Developing teachers' interdisciplinary expertise

Consultation paper

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Contents

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The authors are solely responsible for the content of the paper.

Acknowledgement of Country

We acknowledge the tradition of custodianship and law of the Country on which the University of Sydney and the University of Queensland campuses stand. We pay our respects to those who have cared and continue to care for Country.

Project reference group

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Consultation paper overview

It is well acknowledged that interdisciplinarity is vital to future economic prosperity, health, and social wellbeing (Barry & Born, 2013). Similarly, teachers increasingly face the need to engage in teaching practices that extend beyond their disciplinary specialisation. This includes teaching cross-curricula topics, contributing to STEM and STEAM education and engaging in other integrative teaching and learning practices aimed at helping students develop capabilities to build on firm disciplinary foundations and integrate different areas of knowledge and ways of knowing for addressing transversal real-world challenges.

Despite the stark recognition of the urgent need to develop people's capabilities to work across disciplines (Cooke & Hilton, 2015), pre-service teacher education and in-service teacher professional development programs rarely focus on developing well-rounded teachers' expertise to teach students to integrate disciplinary knowledge and work across disciplinary boundaries. While there are many professional education initiatives in this area, interdisciplinary pedagogies are still described as one of the most poorly understood and implemented aspects of contemporary education, with practices lacking clear theoretical grounding and evidence (Lyall, Meagher, Bandola, & Kettle, 2016). This also applies to pre- and in-service teacher education, where different programs tend to be disjoined and informed by general theories and evidence from teacher professional development with little reference to theory or evidence specific to interdisciplinary knowledge work, teaching or learning (Enderson, Reed, & Grant, 2020; Evans, 2019; Luft, Diamond, Zhang, & White, 2020).

About the project

This consultation paper is developed as a part of the project "Developing teachers' interdisciplinary expertise", funded by the NSW Department of Education Strategic Leveraging grant and led by a research team from the University of Sydney and the University of Queensland. The project aims to translate some findings from the research project "Developing interdisciplinary expertise in universities" funded by the Australian Research Council to NSW teacher education and professional development. The project team will work with a network of pre- and in-service teacher providers to co-create a framework for developing teachers' interdisciplinary expertise, including a set of reusable design resources for integrating the development of interdisciplinary expertise in pre-service teacher education and in-service professional development.

About this paper

This consultation paper presents initial ideas about teachers' expertise for interdisciplinary teaching. It is based on the initial analysis of key curriculum and policy documents, scoping literature review, and the project team's research. It is intended to stimulate discussions and sharing of ideas with a range of potential collaborators.

The outcomes of this consultation will be used to: a) identify the principal challenges teachers face – and the capabilities and resources they need – when developing their students' abilities to engage in productive interdisciplinary project work; and b) co-create a framework for developing teachers' interdisciplinary expertise, including a set of reusable design resources for integrating the development of interdisciplinary expertise in pre-service teacher education and in-service professional development.

This paper specifically seeks to identify and map current practices and needs for developing in-service and pre-service teachers' interdisciplinary expertise in the Australian and, particularly, NSW school contexts. It also expects to create a broad network of teacher educators and other

collaborators across NSW Education and NSW universities interested in collaborating in future stages of the project.

This consultation is structured around four questions:

1. What are the most important areas of teachers' interdisciplinary practices and needs for professional learning?
2. What kind of expertise and resources do teachers need for productive interdisciplinary teaching?
3. What are the key features of effective professional education for interdisciplinary teaching?
4. What are the main barriers and enablers for developing pre- and in-service teachers' expertise for interdisciplinary teaching?

Responding to this paper

The project team is interested to hear from a wide range of people interested in the preparation of teachers for interdisciplinary teaching in K-12 schools, particularly pre- and in-service teacher educators from the NSW universities and professional development providers, students in initial teacher education, schoolteachers, school principals and NSW Education staff overseeing relevant reform and innovation areas. We would like to know about your current experiences, practices and needs. If you are interested in being involved in the consultation by responding to this paper or in participating in follow-up co-design work, please contact us. The consultation meeting-interview with you will take about 45-60 minutes and will be arranged by the project team at a mutually convenient time via Zoom.

Contact: Dr Teresa Swist teresa.swist@sydney.edu.au

Website: https://interdisciplinaryexpertise.org/developing-teachers-interdisciplinary-expertise

Terminology

In this paper, we use the following definitions:

- *Disciplinarity* refers to a body of knowledge or branch of learning with particular characteristic features (concepts, theories, methods, objects, etc.). English Literature, History, Biology, and Physics are examples of disciplines. Disciplines are organised in broader disciplinary areas or disciplinary fields, such as Humanities and Science.

- *Interdisciplinarity* refers to all forms of engagement and collaboration across disciplines and with other non-academic knowledge fields and activity spheres (private, community, industry, etc.). It is used as an 'umbrella' term that includes different degrees of interaction across the fields, from *cross-disciplinarity*, which involves exploration of the same topics from several perspectives without integrating them, to *trans-disciplinarity*, which involves integration and transcendence of existing knowledge fields and the emergence of new worldviews.

- *Expertise* refers to the capacity to perform productively, knowledgeably, and skilfully in relation to the encountered situation and context. It includes the *relationship* between personal attributes (knowledge, skills, dispositions, etc.) and a broader activity system (shared goals, cultural, social, material and knowledge resources, other people, etc.). Accordingly, *interdisciplinary expertise* refers to the capacity for productive, knowledgeable, and skilful engagement in those kinds of knowledge practices that involve several disciplines or other knowledge fields and foster connections between them.

- *Teachers' expertise* and *teaching expertise* are used synonymously. They refer to the relationship between the teacher's attributes and situated in a larger system of teaching activity.

