intrinsic cognitive load. This has particular relevance for STEM education. The efficacy of direct instruction for knowledge acquisition is acknowledged, however, the challenge for STEM teachers is how to bridge the gap between knowledge and application and further strengthen the learners' capacity to innovate and create. This requires a pedagogical strategy that facilitates the resolution of problems and the application of newly acquired knowledge. The dominant pedagogical paradigm that supports design development is iterative experimentation and experience and when considered from a cognitive perspective supports the distributed learning [9] agenda (where learners revisit the critical knowledge base from the perspective of various applications, often projects).

A further challenge facing a design approach manifests in the variance between withholding information and the fact that the knowledge may not yet exist. This approach to learning is best described in many cases as 'lean' or 'Just in time'. Building on direct instruction to focus on application and discovery so as to explore new possibilities should be governed by the dyadic modalities that are framed in balancing the critical and speculative. Aligned with this agenda, Sweller [10] describes the idea of 'goal free' problem solving that refers to problems where there are multiple parts involved in the solution, which can be found in many possible orders and in some incidents where the objective is to identify alternatives and multiple correct answer. Similar to the governing principles of the design approach, alternatives create the bases for further exploration or confirmation dependant on the current and developing knowledge base. Shepard (2017, pg. 38), reiterates the importance of using design as the medium for integration: *"Design Education needs to find new homes in disciplines such as Design Thinking, the Digital Maker Movement, IT and STEAM, along with a new generation of teachers drawn from a wide sphere of approaches to open-ended problem-solving that are not limited to specific [content]"*.

VII. Conclusion

The STEM teacher education described in this article resembles, to a large extent, the mind set for educating engineers, an education where science, mathematics, and technology most often constitutes the knowledge base for learning how to solve engineering problems in various disciplines, as for example computer engineering. Therefore going beyond a single disciplinary agenda, the argument develops a broader perspective, rejecting the single discipline ethos, and proposes an idea in which we consider subject complementarity as the underpinning for further evolution of STEM education, and by association STEM pedagogy. Balancing the critical with the speculative while focusing on non-determinism supports a learning science approach. The practical approach of creating a link between engineering education and teacher education in STEM subjects is advanced as a relevant step to take in order to establish a successful STEM-teacher education. This approach can be best put into practice by building on a design epistemology that shapes the discourse on STEM. Based on an integrative agenda and supported by learning science, this paper presents a new conception of the graduate STEM teacher and challenges the dominant definition of discipline boundaries. The focus on learning science demonstrates not only the empirically proven cognitive strategies that support learning, it also highlights the synergistic agendas that enhances the relationship between Science, Technology, Engineering, and Mathematics. More attention should be devoted to this area as the STEM disciplinary teaching sphere evolves.

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