MODESTUM

EURASIA Journal of Mathematics, Science and Technology Education, 2023, 19(3), em2232
ISSN:1305-8223 (online)

OPEN ACCESS

Research Paper

https://doi.org/10.29333/ejmste/12966

Bridging and brokering across communities of practice: A STEM coach's role in helping teachers access expertise

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Received 08 November 2022 ▪ Accepted 19 December 2022

Abstract

STEM education aspires toward integrated and contextualized instruction, both difficult goals for teachers. Expertise from within and outside the school are resources for helping teachers access content knowledge and practices in their classrooms. In this project, a STEM coach supported teachers to integrate and contextualize STEM instruction. Connectivity between teachers, outside experts, and other resources indicated opportunities for curricular integration and contextualization and was measured through social network analysis and analysis of teacher journals and interviews. The coach dramatically increased connectivity in the district through bridging and brokering relationships, maintaining a global vision for the district's STEM initiative, and navigating interpersonal relationships. Teachers utilized the connectivity to expertise to enhance STEM curriculum. Having a central actor (coach) allowed for rapid and widespread advancement of the STEM initiative.

Keywords: STEM coach, social network analysis, school reform, contextualization, integrated curriculum, community of practice

INTRODUCTION

As STEM (science, technology, engineering, and mathematics) evolves as a global academic discipline, its identity is evolving. The approach is coalescing around curricular integration of traditional academic disciplines (Dare et al., 2018; Johnson et al., 2016) and a focus on curriculum and instruction that is contextualized in real-world applications (Shukshina et al., 2021; Vennix et al., 2017). Though STEM has become a theoretical conduit of integration between disciplines and connectivity across traditional school boundaries, there is little guidance for schools or teachers on how to integrate through STEM.

This study was part of a larger initiative to integrate contextualized STEM into the curriculum of every grade level within Crawford School District (a pseudonym) in the western United States. The district vision included explicit integration of science, technology, engineering, and mathematics into all corners of the K-12 curriculum. This change process asked teachers to reach beyond their established pedagogical practices, including integration of STEM content that was unfamiliar to many of them. In order to increase the available STEM expertise within the school community and to build relevance and student engagement, the Crawford model depends heavily on building connectivity to local experts. We define this connectivity as opportunities to exchange practices and ideas between teacher and expert *communities of practice* (COPs). Such connections are difficult to make, and it requires knowing what expertise is needed, where to find that expertise, finding time to seek out relationships, and then knowing how to communicate within the external communities. Following existing research, we hypothesized that a STEM coach could assist teachers in making and supporting these connections (Marshall & Buenrostro, 2021; Rakap, 2017). To determine how a STEM coach worked to make these connections, we examined the processes that supported or hindered connectivity in the district. We present quantitative and qualitative social network data to address these research questions:

1. To what degree can a STEM coach influence teachers' connectivity to STEM expertise within and beyond a school district?
2. How do teachers experience and use access to STEM expertise as a function of changing

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Contribution to the literature

- This study extends the findings of existing literature to show that instructional coaching can be an effective tool for the difficult task of implementing STEM curriculum in schools.
- The use of a robust quantitative method (SNA) for showing changing professional relationships over time, coupled with the nuanced details of qualitative data positions the study to provide both reliable and useful data that are actionable in both research and practice settings.
- Visualizing existing professional networks and monitoring their change over time would allow future practitioners or researchers to similarly take advantage of actor centrality and bring new ideas into a school system.

professional networks and what role do they perceive for a STEM coach in that process?

Integrated STEM Education in Context of Real World

There is evidence to suggest that STEM-focused schools can increase retention of students in STEM academic pathways, particularly students from underrepresented demographics (Means et al., 2016), due in part to the authentic contextualization of the content. Exposure to robust, relevant STEM learning opportunities must happen before and beyond the high school classroom, and repeatedly in different contexts, to generate and maintain interest in STEM careers, particularly for demographics underrepresented in STEM professions (Maltese et al., 2014; Sadler et al., 2012).

Throughout the world, school science at the secondary level is generally presented as the siloed disciplines of chemistry, physics, biology, and earth science. However, this presentation does not reflect the realities of most professionals who apply science in non-academic settings. Mathematics, engineering, and technology are similarly compartmentalized. In contrast, professionals often apply skills and principles of STEM in concert with each one of those components.

Efforts to implement STEM in schools have been creating curriculum that involves integration of the disciplines (English, 2016; Vasquez, 2014). Bryan et al. (2016) suggest that STEM integration must be more than simply teaching disciplines together. They argue that robust STEM must be anchored in the core concepts of the disciplines; integrated largely through the science, engineering, and mathematical practices; building toward 21st century skills; and should all be in service of solving a real-world problem or task. From a teacher's perspective, this requires a demanding set of professional skills and content knowledge and can impact the degree to which curriculum is actually integrated (Dare et al., 2018; Reiser et al., 2017; Toma & Greca, 2018). Many teachers are interested in integrated STEM, but they often do not believe they are prepared to implement it in the classroom (Shernoff et al., 2017). Interdisciplinary teaching is well served when teachers' own expertise can be complemented with the expertise of learned others. Two natural sources for this expertise can be other teachers within the school and content experts from outside the school system (Maashi et al., 2022).

The degree to which in-school and out-of-school STEM experiences are coordinated can determine whether or not marginalized youths pursue future STEM education or careers (Rahm & Moore, 2016). Beier et al. (2019) showed that just one project-based course in which students solve real-world, client-centered problems positively impacted students' efficacy with and sense of utility for STEM skills, independent of race or gender. Teachers learning in contextualized settings can positively impact their practice and student outcomes (Baron, 2019). Teacher-scientist partnerships (TSPs) in which content experts interact with K-12 classes or teachers over time, can increase student interest in STEM fields (Shein & Tsai, 2015). TSPs also positively impact teachers' understanding of science content knowledge (Drayton & Falk, 2006; Shein & Tsai, 2015) as well as their sense of professional competence (Drayton & Falk, 2006). However, consistent impact of TSPs on classroom practice has been more elusive (Stroupe et al., 2018; Varelas et al., 2005). As Drayton and Falk (2006) wrote, "the cultures of science and of the science classroom are kindred, but they speak very different languages and have very different concerns" (p. 757). There is a danger in approaching the work from the perspective that teachers have a knowledge deficit that must be fixed, or that teachers must become full members of STEM COPs. Rather, teachers and scientists bring different expertise and priorities, resulting in the need for careful negotiations of exactly how teachers and students will be epistemically included (Stroupe et al., 2018). We investigated whether a STEM coach could successfully initiate and scaffold TSPs.

Coaches as Connection Agents

To address the needs of Crawford teachers a STEM coach was hired to work full time in the district. Her primary tasks were to directly support teachers with STEM implementation and to increase connectivity to STEM expertise. The STEM coach was to take a central role in creating and leveraging partnerships within the school district and with expert partners from outside the district. We have reported a more extensive description of the STEM coach role elsewhere (Giamellaro & Siegel, 2018).

Existing research on science coordinators, instructional specialists, and instructional coaches in literacy, math, and science informed the design of the STEM coach role for this project. Despite the variety of professional titles, much of the actual work these educators do is similar across the positions (Lee et al., 2014), while multifaceted within each position (Whitworth et al., 2017). We use the title "coach" to encompass all of these roles.

Coaches are often tenuously positioned between COPs (Giamellaro & Siegel, 2018; Kintz et al., 2015; Marshall & Buenrostro, 2021) which can be professionally challenging, but also beneficial for leveraging change within school systems (Hopkins et al., 2013). Coaches, via work with teachers, can have an impact on students' science understanding and overall student achievement (Marshall & Buenrostro, 2021; Sailors & Price, 2015). While coaches can positively impact teacher practices, this is more likely when the coaching is coupled to broader reform efforts (Hopkins et al., 2013; Kintz et al., 2015), and when coach roles are responsive to teacher needs rather than enforcing external mandates (Kennedy, 2016).

The role of connecting teachers to resources, particularly expertise, is central to coaching, and particularly for science coordinating (Whitworth et al., 2017). It has been shown that coaching can have a significant impact on the uptake and diffusion of information in a school system, though this is constrained by the contextual conditions within the school network (Atteberry & Bryk, 2010; Ma et al., 2018). Within schools, coaches can also help teachers find and use the expertise of other educators (Coburn et al., 2010; Ma et al., 2018; Whitworth et al., 2018) or help teachers decipher how to leverage expertise within a broader reform initiative (Coburn & Woulfin, 2012).

As with other aspects of coaching, leveraging connections is dependent on the context and how the coach approaches the work. The ability of the coach to build relationships with teachers and partners, with a focus on supporting teacher autonomy, are crucial for success in facilitating connectivity (Lee et al., 2014; Whitworth et al., 2018). The mixed success of TSPs is often attributed to differences in culture, knowledge of each other's contexts, and perceived power imbalances (Luft & Hewson, 2014). We anticipated a coach could act as an intermediary within these relationships and mitigate the perceived gap between professional communities. Scholars have been identifying the need for more research to develop an understanding on how coaches do their work and to what degree they achieve their objectives (Luft & Hewson, 2014; Whitworth et al., 2018). Specifically, Daly (2012) argues that "analyzing the social position of the coach in a network and relating that social position to some measure of effectiveness represents an underexamined area" (p. 14).

Situated Practice and Social Networks

We approach this work from the perspective that cognition and knowledge are "embodied, fundamentally social, distributed, enacted, and often work without representations" (Roth & Jornet, 2013). To do so, one must examine the full expanse of lived experience and think of situated cognition as the ability to creatively mobilize and augment knowledge that exists as collective praxis (Roth & Eijck, 2010). Professional practice is bounded as COPs a construct describing members of professional communities as internally co-constructing practice but doing so through interaction with the wider world (Wenger, 1998). Through connections between communities, actors do not just reproduce a community of practice, but also alter it through their own activity, thereby renegotiating meaning (Lave & Wenger, 1991). From this situated perspective, we interpreted the interactions of all of the actors in the school system as co-developing STEM education practice (Siegel & Giamellaro, 2020).