- *Competence, skills and capability* are common terms used in literature to describe various capacities related to expertise. *Competence* often refers to the proven functional ability to appropriately use knowledge, skills, and other personal attributes (dispositions, values, etc.) in work or learning situations (Council of the European Union, 2017; OECD, 2019). *Skills* are sometimes described as a component of competence, but often 'skills' and 'competencies' are used as synonyms (e.g., 21st-century skills/competencies). *Capability* refers to "everything a person can think or do, given an appropriate context" (Eraut, 1998, p. 135). Capability is a broader term than competence. It refers to one's potential and ability in relation to personal choices and contexts, not necessarily demonstrated/proven performance.

Question 1: What are the most important areas of teachers' interdisciplinary practices and needs for professional learning?

Research literature and policy documents show that teachers engage in a range of interdisciplinary practices which broadly relate to two intertwined aspects: 1) teaching and 2) professional learning. *Interdisciplinary teaching, such as teaching integrative, interdisciplinary curricula* and *developing students' transversal capabilities, is at the centre of* teachers' engagement with interdisciplinarity. They are surrounded by a broader set of interdisciplinary professional learning practices related to the i*nterdisciplinary nature of foundational knowledge for teaching* and the *interdisciplinary nature of professional learning* (Figure 1). Each aspect includes several facets, which are detailed below.

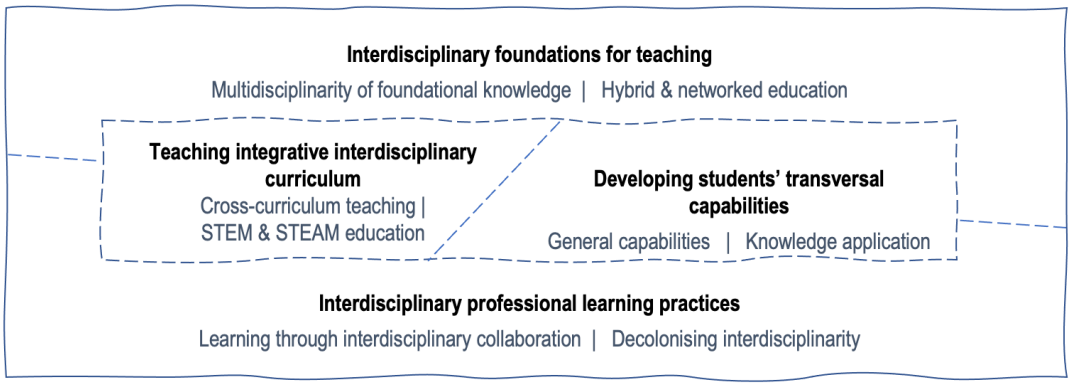

Figure 1: Main facets of teachers' interdisciplinary practices

Interdisciplinary foundations for teaching

Multidisciplinarity of teachers' foundational knowledge. Education as a professional field draws on knowledge from multiple disciplines, such as psychology, neuroscience, sociology, philosophy, anthropology, and others. This particularly is prominent in recent calls for teachers to draw upon multiple social disciplines when addressing issues of diversity, inequity, and social justice (Warren & Venzant Chambers, 2020) and embrace the newest perspectives and evidence on how people learn from the interdisciplinary field of the learning sciences (Nasir, Lee, Pea, & McKinney de Royston, 2021). This aspect is well reflected in the NSW Curriculum Review (Masters, 2020), which asserts that finding from research into how humans learn and the conditions that promote successful learning, which "has spanned a range of disciplines, including neuroscience, cognitive science, educational psychology, educational research and sociology" (p. 91), should be "routine features of initial teacher education programs and ongoing professional learning, as well as informing sequencing in the school curriculum" (p. 111).

Hybrid and networked education. The increasing uptake and fusion of digital technologies into many facets of education, including pedagogical practices, learning environments and educational management, further 'hybridises' teachers' expertise. Teachers are expected to master the pedagogical technological content knowledge (TPAK) (Koehler & Mishra, 2009) and be proficient in a number of disciplinary areas that are specifically related to information and communication technologies (e.g., cybersecurity, cyberbullying); enhance inclusivity by embracing universal design for learning principles that draw on evidence from numerous disciplines (Howard, 2003); make sense of the conflicting evidence and understand the science

that underpins pedagogies and teaching in new physical and hybrid learning spaces (Woolner & Hall, 2010); be knowledgeable about data science, develop data literacy, and be skilful at using learning analytics systems (Mandinach & Gummer, 2016). Remote teaching during the COVID-19 pandemic has raised further questions about the capabilities needed for this kind of teaching, unexpectedly pointing out the importance of networked learning and of weaving knowledge from humanistic and other disciplines when addressing the issues of wellbeing, care, justice, etc. (Hill, Rosehart, St. Helene, & Sadhra, 2020; König, Jäger-Biela, & Glutsch, 2020; Mutton, 2020).

Teaching integrative, interdisciplinary curriculum

Cross-curriculum teaching and learning. Many important topics pertinent in today's society (e.g., sustainability, health, equity) cannot be understood and addressed without engaging with perspectives from multiple disciplinary domains and do not sit comfortably in a separate subject. Simultaneously, integrative cross-curriculum teaching is seen as an unprecedented opportunity to make the teaching profession intellectually engaging (Mockler, 2018). The Australian National Curriculum includes three cross-curriculum priorities (Aboriginal and Torres Strait Islander histories and cultures, Asia and Australia's engagement with Asia and Sustainability) that, while do not require integration, should be taught across disciplinary learning areas. The Shape of the Australian Curriculum (2020) paper recognises the need for teachers to be proficient in cross-curriculum teaching: "Teachers choose how best to introduce essential concepts and processes, and how to progressively deepen understanding of discipline-based content, including through *cross-disciplinary* learning that broadens and enriches each student's learning." (p. 15). The NSW Curriculum Review (Masters, 2020) recognises the importance of the integrative teaching but places greater emphasis on the vertical integration of "theory and practice" and "knowledge and skills" within the subjects than on the horizontal integration across them (p. 113).

