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Studying STEM Faculty Communities of Practice through Social Network Analysis

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ABSTRACT

Stakeholders are increasingly calling for improving instruction in STEM by building environments that enable faculty to sustainably change their teaching practices. This study reports one institutional change effort that effectively facilitated faculty's adoption of evidence-based instructional practices (EBIP), which is to organize faculty into teaching-focused communities of practice (CoPs). We examined the social interactions of faculty within CoPs and investigated whether faculty in CoPs that were actively adopting EBIP (adopting CoPs) had more frequent conversations and collaborations around teaching with their colleagues than faculty in CoPs that did not adopt EBIP (non-adopting CoPs). A sociometric survey was administered to document 89 faculty members' social interactions within 22 CoPs. The social networks of the CoPs were compared using the social network measures of density, connectedness, centrality, breadth, and reciprocity. We found that adopting CoPs had higher density and connectedness than non-adopting CoPs while being less centralized. This result suggests that adopting CoPs used distributed leadership and included all members in communications regarding teaching, while non-adopting CoPs heavily relied on a lone hero to implement change, frequently excluding other members. These findings suggest that organizing faculty into CoPs that support regular interaction on teaching-related activities may be an effective strategy for improving STEM instruction.

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Education research often fails to cross the research–practice divide (Henderson, Beach, & Finkelstein, 2011; Maldonado, 2011; Spalter-Roth, Fortenberry, & Lovitts, 2007); thus national stakeholders are calling for post-secondary science, technology, engineering, and mathematics (STEM) instructors to adopt evidence-based instructional practices (EBIP). EBIP are instructional practices that have research-based evidence

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demonstrating their effectiveness for improving students' outcomes. Research suggests that change efforts have generally been ineffective because they tend to rely too much on individuals to create and spread innovations (Borrego, Cutler, Prince, Henderson, & Froyd, 2013; Henderson et al., 2011; Kezar, Gehrke, & Elrod, 2015). These efforts rely too much on using data to convince individuals, rather than addressing deeper barriers to change such as faculty time, personal identity, and beliefs about teaching that are shaped by the environment around the faculty (Brownell & Tanner, 2012; Henderson et al., 2018). Consequently, there has been an increased focus on using networks and communities to broker the desired change. Reports and researchers are pointing to the idea of communities of practice (CoPs) and other forms of faculty learning communities as a possible solution to the challenge of widespread adoption of EBIP (Austin, 2011; Gehrke & Kezar, 2017). CoPs can provide a supportive environment that challenges instructors' counterproductive beliefs about effective instruction while also spreading knowledge about EBIP and the beliefs that support them (Gehrke & Kezar, 2017).

This study aims to understand the social structures of CoPs that could support STEM faculty's successful adoption of EBIP. Social network analysis is increasingly being used to study how social interactions encourage faculty to change their teaching practices (Daly, 2010). Social network analysis takes the adage "it's not what you know, it's who you know" to its extreme by arguing that "who you know defines what you know" (Daly, 2010, p. 2). Social network analysis reveals that an individual's performance, their access to information, and their practices can be predicted by the characteristics of their social network and the organizational structure around them (Daly, 2010; Quardokus & Henderson, 2014). While most of this research has focused on K-12 settings, recent studies have begun to apply these techniques in post-secondary settings (e.g., Andrews, Conway, Zhao, & Dolan, 2016; Middleton et al., 2015; Quardokus & Henderson, 2015). Kezar (2014) has called for a more balanced approach in studying change in higher education that examines not only formal organizational structures but also the internal networks and social relationships that can broker change. She argues that CoPs may provide a useful lens for understanding both the organizational structures and networks that can facilitate change. We respond to this call by examining the social structures of STEM faculty CoPs that were formed to change teaching practices.

To create institutional change at a research-intensive Midwestern University, we have created two distinct, but conceptually related, programs. The first program (Program I) is based in the College of Engineering and was conceived as a mechanism to improve faculty instruction in large-enrollment (>200 students per semester) courses across the college. The second program (Program II) is a spin-off of Program I that is STEM-inclusive, marshaling faculty from multiple colleges to stimulate the adoption of EBIP across STEM. These programs sought to organize faculty into CoPs to create a supportive environment through which faculty might emergently adopt EBIP (Beach, Henderson, & Finkelstein, 2012; Henderson et al., 2011).

At Midwestern University, we have a deeply collaborative research culture, but a fiercely independent teaching culture. To tailor our change initiative to our institutional culture (Kezar & Eckel, 2002), Programs I/II focused on encouraging faculty to translate their collaborative research practices into collaborative teaching practices. These programs used CoPs to create a new culture of collaborative, joint ownership of courses (this process is described more fully in the Methods section), in which a CoP, rather than an individual, determines which teaching practices to use.

In this paper, we present a social network analysis that compares the network characteristics of faculty CoPs that adopt EBIP (adopting CoPs) and those that do not (non-adopting CoPs). We have examined the whole-network structure of Programs I/II in other publications (Authors), so we focus this study by treating each CoP as a separate unit of analysis. We compare complementary network characteristics to provide deeper insights into the structure and relationships within these CoPs. Through social network analysis we investigate two research questions:

(1) What insights do different network characteristics provide when they are used to examine faculty teaching networks?
(2) Among the social network measures, which characteristics differ between adopting and non-adopting CoPs?

Background

Calls for change in higher education are abundant, yet change is often elusive (Kezar, 2009), particularly in STEM (Henderson et al., 2011; Kezar et al., 2015). Researchers and change agents in STEM have amply documented the barriers to changing teaching practices (Allen & Tanner, 2005; Barker, Hovey, & Gruning, 2015; Brownell & Tanner, 2012; Finelli, Richardson, & Daly, 2013). While change is indeed hard and there are many barriers to better teaching practices, organizational change theories and social network theory mutually reveal many possible avenues to change (Beer, 2007; Colquitt et al., 2013; Daly, 2010; Wenger, 1998). Organizational change theories reveal the importance of capitalizing on external pressures for disrupting organizations, creating senses of justice or trust, shared values, organizational learning, and networks for brokering change (Beer, 2007; Kezar, 2005; Kotter, 2012). Social network theory corroborates many of these findings revealing that change can be brokered by the informal social interactions and structures within an organization rather than solely by the formal administrative structures and units (Daly, 2010; Kezar, 2014).

Programs I/II have focused on disrupting the operational norms of faculty to promote collaboration around instruction and organizational learning on how to teach effectively. This change strategy seeks to create a culture of collaboration around teaching and does not prescribe what EBIP faculty should use. This structural change has been brokered by rallying faculty around a common threat of rapidly increasing enrollment at our institution. Enrollments have increased disproportionately in STEM (e.g., 55% growth in the College of Engineering over 10 years).

Faculty and students are dissatisfied with the large, passive lecture courses on our campus—faculty are demoralized by the added workload and administrative overheads, while students expect the courses to be more personally engaging. Teaching effectively at scale remains a challenge for our organization, and profound learning within the organization is needed to address this challenge. It is apparent that there is an urgent need to change the status quo and create intrinsic motivations for faculty to enjoy teaching more and for students to improve their learning experiences. We chose CoPs as a theoretical framework for designing our change effort and studying its effects.