We focused on the periphery of these COPs as teachers navigated newfound overlap between their own COPs and those of other experts. These peripheries are fertile areas for the diffusion of change-inducing ideas (Wenger, 1998). Crossing COP boundaries and operating at their peripheries is challenging and nuanced but offers the chance for learning through transferring practices between communities (Wenger, 1998). *Brokering*, or the "use of multi-membership to transfer some element of practice into another" (Wenger, 1998, p. 109), allows communities to open new possibilities for meaning. We envisioned the coach as a potential broker who would have legitimacy in multiple communities, in and out of school. As such, she would be able to mobilize attention, address conflicting interests, link practices, and help teachers to transfer practices and ideas back to their own COP (Wenger, 1998).

Being a central actor in a social network, a person with a disproportionate number and weight of ties to others, has repeatedly been shown to position that person to have an outsized impact on the structure and outcomes of the network (Borgatti et al., 2009; Daly, 2012). Central actors within school change networks can develop other actors' capacity and broker skills between them (Daly, 2012). Within social networks, "bridgers" span the gap between otherwise disconnected actors while "brokers" connect otherwise disconnected actors to each other (Daly, 2012). A goal for the coach in this project was to start with bridging to provide teachers with quick access to expertise (Ma et al., 2018) and transition to brokered relationships to avoid the central actor bottleneck effect (Whitworth et al., 2018).

Social network theory (SNT) and social network analysis (SNA) provide an analytical lens for examining the social structures within which practice is situated (Daly, 2012). SNT conceptualizes the degree to which interaction is occurring, as well as the diffusion of information and expertise within a network, thereby telling part of the story on how knowledge is situated in practice. Information diffuses from person to person, but it also evolves in practice as it does so (Frank et al., 2011; Rogers, 2003). These interactions are represented in dyadic, strong, weak, and historic ties within human systems (Coburn et al., 2013) and these relationships can be analyzed quantitatively and qualitatively through the tools of SNA. For this study, it was important to identify the interrelated social networks within the school district because COPs and institutional boundaries do not necessarily coincide (Lave & Wenger, 1991). Assumptions based solely on institutional boundaries might not reveal an accurate picture on how expertise is shared or co-constructed within actual COPs.

Professional Networks and School Change

The structures of social networks have consequences for school performance and reform. The outcomes of social networks may be tied to the resources, including expertise, that are situated amongst the ties, and one's position in a network can impact access to those resources (Coburn & Russell, 2008; Coburn et al., 2012). Lateral ties in a teacher network, a proxy for the degree to which teachers are sharing expertise, can be predictive of student performance (Pil & Leana, 2009) and school networks with strong ties to expertise can have a positive impact on student learning (Bryk, 2010). Highly connected teacher networks are also associated with better implementation of reform initiatives (Grossman et al., 2001). Policy interventions can impact the structure of educator networks, the nature and degree of what flows between network ties, and network outcomes (Coburn et al., 2013; Maashi et al., 2022; Rivera et al., 2010).

Positive professional development outcomes have been demonstrated when teacher networks were expanded beyond one's own school, and when a coach provided the structure to make this happen (Prenger et al., 2017).

METHODS

We used a mixed-methods design to interpret the evolution of the social networks associated with STEM implementation across the Crawford school system, focusing on the interactions of the coach and from the perspectives of multiple educators. The networks were examined quantitatively to measure the degree to which teachers became connected to expertise beyond their own background. Because connectivity alone does not inherently indicate that positive practice is being developed (Coburn & Russell, 2008; Frank et al., 2011), we analyzed qualitative data to examine how teachers were incorporating outside practices into their own COPs (Coburn et al., 2012).

Participants

The western US town of Crawford had a population of 1,375 and 686 students attended school during the primary study year. All three schools, Crawford Elementary, Middle, and High, sit on a common campus and comprise the full school district. Most of the educators associated with the district were included in this study, including teachers (n=34), administrators (n=3), and the STEM coach (n=1). This included teachers from all disciplines and grade levels.

Table 1 shows descriptive characteristics of the participants. The coach, hired from a different state, had twenty years of STEM teaching experience, predominantly at the middle school level. She had experience leading teacher development at the district level and had extensive experience working in TSPs (see Giamellaro & Siegel, 2018 for a more complete description of the coach).

All participants were guided through a consent process in which they were informed about the study, their potential role in it, the mandate and limits of confidentiality, and their written signature of consent to participate. Two district teachers chose not to participate..

Quantitative Network Data Collection and Analysis

Quantitative data collection

District personnel and the STEM coach were asked to complete a digital survey through which they selected from a list everyone in the district with whom they professionally collaborated. This *roster technique*, a common approach for SNA, was used to determine degree of professional interactions across the school district (Atteberry & Bryk, 2010; Avila de Lima, 2010). For each person on the list, participants responded to the prompt "in the last six months, how often have you discussed curriculum or instruction with the following people?" choosing, "less than once a month", "once a month", "2-3 times a month", "once a week", and "2-3 times a week or more". Such interactions represent quantifiable aspects of otherwise multifaceted social relationships that can help establish network structure (Daly, 2012; Ma et al., 2018). The ratings were used as the tie strength in analysis of the networks (Avila de Lima, 2010).

To account for network actors from outside the institutional boundaries, who were not listed on the roster, participants were asked to write in any other people who were not listed on the roster, and indicate their rate of collaboration with them, a process called the *name generator* technique (Avila de Lima, 2010; Marin & Hampton, 2007). The complete instrument (insiders and outsiders) was administered during whole-district faculty meetings and absent participants were asked to complete the task via email. The first survey, administered before the STEM coach was hired, was used to establish a baseline. To sample the period of heightened change associated with the launch year of the initiative, the survey was administered halfway through and at the end of the school year (Coburn et al., 2013). The response rates for each of these surveys was 89%, 88%, and 75%, respectively.

While respondent inaccuracy is a threat to SNA, frequency of interaction is a reliable measure, particularly with the roster method (Avila de Lima, 2010), and participants' perceptions of their interactions are considered to be a more realistic metric of the quality of interactions than are an external observer's tallies (Borgatti et al., 2009). To address the other key threat of non-response bias (Avila de Lima, 2010), we first calculated the *individual internal accuracy correlation,* which measures the degree to which pairs of actors agree with each other on their interactions (Kashy & Kenny, 1990). Because agreement was generally high within these dyads, we used a *symmetrization approach* to average responses within each dyad and a *reconstruction approach* to fill in gaps from nonrespondents with the responses from others in each dyad (Avila de Lima, 2010). Finally, we triangulated network sociograms with qualitative data to detect contradictions (Avila de Lima, 2010).

Quantitative data analysis

A *whole network analysis approach* (Borgatti & Ofem, 2010) was used to examine changes in network characteristics over time. Because this approach allows for analysis at local as well as global levels, it is considered the "gold standard" of network analysis (Avila de Lima, 2010). Gephi software (gephi.org) was used to calculate network metrics from the survey result matrices. *Average path length*, or the fewest number of ties one must follow in network to connect each node to each other, was used as a metric of overall network centrality.

The averaged, nondirectional network *degree* was calculated for each actor, indicating the total number of reported ties, and this was used to indicate how connected each actor was over time as well as the average connectivity of the whole network (Coburn et al., 2010). These values were weighted by the frequency of each reported tie. *Degree centrality*, or ranking actors by weighted degree, is the simplest way to determine the structural importance of each node (Borgatti et al., 2009), and who is most central in a network (Spillane et al., 2010). *Betweenness centrality*, how often an actor lies in between any two others as the shortest path between those nodes (Spillane et al., 2010), was used to indicate a role of bridging otherwise disconnected actors (Daly, 2012). Central actors are indicated by a higher proportion of such interactions (Daly, 2012).

In many social networks, homophily, some quality of sameness with other actors, or physical proximity to others, such as adjacent classrooms, explains much of the structure in a network (McPherson et al., 2001). Social ties are often predicted by teachers' grade level within schools, but this pattern may not hold in a small, rural district in which each grade or specialization has only one or two representatives (Coburn et al., 2013). Because all teachers in Crawford are close in proximity and homophily is confounded by friendships and family ties across the district (Avila de Lima, 2010), we approached the measure cautiously, identifying instead, actual communities of interaction as indicated by network structure. For each of the instances in which the network was modeled, we used the *Lovain method* (Blondel et al., 2008) within Gephi to partition the network into densely connected communities based on reported interactions.

Sociograms were plotted in the Gephi platform using the *Force Atlas* algorithm, which results in a degree-dependent, force-directed graph, developed specifically for SNA visualization of community relationships (Jacomy et al., 2014). Within-district ties of frequencies less than once per month were pruned from the sociograms for ease of visualization.

Qualitative Data Collection and Analysis

Participant journals

Out of the full participant sample nine teachers, one administrator, and the coach volunteered to keep a written journal to chronicle their experience with the district's shift toward interdisciplinary STEM. Journal participants (**Table 1**) were selected to represent a variety of grade levels and disciplines. Journal participants were given a modest stipend and were asked to journal multiple times per week. They were prompted to record any combination of

(1) what they taught,

(2) student reactions,

(3) reflections on their changing practice, and

(4) thoughts on the unfolding STEM initiative.

There was no specific request to discuss the coach or connectivity as we wanted to capture the degree to which the intervention was situated within their normal professional life and a choice to include a journal passage therefore indicated significance for the writer (Brenner, 2006). Participants logged 600 journal entries describing 2,243 events.

Participant interviews

We conducted open conversational interviews (Brenner, 2006; Fontana & Frey, 2000; Patton, 2002) with all participants with the goals of

Table 1. Descriptive characteristics of participants

CN	Grade or subject	Gender	YE	J?
E11	4	F	3	
E12	5	F	23	
E14	1	F	0	
E18	K	F	15	
E20	Other	F	10	
E28	4	F	2	Yes
E33	2	F	23	
E52	5	F	7	Yes
E61	1	F	35	
E73	3	M	10	
E86	2	F	30	
E93	K	F	19	Yes
M10	MS multiple	F	12	
M23	MS multiple	M	1	
M45	MS science	F	16	Yes
M78	MS ELA	F	2	
M95	MS math	M	10	
H10	HS science	M	16	
H11	HS multiple	F	15	
H12	HS other	M	16	
H13	HS ELA	F	16	Yes
H24	HS multiple	M	11	
H37	HS STEM/CTE	M	39	
H48	HS multiple	M	9	
H56	HS math	F	11	Yes
H66	HS other	F	15	
H72	HS social studies	M	4	
H83	HS math	M	2	
H91	HS other	F	14	Yes
C11	Multiple	F	0	
C13	Special education	F		
C20	Other	F	11	Yes
C38	Other	F	4	Yes
C57	Other	F	7	
C90	MS/HS technology	M	18	
C47	STEM coach	F	17	Yes
A11	Administrator	M	20	
A16	Administrator	M	10	Yes
A94	Administrator	F	25	

Note. CN: Code name; YE: Years as educator; & J: Journalist

(1) triangulating their perspectives with those recorded by the journalists and

(2) "understanding informants on their own terms and how they make meaning of their own lives, experiences, and cognitive processes" (Brenner, 2006, p. 357).