Science, technology, engineering and mathematics (STEM) education. STEM education is seen as essential for addressing decreasing students' interests and achievements in STEM disciplines and a growing shortage of professionals in STEM-based industries and services. This comes together with a need to address a growing shortage of STEM teachers who can teach individual STEM subjects, across them and beyond. "Increasing teacher capacity and STEM teaching quality" is a key area for national action in the Australian National STEM school education strategy 2016–2026 (Education Council, 2015). However, the implementation of this strategy itself relies on the teachers' interdisciplinary expertise. For example, it comes with the expectation that STEM teaching and learning will be intertwined with the "development of skills in cross-disciplinary, critical and creative thinking, problem solving and digital technologies" (p. 3) and teachers will be capable of engaging in "effective partnerships with tertiary education providers, business and industry" (p. 6). Similar aims are echoed in STEM initiatives and programs implemented at the State level (NSW Government, 2022). Internationally, there are strong movements to expand STEM education to include arts, humanities and social sciences, known as STEAM (science, technology, engineering, arts and mathematics) (Perignat & Katz-Buonincontro, 2019), but this trend is less common in the current Australian or NSW educational contexts.

Development of students' transversal capabilities

General capabilities. The worldwide attention to the development of general student capabilities or 21st-century competencies has important implications for teacher preparation (Greenhill, 2010; Kereluik, Mishra, Fahnoe, & Terry, 2013). The Australian National Curriculum includes seven general capabilities: Literacy, Numeracy, Information and communication technology capability, Critical and creative thinking, Personal and social capability, Ethical understanding, and Intercultural understanding. The Shape of the Australian Curriculum (ACARA, 2020) paper acknowledges that these capabilities are interdisciplinary "…learning does not fit neatly into a curriculum solely organised by learning areas or subjects that reflect the disciplines. In a world where knowledge itself is constantly growing and evolving, students require a set of knowledge, skills, behaviours, competencies and dispositions – that is, *general capabilities* – that are

developed within and can apply across learning areas." (p. 13). Literature reviews point out that, in order to support students' development of general capabilities, first teachers need to develop these capabilities and master relevant pedagogies (Erstad & Voogt, 2018; Kereluik et al., 2013; Voogt & Roblin, 2012). Quite surprisingly, there are very few specific models or suggestions on how the development of these teachers' capabilities should be done in pre-service or in-service teacher education (Greenhill, 2010).

Knowledge application, vocational education and integrated learning. Students' ability to transfer the disciplinary knowledge that they learn in different subjects and apply it to solving real-world problems in authentic contexts is the ultimate aim of learning. This requires teachers to embrace integrative teaching and learning practices that juxtapose theory and practice, combine guidance with hands-on experiences and position disciplinary knowledge in relation to other perspectives and disciplines when solving real-world challenges (Markauskaite & Goodyear, 2017). The importance of students' skills to apply theoretical knowledge and the role of integrative learning is well acknowledged in the NSW educational context. For example, the NSW Curriculum Review (Masters, 2020) emphasises the importance of vocational subjects and claims that teaching needs to address two unproductive dichotomies: 1) between disciplinary knowledge and general capabilities and 2) between academic and vocational learning: "every subject should adopt an integrated approach to the development of knowledge, skills and attributes and, in the later years of school, should be designed to prepare students simultaneously for further study, life and work" (p. 79). This comes together with the expectation that teachers will use integrative pedagogies. The main focus, however, as mentioned before, is 'vertical' integration within the subjects: "Within each subject, students should be given opportunities to explore meaningful applications of what they are learning" (p. 79).

Interdisciplinary professional learning practices

Learning through interdisciplinary collaboration. Teachers' engagement in professional development with colleagues who have different disciplinary backgrounds is an important aspect of professional teacher learning and work within and beyond the context of integrative, cross-curricular teaching, including teaching students from EALD backgrounds and addressing issues of diversity, equity and inclusivity. In the NSW and broader Australian context, co-creating lesson plans and co-teaching have been a common professional development approach in STEM and cross-curricular areas (ACARA, 2016). Such professional learning relates not only to the immediate outcome (i.e., the success of a lesson or a project) but also to what teachers learn about their own and other disciplines and about how to learn and work across these disciplinary and other knowledge boundaries (Grossman, Wineburg, & Woolworth, 2001). This form of learning also involves collaborations with experts and communities beyond traditional disciplines, such as mentoring by Aboriginal cultural educators (Burgess & Harwood, 2021) and teachers' activism.

Decolonising interdisciplinarity – social, environmental, and epistemic justices. Teachers are increasingly called to engage with the voices and ways of knowing of those who have been underrepresented in Western academic knowledge. While interdisciplinarity is often seen as an opportunity to solve some of these issues, Western interdisciplinary science and pedagogies have often embodied similar injustice issues. For example, females, LGBTQ+, and First Nation People are underrepresented in STEM (Buck, Francis, & Wilkins-Yel, 2020; Murphy, MacDonald, Danaia, & Wang, 2019). Power and prestige hierarchies are common among mathematics, science, technology and engineering disciplines and the teachers teaching them (Ellis & Williams, 2020; Quan, Bracho, Wilkerson, & Clark, 2019). STEM orientation towards economic benefits and employability has been marginalising humanistic and social rationales and disciplines (Takeuchi, Sengupta, Shanahan, Adams, & Hachem, 2020) and limiting opportunities to engage in more socially and environmentally just, post-humanistic ways of thinking and pedagogies (Burnard, Colucci-Gray, & Cooke, 2022). Educational literature points out the need to make epistemological assumptions that underlie current practices of interdisciplinarity and interdisciplinary education explicit (Quan et al., 2019; Takeuchi et al., 2020). Professional

education practices, such as teacher activism that involve deeper epistemological interrogation into the nature of interdisciplinarity and issues of power and equity, are only emerging.

