Chapter 21
Crossing Boundaries – Examining and Problematizing Interdisciplinarity in Science Education

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21.1 Introduction

Recent visions of science education call for creating explicit connections between STEM disciplines in science education. These visions are motivated by realizations of the fundamental social, political, cultural, and economic changes likely to unfold over the course of the twenty-first century (Schwab, 2017). The widespread availability of digital technologies, as well as the ever-growing convergence of digital, biological, and physical innovations raise many concerns over the current disconnected nature of STEM education (European Commission, 2015; World Economic Forum, 2017). Different calls and curricular innovations have attempted to overcome this disconnection by (a) incorporating engineering challenges into the instruction of science and mathematics (Berland et al., 2014); (b) engaging students in mathematical (Lehrer & Schauble, 2012) and computational (Sengupta et al., 2013) modeling as a central component of their science learning; (c) devising integrated STEM curricula (Struyf et al., 2019), and (d) engaging students in scientific inquiry contextualized in real-life problems that inherently require the integration of STEM disciplines (NGSS Lead States, 2013).

This chapter discusses the talks presented in an invited symposium during ESERA 2019 entitled *'Crossing boundaries – Examining and problematizing interdisciplinarity in science education'*. Our goal in this chapter is to problematize disciplinary boundary crossings by examining the potential, affordances, challenges,

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and impairments to science education they entail. The three presentations in the symposium provide rich terrain for this analysis since each took a different vantage point on the issue. Schvartzer et al. (2019) employed ethnography and discourse analysis to examine learners' engagement in detail when learning and using disciplinary knowledge in different interdisciplinary contexts. Levy et al. (2019) reflected on a series of design-based studies as a way to probe the explanatory potential of interdisciplinarity for disciplinary-based problems. Branchetti and Levrini (2019) took a historical and curriculum development perspective to examine the inherent interdisciplinarity of STEM disciplines in discipline-based educational systems. Taken together, this diversity of methodological approaches provides a dynamic platform to zoom in and gradually zoom out on the issues at hand.

In order to contextualize boundary crossing in interdisciplinarity, we begin with a broad overview of the role of interdisciplinarity in science education. This helps set the stage for the conceptualization of interdisciplinarity and illustrates its relevance for STEM education. We raise questions about the curriculum relevance of interdisciplinarity, present examples of interdisciplinary integrations in STEM education and tackle more fundamental questions about the nature of the constituent disciplines of STEM. The literature on STEM education on boundary crossing and integration suffers from a number of under-researched issues; specifically, issues such as what exactly is being integrated and how have not received the attention they deserve. As shown in this chapter, the integration of STEM disciplines often involves a complex and rich dialogical process of bringing together values, language, concepts, and practices from different STEM disciplines, which evolve as a result of this process. This chapter discusses a set of studies that have explicitly and directly addressed this issue from a range of perspectives.

21.2 Interdisciplinarity and STEM Education

An interdisciplinary approach in STEM education involves learning across the subject boundaries of science, technology, engineering, and mathematics for enhanced understanding. STEM education has been advocated in recent curriculum policy and research literature over the last 20 years (e.g. Eurydice, 2011; National Science and Technology Council, 2013). One of the key rationales for interdisciplinarity in STEM education is that many problems are complex and cannot be solved through a single and discrete disciplinary approach. Consider, for example, issues such as climate change and nuclear energy that draw not only on disciplines such as biology and physics respectively but also environmental science. An interdisciplinary approach also provides the opportunity to reflect on how STEM disciplines work and examine potential misconceptions about science and the scientific method (Nagle, 2013). For example, a typical misconception about NOS is that the scientific method is linear and unproblematic, whereas there is a diversity of scientific methods that operate in fairly complex ways (e.g. Woodcock, 2014).