Interviews were opportunities for participants to share their thoughts and feelings about the STEM initiative. The interviewer generally prompted the conversation and let the informants speak about any aspect of the initiative or their professional practice that was at the forefront of their mind, at times pressing for more detail when identified themes were brought up. The interviews were of varying length throughout the year, as limited by participants' availability. The gist of all interviews was recorded in field notes. All participants were interviewed opportunistically multiple times throughout year by the second author, an experienced ethnographer who was embedded in the district full time throughout the study year.

Network sociograms

A central axiom of SNA is that node position determines opportunities and constraints (Borgatti et al., 2009). The sociograms described above were used in conjunction with the qualitative data to interpret this aspect of reported actor interactions (González-Howard & McNeill, 2019) as well as interactions that might be explained by homophily and proximity (Coburn et al., 2010). Because Gephi is interactive, one can easily click on and isolate an egonet of an individual actor from the full network to quickly identify the interactions and communities of a given actor and track interactions over time. This function was used in triangulation with the qualitative data.

Qualitative Data Preparation and Analysis

Journal entries and interview notes were uploaded into a database driven by qualitative data analysis software (Dedoose.com) and excerpted by event, an approach that preserves the context and meaning-making processes of the participants (Ash, 2007). An event was defined as having a unique time, place, actors, and purpose. This process led to 3,420 unique excerpts, across journals and interviews. Each excerpt was descriptively coded to indicate characteristic information about the contributor and the events (Miles et al., 2020). These descriptive codes included data source, type of event, and participants involved. Each participant was also associated with metadata (Miles et al., 2020) to indicate gender, ethnicity, professional position, teaching level and subject, years of experience, and participation in STEM professional development. These descriptors allowed for sorting and aggregation of excerpts as themes emerged associated with these variables. A final level of descriptive coding included an analysis of all excerpts to determine if the STEM coach was referred to in any way. The STEM coach was referenced in 1,134 excerpts (33% of all excerpts) and this subset is the focus of this study.

During the first pass through the data to identify germane excerpts, coders (first Author and research assistants) attached memos to the excerpts to indicate recurring themes (Miles et al., 2020) in the way that participants described the role of the STEM coach as a connector (**Table 2**).

These memos led to three thematic codes describing actions of the coach, *making community contacts*, *relationship building*, and *communicating*, and a theme of teacher *outside collaboration*. Twenty percent of the excerpts were coded and calibrated by two coders until acceptable agreement was achieved (κ=.70).

Table 2. Code definitions

Code	Definition
Community contacts	Coach provides, acquires, maintains contacts with people or organizations from outside the district. Applies only to making contact or basic other basic communication.
Relationship building	The coach building or maintaining relationships/rapport with others. Coach described as intentionally fostering or maintaining a relationship between other individuals or groups. Includes bridging and brokering.
Communication & reporting	Coach is described as reporting to others outside of the district or acting as an information conduit between outsiders and district staff. Includes communication within the district. Includes email, conference presentations, reports, etc. Does NOT include journal writing as it is a data collection tool for research, but it DOES include other communications to the research team.
Teacher outside collaboration	Seeking or using expertise associated with a person from outside of a teacher's class or immediate professional practice. Does not include common institutionally-defined collaborators such as a same-grade teaching partner in elementary or a special education or ESOL specialist.

Table 3. Educator network connectivity over time

	Pre-coach	Six months with coach	One year with coach	Significance
Mean degree†	7.5	5.5	5.7	p>.05
Mean weighted degree	22.9	15.4	17.0	p<.001
Coach degree	0	108	59	N/A
Coach weighted degree	0	282	214	N/A
Average path length ‡	2.1	2.3	1.7	N/A
Graph density§	.23	.07	.11	N/A
Average betweenness¶	.03	.02	.03	p>.05
Coach betweenness	N/A	.58	.41	N/A
Mean percent of ties outside of building	27%	45%	54%	p<.001
Average weighted indegree STEM teachers	29.0	28.7	25.3	N/A

Note. †Degree indicates the number of robust professional ties reported for each teacher. Weighted degree also considers the frequency of contact. Internal weighted degree only considers Crawford staff and STEM coach; ‡Path length indicates the fewest number of nodes (people) in a connected path between any two nodes in the network and shows the connectivity of the network as a whole; §Graph density indicates the proportion of possible ties that are reported as ties; & ¶Betweenness indicates the frequency that a node is the shortest path between any two other nodes

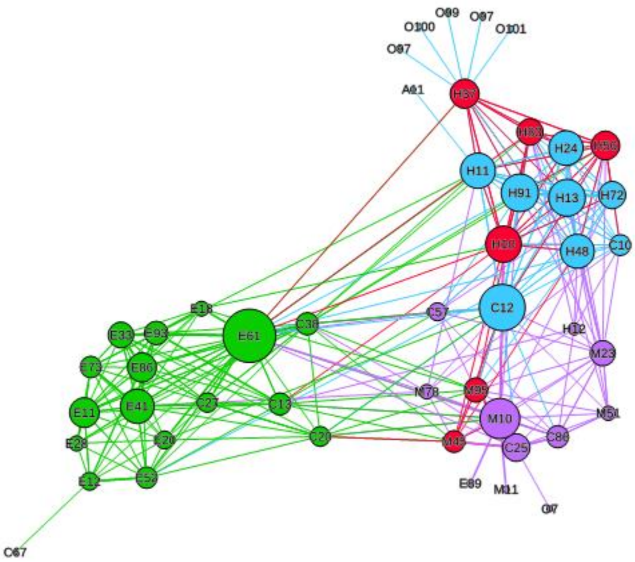

Figure 1. Network sociogram at time one, before STEM coach (Source: Authors' own elaboration, using the Gephi App)

The remaining excerpts were coded individually by the two coders who met regularly to discuss unclear code applications.

The data were examined by code frequency, code co-occurrence, and aggregated through use of the descriptors (Miles et al., 2020). We examined trends and differences by educator group and over time. We then examined the reference texts in context to further illustrate the documented perceptions that participants shared about how they utilized the coach for connections to outside expertise and how they utilized that expertise. The sociograms were also used to trace the pathways of interaction as reported in the narrative data (Coburn et al., 2013) and to make inferences about homophily and proximities stated or implied in the data (Coburn et al., 2010).

RESULTS

Changing Social Networks

The SNA data are shown in **Table 3**. Similarly, the network sociograms are plotted in **Figures 1 - 3**.

Figure 1 depicts the network sociogram before the STEM Coach, and shows the connectivity of the educator network as a function of presence and frequency of professional interactions reported by district staff. Teachers and other collaborators are represented by nodes. Node codes can represent individual teachers

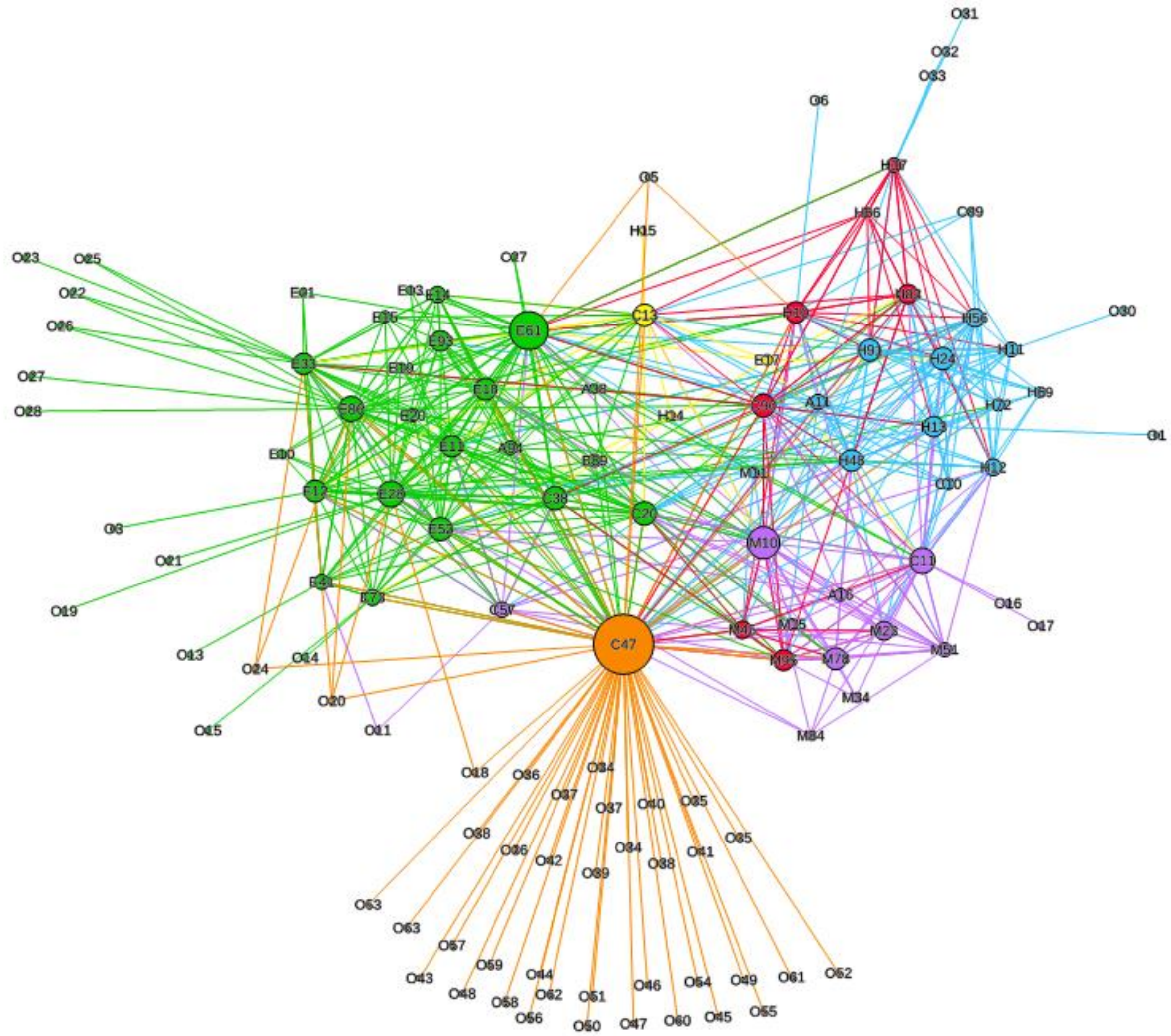

Figure 2. Network sociogram at time two, six months after STEM coach arrival (Source: Authors' own elaboration, using the Gephi App)

that can be referenced in **Table 1**. Codes follow the pattern of E is elementary school, M is middle school, H is high school, C is cross-building educators, A is administrator, and O is outsider. Node size indicates weighted degree (# and frequency of reported ties). The edges (ties) in **Figure 1** represent the professional collaborations indicated by the participants and the weight of those lines represents the frequency of those interactions such that a heavier weight indicates more frequent collaboration. The distances between nodes in **Figure 1** also represent frequency of interaction but consider all network ties for the resulting arrangement. Functional community groups are calculated as clusters of regularly-collaborating actors and each cluster is colored similarly. In **Figure 1**, the green nodes are largely elementary school teachers, purple nodes are largely middle school teachers, and blue nodes are largely high school teachers. The red nodes are teachers from STEM disciplines, and these are colored post-hoc, not representative of a functional group. Each STEM teacher is part of their building's functional community.