Communities of practice

Communities of practice are defined by their domain, practice, and community (Wenger, McDermott, & Snyder, 2002). CoPs are a group of people defined by their common interest in a domain of knowledge, such as teaching (Wenger et al., 2002). CoPs members are, first and foremost, practitioners whose participation in the CoP is focused on improving practices within the domain (Wenger et al., 2002). CoP members develop shared stories, tools, and ways of addressing problems. The community is characterized by joint activities and discussions that share information and help members learn from each other (Wenger et al., 2002). CoP members may not always be together, but they engage regularly enough for this learning and sharing of knowledge to occur (Iaquinto, Ison, & Faggian, 2011). In this study, our CoPs were encouraged to meet weekly as they focused on the practice of teaching a large-enrollment STEM course.

CoPs are typically located within a single organization but its members may only be loosely affiliated or their affiliations may span organizational boundaries. Indeed, there are studies on CoPs that span organizations, particularly through the creation of online or virtual communities of practice (Kezar, Gehrke, & Bernstein-Sierra, 2017). Our study focuses on CoPs within a single institution with some CoPs spanning departmental boundaries. Regardless of scope, there are design principles for creating effective CoPs (Iaquinto et al., 2011).

CoPs focus less on formal structures or roles and more on capitalizing on the community's own agency and energy (MacDonald, 2008; Wenger et al., 2002). Consequently, CoPs should be designed to grow and emerge in response to changes in membership, the interests of members, and their goals (Iaquinto et al., 2011). Further, CoPs should have a regular rhythm or cycles of activities that can maintain engagement with the community without becoming overwhelming (Wenger et al., 2002). Additionally, effective CoPs should have open, collaborative dialogue within and outside their CoP, helping members learn from each other while avoiding group think by inviting new and challenging ideas into the community (Kezar et al., 2017). These findings about CoPs resonate with the structural holes theory from social network analysis, which argues that strong connections between individuals can support deep learning and the creation of institutionalized knowledge, while bridging connections between groups can spark innovation and creativity (Burt, 2004). In Programs I/II, CoPs were designed to capitalize on the common threat of increasing enrollments, to mobilize the agency of the faculty in our CoPs. The regular cycles of delivering courses each term and conducting weekly meetings were intended to promote critical collaborative discussions without becoming burdensome. By providing mentors, we created avenues for CoPs to be infused with ideas from other CoPs.

CoPs can provide an environment for challenging resistant professional identities and beliefs that cause faculty to resist adopting EBIP. Surrounding faculty with respected colleagues can mitigate the perception of identity threat (Wenger et al., 2002). By providing a highly collaborative organizational structure, faculty have a long-term context in which to learn new practices (Lave & Wenger, 1991; Wenger, 1998; Wenger et al., 2002). Through this process, CoPs foster mutual trust and reflective engagement (Wenger, 1998; Wenger et al., 2002), and in such a context, assumptions and beliefs about teaching can change implicitly (Davenport & Prusak, 2000; Hildreth & Kimble, 2002). This type of learning can decrease the learning curve for novices, reduce creation of redundant resources or reenactments of failures, and promote creativity (Lesser & Storck, 2001).

Wenger et al. (2002) describe three levels of participation in CoPs: core, active, and peripheral. Core members often act as leaders, participating intensely in both discussions and activities. Active members are also active in both discussions and activities, just not as intensely as the leaders. Finally, peripheral members are primarily involved through discussing community practices. New CoP members frequently join a CoP on the periphery, observing and learning group norms before becoming more involved (Wenger et al., 2002). Members can move between these levels of participation in any direction over time, so being on the periphery does not necessarily indicate seniority in the CoP. The level and types of interactions within a CoP may be readily observed through social network analysis. Our study explores this connection.

Social networks and changing teaching practices

Social network analysis describes how networks affect the spread of beliefs, behaviors, and diseases (Daly, 2010). These studies have revealed that the characteristics of one's social network is predictive of how well an individual will perform on a target task or achieve desired goals. While social network analysis has been used in a variety of contexts, a majority of research studies on teaching practices have focused on elementary and secondary educational settings (Daly, 2010), revealing how social networks can improve students' outcomes or increase the use of desired teaching methods among instructors (Judson & Lawson, 2007; Neal, Neal, Atkins, Henry, & Frazier, 2011; Penuel, Riel, Krause, & Frank, 2009). These studies have found that increased social connections are predictive of the use of effective instructional practices (Judson & Lawson, 2007). Elementary school teachers who productively changed their teaching methods had more connections with experienced and novice teachers than teachers who did not productively change their teaching methods (Penuel et al., 2009). Neal et al. (2011) found that teachers were more likely to change their teaching practices if they saw a peer using a teaching method than if they saw a mentor using the same technique.

While these studies provide insights into the importance of social networks for improving teaching, faculty in post-secondary contexts have multiple social networks such as research collaborations that may or may not be related to their teaching networks (Quardokus & Henderson, 2015). Accordingly, studies have generally relied on co-authorship or citation networks to study faculty behaviors (Kezar, 2014; Xian & Madhavan, 2014). Few studies have examined how the social networks of faculty influence their teaching practices, though Spalter-Roth, Mayorova, Scelza, and Vooren (2010) found that 75% of sociology faculty primarily teach alone and thus lack the social capital to effectively change their practices.

Social network analysis provides many measures for describing the structure of social interactions (see Figure 1 for illustrations of these measures). Density indicates the degree of dyadic connection in a network. Networks with high density have many interpersonal connections within the community. Connectedness complements density by indicating whether a network is structured as a single cluster or several smaller clusters. High connectedness means that members in a CoP can easily access each other. Centralization indicates the extent to which connections are associated with one or a few people in the network. In a highly centralized CoP, each member of the network connects to a central person who moderates all dyadic communications. However, in a distributed CoP, each member can reach out to others

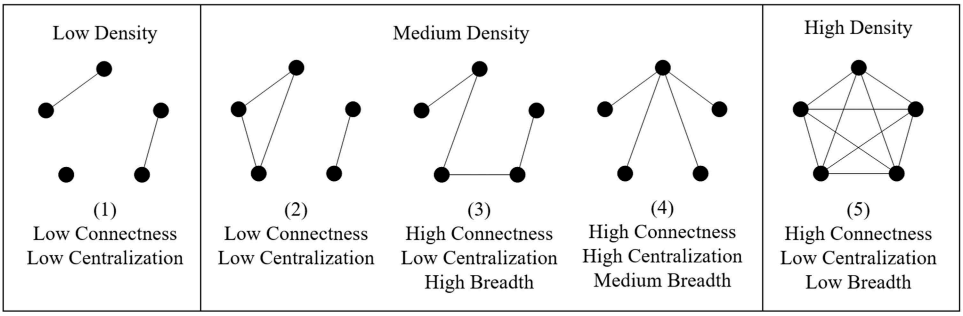

Figure 1. Examples of how different network parameters reveal characteristics of the network.

directly. Transitivity is a measure of group cohesion based on presence of transitive relations; i.e., friend of a friend. High transitivity indicates that members in a CoP are tightly connected (Wasserman & Faust, 1994).

Our study is among the first attempts to study the relationship between these network connections within a community of post-secondary faculty and changes in teaching practices. Quardokus and Henderson (2015) revealed that social network analysis is an effective method to capture the informal structure of teaching discussion networks of academic departments and they proposed that network-level measures such as *density, centralization*, and *transitivity* might inform change initiatives. Middleton et al. (2015) found preliminary evidence suggesting that faculty who have more and deeper teaching network connections, measured by *density* and *connectedness*, are more likely to use learner-centric approaches. Andrews et al. (2016) found that collegial interactions such as sharing teaching-related resources or providing social support were associated with life sciences faculty's change in teaching views and practices. Collegial interactions were related to network characteristics such as *density* and *transitivity*.