An interdisciplinary approach encourages students to explore and integrate multiple perspectives from different subject disciplines, sub-disciplines, and areas of expertise (Golding, 2009). Interdisciplinary teaching can take various forms including integrated STEM courses, coordinated STEM courses and subject-focused courses (Nagle, 2013) and multidisciplinary approaches (Klein, 1990). Hurley (2001) reviewed empirical studies on mathematics-science integration and observed that there was a reasonable increase in science achievement resulting from integration. This effect increased significantly, with large effects on achievement in science associated with higher levels of integration. Hurley (2001) noted that integration is difficult to define given the complexities of timetabling, sequencing and the relative emphasis on the subjects integrated. The studies reviewed also lacked a careful conceptualization of the integration itself. In contrast, Redish and Kuo (2015) showed that the use of mathematics in physics education does not simply involve the transfer of mathematical skills from mathematics classes to physics classes, but rather a transformation of the transferred mathematical constructs themselves, since doing physics involves meaning-making with mathematical constructs in a different way than meaning-making with mathematics constructs employed by mathematicians.

Pang and Good (2000) argued for more sophisticated understanding and explicit discussions of the nature of science and mathematics. They stressed that science seeks to understand the world through empirical evidence external to the field itself whereas mathematics deals with internal, logical deduction. Park et al. (2020) went further than these broad characterizations and examined the disciplinary nuances between science and mathematics as represented in curriculum standards. They found that in the influential Next Generation Science Standards (NGSS Lead States, 2013), in particular, NGSS explicitly points to the similarities and differences between argumentation in science and mathematics:

> … [Like mathematics,] science too involves making arguments and critiquing them. However, there is a difference between mathematical arguments and scientific arguments—a difference so fundamental that it would be misleading to connect any of the standards to MP.3. here. The difference is that *scientific arguments are always based on evidence, whereas mathematical arguments never are*. It is this difference that renders the findings of science provisional and the findings of mathematics eternal. Blurring the distinction between mathematical and scientific arguments leads to a misunderstanding of what science is about. For more information about argumentation in science, see the NGSS science and engineering practice 'Engaging in argument from evidence'. (Appendix p. 140)

Hence, interdisciplinary integration raises some fundamental questions about the nature of the constituent disciplines. For example, what is the nature of knowledge in science, mathematics, engineering, and technology? Is knowledge in each discipline have similar characteristics or are there fundamental differences between knowledge from different constituent STEM domains? Even within domains of science there may be variations about the nature of knoweldge. Fore example, such questions were raised about how laws and explanations might compare in biology and chemistry (Dagher & Erduran, 2014). Park et al. (2020) addressed the issue of the epistemic nature of STEM by focusing on the epistemic components of each disciplinary system. They looked at the impact of the theoretical framework on aims and values, practices, methods and knowledge in science, technology, engineering, and mathematics drawing on the work of Erduran and Dagher (2014). They investigated several curriculum standards such as *Science for All Americans (SfAA)* (American Association for the Advancement of Science, 1990) and *Next Generation Science Standards (NGSS)* (NGSS Lead States, 2013), to examine their coverage of epistemic aspects of STEM.

The curriculum standards of the SfAA and the NGSS were published about 24 years apart and have been very influential in the USA and worldwide. The authors concluded that although there are numerous similarities between the SfAA and the NGSS (e.g., advocating the epistemic aim of "accuracy" in science), the SfAA seemed more detailed on some topics and NGSS in others. For example, while SfAA emphasizes the kinds of methodological approaches utilized in science (e.g., references to hypotheses as well as quantitative and qualitative methods), NGSS details kinds of scientific knowledge in more depth in terms of theories and laws. With respect to aims and values, practices, methods and knowledge in science, technology, engineering and mathematics, the two documents include references to all categories except for aims and values, and methods in the case of the framing of mathematics in NGSS. Whereas mathematics is considered to be critically important for addressing STEM problems, these disparities in curriculum standards will pose challenges to integration in STEM. These observations illustrate the basic assumptions embedded in curriculum standards on the ways in which knowledge operates in disciplines subsumed within STEM fields.