Figure 2 shows the network sociogram six months after STEM coach arrival. At time two, functional community groups have shifted slightly shown as the same colors as in **Figure 1**. A notable exception is that the STEM coach, node C47 is the center of a new community, comprised largely of outside experts (nodes starting with "O"). Teacher C13, a special educator who interacted with the most teachers regarding specific students, also was the center of a small functional community.

Figure 3 demonstrates the network sociogram one year after the STEM coach's arrival. At time three, functional community groups have again shifted with the STEM coach, node C47, becoming the center of the middle school group. Most outsiders have now become part of individual building communities, shifting out of the STEM coach's.

The *mean degree* (**Table 3**) represents the number of other people within the network that each person collaborated with over the preceding six months (the undirected ties). A repeated measures ANOVA determined that changes in degree did not change

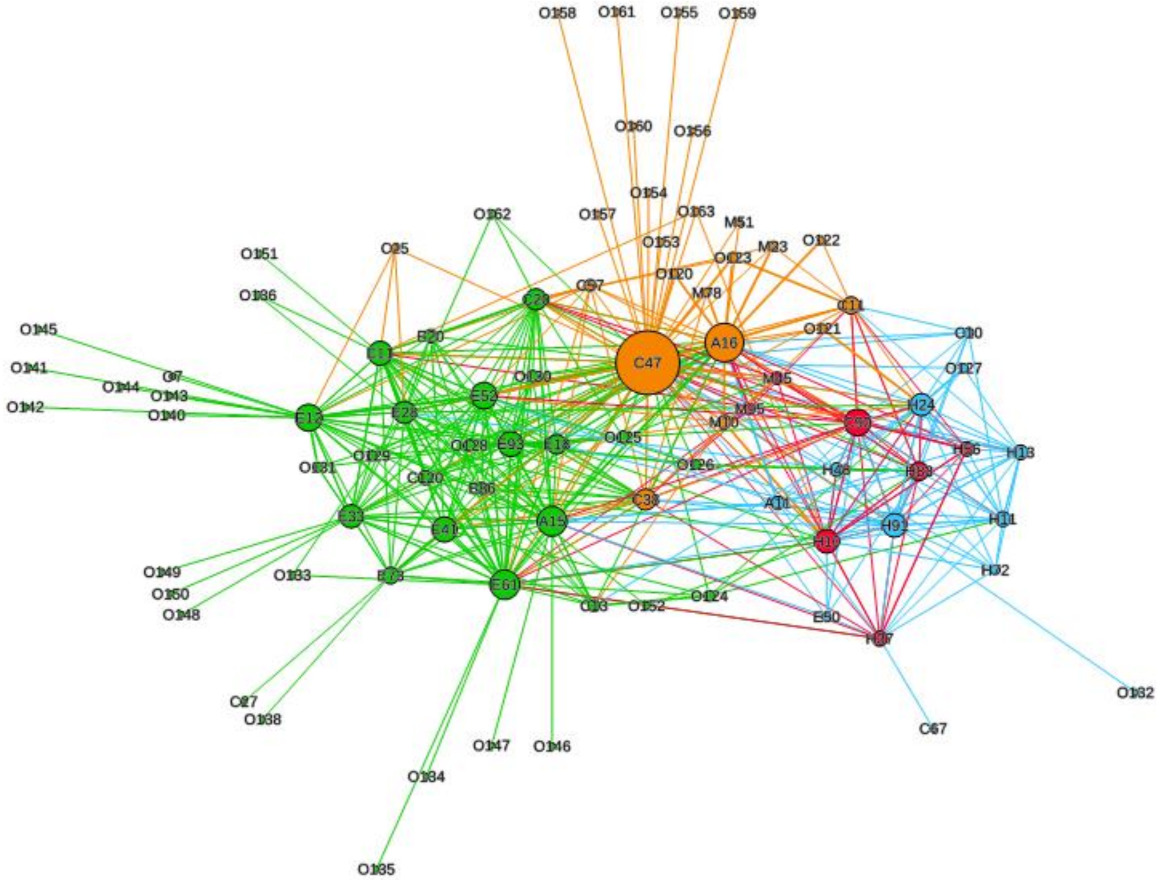

Figure 3. Network sociogram at time three, one year after STEM coach arrival (Source: Authors' own elaboration, using the Gephi App)

significantly across time points, p>.05. The *weighted degree* (**Table 3**) adjusts for the frequency of those collaborative efforts. A repeated measures ANOVA determined that changes in weighted degree across the network were significant $F(2, 70)=9.18$, $p<.001$, albeit with a small effect ($\eta^2=.20$). In other words, over the course of the year and a half, the average teacher did not significantly change the number of collaborators she was professionally connected to, but she did increase the frequency she worked with them.

Betweenness, the measure of how often an actor lies in the shortest network path between any two other actors, did not change significantly for the average teacher in the network, $p>.05$ (**Table 3**). This was determined with a repeated measures ANOVA with a Greenhouse-Geisser correction. The average teacher was the shortest path for only 2-3% of any two other nodes, suggesting the teachers were generally not acting as intermediaries within the networks and that this did not change over time.

The proportion of ties that teachers made to actors outside of their building, an indication of seeking outside expertise, rose from 27% to 45% to 54% over the course of the study (**Table 3**). A repeated measures ANOVA determined that this was a significant change, $F(2, 36)$, $p<.001$, with a medium effect size ($\eta^2=.40$). In other words, homophily and/or proximity were decreasing factors in defining the teachers' COP as they sought external expertise for their STEM work.

The full network structure also evolved over the course of the study. *Average path length* indicates the average number of ties required to most efficiently "travel" from one node to another on the sociograms (**Figure 1**, **Figure 2**, and **Figure 3**). *Graph density* indicates how complete the network is, such that a school system in which every educator worked with every other would result in a value of 1.0. Path length increased from 2.1 to 2.3 and then decreased to 1.7 while graph density decreased from .23 to .07 and then partially recovered to .11 (**Table 3**). Together these metrics indicate that the network became less connected from time one to two and then slightly more connected again by time three. While these network changes seem problematic, examination of the sociograms (**Figure 1**, **Figure 2**, and **Figure 3**) illustrates that the decreased connectivity is not a result of teachers working with each other less, but with outside experts more, resulting in many weak ties outside the original network and resulting in a less connected network overall.

To further examine these interactions, actual (as opposed to institutional) networks were modeled from the interaction data with the Lovain method (Blondel et al., 2008) and represented by separate colors in **Figure 1**, **Figure 2**, and **Figure 3** (except red, which indicates a STEM teacher). At time one (**Figure 1**) the networks align largely to the different buildings. Elementary, middle, and high school teachers were occasionally collaborating across buildings but mostly within their own. By time two (**Figure 2**), this pattern largely remains the same, though the coach (node C47) is central to a new community, made up of many outside experts who also begin to work with some of the teachers. In time two, individual teachers also begin to work with outside experts who functionally become associated with those building-level communities. By time three (**Figure 3**), the coach community and middle school community are merged. Many of the outside experts become increasingly connected and even centrally positioned within the network (e.g. O130, O125, O126, and O128).

Central Actors

It was expected that the teachers who taught in STEM disciplines (science, technology, and math) would become more central actors as other teachers sought them out for collaboration. We used *indegree*, the frequency that others indicated having professional conversations with STEM teachers, to measure how their expertise was sought out over time. Though the number of these teachers did not provide sufficient power for statistical analysis, the trend over time is that STEM teachers were sought out slightly less over the course of the study (**Table 3**), a surprising finding. These patterns are also reflected in **Figure 1**, **Figure 2**, and **Figure 3**, where STEM teachers' egonets, shown in red, remain essentially unchanged over time.

Part of this under reliance on STEM teachers may be explained by the outsized reliance on the coach over that same time period. Within six months of starting, the STEM coach became the most central actor in the district, with a weighted degree eighteen times the average (282, **Table 3**). After one year her degree decreased noticeably (from 108 to 59), though her weighted degree did not change as much (282 to 214, **Table 3**). In other words, the number of her collaborations decreased, but her remaining collaborations strengthened to offset that loss within the network as a whole. Much of this pruning is explained by the high number of outside collaborators who were recruited by the coach to work with the district. She initially sought a wide variety of collaborators and then focused on those for whom professional connections with specific teachers were most beneficial or productive (**Figure 1**, **Figure 2**, and **Figure 3**). The coach's betweenness was also the highest in the district at Time Two (.58 compared to an average .03), suggesting that she was acting heavily as a bridger between actors and then a broker as her betweenness decreased (.41) and teachers' outside connections increased (**Table 3**, and **Figure 1**, **Figure 2**, and **Figure 3**).

Qualitative Themes

Participant journals and interviews were used to further understand how teachers experienced these changing social networks, the coach's role in that process, and then utilized newly connected expertise.

