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RESEARCH ARTICLE

How to Support Teacher Learning of Integrated STEM Curriculum Design

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Abstract

As science, technology, engineering, mathematics (STEM) education continues to be a focus in many schools internationally, STEM teacher learning programs have arisen to support teachers with this integrated approach. Common to STEM teacher programs is teachers creating integrated STEM curriculum; however, missing from this research is how teachers develop the knowledge and skills needed to undertake this curriculum design. Consequently, for those designing STEM teacher programs, the literature provides limited understanding of how to support teachers' learning of integrated curriculum design. This qualitative study investigated STEM teacher programs at ten Australian universities to identify the learning experiences that are perceived to be most valuable by teachers and teacher educators when learning how to design STEM education curriculum. Analysis of curriculum documents and the experiences of 23 individuals involved in STEM teacher programs (i.e., teacher educators, teachers) highlighted that a range of learning experiences is valuable for supporting teachers to develop the necessary knowledge and skills for STEM education curriculum design. Due to their breadth of learning potential, activities like STEM teaching resource analysis, and immersion in STEM education have a particularly important role to play in supporting teacher learning of the content, integration, and teaching required for STEM curriculum design.

Keywords STEM education · STEM teacher education · STEM education professional learning · Integrated curriculum design · STEM curriculum development

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Introduction

Background

Integrated STEM education is popular worldwide due to its potential to increase student interest in STEM subjects, courses, and careers (The Australian Industry Group, 2013; National Academy of Engineering and National Research Council [NAE & NRC], 2014) and develop important workforce skills (e.g., collaboration, communication, critical and creative thinking) (West, 2012). It involves integrating knowledge and skills from multiple subjects using real-life topics and social constructivist pedagogies (Kelley & Knowles, 2016; Moore et al., 2014). The integrated nature of STEM education requires teachers to design, blend, and implement curriculum across multiple disciplines. However, teachers often lack preparation and experience in teaching multiple disciplines. To address this, various programs have emerged such as in-service teacher professional development, initial teacher education subjects, and smaller one-off programs.

As STEM teacher programs have emerged, research has sought to understand their impact on teachers. Limited empirical research exists on teacher learning of STEM education (Li et al., 2022), but those that do describe program curricula, emphasising the common task of designing STEM curriculum (McFadden & Roehrig, 2017; Roehrig, et al., 2012). Despite varying conceptualisations of STEM education, designing an integrated STEM curriculum requires a unique understanding, encompassing knowledge across STEM disciplines, integration methods, student-centred pedagogies, and twenty-first century skills (Kelley & Knowles, 2016; Roehrig et al., 2021). However, the literature offers limited insight into what teachers need for success in this endeavour and the activities that support this learning. This research identifies valuable activities and their role in enhancing teachers' competence in STEM curriculum design, offering guidance for STEM teacher educators in program design.

Literature Review

What do Teachers Need to Know and Be Able to Do to Design STEM Education Curriculum?

Despite debates on the nature of STEM education, common features have emerged. STEM approaches often incorporate pedagogies like inquiry-, problem-, or project-based learning and the engineering design process (Kelley & Knowles, 2016). These pedagogies, rooted in social constructivism (Chin & Chia, 2004), emphasise social engagement and real- life contexts to integrate multiple subject areas. While the efficacy of constructivist pedagogies is debated (Hattie, 2009; Leggett & Harrington, 2021; Yunita et al., 2020), student-centred approaches persist in STEM education due to their value for social interaction for learning (Sanders, 2009).

Constructivist pedagogies in STEM education often incorporate real-life topics to increase student interest in STEM subjects. These topics, such as sustainability issues or epidemiological studies of disease, involve overarching ideas that engage students in relevant and authentic learning (Kelley & Knowles, 2016; Sanders, 2009). This context-based approach supports student engagement (Bennett et al., 2007) and aims to promote interest and participation in STEM opportunities.

Implementing STEM education requires teacher to possess knowledge of multiple disciplines and understand how to blend this knowledge (Johnson & Czerniak, 2023). Integration of disciplinary knowledge can be achieved through various methods. One approach involves using real-life topics that bring together multiple disciplines, as just discussed. Another approach is problem solving where scientific and mathematical knowledge are combined to design solutions or create products (Reynante et al., 2020). For instance, addressing the issue of limited recycling in a school would require scientific knowledge to explore environmental concerns, mathematics to collect and present data on the problem and potential solutions, and engineering/technology knowledge to design innovative solutions or products.

How do Teachers Learn About Curriculum Design?

Designing curriculum involves making decisions about what knowledge areas, pedagogies, and learning activities to include when, how, and why in a learning sequence. In ITE, preservice teachers learn about different curriculum design approaches, such as the 5E instructional model (Bybee et al., 2006). This model offers steps (e.g., engage, explore, explain, elaborate, evaluate) to guide the development of learning experiences. However, general instructional models lack guidance for developing the integrated curriculum required in STEM education; they do not address the specific challenges of blending multiple disciplines in STEM curriculum.

Limited research provides insight into how programs support teachers' learning of integrated curriculum design. Strategies for developing teachers' knowledge in this area include the following:

- Working in heterogenous curriculum design teams (Brown et al., 2018; Chang et al., 2015) with Karppinen et al. (2019) noting the value of bringing together individuals with diverse expertise for developing knowledge
- Selecting appropriate issues and constructing essential questions guide preservice teachers in integrated curriculum planning (Grant & Paige, 2007)
- Analysing existing interdisciplinary units helps develop knowledge of real-life topics (Moser et al., 2019)
- Using frameworks like the design process and collaborative action research aids in organising interdisciplinary teaching and learning (Brown et al., 2018; Karppinen et al., 2019)

This research highlights the importance of various experiences in supporting teachers' learning of integrated curriculum design, as different activities develop different knowledge and skills.