In this study, we compare the features and structures of adopting and non-adopting CoPs based on five network characteristics: density, connectedness, centralization, breadth, and dyad reciprocity. We use *breadth* as a measure of network cohesion instead of *transitivity* because we are more interested in pairs rather than triads in this study. Breadth is an inverse measure of cohesion—communication is less effective if it takes longer for each member to reach others. In a high-breadth CoP, the connection between two people must travel through several other people. In a low breadth CoP, each person can connect directly with each other. Additionally, we use *dyad reciprocity*. Reciprocity indicates whether two CoP members agree that they have interacted. A reciprocated relationship in active conversation or collaboration on teaching-related activities indicates a stronger connection or bond, as compared to the cases that only one partner claims (Tschannen-Moran, 2001).

To summarize, we attempt to achieve two research goals in this study: 1) to examine network characteristics that provide meaningful insights for understanding faculty teaching networks, and 2) to investigate the differences between adopting and non-adopting CoPs with respect to the five network characteristics. It is expected that a CoP with high density and connectedness (all members connect with every other person), low centralization (no person is the central focal point), low breadth (all members are only one link from every other person), and high reciprocity will generally support learning and increased performance between all group members (i.e., a structure similar to Network 5 in Figure 1).

Methods

Structure of the change programs

Program I is a competitive, internal grant program created by the College of Engineering to improve the quality of the large lecture courses on our campus and to enable faculty to explore strategic teaching practices such as improving students' teamwork or design skills in other courses. A call for proposals is issued to all faculty once a year. Faculty generate their own ideas for course reforms and submit proposals to participate. In these proposals, faculty must articulate why their proposed changes to a course or set of courses are strategic and innovative. More importantly, the faculty must demonstrate that there is a team of at least three faculty members who believe that the proposed course changes are needed and worth pursuing. This requirement for submitting a proposal is the basis for creating a CoP that will execute the proposed innovation or reform. Proposed projects are funded for at most three years and are funded at varying levels based on the resource needs of the project. Continued funding for up to three years for these CoPs is contingent on their ability to develop sustainable reforms in teaching. These CoPs are mentored by a mixture of faculty development personnel from the College of Engineering and engineering faculty members, identified as Education Innovation Fellows. These fellows were chosen because they were advocates for high-quality teaching in the college.

Program II is an externally funded program that was inspired by Program I. This program is a STEM-inclusive program that focused on studying the scalability and transferability of Program I beyond the college. The CoPs in Program II were formed by engaging faculty from across the university to work collaboratively in teaching much like how they work collaboratively in research. The emphasis in Program II is on creating CoPs rather than on providing funding to create change. The program offers modest funding to

CoPs (about $4,000 to $15,000 per year) to provide summer salary to faculty or enable a CoP to hire an extra teaching assistant to support their changes. Most CoPs do not spend their allocated funds. The PIs on the Program II grant (two of which are Education Innovation Fellows) mentor each of the CoPs in the same way as the mentors in Program I.

Program I funded 17 CoPs prior to the 2015–2016 school year (when data collection was completed). Similarly, Program II had added five new CoPs beyond the CoPs in Program I. These 22 CoPs comprise the population for our study. Because of their similarity of structure and goals, we refer to Program I and Program II as a single program for the remainder of the paper.

Measures

Sociometric survey

The sociometric survey (see Appendix) was derived from Quardokus and Henderson (2015). Their survey sought to identify the teaching networks of faculty within a department by asking faculty to identify with whom they talked about teaching and the frequency of their interactions. Because the goal of our project was to identify the teaching networks of faculty within our institutional change efforts, we used the survey to collect whole-network data of the participants of Programs I/II.

We modified the Quardokus and Henderson (2015) survey to match the constraints of our project. First, whereas the original survey was designed to map the networks of departments with the largest department being 44 members, our programs span 18 departments and 142 faculty with only subsets of faculty from each department. Consequently, faculty were asked to describe the frequency of their interactions with every member of Programs I/II. Second, during pilot testing, we found that faculty did not like the terminology of "daily/weekly/monthly" as they did not know how to categorize relationships that fluctuated in frequency. The ratings of never, occasionally, and frequently were preferred. Third, because the structure of our intervention was to create CoPs, we decided to distinguish between conversations and collaboration: collaboration is more indicative of deeper involvement, such as seen by core or active members of a CoP, whereas talking can be indicative of peripheral involvement in a CoP or even occur outside a CoP. Consequently, we added an additional category for types of interactions and provided more definitions of teaching, talking, and collaboration than Quardokus and Henderson. Faculty were explicitly told that collaborations are any interaction that moved beyond conversations and led to action such as co-teaching a course or co-designing a survey or test.

CoP evaluations

Each CoP was evaluated by the leadership teams of the individual programs as “adopting” (continued funding in Program I or no intervention required in Program II) or “non-adopting” (discontinued funding in Program I or substantial intervention needed in Program II) according to the performance data collected by the evaluation team. We establish good validity for this evaluation based on the characteristics of the evaluators, the nature of the evaluation criteria, and the breadth and depth of observations of the reviewers.

First, the CoP evaluation was conducted by a diverse panel of faculty and staff who understood and valued the use of EBIP and desired to see their implementation. The leadership team was composed of educational researchers, faculty development personnel, and faculty with a track-record of using EBIP. These evaluations served as the leadership team’s indication to the CoPs whether they believed that these CoPs were successful in adopting EBIP. Each CoP was independently reviewed by at least three different members of the leadership team and any faculty who had a conflict of interest with the CoP being reviewed left the room during deliberations about that CoP. Independent reviewers for Programs I/II have maintained an inter-rater agreement rate of 88% (number of agreements divided by the number of ratings) on the overall rating of CoPs as adopting or non-adopting. Disagreements were resolved through deliberations and consensus building among the leadership team.

Second, the evaluation criteria used to inform these evaluations were informed by the research literature on change and CoPs (Block, 2009; Kezar, 2005; Wenger et al., 2002). The review criteria were designed to evaluate whether the faculty CoPs were creating a supportive environment that supported the emergent adoption of EBIP (Henderson et al., 2011). The review criteria evaluated CoPs based on their process and their outcomes. Each CoP’s process was evaluated on whether they were provided with an environment to enact their emergent changes (administrative support) and whether they engaged in mutual reflection and improvement as a community (collaborative development). Each CoP’s outcomes were evaluated based on whether faculty adopted EBIP or collected evidence to inform their decision making (faculty outcomes); documented evidence of improved student outcomes related to learning, retention, or diversity (student outcomes); and documented evidence that the team could sustain their efforts after funding ceased (sustainability and trajectory). These five review criteria were used to inform the final overall evaluation of the CoP as adopting or non-adopting and align strongly with the goal of measuring whether the CoPs were sustainably adopting EBIP.

Third, the reviews were informed by deep and broad observations of the CoPs. At least one of the raters attended the weekly meetings of the CoP being evaluated (if the CoP had one) and was deeply familiar with the CoP’s team dynamics and achievements. These ratings were also informed by biannual self-reports from the faculty CoPs and from evaluation data collected by graduate research assistants from the College of Education who were part of an external program evaluation team. This evaluation data was compiled from weekly observations of CoP meetings, classroom observations, and interviews with CoP members.