Discussion questions

The above perspectives show that teachers' interdisciplinary expertise is multifaceted. Its development cannot be developed in one course or professional development program and is likely to involve multiple interweaved activities and pathways. Mapping different facets and identifying the most critical aspects in a specific context and time, therefore, is important.

1. What are the main areas of teachers' interdisciplinary practices in NSW schools?
2. What kinds of interdisciplinary practices are the most critical in the current and future teaching contexts in NSW schools? Why?
3. What kinds of interdisciplinary professional education do in-service and pre-service teachers need the most?

In the rest of this discussion paper, we focus on expertise for interdisciplinary teaching.

Question 2: What kind of expertise and resources do teachers need for productive interdisciplinary teaching?

The need to prepare teachers for the above-mentioned interdisciplinary practices is well recognised in various policy documents and research literature. However, there have been surprisingly few models or frameworks that articulate what constitutes teachers' expertise for these interdisciplinary practices or specifically for interdisciplinary teaching.

The main documents and literature reviews that address this question focus on teachers' preparation for specific areas of cross-curricular or integrative teaching, such as preparation of teachers for teaching STEM and sustainability (J.-A. Ferreira, Evans, Davis, & Stevenson, 2019; Imara & Altinay, 2021; UNESCO, 2018) or developing students' 21st-century knowledge and skills (Ellis & Williams, 2020; Greenhill, 2010) with only one framework addressing cross-curriculum teaching competencies in general (Timmerman, 2019b). These frameworks broadly represent two approaches: 1) person-oriented and 2) system-oriented. They foreground the 'what' and 'how' aspects when describing the development of teacher expertise, respectively.

Interdisciplinarity in the Australian Professional Standards for Teachers

The Australian Professional Standards for Teachers include three main areas partly related to teachers' interdisciplinary expertise: 1) the ability to make the content meaningful for a diverse range of students; 2) the use of a range of effective teaching strategies, including encouraging problem solving and critical thinking; and 3) ability to use ICT in teaching. There is a strong focus on the teacher's ability to plan, create resources, take the initiative, be flexible, and use research. Interdisciplinary, cross-curriculum or other integrated kinds of teaching and learning are not explicitly mentioned and the document does not provide more detailed guidance about teacher capabilities in this area.

Box 1: Interdisciplinarity in the Australian Professional Standards for Teachers (AITSL, 2011)

Person-oriented (or competence-oriented) frameworks take an individual approach and foreground teacher functional abilities (aka. competencies) necessary for interdisciplinary teaching. Such frameworks offer detailed lists of competencies that each teacher should develop and demonstrate. For example, the CrossCUT Reference Framework for Cross-Curricular Teaching maps common competencies of cross-curricular teaching that broadly cover three spheres: 1) working with knowledge, information and technology; 2) working with others, and 3) working with society (Timmerman, 2019b). They include 14 competencies and 193 specific areas of teacher knowledge, skills, responsibilities and autonomies.

System-oriented (activity-oriented) frameworks focus on the outcome and process of learning within a larger system. They describe what teachers overall should be capable of knowing and doing and why but emphasise a holistic vision, principles and processes distributed across the system. They attribute capability less to an individual teacher than to the entire distributed activity system. For example, the UNESCO (2018) model for the integration of Education for Sustainable Development in teacher education sketches nine main elements of the framework grouped into three areas: conceptual core, practice, and context. It emphasises the holistic, interconnected and contextual nature of learning and, therefore, details an action-oriented approach that: "positions both leaders and teachers as co-learners while taking action for the transformation of society" (p. 21).

There are two critical tensions that can be observed in the majority of current frameworks describing what constitutes teachers' expertise for interdisciplinary teaching. First, what are the distinct aspects of expertise that are needed for interdisciplinary teaching? Some frameworks and literature include capabilities that are not distinct to interdisciplinary teaching, such as teacher digital capabilities, communication, and cross-cultural competencies (Timmerman, 2018). However, some literature argues that interdisciplinary teaching requires some distinct capabilities, such as 'knowledge integration' (Krug & Shaw, 2016).

Second, what kinds of disciplinary expertise do teachers need, particularly when they teach in interdisciplinary teams? Some literature suggests that teaching interdisciplinary curricula and collaborating in interdisciplinary teams involves particular kinds of expertise in one's core discipline as well as in other (integrated) disciplines (Grossman et al., 2001; Timmerman, 2018). However, how this particular expertise is different from the disciplinary expertise that subject teachers have is rarely discussed.

Insights from researching interdisciplinary expertise in multidisciplinary laboratories

Research on what constitutes interdisciplinary expertise in multidisciplinary research settings shows that this expertise can be understood by looking across three levels of interdisciplinary practices (Figure 2):

- *Micro: personal resourcefulness* involves knowledge, skills, dispositions, and other individual resources to engage in interdisciplinary practices;
- *Meso: distributed activities* involve capabilities distributed among people and tools to carry out interdisciplinary work collectively in a setting; and
- *Macro: knowledge cultures and contexts* involve capabilities to navigate across, interact with, and shape various aspects of interdisciplinary practices that extend beyond the immediate setting of activity (policies, communities, institutions, etc.)

Discussion questions

1. What are the key aspects of teachers' expertise for interdisciplinary teaching at the macro (system, school), meso (curriculum, classroom) and micro personal (knowledge, skills, dispositions, agency) levels?
2. What kinds of environments and contexts are necessary for interdisciplinary teaching?