In the context of STEM teacher programs, the range of supporting activities has received limited research attention. Program descriptions highlight opportunities to develop disciplinary subject matter (Hurley et al., 2024), pedagogies like inquiry- and problem-based learning (Brand, 2020; Du et al., 2019), and interdisciplinarity (Guzey et al., 2016; Wang et al., 2011). Some programs also emphasise the value of STEM learning placements in industry (Hurley et al., 2024), immersion in Makerspaces (Gravel & Puckett, 2023), and STEM microteaching (Menon et al., 2024). Margot and Kettler (2019) in their review of teachers' perceptions of STEM integration and education suggest that PD needs to include the following:

- Time and structure for teachers to explore STEM integration and blending with their curriculum
- Teams of teachers
- Opportunities for teachers to experience STEM concepts and pedagogy

However, literature offers little discussion of the specific learning activities useful for developing teachers' knowledge and skills in STEM curriculum design and which activities are considered valuable by teacher educators and program participants. This study investigates the research question—what activities support teachers' learning of STEM curriculum design and how?—from the perspectives of teacher educators and teachers participating in STEM teacher learning programs.

Methods

Study Design and Context

This qualitative study aimed to understand STEM teacher learning programs in Australia, which has diverse approaches to STEM education and teacher learning. While integrated approaches are mentioned in the Australian Curriculum as cross-disciplinary threads (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2024, they are not included in subject content descriptions. As a result, there is limited curriculum guidance for teachers, leading to varied implementation of STEM education. Furthermore, there is variation in STEM teacher programs. Teacher learning programs include initial teacher education (ITE) and ongoing professional development (PD) for in-service teachers. In Australia, PD can be organised by various providers such as universities, independent providers, and departments of education, while universities run ITE. This study focused on STEM teacher programs offered by universities, which cater to either preservice or in-service teachers in primary and secondary education. A phenomenological approach is used to explore individuals' experiences and perceptions (Edmonds & Kennedy, 2017) to identify and understand the learning activities in STEM teacher programs.

Participants, Their Selection, and Recruitment

This interpretive study acknowledges multiple perspectives (Merriam & Tisdell, 2015) and aims to understand the subjective experiences of participants (Creswell & Creswell, 2018) involved in STEM teacher programs. Participants ($N=23$) were purposefully selected for their experience with STEM teacher programs as teacher educators or program participants. Following ethics approval (ID: 1953719.1), relevant programs were identified through university handbooks and websites, resulting in 21 programs from ten universities (Table 1). The universities varied in type and focus, including Group of Eight, Australian Technology Network, and New Generation universities. The programs differed in length, weekly contact hours, and target audience (preservice or in-service, primary and/or secondary educators). Participants were recruited through various methods, joined voluntarily, and their confidentiality and privacy ensured with pseudonyms and secure data storage.

The phenomenological approach in this study aimed to gather rich, in-depth data from a small sample of participants. Braun and Clarke (2013) propose that a moderate sample size is necessary to comprehend individuals' experiences, encompassing a diverse range of perspectives while still preserving the uniqueness of everyone. In this study, 23 participants (13 teacher educators, three in-service teachers, seven preservice teachers) shared their lived experiences of STEM teacher programs. This sample size reached saturation, where new data did not provide further information. The ten teachers experienced STEM learning at a single institute (university 3) at different times from 2019 to 2021, taught in various metropolitan schools and had different experiences as preservice or in-service teachers. The intentional inclusion of diverse participants and programs allowed for the identification and explanation of varied learning activities in STEM teacher programs, as well as exploration of similarities and differences in curricula and contexts.

Data Collection and Analysis

Data for this study on STEM teacher programs was collected from university handbooks and participant interviews conducted between 2020 and 2021. Despite their limited content, publicly available university handbooks—documents which provide subject/course information such as entry and participation requirements, assessment, intended learning outcomes, fee information—provided subject/ course information, helping to identify learning activities teachers experienced. Participant interviews, conducted in-person or via Zoom, ranged from 60 to 90 minutes in length, averaging 73 minutes, and offered a deeper understanding of STEM teacher learning activities. Written consent for participation and audio recording was obtained and the interviews explored broad curriculum themes such as aims, content, skills, delivery, duration, learning activities, and assessment. Appendices 1 and 2 contain the interview questions. The first author conducted interviews and then all authors worked with the handbook and interview data to develop themes and identify the activities involved in teachers' learning about STEM curriculum design.

Table 1 Universities and STEM teacher learning programs involved in this study

Identifier for universities involved in the study	STEM teacher education programs on offer	Data collected and number of participants from each university		
		Teacher educators	Teachers undertaking STEM teacher education	Handbook documents (publicly available)
UNI 1	1. Graduate certificate for in-service educators; 1-year part-time 2. Single subject for primary preservice teachers in the Bachelor of Education program (15 contact hours)	3 (2 female, 1 male)	0	2
UNI 2	1. Graduate certificate for in-service educators; 1 year part time 2. Individual seminars and workshops introduced to secondary science preservice teachers	3 (2 female, 1 male)	0	5
UNI 3	1. One subject in the Master of Education (science and mathematics specialisation) for in-service educators (24 contact hours) 2. An elective subject in Master of Teaching (primary) for preservice teachers (24 contact hours) 3. An elective subject in Master of Teaching (secondary) for preservice teachers (24 contact hours)	3 (1 female, 2 male)	10 (3 ISTs + 7 PSTs) (9 female, 1 male)	3
UNI 4	1. A subject in Bachelor of Education (primary; STEAM specialisation) (36 contact hours)	4 (2 female, 2 male)	0	1
UNI 5	1. Graduate certificate for secondary in-service teachers; 1-year part-time 2. Master of Education (STEM specialisation) for in-service teachers; 1–1.5-year full-time 3. Master of Teaching (STEM specialisation) for secondary preservice teachers; 2 year full-time	0	0	3
UNI 6	1. Graduate Certificate of Education (specialisation STEM education) for in-service teachers; 1-year part-time 2. Graduate Diploma of Education (specialisation STEM education) for in-service educators; 1-year full-time 3. Master of Education (specialisation STEM education) for in-service educators; 1.5-year full-time	0	0	3
UNI 7	1. Master of Teaching (STEM specialisation) for in-service educators; 1.5 years	0	0	1

