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Learning to teach STEM disciplines in higher education: a critical review of the literature

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Abstract

Enrolments in STEM disciplines at universities are increasing globally, attributed to the greater life opportunities open to students as a result of a STEM education. But while institutional access to STEM programmes is widening, the retention and success of STEM undergraduate students remains a challenge. Pedagogies that support student success are well known; what we know less about is how university teachers acquire pedagogical competence. This is the focus of this critical review of the literature that offers a theorised critique of educational development in STEM contexts. We studied the research literature with a view to uncovering the principles that inform professional development in STEM disciplines and fields. The key finding of this critical review is how little focus there is on the STEM disciplines. The majority of studies reviewed did not address the key issue of what makes the STEM disciplines difficult to learn and challenging to teach.

Introduction: the increasing importance of the STEM disciplines and fields

The term 'STEM' (an acronym for science, technology, engineering and mathematics) was coined by the National Science Foundation in the 1990s as national governments became increasingly aware of the importance of this cluster of disciplines for economic growth (Bybee 2010). Enrolments in STEM disciplines at universities are increasing globally, attributed to the greater life opportunities open to students as a result of a STEM education, as well as increasing financial and academic support for students undertaking undergraduate STEM studies. But while formal access to STEM programmes is increasing (i.e. more students are accepted onto STEM programmes), the retention and success of STEM undergraduate students has not significantly increased (Sithole et al. 2017). There is general consensus in the international literature that undergraduate STEM programmes pose significant challenges to students and that many STEM programmes are marred by high attrition rates, poor student success, and a notable lack of diversity (Killpack and Melón 2016). While the difficulties of mastering STEM knowledge are recognised, there is also growing recognition that students' 'epistemological access' (Morrow 2009) to STEM disciplines is strongly supported when the academics who teach on them are pedagogically competent to do so (Tenenberg and McCartney 2010).

The educational philosopher, Wally Morrow coined the term 'epistemological access' (Morrow 2009) to distinguish between a student's admission into a higher education programme and the student's acquisition of the knowledge and literacies of that programme. By the term, he meant that the admission of students to programmes (particularly students who through economic or social disadvantage were underprepared for higher education) required considerable effort on the part of both the students and the academics who taught them. Morrow (2009) strongly supported the widening of access to higher education, but was concerned that university teachers should understand their roles in providing epistemological access to their disciplines and fields. Morrow's concerns raise warning bells for STEM faculties and departments who have significantly increased their student numbers over the past years. Accepting those who were previously excluded from STEM disciplines and fields into higher education is not enough; STEM academics also need to enable students' epistemological access.

Prior research has built a knowledge base of the kinds of undergraduate STEM pedagogies that might provide epistemological access, such as thinking through problems with peers (Watkins and Mazur 2013), the use of authentic real-world environments and examples' (Nerland and Jensen 2014), making more 'visible' STEM discourses, particularly with regard to assessment practices (Wolff and Hoffman 2014), socially inclusive pedagogies (Killpack and Melón 2016) and the 'mainstreaming' of student support mechanisms, such as academic and technical literacies (Shay, Wolff, and Clarence-Fincham 2016). The effectiveness of these pedagogies for undergraduate STEM student success has been verified through systematic reviews of the research literature (e.g. Savelsbergh et al. 2016). What we know less about, however, is how university teachers in the STEM disciplines learn to teach their subjects. The overarching question guiding this critical study of the literature is: what kinds of professional learning interventions support university teachers' acquisition of systematic pedagogical STEM knowledge?

Who trains university STEM teachers?

Teaching and learning centres have varied histories and trajectories, 'pulling together specialists from areas such as applied language studies, adult education, science education, engineering education and educational technology who care deeply about students and are committed to the improvement of their experience as learners in higher education' (Shay 2012, 314). Academic developers typically come from a wide variety of home disciplines, but are united by their deep interest in student learning. The first academic developers in New Zealand 'were well-qualified academics from "respectable" disciplines … perceived as having the authority to speak in the university' (Barrow and Grant 2012, 469). Many teaching and learning centres continue to be located in faculties, such as the Academic Development Unit in the Faculty of Engineering at Lund University (Olsson and Roxå 2012). But many teaching and learning centres developed outside of faculties, from 'central services such as registry, human resources, or library and information services' (Gosling 2009). Some grew out of student counselling centres, with a focus study skills and the promotion of student well-being

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(Walsh 2017). In their study of nine higher education institutions, Henderson, Beach, and Finkelstein (2011) found that the main providers of educational training to STEM academics were situated in teaching and learning centres outside of faculties with the mission to provide professional development for all instructors at the institutions; they thus provided generic pedagogical training.