Connecting to outside experts

The connections reported as most successful were ongoing partnerships in which students became involved in STEM projects that were applied in the community under the guidance of STEM professionals. This included middle school students working with the local state park rangers to restore a burned section of the park. High school students worked with federal land managers to remove an invasive tree species from a watershed, and then monitored the environmental response over time. To facilitate these types of projects, the coach connected teachers with STEM experts and supported those relationships by helping to translate needs and communication styles across the professions. In addition to creating applied projects for students, the teachers used these experts to speak to their students, as a source for material goods, and as a source for general information about a topic.

The coach described making community connections in 10% of her journal excerpts, though she often described making many contacts together in one excerpt, suggesting the code may be underrepresented. In teacher excerpts, eleven percent referred to the coach contacting outside experts. The teachers often did not know when the coach was making contacts on their behalf, particularly when the leads did not come to fruition.

Administrators particularly valued the coach role of making community contacts, citing it in 26% of their references to the coach. In an interview, the superintendent valued "creating partnerships, business partners, resources. She (coach) can easily connect and has such enthusiasm for great ideas. Teachers don't have the time to do that. She makes connections everywhere... She is determined to create community." Other administrators shared similar thoughts about the lack of time for teachers to make such contacts and the persistence of the coach in trying to enlist outside experts.

Transforming these connections into productive relationships required relationship bridging and brokering. In the following journal passage the coach describes how she tried to broker a relationship between the schools, a local company, and the local water board, so that teachers and students could have a more complete understanding of the complex business and ecological interactions at play:

> Had a meeting with Mike at [Water Bottling Company] and forwarded the information to the

> elementary school staff. They can call [company representative] for specific request to package the water, or to tour the facilities, also [Crawford] County Water Group has the charge of [Crawford] Springs. If students want to visit the source of their drinking water, they'll have to make a connection with those folks, once again I sent it to [elementary teachers], as they have all requested information from and about [Water Bottling Company]. I forwarded the information to the elementary teachers who requested as well as [High School Principal]. I don't feel as if I should be the one to establish a long term relationship with the company. I leave that for [Principal], as he expressed interest in doing that.

We asked the high school principal whether he thought such coach-brokered relationships would be maintained. He replied, "some yes and others no", attributing this more to the dispositions of specific teachers than to the outside partner or to the way in which the coach navigated the relationship. We also noted in our observations that individual teacher dispositions played a central role in how the teachers approached the coach's brokering between COPs. One high school teacher was open to the provision of resources by the coach but did not respond well when the coach tried to teach him how to make and maintain the connections on his own. In one visit to his classroom, he appeared flustered and disorganized, explaining that he had expected the coach to have brought in soil-testing kits for his lesson (bridging). The coach's journals indicated that she had arranged for the teacher to connect with the soil agency and pick up the kits himself (brokering). While the coach was focused on brokering membership across COPs, a few teachers expected the coach to bridge the COP boundaries for them indefinitely.

Connecting people within the district

There was STEM expertise to be found within the district. In some cases, this led to cross-grade partnerships through which older students could become mentors to younger students. In other cases, the coach could bring different classes into a broader project at an appropriate commitment and developmental level. The coach described a lunchroom conversation between teachers in which she began to see conceptual connections that could be utilized by multiple teachers, where outside expertise would be helpful, and how she would need to broker some of those relationships,

> I'm able to talk with [HS science teacher] and [HS career & technical education (CTE) teacher] over lunch. Seems [CTE teacher] is trying to choose what to plant next year, for the school garden. It'll be a mixture of grain and hay. [Science Teacher] is interested, a grain and hay mixture is a good seller in the areas around [Crawford], pretty drought resistant too. That will be a problem this year, so little winter snow. One topic leads to another and I look up hops, hearing about [partner university] professor who is the world's expert on it. Hey, think about growing hops! Great market! I go and do a few searches. Back to malt and Barley. Hey, it is germicidal, and the straw helps kill algae. WOW, a flash. One class grows the barley, another cuts it and puts it into mesh bags to kill the blue-green algae at [a local reservoir and site of a middle school project]? More research? I think I'll talk to [MS science teacher] about it.

As indicated in **Figure 1**, **Figure 2**, and **Figure 3**, the STEM coach quickly became connected to not only the outside collaborators but to almost every person in the district. Her role as a central actor positioned her to reach out to and follow up with each teacher. As such, the coach quickly became a conduit for information flow within the district. The coach reported communication tasks more than any other theme (32% of excerpts) and the majority was conducted within the district. The qualitative data suggest that although direct ties between STEM and non-STEM teachers may not have changed much over the course of the study, collaboration via the coach was a mechanism the network used to share expertise across COPs.

The breadth of the coach's communication extended to students, parents, teachers, administrators, the research team, other community members, and external partners. In some cases, the coach also fostered pathways for others to communicate with each other. Because the coach was in a unique position of having a global view of STEM in the district, because she was perceived to have the time to do it, and because she was willing, she became the communications bridge, through which most participants shared STEM information outside of their immediate professional circles. While there was efficiency and benefit to the STEM coach serving as a communication hub, there were also tensions associated with this role. In several cases the coach was perceived as undermining administrator authority when acting as a communications bridge.

Teachers integrating STEM expertise into curriculum

Teachers regularly recruited experts to visit their classrooms, usually with help from the coach. Once there, the experts were occasionally asked to give traditional talks about their professional fields. More often, teachers asked the experts to participate in the practices of their classroom where the experts could re-situate their knowledge. For example, a third-grade class was working on a project to design containers that could keep ice cream from melting. The teacher, with the help of the coach, invited an engineer from an insulated bottle company to visit. He shared how the engineering design process was utilized within his company. He was then asked to give feedback to students' designs.

Some connections were highly collaborative and blurred the line between COPs. For example, the middle school, through the coach, started and maintained an ongoing collaboration with a local state park. The rangers would often visit classrooms to share their expertise about ongoing projects (e.g. monarch butterfly migration, local flora and fauna, visitation patterns). When a wildfire burned through the park, a trail development project was quickly re-envisioned so that students could help replant native vegetation and redesign interpretive signs to accommodate the changes. The rangers' expertise was incorporated into the direction of the school STEM curriculum rather than being a side topic.

In another example, the fourth-grade teachers were enacting a social studies unit on the Oregon Trail. They used the "storyline method" in which students take part in an ongoing narrative and must solve problems along the way. In one challenge, students learned about the difficulty of finding potable water along the trail. Students were challenged to develop a working water filter and teachers invited a water treatment specialist to share some tips and content knowledge that were outside the teachers' own expertise. Although the coach had brokered this connection, the teacher reflected in her journal that she would personally reach out to the expert the following year when they repeated the lesson, suggesting longevity to the brokered relationship.

Network ties as relationships

Acting as a central communicator and liaison for the district was inextricably entangled with the personal relationships that the coach developed with participants, as well as the relationships she tried to broker between others. For the coach, these connections represented a tremendous amount of interpersonal work. She recognized the importance of this aspect of her work, writing "nothing else really matters if you cannot work with the teachers and discover the teachers' passion." Teachers and administrators described interpersonal relationships with the coach in positive ways.

There were also tensions as all parties navigated the school change process. Some of these tensions were exacerbated by organizational structures. The coach was hired as an outreach employee of the partner university, rather than as an employee of the school district, though she spent 90% of her time working in the district. This arrangement was designed to facilitate safe relationships with teachers such that teachers could be assured that their work with the coach was entirely supportive, rather than an evaluation tool of the administration. However, the arrangement also caused tensions for the coach when she felt the expectations of the various communities were not aligned. Even within the district, the coach could not be temporally or physically in all places at once. Because she was given an office space in the Middle School (all of the schools are adjacent), she was, at times, perceived as favoring that school. Indeed, the SNA data also suggest that the coach became more central to the middle school than to the other building COPs (**Figure 3**).

A tension arose when the coach was unsure if she should be managing relationships between administration and teachers. Because her charge was to support teachers, and because teachers saw the coach as a neutral arbiter of disagreements who would allow complaints to remain anonymous, this facilitation role naturally evolved into positioning the coach as an ad hoc intermediary between administration and teachers. Similarly, administrators saw the coach as a knowledgeable resource who could report back to them on what was going well or poorly in the classrooms she was visiting. There were multiple cases in which this became problematic as the coach wanted to support but also protect teachers. She felt torn about needing to preserve the professional safety of her coaching, weighed against providing information to administrators that could potentially improve instruction in the schools.

DISCUSSION

While curricular integration and connection to authentic practice may represent laudable approaches to STEM and K-12 education in general, these approaches require a breadth of expertise that is not well-captured in traditional teacher preparation nor professional development, suggesting the need for another teacher supports (Dare et al., 2018; Gilbert et al., 2011). Rather than approaching this problem as a singular teacher training response to a complex problem, we sought to expand the network of expertise and experience within each classroom. A project goal was to collectively bring in the context of authentic STEM practice and to integrate STEM by complementing each teacher's expertise with others' STEM expertise. We sought to work along and blur the boundaries of various COPs such that knowledge would be situated within a wider network and more broadly accessible to teachers and students. Specifically, we examined the role of a coach in facilitating increased permeability between actual COPs rather than those suggested by institutional boundaries (Lave & Wenger, 1991). In doing so, we reported on how efforts toward curricular integration were explained by embeddedness in social environments (Borgatti et al., 2009).

Connectivity across Communities of Practice

Our primary research question asked *to what degree can a STEM coach influence teachers' connectivity to STEM content expertise within and beyond a school district*? The data suggest that even in the short term, a coach can effectively connect educators to each other and to other professionals outside the school walls, breaking down some barriers to implementation. We observed significant and widespread changes to the educators' professional networks within and external to Crawford School District and there is strong evidence to suggest that this was largely due to the work and influence of the coach. These findings support other study results that have shown that policy interventions, such as time and space to collaborate can positively impact teacher social networks (Coburn et al., 2013; Daly, 2012), changes that often result in positive professional development (Prenger et al., 2017) and student outcomes (Coburn et al., 2013; Rivera et al., 2010).