Table 1 (continued)

Identifier for universities involved in the study	STEM teacher education programs on offer	Data collected and number of participants from each university		
		Teacher educators	Teachers undertaking STEM teacher education	Handbook documents (publicly available)
UNI 8	1. Graduate certificate for in-service educators; 1-year part-time 2. Master of Education (STEM specialisation) for in-service educators; 1–1.5-year full-time	0	0	2
UNI 9	1. A subject for primary preservice teachers (36 contact hours) 2. An elective subject for early childhood, primary, and secondary preservice teachers (36 contact hours)	0	0	2
UNI 10	1. Bachelor of Education program has three different STEM-based elective subjects for preservice teachers (each 24 contact hours) 2. Master of Education (STEM specialisation); 1-year full-time	0	0	3
Total		13	10	25

UNI university, *PST* preservice teacher, *IST* in-service teacher

Using an inductive approach, data analysis focused on understanding participant experiences in STEM teacher programs rather than generalising to a larger population. Each data set (handbooks, interviews) were analysed separately and compared. Miles et al. (2014) two-cycle approach was used to code the data, assigning small descriptions (codes) to relevant segments and condensing them into categories. Categories were identified by finding commonalities between codes, as shown in Table 2. The identified categories represented the activities teachers engage in to develop their understanding of STEM curriculum design and became the key themes discussed in the findings section. Table 3 illustrates examples of each theme's development from coding to categorising. The analysis identified five categories (activities) supporting teacher's learning of STEM curriculum design: (1) analysing teaching resources; (2) immersion in STEM education; (3) exploring state-based curricula; (4) visiting museums, galleries, and STEM workplaces; and (5) collaborating in curriculum design.

Trustworthiness

We took several steps during data analysis to ensure trustworthiness. We achieved triangulation, by using multiple data sources including interviews and university handbooks (Merriam & Tisdell, 2015). We reread interview transcripts to review, revise, and validate the codes and categories developed, ensuring they accurately reflected the collected data (Miles et al., 2014). Investigator and data triangulation supported coding credibility, with authors independently coding data segments and negotiating interpretations until agreement was reached. Additionally, respondent validation during interviews verified the interpretation of participant experiences.

Researchers' Reflexivity

In qualitative research, the researcher plays an active role in data collection and their biases, values, and beliefs can influence analysis. To address this, we acknowledge that our backgrounds as faculty members with interest in STEM teacher programs may have influenced our perspectives. We used various frameworks for analysis, clearly documented methodological steps and decisions to minimise the impact of our values and bias. We also conducted member checks with participants, ensuring their input in the analysis process, and employed triangulation to support ongoing reflection on data interpretation.

Findings

This study aimed to investigate the learning activities that contribute to teachers' knowledge of STEM curriculum design. Multiple data sets (handbook documents, interviews) were analysed to identify and compare activities to understand their role in teacher learning. The handbook data identified learning activities in STEM teacher programs while interview data offered deeper insights into their value for

Table 2 Example of coding and categorising for the theme 'analysing STEM education teaching resources'

Data examples	Code/s from first cycle coding	Second cycle categorising	Overall theme
Analyse an integrated unit for science education, applying the principles behind curriculum design, integration, and evaluation. (Handbook_UNI 3)	- Analyse an integrated science unit - Apply and evaluate curriculum design and integration principles	Analysing STEM education teaching resources	Analysing STEM education teaching resources - Multiple and varied examples
There was one thing that really stuck in my mind; it was one of the lessons that [our teacher educators] *showed us as an example of how STEM was done, like a STEM curriculum and I still have those resource packs and Mission to Mars was one of them; sustainability was the other one of them.* (Preservice Teacher 1)	- Preservice teachers exploring examples of STEM curriculum - Teacher educators providing STEM teaching examples	Exploring examples of STEM curriculum	
We do a lot of looking at different kinds of units of work that specifically integrates maths and science or coding and science or arts and science… we found a couple of units that were combinations of say science and history. (Teacher Educator 5)	Preservice teachers: - Exploring a variety of STEM teaching resources	Exploring varied STEM teaching resources	
[*We] read through different already written integrated units and picking apart what's working, what might we want to improve on, it was a really good part of it. Focusing on the way different disciplines—both within different streams of science and across the STEM acronym—feed into and rely on one another.* (Preservice Teacher 2)	Preservice teachers: - Reading integrated units - Analysing STEM units - Determining disciplinary integration in the units—analysis	Analysing STEM teaching resources	
They [preservice teachers] *delivered different parts of that* [STEM education curriculum examples] *including a presentation back to the entire cohort at the end. And it became a bit of a PD for everyone, so everyone would hear what everyone else did. … I think it was really quite powerful too; it's really great PD at the end for them* [teachers]. (TE 11)	Preservice teachers: - Delivered STEM education curriculum - Explored peer STEM curricula	Exploring STEM curricula	
Providing a rich variety of examples [STEM education lesson plans and units] *and letting them* [in-service teachers] *explore those examples.* (TE 6)	In-service teachers: - Offered and explored a variety of STEM teaching resources	Exploring varied STEM teaching resources	
Giving them lots of examples [of STEAM education] *about how different educators do that kind of work …* (TE 7)	In- service teachers: - Provided with multiple and varied STEM education examples	Provision of a range of STEM teaching examples	
One thing I should say is when they [in-service teachers] *do that multimedia presentation* [of STEM education curriculum], *they then do a peer review of someone else's work because there's … they need to see each other's to get different perspectives on what's going on.* (TE 10)	In-service teachers: - Present STEM education curriculum to peers - Analyse peer STEM education curricula	Analysing varied STEM curricula	
We got a really wide range of them [STEM education curricula]. *So, there was a lot of STEM-based ones like science and maths or technology and maths and design engineering. They also brought in a few humanities–science ones and those were the ones that kind of really excited me.* (PST 2)	Preservice teachers: - Gained a range of STEM teaching resources - STEM teaching resources were varied in terms of disciplinary content and integration	Provision of varied STEM curricula	
It was good to actually see what other groups did because there was a sportsy group and it was interesting to see how they designed it [STEM education unit] *around their interest which was sports.* (PST 1)	Preservice teachers: - Observed peer STEM education units - Presented STEM education units to peers	Explored STEM teaching resources	