The logic behind the training of STEM academics by non-STEM academic developers is that university teachers, as disciplinary experts, are well versed in the logic of their disciplines (Walsh 2017). Thus the focus of their professional learning should be pedagogy, not STEM. To a certain extent this makes sense, as the logic of teaching STEM subjects (i.e. STEM pedagogy) does not always have the same logic as STEM disciplinary logic. There are, however, studies that show that STEM content and STEM pedagogy are closely connected, and that STEM pedagogical development should be understood as an interdisciplinary project (Henderson, Beach, and Finkelstein 2011). A well-known example of the interdisciplinary base of teaching is the concept of 'pedagogical content knowledge' (PCK) (Shulman 1992), that is, the idea that teachers require disciplinary knowledge as well as pedagogical knowledge in order to teach. 'Constructive alignment' (Biggs and Tang 2011), the social constructivist version of this framework, is more common in higher education, but is not equivalent because it under-specifies the disciplinary knowledge base of what is to be taught. Trowler and Cooper (2002) point out that where there is a 'mismatch between the rules of appropriateness which predominate in an educational development programme and those held by a participant, we can expect trouble' (2002, 9). Teaching methods and assessment tasks proposed by academic developers may be rejected out of hand as 'belonging to a regime of teaching and learning that resides in the Social Sciences and therefore inappropriate to … Science disciplines' (Trowler and Cooper 2002, 17).

Because the scientific knowledge structures of STEM disciplines are complex and specialised, undergraduate students generally do not bring their own understandings of scientific disciplines to their university studies. Indeed, the acquisition of science knowledge is a lengthy process that requires both subject knowledge and training in how this knowledge is structured. It is for these reasons that STEM university teachers usually teach significant amounts of subject content in their classroom and laboratory practice. The 'lecture-demonstration' is thus a 'signature pedagogy' (Shulman 2005) of many STEM disciplines and fields.

There are, however, significant counter-traditions in the teaching of STEM disciplines, based on the idea that teachers' 'craft knowledge' (Van Driel et al. 1997) is acquired through reflection on practice. In professional development, this is often explored through teaching portfolios (Seldin, Miller, and Seldin 2010); but has also been reduced to 'what works' or 'tips and tricks' (Clarke and Boud 2016) in academic development workshops. More radical approaches to the teaching of STEM disciplines at university are emerging and have been influenced by socio-political contexts, the exclusion or low representation of black and non-traditional students in STEM disciplines (Killpack and

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Melón 2016), the 'decolonial turn' in STEM teaching (de Oliveira Andreotti et al. 2015), and the biographies of STEM teachers and students (Jita 2004). These different understandings of the teaching and learning relationship lend themselves to a wide variety of pedagogical approaches.

A theoretical framework for critically reviewing the STEM pedagogical literature

Because we understand STEM pedagogical training to be underpinned by both STEM disciplinary knowledge and pedagogical knowledge, we conceptually framed our research with Legitimation Code Theory (LCT), a social realist framework that has been widely used to study teaching and learning in higher education (Maton 2014; Maton, Hood, and Shay 2015). LCT offers many 'tools' for the analysis of knowledge practices; in this review of the literature we drew on the dimension of Specialisation (Maton 2014) to analyse the ways in which the research literature understands the professional learning of university teachers towards competent STEM pedagogical practice. Specialization is based on the understanding that 'practices and beliefs are about or oriented towards something and by someone' (Maton 2014, 29). Maton argues that it is possible to distinguish between the 'epistemic relations between practices and their focus' (in this case, teaching STEM content knowledge) and the 'social relations between practices and their subjects' (in this case, pedagogy or the teaching and learning relationship). The LCT dimension of Specialization provided a means by which we could analyse the knowledge that under pins practices in STEM pedagogical training, as well as practitioners' orientations and dispositions towards the knowledge base of their practice.