Within SNT, there is a recognition of the "strength of weak ties" (Granovetter, 1983). When a network becomes loosely connected to external actors, these new ties are often associated with new ideas and innovation that become accessible to the network (Daly, 2012), a phenomenon that has been shown to be true for teacher networks (Pil & Leana, 2009). In this study, the teachers became dramatically more connected to outside expertise and teachers reported these to be valuable sources of new and complementary ideas. As would be expected, teachers found some of these new ties to be more useful than others, and this is reflected in the increased weight of some ties and the pruning of others by Time Three. Although student outcomes were not measured in this study, previous studies have shown that such ties to content expertise can have a positive impact on student learning (Bryk, 2010). While the coach was not responsible for all of the new ties to outside expertise, her central role in this process is suggested by the transition of many of the outside actors' membership in the coach's network in Time Two, to later membership in teacher networks by Time Three. The teachers' narratives also support the coach's role in facilitating many of these new and ongoing ties.

While weak ties are associated with innovative ideas, these ideas must be disseminated throughout a COP and reconstructed through practice if they are to become a part of that COP and impact outcomes (Adler & Kwon, 2002; Coburn et al., 2012). For this reason, highly connected teacher COP networks are associated with better implementation of reform initiatives (Grossman et al., 2001). While teachers in this study were making ties to the outside experts, they did not do so at the expense of their existing COPs. Rather, their networks became marginally more connected, suggesting that the ideas from outside experts were likely to be disseminated throughout the buildings. Further, we observed homophily explaining less of the collaboration over time as teachers collaborated outside of their buildings to a greater degree. This suggests that outside ideas were more likely to become situated across multiple COPs.

Our second research question asked how teachers experience and use access to STEM expertise as a function of changing professional networks and also asked what role teachers perceived for the STEM coach in that process. The coach cast a wide net by reaching out to make initial contacts with a wide array of external experts. As that network grew, the coach was also developing professional relationships with the teachers in the district, coming to understand their curricular needs, and professional abilities. With these networks and this knowledge in place, the teachers described the coach connecting them to these existing resources or find new expert resources. The coach, as a practitioner with multi-membership in teaching and STEM COPs (Wenger, 1998), was able to frame and launch the conversations between the teachers and content experts, addressing the interpersonal as well as the logistical needs of the partnership. The teachers experienced the coach as helping to maintain those relationships until they were self-sustaining or exhausted. Teachers' access to expertise via the coach was achieved through the coach's relentless pursuit of potential connections to resources and outside experts, accompanied by a big picture vision of the STEM learning that was planned or happening throughout the district.

Access to Expertise

The results of this study reflect previous research that shows partnerships with outside experts positively impact teachers' sense of professional competence (Drayton & Falk, 2006). STEM, however, represents some important differences. One of the goals of connecting teachers to STEM experts was to help those teachers integrate the disciplines of STEM. This was based on the logic that contextualizing content in real-world applications via expert STEM practice, which tends to be interdisciplinary in nature, should lead to learning contexts, which also reflect some level of integration (Vennix et al., 2017). The breadth and undefined nature of STEM also mean that, unlike a TSP, any given teacher may need to access many different COPs and may have varying degrees of membership in some of those already (English, 2016). The STEM coach attempted to help each teacher navigate to the best fit COP for their curriculum and to provide the right level of bridging, given a specific teachers' comfort with approaching that COP.

Existing research has shown that even with extended immersion into TSPs, teachers can struggle with developing a sense of membership in science COPs due to the lack of time to appropriately develop conceptual competence at the esoteric level that is privileged in science professions (Drayton & Falk, 2006). Teachers can also struggle to translate their peripheral membership in COPs back into the classroom (Stroupe et al., 2018; Varelas et al., 2005). Rather than adopting the perspective that teachers have a STEM knowledge deficit that must be fixed, or that teachers must become full members of STEM COPs, the coach was positioned to help the teachers gain access to the periphery of those STEM COPs where they would participate casually, but legitimately, as "spectator novices" (Davidson & Hughes, 2018). Our data suggest a different outcome. Rather than the teachers spectating in STEM COPs, the patterns in the networks and teacher narratives suggest that it was the STEM experts who were operating at the periphery of the teacher COPs. The data illustrated in the sociogram changes suggest that the STEM coach created a community, albeit loosely tied only through her, amongst the outside experts and then helped those experts to become part of the existing teacher networks. While this interpretation is confounded by the lack of SNA response data from the outsiders, teachers' narrative data support the conclusion. In almost every related excerpt, teachers discussed what outside partners could bring to instruction rather than how they themselves could contribute to the practices of STEM.

If the peripheries of COPs are indeed fertile areas for the diffusion of change-inducing ideas (Wenger, 1998), then perhaps it is more productive to think about TSPs from the perspective of outside experts on the periphery of teacher COPs rather than teachers on the periphery of science COPs. This may be particularly true for teachers who are trying to implement STEM and bring in a broad swath of expertise from multiple COPs. As Stroupe et al. (2018) indicate, teachers must be the gatekeepers and facilitators for how students interact with outside knowledge. This may be an impossible task if teachers must come to deeply understand the breadth of knowledge encapsulated in STEM. Rather, from a coaching perspective, it may be more efficient and effective for a coach to devise a way to bring outsiders into teaching COPs. In that role, the coach can help teachers with the skill of how to integrate content rather than the details of which content to integrate.

Coach as Central Actor

By all measures, the coach became a central actor within the Crawford School District STEM initiative, as has been shown qualitatively in other instructional coaching work (Atteberry & Bryk, 2010). This central position has been associated with the power to leverage change in a system (Borgatti et al., 2009), a result that we noted here and in more detail in previous work reporting on this project. The central position has also been associated with a need for navigating the nuance and complexity of the many ties within a network. This STEM coach was not simply a conduit of information. Rather, she understood the context, developmental level of the students, preparedness of the teacher, and content goals, helping teachers to transform otherwise disconnected experiences into a learning opportunity directly connected to bigger ideas. While some of these tasks could be assigned to individuals or committees of teachers, having all of these connectivity tasks assigned to a central actor allowed for a synergy of efforts and resources that would not be as likely if the tasks were distributed.

Responding to teacher requests for support often meant the coach reaching out to many people and gathering many resources, filtering them down to the few that she felt would work best for a given teacher. In this way, teachers often utilized ties or pathways of connectivity that they were not necessarily aware of. This meant that the coach was often communicating behind the scenes in time-consuming but ultimately productive ways. It is unlikely that teachers could find the time to establish this level of connectivity.

The network did not always evolve as expected, as exemplified by the over-reliance on the coach to the point of her becoming overly central to the middle school community by time three. We also expected to see the STEM teachers become more connected over time as other teachers sought out their expertise to meet the mandates of the STEM initiative. This did not seem to happen as the STEM teachers' connectivity did not noticeably change over the course of the study. However, the STEM teachers did tend to build stronger ties to the coach, suggesting that their expertise may have been filtered through the coach to other teachers. Teachers began to rely on connections built and strengthened by the coach and may also have started to overly rely on the coach to make these connections, even within the district. There would be efficiencies in these pathways between COPs but also a danger should the coach leave the network (Whitworth et al., 2018). In this case it clearly suggested a valuation of the coach, though it may not be an ideal outcome as the coach was an ephemeral resource. While the coach was intentional about launching these professional connections and then trying to hand them off to the teachers, explicitly communicating the structure of this process to the teachers may have helped to maintain that pattern.

Bridging and Brokering

As a central actor in a social network the coach was in a position to have an outsized impact on the structure and outcomes of the network (Borgatti et al., 2009; Daly, 2012). Central actors can develop other actor's capacity and broker skills between them (Daly, 2012). The coach was anticipated to begin the process as a "bridger" who serves as a conduit between COPs and then transitions to a "broker" to connect teachers and experts directly (Daly, 2012; Lave & Wenger, 1991). Doing so required that the coach understand the needs and resources of the teachers as well as the outside partners. She also needed to understand where those needs and resources meshed together, even when it might not have been obvious to the teachers or outside partners. Part of this task required that the coach translate some of the lingo and syntax that are deeply embedded in the worlds of education and STEM. The coach needed to navigate these different cultures and bring them together without herself becoming the lynchpin that held the relationship together.

The SNA data reflect that the coach became a strong bridge between teachers and experts and between teachers themselves, as reflected in the betweenness values and the participant narratives. Teachers valued this coach role highly and may have seen the coach as someone with "multi-membership" in their own COP as well as the experts' (Wenger, 1998) but also someone who was "just ahead" of themselves as a source of innovation rather than an inaccessible expert (Drayton & Falk, 2006). Although some brokering was reported and the coach regularly expressed the idea as a goal, the teachers seemed more comfortable with the bridging role and maintaining the coach as an intermediary, suggesting that they valued or felt more comfortable with the filtered products of the partnership (the expertise) more than the potential of an ongoing professional relationship. In some cases teachers did continue with brokered relationships and seeking out expertise on their own, similar to other cases where an instructional coach was pulled back from an initiative (Coburn et al., 2013).

Relationships as Foundations

Navigating the social and emotional landscape of a district has been repeatedly reported to be a difficulty of instructional coaching as coaches find themselves tenuously but centrally positioned between actors (Giamellaro & Siegel, 2018; Kintz et al., 2015; Marshall & Buenrostro, 2021). In this study, which combined both the interior COPs of the district and the exterior COPs of the outside experts, this navigation problem was associated with every aspect of connectivity the coach managed. While this should be expected, limits also need to be drawn to ensure that a coach only operates across ties where she is empowered to make decisions regarding the negotiations of a relationship (Matsumura et al., 2012). For example, the coach was simply not in a tenable position to act as a relationship bridger or broker between the administrators and teachers and while this was not a goal of the project, it became a de facto role within the district.

The role of interpersonal relationships was connected to all other connecting functions that the coach filled. These relationships were often helpful for initiating or maintaining the work, but at times they were also barriers when the coach was not perceived favorably or when she was not well-positioned to bridge or broker between others. We recognized the importance of interpersonal relationships (Marshall & Buenrostro, 2021), but we did not specifically train the coach to productively navigate them, relying on informal guidance and existing ability. Specifically teaching a coach how to navigate these relationships and then supporting her to do so could contribute to efficacy and sustainability of the role. This could also be helped through intentionality within the system and clearly-defined roles and responsibilities.

The role of communicator exposes a critical tension in the centrality of the coach role. While there is a much-needed service of connecting various participants through centralized communication, it is easy to develop a gap between expectations and actions and similarly easy to project the decisions and ideas onto the coach as communicator rather than the original source. Both have potentially negative implications for the perceptions and effectiveness of the coach as a district-wide connector. Within the district, she became a conduit that may have been needed but also associated her with ideas and perhaps emotions that were not actually attributable to her.