Table 3 Example of coding and categorising for the activities supporting teachers' learning of STEM curriculum design

Data example	Code/s	Category/theme
This practical experience [undertaking a STEM education problem as a school student*] provides students* [in-service teachers*] with an opportunity to engage as a learner to explore how, as educators, they may provide similar opportunities for authentic STEM learning experiences for others.* (Handbook_UNI 2)	- Experiencing STEM education as a school student would	Immersion in STEM education
Providing them [preservice teachers*] copies of the Victorian curriculum and saying look for these [*real-life*] topics and how would you say that they* [each discipline] *line up or don't* [within the topic]. (Teacher Educator 5)	- Investigating state-based curriculum - Finding curriculum connections for a real-life topic	Exploring STEM education possibilities in state-based curricula
[For] *their second assignment they [*in-service teachers*] go into a STEM-based workplace … so what is great about that is it gives them that connection for a possible excursion with the workplace; it gives them a possible speaker to come to their school that they've then connected with.* (Teacher Educator 1)	- Visiting a STEM-based workplace - Interviewing STEM employees - Building connections with individuals to introduce into a STEM curriculum	Experiencing museums, galleries, and STEM workplaces
*For the assessment task [*designing a STEM curriculum*], I had* [in my group] *the English–psychology student and then another physics–maths person… and so the way I was approaching it was very prescriptive which is kind of how you do things in maths, whereas coming from a psychology–English background, she just put everything down and then we can sort it- that ended up working a lot better for the way that we were brainstorming.* (Preservice Teacher 2)	- Mixed disciplinary teachers collaborate when designing STEM curriculum	Collaborating in STEM curriculum design

teacher learning. Although the data were analysed separately for different participants (teacher educators; preservice/in-service teachers; male/female), no significant differences were found between them. Instead, variations were observed between individuals, such as preservice teachers. The analysis of handbook documents and interview transcripts identified five key activities that support teachers' learning about STEM curriculum design. Interview questions which contributed to thematic development included questions 3–5 for teacher educators and questions 4–6 for teachers (see Appendices 1 and 2). Each activity is illustrated in this section, including a discussion of how they facilitate teacher learning.

Analysing STEM Education Teaching Resources

One of the five activities seen as valuable by STEM teacher educators and teachers for learning about integrated curriculum design was the exploration of STEM education teaching resources. Through the interviews, participants provided insight into the types of STEM teaching resources offered to teachers. For example:

> *We do a lot of looking at different kinds of units of work that specifically integrates maths and science or coding and science or arts and science and some of that has the other bits of the S-T-E-M or other outside areas in there … we found a couple of units that were combinations of say science and history. (Teacher Educator 5)*
>
> *There was one thing that really stuck in my mind; it was one of the lessons that [our teacher educators] showed us as an example of how STEM was done, like a STEM curriculum or a STEAM outline, and we had this resource pack and I still have those resource packs and Mission to Mars was one of them; sustainability was the other one of them. (Preservice Teacher 1)*

Highlighted here is that exposure to existing STEM curriculum provided models of integration, including unit plans that combine disciplines and real-life examples. Teachers (both preservice and in-service) found exploring STEM teaching resources valuable for gaining information, such as developing knowledge of 'how STEM was done' (Preservice Teacher 1) with resources demonstrating examples of integrated disciplines and connections. This knowledge assists teachers in constructing an integrated structure for their STEM curriculum design.

Of further note in this learning activity, is the provision of many and varied STEM education curriculum examples for exploration. In their earlier quote, Teacher Educator 5 spoke of 'a lot of looking at different kinds of units of work', while for Teacher Educator 6 'providing a rich variety of examples' was an important inclusion in their STEM teacher program, to help facilitate teachers' understanding of STEM education by 'demonstrating to them or providing them with opportunities to see the integrated possibilities' (Teacher Educator 6).

Yet, learning activities need to move beyond the provision of STEM teaching resources. Brand has previously noted that critical analysis of STEM education activities is valuable for teachers' 'understanding and application of the content'

(2020, p. 5) in STEM curriculum design, and the research presented in this study provides more insight into the nature of the analysis process. For example,

> *[We] read through different already written integrated units and picking apart what's working, what might we want to improve on if we were to run it, was a really good part of it. I think like sort of bringing it back to the what's the point? We are talking about all these high ideas about integration and why it's important but like in the classroom what does it look like? Focusing on the way different disciplines—both within different streams of science and across the STEM acronym—feed into and rely on one another. (Preservice Teacher 2)*

For this preservice teacher, analysis involved identifying integration in the STEM teaching resources and evaluating how disciplines are blended or 'feed into and rely on one another' (Preservice Teacher 2). While participants did not discuss the criteria for determining strengths, weaknesses, or quality of disciplinary integration, analysing STEM teaching resources provided teachers with insights into what constitutes an integrated resource.