We also note that these ratings of the CoPs were completed prior to, and independent from, the collection and analysis of the social network data. To further minimize bias, an independent research assistant who was not affiliated with Programs I/II conducted the social network analysis and accompanying statistical analysis.

Data collection

We administered the 15-minute sociometric survey to all 120 members of CoPs in Programs I/II. We collected surveys using both paper surveys and online surveys that mirrored the paper surveys. A research assistant administered the paper survey during CoP meetings. Online surveys were administered via e-mail solicitation from the research assistant. We collected 26 paper surveys and 65 online surveys for a total of 91 responses (75% response rate). Of those 91 responses, two were not included in the data analysis because one respondent left the university shortly after Programs I/II began and another respondent submitted an incomplete survey. Therefore, the final dataset includes 89 CoP participants.

Of those 89, 64 are male and 25 are female. Sixty-two participants (70%) are Caucasian, 13 (15%) are Asian (including both Asian Americans and international faculty members from Asian countries), and the remaining 14 (15%) are from other ethnic groups or unwilling to provide the information. These participants were recruited from 15 STEM disciplines. The dataset includes 26 full professors, 20 associate professors, 16 assistant professors, and 27 non-tenure-track faculty. Although we collected whole-network data for the entire program, our focus in this study is characterizing the networks of the 22 individual CoPs and comparing the characteristics of adopting and non-adopting CoPs.

If a participant was involved in multiple CoPs, they are listed only under the first CoP they joined. We made this decision because two CoPs were created by pairs of members who had previously worked together in a prior CoP. This process strongly suggests that these pairs worked closely together in their initial CoP making it impossible to determine what network data could be attributed to the second CoP. This decision caused these two CoPs to be removed from analysis. Table 1 presents group size and response rate for each CoP and distribution of participants by CoP. The distribution information includes number of male and female faculty in the CoP, number of Program I/II mentors

Table 1. Distribution of participants by community of practice (CoP).

Community	Adoption of EBIP[1] (A; N)	Group Size	Survey Respondents[2]	Response Rate (%)	Gender (M; F)	Full Prof.	Assoc. Prof.	Assist. Prof.	Non-tenure track faculty
CoP 1	N	3	1(2)	100	1M	0	0	1	0
CoP 2	A	5	5	100	4M; 1F	2	0	2	1
CoP 3	N	4	2(2)	100	1M; 1F	0	2	0	0
CoP 4	N	8	4	50	2M; 2F	2	1	1	0
CoP 5	A	8	4	50	3M; 1F	1	0	0	3
CoP 6	A	5	3	60	2M; 1F	1	0	0	2
CoP 7	N	13	9	69	8M; 1F	3	4	0	2
CoP 8	A	3	3	100	2M; 1F	0	1	0	2
CoP 9	N	3	3	100	2M; 1F	1	1	0	1
CoP 10	A	7	7	100	6M; 1F	1	1	0	5
CoP 11	N	8	5	63	4M; 1F	0	1	2	2
CoP 12	A	4	3	75	2M; 1F	0	2	1	0
CoP 13	N	6	3	50	2M; 1F	1	2	0	0
CoP 14	A	3	3	100	2M; 1F	2	0	1	0
CoP 15	N	7	4	57	3M; 1F	2	1	0	1
CoP 16	A	8	7	88	5M; 2F	1	1	5	0
CoP 17	N	3	3	100	1M; 2F	0	0	0	3
CoP 18	N	5	4	80	3M; 1F	3	1	0	0
CoP 19	A	4	4	100	4M	3	1	0	0
CoP 20	A	5	3	60	1M; 2F	1	0	0	2
CoP 21	A	4	2	50	1M; 1F	0	0	1	1
CoP 22	A	8	7	88	5M; 2F	2	1	2	2

Note. [1]CoPs are categorized as adopting (A) or non-adopting (N) based on ratings from the leadership teams of Programs I/II.
[2]Participant interactions were analyzed only for the first CoP participants joined. Parentheses indicate members who had joined other CoPs first.

in the CoP, and number of faculty at different academic rank. Non-adopting CoPs had slightly lower response rates than adopting CoPs (the average response rate of adopting CoPs was 81%; the average response rate of non-adopting CoPs was 77%), but both response rates were higher than the recommended 60–70% recommended by Borgatti, Carley, and Krackhardt (2006).

Data analysis

The present study investigated the frequency of interactions that a STEM faculty member has with another faculty member within their CoP in terms of having conversations about teaching or actively collaborating on teaching. These conversations and collaborations are represented with a network tie that connects the two network nodes that represent the two faculty members. Two social networks are created—one is a *conversation network*, which is based on whether two faculty members have ever talked about teaching; and the other is a *collaboration network*, which is based on whether two faculty members actively collaborated on teaching. The collaboration network is a strict subset of the conversation network as collaboration requires conversation but goes beyond it.

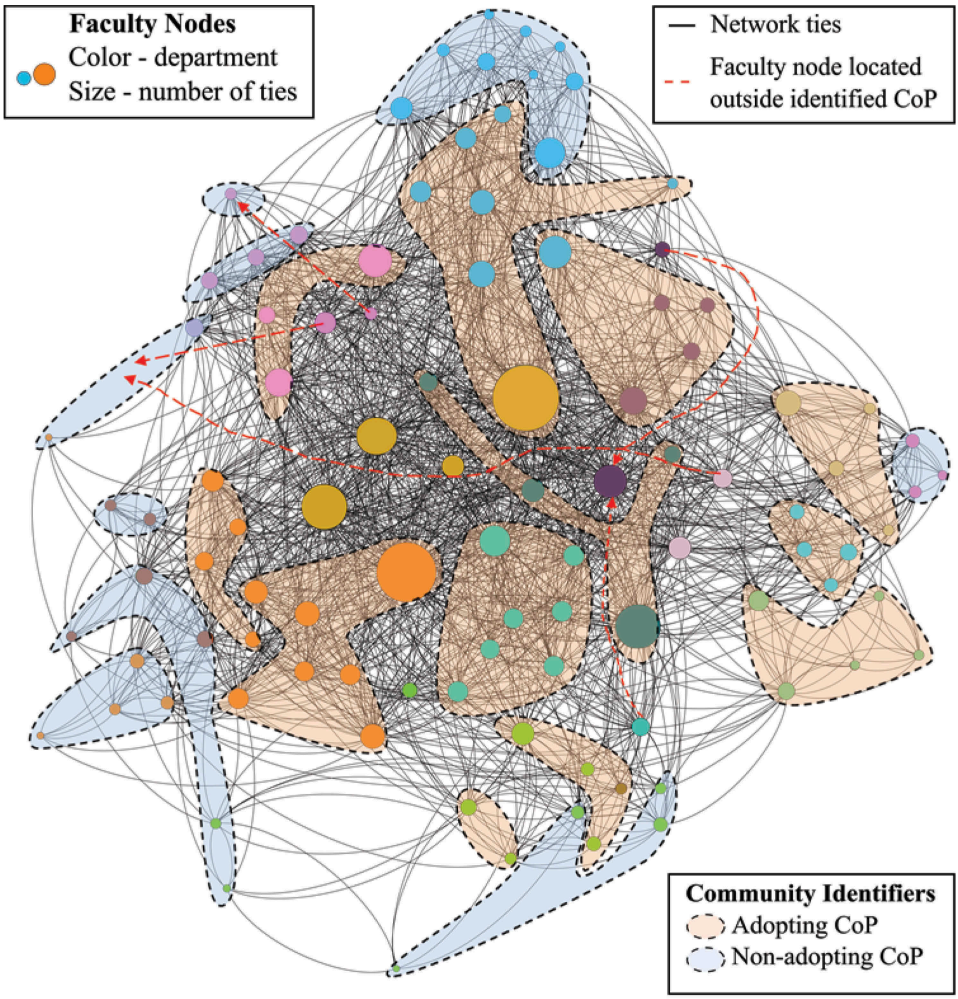

Figure 2. The conversation network of adopting and non-adopting communities showing all ties.