Limitations

While the mixed methods approach allowed for a multifaceted examination of these interacting networks, the complexities of these situated experiences suggests some limitations to the case study. As a small, rural district, the social networks before and during the school change transition might not be typical of larger school districts. Non-professional homophiles due to family, friendship, and other factors of living in a small community were not captured and may have limited the ability of the calculated networks to explain the diffusion of ideas. Similarly, though we methodologically mitigated non-response, this may have impacted the network metrics and representations used in the analysis.

The focus on a single coach also limits the findings, particularly given the importance of individual socio-emotional and professional skills that were underpinning all other results in this study as well as in other coaching literature. This coach brought a skill set, beliefs, assumptions, and myriad other qualities that impacted the work she did. Coaching is perhaps the most nuanced role in a school district and implementing successful coaching interventions will be well-served by a deeper empirical literature base.

Within the bounds of this study, we relied on the logic model that suggests teachers' connections to expertise will lead to some changes in how they bring that expertise and therefore breadth of situated STEM knowledge into the classroom. We also assumed that most of the new network ties were related to STEM due to the heavy emphasis within the district and way in which participants discussed their ties. While the qualitative data suggest this was borne out to some degree, a more systematic investigation tying the expert connections to classroom implementation and outcomes would make a stronger case for this logic model. We suggest this would be an important future direction for research in this field.

CONCLUSION

If student interest and development in STEM is to be successful, it must be pursued across grade levels and contextualized to appeal to the full range of student backgrounds and characteristics (Maltese et al., 2014; Sadler et al., 2012). This will not be possible without a significant mobilization of expertise representing the vast array of applied STEM made available to teachers across K-12 schools. In attempting to "do STEM" by integrating disciplines with authentic STEM people and settings (Vasquez, 2014), we found the STEM coach approach to be a successful tool to support STEM integration across a district by connecting teachers to expertise. Having a central actor allowed for rapid and widespread advancement of the initiative. Visualizing existing professional networks and monitoring their change over time would allow future practitioners or researchers to similarly take advantage of this centrality to bring new ideas into a school system and disseminate them throughout. While the data presented here do not measure the direct impact of a more connected professional network on students, these connections are likely to diversify and integrate the content, perspectives, and identities of the people students are exposed to (Atteberry & Bryk, 2010), all commonly-cited goals of STEM education (Johnson et al., 2016). Further, if this connectivity is considered as an indicator of more integrated and more contextualized instruction, there is ample evidence to suggest that student achievement should respond well to the intervention (Cervetti et al., 2012; Gilbert et al., 2011).

This study takes a step forward in addressing Gamse et al.'s (2016) call for a more systematic look at the mechanisms behind school partnerships with STEM experts. The study also addresses the call to better understand how science coordinators and instructional coaches do their work (Luft & Hewson, 2014; Whitworth et al., 2017, 2018). While this single study was situated within this small school district, influenced by the attendant politics and personalities involved, the findings suggest that there is promise for similar approaches elsewhere.

Author contributions: MG: was the principal investigator on the project & managed all aspects of research & application, including design, data collection/analysis, & district partnership & **DS:** was an embedded ethnographic researcher in the partner district during the study year, conducting most of the interviews & transcribing them as needed, conducted some of the other data collection & some of the data analysis, & contributed to the text & revisions of this manuscript. All authors have agreed with the results and conclusions.

Funding: This study was supported by funding from the Title II-A Oregon University-School Partnership Grant program [Grant Number #TRSUB14.07 (CFDA No. 84.367)] and the Oregon Department of Education's STEM Lab School Grant [Grant Number 31322].

Acknowledgements: The authors would like to thank student Alyssa Lopez for the research assistance. The authors would also like to thank all of the teachers, administrators, and the STEM coach at the partner district for the time and dedication to this project.

Ethical statement: Authors stated that the study was reviewed and approved by the Oregon State University Institutional Review Board (IRB). All related research was approved and monitored by the Oregon State University Human Subjects Institutional Review Board.

Declaration of interest: No conflict of interest is declared by authors.

Data sharing statement: The datasets generated and/or analyzed during the current study are not publicly available due to human subjects protections and the potential for identifying individual subjects. Some de-identified subsets are available from the corresponding author on reasonable request.

REFERENCES

Adler, P. S., & Kwon, S.-W. (2002). Social capital: Prospects for a new concept. *The Academy of Management Review, 27*(1), 25. https://doi.org/10.2307/4134367

Ash, D. (2007). Using video data to capture discontinuous science meaning making in non-school settings. In R. Goldman, R. D. Pea, B. Barron, & S. J. Derry (Eds.), *Video research in the learning sciences* (pp. 207-226). Lawrence Erlbaum Associates.

Atteberry, A., & Bryk, A. S. (2010). Centrality, connection, and commitment: The role of social networks in a school-based literacy initiative. In A. J. Daly (Ed.), *Social network theory and educational change*. Harvard Education Press.

Avila de Lima, J. (2010). Studies of networks in education: Methods for collecting and managing high-quality data. In A. J. Daly (Ed.), *Social network theory and educational change* (pp. 243-258). Harvard Education Press.

Baron, C. (2019). What teachers retain from historic site-based professional development. *Journal of Teacher Education, 71*(4), 392-408. https://doi.org/10.1177/0022487119841889

Beier, M. E., Kim, M. H., Saterbak, A., Leautaud, V., Bishnoi, S., & Gilberto, J. M. (2019). The effect of authentic project-based learning on attitudes and career aspirations in STEM. *Journal of Research in Science Teaching, 56*(1), 3-23. https://doi.org/10.1002/tea.21465

Blondel, V. D., Guillaume, J.-L., Lambiotte, R., & Lefebvre, E. (2008). Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment, 2008*(10), P10008. https://doi.org/10.1088/1742-5468/2008/10/P10008

Borgatti, S. P., & Ofem, B. (2010). Overview: Social network theory and analysis. In A. J. Daly (Ed.), *Social network theory and educational change* (pp. 17-29). Harvard Education Press.

Borgatti, S. P., Mehra, A., Brass, D. J., & Labianca, G. (2009). Network analysis in the social sciences. *Science, 323*, 6. https://doi.org/10.1126/science.1165821

Brenner, M. E. (2006). Interviewing in educational research. In J. L. Green, G. Camilli, & P. B. Elmore (Eds.), *Handbook of complementary methods in education research* (pp. 357-370). Routledge.

Bryan, L. A., Moore, T. J., Johnson, C. C., & Roehrig, G. H. (2016). Integrated STEM education. In C. C. Johnson, E. E. Peters-Burton, & T. J. Moore (Eds.), *STEM road map: A framework for integrated STEM education*. Routledge. https://doi.org/10.4324/9781315753157-3

Bryk, A. S. (2010). Organizing schools for improvement. *Phi Delta Kappan, 91*(7), 8. https://doi.org/10.1177/003172171009100705

Cervetti, G. N., Barber, J., Dorph, R., Pearson, P. D., & Goldschmidt, P. G. (2012). The impact of an integrated approach to science and literacy in elementary school classrooms. *Journal of Research in Science Teaching, 49*(5), 631-658. https://doi.org/10.1002/tea.21015

Coburn, C. E., & Russell, J. L. (2008). District policy and teachers' social networks. *Educational Evaluation and Policy Analysis, 30*(3), 203-235. https://doi.org/10.3102/0162373708321829

Coburn, C. E., & Woulfin, S. L. (2012). Reading coaches and the relationship between policy and practice. *Reading Research Quarterly, 47*(1), 5-30. https://doi.org/10.1002/RRQ.008

Coburn, C. E., Choi, L., & Mata, W. S. (2010). "I would go to her because her mind is math": Network formation in the context of a district-based mathematics reform. In A. J. Daly (Ed.), *Social network theory and educational change*. Harvard Education Press.

Coburn, C. E., Mata, W. S., & Choi, L. (2013). The embeddedness of teachers' social networks: Evidence from a study of mathematics reform. *Sociology of Education, 86*(4), 33. https://doi.org/10.1177/0038040713501147

Coburn, C. E., Russell, J. L., Kaufman, J. H., & Stein, M. K. (2012). Supporting sustainability: Teachers' advice networks and ambitious instructional reform. *American Journal of Education, 119*(1), 137–182. https://doi.org/10.1086/667699

Daly, A. J. (2012). Data, dyads, and dynamics: Exploring data use and social networks in educational improvement. *Teachers College Record, 114*(11), 1-38. https://doi.org/10.1177/016146811211401103

Dare, E. A., Ellis, J. A., & Roehrig, G. H. (2018). Understanding science teachers' implementations of integrated STEM curricular units through a phenomenological multiple case study. *International Journal of STEM Education, 5*, 4. https://doi.org/10.1186/s40594-018-0101-z

Davidson, S. G., & Hughes, R. (2018). Communities of practice as a framework to explain teachers' experiences within the community of science. *Journal of Research in Science Teaching, 55*(9), 1287-1312. https://doi.org/10.1002/tea.21452

Drayton, B., & Falk, J. (2006). Dimensions that shape teacher-scientist collaborations for teacher enhancement. *Science Education, 90*(4), 734-761. https://doi.org/10.1002/sce.20138

English, L. D. (2016). STEM education K-12: Perspectives on integration. *International Journal of STEM Education, 3*, 3. https://doi.org/10.1186/s40594-016-0036-1

Fontana, A., & Frey, J. H. (2000). The interview: From structured questions to negotiated text. In N. K. Denzin, & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 645-672). SAGE.