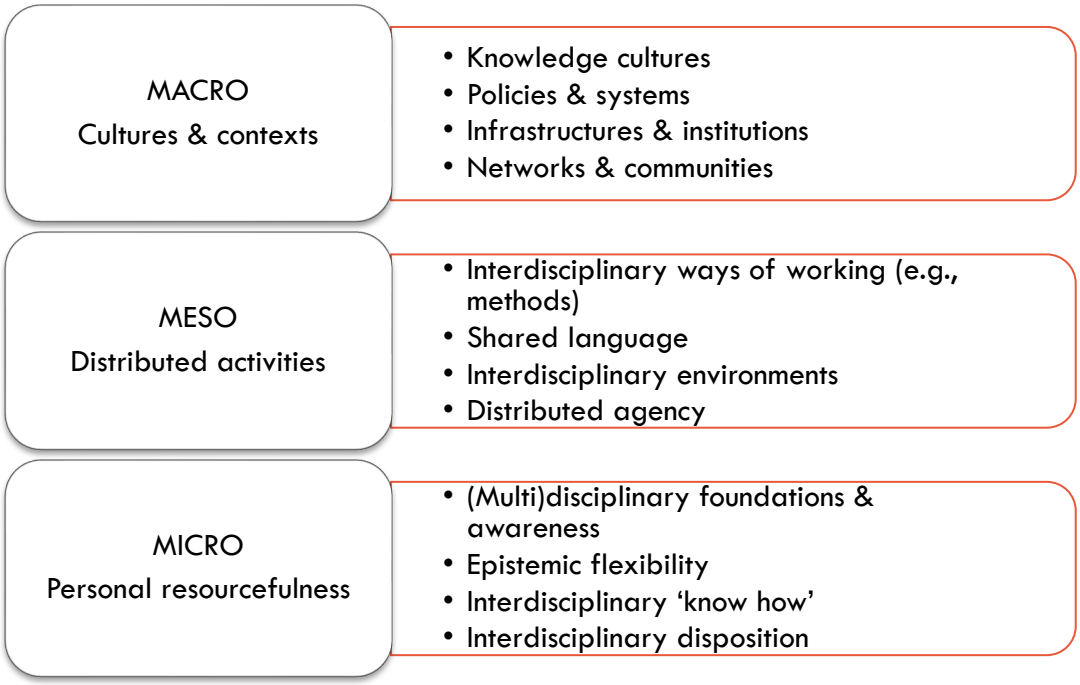

Figure 2: Layers of interdisciplinary expertise in research practices

Question 3: What are the key features of effective professional education for interdisciplinary teaching?

Literature shows that pre-service and in-service teachers' professional development for interdisciplinary teaching includes a range of models (Enderson et al., 2020; Evans, 2019; Grossman et al., 2001; Imara & Altinay, 2021; Jenlink & Jenlink, 2019; Krug & Shaw, 2016; Liu, 2020; Luft et al., 2020; Quan et al., 2019; Wojnowski & Pea, 2014).
Examples include:

- *Standalone interdisciplinary modules or courses* to develop teachers' interdisciplinary capabilities for integrative cross-curriculum teaching, such as the CrossCUT online course (Timmerman, 2019a), and many sustainability-oriented programs (Imara & Altinay, 2021).
- *Embedding interdisciplinary focus and connections within or across existing subjects*, for example, making connections to mathematics in science courses and connections to science in mathematics courses (Watanabe & Huntley, 1998).
- *Embedding interdisciplinary focus in professional learning community activities*, for example, joint discussions of history and English literature readings to create an interdisciplinary humanities curriculum (Grossman et al., 2001).
- *Project-based courses or modules*, where pre-service or in-service teachers learn through practical hands-on projects, such as co-creating integrated curricula and co-teaching (ACARA, 2016; Ryu, Mentzer, & Knobloch, 2019).
- *Short experiential interdisciplinary learning opportunities*, such as hackathons for planning interdisciplinary curriculum modules or expert-modelled integrated days (Harvey & Reid, 2001; Milara et al., 2020).
- *Professional learning alongside students' interdisciplinary project-based learning*, for example, when students' projects involve partnerships with experts from research organisations, museums or zoos.

- *Different combinations of the above and other models*, such as participatory action research with university partners (Hunter, 2020) or intensive professional development sessions combined with teaching and ongoing mentorship (Anderson & Tully, 2020).

Specific programs vastly differ in their duration, the number of participants, included disciplines, and other key characteristics, with some courses being two-hour individually completed online modules and others being learning communities that last have been lasting over two years. However, the rationales for choosing particular models and making specific design decisions are rarely made explicit in the literature. Therefore, it is not always clear why teacher educators and educational institutions make these design choices and how they align their chosen models with specific needs or contexts.

Many of the design principles used for designing interdisciplinary courses tend to be similar to those principles that are known to be effective for designing teacher professional development in general, such as 1) programs are content focused; 2) incorporate active learning; 3) support collaboration; 4) use models of effective practice; 5) provide coaching or expert support; 6) offer feedback and reflection; and 7) are of sustained duration (cf. Darling-Hammond, Hyler, & Gardner, 2017; Luft et al., 2020). Specific pedagogies vary, but as a rule, they relate to authentic, teacher-as-learner-centred participatory approaches (Box 2). The question of what is distinct to effective teacher education for interdisciplinary teaching and how to make productive design decisions remains important.

Pedagogical approaches in teacher education programs for interdisciplinary teaching

- *problem-based learning* focussed on themes important in a local context (e.g., air pollution);
- *project-based-learning* while engaging with a local community or external partners;
- *site visits*, field trips and other kinds of experiential learning;
- *learning through social action*, such as engagement with issues of justice in STEM, teacher-led hackathons and other activist approaches;
- *immersed professional learning* as a part of institution-wide transformations, such as the global EcoSchools program.

Box 2: Examples of common pedagogical approaches

Despite a huge variety of models and programs for professional teachers' learning related to interdisciplinary teaching, the literature reports very positive outcomes (Ellis & Williams, 2020). However, much evidence focuses on evaluations of specific professional education programs and often comes from participants' self-reported immediate feedback about their course experiences and outcomes. There is much less evidence about the transfer, sustainability and broader long-term impact (Luft et al., 2020).