Network visualization

To illustrate the validity of using social network analysis for studying faculty CoPs, we present a visualization of the conversation and collaboration networks (Figures 2, 3, and 4) to demonstrate that algorithmically formed clusters in the network based on the sociometric survey align with Program I/II's documented CoPs. The visualization of social network is performed in a network visualization software Gephi (Bastian, Heymann, & Jacomy, 2009) based on individual's average number of ties with others, using ForceAtlas2 layout algorithm (Jacomy, Venturini, Heymann, & Bastian, 2014). The position of a node is determined by the interaction of attraction forces and repulsion forces acting on the node, which is proportional to its distance to every other node in the network.

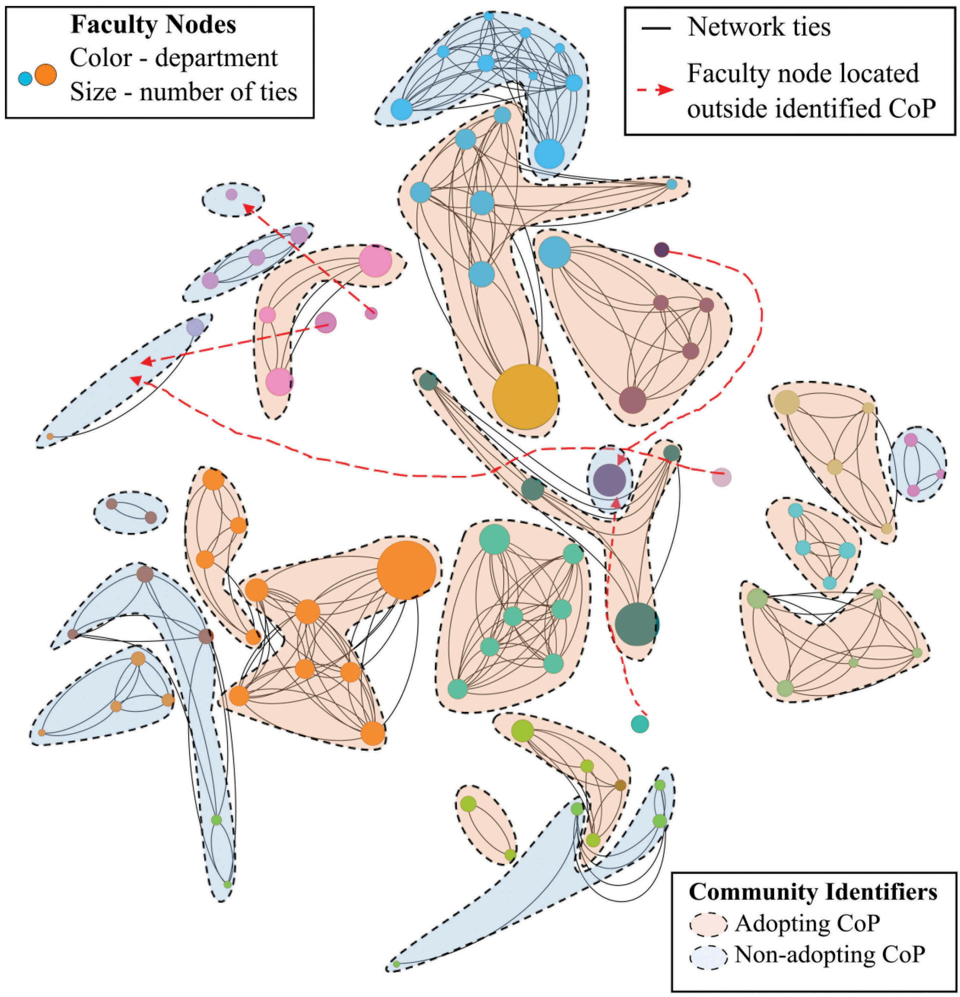

Figure 3. Conversation network of adopting and non-adopting communities showing only intra-CoP ties.

Network comparison

We used UCINET (Borgatti, Everett, & Freeman, 2002) to calculate our five network metrics: *density, connectedness, centralization, breadth*, and *reciprocity*. We compared differences in these metrics between adopting and non-adopting CoPs. Table 2 presents calculations for the five metrics and offers hypotheses for how the adopting and non-adopting CoPs will differ according to each metric. Three CoPs (CoPs 1, 3, and 21) contained one or two members, so they were not included in the analysis due to a lack of degrees of freedom to derive network characteristics. The final dataset for the analysis of network characteristics included 19 CoPs that

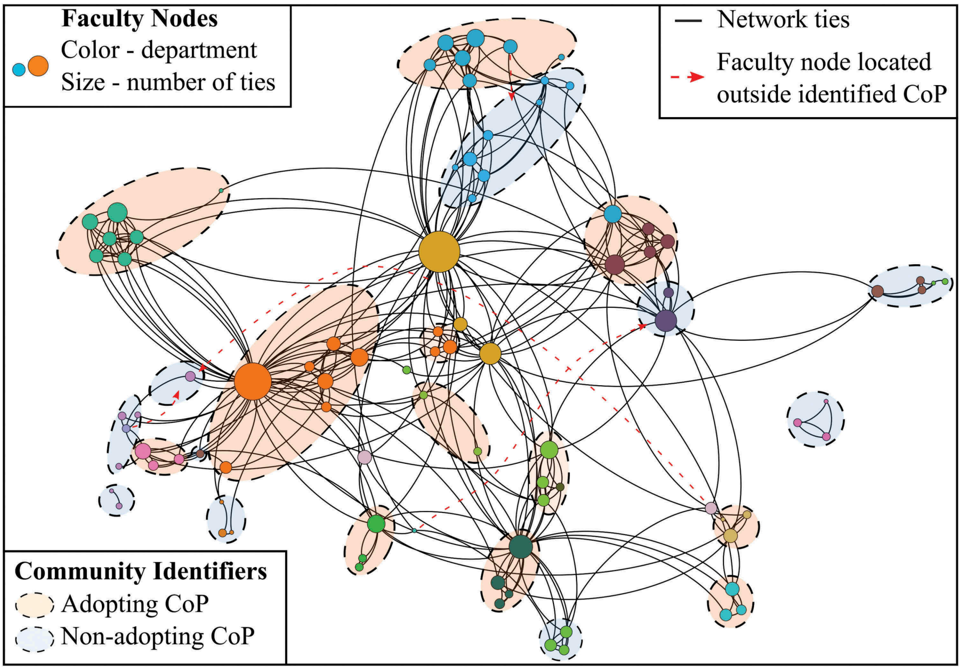

Figure 4. The collaboration network of adopting and non-adopting communities showing all ties.

Table 2. Summary of social network analysis measures discussed in this paper.