The Specialization dimension explains knowledge claims and knowledge practices as always involving both knowledge and knowers, and thus relations to knowledge (i.e. epistemic relations) and relations to knowers and their practices (i.e. social relations). Together, the relative strengths of the two relations give rise to a series of Specialization codes, which encapsulate the basis of legitimation and achievement in the particular field, situation or event. The particular configurations that these relations could take in the training of STEM educators will vary along a continuum of strengths (Maton 2014), that is, some forms of STEM pedagogical training are likely to relate more strongly to the STEM discipline, and other forms of training are likely to relate more strongly to the social aspects of the teaching and learning relationship – with many possible combinations and hybrids. The Specialization dimension allowed us to locate each of the studies in the systematic review within a range of positions that practitioners might see as legitimate within STEM pedagogy, instead of forcing false dichotomies such as 'teacher-centred' or 'learner-centred' practices. As Maton explains: 'The codes are not ideal types – they conceptualise organising principles rather than gather empirical characteristics' (2014, 33). The many possible combinations could be understood as located within the Specialization plane in which the x-axis represents a continuum of weaker to stronger social relations, and the y-axis represents weaker to stronger epistemic relations Figure 1.

The relative strength of epistemic relations and social relations give rise to four principal codes, located across the quadrants of the Specialization plane. Studies located in quadrant

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1 would focus on the training of academic staff in STEM knowledge (an unlikely scenario); studies located in quadrant 2 would focus on STEM pedagogical content knowledge. Studies located in quadrant 3 would focus only on generic pedagogical training, while studies located in quadrant 4 (the undesirable minus/minus quadrant) would have little or no STEM content and little or no pedagogical knowledge. Both top quadrants (1 and 2) have stronger epistemic relations to STEM knowledge, but studies located in quadrant 2, where there are stronger relations to STEM knowledge and stronger relations to pedagogical knowledge are more likely to provide academic staff with the kind of training that might provide support students' epistemological access to the STEM disciplines and fields.

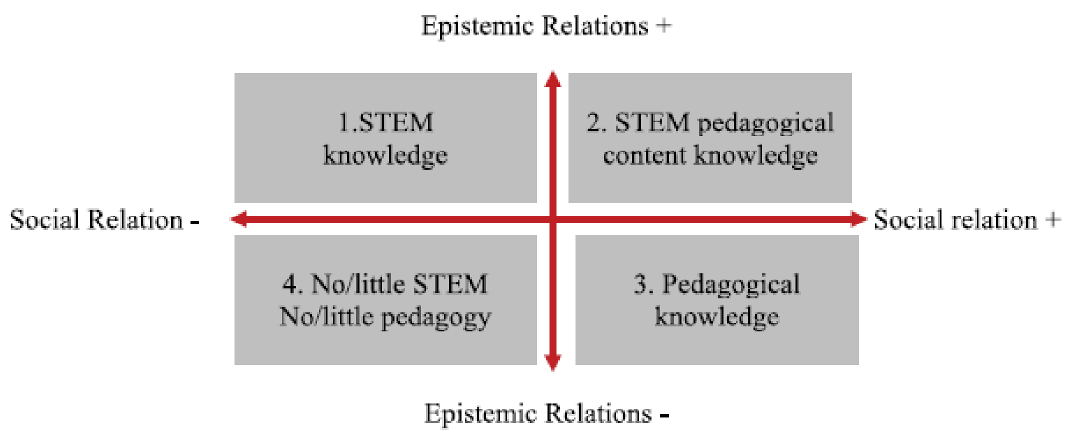

Figure 1. Epistemic relations and social relations in STEM pedagogy training (adapted from Maton 2014).