Current reports describing designs of pre-service and in-service programs rarely engage with epistemological, theoretical, or pedagogical questions about the unique features of different interdisciplinary knowledge practices and how people learn to work across particular knowledge boundaries. For example, reports rarely make a clear distinction between horizontal integration across disciplines and vertical integration between theoretical knowledge and its application in solving practical, real-world challenges. They are also rarely explicit about the relationship between general capabilities and diverse disciplinary and interdisciplinary practices. Integration is often seen as the only possible mode for bringing disciplines together. It is far less common to engage teachers in explicit discourse and reflection on underpinning assumptions and different ways of doing interdisciplinarity. There is a concern that this translates into confusion and inadequate, mainly instrumental interdisciplinary teaching practices. For

example, a research literature review of STEAM practices observed that many educators struggle to understand how creativity is fostered and "While STEAM programs often incorporate problem-based approaches, the design-process, or hands-on experiences, they often overlook the key aspects of arts education which include critique, self-expression, and conveying meaning" (Perignat & Katz-Buonincontro, 2019, p. 41).

Insights from researching interdisciplinary learning in multidisciplinary laboratories

Findings from interdisciplinary research settings converge on three key aspects of productive practices and arrangements that facilitate interdisciplinary learning:

- *Characteristic epistemic activities* – sometimes called 'epistemic games'(Perkins, 1997) – that facilitate interdisciplinary knowledge work at different stages of the projects, such as techniques for exploration of problems from different perspectives, generation and integration of ideas, and transformation of conceptual solutions into actionable outcomes and tangible products (Markauskaite & Goodyear, 2017). For example, innovation teams use diverse characteristic design-thinking activities – from considering context to evaluating outcomes – when designing new services and products (Straker, Nusem, & Wrigley, 2021)
- *Shared infrastructures and objects* that mediate collaboration, knowledge sharing, advancement of ideas and production of joint outcomes. For example, much of interdisciplinary work is done by using shared conceptual, digital and material tools, assembling resources, and co-constructing characteristic knowledge objects (concept maps, models, prototypes, etc.) that help make ideas visible and give materiality and concreteness to joint knowledge work (Nersessian, 2019a; Nicolini, Mengis, & Swan, 2012).
- *Epistemic awareness and joint apprenticeship*, which includes team capabilities to help each other recognise and understand different perspectives, kinds of knowledge and ways of knowing as well as move across each other specialised 'languages' when engaging in joint knowledge work (Hubbs, O'Rourke, & Orzack, 2021; Nersessian, 2019b). For example, some research teams engage in philosophically structured dialogue-based activities designed to enhance mutual understanding of each other ways of thinking and communication in complex multi-disciplinary projects (Hubbs et al., 2021).

Discussion questions

1. What are examples of successful teachers' professional learning for interdisciplinary teaching from your practices?
2. What models have been embraced by your institution for preparing teachers for interdisciplinary teaching? Why?
3. What design principles or features have been most critical for the effectiveness of teachers' learning for interdisciplinary teaching? Why?

Question 4: What are the main barriers and enablers for developing expertise for interdisciplinary teaching in pre- and in-service teachers' education?

Educational research has primarily been focused on barriers to interdisciplinary teaching in schools, but there has been much less literature on barriers encountered in developing expertise for interdisciplinary teaching. Those discussed in the literature are mainly associated with three aspects: 1) broader environments, to include structural, organisational, and epistemic aspects; 2)

participants, to include constructs related to teachers, teacher educators and other collaborators and stakeholders; and 3) relational aspects, to include power and other entwinements and relationships among the above aspects (Figure 3). Most of the mentioned enablers are opposites to the barriers (e.g., no time vs. a dedicated time for interdisciplinary collaboration. That is, they are predominantly related to the absence of constraints. However, some enablers are related to additional facilitating factors or conditions (e.g., collaboration with academic mentors during professional development). The text below elaborates on each aspect. Table 1 presents examples of barriers reported in studies of STEM education in the Australian context.

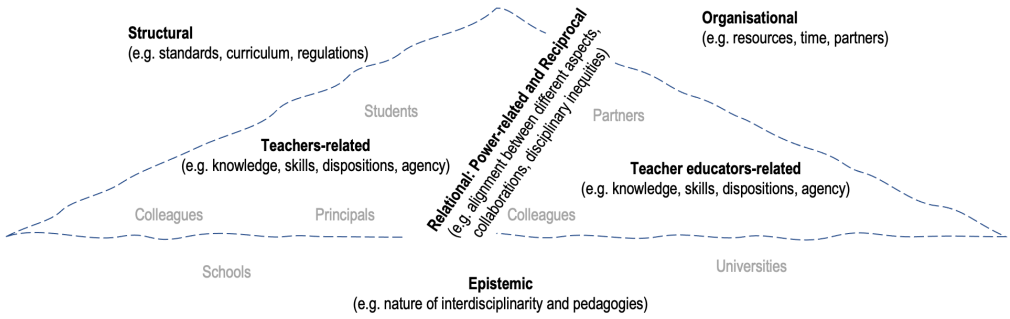

Figure 3: Barriers and enablers in developing expertise for interdisciplinary teaching

Environment-related barriers and enablers

Structural barriers are related to different regulations shaping teachers' preparation for interdisciplinary teaching and tensions emerging between them, such as the unclear role of interdisciplinary teaching and learning in professional teacher standards; teacher education programs overcrowded with disciplinary content (Enderson et al., 2020, p. 349). Persistence of policies promoting integrated teaching and learning, such as the National STEM school education strategy (Education Council, 2015), are seen as important enablers; however, misalignments between various regulations create unproductive tensions, such as tensions between policies promoting professional education for interdisciplinary education (e.g., STEM, general capabilities) and disciplinary focus in high-stake tests and examinations (Ellis & Williams, 2020).