Metric	Calculation	Hypothesis
Density	Proportion of actual ties to all possible ties existing in the network.	Density is expected to be *higher* in adopting CoPs than non-adopting CoPs.
Connectedness	Proportion of pairs of nodes that reach each other by any path to all possible number of connected pairs of nodes.	Connectedness is expected to be *higher* in adopting CoPs than non-adopting CoPs.
Centralization	Sum of the differences between the degree of each node and the maximum node degree divided by the theoretical maximum of this number.	Centralization is expected to be *lower* in adopting CoPs than non-adopting CoPs.
Breadth	$B = 1 - \frac{\sum_{i,j} \frac{1}{d_{ij}}}{n(n-1)}$ d_{ij} is the geodesic distance from i to j, n is the number of nodes, and $1/d_{ij}$ is defined to be zero for unconnected nodes.	Breadth is expected to be *lower* in adopting CoPs than non-adopting CoPs.
Dyad reciprocity	Proportion of reciprocated connections in the network (directed network).	Dyad reciprocity is expected to be *higher* in adopting CoPs than non-adopting CoPs.

contained 3–9 team members, including 11 adopting CoPs and 8 non-adopting CoPs.

Each network characteristic was compared between adopting and non-adopting CoPs using Welch's *t*-test to reflect the unequal variance between the two populations. Each of these five t-tests was applied to both the conversation and collaboration networks. We used an additional set of t-tests to explore how the conversation and collaboration networks varied (i.e., do the conversation and collaboration networks for the adopting CoPs reveal different network characteristics?). Individual level predictors such as gender and academic rank were not included because this study examined the behavior of CoPs, not the behavior of individuals. The amount of funding provided for CoPs was also not included in the model because it showed no correlation with performance of the CoPs (Spearman's correlation $\rho = -0.19$). Since the present study aims to explore the utility of the various metrics and is the first study that examines the network characteristics of faculty CoPs, we are primarily concerned with failing to reject the null hypothesis (i.e., minimizing type II error), which suggests using a large α value, $\alpha = 0.10$. As we perform multiple hypotheses tests, we choose Bonferroni-adjusted p value as the cut-off point, $\alpha = 0.02$. Effect sizes are reported using Cohen's d.

Results

The conversation network

Visualization of conversation network

We visualize the conversation network, whether two faculty talked about teaching, in Figure 2. The ForceAtlas2 algorithm (Noack, 2007) moves connected nodes closer together, visually aggregating existing communities. Each faculty member is represented by a circle: the size of a circle is determined by an individual's average ties (i.e., larger nodes are more connected) and the color indicates that faculty member's department (e.g., the large yellow nodes represent college administrators). A line between two circles indicates that two faculty members have had conversations about teaching-related activities. Dashed circles were added manually and represent the 22 CoPs. The fill color (light orange or light blue) of the dashed circles indicates whether a CoP was rated as adopting or non-adopting, respectively. There are a few cases in which an individual is far from their assigned community—a dashed red line with an arrow is used to indicate where that faculty member belongs.

The network visualization demonstrates that the social networks of faculty reveal in part the CoPs that faculty engage in. Faculty members generally cluster close enough to each other to allow for boundary lines between the CoPs to be drawn. The clustering is sensitive enough to reveal cross-departmental CoPs and multiple CoPs within a department. For example, the blue circles at the top of the diagram are all faculty members from the same department. The faculty from this department clustered into three CoPs: one intra-departmental non-adopting CoP (top), one intra-departmental adopting CoP (below the latter), and one inter-departmental adopting CoP (below and to the right). Notably, there are five nodes that are far enough from their CoPs that a different CoP lies directly between that node and its associated CoP. Each of these nodes are from non-adopting CoPs.

The network visualization reveals a couple other salient clusters in the network when accounting for all network ties. First, faculty teaching networks form strongly around departmental affiliations (i.e., nodes with the same color appear in clusters). Second, adopting CoPs cluster closer to the center of the network while non-adopting CoPs exist primarily on the periphery of the network.

Network characteristics in conversation network

To compare the structure of the conversations within CoPs, we considered only the intra-CoP network ties (see Figure 3), creating a set of 19 sub-networks. A summary of all statistical tests for the conversation network are summarized in Table 3. Members of adopting CoPs were more likely to talk to one another about teaching-related activities as shown by the high density of network, $t(df = 7) = 4.12$, $p = .004$, 95% CI [0.13, 0.47] with a large effect size ($d = 2.24$). There was no significant difference in connectedness between adopting CoPs and non-adopting CoPs, $t(df = 7) = 1.74$, $p = .13$, 95% CI [−0.05, 0.33]. Both adopting and non-adopting CoPs had high connectedness in their conversation network – all the adopting CoPs and a majority (63%) of the non-adopting CoPs were fully connected. The non-adopting CoPs were found to be more centralized than adopting CoPs, $t(df = 7) = -4.15$, $p = .004$, 95% CI [−0.65, −0.18] with large effect size ($d = 2.25$), indicating that communication about teaching was more likely to flow through an individual or small set of individuals in the non-adopting CoPs. Adopting CoPs were more cohesive (low breadth) while non-adopting CoPs were more spread out (high breadth), $t(df = 7) = -3.01$, $p = .019$, 95% CI [−0.39, −0.05] with large effect size ($d = 1.65$). The large effect sizes reveal a stark difference in the composition of the adopting and non-adopting CoPs.

A total of 1222 reciprocated ties and 505 unreciprocated ties were observed in the network, which suggested that 71% of the participants reported that they talked to each other. Members of adopting CoPs did not differ from

Table 3. Comparison of adopting and non-adopting CoPs' conversation networks (N = 19).

	Adopting CoPs M (SD)	Non-adopting CoPs M (SD)	Mean difference	Welch's *t*	Effect size (Cohen's *d*)	95% Confidence Interval
Density	0.98 (0.04)	0.68 (0.20)	0.30*	4.12	2.24	[0.13, 0.47]
Connectedness	1.00 (0.00)	0.86 (0.23)	0.14	1.74	0.96	[−0.05, 0.33]
Centralization	0.04 (0.07)	0.46 (0.28)	−0.42*	−4.15	2.25	[−0.65, −0.18]
Breadth	0.01 (0.02)	0.23 (0.20)	−0.22*	−3.01	1.65	[−0.39, −0.05]
Reciprocity	0.96 (0.07)	0.78 (0.23)	0.18	2.16	1.16	[−0.01, 0.38]

M = mean, SD = standard deviation; * $p < 0.02$.

members of non-adopting CoPs in having a reciprocated conversation with their colleagues, $t(df = 7) = 2.16$, $p = .064$, 95% CI [−0.01, 0.38].

The collaboration network

The visualization of collaboration network

The collaboration network was built on whether two faculty members actively collaborated on teaching. The network visualization in Figure 3 was generated in the same way as the conversation network. This network visualization reveals generally the same observations as the conversation network, but it is considerably easier to observe the formation of CoPs in the collaboration network than in the conversation network.