The four basic codes provide a means of answering questions such as 'what is the knowledge base that is drawn on in this study?'; these codes thus helped us to uncover the underpinning logic of pedagogical training, that is, whether the pedagogical training addressed key issues within the discipline (e.g. its key concepts, procedures and practices) or whether the training was more focused on the social dimensions of pedagogy (e.g. presentation skills, classroom management). By examining these organising principles, we could make more explicit the knowledge underpinning STEM pedagogical training. Thus we used the Specialization plane as a framework to account for and reveal the underlying orientations that motivated the academic development practitioners to make particular choices. Specialization codes uncover the principles of what counts as legitimate knowledge and legitimate ways of knowing. These act to regulate and maintain knowledge and the processes, procedures and dispositions within practices.

In summary, the 'practice' in this literature review is learning how to teach in STEM disciplines. Epistemic relations in the professional development of STEM academics describe stronger or weaker STEM disciplinary content along a continuum, from high levels of STEM content to little or no STEM content. Social relations in the professional development of STEM academics reveal stronger or weaker forms of STEM pedagogical

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knowledge along a continuum, from pedagogies that are highly appropriate to the STEM discipline, to those that are less appropriate, as in Table 1.

Methodology of the systematic review

The search strategy, firstly, required the development of appropriate search terms. These terms were refined through initial pilot searches. The international literature has many ways of describing the professional learning of academic staff in their roles as university teachers – thus a full spectrum of such terms was required (e.g. 'academic development', 'educational development', 'faculty development', 'professional development'). As STEM is a term more commonly used at the school level than in higher education, we excluded school level studies in the searches. When we searched in general academic development journals we included: 'Science, Technology, Engineering, Mathematics', but when searching in STEM education journals this was not necessary as a search term. We searched eight academic databases and cross-checked the search within 17 individual journals.

Table 1. Specialization translation device.

Epistemic relations	Stronger ↕ Weaker	Knowledge of STEM Disciplines	STEM disciplinary content Little or no STEM disciplinary content
Social relations	Stronger ↕ Weaker	Knowledge of pedagogy	Pedagogical knowledge Little or no pedagogical knowledge

We also searched journals that were not linked to academic data-bases. Table 2 provides a schematic representation of the search strategy. The application of the search strategy resulted in an initial data-base of 144 articles, book chapters and conference proceedings. All items in the data-base were read and articles that were not relevant to the topic, or that were 'opinion pieces' rather than empirical research or evaluation studies, or very short papers (i.e. shorter than 2 pages) were excluded, resulting in a final data-base of 77 studies. The data-base is available at https://sites.google.com/site/stempedagogy/critical-review-1.

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Table 2. The search strategy.

Search terms	Databases earched	Cross-checked in
"Science, Technology, Engineering, Mathematics" AND "pedagogical competence" OR "pedagogical content knowledge" OR "faculty development" OR "academic development" OR "professional development" OR "university teaching" NOT "elementary school" NOT "junior school" NOT "high school" NOT "senior school" NOT K-12	ACM Digital Library	*ACM Transactions on Computing Education*
	Elsevier	*Education for Chemical Engineers*
		Journal of Accounting Education
		International Journal of Educational Development
	IEEE Xplore	*IEEE Transactions on Education*
	MEDLINE	*Nurse educator*
		Radiography Practice
		Medical educator
	SABINET	*South African Journal of Higher Education*
		South African Journal of Chemical Engineering
	SCOPUS	*Higher Education*
	Springer	*Canadian Journal of Science Mathematics and Technology Education*
		Engineering Education: a Journal of the Higher Education Academy
		European journal of engineering education
	Taylor and Francis	*International Journal of Mathematical Education in Science and Technology*
		Teaching in Higher Education
		International Journal of Academic Development
Journals not linked to databases *(also searched)*		
Search terms as above	–	*Advances in Engineering Education*
	–	*The Journal of Faculty Development*
	–	*Journal of Technology Education*