Immersion in STEM Education

Teachers in STEM teacher programs commonly engaged in STEM education experiences like those of school students. At times, these immersion experiences occurred at non-school education centres (e.g., government funded centres offering STEM-based experiences for school students):

> *We went to [a science education centre] and that was good. We were looking at [a STEM education experience]; it was diseases and there was some mathematics involved in that and I thought that that was a really, really cool unit just because, if you think about biology, not many people will sort of link it to mathematics but in actual fact there is … and for someone with my very limited biology background, the fact that I was able to enter it and understand the gist of it, that was really powerful, I really, really enjoyed that one too … so first we experienced it [the STEM education activity] as a student, and then we discussed it—so if you were a teacher, how would you go about doing this? (Preservice Teacher 1)*
>
> *We take them [teachers] to [a science education centre] … they have an experience of a version of STEM education that they could consider as, from a teacher's perspective, reflecting on it from a teacher's perspective—what does this mean? How could I do this? So, it gives them the opportunity to learn, as a student, about integrating subjects and it's nice to give them that experience from a student learning perspective. (Teacher Educator 6)*

Some non-school education centres are community settings that school students can attend to participate in STEM-based learning experiences. In these quotes, excursions to science education centres provided teachers with first-hand experiences of STEM education as learners, allowing them to observe and engage with examples of STEM education. Preservice Teacher 1 found this experience to be 'really powerful', as it offered opportunities to develop knowledge of disciplinary integration and real-life topics: key features of STEM curriculum design (Roehrig et al., 2021). Teacher Educator 6 highlights that these teacher-as-learner experiences also facilitate reflection, enabling teachers to analyse the modelled curriculum, conceptualising its interdisciplinary nature for future teaching. Interestingly, both teacher educators and teachers spoke of these immersion activities, the alignment of which indicates its importance.

Not all STEM education immersion activities occurred at non-school education centres; some participants spoke of experiences they valued during their university classes. For example, Preservice Teacher 7 spoke of undertaking a puppet design challenge:

> *Another useful activity that I found rewarding was that there was a sort of STEM task, that we were asked to have a look at and try and do it ourselves, is creating a puppet … So, the task was to create a puppet that had some sort of lever mechanism. And yeah, so I just found things around my house to stick together and that was a fun experience and a good way to sort of ask why—what a multifaceted multidisciplinary lesson would look like? (Preservice Teacher 7)*

As this quote highlights, working through STEM education activities as learners helps teachers to experience the constructivist pedagogies associated with this teaching approach, such as the engineering design process, as well as to consider 'what a multifaceted multidisciplinary lesson would look like' (Preservice Teacher 7). Another teacher elaborated on this puppet design challenge activity, highlighting the role that peer sharing played:

> *So, [the activity] was a STEM production in creating toys with pulleys and gears and incorporating into that. So, the main theme was good—a theatre, little miniature theatre or puppet show and with the physics of mechanics and pulleys. I remember someone very creative using all her makeup; and she's just created a little puppet made out of lipstick, hairdryer, whatever it was. So, we got together and shared experiences, the challenges. I do remember talking about challenges in trying to use that creativity and then applying the science thinking with that creativity … And then at the same time [our teacher educator] wanted us to do the PBL [problem-based learning] sequence—we had a template to follow for creating that [a sequence] with that template. (Preservice Teacher 4)*

Preservice Teacher 4 highlights the importance of sharing and discussing creations with peers after engaging in a design activity and developing a problem-based learning (PBL) sequence. This discussion involved reflecting on the challenges encountered, particularly when blending creativity with scientific thinking. While not explicitly stated, these discussions likely contribute to teachers' understanding of constructivist pedagogies.

Exploring STEM Education Possibilities in State-Based Curricula

Study participants spoke of exploring STEM education possibilities within curriculum documents. When talking of activities in the university classroom, several teacher educators discussed opportunities to explore and analyse state-based curriculum documents:

> *Providing them [preservice teachers] copies of say the Victorian curriculum and saying look for these [real-life] topics and how would you say that they [each discipline] line up or don't [within the topic]. (Teacher Educator 5)*
>
> *I force them, in one week, I literally print out each of the curriculum and they [preservice teachers] actually circle the things that they can make connection between. They do it in pairs so it's not too challenging or too confronting and it's that starting point of actually seeing what would be an appropriate activity or an appropriate STEM challenge for them [school students] based on what they are going to do throughout the year. (Teacher Educator 13)*

These quotes highlight the importance of supporting teachers in identifying STEM education connections within state-based curricula. Teacher Educator 5 suggests starting with a real-world topic and connecting it to disciplinary knowledge, while Teacher Educator 3 encourages teachers to first identify connections between disciplines and then develop a STEM activity. Analysing curriculum documents helps teachers explore potential interdisciplinary connections when designing integrated units and ensures that STEM is incorporated in a way that aligns with curriculum requirements. Teacher Educator 8 elaborates on activities involving curriculum analysis:

> *We just get them [in-service teachers] to identify the parts of the curriculum that are relevant to the integrated topic and it's just about finding links between the different subjects. So, it's identifying which bits of knowledge can be brought in at different points of the sequence, so it's a temporal thing and rather than it just being a spatial crossing of 'we've got to do a bit of this, a bit of this and a bit of this', which is often how STEM is presented, it's recognising that there are key points along the six-lesson sequence. The other way of looking at that integration is to focus on those seemingly generic skills so if you are looking at—critical thinking—then how do you develop a sequence that is based on student thinking critically at a particular time or creatively or to be innovative or to be entrepreneurial, those sort of things; that's one way of looking at it but of course there's different models of integration that you can think about. (Teacher Educator 8)*

In this scenario, the goal was to develop knowledge of integrated curriculum design. Firstly, teachers identified connections between 'the integrated topic' (Teacher Educator 8)—likely a real-life topic that underpinned the curriculum—and specific subject areas. This could involve STEM content, or generic skills, highlighting the potential for both in STEM education. Secondly, the task aimed to enhance teachers' understanding of curriculum construction. Teachers were prompted to consider the timing and placement of specific knowledge and skills within the learning sequence, as well as provide justification for their choices.