Network characteristics in collaboration network

To compare the structure of the CoPs, we again considered only the intra-CoP network ties. All statistical tests for the collaboration network are summarized in Table 4. Like the conversation network, members of adopting CoPs were more likely to collaborate around teaching-related activities as shown by the higher network density, $t(df = 11) = 4.88$, $p < .001$, 95% CI [0.25, 0.65] with large effect size ($d = 2.41$). In contrast with the conversation network, adopting CoPs were more connected than non-adopting CoPs in their collaboration networks, $t(df = 10) = 5.73$, $p < .001$, 95% CI [0.33, 0.74] with large effect size ($d = 2.87$). This finding reveals that non-adopting CoPs involved fewer members in collaborations. Additionally, unlike the conversation network, there was no evidence of a difference in centralization between the adopting and non-adopting CoPs for the collaboration network, $t(df = 13) = -1.01$, $p = .33$, 95% CI [−0.47, 0.17]. During collaboration, both types of CoPs rely on a few key members. Like the conversation network, the adopting CoP networks had less breadth than the non-adopting CoP networks, $t(df = 11) = -5.52$, $p < .001$, 95% CI [−0.69, −0.30] with large effect size ($d = 2.75$), indicating shorter communication channels. The large effect sizes again reveal a stark difference in the composition of the CoPs.

The overall collaboration network contained 220 reciprocated ties and 135 unreciprocated ties, which suggested that 62% of the participants reported

Table 4. Comparison of adopting and non-adopting CoPs' collaboration networks ($N = 19$).

	Adopting CoPs M (SD)	Non-adopting CoPs M (SD)	Mean difference	Welch's *t*	Effect size (Cohen's *d*)	95% Confidence Interval
Density	0.74 (0.15)	0.29 (0.22)	0.43*	4.88	2.41	[0.25, 0.65]
Connectedness	0.86 (0.14)	0.33 (0.23)	0.53*	5.73	2.87	[0.33, 0.74]
Centralization	0.39 (0.29)	0.55 (0.34)	−0.16	−1.01	0.49	[−0.47, 0.17]
Breadth	0.20 (0.14)	0.69 (0.22)	−0.49*	−5.52	2.75	[−0.69, −0.30]
Reciprocity	0.68 (0.18)	0.36 (0.42)	0.32	2.01	1.05	[−0.04, 0.68]

M = mean, SD = standard deviation; * $p < 0.02$.

that they collaborated with each other. Like the conversation network, there was not a significant difference between members of adopting CoPs and members of non-adopting CoPs in having reciprocated collaboration with their colleagues, $t(df = 8) = 2.01$, $p = .080$, 95% CI [−0.04, 0.68].

The difference in characteristics between conversation and collaboration network

The study also compared the differences of the five network characteristics between conversation network and collaborative network for adopting CoPs and non-adopting CoPs. The results are presented in Table 5. These tests revealed that the conversation networks for adopting CoPs were significantly denser, $t(df = 11) = 4.82$, $p < .001$, $d = 2.06$, 95% CI [0.13, 0.34], more connected, $t(df = 10) = 3.13$, $p = .011$, $d = 1.33$, 95% CI [0.04, 0.23], more cohesive (i.e., had less breadth), $t(df = 10) = -4.24$, $p = .002$, $d = 1.81$, 95% CI [−0.28, −0.09], and more reciprocal, $t(df = 12) = 4.84$, $p < .001$, $d = 2.06$, 95% CI [0.13, 0.34], than the corresponding collaboration network. The same held true for the non-adopting CoP networks except that no significant difference was found in reciprocity: density, $t(df = 13) = 3.58$, $p = .003$, $d = 1.79$, 95% CI [0.15, 0.61]; connectedness, $t(df = 13) = 4.61$, $p < .001$, $d = 2.30$, 95% CI [0.28, 0.77]; breadth, $t(df = 13) = -4.29$, $p < .001$, $d = 2.14$, 95% CI [−0.69, −0.23]; and reciprocity, $t(df = 10) = 2.48$, $p = .031$, $d = 1.24$, 95% CI [0.05, 0.80].

In contrast, the adopting CoPs' conversation networks were significantly less centralized than their collaboration networks, $t(df = 11) = -3.99$, $p = .002$, $d = 1.70$, 95% CI [−0.55, −0.16]. However, the non-adopting CoPs' conversation networks revealed no evidence of a difference in centralization when compared with their collaboration networks, $t(df = 13) = -0.57$, $p = .58$, $d = 0.29$, 95% CI [−0.43, 0.25]. This finding suggests a fundamental difference in the social interactions surrounding teaching in the non-adopting and adopting CoPs.

Table 5. Comparison between two types of networks of adopting and non-adopting CoPs.

	Conversation M (SD)	Collaboration M (SD)	Mean difference	Welch's *t*	Effect size (Cohen's *d*)	95% Confidence Interval
Adopting CoPs						
Density	0.98 (0.04)	0.74 (0.15)	0.24*	4.82	2.06	[0.13, 0.34]
Connectedness	1.00 (0.00)	0.86 (0.14)	0.14*	3.13	1.33	[0.04, 0.23]
Centralization	0.04 (0.07)	0.39 (0.29)	−0.35*	−3.99	1.70	[−0.55, −0.16]
Breadth	0.01 (0.02)	0.20 (0.14)	−0.19*	−4.24	1.81	[−0.28, −0.09]
Reciprocity	0.96 (0.07)	0.68 (0.18)	0.28*	4.84	2.06	[0.13, 0.34]
Non-adopting CoPs						
Density	0.68 (0.20)	0.29 (0.22)	0.39*	3.58	1.79	[0.15, 0.61]
Connectedness	0.86 (0.23)	0.33 (0.23)	0.53*	4.61	2.30	[0.28, 0.77]
Centralization	0.46 (0.28)	0.55 (0.34)	−0.09	−0.57	0.29	[−0.43, 0.25]
Breadth	0.23 (0.20)	0.69 (0.22)	−0.46*	−4.29	2.14	[−0.69, −0.23]
Reciprocity	0.78 (0.23)	0.36 (0.42)	0.42	2.48	1.24	[0.05, 0.80]

M = mean, SD = standard deviation; * $p < 0.02$.

Faculty members in adopting CoPs are likely to rely on a central person or team to facilitate collaboration, but everyone can start a conversation about teaching-related activities with others on their own. For the non-adopting CoPs, it appears that a central person or team was essential for both collaboration and conversations around teaching. This type of centralization can create bottlenecks in the flow of information within the community.

Discussion

The social network analysis reveals three core findings. First, the social network structures of the adopting CoPs reveal greater cohesion with larger core and active memberships than non-adopting CoPs. Second, the social network structures suggest that there is more abundant and more efficient information sharing among the adopting CoPs than the non-adopting CoPs. Third, all of the chosen network characteristics appear to provide meaningful information about faculty teaching networks, but all five measures may not be needed in future studies.

Alignment between community of practice theory and social network structures

CoPs are characterized by three different levels of engagement: core, active, and periphery (Wenger et al., 2002). We operationalize participation at a core or active level as engaging in collaboration within the CoP, peripheral participation as engaging only in conversations within the CoP, and a lack of participation as engaging in neither conversation or collaborations within the CoP. Given these definitions, we discuss the differences in the core–periphery structures of the adopting and non-adopting CoPs.

We observe that the adopting CoPs had larger core/active memberships than the non-adopting CoPs. The adopting CoPs have significantly higher density (0.74 vs. 0.29) and connectedness (0.86 vs. 0.33) in their collaboration networks than the non-adopting CoPs (Table 4). While active collaboration was the norm in the adopting CoPs, it was unlikely in the non-adopting CoPs. Additionally, the adopting CoPs actively engaged all peripheral members in dialogue (100% connectedness with 98% of possible ties in conversation networks) but non-adopting CoPs failed to engage all peripheral members (86% connectedness) and had less cohesive group conversations (only 68% of possible ties being connected). Together, these two observations reveal that the adopting CoPs were generally more cohesive and did more to mobilize and engage their memberships to create change.