The data base included a wide varied of research studies, with much of the literature reporting on evaluations of professional learning interventions. Many of these interventions were innovative, and had the intention to move away from the 'traditional workshop format' of academic development (Beddoes, Jesiek, and Borrego 2011). A variety of data collection methods were used to evaluate these activities, from unstructured 'feedback' (e.g. Baiduc, Linsenmeier, and Ruggeri 2016) to more structured approaches, such as 'The Teacher Beliefs Inventory', a semi-structured interview protocol developed 'to examine how instructors' … beliefs about teaching and learning shift during professional development experiences'(Mattheis and Jensen 2014, 325). Ethnographic and case study approaches (e.g. Sunal et al. 2001) were less frequently found in the literature. Analysis of the data enabled researchers to construct models of professional development (e.g. Brancaccio-taras, Gull, and Ratti 2016) and identify barriers to professional development (e.g. Felder, Brent, and Prince 2011). Most of the evaluation studies were untheorised and assumed an unproblematic relationship between the pedagogical training provided, which typically included topics such as: '(1) design lesson plans; (2) use facilitating and lecturing skills in several teaching opportunities; (3) self-reflect on [the] implementation of those activities; and (4) give and receive peer feedback from the community of teachers in the course' (Newton et al. 2010,

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10) and measurable 'outcomes' with regard to student achievements. Those who made use of theoretical frameworks tended to draw on social constructivism (e.g. Hyde and Nanis 2006) or constructivist hybrids, such as 'social cognitive theory and [graduate teaching assistant] teaching literature, with support from the K–12 teaching self-efficacy literature' (Dechenne and Enochs 2010, 2). One study took a social realist approach to evaluation, conceptualising professional learning activities 'as social systems in which there is a constant interplay between individual agency and social structures' producing a 'mandala of faculty development' that modelled the complexity of 'contexts, mechanisms, and outcomes' (Onyura et al. 2017, 171).

Findings: how STEM university teachers learn to teach

We studied the literature with a view to uncovering the implicit epistemic and social relations in the pedagogical training of university teachers in STEM disciplines and fields. The literature was then classified into three broad categories: 1) STEM pedagogical training that addressed issues in disciplinary content as well as how key concepts or processes could be taught (thus underpinned by both stronger epistemic and stronger social relations), 2) studies that focused on pedagogical issues (thus revealing weaker epistemic relations to STEM disciplinary knowledge, but stronger social relations to pedagogy), and 3) studies that did not deal with the discipline or its pedagogy (thus revealing both weaker epistemic and weaker social relations). There were no studies in which we found stronger epistemic relations and weaker social relations (i.e. a study of training on disciplinary content, without pedagogical training); this is probably because STEM university teachers are generally not considered to be in need of STEM training (Walsh 2017).

Reconnecting teaching to the disciplines

It might be expected that research studies on the training and supporting academic staff in STEM pedagogy would have a STEM focus; that is, that the research literature would reveal something about how STEM academics engage in professional learning towards 'explaining concepts, theories and discipline knowledge in a way that students can easily understand them … ensuring the delivery of accurate, up-to-date professional discipline specific information' (Corry and Timmins 2009, 390). However, only about a quarter of the studies (20/77) in the data-base had a STEM focus – this is so uncommon in the literature that Tenenberg and Fincher describe the 'novelty' of their approach as being 'centered on the discipline, rather than treating teaching as a set of generic skills that, once learned, can be applied in any discipline' (2007, 514). One study explained the under-representation of STEM in studies of STEM pedagogy by the likelihood that 'instructional development on most campuses is commonly provided by social scientists (generally education and psychology faculty members) to campus-wide audiences' (Felder, Brent, and Prince 2011, 90).

The studies that specifically focussed on STEM tended to foreground curricular issues, such as helping academics to develop a STEM curriculum and then teach it (Barth and Rieckmann 2012; Frolik et al. 2013). This is not surprising as it would be difficult to avoid