21.3 Boundary Crossing – Three Vantage Points

This section discusses each ESERA presentation separately. Each subsection starts with a brief summary of the main arguments presented by the authors, followed by an analysis of these arguments through the lens of boundary crossing as a dialogical enactment (Akkerman & Bakker, 2011). The discussion of the various boundary crossing in the three presentations can be framed by Akkerman and Bakker's (2011) conceptualization of boundaries as dialogical phenomena with four "dialogical learning mechanisms of boundaries" (p. 150) which represent a family of procedures that promote learning across boundaries. The key constructs in these authors' framework include the following:

- *Identification* – Identification has to do with the ways in which people find out about the diverse practices on each side of the boundary and how they relate to one another. Characteristic processes include *othering* and *legitimating coexistence*. One example is delineating how one practice differs from another.
- *Coordination* – Coordination involves the formation of cooperative and routinized exchanges between practices on each side of the boundary. Characteristic processes include *communicative connections*, *efforts at translation*, *increasing boundary permeability*, and *routinization*. Examples cover efforts at translating

between the worlds on each side of the boundary, or the process of automatizing and operationalizing these practices (i.e., routinization).

- *Reflection* – Reflection refers to the ways in which learners can expand their perspectives on other practices. Characteristic processes include *perspective making* and *perspective taking*. Examples involve making explicit one's understanding and knowledge of a particular issue, or deliberate attempts to take a different perspective than one's own.
- *Transformation* – Transformation encompasses the processes of collaboration and co-development of new practices. Characteristic processes include *confrontation*, *recognizing a shared problem space*, *hybridization*, *crystallization*, *maintaining the uniqueness of intersecting practices*, *continuous joint work at the boundary*. Examples include confronting discontinuities that are not easily surpassed, when creating a shared problem space (often in direct response to this confrontation), and creating a hybrid practice that is meaningful in both worlds and is somewhat different from the original practices from which it emerged.

21.3.1 Learning Physics Through Maker Projects – Between Disciplinary Authenticity and Personal Relevance (Schvartzer et al., 2019)

Schvartzer et al. (2019) discussed the boundary crossing between the Maker movement[1] and the formal instruction of science, as well as school science and personal relevance. They presented an ethnographic case study that followed a pair of students engaged in a long-term (15 month) engineering Maker-based inquiry that was an integral part of the students' formal matriculation in advanced level physics. The study (Kapon et al., 2021) provided a fine-grained examination of the evolving discourse between the students, their project mentor and other members of the educational staff, and revealed how students' forms of participation were socially constructed and evolved over time. The students' engagement was conceptualized as participating in a particular figured world (Holland et al., 1998). To illustrate the boundary crossing involved, the authors juxtaposed it with the figured worlds of authentic scientific inquiry in school (Kapon, 2016) and traditional school physics. Using fine-grained discourse analysis of student-student and student-educational staff interactions in authentic working sessions, complemented by interviews and other ethnographic accounts, the authors identified two legitimate forms of participation that contributed extensively to the engineering Maker-based inquiry goal of

[1] Making is an emerging contemporary "do it yourself" trend that capitalizes on the growing accessibility of digital fabrication tools and open source hardware and software (Dougherty, 2012). It has been argued that the Making movement has great promise for STEM education because it can lead to a democratization of knowledge in engineering and science (Blikstein, 2013), alternative pathways to engineering (Martin & Dixson, 2016), and be a venue for STEM learning that offers equitable opportunities to engage underrepresented youth (Calabrese Barton et al., 2016).

creating a working artefact: participating as an engineer and participating as a technician. The analysis articulates the social construction of these forms of participation and showed that participating as an engineer facilitated many foundational aspects of learning and doing physics. However, while participating as a technician fostered a sense of agency and efficacy with regard to physics in a student who did not find ways to express himself in the regular physics classroom (i.e., promoting personal relevance – Kapon et al., 2018, 2021), it did not facilitate the learning of scientific content and practices.