In addition to greater cohesion among adopting CoPs, we observe significant differences in how dialogue and activities were distributed. Adopting

CoPs had significantly lower breadth in conversations and collaborations than non-adopting CoPs, revealing that adopting CoPs more closely involved all members in conversations and collaborations. Both types of CoP have cores smaller than their total membership, as revealed by their moderately centralized collaborations (Wenger et al., 2002); but the non-adopting CoPs were also centralized in their conversations, while the adopting CoPs were not. These findings suggest that the adopting CoPs were a single cohesive community in which a few members were more active and collaborative, whereas the non-adopting CoPs had a weaker sense of community in which a few members brokered both conversations and collaborations. Peripheral members of non-adopting CoPs engaged primarily with central figures and rarely with other peripheral members.

We assert that the network analysis reveals a *core–periphery* structure for the adopting CoPs and a *hero–periphery* structure for the non-adopting CoPs. The core–periphery structure of adopting CoPs is characterized by active and distributed engagement by all members of the CoP. In contrast, the "hero" model for the non-adopting CoPs reveals a community that exists to support the heroes and their efforts rather than to create a community through which all members learn. Peripheral members of these communities interact only with the "hero" and not the broader community, and as we saw in our CoP evaluations, peripheral members do not adopt the reforms adopted by the heroes. The structural differences between the adopting and non-adopting communities are accompanied by large effect sizes, revealing that these differences are not subtle. Even despite the small sample size, there is strong support in the data for the importance of creating faculty communities that mutually support and sustain the adoption of EBIP (Gehrke & Kezar, 2017; Henderson et al., 2018). These differences suggest that social network analysis may be a useful tool for change agents to monitor the potential effectiveness of CoPs, diagnose potential problems, or potentially identify emergent CoPs that could be nurtured and leveraged for change.

Social networks and information flow

The adopting CoPs have higher density, more connectedness, and less breadth than the non-adopting CoPs. Network density and connectedness in the adopting CoPs is at or near 100%, which means that all members of the CoP are included in teaching conversations, whereas the non-adopting CoPs did not involve all purported members (connectedness below 100%). Chow and Chan (2008) have documented that organizational members working in high-density social networks are more inclined to share knowledge with others because sharing is considered as a social norm in the network. In addition, people working in highly connected networks also receive greater social pressure in terms of sharing knowledge because they need to maintain good communication with colleagues in order to build good relationships (Chow & Chan, 2008). Therefore, a high density of adopting CoPs reveals that there is likely much more communication in the adopting CoPs than the non-adopting CoPs. This higher level of communication suggests higher levels of knowledge sharing and higher potential for learning.

High density, more connectedness, and less breadth also indicate that the social networks of adopting CoPs have a more balanced power structure. Tsai (2002) reports that the frequency of social interactions among organizational members has a highly positive effect on knowledge sharing. However, knowledge sharing is less likely to occur in organizations that have a hierarchical structure (i.e., high centralization). Having a more distributed power structure may be critical in enabling the adopting CoPs to enact more EBIP.

Methodological recommendations for future studies

Both types of CoPs had high reciprocity for both their conversation and collaboration networks. A lack of reciprocity in networks can indicate popularity or status of an individual within the network, as less popular individuals aspire to have connections with these popular individuals (Ball & Newman, 2013). The high dyad reciprocity in the networks suggests participation in the CoPs is not related to earning favor with other faculty and that centralization is due to activity levels and not popularity or social aspirations. Consequently, dyad reciprocity may not be the most useful measure for studying teaching CoPs in future studies.

For this study, breadth is nearly perfectly anti-correlated with density. Given the small size of the faculty CoP networks, there are not sufficient degrees of freedom for breadth and density to provide different perspectives on these networks. Given the complexity of calculating breadth relative to density, density appears to be the preferable metric. Future studies could likely focus solely on density, connectedness, and centralization to understand the dynamics of faculty teaching CoPs (cf. Middleton et al., 2015; Quardokus & Henderson, 2015).

Future work

The whole-network visualizations revealed what appears to be a core–periphery structure when accounting for the interconnections between the CoPs (i.e., the adopting CoPs cluster toward the center while non-adopting CoPs exist on the periphery). Future studies will need to explore the nature of these inter-CoP connections. Future studies could treat the CoPs as supernodes and examine the social networks that exist between the CoPs. Alternatively, future studies could examine the social networks of individuals to better understand how new adopting CoPs could be readily formed.

Future research will also seek to examine correlations between the presented social network parameters and the amount of EBIP used in lectures by participants of Programs I/II relative to non-participants. We also plan to track the spread of EBIP across the social network to identify what social network patterns lead to the spread of innovations across CoPs. While this study provides insights into what social structures of CoPs may make them effective and which social network metrics can help us identify them, these follow-on studies will provide more insights into understanding the value of CoPs in promoting the effective use of EBIP among STEM faculty.

Conclusion

While the idea of organizing STEM faculty into CoPs to stimulate the adoption of EBIP has had theoretical support from the literature, this study provides the first evidence for what network structures in a faculty CoP can lead to sustained improvement in instruction. Our findings confirm the expectation that social network analysis may be useful in understanding faculty teaching communities and that CoPs may provide a useful lens for interpreting social network data (Kezar, 2014; Quardokus & Henderson, 2015). Our findings suggest that the model of collaborative joint ownership of reforms can be brokered when a few key members may drive the reforms and actively engage all members of a community in distributed decision making regarding those reforms. This constant communication and cohesion across the entire community may lead to the learning and improved teaching performance that has long eluded efforts to change individual STEM faculty who make their teaching decisions in isolation.

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Appendix

First Page of the Sociometric Survey

This survey is part of an ongoing evaluation of Program I and Program II. This survey should take around 5 minutes to complete and will evaluate the structure and outcomes of Program

I/Program II and not the performance of individuals. The survey contains a list of faculty who have had official roles in Program I/Program II projects during the 2013–2014 and 2014–2015 school years.

The survey is part of a social network analysis to help map the spread of information and teaching methods across Program I/Program II. We ask you to characterize the frequency of your interactions with each person in the survey. Please indicate the frequency with which you either *talked* and/or *collaborated* with an individual about *teaching-related activities* during each school year (definitions are below). For example, if you attended a monthly curriculum committee meeting with Jane Doe for 2013–2015 (12 meetings per year) and worked on a subcommittee to co-develop a course proposal for 10 meetings during 2013–2014, your entry for Jane Doe would look like the entry below. Please use your best estimates of these interactions based on your recollection. Use may use either frequencies or total number of interactions, whichever is easier. **An empty row will be interpreted as "Never Interacted about Teaching," so you may skip rows or departments**.

The final question of the survey will ask you to identify 5 people who have been most impactful in your teaching-related activities.

Definitions

Teaching: includes in-class instruction, course design, curriculum design, education research
Talk: Any personally directed communication, including collaborations, about teaching-related activities (e.g., 1-on-1 conversation, attendance at a small meeting (<20 people) during which you interacted, personal e-mail correspondence)
Collaboration: Any jointly-owned, coordinated effort to change or sustain teaching-related activities (e.g., co-teaching a course, redesigning a course together, co-design a class survey or test). Collaborations move beyond conversation to action.