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STEM content when curriculum development is the vehicle for professional learning. A cluster of studies focussed on teaching specific STEM concepts and topics, such as 'systems thinking and wireless sensor networks, … electromagnetics, radio frequency (RF) circuit design, communication systems, and embedded systems' (Frolik et al. 2013, 2) and 'process control' (Jwaid, Clark, and Ireson 2014). Some studies drew on versions of Shulman's (1992) Pedagogical Content Knowledge (PCK) framework (Viiri 2003; Marquez, Sánchez, and Valera 2013), and the subsequent Technological Pedagogical Content Knowledge (TPACK) model (Jwaid, Clark, and Ireson 2014). Marquez, Sánchez, and Valera (2013) argue that the PCK framework enabled STEM academics to 'gradually develop their teaching competencies by participating in real education innovation activities that are properly inter-regulated by mentors who have experience in research into sciences and engineering education' (2013, 823). One initiative that explicitly linked disciplines and pedagogical development was the 'research knowledge utilization' (RKU) framework (Porter et al. 2006) which mapped the relationship between innovation in discipline-based research and its possibilities for application to STEM teaching. The intention of the RKU model was to enable staff to overcome the conflicting roles of researcher and teacher. The explicit linking of discipline and pedagogy opened up a space for 'methodological ecumenicalism' (Tenenberg and McCartney 2010), particularly in computer education. The authors argue that since 'computing education is in its early development … we have far more to gain by profligate method borrowing' (2010, 4). By way of example, White and Irons (2009) drew on social science methods to enable computer science educators to link research and teaching in mapping an undergraduate curriculum in alignment with the Discovery-Application-Teaching-Integration model (Boyer 1991).

The notion of drawing on methods and concepts from other disciplines to broaden and enhance disciplinary perspectives in the academic development of STEM university teachers is argued in several studies (e.g. Wistoft 2009; Olsson and Roxå 2012) thus discipline-based academic development is 'a cross-disciplinary subject that includes research about teaching, learning, and knowledge formation' (Olsson and Roxå 2012). In the context of engineering, Felder and colleagues warn that 'in the absence of discipline-specific examples it is easy for engineers to dismiss programme content as irrelevant to their courses, subjects, students, and problems' (2011, 2). This need for a greater focus on the discipline, does not imply that there is no role for academic developers, particularly those who have applied linguistics, education, psychology or sociology as a home discipline. Indeed, the literature suggests that social scientists can understand STEM disciplines and are thus able to point out to STEM educators, for example, that a pedagogy that places 'an over-emphasis on facts or techniques misrepresents the true nature of real scientific practice' (McWilliam, Poronnik, and Taylor 2008, 229).

Reflective practice in learning to teach the STEM disciplines

This category represents the majority of studies (43/77) in the data-base, all of which foreground pedagogy and background the STEM disciplines. The studies report on socially inclusive pedagogies (Killpack and Melón 2016), partnerships with industry in support of pedagogies of employability (Yuen et al. 2017), the role of mentoring relationships in STEM

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pedagogical training (Baiduc, Linsenmeier, and Ruggeri 2016), and collaborations and networks in academic staff development (Slowinski, Walz, and Alfano 2016). Most of the interventions reported on had the explicit intention to determine the extent to which professional learning interventions had enabled STEM faculty to move away from 'teacher-centred' approaches (Lockwood, Miller, and Cromie 2014) toward the 'exploration' (Brancaccio-taras, Gull, and Ratti 2016) or 'attainment' of student-centred teaching (Mattheis and Jensen 2014). A number of studies addressed pedagogical training that was appropriate to particular institutional types, that is, particular pedagogies for research-intensive (Newton et al. 2010) and teaching-intensive (Branoff, Lari, and Hsiang 2006) institutions; but disciplinary differences were not made explicit. A very wide variety of professional learning activities was noted: formal qualifications (Lockwood, Miller, and Cromie 2014), short courses, workshops (Simon et al. 2011), mentoring (Baiduc, Linsenmeier, and Ruggeri 2016) induction, collaboration (Slowinski, Walz, and Alfano 2016), seminars and reading circles – as well as innovative activities, such as requiring new academic staff to attend an undergraduate course in their first year of teaching so that they could 'experience the entire contents of the course in the same order that their students will' (Suchan et al. 2006, 17); or inviting colleagues to peer-review each other's teaching practice (Pembridge, Allam, and Davids 2015). A common theme across most of the studies in this category (and in university teacher development generally) was the important role of critical reflection on practice in the attainment of pedagogical competence. A number of studies propose teaching portfolios as a vehicle for reflecting on teaching (e.g. O'Mara et al. 2000). Sidhu points out that 'the primary aim of a [teaching portfolio] is to improve quality of teaching by providing a structure for self-reflection, which in turn aids professional development' (2015, 328).