The Schvartzer et al. presentation is an interesting case to examine boundary crossing as a dialogical phenomenon (Akkerman & Bakker, 2011). The juxtapositions of the different figured worlds (engineering Maker-based inquiry, authentic scientific inquiry in school, and school science) is a manifestation of *identification*. Specifically, it involves a process of *othering*; namely, discussing one figured world in light of the other and delineating the differences. The focus of the study was the nature of the practices and the roles involved (i.e., participating as…). The findings highlighted participating as engineer as an important legitimate form of participation in the figured world of engineering Maker-based inquiry, while providing various and frequent opportunities to engage in meaningful acts that characterize legitimate participation in the figured world of authentic scientific inquiry. This observation marks participation as an engineer as a *shared problem space* between the two figured worlds, which is a hallmark of what Akkerman and Bakker termed the *transformation* of practices. The study showed that participating as a technician was an important form of participation in the figured world of engineering Maker-based inquiry, and contributed to its ultimate goal of creating a working artefact, although at the same time it constituted an insignificant form of participation in the figured worlds of authentic scientific inquiry and school physics. This incongruency points to one of the arenas of c*onfrontation* between Making and doing science. One of the school staff members who took part in the study articulated this confrontation in an interview as stemming from the different goals of the figured worlds. For him this insight resulted from the *reflection* prompted by the interview. Resolving the *confrontation* between Making and doing science in school thus may require some sort of *hybridization* of practices, which may most likely result in further *transformation* of both.

21.3.2 Slipping Between Disciplines: How Forming Causal Explanations May Compel Crossing Disciplinary Boundaries (Levy et al., 2019)

Levy et al. reflected on instances of boundary crossing in three design-based studies in their group. They argued for boundary crossing between STEM disciplines when practices and explanatory means in one discipline can significantly improve mechanistic explanations of phenomena in another discipline and thus enhance students' understanding. Their argument was supported by three design-based studies that examined students' learning in technological learning environments that deliberately incorporated representational change in chemistry and in biology. In the first study (Zohar & Levy, 2019) a force-based explanation, which characterizes explanations in physics (classical mechanics), was incorporated into the instruction of chemistry to support students' understanding of chemical bonding, a notoriously difficult concept for students to grasp. The pre-post interviews suggested a significant improvement in high school students' understanding of the chemical bond as a dynamic equilibrium between forces of attraction and repulsion. In the second and third studies (Dagan et al., 2019; Dubovi et al., 2018) ideas and representations from chemistry; i.e., conservation of matter at a molecular level, were implemented and adapted into a learning environment that aimed to support learners understanding of the biochemical process related to diabetes, by specifically helping learners to visually follow individual molecules throughout the system. One study examined nursing students studying the related pharmacology, and another study examined the learning of adolescent patients during routine visits to a diabetes clinic. The pre- and post- tests results highlighted the growth in the learners' conceptual understanding, and their ability to transfer the learned reasoning to other relevant problems. Levy et al. argued that "*the explanations and representations developed in these studies were particularly generative in supporting the understanding of difficult topics, transferring this knowledge to other topics, and supporting related behaviors.*" (Levy et al., 2019).

Levy et al.'s presentation highlights several facets of boundaries as dialogical phenomena (Akkerman & Bakker, 2011). In our view, the most striking learning mechanisms can be attributed to *coordination* and *transformation*. These authors explicitly worked to *enhance boundary permeability* in the digital learning environments they designed. Specifically, the representations of force diagrams in the case of chemical bonding, and the representations of the molecular dynamics in the case of diabetes, were an integral part of the learning environment, but the learners did not seem to experience any discontinuity in their forms of reasoning when "shifting" from chemistry to physics or from chemistry to biology. The "new" representations formed an integral part of the design, so that no explicit transitions were required. The reported transfer suggests that at least some level of *routinization* was achieved as well. The designers identified a potential *shared problem space*, and the new representations they introduced to this space generated a *hybridization*, since the original practices took on a new form. For example, the use of force diagrams in the chemistry learning environment was not identical to the use of force diagrams in classical mechanics.