Organisational barriers are related to practical arrangements embedding interdisciplinary aspects in pre- and in-service teacher education, such as the time needed for academics to develop high-quality courses for interdisciplinary teaching; practical constraints embedding interdisciplinarity into disciplinary pre-service teacher education structure; lack of funds or other resources; lack of time and space for interdisciplinary professional learning; challenges establishing sustainable partnerships and sustaining continuous professional learning (ACARA, 2016; Enderson et al., 2020; J.-A. Ferreira et al., 2019; Tytler, Williams, Hobbs, & Anderson, 2019). Typical organisational enablers are related to a dedicated time for teachers and teacher educators to learn, collaborate and plan interdisciplinary curricula (ACARA, 2016; Harvey & Reid, 2001; Timmerman, 2018).

Epistemic barriers are related to the nature of interdisciplinary knowledge practices and pedagogies for developing students' capabilities to work across disciplines, such as: the distinct nature of knowledge, knowledge practices and language in each discipline, and the distinct role of each discipline in integrative knowledge practices (Couso & Simarro, 2020; Liu, 2020); a range of different purposes of integrative teaching (Wojnowski & Pea, 2014), lack of clarity about integrative pedagogies (Perignat & Katz-Buonincontro, 2019) and how each discipline should be taught in integrative curricula (Enderson et al., 2020). For example, in STEM education, "the "T" and the "E" are often misunderstood" (Enderson et al., 2020, p. 350). In contrast,

epistemic clarity about the purposes of interdisciplinary teaching and deep teacher engagement with epistemological and pedagogical questions are conditions supporting teachers' interdisciplinary learning (Grossman et al., 2001; Harvey & Reid, 2001).

Participant-related barriers and enablers

Participant-related barriers and enablers are associated with the resourcefulness of people involved in interdisciplinary teaching and learning, including their knowledge, skills, dispositions and other experiences that they bring to the interdisciplinary education settings. Teachers and teacher educators are at the heart of this, with a number of other participants and stakeholders being important contributors to how teachers engage in interdisciplinary professional learning and teaching.

Teacher (as a learner)-related barriers concern teacher knowledge, skills and dispositions (beliefs, motivation, agency) necessary to engage in learning for interdisciplinary teaching: lack of interest or willingness on the part of teachers to engage in interdisciplinary learning (Timmerman, 2018); teachers are feeling sceptical, insecure and reluctant to engage in interdisciplinary education (Ellis & Williams, 2020); lack of teacher confidence in their abilities; lack of awareness and understanding curriculum requirements of other subjects (Timmerman, 2018), lack of subject knowledge (Hunter, 2020). Reported enablers are mainly associated with similar aspects, such as appreciation of the importance of interdisciplinary teaching, understanding and insight into other subjects/disciplines, open-mindedness and willingness to collaborate and learn about other disciplines (Harvey & Reid, 2001; Timmerman, 2018). One of the distinct enablers is pre-and in-service teachers' personal resourcefulness developed through personal daily lives, such as "experiences as a student, personal interests, and their disciplinary identities" that provide a foundation for interdisciplinary teacher learning (Ryu et al., 2019, p. 502).

Teacher educator-related barriers concern teacher educators' knowledge, skills and dispositions to prepare teachers for interdisciplinary teaching: teacher educators' knowledge and confidence in making connections to the disciplines beyond their core expertise; seeing interdisciplinary connections as adds-on to the discipline-focussed teacher education (Watanabe & Huntley, 1998); philosophical differences about interdisciplinarity between teacher educators and their scepticism about the value of interdisciplinary teacher education (Harvey & Reid, 2001); lack of training and expertise of interdisciplinarity and interdisciplinary pedagogies when developing teacher education programs (Enderson et al., 2020), Enablers often relate to teacher educators' positive disposition towards interdisciplinary education and resilience in the presence of various barriers (Harvey & Reid, 2001).

Stakeholder- and other contributor-related barriers and enablers related to other participants, such as school and university leaders, external partners, and students, who contribute in their roles to interdisciplinary teaching and learning activities. For example, the lack of school leadership, school students and even parents' support of interdisciplinary learning is a barrier to teachers' professional learning in this area (Hobbs, Doig, & Plant, 2019). Further, differently from subject-focussed professional education, interdisciplinary teacher education usually involves collaborations and partnerships between tertiary institutions, schools and external partners from industry, community or research organisations. For example, the presence of tertiary mentors in school-based professional development programs is an enabler. Simultaneously, the literature points out obstacles and tensions. For example, "disciplinary egocentrism", which is described as a lack of students' readiness to engage in multidisciplinary education, as MacDonald, Hunter, Wise, and Fraser (2019) argue, "can also be applied to a wide range of key education stakeholders, such as teachers, academics and indeed STEAM industry experts who are unable or unwilling to value alternative approaches to their respective discipline areas (Yoder, Bodary & Johnson, 2016)." (p. 76).