Other participants spoke of inviting guest speakers to illustrate the curriculum possibilities for STEM education. For some programs, the guest speakers were from state-based curriculum bodies.

> *We've worked with someone from the VCAA [Victorian Curriculum and Assessment Association], and they provide ideas and to give them [teachers] the curriculum … in a sort of creative way, making connections between different disciplines or different strands in the curriculum. Sometimes looking at the order of things, sometimes saying well something that's in Year 8, you may want to swap it with something in Year 9 to create connections. You can make all these cross-connections if you do a project, and they [VCAA] have examples of projects that link you know between those disciplines. (Teacher Educator 6)*

Guests from a state-based curriculum body highlighted links between and across state curriculum dot points, offering teachers insight into curriculum integration. Additionally, they showed teachers how a STEM curriculum can fit within curriculum requirements even where STEM is not explicitly mentioned, and content is arranged in a largely disciplinary way.

> In other instances, the guest speakers were teachers implementing STEM education in schools:
> We get teachers in who are running STEM programs … they [preservice teachers] like hearing from teachers on the ground; we usually try to get a mixture of primary and secondary [STEM educators] … [We get them] to just to come and talk about how they designed their program, what it looks like, how it connects with aspects of curriculum. (Teacher Educator 1)

Teacher Educator 1 acknowledges the value of 'hearing from teachers on the ground', as it provides insight into the design of STEM education schools. These educators can share knowledge about connecting STEM education with state-based curriculum, discuss valuable STEM education approaches, and address challenges they encounter. Although the interaction between teachers and guest speakers is not extensively discussed, hearing from current STEM teachers likely adds authenticity to learning about STEM education, as they can speak from their immediate classroom experiences.

Experiencing Museums, Galleries, and STEM Workplaces

Many STEM teacher programs featured experiences with museums, galleries, and STEM workplaces; yet, programs offered different ways of encouraging teachers to connect with these locations. For example, a program at university 5 organises a 5-day industry placement:

5 days working in the STEM industry is aimed at broadening and deepening preservice teachers' understandings and relevance of STEM in relation to education, industry, and the wider community. (Handbook_University 5)

Participating in a STEM workplace immersion is an important component of this course, providing teachers with insights into 'the relevance of STEM' (Handbook_University 5). This experience helps teachers understand the relationship between STEM disciplines and their role in industry or society and develop knowledge of real-life topics for integration into their teaching. Alternatively, Teacher Educator 3 suggests engaging in 'an immersion, where they can select anywhere to immerse themselves, and this could be an art gallery' (Teacher Educator 3), to complete 'a STEAM based project and implement that' (Teacher Educator 3). With the aim of 'building partnerships with outside organisations to enhance STEM education' (Handbook _University 2), these community-based experiences inspire teachers in designing STEM learning sequences.

Teacher Educator 5 also mentions visits to museums and galleries as stimuli for designing STEM education curriculum:

We kind of set the excursions up to say 'look what we're wanting you to do is think about how you can use these specific locations as a way of drawing inspiration for different kinds of units. Imagine that you were in a school that was located near an art gallery and sometimes those places will have things that you can utilise and build on within your design of [STEM] units within the classroom'… then we went up to [another science] exhibition that … was all about disposables, so that would lend it's itself nicely to a kind of science integrated unit of some kind.

Organising excursions to museums and galleries provides teachers with inspiration for designing STEM learning experiences. These settings offer opportunities to explore real-life topics that can be integrated across multiple disciplines, aligning with the context-based teaching approach in STEM education. Teacher Educator 5 also highlighted the authentic nature of topics encountered during excursions and industry experiences. Through 'exposure to authentic contexts for integrating science, technology, engineering, and mathematics' (Handbook_University 5), teachers encounter real-life topics that may be 'personally meaningful' (Moore et al., 2015, p. 5) for school students.

Several teachers discussed that excursions to museums and galleries helped their understanding of integrated curriculum design, primarily for developing knowledge of how the disciplines may be blended. For example, the following quotes, from two preservice teachers encountering museum exhibits, highlight what they learned from the experience:

I was just really ingrained with the idea that it [STEM education] had to be just a bit of physics and a bit of maths and solve the problem. But I never thought about … the balancing between the different disciplines. You realise that a STEM unit can be delivered, that the teacher can focus more on one discipline, one particular subject, as opposed to another. (Preservice Teacher 4)

> *It's one thing to read a unit that has this information that is dictated, then it's one thing to actually see it [integration] being played out in real life. So, that was I think the most valuable part of looking at the [science–music] museum because and I believe that was the starting point of [us] thinking, starting to think about [designing STEM education]. (Preservice Teacher 5)*

Experiencing museum and gallery exhibitions helped teachers explore disciplinary integration in STEM education. For instance, Preservice Teacher 4 questioned the composition of an integrated unit after experiencing a museum exhibit, considering the proportional representation of each discipline. These quotes indicate that exploring and analysing exhibits are valuable for understanding how to integrate disciplines under a common topic or problem. Preservice Teacher 5 emphasised the significance of witnessing integration in museum exhibits and 'seeing it [integration] being played out in real life'.

Collaborating in STEM Curriculum Design

Participants frequently discussed and engaged in activities involving the creation of STEM education teaching resources, often as assessment tasks. Teacher Educator 5 mentions that for 'their final assessment task, they [preservice teachers] have to design an interdisciplinary unit, and it has to involve science and at least one other subject area', while preservice teachers in another program must 'give us two fully developed lesson plans and create [STEM teaching] resources' (Teacher Educator 12). While the creation of unit plans and teaching resources is typical in ITE, participants emphasised the value of collaboration in completing these assessment tasks.