21.3.3 Disciplines and Interdisciplinarity in STEM Education to Foster Scientific Authenticity and Develop Epistemic Skills (Branchetti & Levrini, 2019)

Branchetti and Levrini described the tension between the robust separation between disciplines in traditional schooling and the need to develop STEM interdisciplinary skills for the labor market. They argued that discipline-based instruction can and should continue to play an important educational role in current schooling, provided it is used as a platform to develop students' epistemic skills rather than knowledge per-se. By examining the structural role of mathematics in the development of physics, they further argued that throughout the history of science, interdisciplinarity has been an important authentic aspect of disciplinary-based science. This argument formed the basis of their claim that even from a disciplinary authenticity perspective, students should explicitly learn and experience the interdisciplinary aspects of the disciplined-based sciences they study in school. These arguments were illustrated by two case studies involving efforts at curriculum development. In the first case (Branchetti et al., 2019) the designers had to cross boundaries between physics and mathematics to effectively support college level students' understanding of the nature, meaning, and significance of quantum mechanics to the problem of blackbody radiation, which puzzled scientists at the end of nineteenth century. In the second case the designers grappled with how to meaningfully introduce the complex and novel idea of artificial intelligence to secondary school students. The presentation showed that interdisciplinarity should not be confused with a–disciplinarity or multidisciplinarity, and that epistemic skills can be more effectively developed when different disciplines are compared and contrasted, and when both specific and transversal skills are made explicit.

Branchetti and Levrini's presentation constitutes an intriguing case of boundaries as dialogical phenomena (Akkerman & Bakker, 2011). They clearly acknowledged the importance and the unique features of the individual disciplines in students' education. "*The meaning of interdisciplinarity cannot ignore the meaning of 'discipline'. The term 'discipline' contains the Latin root 'discere', whose meaning is to learn. Disciplines can be seen as re-organizations of knowledge within the scope of teaching it.*" They claimed that disciplinary-based teaching is far more than a repository of knowledge since it must "*transform knowledge into rigorous and recognizable definitions and its practices into repeatable methods.*" (Branchetti & Levrini, 2019). This is an example of stressing the importance of *identification* (Akkerman & Bakker, 2011) of the unique epistemic practices of each discipline to students' learning. Branchetti and Levrini emphasized the process of *othering* each discipline as a crucial aspect of interdisciplinary learning. The case study of the curriculum development in quantum mechanics (boundary crossing between mathematics and physics) employed *reflection* as a central learning mechanism, in that the students were explicitly engaged in deliberate attempts to employ different historical perspectives to examine the problem at hand. *Reflection* and *coordination* (Akkerman & Bakker, 2011) were central learning mechanisms in the second case study of curriculum development as well (teaching artificial intelligence to high school students). The artificial intelligence example illustrated how disciplinary knowledge could foster the learning of new disciplines or when dealing with new problems that are not yet organized into a discipline. For example, the designers made an analogy between some of the epistemic differences between mathematics and physics reasoning to explain the epistemic differences between the logical approach and the machine learning approach to artificial intelligence.

21.4 Examining the Three Vantage Points on Boundary Crossing

The three presentations discussed above highlight the multidimensional nature of crossing boundaries between STEM disciplines. The first presentation (Schvartzer et al., 2019) demonstrated how the dialogical nature of crossing boundaries is socially constructed in discourse. The second presentation (Levy et al., 2019) demonstrated how specific boundary crossing in design (i.e., changes in representation) come to bear on students' learning. The third presentation (Branchetti & Levrini, 2019) demonstrated the historical and curricular considerations involved.