Barriers	Examples from the Australian STEM context
Environment-related	
Structural	The National STEM Education Strategy promotes teachers' professional development in STEM, but STEM is absent from the Australian National Curriculum in terms of a recognised learning area or a cross-curricular priority; there is no explicit emphasis on interdisciplinary teaching in the Australian professional standards for teachers (Ellis & Williams, 2020).
Organisational	ACARA's STEM Connections report observes that interdisciplinary projects "can have significant implementation issues, regardless of the implementation model, in traditional school settings, as timetabling structures do not necessarily have the flexibility to accommodate such projects" and such process "can result in inconsistent content coverage" (ACARA, 2016, p. 19).
Epistemic	A STEM project reports "tensions arising between: criterion based assessment versus descriptive assessment; a focus on disciplinary content versus STEM practices or inquiry processes; and a focus on reporting versus a focus on student engagement." (Hobbs et al., 2019, p. 224)
Participant-related	
Teacher-related	Not all teachers are equally enthusiastic about STEM: "Educators working within technology education have indicated that they feel threatened by STEM education"; and some teachers in Australian schools "feeling threatened by the inequity of STEM, or as an alternative to replace disciplinary subjects" (Ellis & Williams, 2020, p. 430).
Teacher educator-related	Academics do not always have a disposition (willingness or ability) to value alternative disciplinary perspectives and world views (MacDonald et al., 2019).
Participant and stakeholder-related	Challenges "convincing school leadership, other teachers, students and even parents of the value of rethinking the curriculum to include STEM learning opportunities" (Hobbs et al., 2019, p. 225).
Relational	
Power-related	Commonly observed power-related barriers in Australian STEM include: general inequity among disciplines in the Australian Government's STEM documents (Barlow & Ellis, 2016); more central role of science in an integrated approach to STEM education and lack of clarity about the role of technologies (Ellis & Williams, 2020); and significant "gender gap" (Ellis & Williams, 2020)
Reciprocal	Challenges "associated with school-industry collaborations when attempting to make links between school content and the world of work"; "teachers and industry representatives often do not share a common language, and the language of industry may not be understandable for students" (Hobbs et al., 2019, p. 225).

Table 1: Examples of barriers discussed in the context of STEM education in Australia

Relational barriers and enablers

Various barriers and enablers often are interrelated and rarely encountered in isolation; and many tensions emerge at the intersections of personal learning for interdisciplinary teaching and environment-related aspects. For example, a study on teacher sustainability education points out, "Research indicates individual teacher educators are motivated to change and have the ability to incorporate EfS [Education for Sustainability] (Steele, 2010). The greatest constraint is providing overall systemic support for such changes to happen." (Ferreira et al., 2019, p. 56).

Most barriers and enablers are related either to more hierarchical power relations or to more horizontal and reciprocal entwinements and relationships among various aspects.

Power-related barriers concern broader cultural stereotypes, political decisions and agendas that influence the distribution of social and epistemic power, create inequities, and result in negative responses and tensions, such as disciplines (subjects) are not positioned as equally important (English, 2016; Liu, 2020); not all subjects are included or have equal roles in the interdisciplinary curriculum; interdisciplinary education is seen as competing with disciplinary teaching (Ellis & Williams, 2020); vocational skills and general capabilities are considered as less important than academic subjects (Masters, 2020) (see Box 3). Explicit arrangements that promote epistemic and social equity, such as inclusivity of all disciplines and non-academic perspectives, as well as transformational pedagogies that expose and engage teachers with the issues of gender, cultural and racial diversity, are seen as enablers helping develop awareness and greater inclusivity in interdisciplinary teaching (Quan et al., 2019).

Skills in applying knowledge

"In the current school curriculum, the acquisition of skills is often treated differently from the acquisition of knowledge, and given a lower priority. This is particularly true in the later years of school where subjects are divided into academic subjects focused primarily on providing a knowledge base for further learning of a subject, and vocational subjects focused primarily on providing skills for particular occupations. But it is also reflected in approaches to general capabilities, which are often treated as conceptually different from, and *less important than*, disciplinary knowledge."

Box 3: Examples of power-related barriers from the NSW curriculum review (Masters, 2020, p. 87)

Reciprocal barriers and enablers are related to alignments within and across the contextual and human-related aspects, joint learning and systemic change: collaborating and learning in multi-disciplinary teaching teams; overcoming challenges of 'siloed' school and university structures; understanding each other languages; creating collaborations and partnerships with external partners; collaborating with colleagues involved in similar interdisciplinary teaching practices in other institutions, involving other colleagues, designing curriculum that can be enacted within the existing conditions, learning and change for interdisciplinary teaching across all levels of the system (ACARA, 2016; Mohamad Hasim, Rosli, Halim, Capraro, & Capraro, 2022; Tytler et al., 2019).

Critical tensions

Different aspects are interrelated, and enabling conditions are rarely a simple sum of its parts. Two overarching tensions emerge from synthesis.

The tension between curriculum/logistical and epistemic/relational aspects in teacher education programs. Pre-service and in-service teacher education programs for developing teacher interdisciplinary expertise for interdisciplinary learning often are project-based and focus on pedagogical and logistical aspects of interdisciplinary curriculum development and implementation (e.g., by organising teachers' learning through collaborative lesson planning and implementation projects) (Luft et al., 2020). In contrast, the literature suggests that some critical barriers and enablers are related to epistemic and relational aspects, such as teachers' philosophical dispositions towards interdisciplinary education (Harvey & Reid, 2001), the need for teachers' deeper understanding of disciplines and interdisciplinarity (Ryu et al., 2019), understanding external partners' language (Hobbs et al., 2019).

The tension between the focus on institutional mainstreaming vs. teacher flexibility. The scalability, adaptability to change and sustainability of interdisciplinary teaching practices are often seen as critical aspects for the broader adoption of interdisciplinary education; and success is often attributed to the overall system's capability to achieve institutional mainstreaming (J. A. Ferreira, Ryan, & Tilbury, 2007). Beyond some research on the transfer of learning from professional education programs to classroom practices (Luft et al., 2020), there is far less discussion about how to develop teachers' flexibility to engage in interdisciplinary teaching practices across diverse (social, material and epistemic) settings and changing contexts.

Discussion questions

1. What are the main barriers and enablers for developing pre- and in-service teachers' expertise for interdisciplinary teaching in the NSW context?
2. How could pre- and in-service teacher education prepare teachers to address larger structural, organisational and epistemic barriers?
3. How could teacher education develop teachers' flexibility and adaptability to engage in interdisciplinary teaching in diverse and changing contexts?

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