> *I typically have groups of four [in-service teachers] working together and I tried to vary the groups as much as possible—primary school teachers with a secondary teacher, some who've got a science background, some who've got a technology background, someone who's got a maths background. So, we have a real interdisciplinary kind of team. That's what I try to do, so I try to make it [the teacher collaboration] as diverse as I possibly can. (Teacher Educator 9)*

In many programs, teachers were encouraged to collaborate in teams with diverse disciplinary expertise. Teachers spoke of their learning when working in mixed disciplinary collaborations to design STEM unit plans:

> *He picked up a lot of science ideas from me. But he already had a lot of the understanding of the big picture stuff from his robotics experience and his general interest in science. I picked up a lot from him. (Preservice Teacher 3)*

Diversity within the teacher collaborations provided opportunities for peer learning and sharing of disciplinary expertise. Teachers spoke of the discussions that arose during collaboration, providing opportunities for 'gaining from each other's expertise' (Preservice Teacher 6) such as subject matter knowledge and pedagogy.

Discussion

Curriculum design traditionally considers content, pedagogy, timing and rationale. In STEM education curriculum design, teachers must also blend mixed- disciplinary content into an integrated learning experience. This research confirms that STEM curriculum design is a common task in STEM teacher programs and identifies key learning experiences that support teachers in this endeavour. Each activity has the potential to develop various knowledge areas, but these activities are common in teacher programs overall. This discussion explores the importance of each activity for teacher learning of STEM curriculum design, providing insight for teacher educators designing STEM teacher programs.

Supporting Teacher Learning of the Content of STEM Education Curriculum

STEM education aims to develop student interest and achievement in the STEM disciplines—Science, Technology, Engineering, Mathematics. Therefore, disciplinary knowledge and skills are the 'content' of a STEM education curriculum, in addition to knowing how to integrate these appropriately, as discussed in the next section. The mixed-disciplinary nature of STEM education necessitates teachers to possess knowledge of multiple disciplines, and the importance of disciplinary knowledge has been emphasised as key for the success of STEM integration (National Academy of Engineering and National Research Council [NAE & NRC], 2014; Shernoff et al., 2017). However, few STEM teacher programs, discussed in the literature, address the development of teachers' knowledge in disciplines beyond their own.

While teacher teams are a common feature of STEM teacher programs (Nadelson & Seifert, 2013; Roehrig et al., 2012), there is limited discussion of their nature and importance in supporting teacher learning of STEM curriculum design. Collaborative work has been shown to enhance teachers' subject matter knowledge (Voogt et al., 2011, 2016), and this study confirms the significance of collaboration, particularly among teachers with mixed-disciplinary expertise for sharing and developing disciplinary knowledge—both content and pedagogical. When designing STEM teacher programs, teacher educators should consider (1) incorporating activities that foster disciplinary knowledge development and (2) provide opportunities for teachers with diverse disciplinary expertise to co-create STEM education curricula.

Supporting Teacher Learning About Content Integration in STEM Education Curriculum

STEM education requires the integration of disciplinary knowledge and skills, necessitating teachers to possess both relevant knowledge and the ability to apply it (Boix Mansilla, 2005). This application involves understanding connections between disciplines and effectively blending content into learning experiences. While various approaches to curriculum integration exist (e.g., solving problems, modelling, argumentation), this study illustrates the common use of real-life topics to integrate knowledge from diverse disciplines. Existing programs support teachers' understanding of disciplinary connections (McFadden & Roehrig, 2017; Ring et al., 2017) or real-life topics (Nadelson et al., 2012) but provide limited insight into knowledge development. This study identifies key activities that support teachers' learning of content integration in STEM education curricula.

This research identifies four activities that support teachers in developing their knowledge of content integration in STEM education curriculum: (1) analysing existing STEM education teaching resources; (2) immersion in STEM education experiences; (3) exploring STEM education possibilities in state-based curricula; (4) excursions to museums, galleries, and STEM workplaces. Each activity helps teachers identify curriculum and disciplinary connections and consider how to integrate knowledge and skills. Moreover, they offer teachers examples of how disciplinary knowledge may be blended into an integrated curriculum, under the umbrella of a real-life topic, supporting teachers to visualise integrated curriculum design in preparation for developing their own.

This study indicates that, in Australian teacher learning, there are various ways of gathering knowledge of how to integrate content in STEM education curriculum design. The diverse range of learning activities identified in this study is important for several reasons. Firstly, the inclusion of different opportunities to explore multiple real-life topics is valuable for addressing the diverse interests and needs of students (Chen & Cowie, 2013). Secondly, because 'teachers will begin doing STEM integration in the manner which is most comfortable to them' (Wang et al., 2011, p.11), the diversity of activities introduces different approaches to STEM education so that teachers can choose which best suits their educational context.

Supporting Learning of Pedagogies for Teaching STEM Education

Considering pedagogical approaches is a key aspect of curriculum design as it encompasses methods for a teaching-specific content. In the context of STEM education, constructivist pedagogies, such as inquiry-, problem-, project-based learning and engineering design are common teaching approaches (Kelley & Knowles, 2016). However, challenges exist in implementing these pedagogies in K-12 settings, including limited availability of instructional materials, national curriculum, and examination requirements (Sikoyo, 2010; Silva et al., 2021) and teachers' limited knowledge, familiarity, or confidence with implementing constructivist approaches (Seng, 2014; Silva et al., 2021). In the context of STEM education, challenges include teacher's limited understanding of and anxieties about implementing inquiry approaches (Asghar et al., 2012) which can inhibit the integration achieved (Johnson & Czerniak, 2023).