Frank, K. A., Zhao, Y., Penuel, W. R., Ellefson, N., & Porter, S. (2011). Focus, fiddle, and friends: Experiences that transform knowledge for the implementation of innovations. *Sociology of Education, 84*(2), 137-156. https://doi.org/10.1177/0038040711401812

Gamse, B. C., Martinez, A., & Bozzi, L. (2016). Calling STEM experts: How can experts contribute to students' increased STEM engagement? *International Journal of Science Education, Part B, 7*(1), 31-59. https://doi.org/10.1080/21548455.2016.1173262

Giamellaro, M., & Siegel, D. R. (2018). Coaching teachers to implement innovations in STEM. *Teaching and Teacher Education, 76*, 25-38. https://doi.org/10.1016/j.tate.2018.08.002

Gilbert, J. K., Bulte, A. M. W., & Pilot, A. (2011). Concept development and transfer in context-based science education. *International Journal of Science Education, 33*(6), 817-837. https://doi.org/10.1080/09500693.2010.493185

González-Howard, M., & McNeill, K. L. (2019). Teachers' framing of argumentation goals: Working together to develop individual versus communal understanding. *Journal of Research in Science Teaching, 56*(6), 821-844. https://doi.org/10.1002/tea.21530

Granovetter, M. (1983). The strength of weak ties: A network theory revisited. *Sociological Theory, 1*, 201-233. https://doi.org/10.2307/202051

Grossman, P., Wineburg, S., & Woolworth, S. (2001). Toward a theory of teacher community. *Teachers College Record, 103*(6), 942-1012. https://doi.org/10.1111/0161-4681.00140

Hopkins, M., Spillane, J. P., Jakopovic, P., & Heaton, R. M. (2013). Infrastructure redesign and instructional reform in mathematics. *The Elementary School Journal, 114*(2), 200-224. https://doi.org/10.1086/671935

Jacomy, M., Venturini, T., Heymann, S., & Bastian, M. (2014). ForceAtlas2, a continuous graph layout algorithm for handy network visualization designed for the Gephi software. *PLoS ONE, 9*(6), e98679. https://doi.org/10.1371/journal.pone.0098679

Johnson, C. C., Peters-Burton, E. E., & Moore, T. J. (2016). *STEM road map: A framework for integrated STEM education*. Routledge. https://doi.org/10.4324/9781315753157

Kashy, D. A., & Kenny, D. A. (1990). Do you know whom you were with a week ago Friday? A re-analysis of the Bernard, Killworth, and Sailer studies. *Social Psychology Quarterly, 53*(1), 55. https://doi.org/10.2307/2786869

Kennedy, M. M. (2016). How does professional development improve teaching? *Review of Educational Research, 86*(4), 945-980. https://doi.org/10.3102/0034654315626800

Kintz, T., Lane, J., Gotwals, A., & Cisterna, D. (2015). Professional development at the local level: Necessary and sufficient conditions for critical colleagueship. *Teaching and Teacher Education, 51*, 121-136. https://doi.org/10.1016/j.tate.2015.06.004

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press. https://doi.org/10.1017/CBO9780511815355

Lee, V. R., Leary, H. M., Sellers, L., & Recker, M. (2014). The role of school district science coordinators in the district-wide appropriation of an online resource discovery and sharing tool for teachers. *Journal of Science Education and Technology, 23*(3), 309-323. https://doi.org/10.1007/s10956-013-9465-5

Luft, J. A., & Hewson, P. W. (2014). Research on teacher development programs in science. In S. K. Abell, & N. G. Lederman (Eds.), *Handbook of research on science education*. Routledge. https://doi.org/10.4324/9780203097267

Ma, S., Herman, G. L., Tomkin, J. H., Mestre, J. P., & West, M. (2018). Spreading teaching innovations in social networks: The bridging role of mentors. *Journal for STEM Education Research, 1*(1-2), 60-84. https://doi.org/10.1007/s41979-018-0002-6

Maashi, K. M., Kewalramani, S., & Alabdulkareem, S. A. (2022). Sustainable professional development for STEM teachers in Saudi Arabia. *EURASIA Journal of Mathematics, Science and Technology Education, 18*(12), 1-14. https://doi.org/10.29333/ejmste/12597

Maltese, A. V., Melki, C. S., & Wiebke, H. L. (2014). The nature of experiences responsible for the generation and maintenance of interest in STEM. *Science Education, 98*(6), 937-962. https://doi.org/10.1002/sce.21132

Marin, A., & Hampton, K. N. (2007). Simplifying the personal network name generator: Alternatives to traditional multiple and single name generators. *Field Methods, 19*(2), 163-193. https://doi.org/10.1177/1525822X06298588

Marshall, S. A., & Buenrostro, P. M. (2021). What makes mathematics teacher coaching effective? A call for a justice-oriented perspective. *Journal of Teacher Education, 72*(5), 594-606. https://doi.org/10.1177/00224871211019024

Matsumura, L. C., Garnier, H. E., & Spybrook, J. (2012). The effect of content-focused coaching on the quality of classroom text discussions. *Journal of Teacher Education, 63*(3), 214-228. https://doi.org/10.1177/0022487111434985

McPherson, M., Smith-Lovin, L., & Cook, J. M. (2001). Birds of a feather: Homophily in social networks. *Annual Review of Sociology, 27*(1), 415-444. https://doi.org/10.1146/annurev.soc.27.1.415

Means, B., Wang, H., Young, V., Peters, V. L., & Lynch, S. J. (2016). STEM-focused high schools as a strategy for enhancing readiness for postsecondary STEM programs. *Journal of Research in Science Teaching, 53*(5), 709-736. https://doi.org/10.1002/tea.21313

Miles, M. B., Huberman, M. A., & Saldana, J. (2020). *Qualitative data analysis: A methods sourcebook*. SAGE.

Patton, M. Q. (2002). *Qualitative research and evaluation methods*. SAGE.

Pil, F. K., & Leana, C. (2009). Applying organizational research to public school reform: The effects of teacher human and social capital on student performance. *Academy of Management Journal, 52*(6), 1101-1124. https://doi.org/10.5465/amj.2009.47084647

Prenger, R., Poortman, C. L., & Handelzalts, A. (2017). Factors influencing teachers' professional development in networked professional learning communities. *Teaching and Teacher Education, 68*, 77-90. https://doi.org/10.1016/j.tate.2017.08.014

Rahm, J., & Moore, J. C. (2016). A case study of long-term engagement and identity-in-practice: Insights into the STEM pathways of four underrepresented youths. *Journal of Research in Science Teaching, 53*(5), 768-801. https://doi.org/10.1002/tea.21268

Rakap, S. (2017). Impact of coaching on preservice teachers' use of embedded instruction in inclusive preschool classrooms. *Journal of Teacher Education, 68*(2), 125-139. https://doi.org/10.1177/0022487116685753

Reiser, B. J., Michaels, S., Moon, J., Bell, T., Dyer, E., Edwards, K. D., McGill, T. A. W., Novak, M., & Park, A. (2017). Scaling up three-dimensional science learning through teacher-led study groups across a state. *Journal of Teacher Education, 68*(3), 280-298. https://doi.org/10.1177/0022487117699598

Rivera, M. T., Soderstrom, S. B., & Uzzi, B. (2010). Dynamics of dyads in social networks: Assortative, relational, and proximity mechanisms. *Annual Review of Sociology, 36*(1), 91-115. https://doi.org/10.1146/annurev.soc.34.040507.134743

Rogers, E. M. (2003). *Diffusion of innovations*. Free Press.

Roth, W.-M., & Eijck, M. V. (2010). Fullness of life as minimal unit: Science, technology, engineering, and mathematics (STEM) learning across the life span. *Science Education, 94*(6), 1027-1048. https://doi.org/10.1002/sce.20401

Roth, W.-M., & Jornet, A. (2013). Situated cognition. *Wiley Interdisciplinary Reviews: Cognitive Science, 4*(5), 463-478. https://doi.org/10.1002/wcs.1242

Sadler, P. M., Sonnert, G., Hazari, Z., & Tai, R. (2012). Stability and volatility of STEM career interest in high school: A gender study. *Science Education, 96*(3), 411-427. https://doi.org/10.1002/sce.21007

Sailors, M., & Price, L. (2015). Support for the improvement of practices through intensive coaching (SIPIC): A model of coaching for improving reading instruction and reading achievement. *Teaching and Teacher Education, 45*, 115-127. https://doi.org/10.1016/j.tate.2014.09.008

Shein, P. P., & Tsai, C.-Y. (2015). Impact of a scientist–teacher collaborative model on students, teachers, and scientists. *International Journal of Science Education, 37*(13), 2147-2169. https://doi.org/10.1080/09500693.2015.1068465

Shernoff, D. J., Sinha, S., Bressler, D. M., & Ginsburg, L. (2017). Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education. *International Journal of STEM Education, 4*, 13. https://doi.org/10.1186/s40594-017-0068-1

Shukshina, L. V., Gegel, L. A., Erofeeva, M. A., Levina, I. D., Chugaeva, U. Y., & Nikitin, O. D. (2021). STEM and STEAM education in Russian education: Conceptual framework. *EURASIA Journal of Mathematics, Science and Technology Education, 17*(10), em2018. https://doi.org/10.29333/ejmste/11184

Siegel, D., & Giamellaro, M. (2020). Defining STEM within a school district: A co-constructed and evolving process. *Cultural Studies of Science Education*. https://doi.org/10.1007/s11422-019-09959-2

Spillane, J. P., Healey, K., & Kim, C. M. (2010). Leading and managing instruction: Formal and informal aspects of the elementary school organization. In A. J. Daly (Ed.), *Social network theory and educational change* (pp. 129-158). Harvard Education Press.

Stroupe, D., Caballero, M. D., & White, P. (2018). Fostering students' epistemic agency through the co-configuration of moth research. *Science Education, 102*(6), 1176-1200. https://doi.org/10.1002/sce.21469

Toma, R. B., & Greca, I. M. (2018). The effect of integrative STEM instruction on elementary students' attitudes toward science. *EURASIA Journal of Mathematics, Science and Technology Education, 14*(4), 1383-1395. https://doi.org/10.29333/ejmste/83676

Varelas, M., House, R., & Wenzel, S. (2005). Beginning teachers immersed into science: Scientist and science teacher identities. *Science Education, 89*(3), 492-516. https://doi.org/10.1002/sce.20047

Vasquez, J. A. (2014). STEM: Beyond the acronym. *Educational Leadership, 72*(4), 10-15.

Vennix, J., den Brok, P., & Taconis, R. (2017). Perceptions of STEM-based outreach learning activities in secondary education. *Learning Environments Research, 20*(1), 21-46. https://doi.org/10.1007/s10984-016-9217-6

Wenger, E. (1998). *Communities of practice*. Cambridge University Press. https://doi.org/10.1017/CBO9780511803932

Whitworth, B. A., Maeng, J. L., & Bell, R. L. (2018). Exploring practices of science coordinators participating in targeted professional development. *Science Education, 102*(3), 474-497. https://doi.org/10.1002/sce.21337

Whitworth, B. A., Maeng, J. L., Wheeler, L. B., & Chiu, J. L. (2017). Investigating the role of a district science coordinator. *Journal of Research in Science Teaching, 54*(7), 914-936. https://doi.org/10.1002/tea.21391