University teachers are generally assumed to possess systematic knowledge related to their disciplines or fields, but need to engage in professional learning to acquire a similar systematic knowledge base with which to underpin their teaching practice and curricular decision-making (Walsh 2017). About a third of the studies (20/68) entailed supporting teaching assistants in acquiring pedagogical knowledge. This is not surprising as 'Science, technology, engineering, and mathematics (STEM) graduate teaching assistants play a significant role in the learning environment of undergraduate students' (Dechenne and Enochs 2010, 1). Facilitating 'graduate-student interaction with outstanding teaching-faculty mentors' is key to 'producing the next generation of high-quality university teachers' (Lockwood, Miller, and Cromie 2014, 17). Some of the studies have a focus on 'new faculty members [who] are often surprised by and uncomfortable with the number and breadth of courses they are expected to teach' (Newton et al. 2010, 15). Thus, the assumption that STEM university teachers have mastered the particular STEM discipline that they are teaching might need further investigation. With regard to the high numbers of teaching assistants and new academics undertaking professional learning programmes it is a concern that there was little in this cluster of studies that was STEM-specific (i.e. pedagogies that addressed STEM concepts, processes and values).

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Broad, generic issues

The final cluster of studies (14/77) while seeming to address STEM pedagogy, on closer inspection contained very little about either STEM or pedagogy. In most of these articles STEM was the context or background of the study, rather than its specific focus. In reporting on professional learning, this group tended to foreground educational technologies, such as the potential of blogs for electronic teaching portfolios (Goh 2016) or the 'My Reflection' mobile app that reminds one to critically reflect on practice (Ibrahim et al. 2016). Some articles discussed decontextualised presentation skills (Wyse, Long, and Ebert-May 2014), while others lost their focus on STEM pedagogy in wider professional development issues, such as the 'triple nexus' of teaching, research and scholarly engagement (Stevenson and McArthur 2015), or foregrounded the importance of motivators, institutional incentives and stakeholder cooperation (Janz, Wilkinson, and Kinley 2008) rather than STEM pedagogy. Despite the STEM context, this cluster of studies was extremely generic. Although some of the interventions were innovative, or were built around an important or interesting idea, this had not been fully developed and their potential or actual contribution to STEM pedagogy had not been addressed.

Table 3. Summary of findings on STEM pedagogy training.

Epistemic relations: STEM Knowledge			Social relations: Pedagogical Knowledge		
Concept	Indicators	Example	Concept	Indicators	Example
Knowledge of the STEM disciplines and fields	Evident STEM content	'*… our insight to the process of teaching the material … grew*' (Tenenberg and Fincher 2007).	Knowledge of pedagogy	Evident Pedagogical content	'*This workshop focused on listening effectively, giving constructive criticism and support*' (Lockwood, Miller, and Cromie 2014).
	No/little STEM content	'*Some of the issues were: low student attendance, low student achievement scores, and time management …* ' (Yuen et al. 2016).		No/little Pedagogical content	'*… student learning and pedagogical practice were not major emphases …* ' (Wyse, Long, and Ebert-May 2014).

Table 3 summarises how the research on the professional education of STEM university teachers engaged with STEM knowledge and pedagogy. We have shown how the epistemic relations to STEM knowledge and social relations to pedagogy varied across the research studies. Some of these variants are discussed below.

There are many issues to address in STEM pedagogical training – as the variety of studies indicates. Issues such as student motivation, the ability to make a clear presentation, or give useful feedback to students – or even to create a space to discuss issues beyond student learning and pedagogy are often important and context-depended. But while all the studies reviewed have some value, the focus that this paper has taken on supporting students' epistemological access to STEM disciplinary knowledge is more likely to occur when there is evident STEM content in university teacher training.