Whereas in Branchetti and Levrini's work, the design effort seemed to reside in carefully reconstructing the boundary through *identification* and *reflection*, in Levy et al.'s work the design effort seemed to reside in overcoming the boundary and facilitating effortless movement between the disciplines (i.e., *coordination* and *transformation*). All three studies highlighted the affordances for learning. Schvartzer et al. (2019) and Branchetti and Levrini (2019) stressed the potential contribution to students' sense of personal relevance, and the possibilities of connecting school science to modern societal and economic trends of interdisciplinarity; Branchetti and Levrini (2019) and particularly Levy et al. (2019) pointed to the different explanatory affordances entailed by boundary crossing. Nevertheless, Schvartzer et al. (2019) and Branchetti and Levrini (2019) also highlighted conflicts. Specifically, Branchetti and Levrini (2019) noted the importance of maintaining the identity of separate STEM disciplines as means of learning epistemic practices, and identified this effort as crucial for any meaningful boundary crossing. Schvartzer et al. (2019) underscored the discontinuities in practice that should be resolved to enable the integration of Making and engineering practices in the instruction of science. Taken together, these affordances and constraints reflect the complex dialogical nature of boundary crossing (Akkerman & Bakker, 2011) in STEM education and articulate it as an ongoing challenge for future research and development.

Taken together the presentations not only highlight why interdisciplinarity is important for science education but also raise questions about what counts as a "discipline" in the first place. Branchetti and Levrini's presentation traced the etymology of the word 'discipline' to the Latin root 'discere' meaning "to learn". In so doing, they emphasized the value of interdisciplinarity in forging new insights through boundary crossing as indicated in the following quote from their presentation:

> *Starting from a concrete problem, we showed the integration of S-T-E-M disciplines into a new STEM field of research and application, but we also used the traditional S-T-E-M disciplines epistemologies to shape and clarify the differences between the approaches, and we contributed indirectly to a better understanding of the traditional disciplines themselves* (Branchetti & Levrini, 2019)

A similar account of metaphor use emerged in Levy et al.'s work when they utilized terminology such as "slipping" and "sliding" to capture and conceptualize the features underpinning interdisciplinarity.

All three groups of researchers showed the relevance of interdisciplinarity for a range of stakeholders including science students (Schvartzer et al., 2019) and nursing students (Levy et al., 2019). A multiplicity of disciplines were represented including artificial intelligence (Branchetti & Levrini, 2019) as well as the boundaries between traditional disciplines such as physics-chemistry, chemistry-biology (Levy et al.) and physics-engineering (Schvartzer et al.). This set of studies utilized a range of methodological approaches including discourse analysis (Schvartzer et al., 2019), design-based research (Levy et al., 2019) and historical case studies (Branchetti & Levrini, 2019).

21.5 Discussion and Conclusion

This chapter illustrates the opportunities and challenges of boundary crossings in STEM education. The literature on interdisciplinarity in science education points to the curricular and instructional rationales as well as the relevance of interdisciplinarity for science education. The ESERA 2019 conference presentations provide a wealth of perspectives for characterizing and detailing how interdisciplinary boundary crossing can be situated in science education. Whereas Schvartzer et al. (2019) problematized learners' engagement when learning or using disciplinary knowledge in different interdisciplinary contexts and problems, Levy et al. (2019) drew attention to the explanatory potential of interdisciplinarity for disciplinary-based problems. Branchetti and Levrini's (2019) presentation problematized the inherent interdisciplinarity of STEM disciplines in discipline-based educational systems from a historical and curriculum development perspective. The discussion of the various boundary crossing in the three presentations was framed by Akkerman and Bakker's (2011) conceptualization of boundaries as dialogical phenomena which provides a distinct analytical lens for a discussion of the interdisciplinarity embedded in each project. The enactment of boundary crossing in these three projects provides concrete evidence on ways in which recent policy calls in STEM education can be materialized at the level of teaching and learning. As such, they highlight how higher order twenty-first century skills can be fostered meaningfully and constructively in education.

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