The findings highlight the value of immersion in STEM education experiences for providing opportunities for teachers to develop knowledge of constructivist pedagogies. Immersion activities, where teachers participate as school students, offer benefits such as increased emotional engagement with STEM (Kim et al., 2015) and enhanced self-efficacy (Kelley et al., 2020); yet, this study specifically identifies their usefulness in teacher learning of constructivist pedagogies. While this study did not identify what knowledge of constructivist pedagogies teachers could develop nor how, immersion experiences likely ‘make the tacit explicit’ (Loughran, 2006, p. 62), enabling teachers to see the questions, concerns, and challenges that may arise within a learning activity and develop their pedagogical reasoning. In the context of STEM education, teacher-as-school-student experiences could provide a starting point for envisioning the integration of constructivist pedagogies with disciplinary knowledge and skills and real-life topics. Moreover, these experiences may offer additional insights into the challenges of learning with constructivist pedagogies.

Conclusion, Implications, and Future Research

Given that ‘designing instructional materials for integrated STEM education is new for many teachers’ (Guzey et al., 2016, p. 14), it is unsurprising to find that creating STEM curriculum is a common activity in STEM teacher learning programs (Du et al., 2019; Kim & Bolger, 2017; Ryu et al., 2019). This paper’s findings highlight key experiences valued for helping teachers learn and integrate STEM education content. However, the complexity of STEM education and teacher learning means that different activities lead to different learnings. Therefore, STEM teacher programs should include targeted activities for teachers to develop their necessary knowledge and skills.

In practice, introducing the activities identified in this study requires two key elements: relationship building and time. While some activities can be implemented in regular university classrooms, a program with multiple activities necessitates the establishment of relationships with educational settings beyond universities (e.g., museums, local industry). This allows teachers to gain diverse experiences and develop the necessary knowledge to design STEM curriculum. However, implementing a range of activities requires time, which is limited in teacher programs. Therefore, the designers of STEM teacher programs (e.g., teacher educators) will need to decide which activities to include. This paper recommends the ‘best’ options to support teacher educators in this decision-making process.

This study aimed to identify valuable activities for supporting teacher learning of STEM curriculum design. Without disputing the benefit of each of the activities identified in this study, the findings suggest that analysing STEM teaching resources and immersion in STEM education experiences offer teachers opportunities for broader learning. If time is limited, these two activities could be prioritised in STEM teacher programs, recognising the value of exposure to diverse resources and immersion experiences.

The study’s findings provide insights into STEM teacher programs; yet, its limitations suggest areas for further research. Firstly, the small number of participants and single context (e.g., Australia) may limit the range of learning experiences identified. For example, other studies highlight the common activity of adapting STEM curriculum resources in STEM teacher programs (Kelley et al., 2020; Singer et al., 2016), which was not mentioned by participants in this study. Investigating a broader range of contexts, such as STEM teacher programs in other countries, is necessary to determine the availability, effectiveness, and benefits of the identified activities and explore other valuable learning experiences, particularly where variations in curricula (e.g., NGSS vs Australian Curriculum) likely impact on STEM education implementation, and thus the needs of teachers. Additionally, future research should examine how teachers implement and enact their STEM curriculum design after participating in STEM teacher programs to identify the most valuable activities for transferring knowledge to the classroom. For example, a longitudinal study which investigates the learning of participants from teacher programs and through implementation in a range of schools; this could identify variation in teacher needs to influence STEM teacher program design. Lastly, given differences between preservice and in-service teachers' experiences were expected but not observed in this study, further research is needed to better understand their distinct needs and inform the design of programs focused specifically on initial teacher education or professional development. With different levels of teaching experience, it may be that particular activities are more valuable for preservice teachers than in-service, or more/less time is required for a specific learning opportunity.

Appendix 1. Interview Protocol for STEM Teacher Educators

1. What is your perception of integrated STEM education?
2. Can you tell me about the sequence of your approach to STEM teacher education? For example:

   - In what order will the content and skills be delivered? Why?
   - How is it delivered? (e.g., online, face-to face, etc.) Why?
   - What is the duration of this approach to STEM teacher education? Why?

3. Can you tell me about the scope of your approach to STEM teacher education? For example:

   - What do you believe are the main aims?
   - What would you like your students to gain?
   - What kind of things are you covering/emphasising?
   - What STEM content will be the focus? Why?
   - What STEM skills will the focus? Why?
   - How will content be integrated? Why?
   - How will skills be integrated? Why?
   - How will content and skills be integrated? Why?
   - If at all, how is the balance between the STEM subjects achieved?

4. Can you tell me about how student learning will be supported throughout your approach to STEM teacher education? For example:

- What strategies are embedded to support student learning? Why?
- What pedagogical practices are a particular focus? Why?

5. Can you tell me about student assessment throughout your approach to STEM teacher education? For example:

- What formal assessment will occur? Why?
- When will this formal assessment occur? Why?
- What informal assessment will occur? Why?

Appendix 2. Interview Questions for Teachers Experiencing STEM Teacher Programs

1. Have your perceptions of STEM education changed over the course of the program? (yes/no). Explain your response.
2. What place does integrated STEM education have in school curriculum?
3. Describe your current or future integrated STEM classroom. Consider:

- Your teaching and learning objectives
- Pedagogical approaches used
- Assessment

4. Describe the implementation of the integrated STEM teacher learning program. Consider:

   a. Delivery of the program (e.g., online, face-to face)
   b. Activities undertaken
   c. Pedagogical approaches experienced
   d. Assessment undertaken

5. If you were to *describe* 3–5 key activities experienced during the program, what would they be?
6. How did the program prepare you for your future integrated STEM teaching?

Abbreviations STEM: Science, technology, engineering, and mathematics; 5E: Engage, explore, explain, extend (or elaborate), and evaluate; ITE: Initial teacher education; PD: Professional development; PBL: Problem- based learning; UNI: University; IST: In-service teacher; PST: Preservice teacher

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Declarations

Ethics Approval Approval was obtained from the Education, Fine Arts, Music, and Business Human Ethics sub-committee (I.D. 1953719.1) at The University of Melbourne.

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