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Conclusion: the missing STEM

The key finding of this critical review of the literature on learning to teach the STEM disciplines in higher education is how little focus there was on the STEM disciplines themselves; the majority of studies reviewed did not address the key issue of what makes the STEM disciplines difficult to learn and challenging to teach. We did not, for example, find studies that drew on STEM 'threshold concepts' (Meyer and Land 2005) in academic staff development, although this approach is more common in research studies on STEM student learning (e.g. Male and Bennett 2015). Instead, interventions to improve teaching in the STEM disciplines tended to focus on the practical issues of lesson planning, facilitation, presentation skills, and reflective practice. While these generic aspects of teaching in higher education are important, they are only a part of STEM pedagogical competence. What was missing in the studies was the kinds of professional learning that would enable STEM university teachers to provide 'epistemological access' (Morrow 2009) to STEM knowledge: to its logic, systems, processes and values. This provision should be at the heart of STEM academic development, yet the literature shows how little we know about teaching STEM concepts. The professional development of STEM university teachers has over-emphasised generic forms of teaching practice and neglected discipline-specific teaching practice. This is, in a sense, understandable because STEM university teachers are presumed to have expertise in STEM, but this assumption should be challenged. For many STEM academics their areas of specialism are removed from the undergraduate curriculum and its more basic concepts; in the case of teaching assistants, new academics, or lecturers required to teach outside of their specialisms, the particular undergraduate subject might not be all that familiar. Thus many university teachers may need to re-visit key concepts in the STEM curriculum for undergraduate teaching. Although teaching STEM is different from STEM-based professional practice or research, the normative structure of STEM pedagogy derives from STEM disciplines and fields, and not from a generic pedagogy. The focus on generic pedagogy, rather than STEM pedagogy, can thus only partly address STEM pedagogical competence. Muller points out that the assumption in higher education teaching that 'the issue is pedagogical rather than epistemic [and] that the problem lies with the practices of teaching and learning rather than with the logic of the knowledge' is to deny the importance of 'epistemological access' to disciplinary knowledge (2014, 260).

Directions for further research

This study did not intend to imply that there is no STEM pedagogical training at universities; it is highly likely that there is commendable STEM pedagogical training in many universities – but these interventions have not found their way into the published literature. This is where more research is needed. It is proposed that a follow-up study is conducted using an 'evidence-informed' systematic review of non-research evidence (Chambers and Wilson 2012) on the pedagogical training of STEM academics. The 'evidence-informed' review, developed by McMaster University, includes criteria for the appraisal of the relevance and trustworthiness of non-research evidence (Yost et

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al. 2014). Such a review would include sources of evidence such as course outlines, training manuals and materials (e.g. Fry, Ketteridge, and Marshall 2009) that are available from both faculty-based and institution-based teaching and learning centres, as well as other training providers, such as the UK-based Higher Education Academy, newspaper articles (e.g. De Kadt and Leibowitz 2016) and government reports (e.g. European Higher Education Area 2003). Such an evidence-informed systematic review is likely to provide a wider, richer and more contextualised understanding of the actual practices being implemented.

Implications for STEM pedagogical training

The small group of studies identified that address STEM disciplinary content and appropriate pedagogies offer some insights into what STEM pedagogical competence might comprise and how university teachers might be supported in achieving such competence. Pedagogical training that focuses both on key disciplinary concepts and on how to teach these (e.g. Barth and Rieckmann 2012; Frolik et al. 2013), or that draws on the pedagogical training afforded by PCK approaches (or variants of these) (e.g. Marquez, Sánchez, and Valera 2013; Jwaid, Clark, and Ireson 2014) enable STEM academics to develop interdisciplinary understandings of STEM pedagogy. There is, for example, a growing literature on STEM 'threshold concepts' (Male and Bennett 2015) and on 'concept mapping' (Kinchin 2014) in STEM disciplines and these approaches could be productive for academic staff development. Training of academics in problem-based learning and the ways in which these approaches might impact students' understanding of STEM disciplinary concepts (e.g. Savin-Baden 2000) could be included in professional development workshops or courses. There are emerging academic development studies in lengthening (Shay, Wolff, and Clarence-Fincham 2016), as well as pressure for fast-tracking (Hertzog and Chung 2015) time-to-qualification in STEM programmes, and these create opportunities

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